OPERATIONAL COCKPIT DISPLAY OF GROUND-MEASURED HAZARDOUS WINDSHEAR INFORMATION

by

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Abstract

System design issues associated with the dissemination of windshear alerts from the ground are studied. Two issues are specifically addressed: the effectiveness of different cockpit presentation modes of ground-measured information, and assessment of the windshear hazard from ground-based measurements. Information transfer and presentation issues have been explored through pilot surveys and a part-task Boeing 767 'glass cockpit' simulation. The survey produced an information base for study of crew-centered windshear alert design, while the part-task simulations provided useful data about modes of cockpit information presentation for both windshear alert and ATC clearance delivery. Graphical map displays have been observed to be exceptionally efficient for presentation of position-critical alerts, while some problems with text displays have been identified. Problems associated with hazard assessment of ground-measured windshear information are also identified. Preliminary analysis has resulted in recommendations for improved windshear hazard quantification and for alert content modifications.

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Associate Professor of Aeronautics and Astronautics

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1. Introduction

The most critical weather hazard confronting commercial aviation today is low-altitude windshear. The magnitude of this hazard has been only recently realized, and systems for alleviating it are under intense development. Technological advances in low-altitude windshear detection, ground-to-cockpit datalink capability, and electronic cockpit information display create the possibility for new and improved methods of informing flight crews about windshear hazards in the terminal area. However, the availability of better data sources and multiple modes of communication also leads to a number of system integration problems. Issues including the reduction, transfer, and presentation of data must be addressed in order to effectively implement advanced windshear alerting systems. Careful system design needs to be performed, centered around the needs of the flight crew and the capabilities of the available equipment.

This thesis is the result of efforts to resolve both information transfer and crew interface issues, and issues of evaluation of ground-measured data to produce an accurate and meaningful assessment of the windshear hazard. The information transfer and crew interface issues have been addressed in two ways: (1) a pilot opinion survey to acquire a database of user needs and preferences for windshear alert system development, and (2) a part-task simulation experiment to study the effectiveness of several types of cockpit presentations. Windshear hazard assessment issues have also been examined, and some preliminary analysis performed to both identify problems and suggest an effective hazard assessment criterion for ground-measured windshear data.

The results of this work are presented as follows. Chapter 2 outlines the primary motivation for this work, including a discussion of low-altitude windshear as an aviation hazard, the current state of technology for windshear detection and warning, and observations taken from test implementations of a proposed ground-based windshear alerting system. Chapter 3 describes the pilot opinion survey, and Chapter 4 details the ensuing part-task simulator study of potential cockpit presentation modes. The subject of windshear hazard assessment is discussed in Chapter 5, and a summary of this work is presented in Chapter 6.

2. Background

2.1. Terminal Area Windshear

Low-altitude windshear is the leading weather-related cause of fatal aviation accidents in the U.S. Since 1964, there have been 26 accidents attributed to windshear resulting in over 500 fatalities [National Research Council, 1983; Wolfson, 1988]. Low-altitude windshear can take several forms. Macroscopic forms, such as gustfronts caused by colliding warm and cold air masses, can generally be predicted and avoided. However, the small intense downdrafts known as microbursts are far more dangerous and difficult to detect. Microbursts begin with a cool downdraft formed at the base of a cumulus or cumulonumbus cloud. If the downdraft is strong enough to impact the surface, it spreads out radially and creates an small area (1 to 4 km in diameter) of intense windshear. Such conditions typically last for short periods (10-30 min), but can be very dangerous to aircraft at low altitudes, particularly on takeoff or final approach. Initially, the aircraft experiences a strong headwind, which causes a momentary increase in lift. Next, the aircraft enters an area of downdraft, and then a sharp tailwind. This combination results in loss of effective airspeed and corresponding loss of lift. (Figure 2.1). It may also serve to destabilize the flight trajectory. The resulting performance loss can in some cases be sufficient to result in ground impact. In addition, microbursts can be accompanied by strong edge vortices, which can further destabilize the aircraft. Most fatal windshear accidents have been attributed to microbursts.[Wolfson, 1988]

An additional factor which makes microbursts particularly dangerous is that they are generally not obvious either visually or to standard airborne weather radar. Microbursts have been observed to occur both during periods of severe rain or during periods of little or no low-altitude precipitation. For meteorological and instrumentation purposes, it is

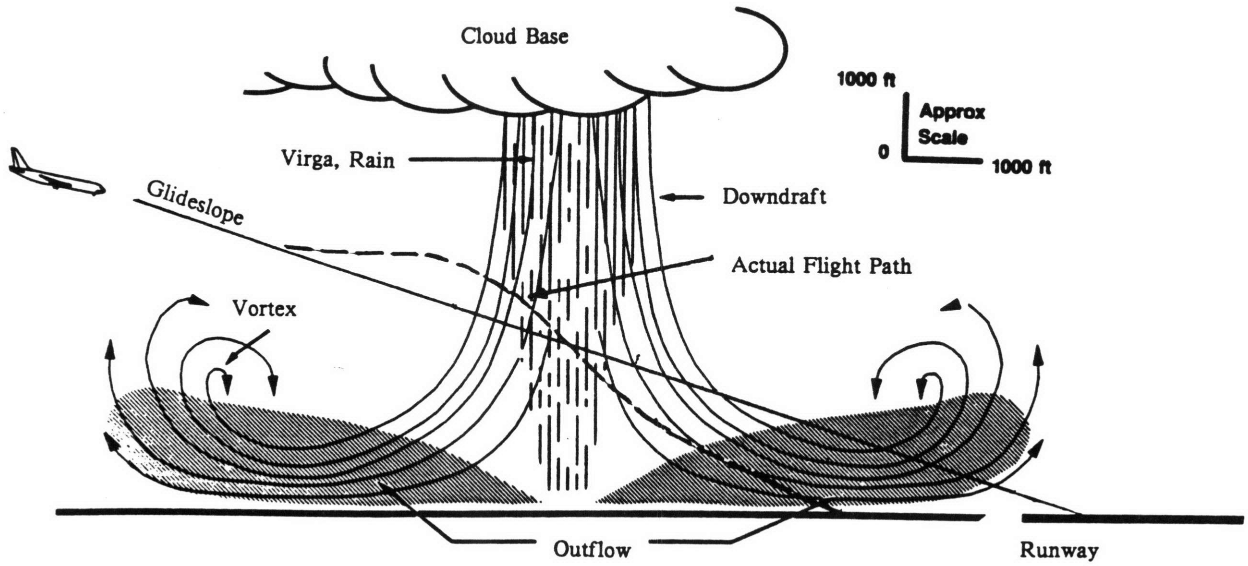


Figure 2.1 Microburst Windshear Encounter on Approach

convenient to distinguish between 'wet' and 'dry' microbursts. Dry microbursts, more common in the western U.S., can sometimes be detected by the presence of curling clouds of dust on the ground or vertical cloud shafts known as 'virga'. Wet microbursts cannot generally be distiguished from benign rain cells with radar reflectivity information.

Microbursts have been observed with intensities greater than most aircraft could be reasonably expected to survive. Avoidance is the best way to handle a windshear hazard. This indicates a need for reliable remote detection, allowing the flight crew adequate advance warning to plan and execute a maneuver to avoid microburst penetration.

2.2. Windshear Detection

2.2.1. Current Systems

Current procedures for microburst detection and warning center around the Low-Level Windshear Alert System (LLWAS), Pilot reports, and improved pilot education through efforts such as the FAA's *Windshear Training Aid* [1987]. LLWAS is a system of anemometers currently in service at most major U.S. airports designed to measure shifts in wind speed and direction within the airport perimeter. Although capable of detecting macroscopic phenomena such as gustfronts, the anemometer spacing is larger than the characteristic surface dimension of many microbursts, and thus LLWAS remains fairly ineffective for detection of microburst windshear. The *Windshear Training Aid* states: "If an LLWAS alert (triggered by wind speed and/or direction differential) occurs, it indicates the presence of something shear-like, though not necessarily indicative of magnitude or location. However, the absence of an alert does not necessarily indicate that it is safe to proceed!" Improved LLWAS systems are being placed at some major airports [Smythe, 1989], and in recent events at Denver Stapleton Airport (7/8/89) have demonstrated the capability to detect a strong microburst on approach [McCarthy, 1989].

Airborne reactive windshear sensors are also available, and will soon be common equipment on commercial aircraft. These *in-situ* sensors compare inertial measurements of aircraft state (accelerations) with air data system measurements (airspeed, altitude, etc.) to provide a real-time measurement of the immediate windfield. Thus, microburst penetration can be detected based on a time history of the wind measurements. This sensor is clearly the last resort warning, as avoidance of the event is no longer possible.

Pilot reports (PIREPS) of windshear can provide extremely useful data. The availability of PIREPS necessarily requires that an aircraft penetrate a microburst, which is not desirable; but the information, unlike LLWAS, provides strong evidence of a windshear hazard for subsequent aircraft. It is therefore desirable to integrate PIREPS with any sensor data available in future windshear detection systems. As digital datalinks become available, it may be possible to automate this process. Data from airborne reactive (and eventually, look-ahead) sensors could be transmitted directly to the ground without need for pilot intervention. It should be noted that both PIREPS and LLWAS alerts can provide evidence of windshear presence, but their absence is not evidence that there is no windshear present.

The *Windshear Training Aid* itself is designed to inform pilots and controllers about windshear, primarily how to recognize and avoid or recover from microburst encounters. Avoidance is practiced through the use of LLWAS information, weather reports, and visual clues. A program of flight crew windshear awareness training is also recommended, including windshear models for flight simulator training. The usefulness of windshear awareness and recovery training is limited, however. High pilot workload in the terminal area and the relative rarity of hazardous windshear makes it difficult for even well-trained crews to fully assimilate the evidence of windshear before penetration.

2.2.2. Emerging Technologies

To meet the need for improved windshear warning, new systems for detection are under development. Both airborne and ground-based systems are under consideration. Airborne look-ahead systems are still primarily experimental. Candidate technologies include doppler radar [Bracalente, et. al., 1988], doppler lidar [Targ and Bowles, 1988], and infrared radiometry [Adamson, 1988]. To be an effective, dependable windshear avoidance tool, an airborne system must be able to detect windshear ahead of the aircraft to a range of 1 - 3 km, thus typically providing 15 to 45 seconds of warning. Also, the sensor should work for either wet or dry microbursts with enough resolution to adequately measure size and intensity. None of these systems have yet reached the point of both demonstrated reliability and economic feasibility, but all are under active development.

Ground-based remote sensing technology is much more developed. LLWAS and PIREPS often yield useful data, but are not always available or accurate. Ground-based doppler weather radars are entering the last stages of development, and have advantages over airborne systems in terms of ground clutter suppression, size and power. The Terminal Doppler Weather Radar (TDWR) system, based on a pencil-beam doppler weather radar located 10-15 km from major airports, is planned for deployment at 47

MICROBURST DETECTION

Data	Probability of detection* ΔV<20 m/s	ΔV≥20 m/s	Total	Probability of false alarm
Huntsville 1986	88%	100%	91%	5%
Denver 1987	90%	99%	92%	5%
Combined	90%	100%	92%	5%

GUST-FRONT DETECTION

Data	Probability of detection ΔV≤15 m/s	ΔV>15 m/s	Probability of false alarm
Denver 1987	81%	93%	5%

* ΔV = net wind change in shear region (only events with ΔV values greater than 10 m/s are scored.)

Table 2.1 Doppler radar windshear detection results [from NCAR, 1988]

locations in the early 1990's [Merritt et. al., 1989]. Experiments performed with TDWR testbed radars at Huntsville, AL in 1986 and at Denver, CO in 1987 and 1988 have shown impressive results (Table 2.1). For microbursts exhibiting a radial divergence of greater than 20 m/s detection is almost certain, and for less intense shears about 90% certain. The predominance of wet microbursts at Huntsville and dry microbursts in Denver shows the versatility of the ground-based doppler radar. The ability of such systems to integrate data aloft with wind measurements near the surface allows for earlier forecasting of microburst locations and outflow strengths. Airport surveillance radars (ASR-9) have also shown some capability for windshear detection; these may be used as windshear sensors at locations which do not warrant TDWR installations or as an additional sensor to complement TDWR and enhanced LLWAS installations [Weber and Noyes, 1989].

In the near term (early 1990's) ground-based doppler radars, along with existing and improved LLWAS installations, will be the primary sources of advance windshear alert data. This data will be supplemented by onboard reactive windshear alert systems, PIREPS, and eventually airborne look-ahead sensors when they become operational and economically feasible. Since the most reliable and widely available data from these systems will be generated and analyzed on the ground, systems and methodology for synthesizing windshear alerts, uplinking them to the aircraft, and displaying them to the flight crew need to be evaluated.

2.3. Terminal Area Communications Options

The only communication link available at present for windshear alerts is standard VHF verbal radio communications. However, the high density of radio communications in the terminal area for ATC purposes makes the addition of windshear alert transmissions undesirable. Alerts in this environment add to radio frequency saturation problems, to controller workload, and are more easily misinterpreted or missed by flight crews.

Digital ground-to-air data transfer is an area under active development. Several methods of digital ground-to-air data transmission are currently or nearly available. ACARS, a privately-sponsored system for the uplink and downlink of digital information related to commercial aviation, is currently in use by many major airlines. It provides an alphanumeric datalink capability for flight management information, helping to relieve congestion on crowded ATC voice frequencies. With the addition of satellite relays, ACARS coverage will extend to most international commercial air routes.

Another system slated for near-term deployment is the FAA's Mode-S surveillance datalink. Mode-S is an extension of the altitude encoding Mode-C transponder in the ATC Radar Beacon System allowing message delivery from ATC to individual aircraft. Each individual message can carry 48 useful bits of information, and the time for the interrogation beam to scan the entire coverage area is 4 to 12 seconds. Messages can be also be linked in groups of up to 4 frames or sent as a longer Extended Length Message (ELM) with less urgency [Orlando, Drouhilet 1986]. The Mode-S system is the most likely (near-term) candidate for digital uplink of hazardous weather information in the terminal area due to its ability to quickly send data to individually selectable aircraft. This imposes a length constraint (bit limit) on the alert design, since it would be most desirable to send urgent alerts in the surveillance mode (48 bits). The Mode-S system will be deployed in the early 1990's.

In the long term, the Aviation Satellite Communications System (SatCom) is being developed. The goal is a standardized worldwide system for digital voice and data communications, based on nine existing satellites in geosynchronous orbit.[9] Other systems such as digital ATIS or enroute weather channels are also envisioned for future development. The role of these systems in transmission of hazardous weather alerts is not clear.

2.4. System Implementation Problems

The initial field evaluations of the proposed TDWR-based windshear alerting system have brought to light some important issues which need to be resolved before an integrated ground-based windshear avoidance system can be implemented.

2.4.1. TDWR Operational Evaluations

Operational Evaluations of the proposed TDWR system have been performed at Denver's Stapleton Airport (1988), at Kansas City International Airport (1989), and will continue at Orlando in the summer of 1990. In these evaluations, software algorithms are used to process the TDWR data and produce microburst and gustfront alerts. These alerts are then sent by ground line to the control tower and to terminal radar approach control (TRACON). The microburst information is updated at 1 minute intervals, while the gustfront product is updated every 5 minutes. The details of the alert generation are discussed more fully in Section 5.3.

The information is displayed in two formats in the control tower. The local tower controller, who has primary responsibility for the dissemination of microburst alerts, has an alphanumeric display, shown in Figure 2.2, which can present either TDWR or LLWAS information in the same format. This is done to minimize the transition between periods of TDWR and LLWAS-only operation. The tower supervisor and the TRACON also have the geographical situation display (GSD) which is shown in Figure 2.3. This color display presents the locations of microbursts, gustfronts and precipitation on a plan view of the runway configuration. In addition, LLWAS wind vectors are displayed.

Type of wind shear	Runway	Threshold winds			Wind shear Headwind change (kts)	Location
	CF	190	16	G 25		
MBA	35 LD	160	22		50-	RWY
MBA	35 RD	180	5		25-	RWY
MBA	35 LA	030	23		55-	1 MF
	35 RA	180	10		60-	3 MF
MBA	17 LA	180	5		25-	RWY
MBA	17 RA	160	22		55-	RWY
	17 LD	180	10		60-	RWY
MBA	17 RD	030	23		55-	RWY

Figure 2.2 Example of controller's alphanumeric display (from NCAR, 1988)

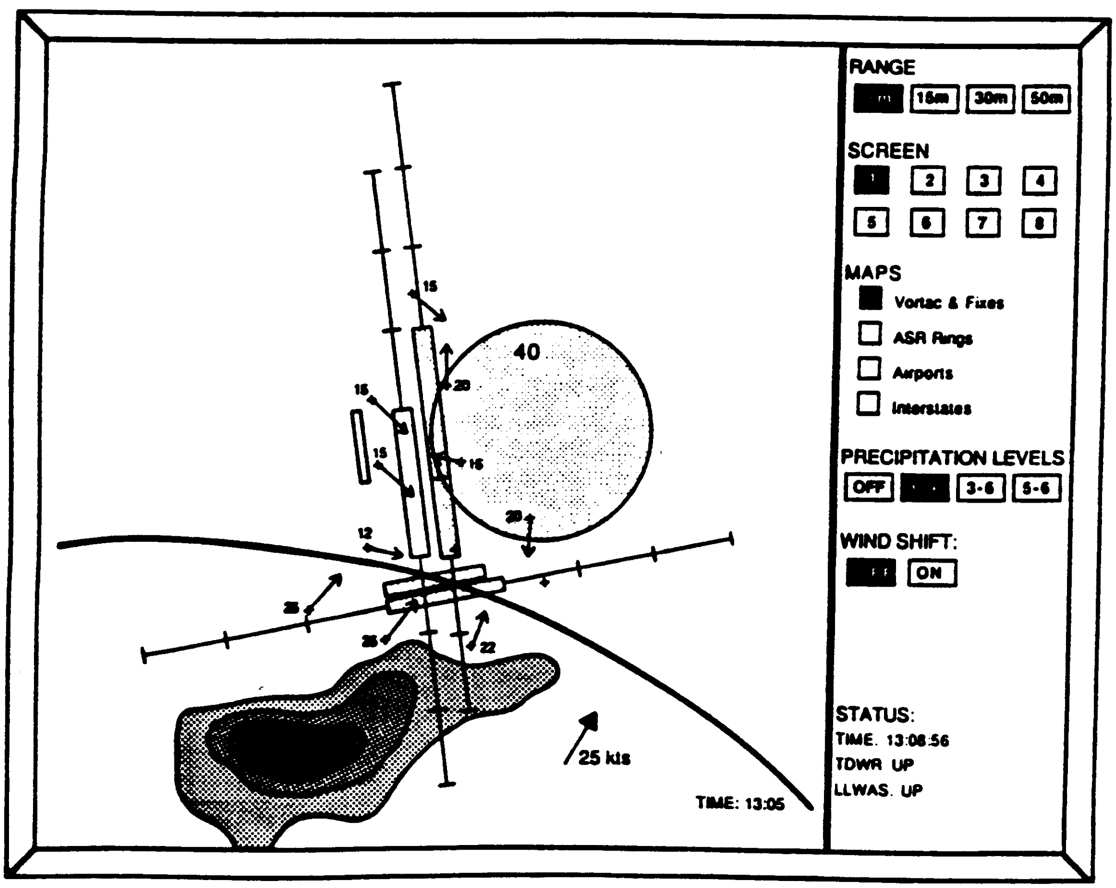


Figure 2.3 Geographical situation display (GSD) used in the control tower and TRACON (from NCAR, 1988)

2.4.2. July 11, 1988 Incident

An event which illustrates many information transfer issues associated with dissemination of microburst alerts occurred during the 1988 TDWR operational demonstration at Stapelton International Airport in Denver. On July 11, a period of severe microburst activity occurred. It is instructive to evaluate the warnings and responses of the five aircraft which initiated and abandoned approaches immediately prior to the closure of the airport.

The period of intense microburst activity began at the Stapelton airport shortly after 2200 UTC. At this time arriving aircraft were landing on runways 26L and 26R. Departing aircraft were using runways 35L and 35R. On the arrival ATIS, aircraft were informed of a convective SIGMET for the eastern Colorado area,and that the doppler radar windshear detection demonstration was in progress. After 2203 UTC the ATIS was updated to include "low level windshear advisories in effect".

The evolution of the microburst event can be seen in the geographical situation displays presented to the tower supervisor at at 2201, 2207 and 2212 UTC (Figure 2.4). At 2201 UTC there was an area of precipitation southwest of the airport and a region of 25 kt windshear within 2 miles of the airport center. By 2207 UTC a gustfront had developed over the airport with some light precipitation. Several microbursts had developed with the gustfront including a 45 kt headwind to tailwind cell located on the approach to runways 26L and 26R. By 2212 UTC (only 11 minutes after the 25 knot event) the microburst had increased in strength to 80 kts and the precipitation had increased. This microburst event continued at high intensity to 2222 UTC when it began to abate. Windshear values of 30 kts were still being measured at 2230.

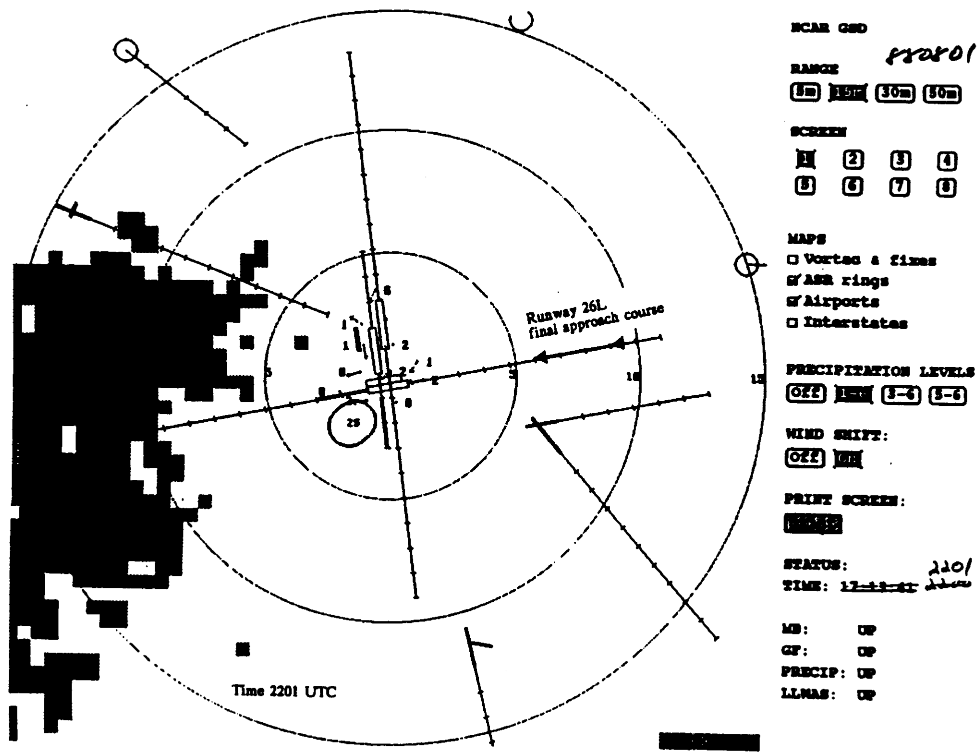


Figure 2.4a[1] Geographical situation display plot - situation at DEN at 2201 UTC on July 11, 1988.

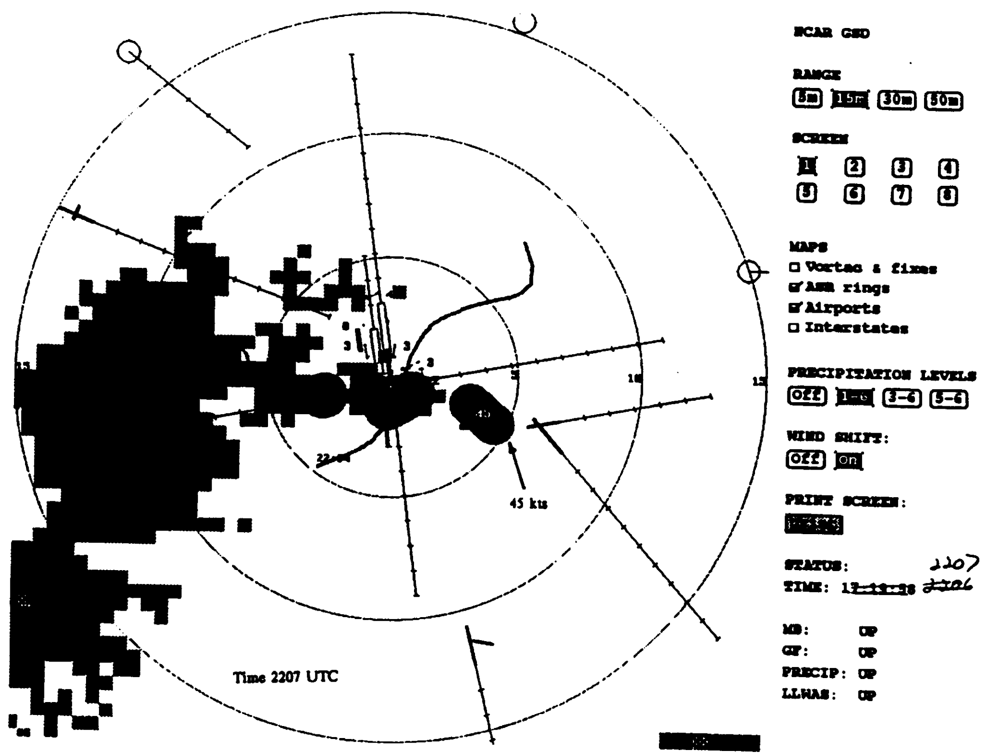


Figure 2.4b[1] Geographical situation display plot - situation at DEN at 2207 UTC on July 11, 1988.

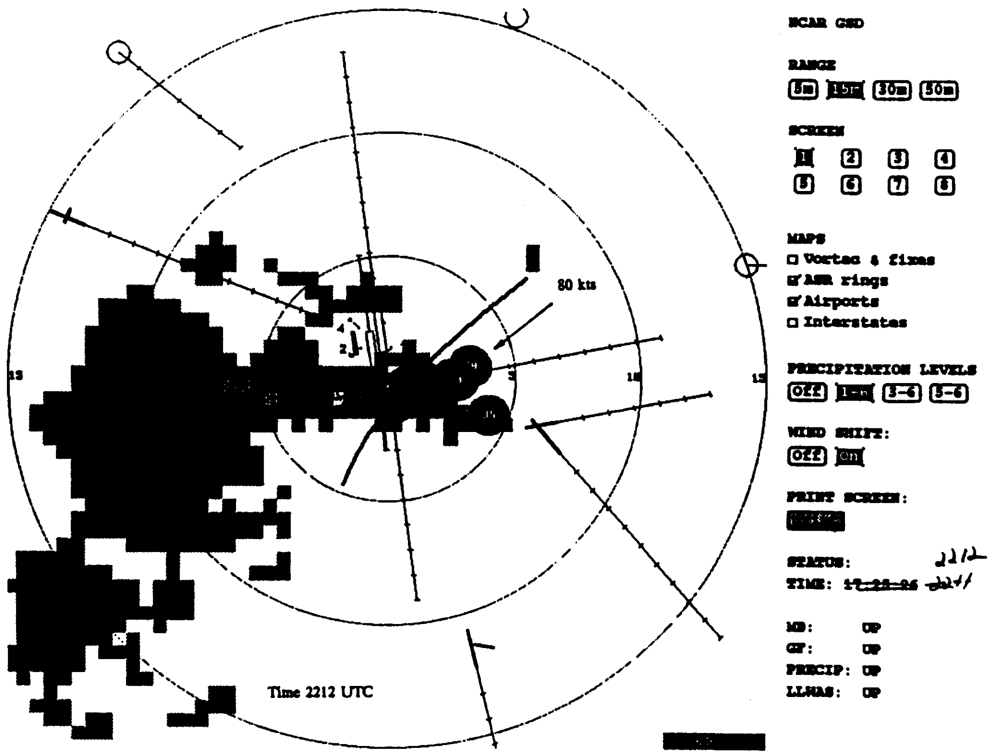


Figure 2.4c[1] Geographical situation display plot - situation at DEN at 2212 UTC on July 11, 1988.

[1]The plots in Figures 2.4a,b, and c, the ATC transcripts in Table 2.2, and the data used to produce Figures 2.5 and 2.6 was originally provided to the author by Wayne Sand of the National Committee on Atmospheric Research. It has now been published in a comprehensive report on the events of 7/11/88 at Denver-Stapleton Airport. [Schlickenmaier, 1989]

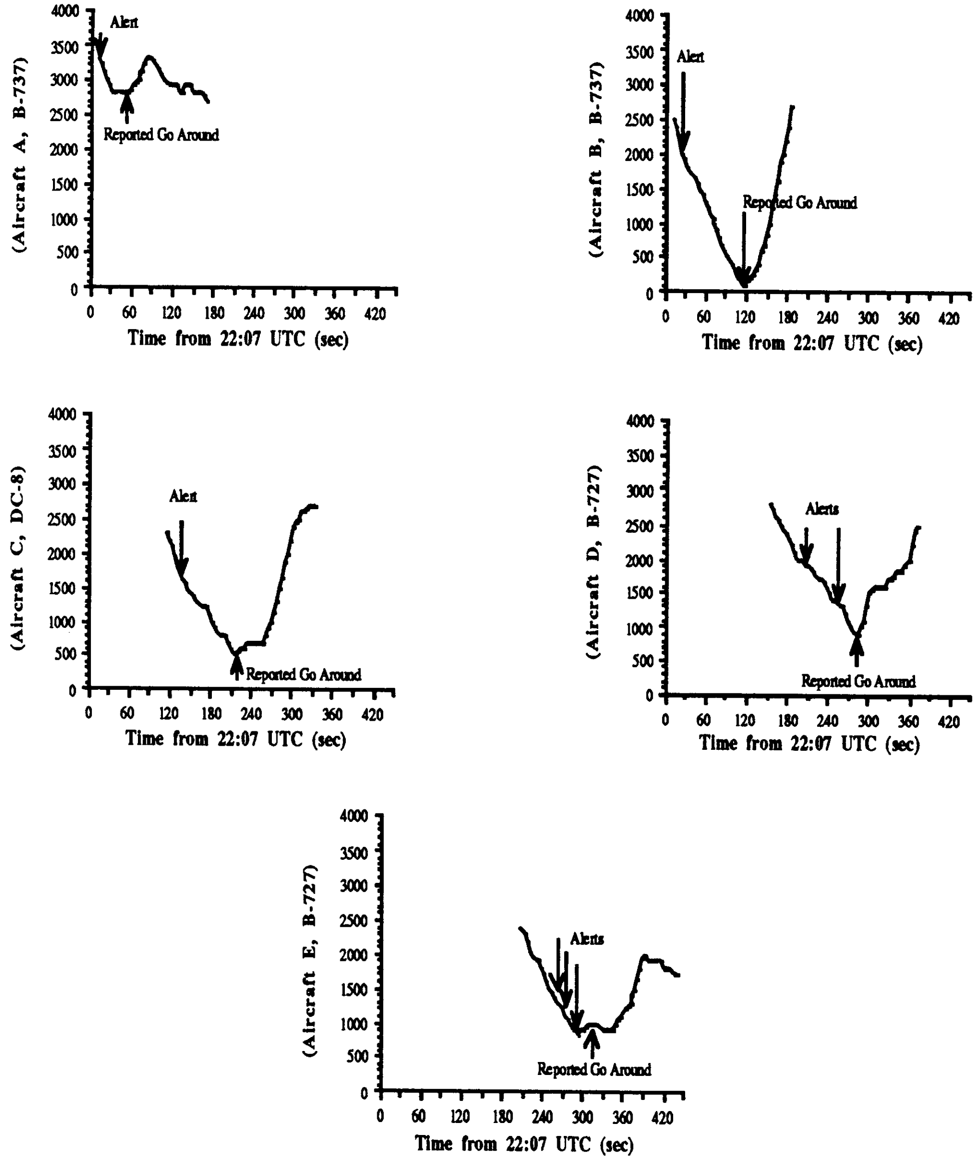


Figure 2.5[1] **Aircraft altitude (AGL) vs. time for July 11, 1988 events**

The altitude versus time plots generated from Mode C transponder replies for the 5 aircraft which initiated approaches between 2207 and 2214 UTC are shown in Figure 2.5. Also shown are the times at which microburst alerts were given to the aircraft and the time of reported missed approach. All aircraft which penetrated the microburst reported intense windshear. Transcripts of the verbal microburst alerts given to each aircraft by the local tower controller are presented in Table 2.2. It is unknown if there were any microburst alerts issued to these aircraft by the TRACON approach controller. However, the fact that 4 of the 5 aircraft elected to continue the approach indicates that this was unlikely.

	Aircraft A
22:07:15	"Aircraft A, Denver tower, runway two six right, cleared to land. Microburst alert, centerfield wind two two zero at none, a forty knot loss, one mile final as reported by machine, no pilot report."
	Aircraft B
22:07:35	"Aircraft B, Denver tower, runway two six left cleared to land. Winds two one zero at five, a forty knot loss, one mile final microburst alert, not substantiated by aircraft."
	Aircraft C
22:09:35	"Aircraft C heavy, Denver tower, microburst alert, threshold wind one four zero at five, expect a fifty knot loss, two mile final, runway two six left, cleared to land."
	Aircraft D
22:11:05	"Aircraft D, caution have turbulence from the heavy DC-8. He is going around. We have a microburst alert, threshold winds, zero nine zero at three. Expect a seventy knot loss on a three mile final."
22:11:45	"Microburst alert, runway two six. Threshold wind, one five zero at five, expect an eighty knot loss on a three mile final."
	Aircraft E
22:12:05	"Aircraft E, microburst alert, threshold wind one six zero at six, expect an eighty knot loss on a three mile final, say request."

Table 2.2[1] Transcripts of verbal microburst alerts issued to each aircraft

Several issues important to the development of microburst alerting systems are apparent from this data. The variability in aircrew interpretation of microburst warnings can be seen by comparing the response of aircraft A to that of aircraft B. The aircraft were approaching parallel runways and were issued virtually identical alerts within 30 seconds of each other. Aircraft A elected to immediately abandon the approach based on the microburst alert and visual observations of a descending rain shaft. This aircraft never penetrated the primary microburst area. Aircraft B elected to continue the approach, penetrated the microburst, and descended to within 100 ft of the ground 1 nm short of the runway threshold before executing a missed approach.

Another issue which arises from the data is the delay between the generation and the voice transmission of the alert to the aircraft by ATC. Figure 2.6 plots the delay to alert for each aircraft based on the first TDWR generated microburst alert at 22:06:17 UTC and the assumption that no alerts were given to these aircraft by the TRACON. It can be seen that the shortest delay was approximately 60 seconds and that a delay of 350 seconds was encountered for the last aircraft to report to the tower (Aircraft E). The delays in excess of 100 seconds are likely a result of the effort to make the TDWR alerts apear like LLWAS alerts. The primary windshear alert responsibility therefore rested with the tower controller who did not have contact with the aircraft until they were at the outer marker. It does appear, however, that a minimum delay on the order of 60 seconds can be expected for the dissemination of verbal alerts even if the aircraft is in contact with the controller who has

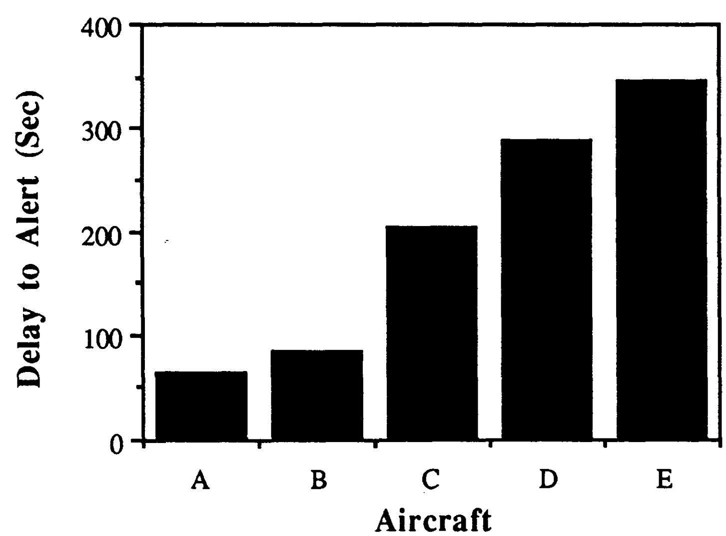


Figure 2.6[1] Delay between first microburst alert and transmission of alert to aircraft

alerting responsibility.

A third issue which arises is that the initial microburst alert for aircraft A, B, and C was imbedded within a routine landing clearance message. The routineness of the message may have resulted in a lack of urgency associated with the alert. This possible lack of urgency coupled with the high cockpit workload which occurs at the outer marker may have contributed to the difficulty some crews had in fully assessing the magnitude of the hazard. It is also worth noting that the tower controller relied primarily on the alphanumeric display. It is interesting to consider whether his level of urgency may have increased if he had access to the geographical situation display and could have more easily visualized how the situation was developing.

The final point which comes out of the analysis is the importance of PIREPS. Both the flight crews and the tower controller were more likely to react conservatively to the microburst alert after several aircraft had gone around and reported wind shear. This, coupled with the increasing microburst intensity, explains why the later aircraft initiated their missed approaches at higher altitudes than aircraft B which had no PIREP information to confirm the microburst alert. It should be noted here that *none* of these aircraft made an official PIREP; the windshear reports received were inferred from the go-around messages and some radio comments from aircraft which had already executed missed approaches.

2.4.3. PIREPs from 1988 Operational Evaluation

A recent report about the 1988 TDWR Operational Evaluation indicates that another potential problem with windshear alerting systems is overwarning [Stevenson, 1989]. PIREPS (from during or after the event) were collected from 111 pilots who landed or took off during alert periods. Of this group, 34% indicated that 'nothing was encountered', while another 31% reported something like 'nothing much was encountered'. These situations were not considered to be true false alarms (since TDWR-measured windshear was in fact present) and are better designated "nuisance alarms." A nuisance alarm rate this high can unnecessarily disrupt airport operations as well as damaging pilot confidence in the windshear alert system. The problem of overwarning is not an information transfer issue but rather a measurement and data processing issue. More specifically, it concerns hazard evaluation of the data and the resulting alert content.

2.5. Research Focus

The specific focus of this research has been the evaluation, transmission, and presentation of ground-based doppler weather radar derived information through a limited bandwidth digital datalink (Mode-S). Assuming the near-term deployment of both ground-based doppler weather radars and the Mode-S ground-to-air digital datalink, possible paths of information flow are illustrated in Figure 2.7. In this environment, data from LLWAS and TDWR sensors can be combined with pilot reports (PIREPs) to form the current windshear database. These PIREPs may be verbal, or reported automatically by an airborne *in-situ* sensor over the digital datalink. This data can then be processed to varying degrees, and transmitted to the aircraft via voice communications or digital datalink. Several issues are raised by this implementation scenario. One of these is the degree of data processing done on the ground; this can range from transmission of essentially raw data (as in the original LLWAS implementation, for example) or complete processing of the data into an executive decision to close the runway. One consideration is purely operational; What should be the distribution of decision-making responsibility between the pilot and the ATC controller? Another consideration is technical; Given the available weather information, what is the (quantitative) hazard posed by the current weather situation to a particular aircraft or aircraft type? As described in the Introduction, this research has concentrated on the issues of alert transmission and presentation (the crew interface) and assessment of the windshear hazard based on the available data.

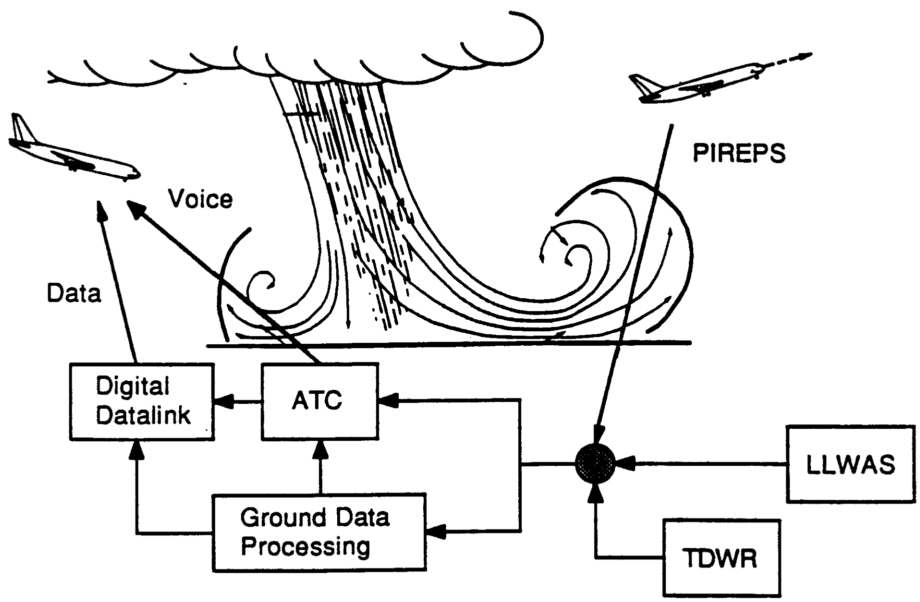


Figure 2.7 Possible Windshear Data Collection and Distribution in the Advanced ATC Environment

2.5.1. The Crew Interface

The first issue studied is the content and cockpit presentation of uplinked windshear alerts. User input was solicited through pilot opinion surveys, and then used to design a part-task simulation experiment. The primary results deal with the use of electronic instrumentation for presentation of uplinked information; specifically the relative merits and disadvantages of voice, alphanumeric (textual), and graphical modes of presentation. In this context, *voice* or *verbal* mode refers to standard ATC radio communications, *alphanumeric* or *textual* mode refers to presentation (on some electronic or paper device) of the literal text of a message, while *graphical* mode refers to a combined pictorial/text presentation of the alert information on some electronic map or map-like display. Alphanumeric and graphical presentations presuppose the existence of a ground-to-air digital datalink.

2.5.2. Windshear Hazard Assessment

The second issue examined is the evaluation of ground-measured windshear data to determine a hazard index. This hazard index should both accurately quantify the windshear hazard present and be meaningful to the flight crew. Overwarning must be minimized, since a large number of false or nuisance alerts can disrupt airport operations and damage pilot confidence in the alerting system. Analysis has identified some of the issues and problems involved, and some recommendations for both current alerts and further research have been made.

3. Pilot Opinion Survey

3.1. Objectives

In order to assess the functional requirements of an advanced integrated ground-based windshear alerting system, the needs and preferences of the end user must be determined. To this end, an opinion survey of active transport-category aircraft crews was conducted. The goals of the survey were to assemble data in the following areas:

1) User assessment of current windshear alerting/avoidance procedures.

2) User confidence in currently available windshear alerting information.

3) Desired information content of advanced windshear alerts.

4) Desired presentation and timing of advanced windshear alerts.

5) User opinions on operational procedures to be followed in case of hazardous windshear detection.

This database was intended to be used as an aid for user-centered design of windshear alert messages and for design of the part-task simulator experiments described in Chapter 4.

3.2. Survey Design

Design of the survey involved two major issues: selection of the target group and design of the questions. For the windshear survey, the desired characteristics of the target group were (1) active transport-category aircraft pilots (2) who frequently land and depart from airports noted for windshear. Also, the survey was conducted in concert with another MIT survey on cockpit automation. This, along with the fact that input on possible integration of windshear alerts with electronic displays was desired, led to requirement (3) limiting the survey to pilots qualified on aircraft with electronic displays (EFIS) and flight management computers (FMC).

These requirements were met by polling United Airlines pilots of Boeing 757, 767, 747-400, and 737-300 aircraft. United pilots were chosen since Denver-Stapleton airport is a major United hub, and experiences frequent windshear during the summer months. Also, United and the Air Line Pilots' Association (ALPA) were extremely cooperative in supporting and distributing the survey. The survey was distributed to 250 pilots, from whom 51 responses were received. All the respondents were guaranteed anonymity, and the surveys were kept confidential.

The survey questions were divided into two main sections. Part A dealt with current windshear avoidance procedures, while Part B dealt with requirements and user preferences for advanced windshear avoidance systems. In addition, data was collected on each respondent's transport-category aircraft flight experience. The survey is included as Appendix A. The Part A questions were intended to fulfill objectives 1) and 2) listed above, while Part B was directed at 3) 4) and 5). The majority of questions involved numerical rankings for statistical evaluation, although a few short essays were included to solicit pilot commentary. Finally, pilots were invited to describe any hazardous windshear encounters they had experienced.

3.3. Results

Significantly, 51% of the respondents have had what they considered to be a hazardous windshear encounter; most of these occurred at Denver-Stapelton airport, a UAL hub and an area noted for heavy microburst activity during the summer months. It should also be noted, however, that pilots who have had a hazardous windshear encounter may have been more likely to respond to the survey. Even if all of the non-responding pilots have not had a hazardous windshear encounter, 50% of respondents constitutes 10% of the entire population sample, which is very significant.

3.3.1. Current Windshear Avoidance Procedures

The first task of the survey was to examine general attitudes about microbursts and currently available windshear alert information. For this purpose, a series of opinion questions (scale of 1 to 5) were posed. A sample scale:

1	2	3	4	5
disagree strongly	disagree	neither agree nor disagree	agree	agree strongly

A response of 4 or 5 was scored as "agree", responses of 1 or 2 scored as "disagree" for the following results:

- Most of the pilots (90%) agreed that "Microbursts pose a major safety hazard to transport category aircraft."

- Only 15% of the respondents agreed that "Currently available windshear alert data is sufficient for safe operation in the terminal area," while 44% disagreed.

- *All but one* (98%) of the pilots felt that "a system to provide aircrews with better and more timely windshear alerts is <u>necessary</u>."

These responses clearly indicate that pilots are dissatisfied with current windshear alert data and would be receptive to improvements. The pilots were also asked to rate the usefulness of currently available windshear data (Figure 3.1). Significantly, PIREPs and visual clues are both considered more useful for windshear avoidance than LLWAS. However, neither PIREPs or visual information are always available. Even in the 7/11/88 incident (Section 2.4.2) there were no official PIREPS. This emphasizes the need for an improved remote detection and advance warning system, and the importance of good PIREP collection and distribution. Comments on this question also indicated that LLWAS data presentation can be confusing when more than one quadrant is given, and that pilots are well aware of the lack of correlation between radar reflectivity patterns and the presence of windshear. Some related pilot comments:

> "The best real time data comes from pilot reports to tower controllers (ATC) to subsequent flights. The biggest drawback to this system is the workload on the controllers and more radio traffic."

> "It is very distracting and difficult to interpret the rapid fire w/s alerts tower issues during the final approach and landing. At a time when full concentration is needed to fly the a/c tower blurts out "w/s alert centerfield wind 010/10, eastboundary 090/25, southboundary 170/5 westboundary ...etc., etc. Just hearing it at 800' off the ground is not enough. You have to distract yourself and visually picture what each of the 4 or 5 wind vectors look like. We need to develop a more precise quickly assimilated alert and limit the excess verbiage and interpret. Tell me windshear is present, its intensity and any gain or loss in kts."

> "Info is available at times, but is not provided to the stream of aircraft that is segmented on separate frequencies. Too many times an early encounter is not passed on to following aircraft in a timely manner."

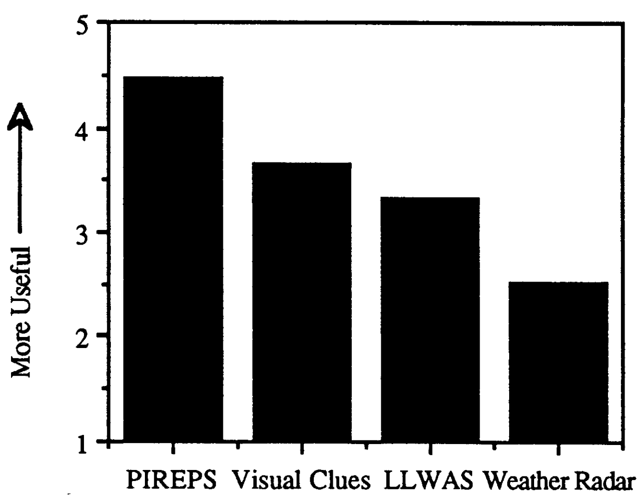


Figure 3.1 Pilot ranking of windshear information sources

3.3.2. Future Windshear Alerting Systems

The survey portion dealing with future windshear alerting systems assumed the existence of a ground-to-air datalink and an Electronic Flight Instrumentation System

(EFIS). Design issues for this scenario include decisions about both message content and mode of presentation. Because of the high workload in terminal area operations, it is important to consider the manner in which information is presented to the flight crew. In the integrated ground-based system considered in Chapter 2, there are three modes of information presentation available in a modern cockpit: *verbal, alphanumeric,* and *graphical.* These modes have been defined in Section 2.4.1. Issues to be considered include crew workload, preferences, and the capabilities of the aircraft instrumentation.

Responses indicate that pilots are receptive to graphic displays (Figure 3.2). The specific suggestion of integrating windshear information with an EFIS moving map display was strongly supported, with a ranking of 4.3 out of 5. Also of interest was the high preference for ATC voice alerts (3.9/5), which is likely a result of a practiced ability to interpret radio communications. Display of windshear alerts on some alternate graphical display (other than the EFIS moving map) was also ranked above alphanumeric displays and ATIS. Comments received indicated that the low ranking of ATIS was due to the long time between updates.

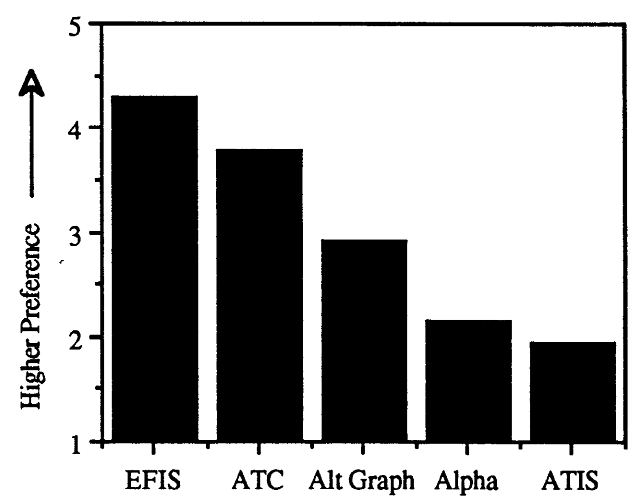


Figure 3.2 Pilot rankings of possible relay/presentation modes for ground-generated windshear alerts

Due to time limitations of VHF verbal communications and bit limitations of digital datalinks, the amount of information space available for a given alert is limited. For this reason, message content is critical. Thus, a question dealing with the message content of microburst alerts was included. The responses indicate that location and intensity of microbursts are clearly the most important information items. Size, microburst movement, and intensity trends are of secondary importance, and shape data is generally felt to be least important. Ranking of this information allows the design of alerts which fit within the message length constraints and still retain enough relevant information to be useful. In this case, the data indicates that the message must include location and intensity. Later work with the part-task simulation indicated that size would be desirable also, since it is also related to the intensity.

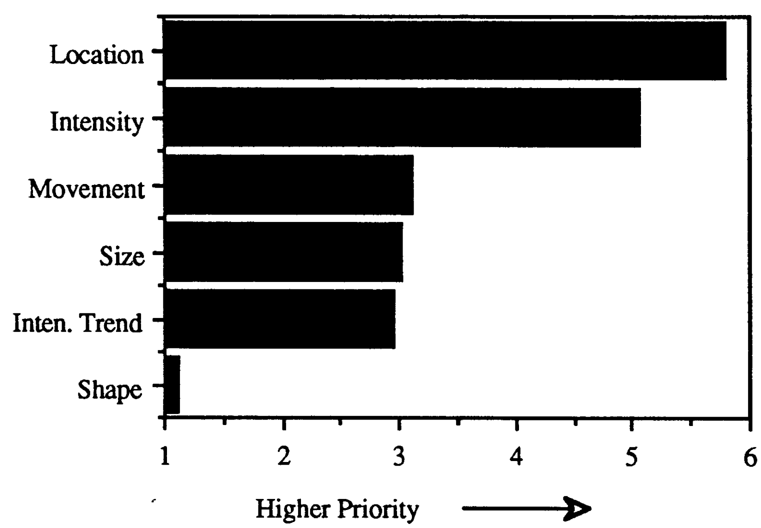


Figure 3.3 Pilot ranking of microburst information by importance

The survey also addressed timing of microburst alerts. There was no consensus as to in what phase of flight (during the approach) alerts should be given; the most common response was "as soon as detected." This topic needs to be further examined, since the high workload environment during terminal area operations makes timing of the warning crucial. This question should perhaps have been phrased as an essay, to invite qualitative evaluation of the options.

The respect with which pilots treat the windshear threat was emphasized in a question about threshold shear levels. The average response was that approximately 10 knots of headwind-to-tailwind shear component (i.e. airspeed loss) should constitute a windshear advisory and only 15 knots a windshear warning. Also, it was almost unanimously expressed that decisions about the threat posed by a particular windshear situation should be made entirely by the pilot, and the controller's role should be to maintain safe separation during avoidance maneuvers. These responses generally indicate that the pilots would like to have all the information available as soon as measured, and the sole responsibility for evaluation of a particular hazard situation. Some typical responses to this question were:

> "Pilot is responsible for aircraft's operation and assessing any and all threats. Threat varies by aircraft type and performance. Controller can't determine that."

> "He [the pilot] knows his airplane limits and must take the evasive action if necessary. Controller is essential as a data gatherer and separator from other traffic."

> "[The controller] is at the location longer and should be more familiar with trends, etc."

Due to crew and ATC saturation problems, it is impractical to plan on distribution of all available windshear information by voice to all aircraft in a congested terminal area. This emphasizes the need for a uniform hazard assessment criterion for ground-measured information and a defined threshold above which the threat becomes significant.

3.4. Cockpit Automation Survey

As part of a similar research project concerned with use of advanced cockpit displays for ATC clearance amendments, a survey on cockpit automation was developed and distributed to the same subject group [Chandra, 1989]. Since crew use patterns of the EFIS have a strong impact on the implementation of alphanumeric or graphical windshear alerts, some mention of the results of this survey is in order. This survey was specifically concerned with use of a Flight Management Computer (FMC) in concert with an EFIS, and was intended to evaluate crew acceptance and usage patterns of these automated systems. In general, regardless of flight hours with the FMC, pilots expressed a decided preference for automated aircraft over non-automated ones with an overall mean of 82% (Figure 3.4). Also, the consensus was that the FMC significantly reduces workload in most phases of flight, with the exception of the pre-flight programming required.

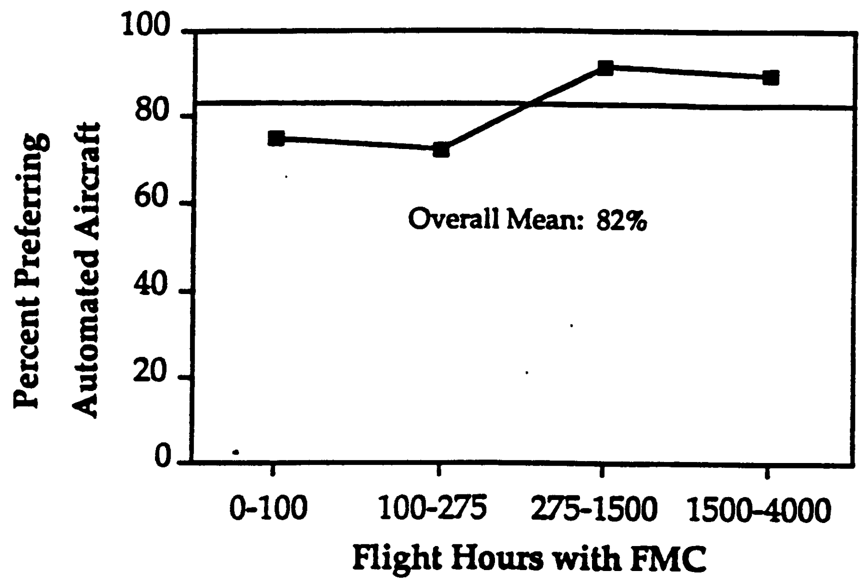
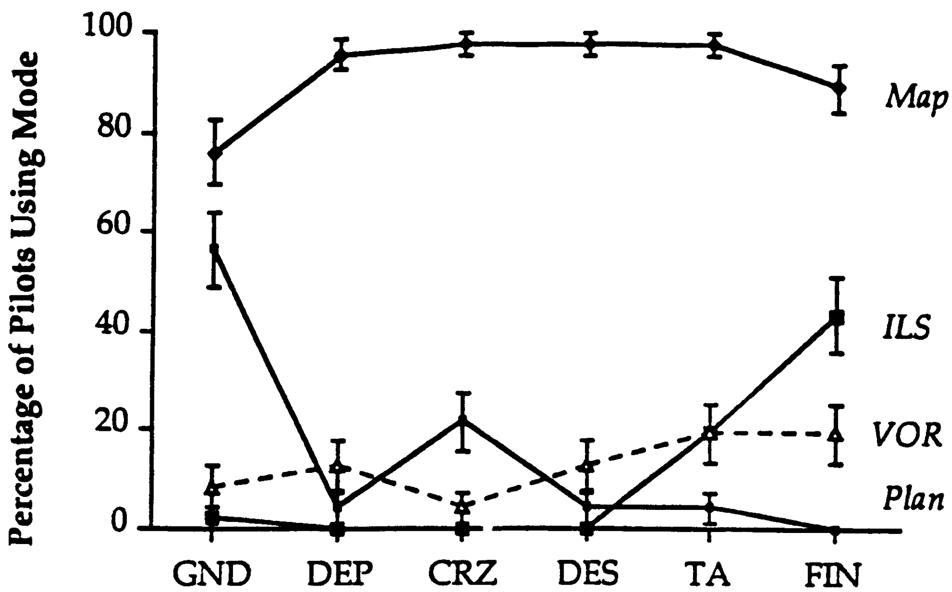


Figure 3.4 Crew Preference for Automated Aircraft: reprinted from (Chandra, 1989) by permission of author

The crew use pattern of the Electronic Horizontal Situation Indicator (EHSI) was also addressed. The EHSI is a map-like display of the aircraft's currently programmed flight path in addition to weather and other navigational information. The data, illustrated in Figure 3.5, demonstrates that the crews use the moving map mode of this display a significant portion of the time in all phases of flight. Significant use of other modes include use of Plan (north-up) mode during ground operations for flight path programming and use of the ILS mode during final approach. Since the simulation scenarios are set during descent and approach, Map and ILS modes were included in the EHSI simulation.



Phases of Flight:

GND = Ground Operations
DEP = Departure
CRZ = Cruise
DES = Descent
TA = Terminal Area
FIN = Final Approach

Figure 3.5 Use of EHSI Modes by Phase of Flight: reprinted from (Chandra, 1989) by permission of author

An effort was also made to determine the information density of the EHSI in Map mode. Figure 3.6 indicates that the "information load" on the EHSI peaks during descent and terminal area operations. This information load statistic was calculated by asking respondents to rank on a scale of 1 to 5 their need for each of the discrete items shown on the map display (see Figure 4.2), and then averaging all of the results for each mode to get the plotted result. The high ratings during descent and terminal area operations indicate a potential clutter or information overload problem for alphanumeric or graphical alerts which use the map display, re-emphasizing the need for a well-designed alert system.

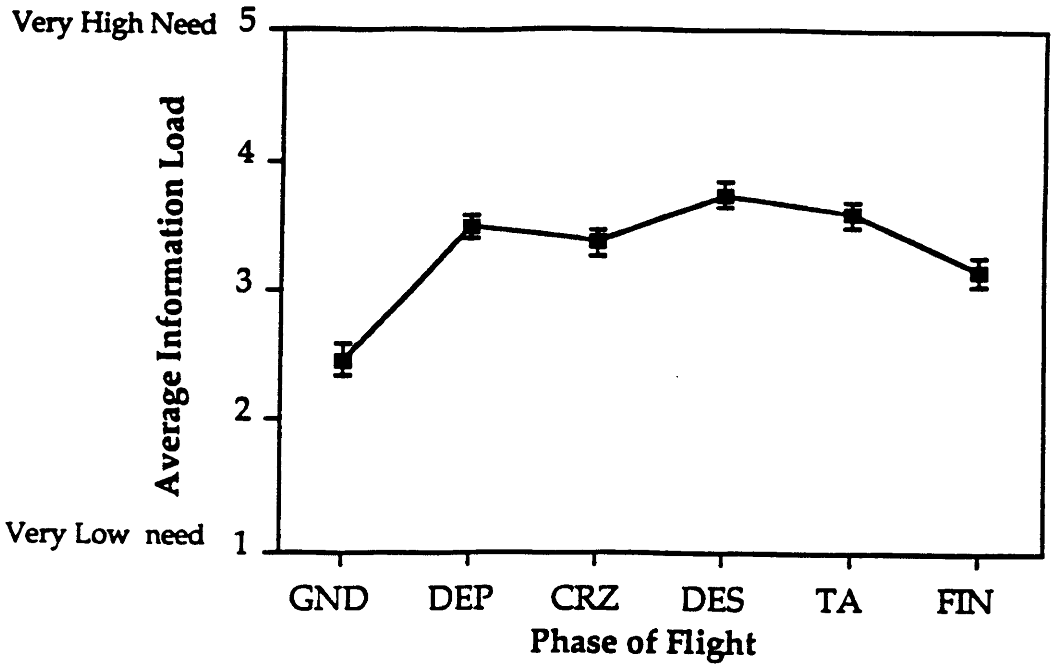


Figure 3.6 EHSI Information Load by Phase of Flight: reprinted from (Chandra, 1989) by permission of author

4. Flight Simulator Study

4.1. Objectives

The analysis of the survey data indicated both the need and the users' desire for better terminal area windshear alerts, including use of digital datalinks for information delivery and electronic displays for cockpit presentation. The next step was to evaluate the effectiveness and crew acceptance of such a system. To this end, a part-task simulator experiment was proposed with the following objectives:

- Evaluate the advantages and disadvantages of both alphanumeric (textual) and graphical alerts in comparison to conventional verbal communications
- Examine operational issues (timing, information content & density) raised by such implementations
- Obtain pilot feedback on these alerts, with a view towards isolating the most efficient presentation and information content

4.2. Simulator Design

4.2.1. Functional Requirements

The above objectives defined the functional requirements of the simulation. The simulation needed the capability to simulate all three presentation modes - *verbal*, *alphanumeric*, and *graphical* as defined in Chapter 2 - in a modern "glass cockpit." The simulation also needed to be complete and realistic enough to accurately simulate the terminal area flying task, so the impact of these messages could be examined in terms of crew workload and performance improvement or degradation. The ability to simulate the specific case of windshear/microburst alerts was required, as well as the ability to simulate electronic delivery of ATC clearances. This latter requirement was due to a parallel study being performed to evaluate the advantages of automated ATC clearance delivery. [Chandra, D., MIT MS Thesis, 1989]

This experiment was concerned with cognitive decision-making issues rather than the details of pilot performance. This allowed the use of a part-task simulation which included only the autoflight systems and electronic displays related to the particular cognitive task at hand. The workload deficit inherent in a part-task simulation was offset by the lack of a second pilot and imposition of a sidetask. The subjects generally agreed that the simulation was accurate for the tasks they were asked to perform. Also, no windshear dynamics were included, in that the data of interest was the cognitive go/no-go decision and whether or not penetration occurred. The major advantages of the part-task simulator are the ease of setup and operation and the flexibility of the electronic displays. Alphanumeric and graphical message formats are easy to implement and change.

4.2.2. Simulator Elements

To meet the above requirements, a part-task simulation of the Boeing 757/767 class of aircraft with its Electronic Flight Instrumentation System (EFIS) was developed. The simulator (Figure 4.1) contains the following elements:

Electronic Flight Instrumentation System (EFIS) and other instruments:

- EADI - Electronic Attitude Director Indicator: artificial horizon, autopilot annunciations, groundspeed, radio altitude

- EHSI - Electronic Horizontal Situation Indicator: moving map display with either track-up MAP mode with programmed path and navigational information, or heading-up ILS mode with glideslope and localizer needles. Both modes can be operated in 6 different ranges and permit overlay of airborne weather radar (WXR) reflectivity information. The EHSI was also used for graphical microburst windshear alerts. (Figure 4.2).

- Airspeed Indicator, Altimeter, and Vertical Speed Indicator: electronic "moving tape" displays of these instruments.
- Marker Beacon indicators, Flap indicator dial, Gear lights
- Alphanumeric display window, used for display of alphanumeric windshear alerts
- Sidetask display: A simple meter and buttons were displayed below the EHSI to provide a mouse-driven following sidetask for workload monitoring

Flight Management Computer (FMC):

- CDU - Control Display Unit: an alphanumeric display and keyboard for pilot input and control of the FMC. The simulator CDU has "pages" (display screens) for route legs (horizontal and vertical path programming), direct-to (for flight directly to a fix or waypoint), and for setting the intended landing airport and runway.

Control Panels:

- Autopilot Glareshield Panel: a simulation of the controls for the 757/767 autothrottle and autoflight systems, including LNAV/VNAV flight (following FMC-programmed lateral and vertical paths) and the various capture ("select") and hold modes for airspeed, heading, vertical speed, and altitude guidance.
- EHSI Panel: allows setting of the map display range from 10 to 320 nm, switching between MAP and ILS modes, and suppression of WXR, navaid, intersection, or airport information if desired.

- Flaps and Gear Panel: includes a switch for landing gear and a rotary dial for flap setting.

Communications:

- Headsets were provided for the pilot and simulation controller for verbal ATC communications; this system also provided a switch which the controller used to trigger some simulation events.

Air Traffic Control:

- A workstation in a room away from the simulator hardware was assembled, which included live video of the simulation, controller communications gear, and both audio and video recording equipment. The simulation controller monitored the experiment from this area and controlled the timing of ATC clearances and windshear alerts.

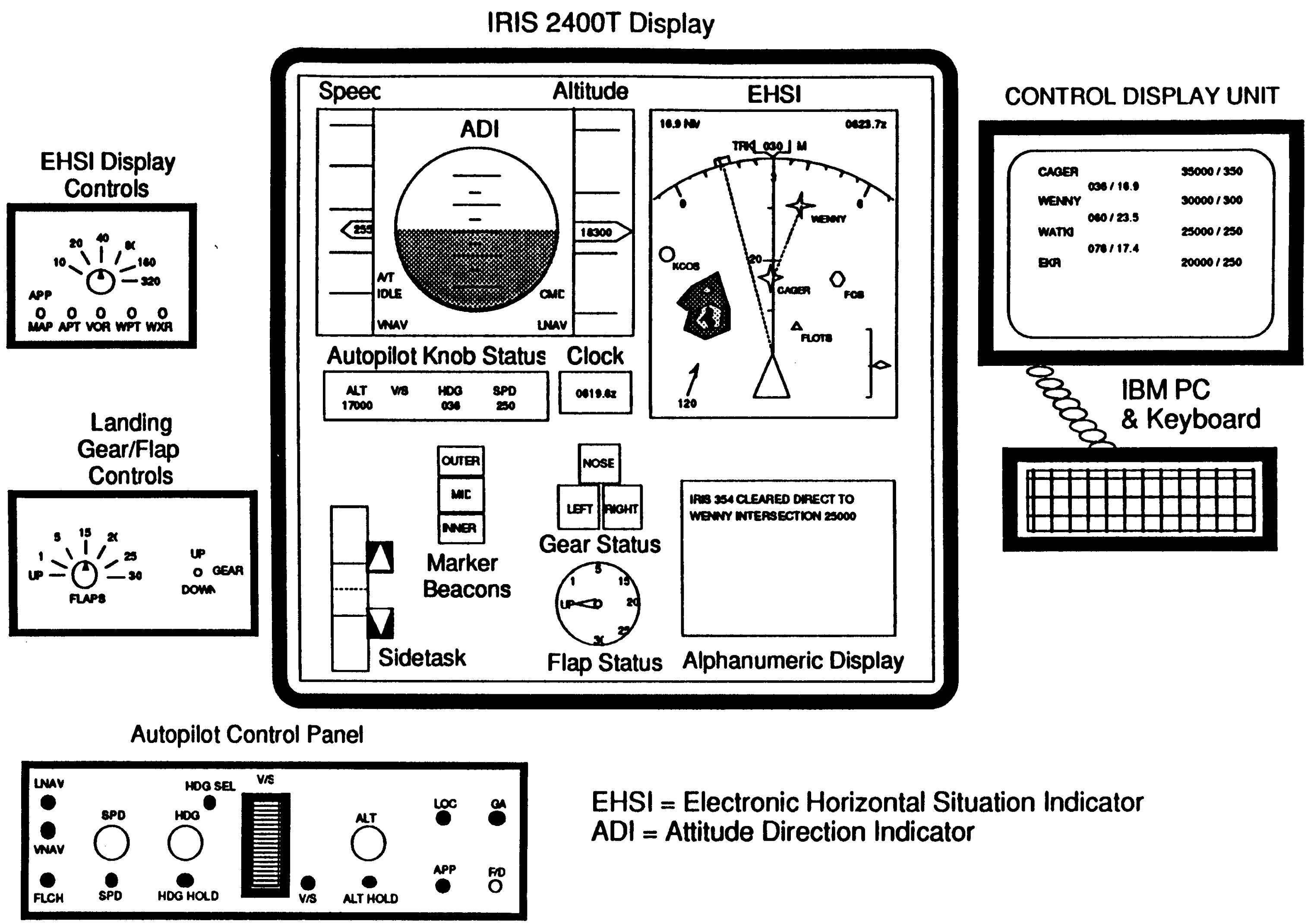


Figure 4.1 **Boeing 757/767 part-task simulator**

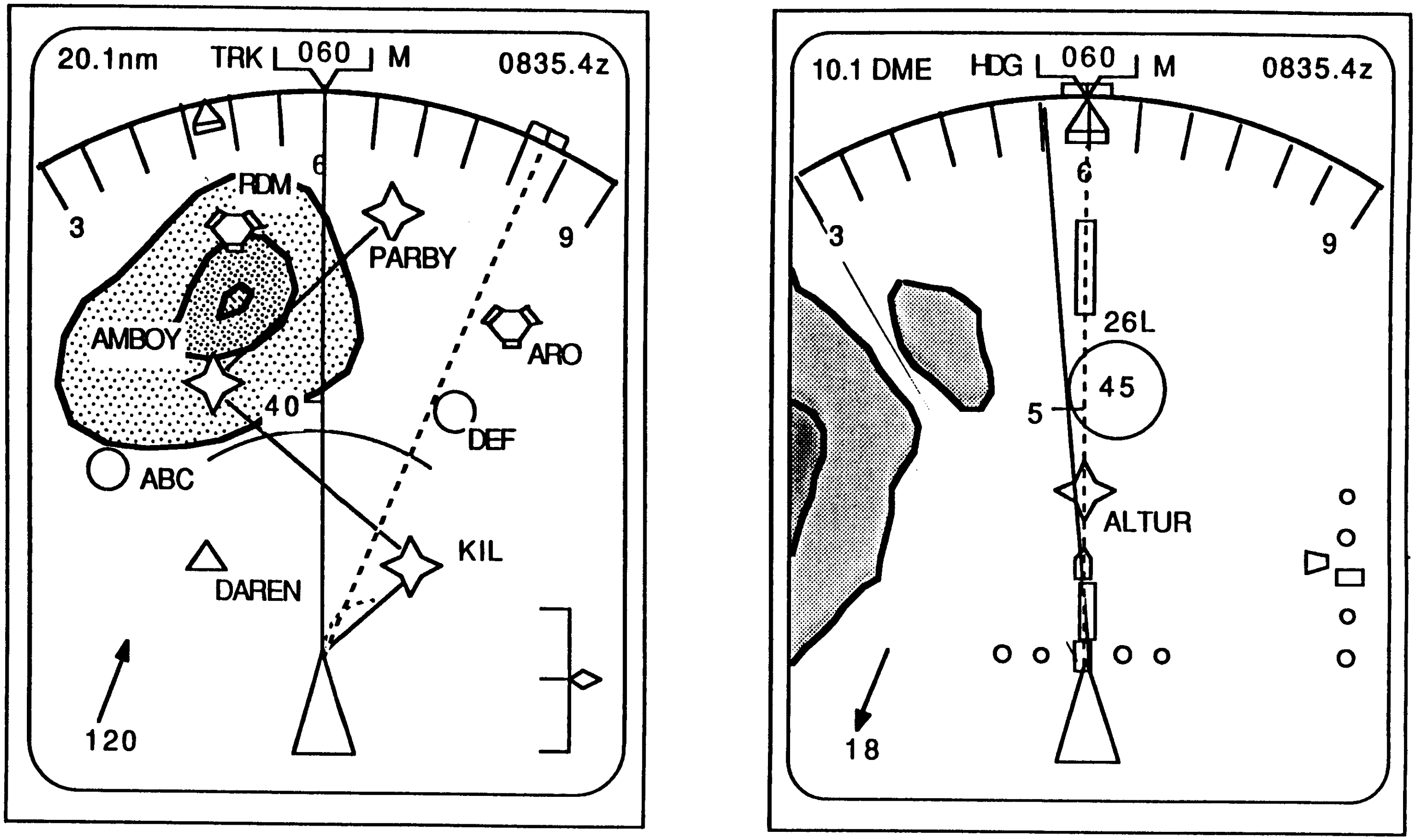


Figure 4.2 Boeing 757/767 EHSI display modes: MAP (left) and ILS (right)

The core of the simulation is the EHSI display (Figure 4.2). It serves as the primary navigational instrument, as a display of weather radar returns, and as the microburst alert instrument when the graphical presentation mode is being simulated. For these reasons, the EHSI was simulated as closely as possible for the MAP and ILS modes. In MAP mode, the EHSI displays the FMC-programmed track with waypoints and vertical profile points (start of descent, end of climb, etc.), destination airport, off-track airports, intersections, and navaids, vertical deviation indicator, distance and ETA to next waypoint, position of heading bug, wind velocity and direction, and weather radar returns. The weather radar returns and off-track airports, intersections, and navaids can be suppressed with toggle switches. The MAP mode is oriented heading-up and the range can be set at 6 discrete ranges from 10 nm to 320 nm. The ILS mode switches to track-up orientation, and adds glideslope and localizer deviation displays. The selected runway, localizer track, and final approach fix are displayed instead of the programmed path. Weather radar returns can still be displayed, but off-track airports, intersections, and navaids are not. DME distance to the runway is displayed rather than waypoint distance and ETA. Graphical microburst alerts appear in either MAP or ILS mode (as described below).

4.2.3. Hardware and Software

Two computers were required to implement this system. An IRIS 2400T graphics workstation was used for the electronic displays and calculation of flight dynamics and auto-navigation, and an IBM-XT was used to simulate the flight management system. The autopilot flight controls and display controls were simulated by a set of electronic control panels (autopilot glareshield panel, EHSI controls, flaps, gear), which were monitored through some data acquisition hardware by the IBM. The computers and control hardware were networked together with RS-232 serial connections.

The software for this system was extensive, and consisted of two large programs for the two computers. The IRIS software was written in C, and performed the main simulation control including color rendering of the electronic displays, simulation of the aircraft/autopilot dynamics, and implementation of the FMC navigation algorithms. The IBM software, written in Turbo Pascal, simulated the user interface to the FMC and monitored pilot inputs through the control panels. Both programs recorded all pilot inputs and the aircraft state for data analysis and playback purposes.

4.3. Experimental Design

The initial set of experiments was designed to answer the question: what are the advantages and disadvantages of graphical, alphanumeric, and verbal presentations in the context of both windshear alerts and ATC amendments? To accomplish this goal, a set of nine descent and approach scenarios into Denver-Stapelton airport was devised. The selection of the Denver terminal area is advantageous for two reasons: 1) the high incidence of dry microburst activity observed there and 2) the large number of descent profile and landing runway combinations possible. The inclusion of both ATC amendments and microburst alerts into the same scenario was useful in preventing the subject from anticipating or overreacting to repeated windshear alerts.

4.3.1. Scenarios

Each of the scenarios was divided into two phases. The aircraft was positioned at the outer limit of the terminal area, and given an initial flight plan (pre-programmed into the FMC). During the descent phase, the pilot was given three clearance amendments which required reprogramming of the FMC for compliance.

The second phase of the scenario began when the aircraft was vectored onto the final approach course. At this point, windshear alerts could occur. Microbursts were positioned either as a threat on the approach path or as a non-threat on the approach or departure end of another runway. In addition, microbursts could be positioned on the missed approach path. The alert was given either close in at the outer marker (6 to 9 nm from touchdown) or further out at 20 nm with a second message at 10 nm from the runway threshold.

The nine generic scenarios were divided into three blocks of three by presentation mode. In each block, all amendments and windshear alerts were given in the assigned mode: verbal, alphanumeric, or graphical. Verbal clearance amendments were given according to current ATC operating procedure. Alphanumeric clearance amendments were activated remotely by the controller, generating an audible alert, and the text of the message appeared on the CDU(Control Display Unit: the input screen for the FMC). In the graphical mode, clearance amendments when activated appeared directly on the EHSI as an alternate route (dashed white line), and could be accepted or rejected with a single FMC keystroke.

Microburst alerts always contained warnings for all possible approach runways, not only the one being used by the approaching aircraft. This was to ensure that all modes had the same information content, and to measure the pilot's facility to determine threat from non-threat situations in all three modes. Verbal microburst alerts were given as standalone messages by the controller. Textual microburst alerts appeared in an alphanumeric window just beneath the EHSI display. A typical verbal or textual alert: "IRIS 354, Microburst Alert. Expect four-zero knot loss, 2 mile final approach runway one-seven-left." Graphical microburst alerts appeared in the appropriate location on the EHSI map (in either MAP or ILS mode) as flashing white circles with the intensity (headwind-to-tailwind divergence value in knots) drawn over them. An example is shown on the ILS mode display in Figure 4.2. Verbal cues were given (i.e. "IRIS 354, Microburst alert.") in all modes, so that the time of notification was kept constant; this would not be the case in an actual cockpit, where an automated audible alert would most likely be used. Over the subjects tested, all scenario blocks were tested in all the modes, and the order in which the subject encountered the modes was rotated. This process was used to attenuate learning and scenario-dependent effects.

4.3.2. Subject Selection

With the aid of the Air Line Pilots' Association, eight active 757/767 qualified line pilots volunteered for the experiment. The subjects were all male; 5 were captains, and 3 were first officers. The pilots ranged in age from 30 to 59 years, with a mean of 47 years. In addition, several other pilots of varying experience volunteered to assist in the preliminary stages of developing the simulator and the scenarios.

4.4. Experimental Procedure

At the start of the session, the pilot was given all of the appropriate charts for the Denver-Stapelton area, the initial clearances for the nine scenarios, and the required checklists. He was then asked to complete the first stage of a NASA-designed workload evaluation [Hart, Staveland], which asked him to prioritize the different types of workload for the specific task of flying a 757/767 aircraft. At this point, the features of the simulator were demonstrated, and a sample scenario flown in which all of the three modes were encountered for both phases of flight. After all the subject's questions were answered, the testing began. Each of the nine scenarios lasted from 20 to 35 minutes. During the flights, one of the experimenters served as the ATC controller and one remained in the cockpit with the pilot to answer questions about physical operation of the simulator. After each scenario the pilot completed an evaluation sheet in which he described what level of workload he felt he was under, as well as his level of performance. After the scenarios were all complete, there was a debriefing session in which the pilot's impressions of both the simulator and the presentation modes tested were solicited. The data taken included:

- Computer recording of flight data, control inputs, sidetask performance, and FMC programming
- Audio tapes of ATC communications and 'cockpit' voices
- Videotape of EFIS displays
- NASA subjective workload evaluation sheets
- Post-session debriefing

From this data was determined the percentage of "correct decisions", time taken to make decisions, level of workload, and a number of qualitative observations. An "incorrect decision" was scored for either (1) microburst penetration or (2) a missed approach in response to a non-threatening microburst alert.

4.5. Results

4.5.1. Decision Making, Workload, and Pilot Preferences

The major quantitative results are illustrated in Figures 4.3 through 4.5. It was found from all three figures of merit - performance, workload, and preference - that the graphical presentation mode was superior. Also, the textual (alphanumeric) presentation mode proved roughly equal or slightly inferior to standard verbal communications. This data set was based on runs with eight 757/767-qualified active line pilots, all with considerable FMC experience.

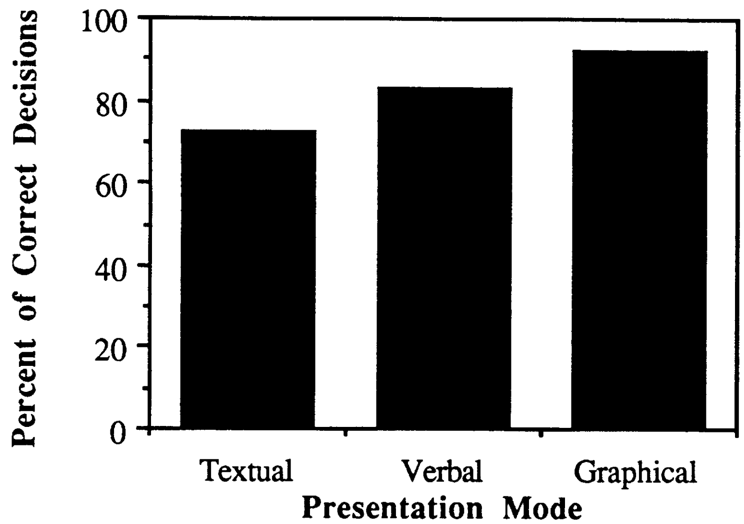


Figure 4.3 Part-task simulation results - response performance to windshear alerts by mode

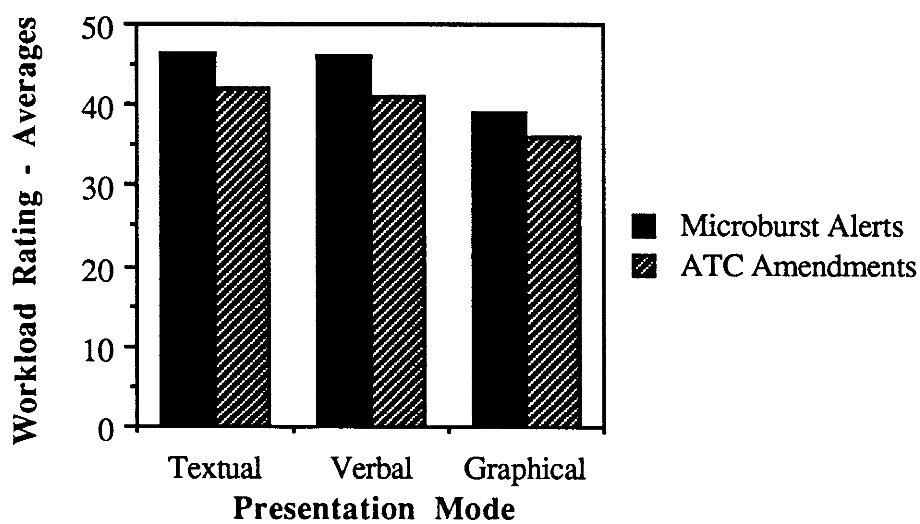


Figure 4.4 Part-task simulation results - subject workload by mode

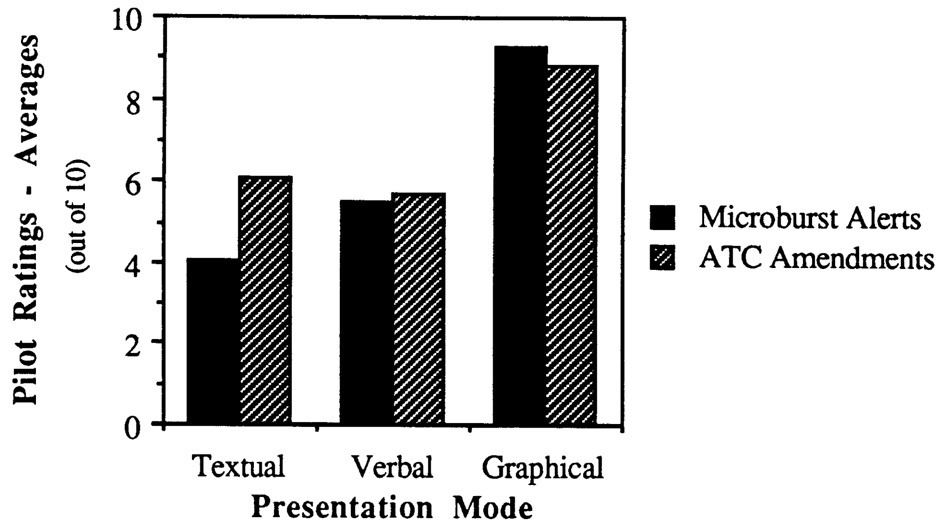


Figure 4.5 Part-task simulation results - pilot preference by mode

These numerical data were interpreted based on qualitative observations and pilot comments. In general, the graphical mode was most effective. Placing the data on the EHSI map display allowed the pilot to quickly visualize the situation, and spend less time orienting himself to the change in conditions resulting from the amendment or alert. Information on the EHSI seems to be more consistent with the cognitive map formed by the pilot. The rapid comprehension also meant a minimum of added "head-down" time, which appealed to the pilots. In the case of microburst alerts, the positional information contained in the graphical mode actually led several pilots to request and program non-standard missed approach procedures in advance in order to avoid the windshear areas completely. When the pilots were given the same information in the other modes, this was generally not observed.

Evaluation of the results for textual and verbal modes was more difficult. For windshear alerts, which are not copied down, more erroneous decisions are made with the textual than with the verbal mode. This implies that the information, given during the time-critical final approach phase, is more prone to misinterpretation when presented as text as when given verbally. This is consistent with the low preference rating expressed by the pilots for the textual microburst alerts. In most cases the pilots indicated that they did not like to look away from the instruments to read the textual alerts, most likely leading to poor comprehension. Some older pilots also commented that they had difficulty refocussing on the text when the alert appeared.

Verbal alerts also performed better than textual in the workload ratings for both experiments, and the performance advantage of verbal over textual for the windshear alerts was fairly large. It is apparent that the pilots had a great deal of experience in comprehending and retaining verbally transmitted information. For this reason, even though the verbal and textual modes contained exactly the same information, and the textual information stayed visible for several minutes, the verbal alerts were more effective.

4.5.2. Qualitative Observations

Some further observations were taken from the experimenters' notes and pilot comments:

- Textual alerts in time-critical situations - such as final approach - require too much head-down time.

- Digitally transmitted information in either mode, textual or graphical, leads to a loss of prosodic (voice inflection) information. Since controllers sometimes use voice inflection to distinguish urgent alerts from normal communications, this is in some sense a loss of information.

- Digitally transmitted information, if directed to specific aircraft, prevents pilots from hearing instructions given to other aircraft in the terminal area. Some pilots stated that hearing the communications to other aircraft in the vicinity gave them a better understanding of the overall situation and enabled them to be better prepared when an alert arrived. Other pilots indicated that they could do without the information.

- A final observation that has implications for the design of cockpit data presentation is that many pilots took the most time-critical portion of a message, resolved it, and then went on to complete the task when the time pressure was off.

4.6. Conclusions

The consistency between the survey and simulation results allows the following conclusions to be drawn. Pilots appear to be generally receptive to the idea of automated ground-to-air information transfer for windshear alerts. However, the presentation of the information is critical. From the pilot opinion survey results, the post-simulation interviews (pilot preferences), and the simulation results (workload, performance) it is clear that graphical presentation of both windshear alerts and clearance amendments is significantly more effective than verbal communications. This may possibly be generalized to any situation which requires the pilot to recognize and interpret spatial information quickly; the graphical presentation mode seems to allow much quicker comprehension of such information. To obtain this benefit, the detailed format of such graphical information must be carefully designed to present only the necessary information in clear fashion without clutter or data overload.

In the case of windshear alerts, the pilots identified this minimum presentation to be a simple symbol showing location, approximate size, and intensity. The proposed Mode-S datalink, for example, allows 48 bits of useful information every 4 to 12 seconds in surveillance mode. This minimum alert presentation can likely be expressed in 24 bits or less, allowing two messages per scan. Therefore, the Mode-S link has the capability to be used in surveillance mode to display and track several microbursts, while maintaining the 1 minute update rate achieved by TDWR in the current configuration.

Information received over a digital datalink may also be presented as alphanumeric (textual) messages; again, the survey and the simulations were consistent in the results. The textual mode of presentation was rated poorly by the pilots, and did not effect either a reduction of workload or an improvement in performance. Pilots disliked in particular the additional head-down time required to read textual information. The speed of comprehension did not seem to improve with textual warnings; the familiarity of operational pilots with verbal communications seemed to outweigh the advantage of having the text of the message displayed indefinitely. Finally, textual messages appear to offer no advantage over verbal messages for comprehension of spatial information.

The part-task simulation experiment which has been performed has given useful results; repetition of this experiment on a full-mission simulation would provide good supporting data and allow exploration of other factors which could not be realistically evaluated with the current simulator hardware. The effects of realistically crowded radio communications and the full set of cockpit tasks and distractions should be included for a thorough evaluation of the issues explored here.

5. Assessment of the Windshear Hazard

5.1. Motivation and Problem Definition

As illustrated by review of the PIREPS received during the 1988 TDWR Operational Evaluation (see Section 2.4.3), difficulties in quantifying ground-measured windshear data can result in "nuisance alarms," which can degrade both pilot confidence in the alerting system as well as unnecessarily hindering airport operations. This is the motivation for more carefully investigating the measurement issues which affect the problem of windshear hazard assessment. These issues arise from both the geometrical difficulty involved in measuring low-altitude spatially small windshear events from the ground, and from the limitations of the sensor employed. The ultimate aim of studying these issues is to aid in development of a hazard criterion which:

1) Is derivable from the available ground-based sensor data (i.e. doppler weather radar, LLWAS, etc.)

2) Is an accurate measure of the performance loss experienced by an aircraft penetrating the windshear event

3) Can be simply and clearly expressed to the pilot such that he can quickly understand the implications of the alert and make an informed decision

5.2. Windshear Threat: Energy-Height Analysis

An analysis has been conducted by researchers working in the NASA Langley Research Center airborne windshear detection system program which provides a useful starting point for quantifying the performance degradation of windshear on aircraft. [Targ and Bowles, 1988; Hinton, 1990] The effect of windshear, neglecting short period disturbances and motions, can be examined from the perspective of energy losses and gains. The energy state of an aircraft can be quantified by summing the air-relative kinetic energy and the ground-relative potential energy. The air-relative kinetic energy is used since the air-relative velocity (airspeed) rather than the inertial speed indicates the immediate climb capability of the aircraft; similarly, the altitude above ground-level is the measure of potential energy relevant to aircraft recovery. This energy sum per unit weight (specific energy), also referred to as "potential altitude" or "aircraft energy height," can be written:

$$h_p = \frac{E}{W} = \frac{V^2}{2g} + h \qquad [5.1]$$

where V refers to aircraft airspeed and h to altitude above ground level (AGL). Assuming that airspeed can be converted to climb rate with no energy losses, the rate of change of this quantity also indicates the potential rate of climb of the airplane:

$$\dot{h}_p = V\left(\frac{\dot{V}}{g}\right) + \dot{h} \qquad [5.2]$$

Combining this definition with the equations for an aircraft flying through a non-uniform atmosphere, and assuming a small inertial flight path angle (a good assumption for approaching or departing transport-category aircraft), the potential rate of climb becomes:

$$\dot{h}_p = V\left(\frac{T-D}{W}\right) - V\left[\frac{\dot{W}_x}{g} - \frac{W_z}{V}\right] - V\left(\frac{\dot{V}}{g}\right) \qquad [5.3]$$

where W_x refers to the (tailwind positive) horizontal wind component, W_z refers to the (downdraft positive) vertical wind component, T is engine thrust, and D is the drag on the aircraft. The bracketed term in the above expression contains the effect of the windshear on potential rate of climb, and is referred to as "F-factor" or simply F. It should be noted that the dot notation on the horizontal wind component indicates a substantial derivative, since the wind components are dependent on both time and the aircraft's instantaneous position. Rewriting this equation for the case of constant airspeed:

$$\dot{h}_p = V\left(\frac{T-D}{W} - F\right) \qquad [5.4a]$$

$$F \equiv \frac{\dot{W}_x}{g} - \frac{W_z}{V} \qquad [5.4b]$$

From this, it is apparent that F can be viewed as a direct measure of the loss in available climb rate (for a constant airspeed trajectory) or, equivalently, the loss in available excess power due to the presence of a windshear. If F exceeds the *excess* thrust-to-weight ratio, the aircraft then has no available climb rate, which clearly constitutes a hazardous situation. Therefore, F is an *instantaneous* measure of the hazard posed by the immediate windfield. It is a non-dimensional quantity, and a function purely of windfield and airspeed. Note also that F has separate components due to the head-to-tailwind shear and to the downdraft. These will be referred to later as F_x and F_z. A threshold value of F for a particular aircraft and configuration can be set, and exceedance of this threshold for a predetermined period of time indicates the presence of a windshear hazard. One reference [Targ, Bowles 1988] indicates that this threshold value should be between 0.1 and 0.15 for jet transports in typical landing and take-off configurations. Since F is dependent purely on airspeed and the immediate windfield values and time rates of change in the aircraft frame, it is ideal for application to onboard reactive windshear detection systems. An accelerometer-based inertial reactive system can directly measure all of the required quantities and provide an accurate alert of windshear penetration.

Some limitations of the F-factor quantity should also be emphasized. F is an instantaneous measure of the effect of a windfield on the aircraft energy state; it does not explicitly include aircraft dynamics (i.e. inertial lags, autopilot control effects, changing thrust and airspeed). A portion of the windshear hazard also comes from severe turbulence which can destabilize the aircraft and degrade performance; this is not included in the model. The crash of Delta 191 at Dallas-Fort Worth Airport in 1985 is a related historical case. [Fujita, 1986] The microburst winds during this event contained several strong vortices. When the aircraft penetrated these vortices, the scale was small enough that differential winds on the wings caused large rolling motions (up to 20°). In addition, there were large angle-of-attack excursions. This would indicate that these disturbances, caused by tight, strong vortices on the scale of the aircraft length/wingspan, had significant impact on the aircraft's performance Piloted simulations have been performed with simulated winds from the DFW case, and have borne out this conclusion. [Hinton, 1989]

It should also be noted that F can be difficult to measure with remote sensors, and is not an intuitive quantity to pilots; these issues are addressed below. For the "typical" microburst, producing a headwind shearing quickly to a tailwind over a few kilometers distance, F is an excellent way of quantifying the performance loss to be expected.

5.3. Ground-Based Single-Doppler Measurements of Windshear

The use of a single ground-based doppler radar to detect low-altitude windshear imposes some limitations on the data analysis which can be performed. If two doppler radars were employed, all three components of the entire windfield around the airport could theoretically be resolved. However, this is not economically feasible, and therefore efforts have been focussed on use of single doppler radar measurements with appropriate processing. This section presents an outline of how doppler radar measurements are used in the TDWR system, and identifies some of the problems which arise and how they impact the operational use of TDWR.

5.3.1. Ground-Based vs. Airborne Remote Measurements

One issue which relates to ground-based measurements in general is the difference in reference frame between the ground and the aircraft. Ground-based sensors such as TDWR can acquire data about the entire terminal area and therefore have good knowledge of the entire weather situation, but lack precise data about the aircraft state. An airborne look-ahead system will have aircraft state information available, but will likely be limited to measuring the windfield directly along the aircraft flight path. Thus, the airborne measurement is best suited to quantification of the immediate threat. The ground-based measurement is well suited for identifying the presence of a threatening windshear at any point in the area, and thus is best employed as an advance warning sensor for windshear avoidance.

The ideal system would then be a combination of ground-based and airborne components. A ground-based doppler radar system would be used for microburst location and overall intensity estimation, thus identifying which aircraft in the terminal area are at risk. This "front-line" system would then alert the threatened aircraft of the presence of windshear and the maximum shear intensity which may be encountered. The pilots of the threatened aircraft could then either take immediate avoidance action, or employ their airborne look-ahead sensors to determine if and when to take such action. As the last line of defense, airborne *in-situ* (reactive) sensors would provide the alert if a hazardous windshear is penetrated.

However, airborne look-ahead systems with the capabilities required to implement the aforementioned alert system are not currently available, and will not be installed on a significant number of aircraft for at least several years. TDWR systems, on the other hand, will be available at several airports in the next couple of years, but will never be available at all airports. Even after the airborne systems become feasible, it is likely that not all aircraft operators will install them for economic reasons. This implies that having both ground-based and airborne data available will never be guaranteed. As a result, it is desirable to have the capability to do both general threat detection and hazard quantification with the ground-based system to best obtainable accuracy. For this reason, development of good hazard estimation for the ground-based radar measurements compatible with airborne *in-*

situ measurements is desirable, and requires analysis of the nature of the single-doppler measured data.

5.3.2. TDWR Windshear Alarms

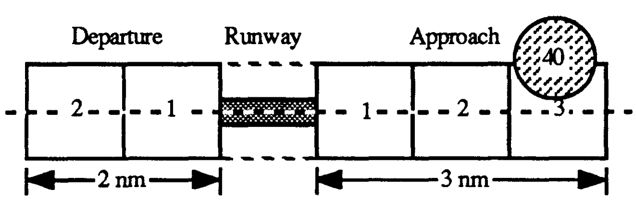
The initial step in this analysis is to examine the characteristics of the prototype TDWR system which is currently being tested. In Chapter 2, the promising results of these tests as well as some problems encountered were discussed. In this section, details of the measurements will be discussed.

The windshear-related products of the TDWR system are gustfront and microburst detection. The TDWR, based approximately 15 km from the airport, uses a pencil-beam of 1° half-power beamwidth to measure both reflectivity and wind velocities. A low-elevation scan of the airport vicinity (approximately 120° in width) is performed every minute for microburst detection, and two full circle scans are performed every 5 minutes for gustfront detection. In addition, a series of higher elevation scans of the airport vicinity are conducted in between surface scans to obtain data for microburst precursor detection. This scan strategy is designed to produce new microburst alert information every minute, and a gustfront prediction every 5 minutes. [Merritt et al. 1989]

The resulting data is then analyzed to detect features characteristic of existing or imminent microbursts, or gustfronts. A surface microburst is detected by identifying regions of velocity divergence; if the detected wind component radial to the radar shows a steady rapid increase with range, a surface outflow is present and a shear segment is scored. Definite groups of these segments are "boxed" by the processing algorithm, subjected to tests for significant strength and size, and identified as microburst regions. In addition to surface outflows, reflectivity and velocity features aloft are processed by an AI algorithm to detect microburst precursors (an indication that a surface outflow will occur in

5 to 10 minutes). Also, the doppler measurements are evaluated for radial convergence for gustfront detection and corresponding windshift estimation.

The result of this analysis is identification of the microburst and gustfront areas indicated by the symbols on the Geographical Situation Display in Figure 2.3. The final task is to identify when these constitute a threat, i.e. when to issue an alert. This criterion was determined by a TDWR/LLWAS User Working Group of pilots, air traffic controllers, FAA officials, researchers, and others. [NCAR, 1988; Sand and Biter, 1989] The resulting criterion for microburst alerts is described in Figure 5.1. The "wind shear warning boxes" in the figure were defined by the Working Group based on the assumption that aircraft below 1000 ft AGL in landing or take-off configuration are most susceptible to windshear. The boxes are 1 nm squares extending 3 nm from the runway landing threshold, 2 nm from the departure end of the runway, and directly over the runway. A microburst event of measured divergence greater than 30 knots which impacts any part of these boxes triggers a microburst alert; events of 20 to 30 knots divergence trigger a "wind shear with loss" alert. This alert is radioed to the pilot as he contacts the tower for his final approach. A sample is shown in Figure 5.1.



The alert corresponding to the 40 knot microburst pictured above might be:"United 226, Denver tower, threshold wind one six zero at six, expect a forty knot loss on three mile final."

Figure 5.1 TDWR microburst alerting corridor

As discussed in Chapter 2, mixed results have been achieved by this system. It is clear that the probability of microburst detection is very high and that the use of the TDWR system for locating microbursts and providing advance warning is very promising. However, the method used for determining the microburst hazard resulted in cases of overwarning or nuisance alarms. Therefore, with this baseline system in mind, some of the measurement difficulties were analyzed with the goal of providing more relevant hazard assessments from the TDWR measurements.

5.3.3. Geometrical Issues

The largest contributing factors to the overwarning problem are due to situation geometry. These factors result from both the geometry of the aircraft penetrating the microburst and the geometry of the radar measurement. The first category includes issues such as off-center microburst penetration, and variations in altitude of penetration. The second includes issues such as radar beam averaging and the limitations of measuring only the velocity component radial to the radar. This section outlines the major measurement limitations, which will be further analyzed in Section 5.4.

With the current warning methodology, off-center microburst penetrations are likely the major cause of overwarning. As stated above, if any part of the identified microburst area enters any part of the warning boxes, an alert is triggered. This implies that, under the current strategy, the same alert is given in both the case of a microburst marginally encroaching on the warning box and in the case of the microburst occurring directly on the flight path. In many of the cases of apparent "nuisance alarms" documented by Stevenson [1989] the estimated microburst position was off to one side of the flight path.

Another geometrical issue is variation in altitude of penetration. Looking at the approach scenario, aircraft encountering microbursts in the 1, 2, and 3 mile warning boxes will reach those events at varying altitudes. This has some impact on the windfield experienced. Microbursts, being small-scale events, can have large variances in wind velocity with altitude. In addition, there is a measurement issue involved. The radar has a finite beamwidth on the order of 1°. For a radar situated several miles from the airport, as in the TDWR evaluations, this means that the microburst scan effectively measures an average radial wind velocity over the lowest 500 to 1000 feet AGL. Thus, the low-altitude windfield variations cannot be differentiated, and the same warning must be issued regardless of the altitude of the encounter.

Another obstacle to accurate windfield measurement is microburst asymmetry. For divergence estimating purposes, the asymmetry ratio of a microburst can be defined as the ratio of shear in the direction of maximum divergence to shear in the direction of mimimum divergence. In the JAWS (Joint Airport Weather Studies) Project, multiple doppler radar measurements of Colorado microbursts were taken and 3-component windfields derived. Analysis of this data [Wilson, et. al. 1984, Hjelmfelt 1987] indicates that the microbursts measured have an average asymmetry ratio of greater than 2 with extreme cases of greater than 5. A similar study of Oklahoma downbursts indicated asymmetries up to 5.5 [Eilts, Doviak 1985]. This indicates that a single doppler measurement of one radial microburst slice can significantly over or underestimate the intensity of the shear present.

5.3.4. Operational Issues

Aside from measurement issues, there are some operational issues which can also contribute to the overwarning problem. These are largely due to the difficulty in presenting an accurate verbal picture of the situation to the flight crew which indicates what the particular aircraft involved is likely to experience.

One operational issue which may contribute to the overwarning problem is the reference in current microburst alerts to "loss." In reality, the quantity measured by the radar is the velocity *divergence* across the event. This value is reported to the aircraft as the maximum headwind loss possible in knots, which is to be interpreted as the maximum airspeed loss the aircraft could experience. [Sand and Biter, 1989] However, even in the case of an aircraft flying directly through a symmetric microburst at constant altitude, the actual winds experienced will be an initial airspeed gain of half the reported value, followed by an airspeed loss of the whole value. The maximum loss *with respect to reference airspeed* as set before penetration is actually half of the reported value, while the maximum loss encountered *with respect to the greatest airspeed achieved* is the whole value. This may generate confusion among flight crews, who are likely to consider losses in comparison to the reference airspeed.

An additional factor which may add to discrepancies between what is measured and what is experienced is that the actual airspeed changes which occur on the aircraft are to some degree dependent on the dynamics of the pilot/autopilot/aircraft system. The response of the aircraft to a microburst depends on the spatial scale of the event. Small microbursts may cause airspeed fluctuation, but little flight path deviation; correspondingly, a long period disturbance will tend to excite the phugoid of the aircraft and initiate a glideslope deviation. In either case, the energy management strategy of the flight controller (human or machine) will have an impact on what is experienced in terms of airspeed loss and altitude deviations, and can therefore affect how a report of "loss" is perceived by a particular pilot flying a particular aircraft.

A final factor which must be considered in relation to this section is that flight crews are not meteorologists or flight dynamicists, and that any intensity measure which is employed must be designed with this in mind. The last two issues mentioned here pose problems which are not due to the measurement but rather to pilot perceptions of how the system operates and what it measures.

5.4. Analysis of Geometric Factors

From the factors discussed in the previous section, it is likely that the encounter geometry has the most impact on the differences between what is measured and what is actually experienced. Encounter geometry in this case includes both effects of penetrating the microburst laterally off center and altitude dependent variations in the windfield. To evaluate the impact of these effects, a series of analyses were conducted. These include plots of winds along the flight path and flight simulations of microburst encounters.

5.4.1. Static Windfield Analysis

The simplest analysis which demonstrates the effects of these geometric factors is to examine the winds that would be encountered along the glideslope by a "perfectly piloted" approaching aircraft. This was done both with a simple analytical microburst model and with data from a detailed numerical simulation.

5.4.1.1 Description of Simple Analytical Microburst Model

This model was developed at NASA Langley Research Center [Oseguera, Bowles 1988] and is based on boundary layer stagnation flow dynamics. The characteristics of this flow were combined with numerical relationships derived from a more sophisticated model to obtain analytical, differentiable windfield equations. The resulting model is time-invariant, axisymmetric, and produces the correct large-scale windfield behavior. No short scale motions (turbulence, ring vortices) are included. The model is defined by 3 parameters: downburst shaft radius, maximum outflow velocity, and altitude of maximum outflow. An example of typical windfield components are plotted against range and altitude in Figure 5.2.

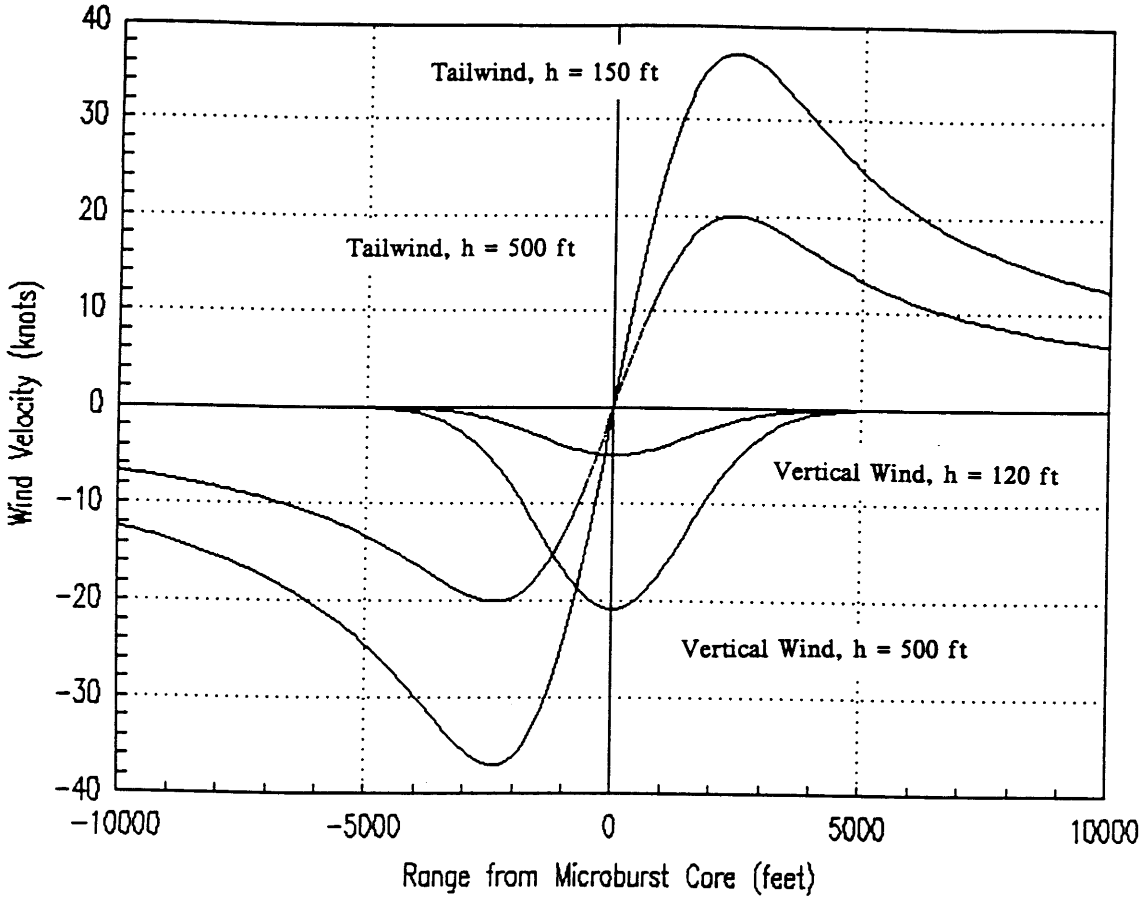


Figure 5.2 Oseguera and Bowles Microburst Model - Example Winds

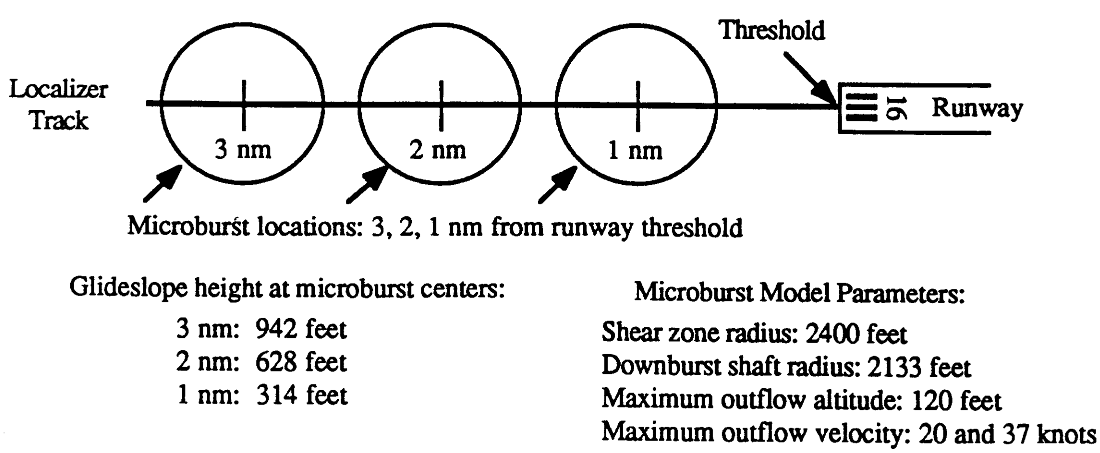


Figure 5.3 Geometry for Microburst Altitude of Penetration Analysis

To examine the effects of differing altitudes of penetration, plots were made of the windfields along the glideslope for an aircraft penetrating a microburst at 1, 2, and 3 nm from the runway threshold (Figure 5.3). For an aircraft on a 3° glideslope, this corresponds to penetration of the microburst core at altitudes of 314, 628, and 942 feet AGL respectively. The model parameters used were for microbursts of 40 knots total divergence (20 knots max outflow) and 74 knots divergence (37 knots outflow) with a downburst shaft radius of 2133 feet and max outflow altitude of 120 feet. These parameters correspond closely to the sample windfield in the Oseguera and Bowles paper [1988]. The headwind and downdraft components which then occur along the glideslope are plotted (for the 40 knot divergence case) in Appendix B (Figures B.1 - B.3). In addition, if a perfectly controlled constant airspeed trajectory with no glideslope deviation is assumed, the total F-factor and its components can be computed. The results are summarized in Table 5.1.

Microburst Distance from Threshold	Peak Winds (knots) Headwind	Tailwind	Downdraft	Peak F-factors F_x	F_z	Ftotal
1 nm	12.1	18.7	8.21	0.13	0.058	**0.19**
2 nm	6.82	10.8	13.2	0.078	0.094	**0.17**
3 nm	3.85	6.10	16.1	0.044	0.12	**0.16**

Table 5.1a Effects of Altitude of Penetration - Simple Microburst Model: Peak winds and F-factor components encountered by an aircraft approaching through a 40 knot microburst located at varying distance from the runway threshold.

Microburst Distance from Threshold	Peak Winds (knots) Headwind	Tailwind	Downdraft	Peak F-factors F_x	F_z	Ftotal
1 nm	22.3	34.6	15.1	0.26	0.11	**0.36**
2 nm	12.6	20.0	24.4	0.15	0.17	**0.32**
3 nm	7.13	11.3	29.9	0.082	0.21	**0.29**

Table 5.1b Effects of Altitude of Penetration - Simple Microburst Model: Peak winds and F-factor components encountered by an aircraft approaching through a 74 knot microburst located at varying distance from the runway threshold.

These results indicate that, although the windshear encountered varies from primarily downdraft in the 3 nm example to primarily head-to-tail shear in the 1 nm example, the total F-factor remains roughly constant. There is a small increase in F as the penetration altitude nears ground level. Therefore, for this simple model, F is an excellent hazard criterion. A feature to note is that, although the total F is basically invariant with altitude, the components of F due to head-to-tailwind shear (F_x) and the component due to downdraft (F_z) do vary. As with the velocity fields, the horizontal shear component is more important at low altitudes and the downdraft is more significant at higher ones. The ratio of F_x to F_z is about 1 at around 600 feet, for the downburst radius and altitude of maximum outflow parameters used in these two microbursts. The problem this causes is that a ground-based doppler radar can only directly measure F_x, not total F. This is made more difficult by the finite radar beamwidth. As noted in Section 5.3.3, the radar beam effectively averages over the lowest 500 to 1000 feet AGL of the windfield, and all of these encounters occur at less than 1000 feet AGL.

It should also be noted that the "40 knot divergence microburst" as defined here refers to the maximum horizontal shear across the event at the altitude of maximum outflow (120 feet). This does not indicate that the TDWR would measure a 40 knot divergence; due again to finite beamwidth, the measured shear will be somewhat less. The actual value depends on the range from the radar (amount of beam spreading), the altitude variations within the microburst windfield, and the gain pattern of the antenna.

To evaluate the effects of lateral offset, the same microburst model (with 40 knot maximum divergence) was used with lateral displacements of 500 to 5000 feet, for an event centered 2 nm from the runway threshold [Figure 5.4] The results for this case are presented in Figure 5.5, and show that the peak F experienced drops off quickly with offset distance. All of these events are well within the TDWR warning corridor, and for offsets of less than 2500 feet, the microburst identification circle (which encompasses the area of maximum divergence) also intersects the flight path. Encountering this microburst at an offset distance of 2500 feet would result in a peak F which is only 40% of that which would be experienced with no offset. An alert would be issued in this case for displacements up to 4800 feet; this particular microburst at that offset would have no impact on the aircraft trajectory. This is not to say that such an event is not a potential hazard, but that a pilot receiving such an alert while accurately tracking the localizer would possibly interpret it as a false alarm.

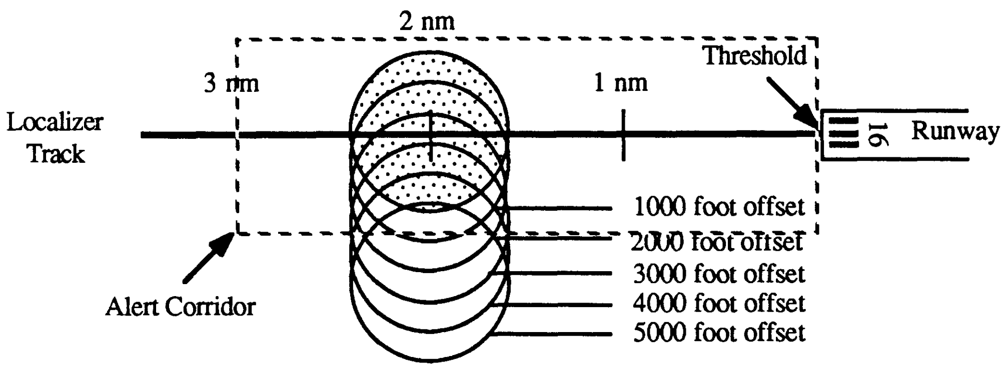


Figure 5.4 Geometry for Lateral Offset Microburst Windfield Analysis

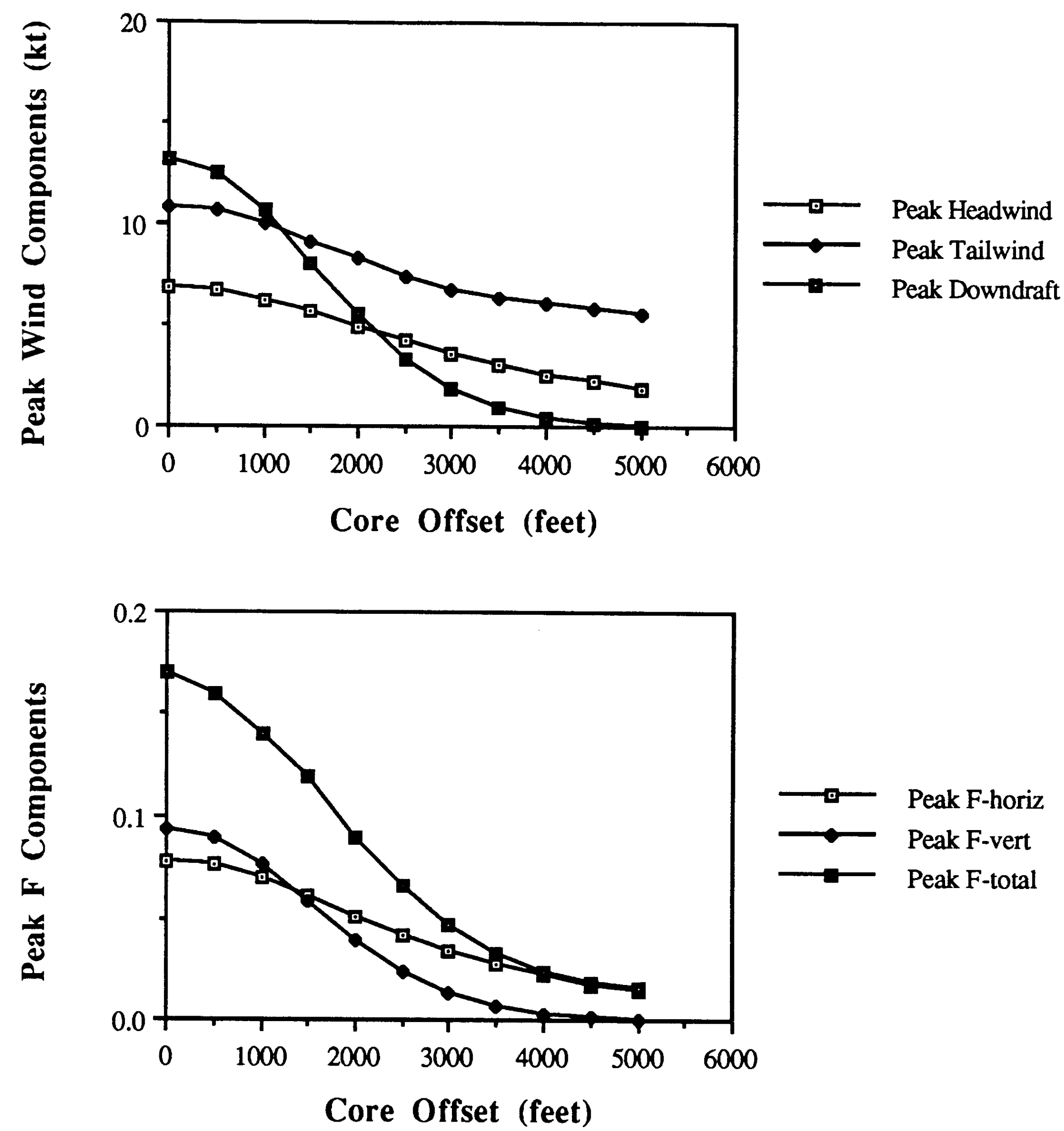


Figure 5.5 Effects of Lateral Offset - Simple Microburst Model: Peak winds and F-factor components encountered by an aircraft approaching through a 40 knot microburst located 2 nm from the runway threshold and at varying lateral offset from the localizer track.

5.4.1.2 Detailed Model Winds

For a more realistic investigation, windfields from a more detailed model were also examined. The data used was generated with.the Terminal Area Simulation System (TASS), an unsteady 3-dimensional computational model capable of realistic simulations of convective weather and storms [Proctor, 1987]. The data set was generated by simulation of the microburst events which occurred on July 11, 1988 at DEN, which caused several aircraft to abort approaches (see section 2.4.2). The data was obtained through MIT Lincoln Laboratory from MESO, Inc. The actual approach made (and aborted) by Aircraft C (a DC-8) was under the conditions illustrated in Figure 5.6. Figure 5.7 is a 3-D surface plot of vertical windspeed from TASS data for an altitude of 930 feet; the minima in this plot indicate the location of microburst cores.

To examine the effects of encountering the detailed model microbursts at different altitudes, the winds over approaches to a runway threshold displaced along the localizer path were plotted (Figures B.4 to B.7). These hypothetical threshold positions are marked in Figure 5.8. Note that this situation is considerably more complex than in the previous analyses since there are multiple microbursts occurring simultaneously along the flight path. The peak values experienced along these paths are shown in Table 5.2. Note that, despite the complex situation geometry, the general behavior of the winds and of F exhibits similar behavior to the simpler model. This includes the near invariance of F-total with altitude and the varying ratio of peak F_X to peak F_Z. For the simple microburst model, it was found that this ratio was near 1 when the microburst core was encountered 2 nm from the threshold at an altitude of 628 feet AGL). Using the TASS windfield, for the case where the runway threshold was displaced 1 nm to the west, this ratio is approximately 1 also (Table 5.2). Examining the F-factor profile for this case (Figure 5.9) and the encounter geometry indicates that this also corresponds to crossing the center of the windshear area at approximately 2 nm from the threshold and at an altitude of approximately 700 feet. It should also be mentioned here that the Oseguera and Bowles microburst model derives its "empirical" numerical relationships from TASS results (although not for this particular event), and that repetition of this experiment for actual measured dual-Doppler windfield data would be desirable.

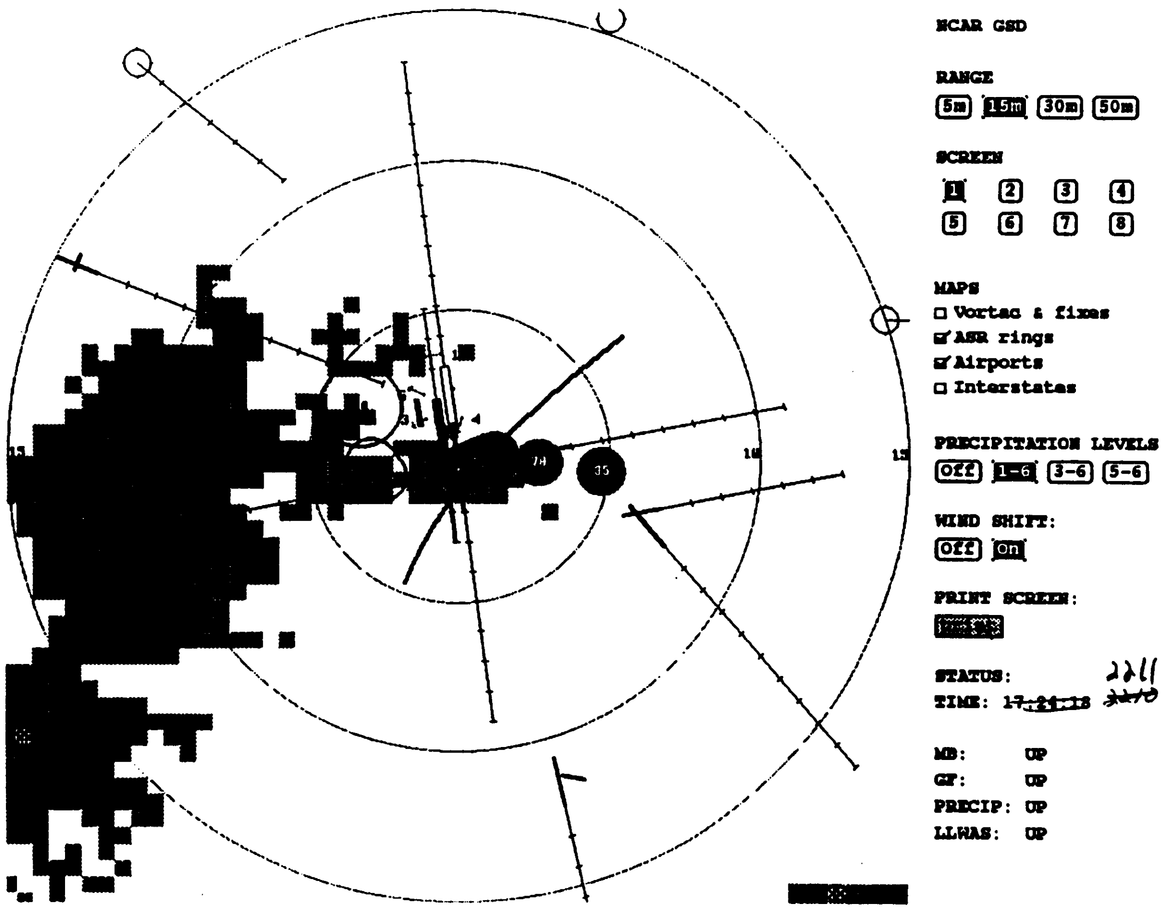


Figure 5.6 **Conditions at 2210.75 UTC at DEN on 7/11/88:** This is a copy of the GSD display for 2211 UTC, which shows the conditions under which Aircraft C made a missed approach to Runway 26L.

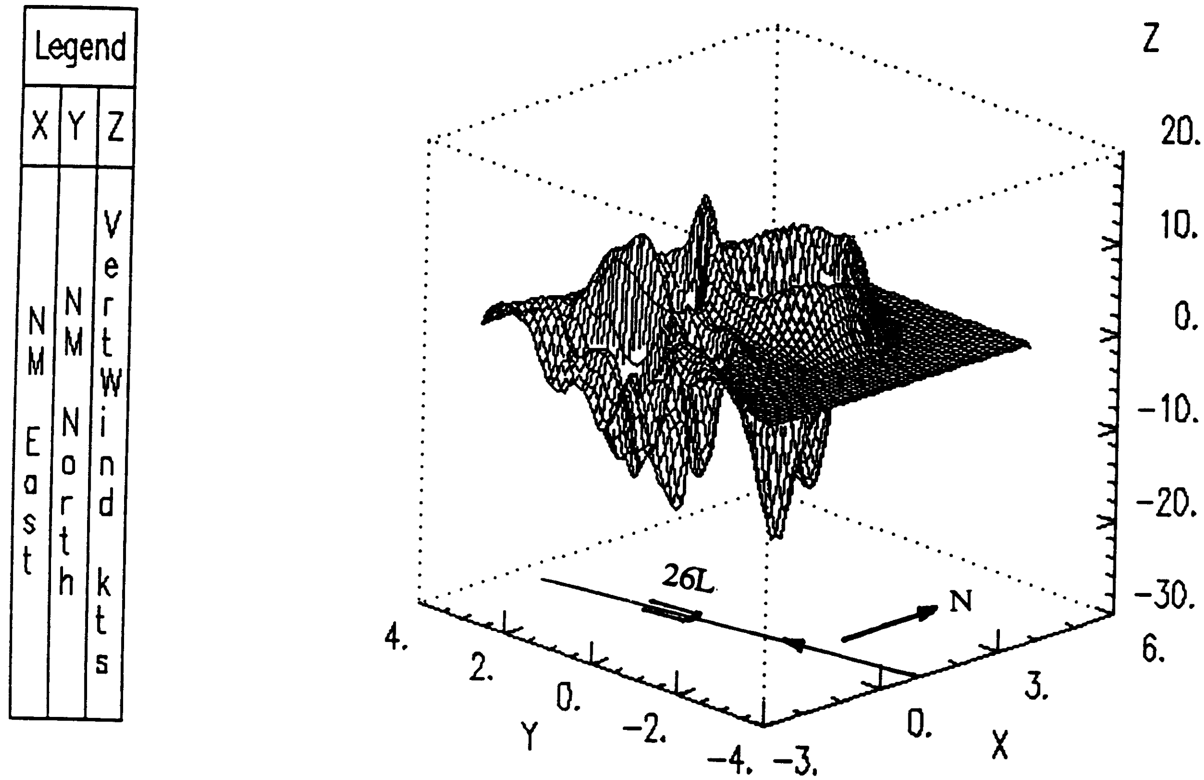


Figure 5.7 TASS Vertical Windspeeds for 2210.75 UTC on 7/11/88 at Altitude of 930 feet AGL: The runway position for this plot is at (0,0). Windspeeds are given positive up in knots; the minima in this plot represent the positions of microburst cores.

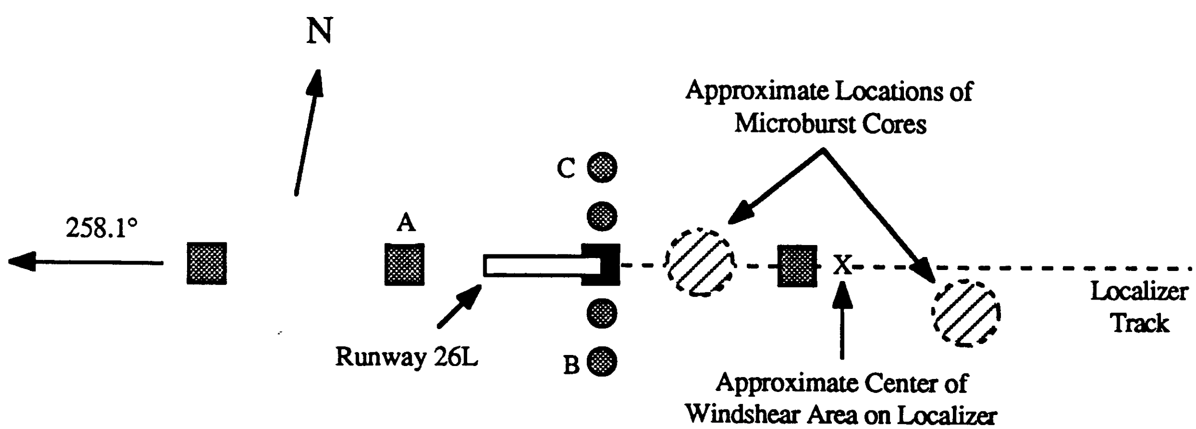


Figure 5.8 Geometry for TASS-Based 7/11/88 Windfield Analyses: The squares mark the hypothetical runway threshold positions used for Table 5.2 data; the circles mark the positions used for Table 5.3.

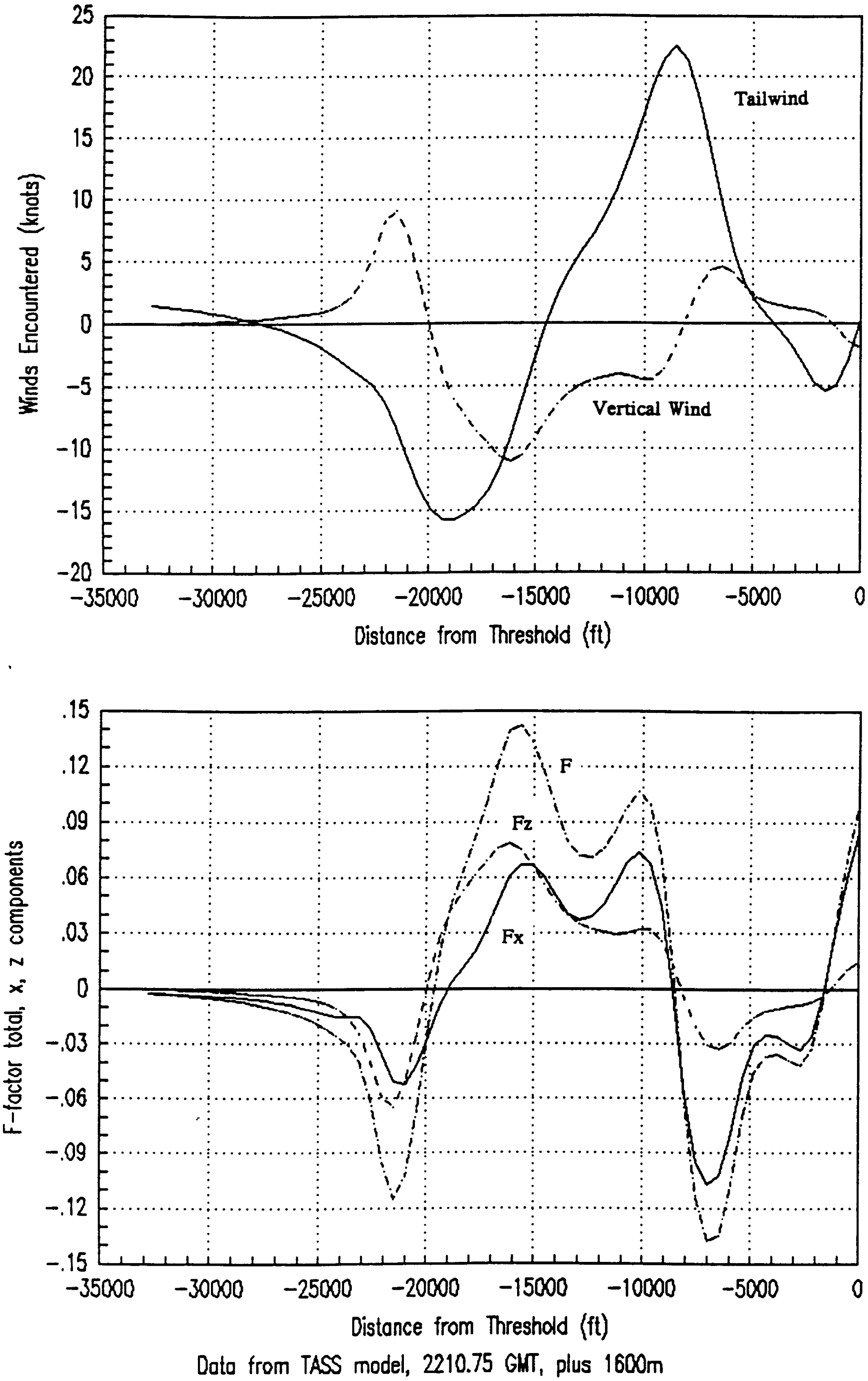


Figure 5.9 Winds and F-factors (from TASS data) for aircraft approaching DEN 26L at 2211.75 UTC, runway threshold displaced 1 nm to the West along localizer track: This runway position is marked as "A" in Figure 5.8.

Runway Displacement	Approx. Altitude of Encounter	Peak Winds (knots) Headwind	Tailwind	Downdraft	Peak F-factors F_x	F_z	Ftotal
-1 nm	70 feet	26.1	14.7	3.50	0.083	0.025	**0.11**
0 nm	380 feet	21.6	24.2	7.32	0.090	0.052	**0.13**
+1 nm	690 feet	15.7	22.6	11.0	0.084	0.079	**0.14**
+2 nm	1000 feet	9.51	16.6	11.9	0.051	0.085	**0.13**

Table 5.2 Effects of Altitude of Penetration - TASS model: Peak winds and F-factor components encountered by an aircraft approaching runway 26L through 7/11/88 event at 2210.75 UTC, with location of runway displaced along localizer track. The approximate altitude of encounter indicates the glideslope altitude of the approximate center of the windshear area.

It is also of interest to look at the effect of a lateral offset on the detailed windfield data. The resulting data (Table 5.3, Figures B.8 - B.11) support the contention that fairly small lateral offsets can have a considerable effect. In these cases, the total distance between the two end paths is less than a mile, but the nature of the windfield experienced changes considerably. In addition to the changes in F and F components, the duration and position of peak F along the flight path change somewhat. The case where the runway is displaced 800 meters to the south (Figure 5.10a) has two regions along the last two miles of approach where F exceeds 0.15. In the case where the runway is displaced 800 meters to the north (Figure 5.10b), the peak F at this same point is only about 0.08. However, there is another very strong area of shear inside 1 nm from the threshold. This region produces a strong performance *increase* (F = -0.15) at 3000 feet followed by a performance decrease which peaks at F = 0.12 at the touchdown point. Note that these cases are different than the ones for the simple windfield model, since all of the offset trajectories intersect some significant portion of the complex shear area shown in Figure 5.6.

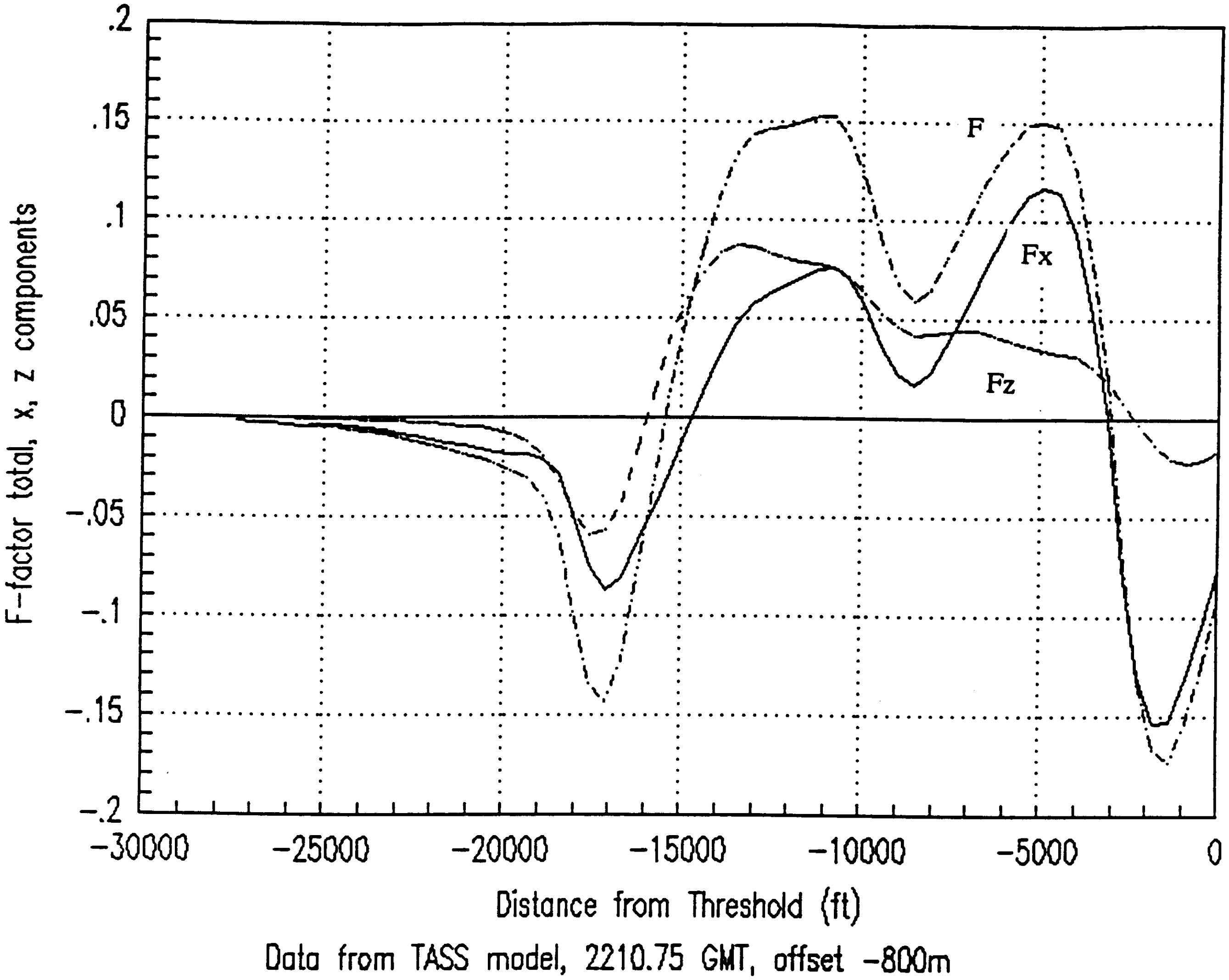


Figure 5.10a F-factor experienced (from TASS data) by an aircraft approaching DEN 26L at 2211.75 UTC, runway threshold offset 800 meters to the South: This runway position is marked as "B" in Figure 5.8.

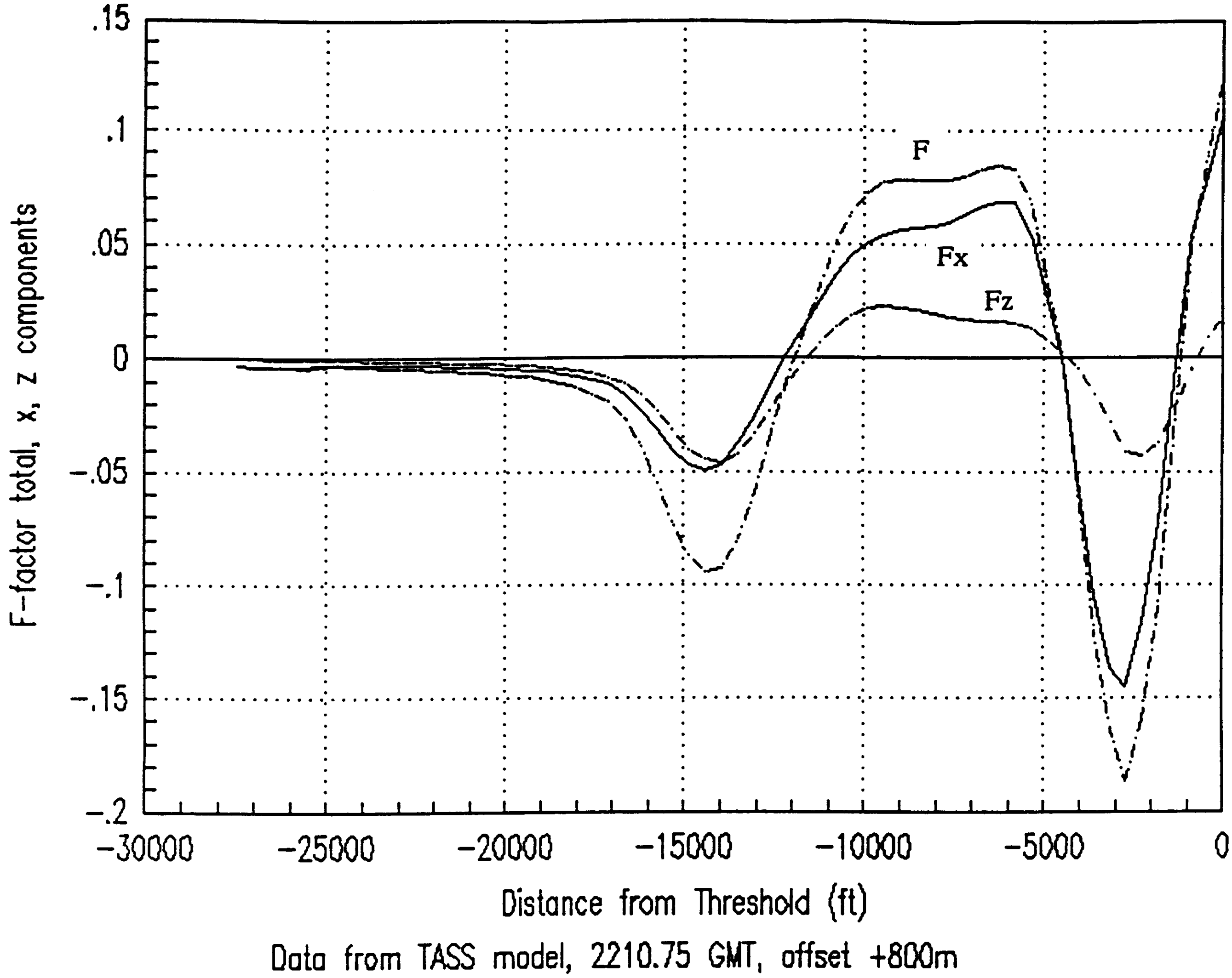


Figure 5.10b F-factor experienced (from TASS data) by an aircraft approaching DEN 26L at 2211.75 UTC, runway threshold offset 800 meters to the North: This runway position is marked as "C" in Figure 5.8.

Lateral Displacement of 26L Threshold	Peak Winds (knots) Headwind	Tailwind	Downdraft	Peak F-factors F_x	F_z	Ftotal
+2625 ft (+800 m)	15.5	14.3	3.2	0.11	0.023	**0.12**
+1312 ft (+400 m)	18.9	20.1	4.5	0.079	0.032	**0.097**
0 ft (0 m)	21.6	24.2	7.32	0.090	0.052	**0.13**
-1312 ft (-400 m)	23.6	28.3	10.2	0.10	0.073	**0.16**
-2625 ft (-800 m)	24.9	31.2	12.2	0.12	0.090	**0.15**

Table 5.3 Effects of Lateral Offset - TASS Model: Peak winds and F-factor components encountered by an aircraft approaching through the 7/11/88 event at 2210.75 GMT. The runway threshold has been displaced laterally varying distances from the actual position to illustrate the small-scale variability of the.windfield. A positive displacement indicates shifting of the threshold to the North.

5.4.2. Aircraft/Windshear Interaction Simulation

5.4.2.1. Aircraft/Windshear Model

To extend the results of the above static analyses, a set of longitudinal flight simulations were conducted through the same windfields. Since aircraft do not maintain perfect control of airspeed and glideslope during the approach, and the engine thrust varies as a control input, the static windfield analyses cannot predict the actual approach profile deviations which occur. It is therefore of interest to correlate the peak F-factor encountered with the dynamic effects encountered by a typical aircraft with a typical control strategy. For this purpose, an aircraft simulation using the longitudinal dynamics of a Boeing 727 aircraft with simple elevator and throttle feedback laws was used. The equations of motion and aircraft characteristics of this model are discussed in Appendix C.

5.4.2.2. Aircraft Approach Through an Idealized Microburst

The first case tested was to run the aircraft through the series of approaches corresponding to the Oseguera and Bowles model windfields in Figure 5.3. Since F-total for these three approaches was approximately the same, similar flight path deviations are expected. Figures 5.11a-d show typical results for these runs; in this case, for penetration of the 40 knot max divergence microburst 3 nm from the runway threshold. For this control strategy, airspeed and airspeed rate are fed back for throttle commands, and the elevator commands are derived from glideslope and pitch deviations. The typical system response to a microburst is to reduce thrust during the period of headwinds, increase to full as the downdraft is reached, and back off again as the aircraft leaves the event. The result of this is that the initial headwind, which increases slowly, is completely attenuated, but the combined head-to-tail shear and downdraft in the microburst core cause a losses in both altitude and airspeed. The response of the control system (full throttle) causes a sharp gain in airspeed and slight ballooning above the glideslope as the microburst is left behind.

Table 5.4 summarizes the results for these three runs, and shows that in each case the airspeed and glideslope deviations are very similar. In addition, the peak F-factors as measured from the aircraft frame (as if measured with an *in-situ* sensor) are very close to those calculated from the static windfield analysis. F-total is essentially invariant with altitude, and the F_x to F_z ratios are also similar. For this "typical" aircraft and control model, the computed "airspeed loss" from nominal approach speed is about 12 knots. It should be noted, however, that the control system used will certainly have some impact on the numerical results. For example, a control system which maintains tighter glideslope tracking would have larger airspeed deviations.

Microburst Distance from Threshold	Max Deviations from Nominal Approach		Peak F-factors		
	A/S Loss (kts)	Altitude Loss (feet)	F_x	F_z	Ftotal
1 nm	13.7	138	0.13	0.075	0.19
2 nm	12.6	134	0.094	0.092	0.18
3 nm	11.6	132	0.071	0.10	0.17

Table 5.4 Effects of Altitude of Penetration - B727 Simulation: Peak winds and F-factor components encountered by an aircraft approaching through a 40 knot microburst located at varying distance from the runway threshold.

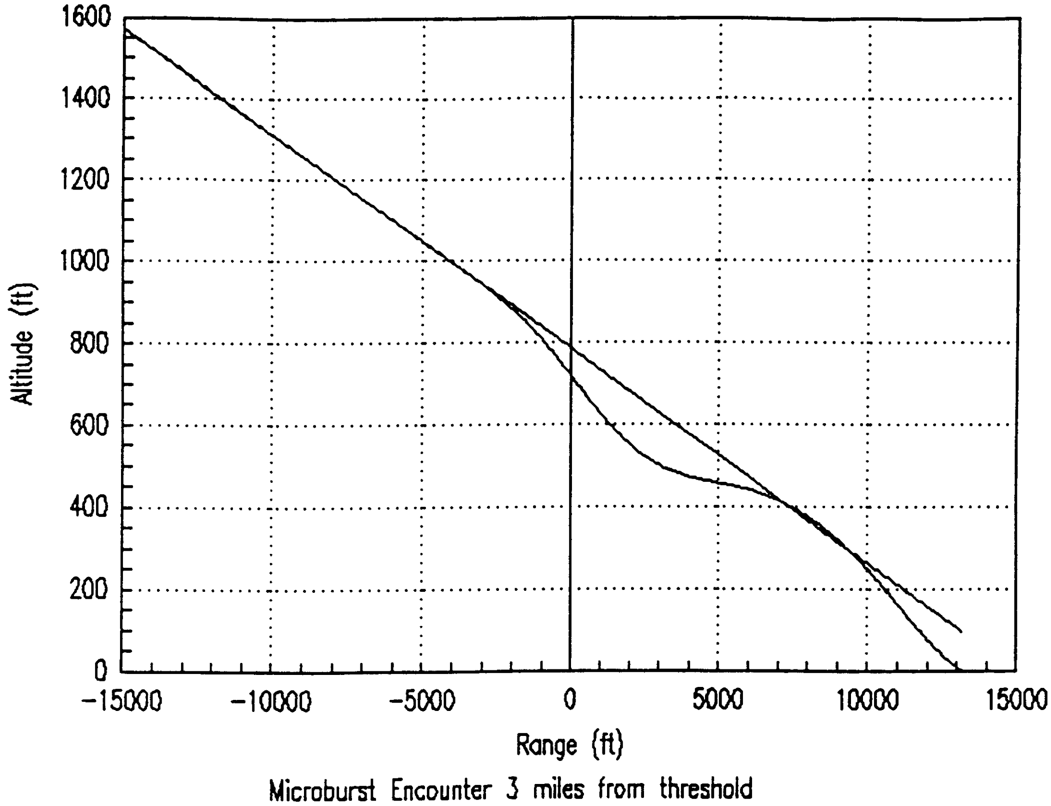


Figure 5.11a Typical Altitude vs. Range Profile for Simulation Run

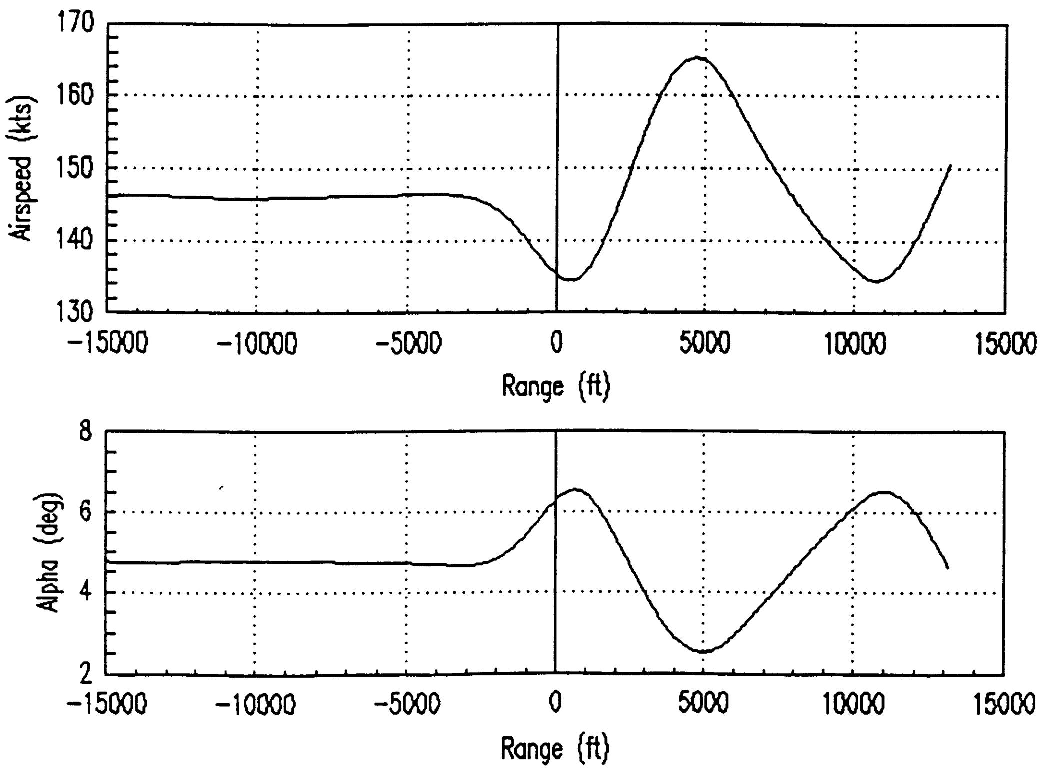


Figure 5.11b Typical Airspeed, Angle of Attack Profile for Simulation Run

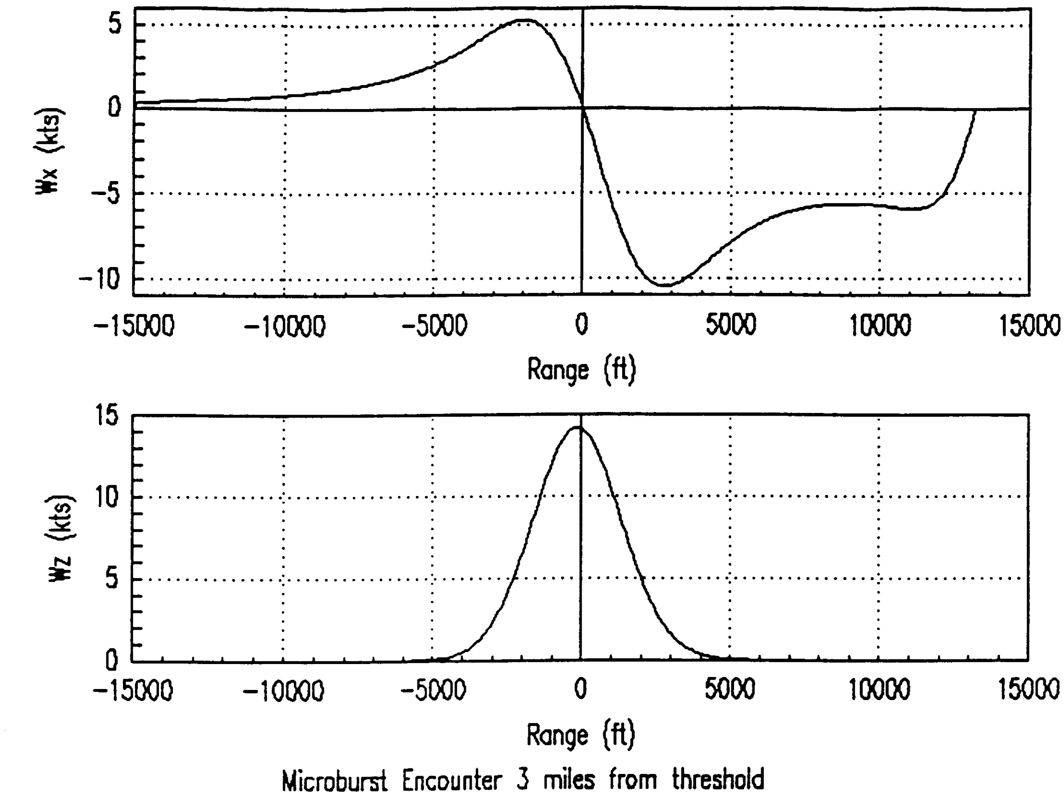


Figure 5.11c Typical Windfield Encountered for Simulation Run

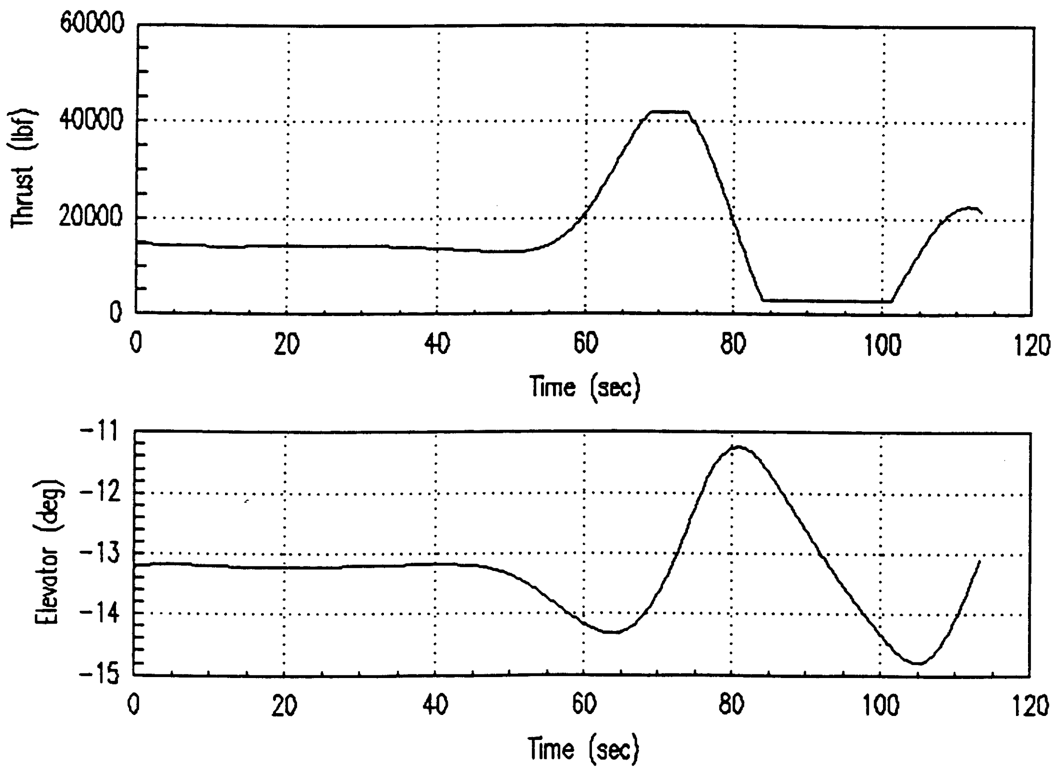
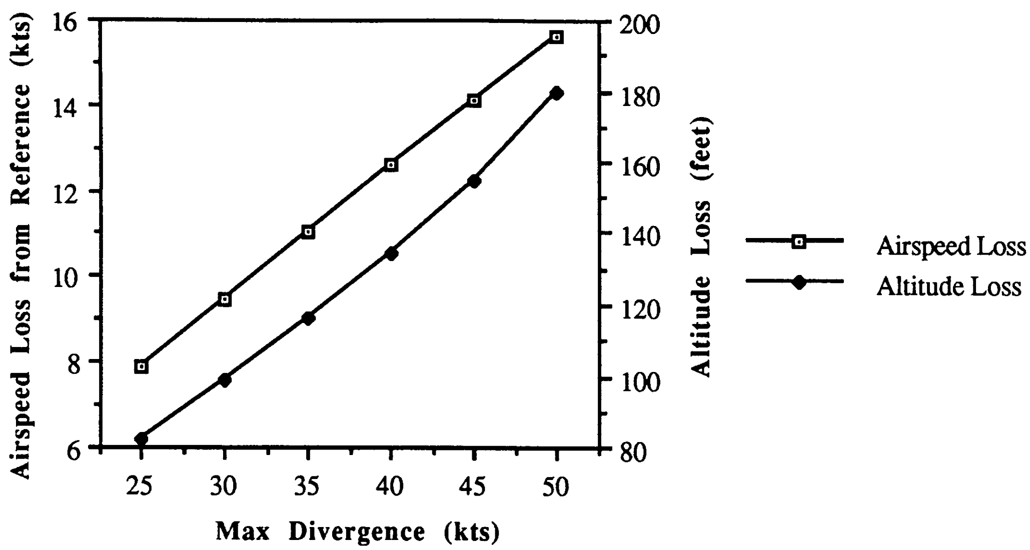


Figure 5.11d Typical Control History for Microburst Penetration

In order to examine how the airspeed losses and glideslope deviations change with microburst intensity, another series of runs was performed for microbursts of varying intensities with the same size and altitude parameters (Figure 5.12). For this model, the peak F encountered is a linear function of the microburst's maximum (120 foot AGL) divergence value. The maximum airspeed loss below approach speed and altitude loss below glideslope also increase with intensity. Note that throttle saturation causes the slope of the altitude loss curve to steepen at higher intensities, since there are physical limits on both rate of thrust increase and total thrust available. Again, as mentioned above, the hypothetical TDWR divergence measurement for these microbursts will be somewhat less that the maximum divergence value. However, the airspeed loss as seen by this aircraft is much less than the maximum value, and even for the 50 knot case does not bring the aircraft near stall; the altitude loss is actually more of a danger, in this case. For a low-altitude encounter, 180 feet of loss could be fatal. If a tighter glideslope tracking scheme could be devised, the altitude loss could be traded for airspeed loss; but the total energy loss due to the microburst would be approximately the same. For either case, the conclusion is that the F-factor is a good quantification of the hazard, while airspeed loss is a symptom of the hazard.



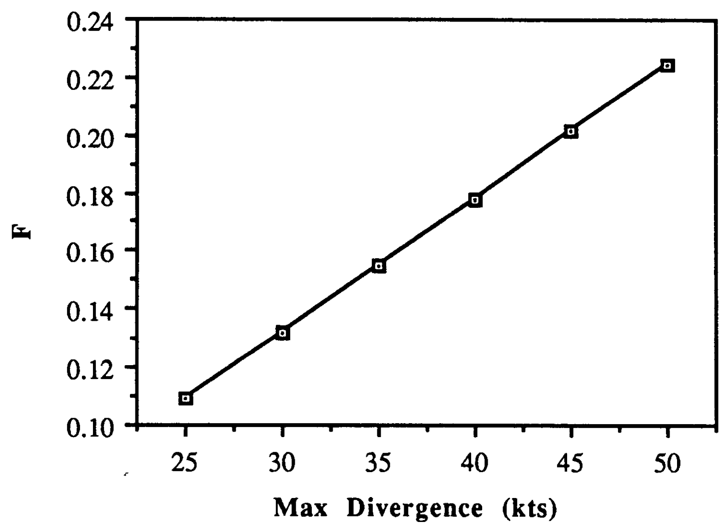


Figure 5.12 Performance Degradation due to Microbursts of Varying Strength on Approach: These plots show the dependence of maximum airspeed and altitude losses for the B-727 model, and peak F encountered, when approaching through microburst with core location 2 nm from runway threshold. This windfield is from the Oseguera and Bowles model.

5.4.3. Implications for Windshear Alert Content

From the static windfield analysis, there are two main points to observe. First, for both the simple and the complex models, the F-factor for a constant-airspeed trajectory through the microburst is basically invariant with altitude. The head-to-tailwind shear, however, is not. Second, for these models, the total F-factor experienced falls off quickly when the microburst is penetrated off-center. This implies that the current alert methodology (with 1 nm wide alert corridor) will warn in many cases of shear that will have little or no effect on an aircraft which is accurately tracking the localizer. Although a microburst this near to the flight path clearly constitutes a potentially hazardous situation, especially since aircraft may not necessarily be tracking the localizer exactly, it is clear that this effect could have caused pilot-perceived "nuisance alarms."

From the simulation runs, the main point to observe is that expected airspeed loss is not a good measure of hazard; the amount of airspeed loss experienced by a particular aircraft depends on the energy management strategy employed. However, the airspeed and altitude losses do correlate roughly linearly with peak F-factor, since F is based on the total energy loss. However, the critical point to observe is that F is both invariant with altitude and *scales linearly with total divergence value for a microburst of given scale parameters*. This indicates that the TDWR measurement of radial divergence, with suitable correlations based on known microburst characteristics, could be used to determine the altitude invariant F-factor parameter and hence the hazard posed by the microburst. It should be noted that his is a result *based only on the models analyzed here,* and further work with different models and model parameters is required to generalize this result . The major difficulty to overcome is to develop the correlations and analytical relationships necessary to take a radial shear measurement (yielding microburst intensity and size) and the knowledge of the overall weather situation (both reflectivity and doppler velocities) to produce a number which represents the total F based on the measured radial shear and the *predicted* vertical downdraft component. If this meterological analysis can be done, most likely using measured dual-doppler windfields and/or numerical modeling, the fidelity of the TDWR hazard assessment could be improved.

5.5. Recommendations

5.5.1. Near-Term TDWR Alert Modification

The easiest way to make TDWR alerts more effective in the short term is to make the wording of the alert more precise. In this way, for example, the lateral offset issue could be handled. As suggested by Stevenson [1989] it would be simple to add the approximate lateral location of a microburst to the alert by adding something like "left of the approach," "right of the approach," or "on the approach." This would clarify (to both crews and controllers) some of the cases where there is a TDWR report of a microburst and very little effect on the aircraft, alert the pilot where to look for signs of a microburst, and give the crew information useful in planning a missed approach which will avoid the windshear area if necessary. Another possible modification would be to the intensity description. Describing the windshear event in terms of airspeed gain and loss is logical for gustfronts, but not strictly correct for a microburst which contains both gain and loss. One alteration might be to report a microburst as a "[value] knot divergence," which conveys the idea of encountering first a gain and then a loss.

In addition to, and in connection with, modifying the alert language, better aircrew education about the details of TDWR alerts would be helpful. The possibility of a microburst being to the side of the flight path should be discussed, and the real meaning of the windshear divergence value should be explained. A discussion of the energy-height concept (F-factor) and how it relates to the impact of a microburst on the aircraft trajectory would be useful. Crews should also be aware of the measurement limitations of the sensing system.

5.5.2. Further Analysis and Improvements

Based on the above analyses, a way to get improved intensity estimation is to base the hazard assessment on F-factor rather than windfield divergence. As discussed in Section 5.4.3, to obtain an estimate of total F requires some way of predicting the vertical contribution to F from the measured radial velocities and dimensions and other available data. This will require some correlation of microburst statistics and known analytical (i.e. continuity) or empirical relationships. For the Oseguera and Bowles model microburst, F is a linear function of divergence for a microburst of given scale parameters. The variation of F with those scale parameters could also be correlated. So, if TDWR data can be used to measure core radius (a natural result of the data) and altitude of maximum outflow (not obvious) as well as the shear strength, the total F can be predicted. The validity of this model and correlations with regard to naturally occurring microbursts would then have to be determined (from numerical models and dual-doppler measured data) and the correlations modified. This analysis is beyond the scope of this thesis.

An additional factor in the intensity measurement which should be explored is the impact of vortices and other short-scale disturbances on the hazard. As noted in Section 5.2, these motions can cause significant control difficulties and therefore aggravate the energy loss portion of the hazard. This is a limitation on the F-factor as a hazard measurement which should not be overlooked, but is clearly difficult to measure and quantify.

Another area where improvement would be helpful is in the measurement of microburst asymmetry. The penalty of using a single doppler radar to measure windshear is that the asymmetry of microbursts places a limit on the validity of the shear value obtained. It would be desirable to at least determine whether the value measured is on the low or high side when compared to the shear value along the flight path. Techniques for estimating microburst asymmetry are being explored. [Eilts, 1989]

The final piece to this problem is then how to operationally use the resulting hazard assessment. It is undesirable to give the pilot F-factor, for example, since it is not an easily-interpreted quantity and therefore not suited to this time-critical application. Also, peak F does not take into account all of the available information. It would make more sense to combine the F-factor estimate from TDWR with other available information (microburst precursors, gustfront products, precipitation, turbulence, LLWAS alerts, PIREPS) to produce a "Level 1, 2, 3" form of alert. The alert levels should then correspond to recommended or required actions to be taken. For example, Level 1 could represent a "high windshear potential" advisory, Level 2 a "low intensity windshear present" advisory, Level 3 a "microburst/significant windshear present" *warning* (takeoffs or approaches at pilot discretion), and Level 4 signifying "critically dangerous windshear present," requiring halting of runway operations and missed approaches by all approaching aircraft.

The issues to be resolved before such a system could be implemented include (1) determination of peak F-factor thresholds for the alert levels (2) how to include the other information mentioned above (especially TDWR gustfront detection and LLWAS) into the alert level criteria. In addition, the meaning of these levels for different classes of aircraft needs to be determined.

6. Summary

6.1. Crew Interface Research

A pilot opinion survey and a flight simulator experiment have been performed in order to examine issues related to dissemination of ground-measured windshear information to flight crews with and without a digital datalink.

- Survey results (Chapter 3) indicated that the currently available windshear avoidance information is not sufficient, and that a better system is highly desirable. A preference for graphically presented microburst alerts was expressed, and some specific questions about the makeup and timing of microburst alerts were answered. The survey results were then used in design of the flight simulator experiment.

- Simulation experimental results (Chapter 4) indicate that presentation of windshear alerts as graphical symbols on a moving-map display is significantly more effective than verbal alerts. Pilot performance improved, and pilot workload decreased. Both the survey results and comments from the simulation subjects indicate a strong pilot preference for graphical presentations. It is believed that the map representation is more consistent with the pilot's cognitive map and that graphical information is therefore more quickly and accurately assimilated.

- Presentation of windshear alerts as text on an electronic display proved inferior to standard verbal communications in terms of workload increase, pilot performance, and pilot preference. The survey respondents indicated that too much 'head-down' time is required to read text messages during final approach; this was corroborated by the simulation subjects. In time-critical situations (i.e. microburst alerts) it was apparent that textual messages were more subject to misinterpretation than verbal ones. In the non time-critical case of clearance amendments, no significant differences in performance or reduction in workload was observed. In either case, the familiarity of pilots with verbal communications allowed them to comprehend the message quicker than in the textual mode.

- Some more general cockpit display design considerations were observed in this study. The use of an aircraft-directed digital datalink such as Mode-S allows more sophisticated information presentation, but deprives the flight crew of listening to transmissions to other aircraft as well as prosodic (voice-inflection) information from the controller. Also observed in the simulations was the fairly universal and consistent practice of separating information into time-critical and non-time-critical pieces.

6.2. Windshear Hazard Assessment

Analyses have been performed to obtain data which can be used to improve hazard assessment of low-level windshear based on ground-based doppler radar measurements (Chapter 5). Study of the nature of these measurements has been combined with analysis of microburst model windfields and longitudinal approach flight simulations in order to recommend improvements to current hazard assessment and alerting procedures.

- A recent study of PIREPS from the 1988 TDWR Operational Evaluation [Stevenson, 1989] indicates that overwarning is a problem with the current alert methodology. Therefore, the current procedures for hazard assessment and alert generation were studied and some contributing factors to the problem identified. These can be categorized into situation/measurement geometry and operational issues.

- The primary situation geometry factors which can contribute to overwarning are off-center microburst penetration and variations in altitude of penetration. Current procedures do not account for these variations and produce the same alerts for potentially very different windfields along the flight path. Measurement geometry factors include microburst asymmetry and finite radar beamwidth. These can both contribute to incorrect estimation of the strength of a microburst and hence inaccuracies in hazard assessment. Operational issues concern alert format and dissemination. One potential source of confusion with the current alert format is the reporting of measured divergence values as "airspeed loss" when in actuality this measurement indicates an initial gain of one-half the measured divergence followed by a loss of the entire value. Another factor is the dependency of the actually experienced airspeed/glideslope deviations on the dynamics of the pilot/autopilot/aircraft system.

- Insight into the geometrical factors mentioned has been gained through analysis of windfields generated by both a simple and a more detailed microburst model. Using the F-factor hazard criterion, the expected performance loss along flight paths projected through these windfields was computed. The results for both models indicate that F, which includes both headwind-to-tailwind shear and downdraft effects, does not vary much with altitude of penetration although the ratio of effects due to the horizontal and vertical winds does vary strongly. In addition, it was found that traversing a microburst off-center has a strong effect on the windshear experienced. For the simple model, F falls off rapidly with off-center distance; at offset distances for which alerts are still given under the current methodology, the windshear can vary from severe to almost negligible. The detailed model, which contained multiple microbursts, indicates that moving the flight path laterally with respect to the windfield produces significant variation in the windshear hazard and location.

- Simulations of a typical jet transport with a typical control strategy flying through these windfields were also performed. The results indicate that, discounting the effects of turbulence, F-factor is a good indication of the airspeed/glideslope deviations to be experienced. The ratio of airspeed deviation to glideslope deviation varies with the control strategy employed, which indicates that "airspeed loss" is not a good terminology to use in the alert message. This indicates that improved results would be obtained by basing alerts on F-factor. Since vertical winds and hence total F-factor are not directly measureable by a single ground-based doppler radar, this will require a technique for correlating the measureable quantities (radial velocity components, reflectivity contours, etc.) with historically observed (or simulated) microburst characteristics and analytical equations in order to determine the peak F-factor along the projected aircraft flight path.

- In the near-term, the effectiveness of TDWR alerts could be improved by modifying the alert wording. These modifications include: (1) add the phrase "left of approach," "right of approach," or "on approach" to the alert to give crews information about the microburst lateral position relative to the localizer track, and (2) Describing microburst events as "divergence" rather than "loss" to indicate that there are both headwinds and tailwinds involved. In addition, better aircrew education about the details of TDWR alerts is recommended. The briefing should include the possibility of a microburst being to the side of the flight path, the meaning of the windshear divergence value, and the measurement limitations of the sensing system.

- If enough of the measurement and data processing obstacles can be overcome to produce a good estimate of total F, an effective format for ground-based alerts based on F needs to be devised. This author suggests use of the F-factor estimate from TDWR in combination with other data sources such as TDWR microburst precursor information, TDWR gustfront products, precipitation, LLWAS alerts, and PIREPS to produce a "Level 1,2,3,4" type of alert. The alert levels should correspond to a set of recommended and/or required actions to be taken by the pilot and controller (see Section 5.5.2).

Appendix A Terminal Area Windshear Survey

The Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology is currently doing research in low-level windshear detection and warning procedures, specifically the transmission of windshear data from ground sensors to the flight crew. The first step in this research is to conduct a survey of pilot opinions regarding current and possible future terminal area windshear alert procedures.

Participation in this survey is completely voluntary. It is not necessary to give your name at any point, and you may decline to answer any of the questions. All information obtained from any individual survey will remain confidential. If you have any questions, feel free to contact :

Prof. R. John Hansman
Aeronautical Systems Laboratory
MIT Rm. 33-115
77 Massachusetts Ave.
Cambridge, MA 02139
(617) 253-2271

Please return this survey in the enclosed stamped envelope. Thank you for your time and cooperation.

Transport Category Aircraft Flight Experience

Aircraft Type	Position	Apprx. Flight Hours
__________	__________	__________
__________	__________	__________
__________	__________	__________
__________	__________	__________
__________	__________	__________

Approximate Total Flight Hours Over the Last Year __________

A. Current Procedures

1) Terminal area windshear/microburst events pose a major safety hazard to transport category aircraft.

1	2	3	4	5
disagree strongly	disagree	neither agree nor disagree	agree	agree strongly

2) How much confidence do you have in current ATIS-distributed microburst cautions and forecasts?

1	2	3	4	5
no confidence		moderate confidence		total confidence

3) Listed below are four currently available sources of information about windshear in the terminal area. Please rank them in order of usefulness, from 1 (most useful) to 4 (least useful).

_____ Low Level Windshear Alert System (LLWAS)
_____ Pilot Reports (PIREPS)
_____ Airborne Weather Radar
_____ Visual Clues (Thunderstorms, Virga etc.)

4) Here is a sample Low Level Windshear Alert (LLWAS) alert message:

Windshear alert. Centerfield wind 270 at 10. East boundary wind 180 at 25.

a) How useful to you is the data content of LLWAS messages?

1	2	3	4	5
useless		moderately useful		very useful

b) Is the data presented in a clear and understandable format?

1	2	3	4	5
very confusing				very clear

c) How often does the data get to you in time to be of use?

1	2	3	4	5
never		about half of the time		always

d) LLWAS is an effective method of preventing hazardous windshear encounters in the terminal area.

1	2	3	4	5
disagree strongly	disagree	neither agree nor disagree	agree	agree strongly

5) a) How effective is airborne weather radar for detection and avoidance of microbursts?

1	2	3	4	5
ineffective				very effective

b) How often do you use your weather radar in the terminal area?

1	2	3	4	5
never		about half of the time		always

c) What are your reasons for using or not using weather radar in the terminal area?

6) How much confidence do you have in pilot reports (PIREPS) of windshear?

1	2	3	4	5
no confidence		moderate confidence		total confidence

7) Currently available windshear alert data is sufficient for safe operation in the terminal area.

1	2	3	4	5
disagree strongly	disagree	neither agree nor disagree	agree	agree strongly

8) Given that new ground-based doppler weather radars can produce reliable windshear information, a system to provide aircrews with better and more timely windshear alerts is <u>necessary</u>.

1	2	3	4	5
disagree strongly	disagree	neither agree nor disagree	agree	agree strongly

B. Future Windshear Warning Systems

1) Assuming windshear is detected by reliable ground-based sensors, how should this information be relayed to the flight deck? Please rank in order of preference. (1 = most preferable, 5 = least preferable)

_____ Voice (ATIS)

_____ Voice (ATC)

_____ Alphanumeric/Text uplink (similar to ACARS)

_____ Graphical display of windshear location on EFIS display

_____ Graphical display of windshear location on separate graphic device

2) Assume a microburst has been detected which conflicts with your flight path in the vicinity of the runway threshold. When should you be alerted? Please rank the following in order of preference. (1 = most preferable, 5 = least preferable)

_____ On ATIS

_____ When entering terminal area (approx. 10000 ft. AGL)

_____ When cleared for approach

_____ At outer marker (approx. 2000 ft. AGL)

_____ As soon as detected, whatever the aircraft location

3) Listed below are possible microburst locations. How important is it to be alerted for each condition? Please rate each condition individually (i.e. don't rank them) on a scale of 1 to 4, where 1 indicates unimportant and 4 indicates critically important.

_____ Anywhere within 5 nm of destination airport
_____ Anywhere within 10 nm of destination airport
_____ Anywhere within 25 nm of destination airport
_____ Within 2 nm laterally of final approach path (inside marker) and runway
_____ Within 2 nm laterally of final approach path (inside marker) and runway and on published missed approach path

4) For the equipment that you most often fly (Type: _____________), what do you consider to be the minimum head-to-tailwind component (i.e. airspeed loss) which requires a windshear advisory? ________ kts. What minimum component is required for a windshear warning? ________ kts.

5) A windshear alert could contain the following items of information. Please rank them in order of importance. (1 = most important, 6 = least important)

_______	Location	_______	Shape
_______	Intensity	_______	Intensity Trends
_______	Size	_______	Movement

6) Improved ground-based systems can reliably detect windshear events and provide useful real-time data. The responsibility for judging the threat due to a particular windshear event from the available data should lie with; (choose one)

a) the controller

b) the pilot

Please comment briefly on your decision.

7) Have you ever had a potentially hazardous windshear encounter? If so, please describe it briefly.

8) Please add any comments or suggestions you have.

Appendix B Microburst Model Windfields

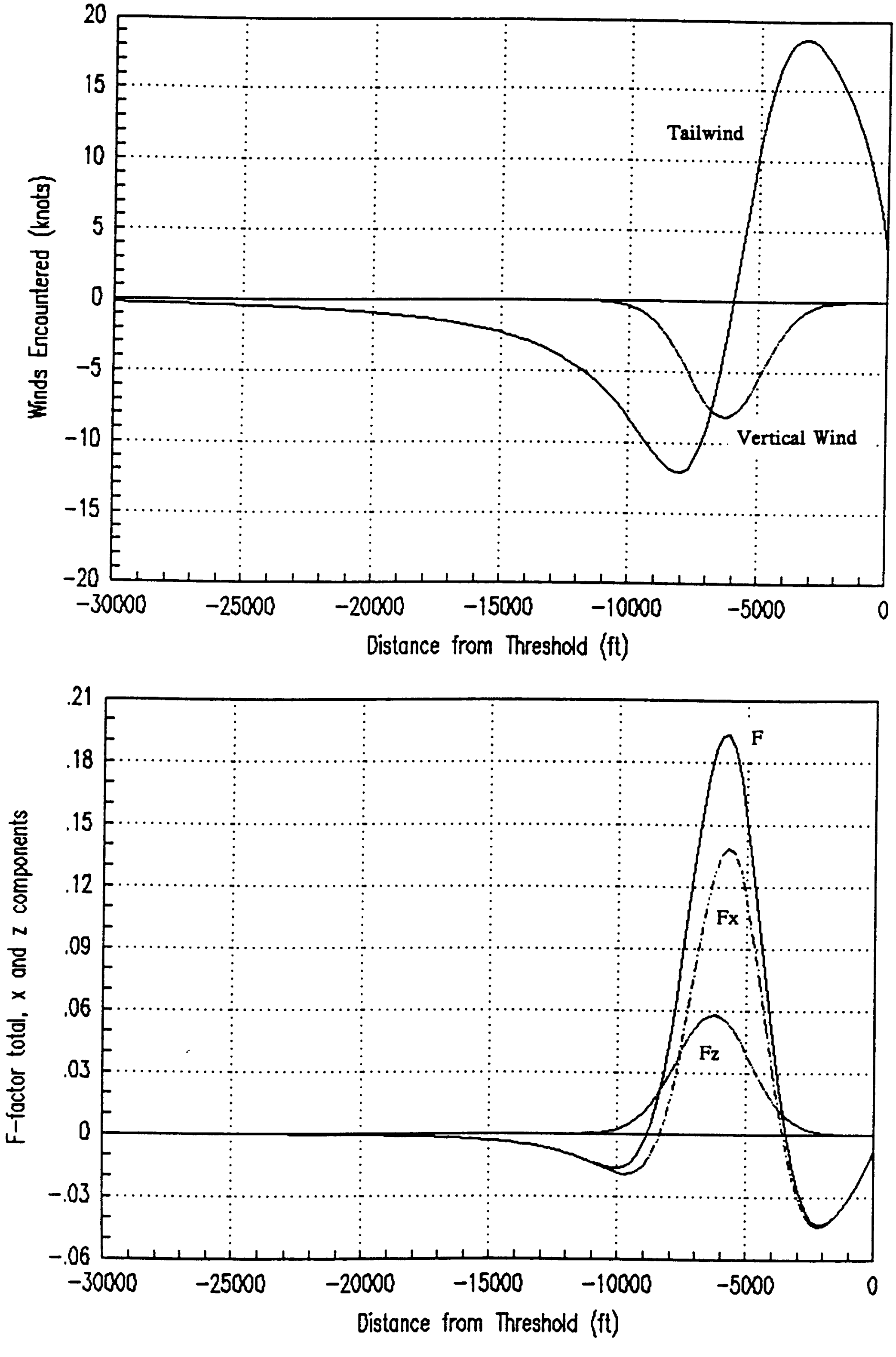


Figure B.1 Windfields and F-factor for approach through a microburst located 1 nm before runway threshold (Oseguera and Bowles model)

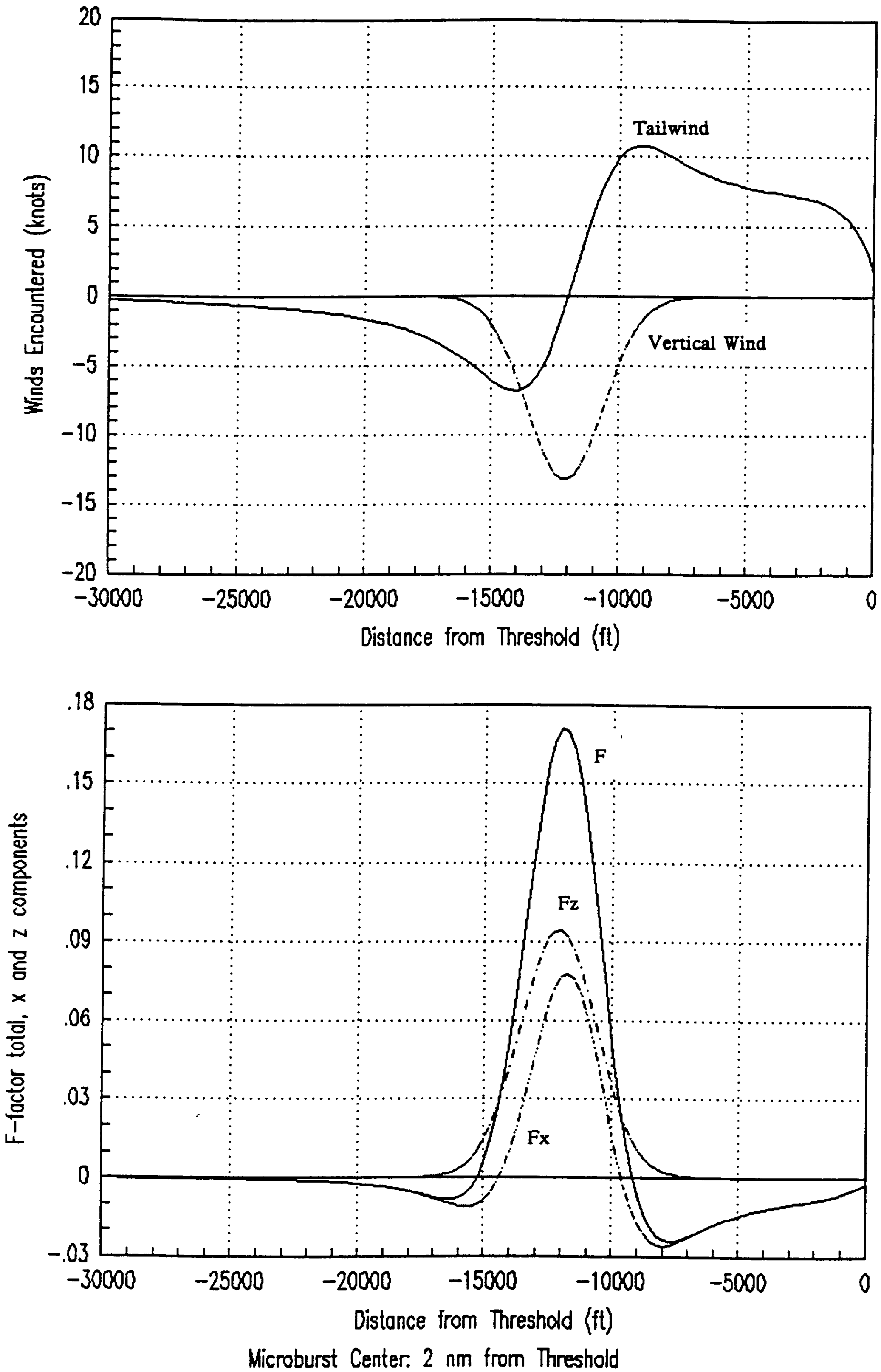


Figure B.2 Windfields and F-factor for approach through a microburst located 2 nm before runway threshold (Oseguera and Bowles model)

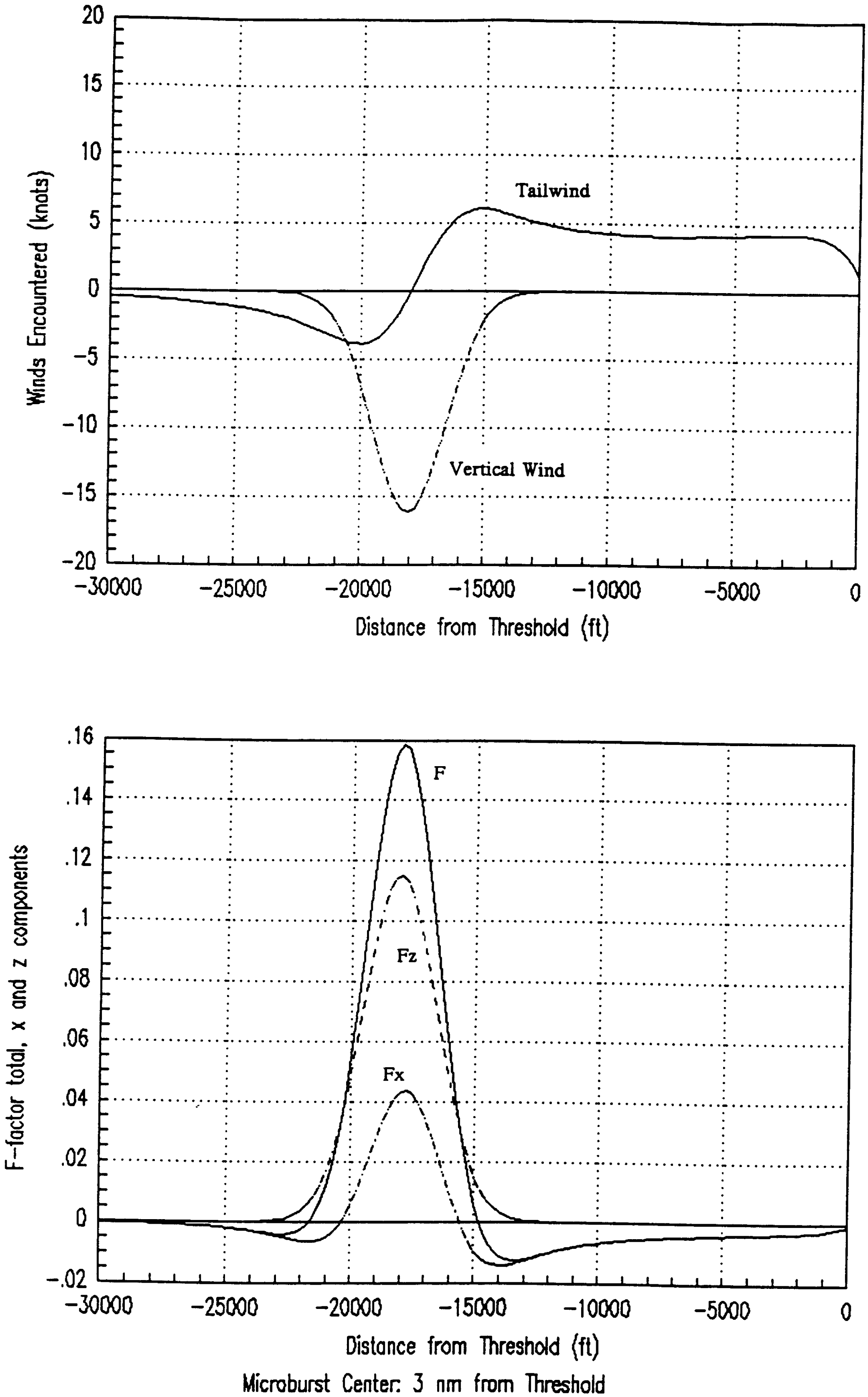


Figure B.3 Windfields and F-factor for approach through a microburst located 3 nm before runway threshold (Oseguera and Bowles model)

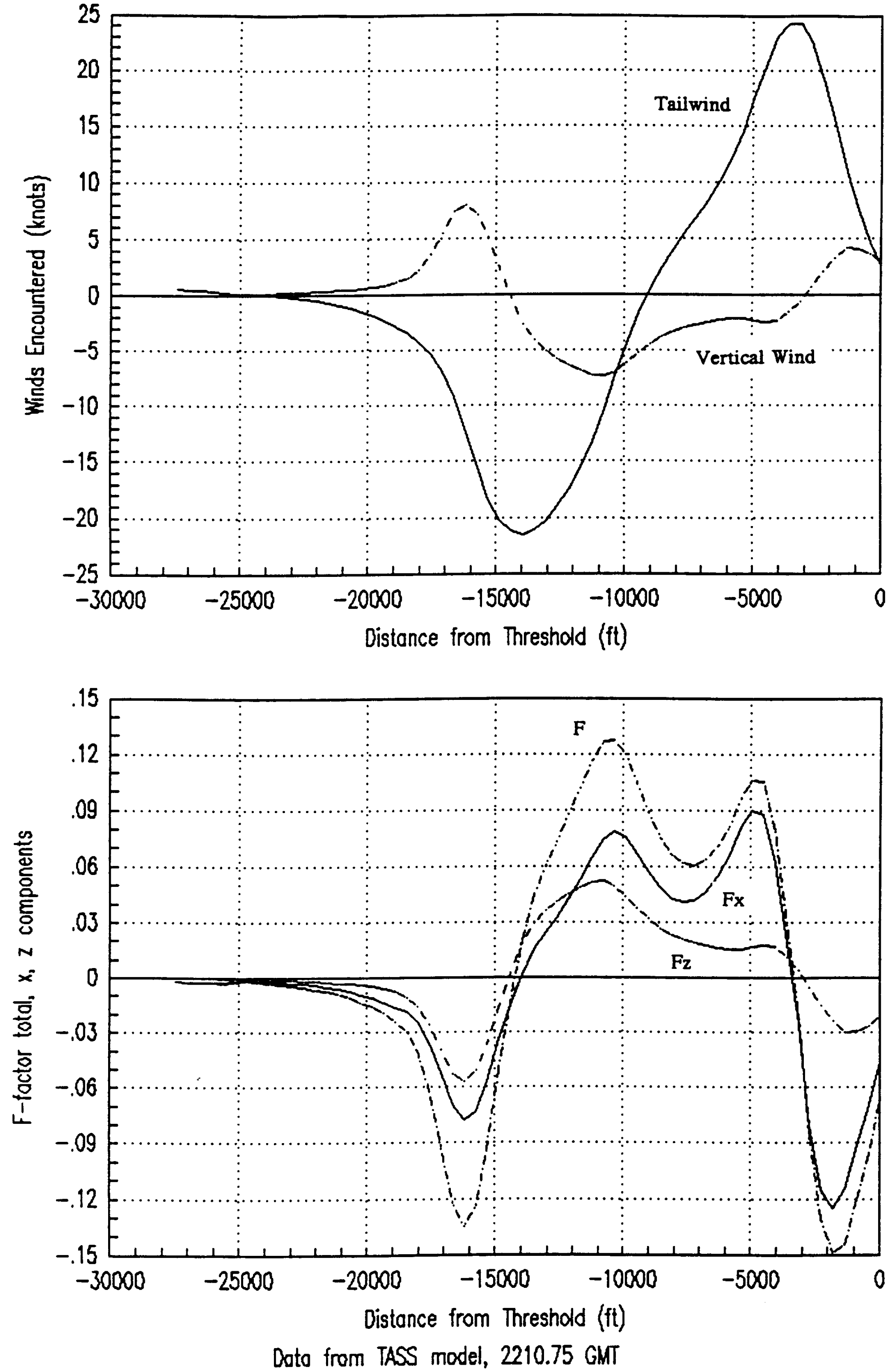


Figure B.4 Windfields for approach to DEN 26L on 7/11/88 from TASS data, runway threshold in normal position

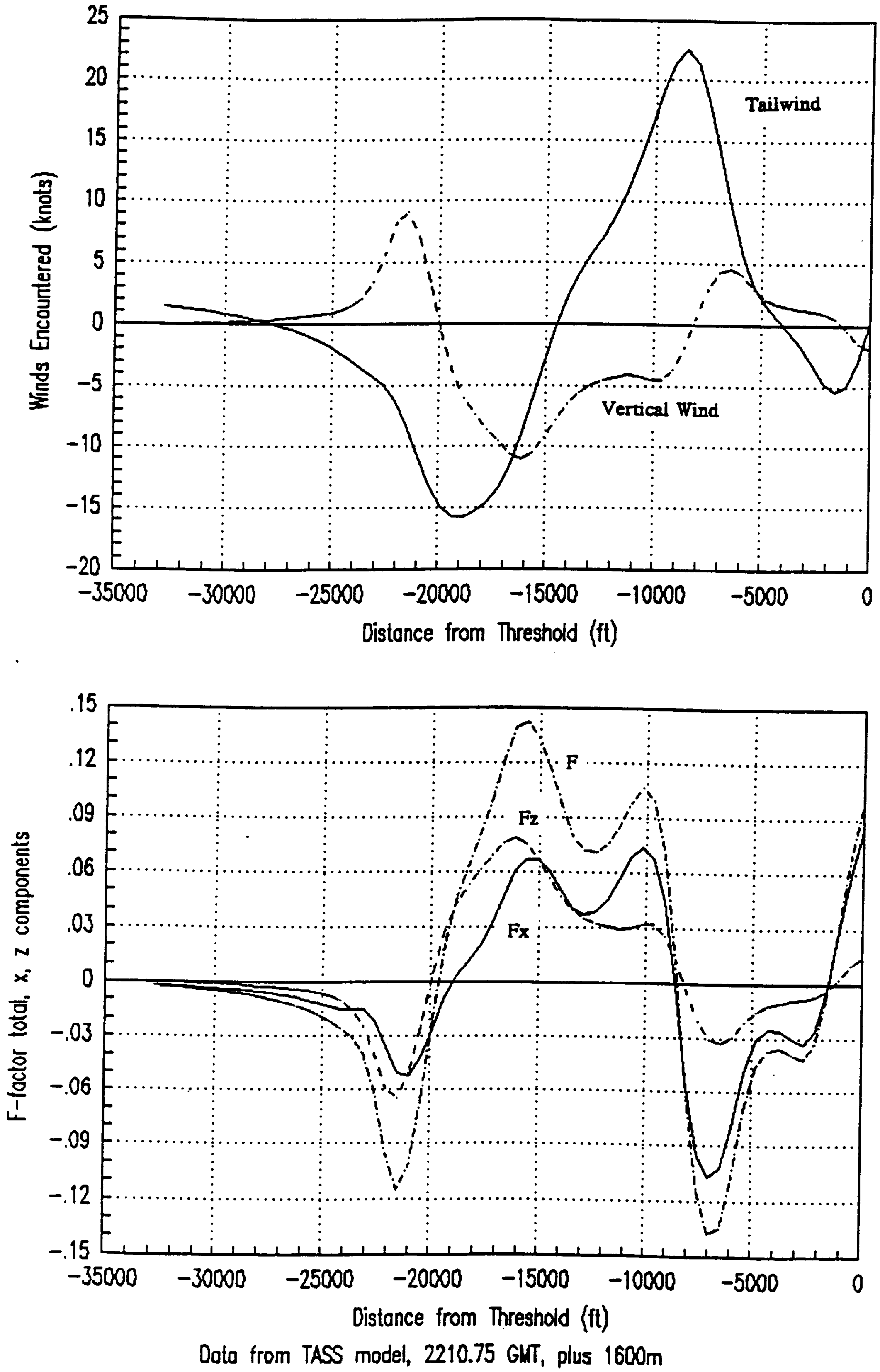


Figure B.5 **Windfields for approach to DEN 26L on 7/11/88 from TASS data, runway threshold displaced 1 nm Westward along localizer track**

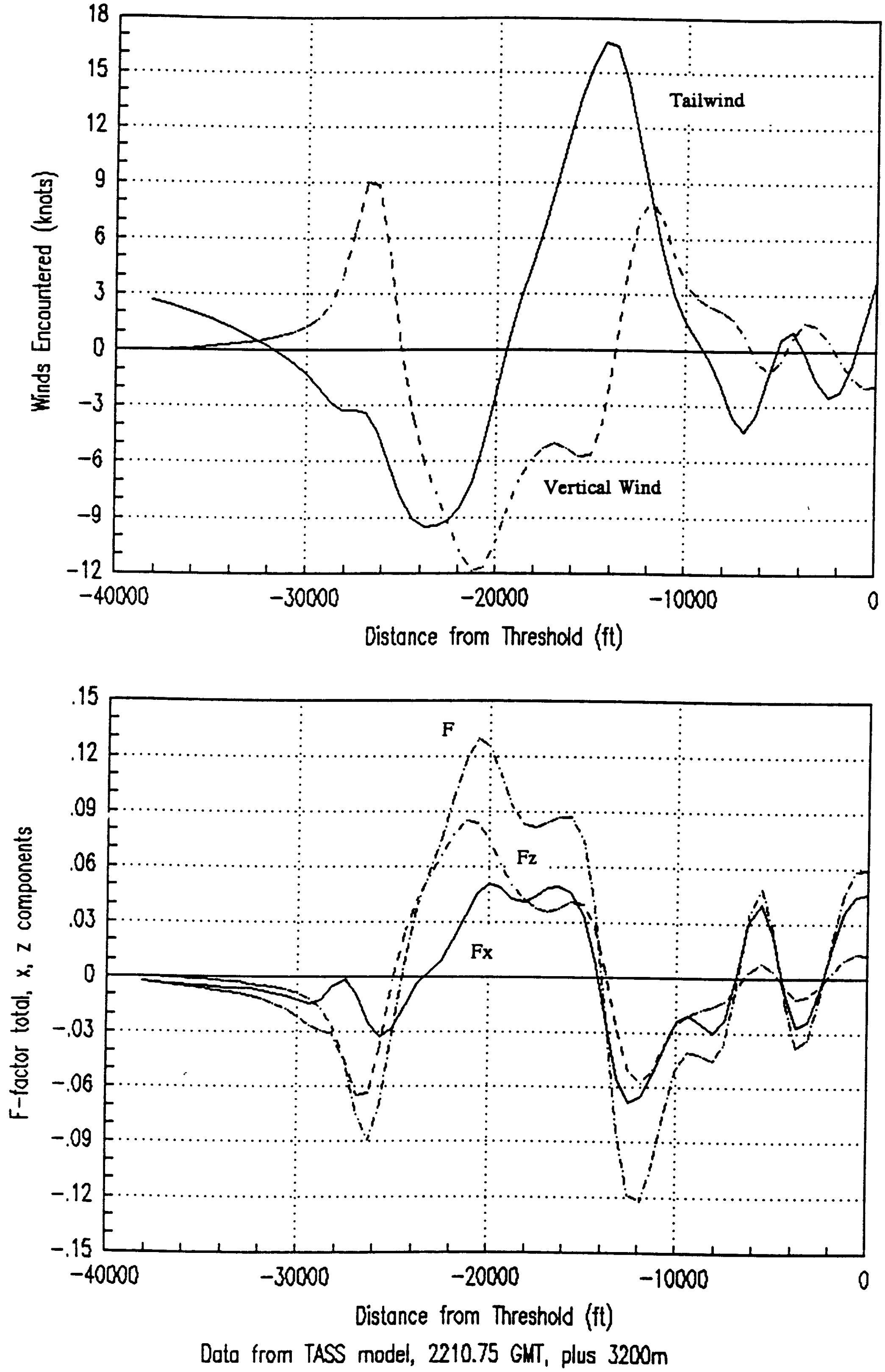


Figure B.6 Windfields for approach to DEN 26L on 7/11/88 from TASS data, runway threshold displaced 2 nm Westward along localizer track

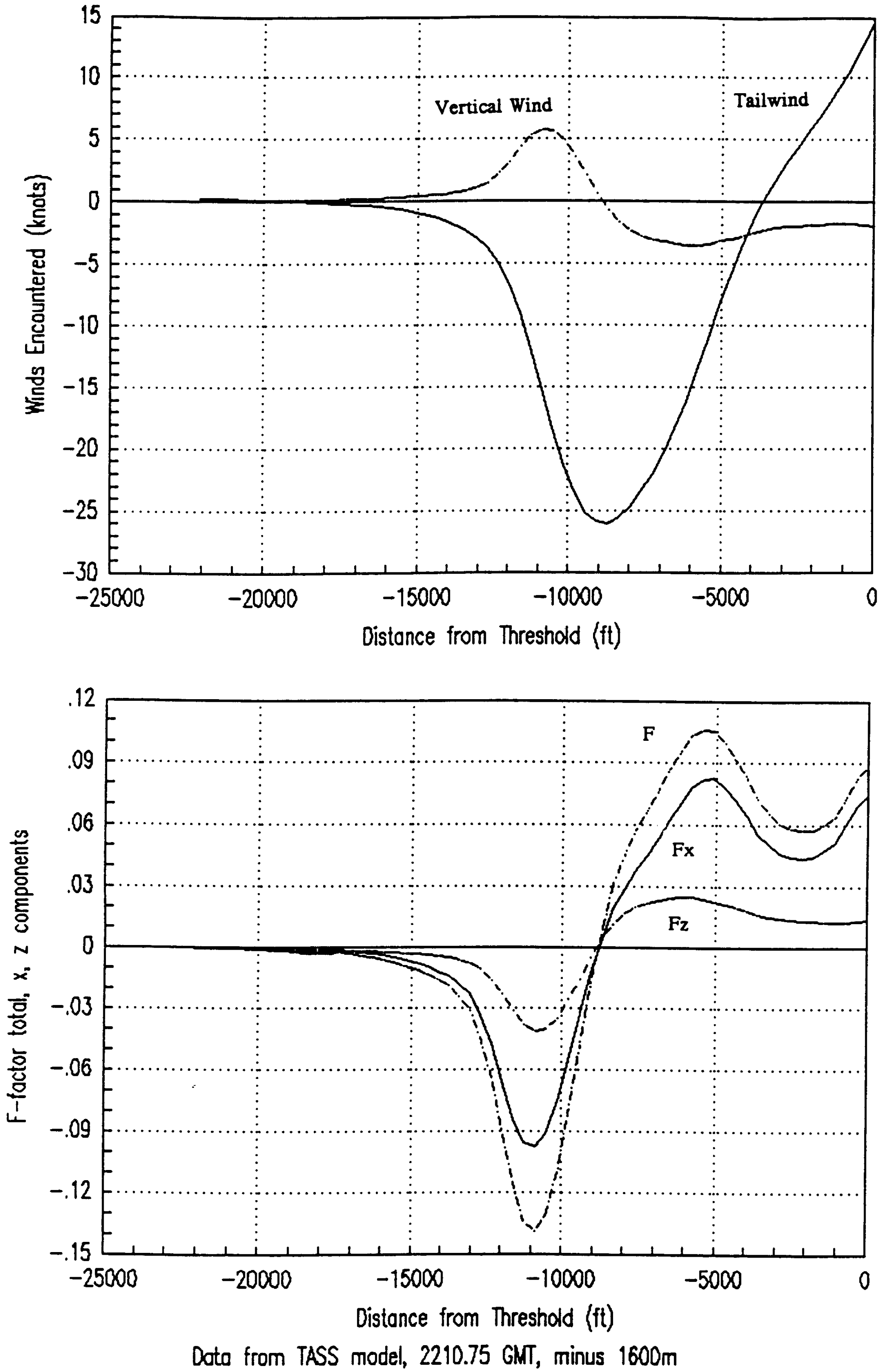
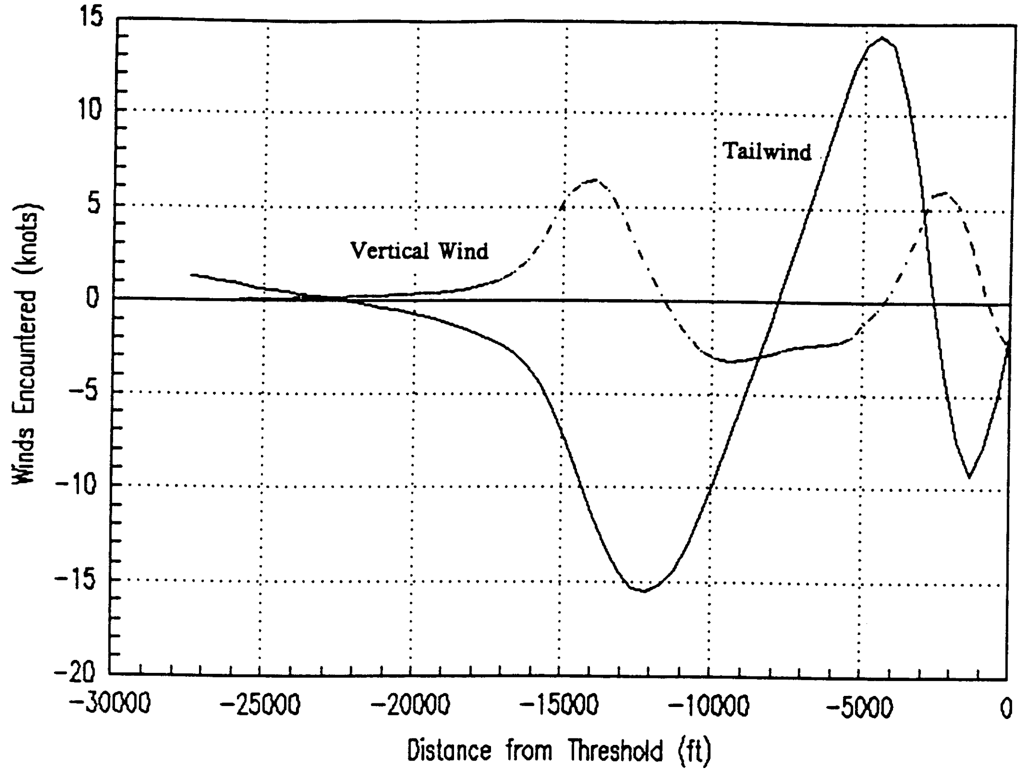
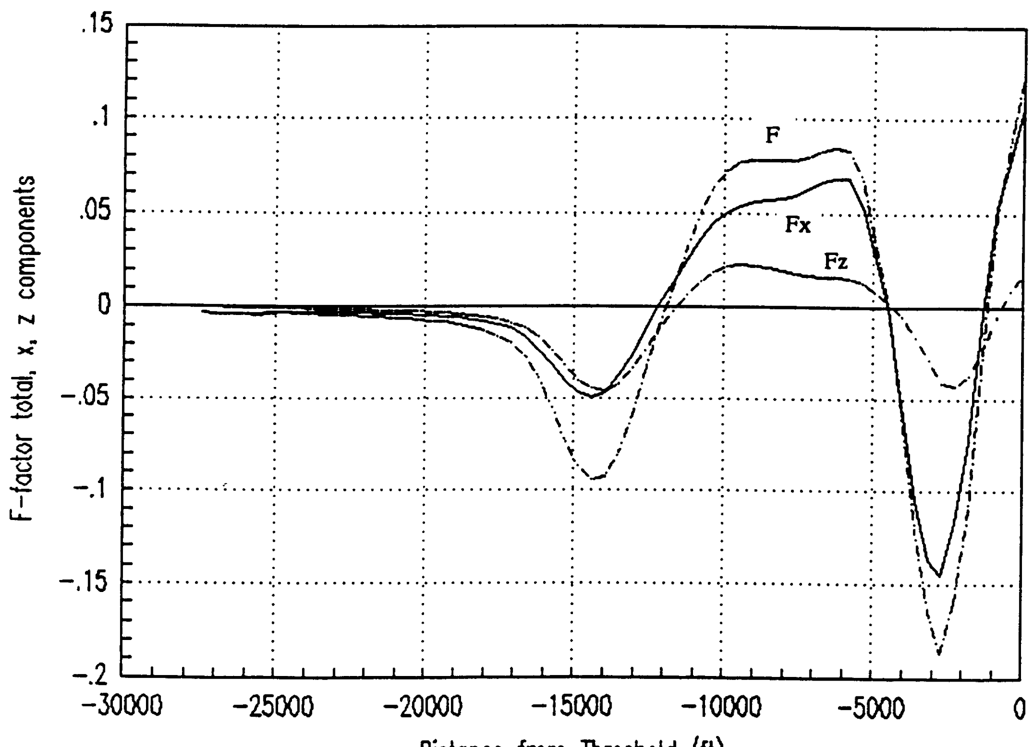


Figure B.7 Windfields for approach to DEN 26L on 7/11/88 from TASS data, runway threshold displaced 1 nm Eastward along localizer track





Data from TASS model, 2210.75 GMT, offset +800m

Figure B.8 Windfields for approach to DEN 26L on 7/11/88 from TASS data, runway threshold offset 800 meters to the North

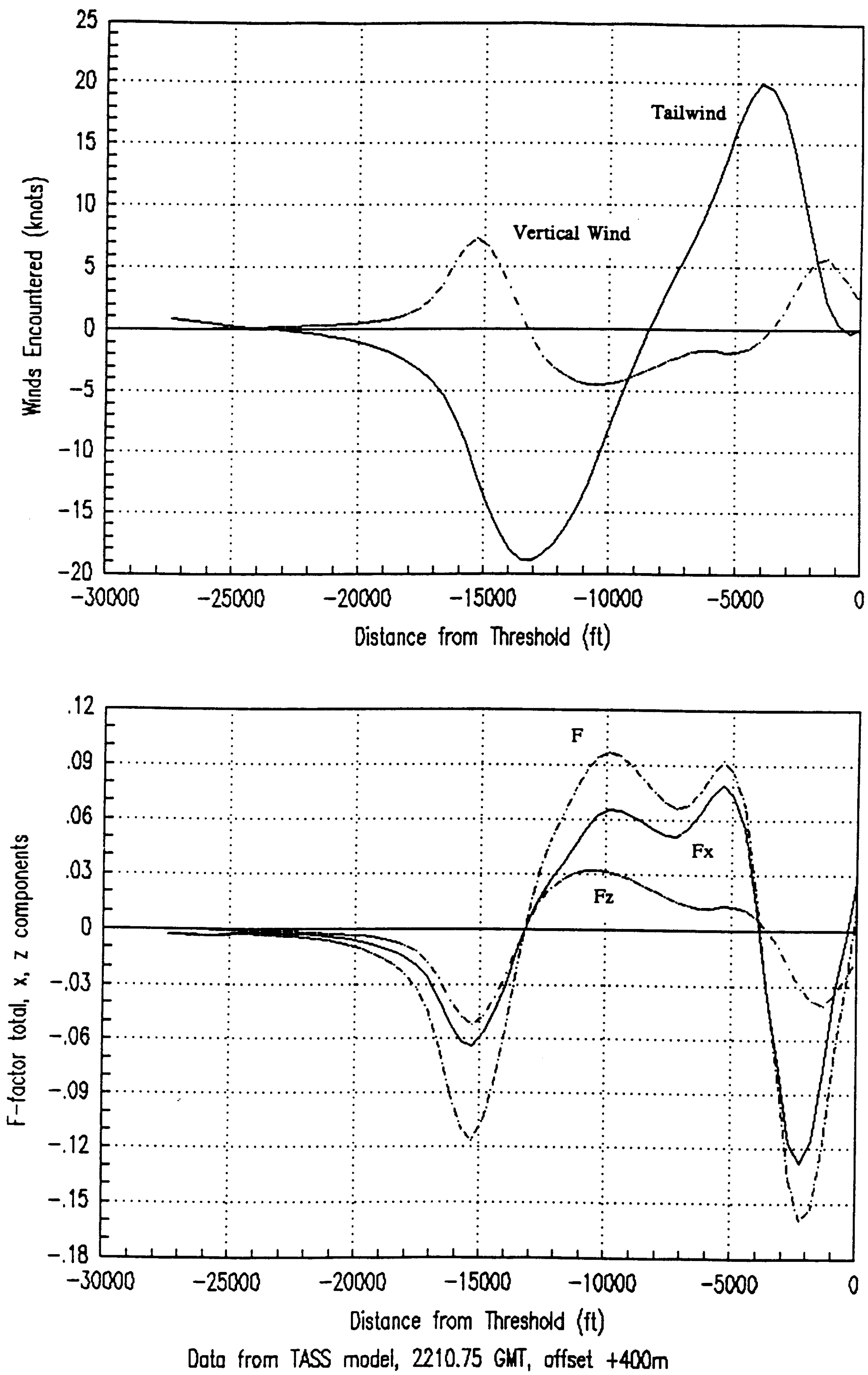
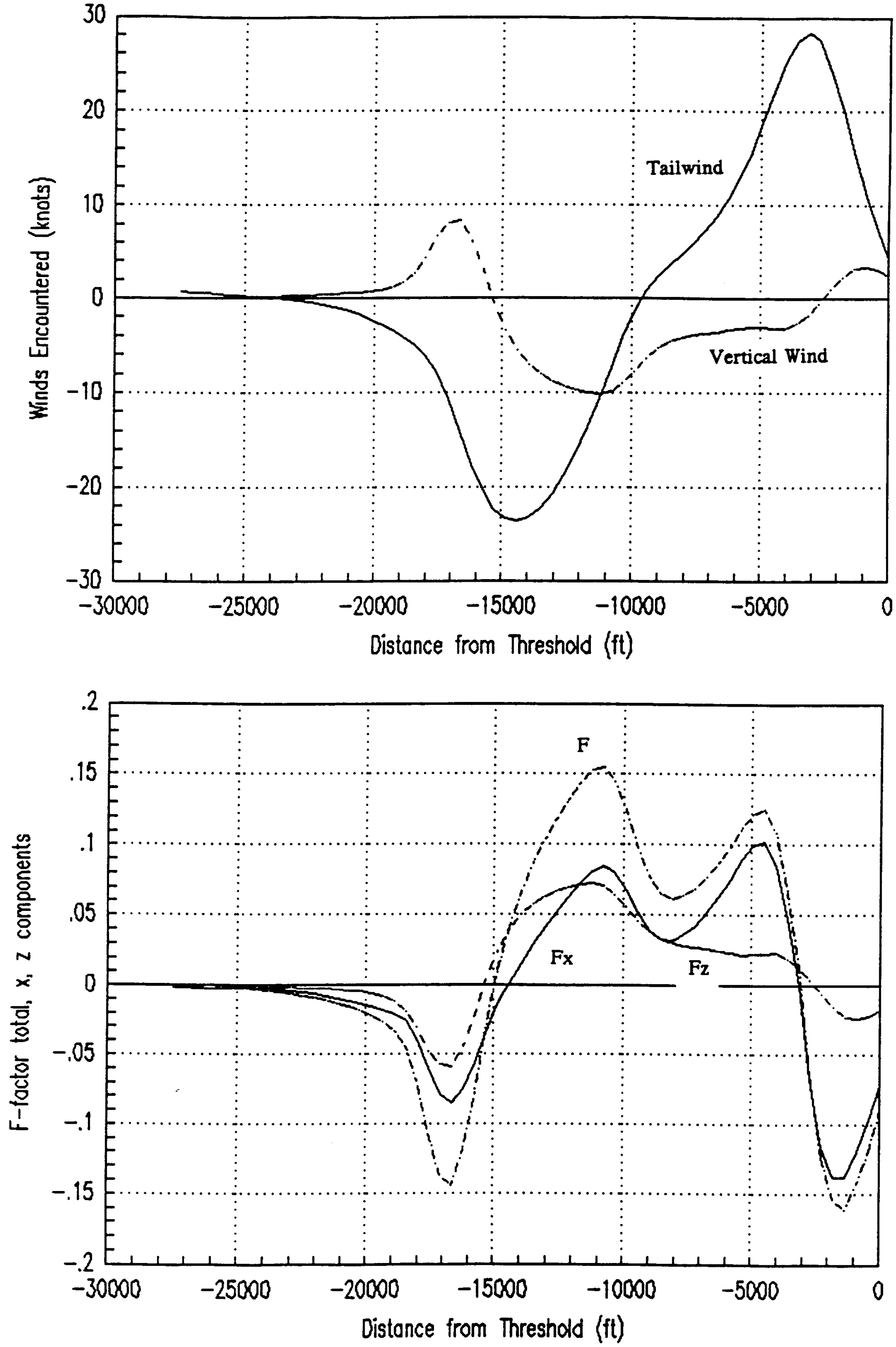


Figure B.9 Windfields for approach to DEN 26L on 7/11/88 from TASS data, runway threshold offset 400 meters to the North



Data from TASS model, 2210.75 GMT, offset -400m

Figure B.10 Windfields for approach to DEN 26L on 7/11/88 from TASS data, runway threshold offset 400 meters to the South

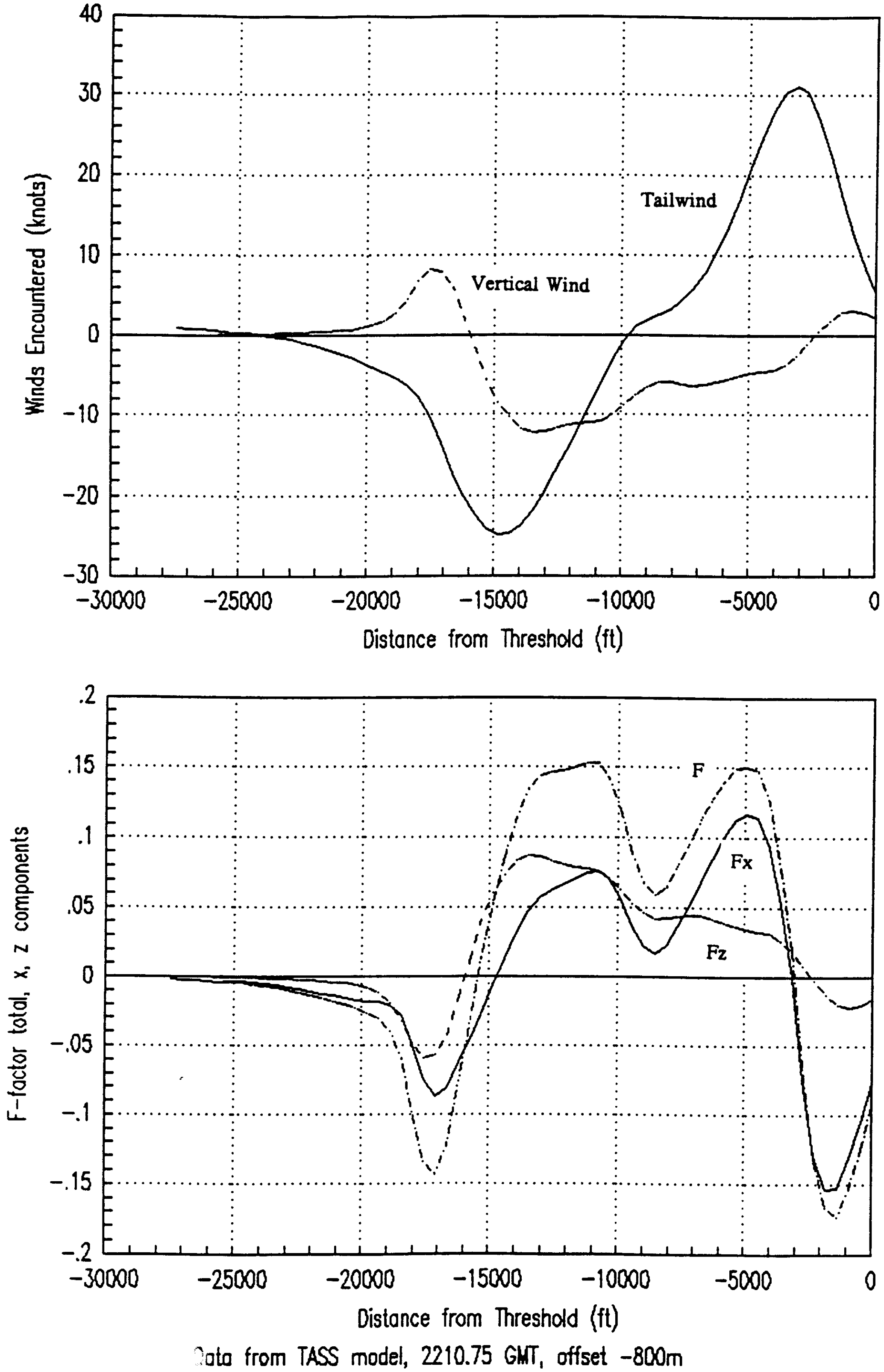


Figure B.11 Windfields for approach to DEN 26L on 7/11/88 from TASS data, runway threshold offset 800 meters to the South

Appendix C   Aircraft/Windshear Interaction Simulation

The simulation used for the analyses in Chapter 5 is a non-linear longitudinal simulation based on the inertial (earth-reference) axis equations of motion in Psiaki and Stengel (1985). The equations are reproduced here:

$$\dot{V}_i = \frac{-\bar{q}S\,[C_D\cos(\alpha_i - \alpha_a) + C_L\sin(\alpha_i - \alpha_a)] + T\cos\alpha_i}{m} - g\sin\gamma_i \qquad [B.1]$$

$$\dot{\gamma}_i = \frac{\bar{q}S\,[C_L\cos(\alpha_i - \alpha_a) - C_D\sin(\alpha_i - \alpha_a)] + T\sin\alpha_i}{mV_i} - \frac{g\cos\gamma_i}{V_i} \qquad [B.2]$$

$$\dot{q}_i = \frac{\bar{q}S\bar{c}C_M}{I_{yy}} \qquad [B.3]$$

$$\dot{\alpha}_i = q_i - \dot{\gamma}_i \qquad [B.4]$$

$$\dot{h} = V_i \sin \gamma_i \qquad [B.5]$$

$$\dot{r} = V_i \cos \gamma_i \qquad [B.6]$$

$$\alpha_a = \alpha_i + \gamma_i - \tan^{-1}\left(\frac{V_i \sin \gamma_i + w_z}{V_i \cos \gamma_i + w_x}\right) \qquad [B.7]$$

$$V_a^2 = V_i^2 + w_z^2 + w_x^2 + 2V_i(w_z \sin \gamma_i + w_x \cos \gamma_i) \qquad [B.8]$$

$()_i$	inertial quantity	$()_a$	wind-relative quantity
$\dot{()}$	time derivative of a quantity	g	gravitational acceleration
α	angle of attack	V	aircraft velocity
γ	flight-path angle	θ	pitch angle
q	pitching rate	m	aircraft mass
I_{yy}	pitching moment of inertia	S	wing area
$\bar{c}$	wing mean aerodynamic chord	$\bar{q}$	dynamic pressure, $0.5\rho V_a^2$
T	thrust	δ_e	elevator deflection
w_x	horizontal wind (tailwind +)	w_z	vertical wind (down +)
h	altitude	r	groundtrack distance
C_L	lift coefficient	C_D	drag coefficient
C_M	pitching moment coefficient		

The aerodynamic coefficients in these equations (C_L, C_D, C_M) are in general non-linear functions of the flow quantities. The expressions used in this simulation were taken from Turkel, et. al. (1981) who in turn took them from a Boeing 727 airline flight simulator. The B-727, a very common jet transport in the middle gross weight range (140,000 lb), is a good choice for the "typical" commercial aircraft. The relevant aircraft configuration and aerodynamic characteristics are given below (for B727 in landing configuration) along with the lift, drag, and moment coefficient relations.

Flaps 30°
Gear Down
Glide Slope Angle -3.0°

V	trim airspeed, 70.0 m/s
m	aircraft mass, 63,958 kg
I_{yy}	moment of inertia, 6.1 x 10^6 kg•m^2
$\bar{c}$	mean aerodynamic chord, 4.57 m
S	wing area, 145.0 m^2
C_{L_o}	0.74
C_{L_α}	6.99/rad
$C_{L_{\delta_e}}$	0.361/rad
C_{L_q}	10.0/rad
$C_{L_{\dot{\alpha}}}$	-7.6/rad
C_{D_o}	0.152
C_{D_α}	0.3/rad
$C_{D_{\alpha^2}}$	2.4/rad^2
$C_{D_{\delta_e}}$	0.0/rad
C_{M_o}	-0.25
C_{M_α}	-1.40/rad
$C_{M_{\delta_e}}$	-1.59/rad
C_{M_q}	-30.0/rad
$C_{M_{\dot{\alpha}}}$	-2.16/rad

$$C_L = C_{L_o} + C_{L_\alpha}(\alpha) + C_{L_{\delta_e}}(\delta_e) + \left(\frac{\bar{c}}{2V}\right)C_{L_q}(q) + \left(\frac{\bar{c}}{2V}\right)C_{L_{\dot{\alpha}}}(\dot{\alpha}) \quad \text{[B.9]}$$

$$C_D = C_{D_o} + C_{D_\alpha}(\alpha) + C_{D_{\alpha^2}}(\alpha^2) + C_{D_{\delta_e}}(\delta_e) \quad \text{[B.10]}$$

$$C_M = C_{M_o} + C_{M_\alpha}(\alpha) + C_{M_{\delta_e}}(\delta_e) + \left(\frac{\bar{c}}{2V}\right)C_{M_q}(q) + \left(\frac{\bar{c}}{2V}\right)C_{M_{\dot{\alpha}}}(\dot{\alpha}) \quad [B.11]$$

In addition, to simulate lags in engine response to throttle, the following equation for thrust response to throttle advance rate *u(t)* was included. Note that t_c represents the engine lag time constant and was set to 2 seconds.

$$\ddot{F} = \frac{u(t) - \dot{F}}{t_c} \quad [B.12]$$

Finally, a control system was chosen. In Turkel, et. al. (1981) a strategy which fed back airspeed deviation and rate to throttle rate and glideslope and pitch deviations to elevator was shown to have similar characteristics to a test pilot when flown through a variety of simple windshear profiles. The test pilot performed much better in tracking the glideslope, but the control system exhibited similar characteristics to the pilot and could be said to represent a "typical" glideslope tracking strategy. This control system is as follows:

$$u = K_{uv}\left[(V + t_c\dot{V}) - V_{trim}\right] \quad [B.13]$$

$$\delta_e = \delta_{e\,trim} + K_{e\dot{z}}(\dot{z} - \dot{z}_{GS}) + K_{e\theta}(\theta - \theta_{trim}) \quad [B.14]$$

Control gains:

K_{uv}	-2000 (N/s)/(m/s)
t_c	2 sec
$K_{e\dot{z}}$	0.01 rad/(m/s)
$K_{e\theta}$	0.1 rad/rad

The trim values in this case were for a 3° glideslope approach at 75.1 m/s airspeed. Thrust non-linearities were also included. Maximum thrust was taken as 187,000 N (42,000 lb), minimum thrust as 13,350 N (3,000 lb) and a maximum thrust change rate of 36,000 N/s (8,000 lb/s). These equations, in conjunction with the windshear models described in the text, were simulated on a Sun 3/80 workstation with MATRIX$_X$/WS

SYSTEM BUILD software. The Oseguera and Bowles (1988) model was built into the model as analytical equations; TASS data was incorporated as 2-D discrete (range and altitude) interpolation tables.

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