# DESIGN AND CONDUCT OF A WINDSHEAR DETECTION FLIGHT EXPERIMENT

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## Summary

A description of the design and conduct of a series of flight experiments which tested the performance of candidate windshear detection devices is presented. With prototype windshear sensors installed, a NASA Boeing 737 test aircraft conducted numerous low altitude penetrations of microburst windshear conditions. These tests were preceded by extensive preparations which included piloted simulations, determination of safe operating limits, and the development of unique flight test hardware, displays, and procedures.

The test aircraft and more than 50 research and support personnel were deployed to Orlando, Florida, and Denver, Colorado, during June and July 1991 for field testing. Upon receiving a forecast of developing weather activity, the aircraft crew launched and proceeded to the storm location, guided by uplinked ground radar information and voice communications with ground weather personnel. The tests required constant monitoring of numerous factors including aircraft flight parameters, ground obstructions, windshear magnitude, lightning, escape routes, ATC coordination, storm cell development, and others.

The flight tests were extremely successful, safely recording more than 25 low altitude microburst windshear and strong gust front approaches and penetrations, along with completing a full test matrix of additional requirements related to windshear sensor performance. Data quality from the tests was excellent and indicates strong potential for airborne remote sensors to accurately predict and warn the flight crew of hazardous windshear conditions with ample time for precautionary crew action.

## Notations

| | |
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| $\gamma_p$ | Potential Flight Path Angle |
| T | Thrust |
| D | Drag |
| W | Weight |

## Introduction

Windshear refers to a change in windspeed in a given direction over a particular distance or length of time. As early as airplanes began to fly, windshear has been present, though most windshear is not hazardous to an aircraft in flight. For example, an aircraft may descend from the jet stream to low altitude and experience a shear in excess of 200 knots. The direction in which the wind is blowing may change through a full 180° during the course of a flight. Also, the wind field through which an aircraft is flying may grow or diminish greatly in strength over time. All of these events can be correctly called 'windshear' but may have no impact on an aircraft's continued safe flight.

A certain subset of windshears, however, may be of critical impact to flight safety during low-altitude, low-speed flight. An aircraft in the takeoff and landing phases of flight has minimal excess energy since both altitude and airspeed are low. Moreover, a large, transport-type aircraft cannot readily change its energy state in this flight phase since deployed high-lift devices and landing gear result in high drag and jet engine response to throttle commands can take some time (and the option to trade altitude for airspeed is minimally or not available at all).

A flight safety hazard exists if a sustained energy reducing windshear (decreasing headwind, downdraft, or increasing tailwind) takes away aircraft energy faster than engine thrust can add it back. In such a condition, the aircraft is forced to either reduce airspeed or descend Given a low airspeed, low altitude initial condition, either option may be hazardous. Additionally, late application of full thrust by the pilot or, in fact, thrust reductions (in an attempt to initially maintain glide slope speed and altitude) during an energy increasing shear which often precedes hazardous shear can more easily lead to an accident.

A weather condition called a microburst can generate hazardous low-altitude windshear. A microburst is formed when a column of air at high altitude quickly cools due to evaporation of ice, snow or rain and, becoming denser than the surrounding atmosphere, falls rapidly to the ground. Upon nearing the ground, the downward moving air spreads rapidly in all directions away from the descending core (Figure 1). Windspeed changes in excess of 40 meters per sec-ond (80 knots) over 4 kilometers have been recorded in such events.

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An aircraft flying through the center of a microburst first experiences a performance-enhancing increasing headwind which is rapidly followed by a performance-degrading sequence of decreasing headwind, downdraft, and increasing tailwind. A metric termed 'F-factor' has been developed by NASA researchers which quantifies the aircraft performance loss that a specific windshear produces.[1] An added 'atmospheric' term to the standard $\gamma_p=(T-D)/W$ performance equation, the F-factor is nondimensional and relates to the equivalent specific excess thrust (thrust minus drag divided by weight) required to maintain steady flight conditions due to the changing winds. Since a typical twin engine turbojet transport category aircraft may have engines capable of producing a specific excess thrust of 0.17 (maximum thrust at maximum gross weight), a microburst which produces a sustained shear of greater than 0.17 F-factor exceeds the performance of the aircraft. This aircraft would then be forced to either lose airspeed, altitude, or both, regardless of pilot control inputs.

Another way of looking at the F-factor quantity is as the reduction of potential climb angle a given windshear takes away from an aircraft's performance capability. A sustained shear with an F-factor index of 0.14 results in an approximately 8° reduction in potential climb angle capability (0.14 radians = ~8°). Since a typical 4-engine transport aircraft at maximum gross weight has a maximum potential climb angle of less than 6°, this shear would again necessarily cause an airspeed or altitude loss.

An important consideration in determining the impact of a given shear or F-factor level is the length of time over which the aircraft is exposed to the shear. Very quick wind changes which do not persist over a significant distance are categorized more properly as turbulence than hazardous windshear. Although turbulence can indeed be a safety issue, this is more so because of controllability or aircraft structural impact than energy loss considerations. Windshears which are of importance to the energy state of an aircraft are those which result in F-factor values near the maximum specific excess thrust of a particular aircraft (Figure 2) and which persist at that average magnitude over approximately 15 seconds or more.

## Background

Inadvertent encounters with low-altitude windshear are a leading cause of transport aircraft accidents and passenger injuries and fatalities. Since 1964, windshear has been a causal factor in at least 26 U.S. air carrier accidents, resulting in over 500 fatalities and 200 injuries.[2] In 1986, NASA and the FAA signed a Memorandum of Agreement (MOA) to establish a joint program to investigate the feasibility of remote airborne windshear detection and measurement. In 1990, this MOA was expanded to include the integration of both airborne and ground-based windshear measurement information.

Piloted simulation tests have shown that as little as 20 seconds of advanced warning of hazardous windshear conditions allows a pilot to add engine power and fly through even very strong windshear conditions with minimal altitude or airspeed loss.[3] A variety of sensor technologies which could provide this early windshear warning have been investigated and developed at NASA Langley Research Center and by industry over the past 5 years. This research has included the study of the basic atmospheric physics and meteorology of microbursts which spawn windshear conditions, numerical simulation of windshear velocity, precipitation and thermal fields[4] and simulation of the potential measurement performance of candidate sensor technologies.[5] Based upon these studies, Doppler radar, lidar, and passive infrared technologies all showed promise in providing airborne forward-looking windshear detection.

NASA Langley has also developed an advanced algorithm formulation which calculates the F-factor windshear index level due to the shear immediately surrounding the aircraft. In addition, NASA has developed algorithms which process data transmitted to the aircraft from ground-based Terminal Doppler Weather Radar combined with aircraft measured data to generate an F-factor index.

## Research Hardware and Aircraft Installations

Except for the lidar system which is to be tested in 1992, research implementations of each of the above-mentioned windshear detection systems have been installed on NASA Langley Research Center's Boeing 737 research aircraft. A brief description of the background, design, function and aircraft installation of each system is detailed below:

Radar: By applying Doppler processing algorithms to the received signal from an airborne radar, the line-of-sight velocity of the reflecting medium can be determined. Separating the ground return ('clutter') signal from the desired airborne precipitation velocity signal (from which windspeed is derived) is the chief limiting factor in airborne radar Doppler processing. Since 1986, NASA Langley has developed and refined a radar and ground clutter simulation model to investigate radar design and signal processing methods to allow an airborne radar to accurately detect and measure hazardous windshear.[6] Synthetic aperture radar data from multiple airport sites has been stored in a data base to model stationary terminal area ground clutter levels and moving clutter targets have been modeled on the roads and highways surrounding the airport terminals and approach corridors. Against these clutter sources, parametric variations in radar design features have been investigated to determine the feasibility and potential design of an airborne radar windshear detection system.

Based upon these research simulation studies, Rockwell Collins, Inc., modified a Model 708 X-band weather radar system to NASA specifications, which allow research variation and output of basic radar parameters. NASA then designed and integrated a complete radar operation, processing, display, and data recording station for airborne research.

The components of this system are shown in Figure 3. The research radar receiver/transmitter (R/T) unit was installed in the forward galley area of the test aircraft in parallel with a standard Collins Model 708 R/T installed in a lower electronics bay forward of the nose landing gear. Both systems used a common flat plate antenna accessed through a wave guide switch. Additionally, a 2,000 watt high power amplifier could be connected via a second wave guide switch to increase the output power of the research radar. The radar control pallet (Figure 4) was located in the rear of the aircraft and operated by two research engineers.

The research radar typically operated with a ±30 degree azimuth scan and a variety of antenna elevation tilt control strategies. The signal processor produced multiple research display formats including range/azimuth reflectivity, velocity, and F-factor shear hazard maps (Figures 5-7). When the research radar was in operation, the standard weather radar was not operable, though the aircraft pilot could readily switch off the research radar system and return to operation and display of the standard system if required.

Infrared: Since a microburst is formed by a column of cool air rapidly descending through warmer ambient air, a warm/cool/warm temperature sequence is typically experienced by an aircraft penetrating through a microburst. A forward-looking infrared device which can sense temperatures well ahead (~5 km) of an aircraft may be able to identify this thermal signature, the magnitude of which tends to correlate with the total windspeed change across the microburst. Important to the success of such an instrument is the uniqueness of the thermal signature--that is, whether non-hazardous atmospheric conditions present similar temperature differences--and the degree to which a temperature difference which does exist in a microburst accurately correlates with the actual windshear hazard.

An instrument developed by Turbulence Prediction Systems of Boulder, Colorado (with partial support from a NASA Small Business Innovative Research (SBIR) contract) has been installed on the research aircraft. The device is mounted in a forward left side cabin window and receives atmospheric infrared energy through a small periscope assembly exterior to the aircraft (Figure 8). A hazard index based upon the differential between long range (3 - 5 km) and ambient temperatures is computed in real time internal to the device and, along with numerous other infrared system parameters, monitored, displayed (Figure 9), and recorded on the aircraft's data system.

In Situ: As both an independent research development to improve current generation reactive windshear alerting systems and to provide the forward-look research sensors an accurate 'truth' measurement during research flight testing, NASA has developed an advanced in situ windshear measurement algorithm. Fully described in reference 7, this algorithm provides the vertical, horizontal, and total F-factor shear index value of an aircraft's immediate environment based upon airspeed, accelerometer, angle of attack, groundspeed, and other aircraft sensor inputs. The algorithm includes filtering equations to reduce turbulence feed-through.

The in situ algorithm has been extensively tested in both piloted simulation and in a hot bench laboratory utilizing flight software code. Following this development effort, the software was implemented on the research aircraft microvax computers for real-time operation. A display of various algorithm values and outputs was also designed and implemented on the research aircraft to allow real-time monitoring of windshear levels encountered during microburst penetrations (Figure 9).

Terminal Doppler Weather Radar (TDWR): The FAA is currently implementing a program to develop and install powerful ground-based Doppler radar systems for windshear detection at major terminal areas around the country. This TDWR program is now in the final testing stage under the direction of MIT Lincoln Laboratories and utilizes a prototype radar system installed near Orlando International Airport for field testing. Additionally, a similarly capable TDWR-type research radar is operated by the National Center for Atmospheric Research and provides windshear alert support to Stapleton International Airport in Denver, Colorado. As presently configured, both radars produce a display used by air traffic control personnel which identifies areas of wind divergence above a given threshold in proximity to runway approach and departure paths. ATC personnel then include windshear caution and strength information as part of takeoff and landing clearances.

As part of the NASA/FAA joint program in windshear sensor research, NASA is investigating methods of automatically transmitting and displaying TDWR-derived windshear measurements to an aircraft via radio data link. In addition, further airborne processing of the TDWR wind divergence information with other aircraft sensor data allows for the computation and display of a TDWR-based, F-factor index.

An automatic data link using VHF packet radio equipment has been implemented on the NASA research aircraft. Wind divergence location, magnitude, areal extent and other information are transmitted to the aircraft for further processing and onboard display (Figure 10). This information is updated approximately once per minute as the TDWR radar completes a full scan sequence.

## Research Facility

The test aircraft is a Boeing 737-100 pre-production model modified for experimental purposes with a fly-by-wire research cockpit in the passenger cabin and an extensive suite of sensor and data recording equipment (Figure 11). A diagram of the location of the research systems is shown in Figure 12. The aircraft is powered by two Pratt and Whitney JT8D-7 engines and operated with a standard 737 control system from the forward flight deck (FFD). The aircraft may also be controlled by the research flight deck (RFD) located in the aircraft cabin. RFD control inputs are made through variable-feel sidearm controllers and modified by advanced automatic flight control software operating in one of two general purpose microvax computers. The second microvax primarily controls inputs to eight multi-function color displays in the RFD, with presentation formats including Primary Flight Displays (PFD), moving map navigation displays, engine parameters, and checklists. Engine power is controlled through either fully automatic or manual throttle inputs. When the RFD is in operation, the FFD pilots function as flight safety monitors and can disengage the research flight system at any time. Figure 13 shows the standard arrangement of the RFD.

The aircraft is equipped with two VHF, one UHF, and three intercom voice communication channels. Guidance, navigation, and control inputs utilize an Air Data/Inertial Reference System (ADIRS), GPS, MLS, multiple augmented control modes, and a variety of other research systems. Approximately 22-30 research and support personnel participate onboard during a typical research flight.

More than 500 parameters are recorded on the aircraft's primary magnetic tape data system in flight. Four videotape systems record the PFD and navigation primary displays as well as images from a forward-looking camera mounted in the nose of the aircraft and a second camera located in the Research Flight Deck. Three eight-channel stripchart recorders are available for research use. The research radar and lidar systems also include additional high-speed, magnetic-tape recorders for the high data volume research requirements of each system.

## Flight Test Design

The objective of NASA's Windshear Airborne Sensors Flight Test Program is to safely develop, validate, and demonstrate advanced windshear sensor technologies over a representative range of meteorological and other operational environments. A fundamental philosophy which shaped the design and operation of the test flights was the use of the in situ algorithm to be the 'truth' measurement of true windshear magnitude. Thus, a forward-looking sensor in continuous operation could compare predicted shear hazard values with in situ measurements as the aircraft flew through or near a position in space previously sampled by the remote sensor. Close agreement between a forward-looking sensor and an in situ measurement would indicate that both the sensor can accurately measure shear hazard from a remote distance and, importantly, that atmospheric windshears are of slow enough evolution that an accurate remote measurement 3-5 km in front of the aircraft is a good estimate of actual shear magnitude 30 to 60 seconds in the future. Both of these conditions are required for the success of a forward-looking windshear detection system.

The specific goals of the 1991 flight test program were threefold. First, the operational feasibility of TDWR/aircraft data communication and the performance of an airborne algorithm to process TDWR data into windshear information was to be evaluated and demonstrated. Second, clear air airborne radar ground clutter measurements were to be collected at multiple airport locations along different runway approach paths to assess moving and fixed ground clutter suppression techniques. Third, the most difficult and critical test was to evaluate the windshear detection performance of the IR, radar, and in situ systems in actual atmospheric and operational conditions.

## Flight Operations and Safety Simulation

In order to establish windshear flight test operating procedures and confirm safety margins for actual flight testing, a flight operations and safety simulation was conducted using the NASA Langley Transport Systems Research Vehicle (TSRV) fixed-base piloted simulation facility. The simulation used the standard TSRV 737 math model which incorporates performance data in look-up tables based upon wind tunnel and flight tests. An Attitude Control Wheel Steering flight control mode only was utilized. The standard TSRV RFD displays were masked as appropriate to only simulate display information available in the forward flight deck of the research aircraft, where all windshear penetrations were flown. The analytic, symmetric Bowles/Oseguera microburst model[8] was used to simulate microburst winds. A computer-generated image of the Denver area was utilized as a visual scene and included lightning effects and a transition to and from zero visibility upon entering and exiting the microburst. Continuous moderate turbulence was modeled using Dryden model root mean square velocities of 4 ft/s in all axes.

A number of parameters were varied to investigate operating limits and procedures. Initial aircraft altitude was set to 500, 750, and 1000 feet above ground level. Since flight operations were to be conducted at both Denver and Orlando sites, the Denver site conditions of approximately 5200 ft MSL base altitude was used. Initial indicated airspeeds of 150, 175, 200, and 225 knots were evaluated. A reactive-type shear warning light enabled approximately 5 seconds after shear entry was compared to a no automatic warning condition. Aircraft gross weight performance effects were evaluated at both 85,000 and 95,000 pounds. Shear penetrations were flown both directly through the microburst center and offset to the side to evaluate the effects of possible additional lateral control requirements. Four shear levels were tested, varying from an F-factor averaged over 1 kilometer of approximately 0.2 to approximately 0.4. These shear magnitudes can be roughly categorized as strong to extremely strong.

Four research pilots participated in the simulation and each flew the entire test matrix. Each pilot was briefed on the simulation setup and design. Control strategy for the shear penetrations was to approach the microbursts at a constant initial altitude and airspeed and, upon penetrating through the shear, add power as required while minimizing first altitude loss and secondly, airspeed loss. (This strategy was desired for flight test purposes since in situ measurement comparisons with predicted shear strength was desired at the same altitude, though not necessarily at the same airspeed.) A number of familiarization runs with the simulation procedures began each simulation session. The shear test cases were run in a random order so the shear strength was not known to the pilot prior to shear entry. Post-run statistical calculations included analyses of minimum and maximum altitude, airspeed, angle of attack, normal acceleration, pitch attitude, engine pressure ratio, and F-factor index.

Simulation results showed that for complete flight test safety, a minimum initial altitude of 750 feet and initial airspeed of 200 knots were appropriate. Microburst wind variations with altitude did not significantly impact flight performance or control, nor did laterally offset penetrations away from the microburst core. The onset of the shears was readily apparent to the flight crew based upon careful monitoring of standard flight instruments and was recognized quicker than the 5 second delayed automatic warning. For even the most severe windshear cases, the maximum angle of attack was less than that required to reach the stick shaker limit (~11°) for all penetrations which began at 200 knots or greater airspeed. The highest workload task during these tests was in power management, and all pilots anticipated that actual flight conditions which included a two-person crew would significantly improve throttle control. Finally, for each pilot, flight control technique and aircraft performance management improved with simulation experience, an expected result of 'learning' the simulation, but also a desired result in preparation for actual flight testing.

## Flight Test Safety and Planning

Based upon the conduct and results of the simulation tests described above, and upon anticipated research and flight operations requirements, six overall guidelines were established as follows to assure adequate safety margins for the flight tests.

1. Minimize weather exposure. The type of weather events for which data was required was examined to minimize aircraft exposure to severe weather. For example, storm cells embedded within strong frontal activity were not penetration candidates since relatively isolated storm cells can produce the same strength microbursts with much clearer approach and exit pathways. In addition, the RFD personnel always provided the FFD pilots with an 'escape' vector in the event the storm was stronger than expected.

2. Establish operational limits and procedures. Through both piloted simulation and analysis, the following limits and procedures were established:

a. F-factor: As determined from TDWR ground radar and as calculated using a reference airspeed of 210 knots, the maximum F-factor for penetration was 0.15. This limit included consideration of the possible quick growth of microburst strength between update intervals of the TDWR ground radar (approximately 1 minute apart).

b. Altitude: Unrestricted with TDWR F-factor <0.10. Restricted to >750 ft AGL with TDWR F-factor >0.10 and < 0.15

c. Airspeed: Unrestricted with TDWR F-factor <0.10 Restricted to >210 KIAS with TDWR F-factor >0.10 and < 0.15

d. Reflectivity. Allowable reflectivity levels within a storm cell were limited so as to avoid extremely heavy rain rates and, most importantly, hail. The limits were higher at the Orlando site due to the lower probability of hail given a certain reflectivity level. Due to the availability of both high and low altitude radar reflectivity data at Orlando, the two-level hail avoidance algorithm described in Ref. 9 was able to be utilized. The limits used were:

Orlando Site: <50 dBz surface; <45 dBz 1400 meters above freezing level.

Denver Site: <45 dBz surface

e. All shear penetrations to be piloted from the FFD of the research aircraft, with groundspeed callouts from the RFD.

f. Engine air igniters on during shear penetrations (to minimize flameout potential due to water ingestion).

g. All ground obstructions near the test sites of height greater than approximately 200 feet were identified and programmed into the moving map navigation display in the RFD.

3. Minimize lightning effects. Though the risk of a lightning strike to the aircraft was considered low since the risk of triggered lightning is almost negligible below 6000 ft MSL, the test flights were to be conducted underneath active thunderstorm cells and, thus, would expose the test aircraft to a chance of lightning strike. Limited lightning hardening modifications were made to the aircraft to improve grounding connections, inspect fuel tank sealants and bonds, and miscellaneous other items. In addition, only JP-5, JP-8, Jet A, or Jet A-1 fuel was allowed. Lower flashpoint JP-4, Jet B fuels were not to be used.

4. Maintain communications with ground support.

a. All microburst penetration flights required continuous voice communication with personnel located at the TDWR operations site. These radar operators and meteorologists were extremely important in both assessing developing weather activity and monitoring shear strength and reflectivity information.

b. Continuous coordination with Air Traffic Control personnel was also of critical importance since all maneuvering was to be conducted at low altitude in and around the Terminal Control Areas of both Orlando and Stapleton airports.

5. Flight crew training. Prior to the research test flights, the flight crew completed specific training activities.

a. The FAA Windshear Training Aid was reviewed for basic background in windshear recovery procedures.

b. The flight crew participated in a piloted simulation which included hundreds of windshear penetrations. This simulation accomplished a number of objectives, including: a review of the early recognition of the onset of windshear conditions; the establishment and repeated practice of control strategies for windshear penetrations; and the confirmation of Boeing 737-100 performance capabilities in windshears of various sizes and strengths.

c. The flight crew participated in special windshear recovery training in a 737 airline training simulator.

6. Phased approach. A phased approach was established to gradually increase the maximum windshear strength limit to the final 0.15 F-factor level in three steps. First, a microburst with shear of less than 0.10 (as measured by the TDWR) was to be penetrated. Second, a shear of F-factor greater than 0.10 and less than 0.13 was required. Third, any shear with F-factor less than 0.15 was acceptable for test measurements.

The RFD was specially configured (Figure 14) for these tests as the experiment control center. Pre-penetration maneuvering was often flown from the RFD due to the centralized information displays located there, though as mentioned, all penetrations were flown from the FFD. The RFD left side displays were maintained in the standard ADI, Nav, engine monitoring and checklist formats, while the right side utilized all four available displays and two additional CRT's installed in the upper right 'windscreen' area. These six displays depicted outputs from the radar, IR, and in situ research sensor systems, video output from a camera in the nose of the aircraft, two TDWR uplink displays (one specialized for flight operations, one for research purposes), and a moving map navigation display with ground obstacle positions and heights highlighted.

Prior to the deployment of the research aircraft, radio voice and data communications equipment were installed and checked at each site. Air traffic control personnel at both sites were briefed on the objectives of the research program and cooperative flight and ATC operational procedures were established. Finally, aircraft site basing arrangements were made at Orlando International Airport with a fixed-based operator and at Buckley Air National Guard Base in Denver.

Rehearsal flights based at Langley Research Center were conducted 2 weeks prior to the deployments to establish and practice flight operations procedures. Microburst data recorded by the Orlando TDWR system in 1990 was accessed via modem, processed, and relayed to the test aircraft to simulate live conditions. The timing and internal aircraft communications required to maneuver the aircraft from a loiter position, descend to the test altitude, and penetrate the developing shear on a radial line from the TDWR site (to maximize Doppler measurement data correlation between airborne and ground radars) were developed. Along with flight tests conducted to finalize the development and integration of the IR, radar, in situ, and TDWR systems, these preparation flights established the aircraft's and crew's readiness for field deployment and actual microburst windshear penetration tests.

## Flight Operations

Windshear penetration flight operations were conducted within an approximately 25 nautical mile range of both Orlando International Airport June 10-20, 1991, and Denver Stapleton Airport July 8-24, 1991. A typical day's flight activity began with a weather briefing the previous evening to determine the approximate time of day during which favorable weather development might occur. Research system hardware and software preflight checks were conducted on the morning of the flight day, while weather information from sounding balloons was collected. In Orlando, TDWR personnel from MIT Lincoln Laboratories along with a NASA meteorologist continuously assessed the day's developing weather and microburst potential. At the Denver site, personnel from the National Center for Atmospheric Research (NCAR) operated the Mile High Radar (equivalent to Orlando's TDWR) and similarly assisted the NASA tests. Based upon an approximately 30-minute prediction of developing windshear activity in the test area, the research crew boarded and launched the test aircraft.

The radio uplink, airborne processing, and display in the RFD of TDWR information provided real-time information on developing windshear conditions. The RFD crew would then assess (and sometimes control) aircraft positioning requirements so as to begin a penetration flightpath from an approximately five mile range from the microburst along a radial path extending to or from the TDWR site. Often, TDWR personnel were able to predict developing microburst conditions prior to their identification by the TDWR automatic wind divergence calculation process.

Simultaneous with the approach toward the microburst shear, a number of onboard activities occurred. Throughout the maneuvering, the FFD crew coordinated anticipated flightpaths and clearances with air traffic control personnel. TDWR ground personnel monitored both low-level and high-altitude storm cell reflectivity measurements and relayed the information to the aircraft to satisfy hail avoidance limits. The RFD crew continuously communicated maneuvering requirements and safety limits to the FFD crew in order to penetrate the desired portion of the microburst at the appropriate time. While on final approach to the microburst, the RFD crew increased monitoring and communications to the FFD regarding expected shear strength (based upon processed TDWR data), aircraft groundspeed (more accurately displayed in the RFD), storm cell reflectivity, recommended routes for either aborts prior to penetration or repositioning following penetration, and the position of any important ground obstacles near intended routes. Other onboard communications coordinated research sensor operation, and the operation of the aircraft data system and other aircraft support systems. The FFD crew determined the microburst entry speed (typically between 210 and 230 knots) and altitude (between 800 and 1100 feet) and additionally assessed whether lightning activity levels were excessive. When possible, a given microburst would be penetrated a second or third time until shear levels dissipated. Microburst lifetime with appreciable shear levels was typically from 5 to 15 minutes. This relatively short duration necessitated extremely efficient coordination among aircraft, ground radar, and ATC personnel in order to plan and execute the maneuvering required to repeatedly approach and penetrate the microburst cells in minimum elapsed time.

The visual appearance of microburst cells varied widely. Many were isolated cells with well-defined rain shafts which bowed outwards near the ground, indicative of the wind profile. Others, however, were part of larger rain cell systems and were not so readily identifiable. At times, different approach directions resulted in very different visual appearances of the same microburst. Rain rates and rain shaft diameters also varied widely from narrow (~0.5 km) with relatively light rain (35 dBz) to much larger (>2 km) with heavy rain (>50 dBz) The expanding gust front from the storm cell was also typically characterized by increased turbulence from 0.5 to 1 km or more prior to the storm cell entry.

Following concurrence by the FFD crew that a penetration was warranted, the aircraft entry airspeed and altitude initial conditions were chosen and the current groundspeed noted. On penetrations with any significant shear, the initial performance-enhancing headwind increase was readily apparent to the flight crew and provided good warning of the imminent onset of performance-decreasing shear. The flight crew attempted to maintain groundspeed constant at the initial value throughout the penetration. During the penetrations, the workload between the two man FFD crew was split so that the pilot flying controlled aircraft attitude while the other pilot managed the throttles in response to groundspeed callouts from the RFD. (At all other times during the test flights, the non-flying pilot's attention was completely concerned with ATC and RFD coordination and traffic awareness.) Airspeed was allowed to vary as required to maintain constant groundspeed. Turbulence levels within the microbursts often reached moderate and sometimes higher levels, but was of short enough duration so as to not be of significant difficulty.

In the Denver area, strong gust fronts were also penetrated in a very similar manner. These gust fronts were first identified by the ground radar and their position communicated to the aircraft. The fronts were typically relatively clear air phenomena (<15 dBz), and were associated with outflows from very large nearby thunderstorm activity. Very nearly the opposite of a divergent microburst, gust fronts are characterized by converging winds and produce strong performance increasing shear. The fronts penetrated in Denver also included the greatest turbulence levels observed during the flight tests.

## Results and Conclusions

The 1991 flight test program is considered to have been extremely successful. Without any significant safety of flight incidents, approximately 19 microburst windshear penetrations were recorded and greater than 30 weaker divergences were also measured. Approximately eight strong gust front penetrations were recorded, as were five approaches to storm cells which exceeded flight limitations, but were measured with onboard remote sensors. The maximum in situ windshear measured reached an F-factor index level of 0.17, well in excess of an alert threshold for commercial aircraft reactive sensors. Low reflectivity "dry microburst" windshear measurements desired at the Denver site were not collected, due to unfavorable weather conditions, though the low reflectivity strong gust front shears which were recorded provided nearly equivalent data. The maximum performance increasing shear penetrated at Denver reached an F-factor level of -0.24.

The airborne and ground-based sensor systems acquired outstanding high resolution measurements of microburst dynamics and structure. For the first time ever, an in situ measurement of hazardous shear was correlated with other independent measurements. Also for the first time ever, an airborne radar detected and accurately measured areas of hazardous windshear. The radar ground clutter data collected at both sites are expected to form the basis for eventual national certification standards

Additional sensor performance and flight test operations observations are listed below. Highly detailed reports on the results of each one of the sensor systems are forthcoming from the research groups at NASA Langley.

1. The TDWR ground radar data link, airborne processing and display were definitively demonstrated as both a feasible and extremely useful automatic windshear communication system.
2. All in situ algorithm hazard computations appeared to correlate well with aircraft performance. No false in situ alerts were generated, no nuisance alerts were generated, and two valid hazard alerts were annunciated.

3. The airborne radar detection system identified and tracked high hazard areas in flight. Ground processed data shows multiple alerts generated within storm cells and with significant advance warning (Figure 15).
4. The test procedure was shown to be both safe and productive, allowing a transport size aircraft to maneuver quickly at low altitude in and near hazardous weather conditions. The aircraft did not experience a lightning strike.
5. A short period of light to moderate turbulence prior to entry into, and on exit from, the microburst rain shafts was frequently encountered and considered to be associated with the expanding gust front from the microburst core.
6. Visual indications of windshear strength are not apparent, though at times a bowing out of the rainshaft shape due to divergent winds at low altitude was observable (Figure 16). However, at other times, the microburst windshear was embedded within multiple rain cells and a distinct shape could not be observed. Additionally, strong performance increasing shears penetrated in the Denver area were clear air phenomena with no associated visible moisture.
7. As expected from the piloted simulations, shear entry airspeeds of 210-240 knots were sufficient for the test aircraft to experience the energy loss of the penetrated shears with little altitude loss. Additionally, advanced knowledge of the location and strength of the shears allowed the pilots to quickly and readily manage engine throttle, airspeed, and altitude control during the penetrations.

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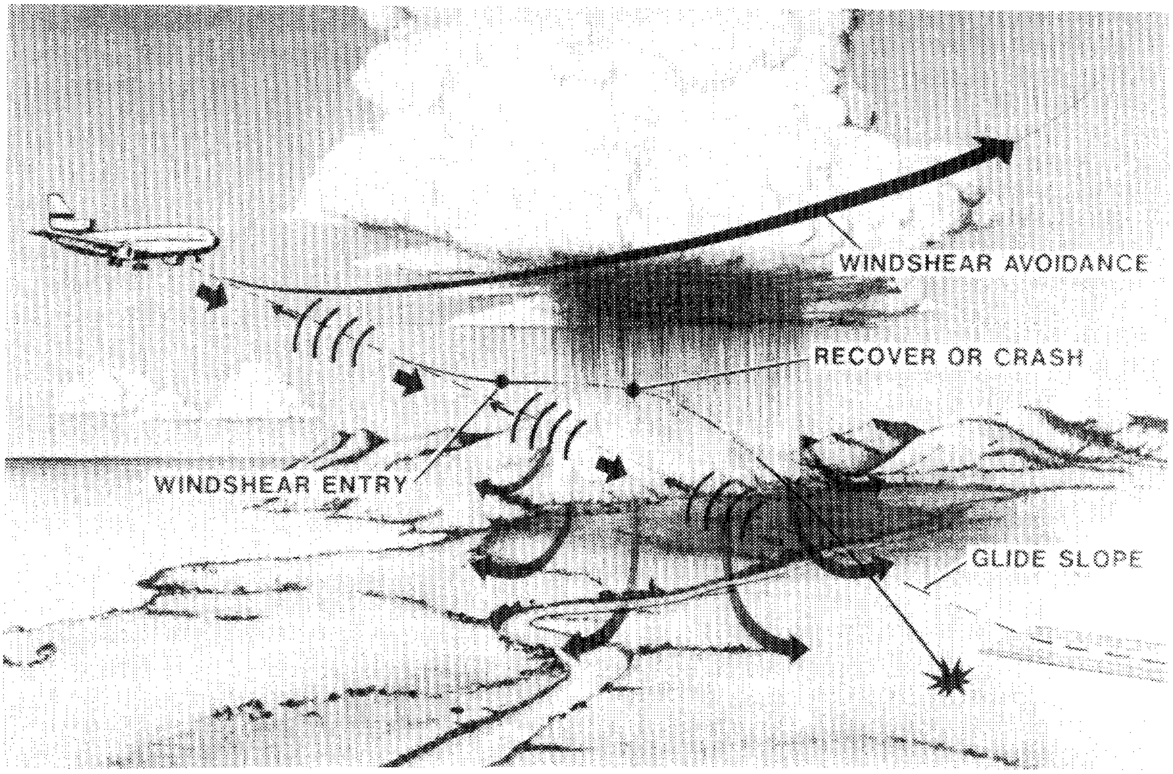


Figure 1. The windshear problem.

| # Engines | Approximate Maximum Specific Excess Thrust |
|---|---|
| 2 | 0.17+ |
| 3 | 0.13 |
| 4 | 0.11 |

Figure 2. Turbojet transport aircraft maximum performance at maximum gross weight.

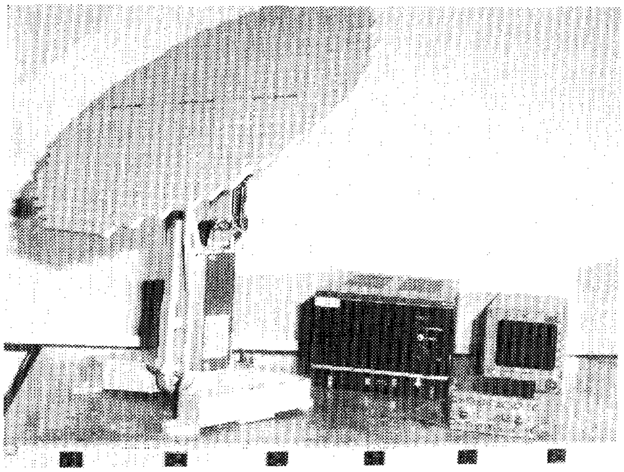

Figure 3. Airborne radar antenna, receiver/transmitter, display, and control units.

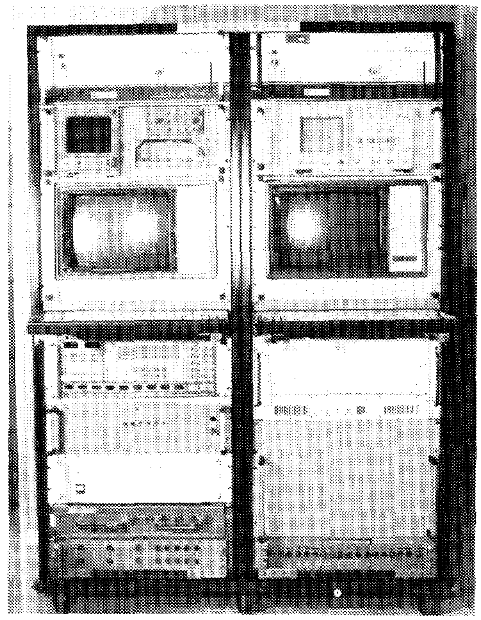

Figure 4. Airborne radar research control pallet.

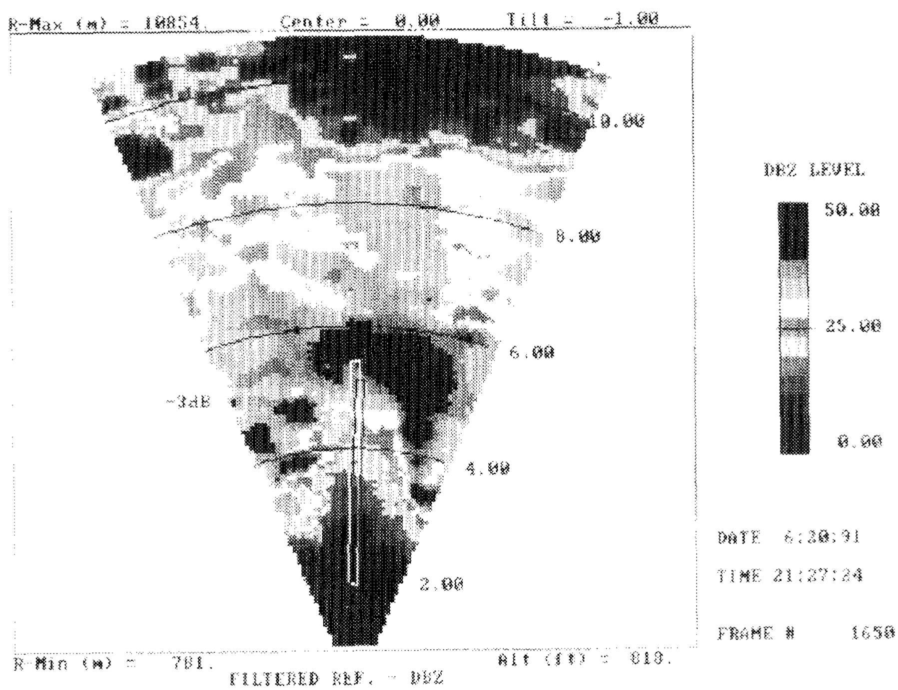


Figure 5. Airborne radar reflectivity display showing storm cell with maximum reflectivity near 50 dBz 5 km ahead of the aircraft.

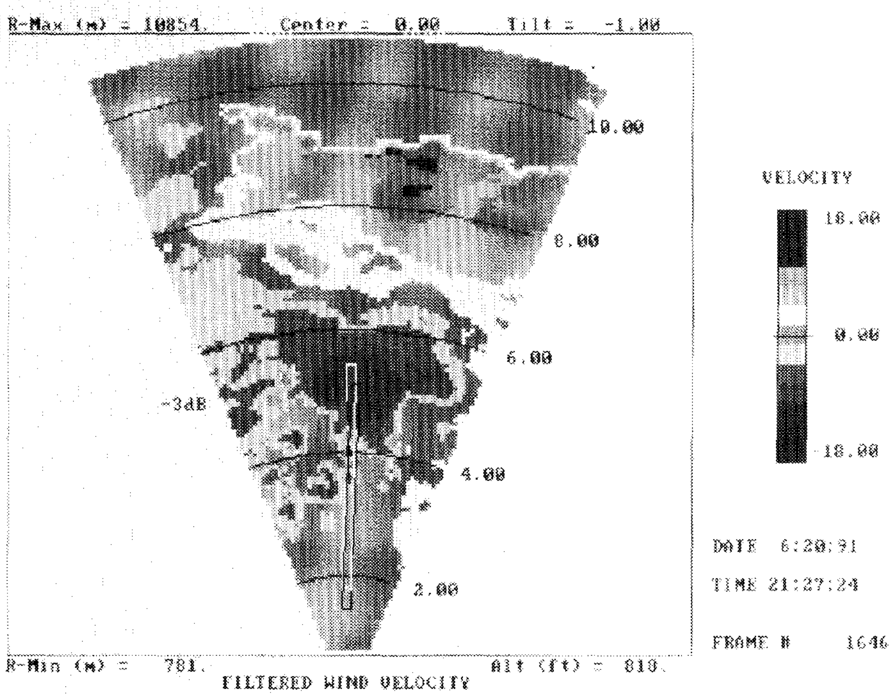


Figure 6. Airborne radar velocity display showing 12 m/s headwinds 5 km from the aircraft and 12 m/s tailwinds 8 km from the aircraft. An area of zero Doppler wind is 6.5 km from the aircraft.

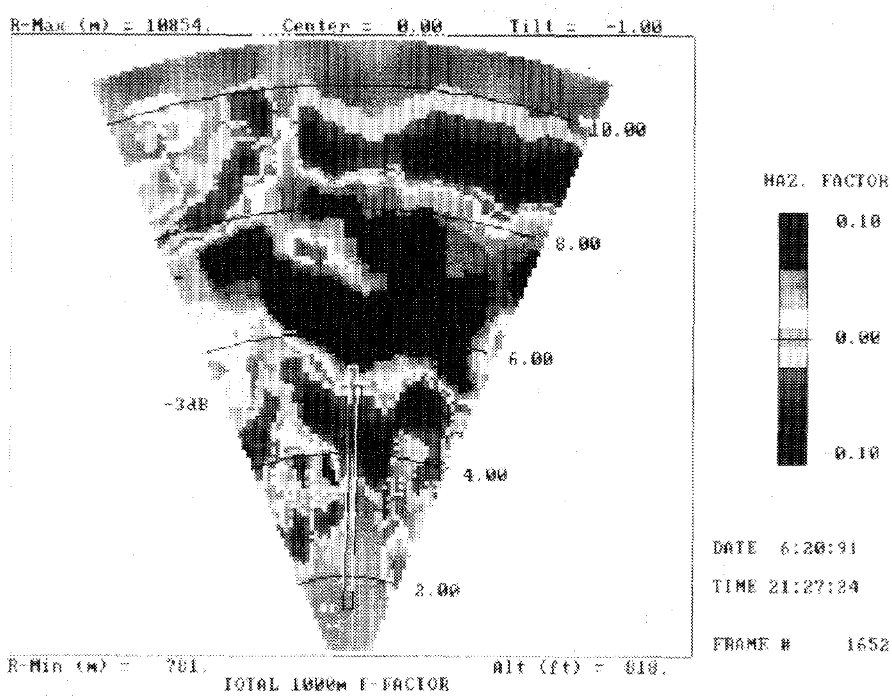


Figure 7. Airborne radar shear display showing an area of strong shear between 6 and 8 km ahead of the aircraft.

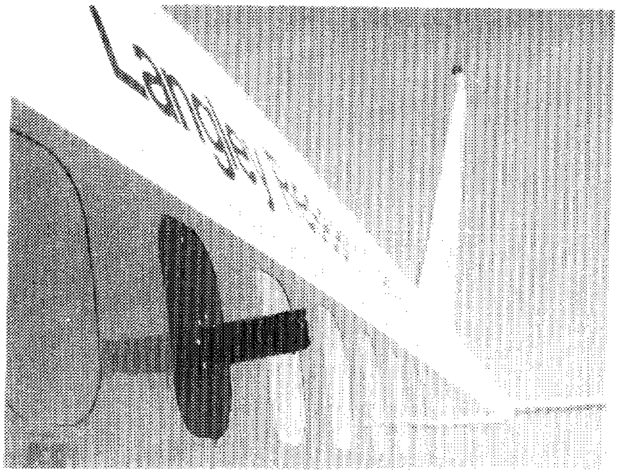

Figure 8. Infrared periscope.

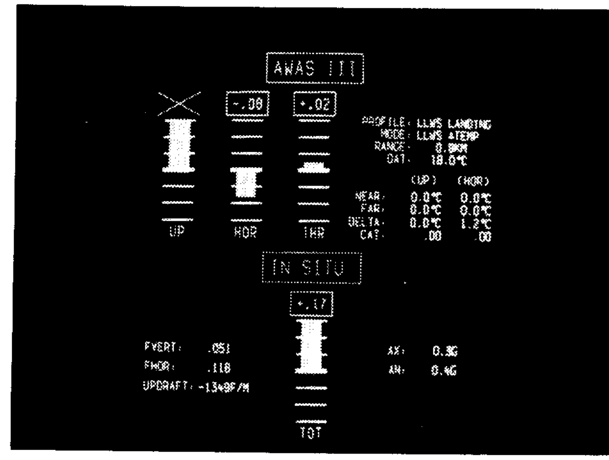


Figure 9. Research display of IR ('AWAS III') and in situ sensor data.

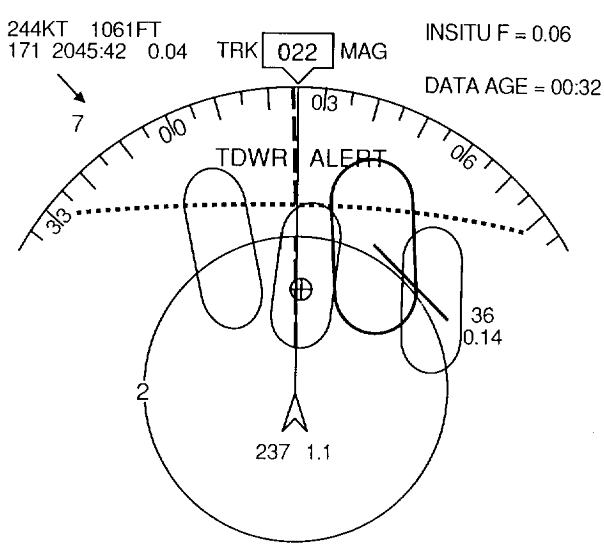


Figure 10. Research display of TDWR data showing microburst icons approximately 1 nmi in front of the aircraft symbol, with the tagged icon containing a 36 knot shear with an F-factor hazard index of 0.14. Aircraft airspeed is 244 knots, groundspeed is 237 knots, altitude 1061 feet with a left quartering headwind of 7 knots.

Figure 11. NASA Langley Research Center
B-737 Transport Systems Research Vehicle.

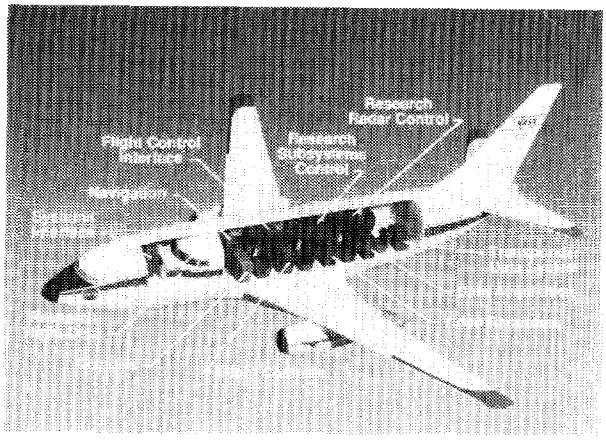


Figure 12. Research aircraft interior layout.

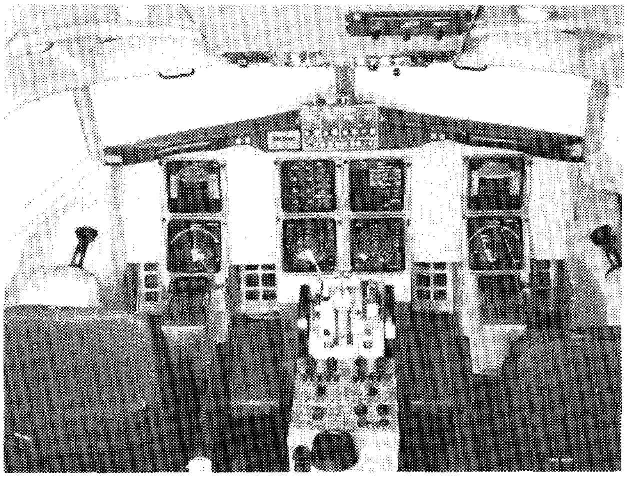

Figure 13. Research Flight Deck
standard configuration.

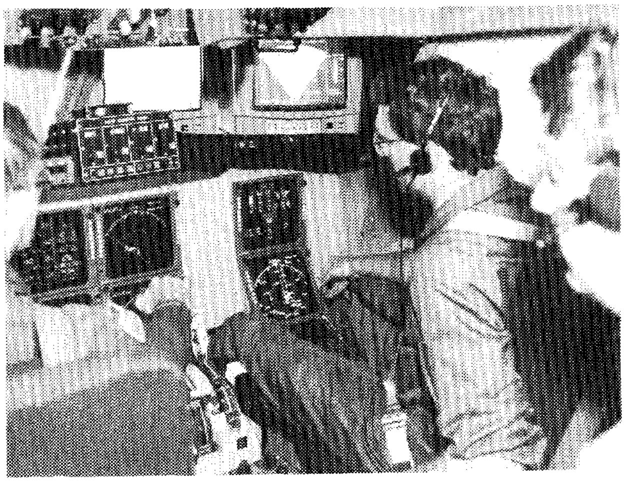

Figure 14. RFD during windshear research flight.

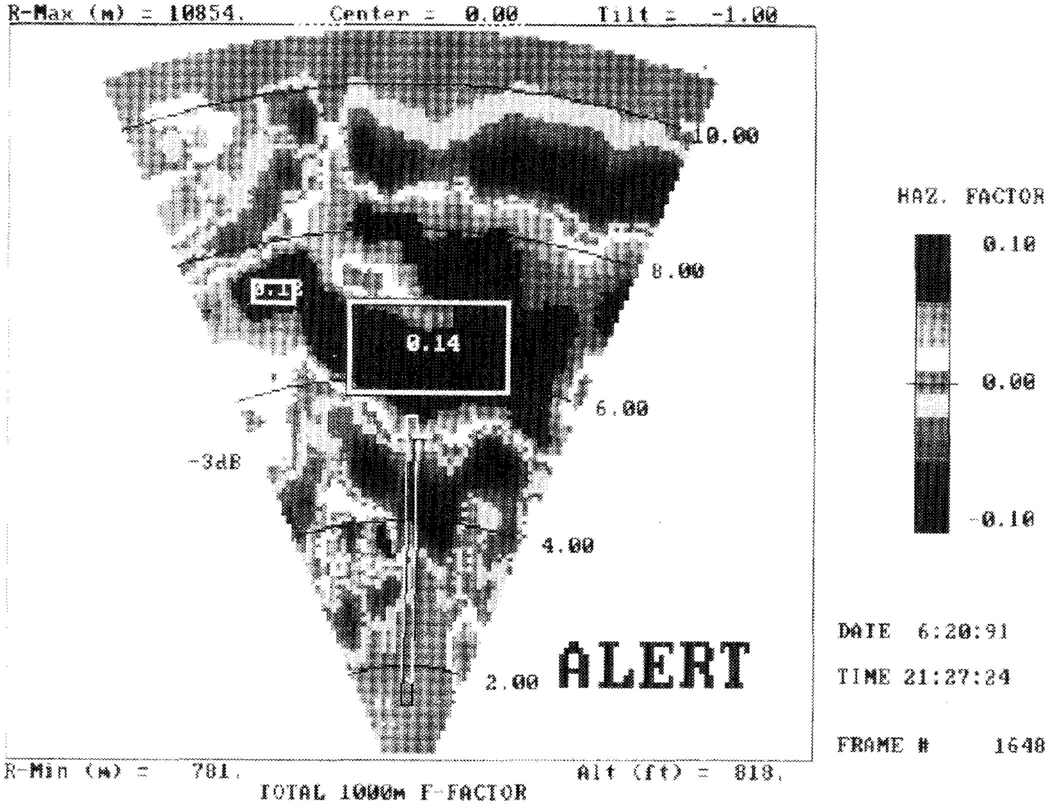


Figure 15. Airborne radar display showing shear hazard levels above threshold in two areas with average F-factor values as shown.


Figure 16. Orlando, Florida, microburst approximately 1 minute prior to penetration.