Cockpit Display of Hazardous Weather Information *

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Abstract

Information transfer and display issues associated with the dissemination of hazardous weather warnings are studied in the context of windshear alerts. Operational and developmental windshear detection systems are briefly reviewed. The July 11, 1988 microburst events observed as part of the Denver TDWR operational evaluation are analyzed in terms of information transfer and the effectiveness of the microburst alerts. Information transfer, message content and display issues associated with microburst alerts generated from ground based sources (Doppler Radars, LLWAS and PIREPS) ars evaluated by means of pilot opinion surveys and part task simulator studies.

1. Introduction

Technological advances in ground-to-cockpit datalink capability, information display, and hazardous weather detection create the possibility for new and improved methods of informing flight crews about weather hazards. However, the availability of increased information and multiple modes of communication also lead to problems of system integration. Issues including the selection, transfer, and presentation of information must be addressed in the development of advanced systems for the display of hazardous weather information. In addition, design procedures, centered around the needs of the flight crew and the capabilities of the available equipment should be applied.

The display and information transfer issues related to advanced windshear alerting systems in the terminal area have been chosen as an initial point of focus. This problem was chosen both to investigate general issues related to the dissemination of hazardous weather information and to focus on specific issues of a critical near term need. Windshear in the terminal area is one of the most dangerous weather-related problems faced by aviation today.[1]. The real-time detection of windshear hazards is a very active field of research,[2,3,4] and thus provides a useful testing ground for issues related to advanced data uplink and display of hazardous weather information.

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 [1,5]. 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 cumulonimbus cloud. If the downdraft is strong enough to impact the surface, it spreads out radially and creates a 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. (Fig. 1). It may also serve to destablilize 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.[5]

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 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.

Fig. 1: Microburst windshear encounter on approach (from Ref. 2).

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*AIAA-89-0808. #Some original figures were not available at time of publication.

2.2 Microburst Detection

2.2.1 Current Procedures

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*.[6] 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 that "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!".[6]

Pilot reports (PIREPS) of windshear provide the most reliable data. The availability of PIREPS necessarily requires that an aircraft penetrate a microburst, which is not desirable; but the information, unlike LLWAS, provides conclusive evidence of a windshear hazard for subsequent aircraft. It is desirable to integrate PIREPS with any sensor data available in future windshear detection systems.

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. In past accidents, these clues have been largely ignored; increased windshear training emphasis is being used to increase pilot awareness of these events. However, high pilot workload in the terminal area and the relative rarity of hazardous windshear makes it difficult for crews to fully assimilate the evidence of windshear before penetration.

2.2.2 Emerging Windshear Detection 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, doppler lidar, and infrared radiometry. [2,3,4] 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 the methods mentioned have yet fully demonstrated these capabilities in flight.

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 radars have been succesfully demonstrated for microburst detection (JAWS, Huntsville, Denver) [5] and have an advantage over airborne systems in terms of ground clutter suppression, size and power. Experiments performed at Huntsville, AL in 1986 and at Denver in 1987 and 1988 have shown impressive results (Table 1). 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.

MICROBURST DETECTION

Data	Probability of detection* $\Delta V<20$ m/s	$\Delta V\geq20$ 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 $\Delta V\leq 15$ m/s	$\Delta V>15$ 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 1:Doppler radar windshear detection results [7]

The demonstrated capability of ground-based doppler radar for windshear detection and forecasting makes it the most viable system for near term use for microburst avoidance information. The combination of doppler radar, improved LLWAS systems and PIREPS makes an integrated ground-based system the primary focus for system integration and automated datalink issues.

2.3 Ground-to-Air Data Transfer

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 a high-speed alphanumeric datalink 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. The first satellite transmissions are expected to begin in the third quarter of 1989 in the Pacific Ocean region [8].

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 with less urgency.

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.

2.4 Information Transfer Issues in the 1988 Denver TDWR Evaluation

An event which illustrates many of the information transfer issues occurred during the 1988 Terminal Doppler Weather Radar (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.

2.4.1 TDWR Setup

In the 1988 operational evaluation, the TDWR radar was operated by the MIT Lincoln Laboratory and located at the Buckley AFB southeast of the Stapelton airport. Microburst and gustfront alerts were generated from the doppler weather radar data by an automatic algorithim and confirmed on line by an NCAR meterologist. The alerts were then sent by ground line to the Stapelton control tower and the terminal radar approach control (TRACON).

The information was displayed in two formats in the control tower. The local tower controller, who had primary responsibility for the dissemination of microburst alerts, had an alphanumeric display (Fig. 2) which could present either TDWR or LLWAS information in the same format. This was done to minimize the transition between periods of TDWR and LLWAS-only operation. The tower supervisor and the TRACON also had the geographical situation display which is shown in Fig.3. This color display presented the locations of microbursts, gustfronts and precipitation on a plan view of the runway configuration. In addition, LLWAS wind vectors are displayed. In the tower a local controller working arrivals to Runways 26L and 26R would have to cross the tower cab to have access to the geographical situation display.

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

Fig. 2: Example of controllers alphanumeric display (from Ref. 7).

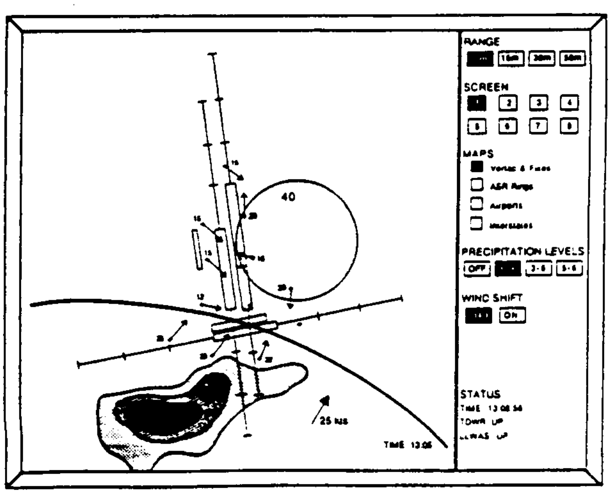

Fig. 3: Geographical situation display used in the control tower and TRACON (from Ref. 7).

2.4.2 July 11, 1988 Scenario

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 (Fig.4). At 2201 UTC there

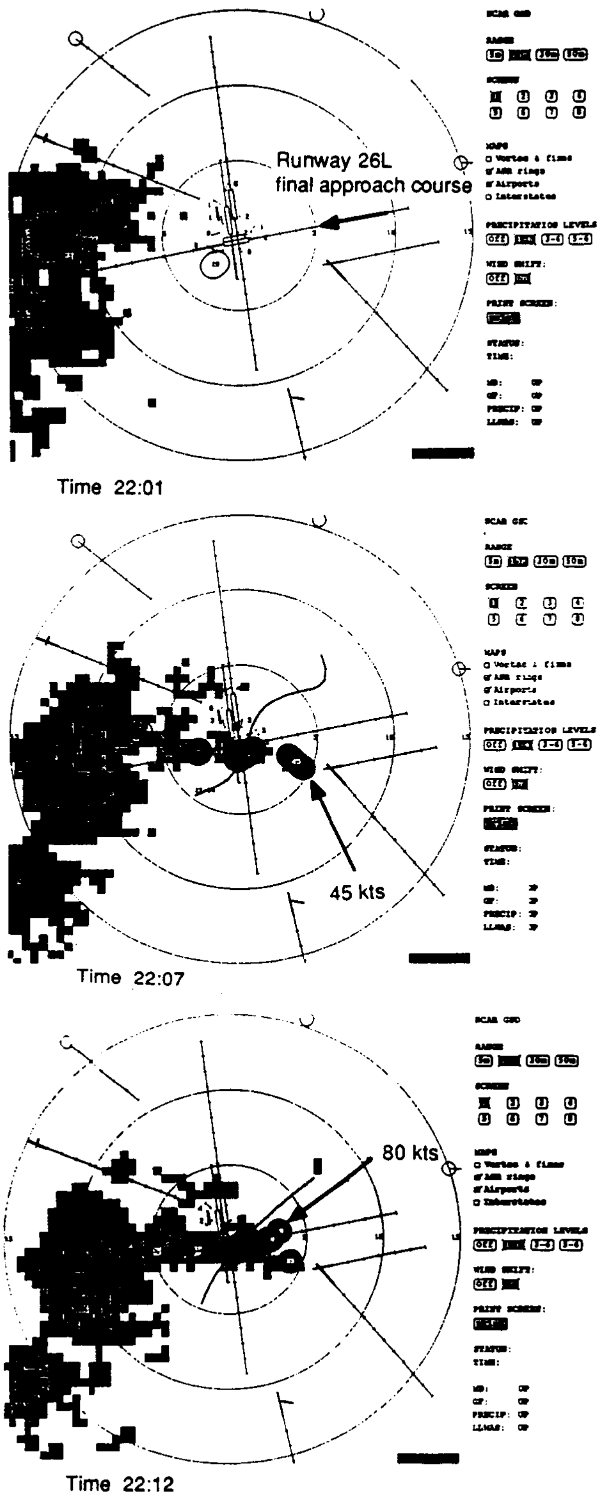

Fig. 4: Geographical situation display plots showing the evolution of the severe microburst event of July 11.

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 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.

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 Fig. 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. 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.

2.4.3 Implications of the July 11 Experience

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 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. Fig.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 of approximately 60 seconds can be expected for the dissemination of verbal alerts even if the aircraft is in contact with the controller who has alerting responsibility.

A third issue which arises is that the initial microburst alert for each aircraft 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

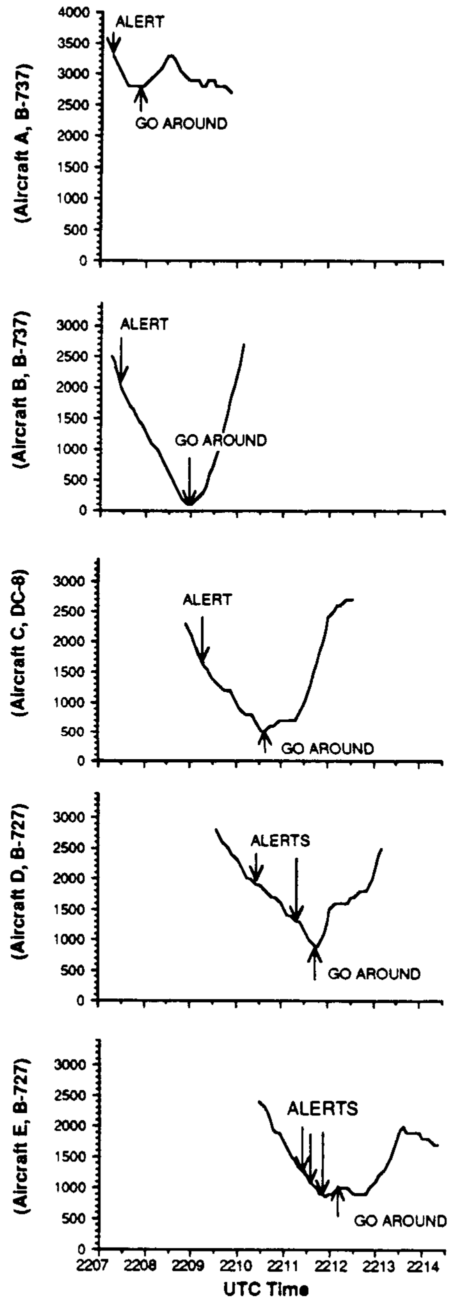

Fig. 5: Plots of aircraft height (AGL) versus time.

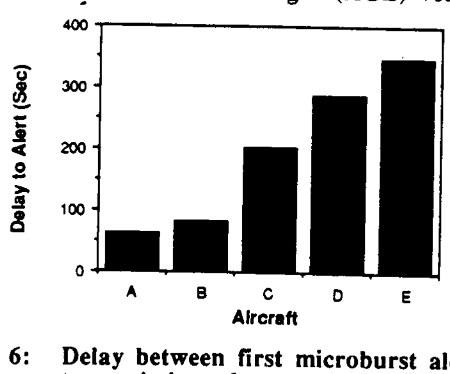

Fig. 6: Delay between first microburst alert and transmission of alert to aircraft.

	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: Transcripts of verbal microburst alerts issued to each aircraft.

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.

3. Research on Windshear Detection and Warning in the Advanced ATC Environment

3.1 Problem Statement

The integration of ground-based information sources with digital datalinks such as Mode-S shows great potential for the accurate prediction and delivery of microburst windshear alerts with minimal delay. Fig. 7 illustrates possible information flow configurations for such a system. The multiple potential data paths are dependent on the acceptable degree of automation. Clearly, the delay between detection and alert is minimized with a fully automated process whereby computer algorithms determine alerts from PIREPS, TDWR, and LLWAS data and use Mode-S to directly distribute them. However, putting the controller in the loop to some degree would help filter false alarms and more efficiently control the destination of the data.

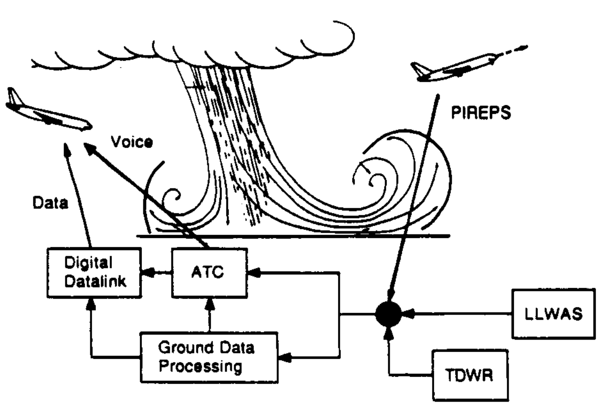

Fig 7: Possible windshear data distribution in the advanced ATC environment.

A number of other information issues also require consideration. The content, timing, transmission, and presentation of windshear information all need to be determined. Automated links such as Mode-S are subject to bit limitations and reliability considerations. This has an impact on message content and distribution. The timing and priority of alerts must be considered to get maximum efficiency and to generate the least possible confusion. The high workload of both controllers and flight crews during terminal area operations adds a further measure of difficulty. Finally, the varying levels of instrument sophistication in civil aircraft must be considered. The advanced moving map displays in modern transport category aircraft allow for development of user-oriented graphical presentations, while many general aviation aircraft have no visual display capability.

3.2 Investigations

Several investigations are being performed to address the issues discussed above. Flight crew opinion surveys are being used to obtain user input on a number of factors. Data is sought on current operational issues such as LLWAS and other available windshear information sources, as well as pilot perceptions of the microburst threat. Also, issues of data transmission and presentation are addressed. In addition, some issues are being addressed through flight simulation studies. A simple experiment based on a general aviation simulator was conducted to compare voice communication with graphical data presentation modes. Also, a part-task simulation of the Boeing 757/767 has been developed in order to do more sophisticated investigation into optimization of graphical warning formats, information content and delivery timing, and the effect on pilot workload.

3.3 Results

3.3.1 Current Windshear Procedures

For user input on current windshear alert systems and requirements for future systems, a pilot opinion survey is being conducted. A preliminary sample of 20 United Airlines line and training pilots has been completed, and a further distribution of 250 is under way. Initial results show several consistent trends. It is almost universally agreed (94%) that microbursts pose a major safety hazard to transport aircraft. Fifty-three percent of the respondents have had what they considered to be a hazardous windshear encounter; most incidents occurred at DEN, a United operations hub. When posed the question "Currently available windshear alert data is sufficient for safe operation in the terminal area," only 17% of the respondents agreed, while 56% disagreed. All but one of the pilots felt that "...a system to provide aircrews with better and more timely windshear alerts is necessary." The results clearly indicate that flight crews are not completely confident in currently available data and would be very receptive to improvements. Figure 8 shows the pilots' average ranking of possible sources of windshear information.

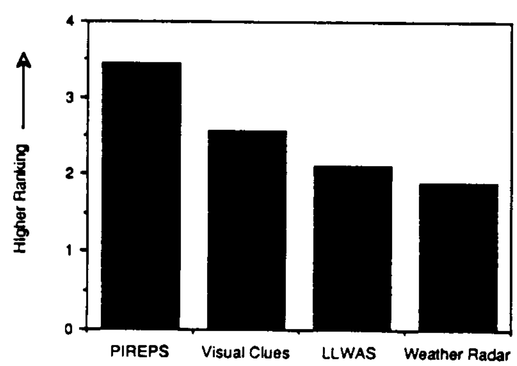

Fig. 8: Pilot ranking of windshear information sources.

Significantly, PIREPS and visual clues are both considered more useful for windshear avoidance than LLWAS alerts. Yet, neither pilot reports or visual clues are always available; this underlines the need for a detection system which can reliably provide some degree of advance warning.

3.3.2 Modes of Information 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. This was illustrated by the Stapleton incident; even though data was available, it was difficult to effectively communicate it to the flight crew. There are several possible modes of information presentation in the cockpit: *voice, alphanumeric*, or *graphical*. Issues to be considered include crew workload, preferences, and the capabilities of the aircraft instrumentation. The widespread use of CRT displays in modern transport aircraft, for example, opens up new possibilities for totally automated graphical information displays. Moving map displays, such as the Electronic Flight Instrumentation System (EFIS) used on the Boeing 757-767 generation of aircraft, are good candidates for display of critical weather information.

Responses from the pilot survey indicate that pilots are receptive to graphic displays. (Fig. 9). The specific suggestion of integrating windshear information with an EFIS-type moving map display was strongly supported. Also of interest was the preference of ATC voice alerts over alphanumeric links or ATIS information. Comments received indicated that the low ranking of ATIS was due to the time between updates.

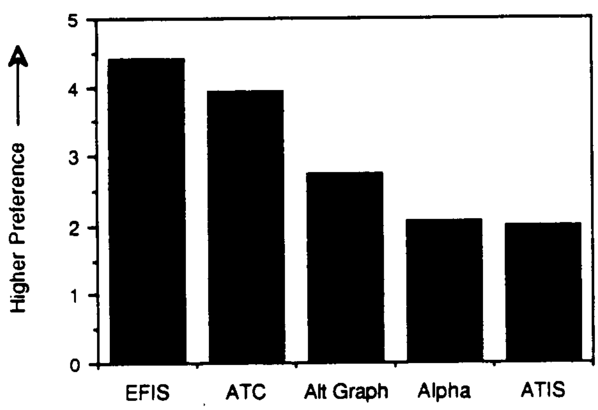

Fig. 9: Pilot rankings of possible relay/presentation modes of windshear information from the ground

A preliminary experiment has been conducted with a general aviation simulator to compare the efficiency of voice and graphical modes of presentation. Eight GA pilots with 210 to 1,700 total flight hours were tested. The scenario involved a microburst which appeared during an ILS approach, when the aircraft reached the outer marker. Avoidance of the microburst required a non-standard missed approach. The information was presented by voice, on a runway-fixed graphic display of microburst position, and on a graphic display showing both the microburst and aircraft positions. The data (Table 3) shows the effectiveness of the graphic displays. Avoidance improved significantly with the graphic displays, even though the same information was presented at the same time in each case.

Presentation Type	Avoidance Rate
Voice (JAWS format)	43%
Runway-Fixed Graphical Display: Microburst position only	62%
Runway-Fixed Graphical Display: Microburst + Aircraft position	94%

Table 3: Results of experiment with general aviation simulator and computer graphic display.

These results considered, the incident at Stapleton Airport serves as an illustration of the problems of voice communication. Crew and ATC workload in terminal phases of flight is high, leading to possible confusion and error. The simulation indicates that even under fairly light workload, the difficulty involved in fully interpreting the microburst threat from a voice warning can mean the difference between avoidance and penetration. Further evaluation of communication modes, including a variety of alphanumeric and graphic formats, will be performed with the part-task 757/767 simulator.

3.3.3 Message content and timing

The issue of what data is necessary and when it should be presented is important for either voice or digital transmission. In either case, a limited amount of information can be contained, and the timing must be determined to give the crew maximum awareness while minimizing the increase in workload. An initial viewpoint can be obtained from the pilot surveys. 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 inconsequential.

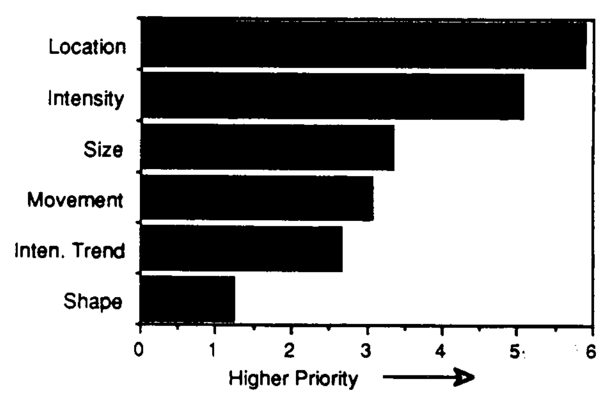

Fig. 10: Pilot ranking of microburst information by importance

The issues of what constitutes a hazardous microburst, who should be informed, and when are more difficult to resolve. The surveys are less clear in this case; the most common response was that aircraft should be alerted as soon as microbursts are detected anywhere around the airport vicinity. A few pilots defined a particular phase of flight, i.e. at the outer marker, when cleared for approach, or immediately upon entering the terminal area, as the best point for delivery of microburst alerts.

In response to a question about threshold shear levels, there was general agreement that a windshear advisory should be issued for approximately 10 knots of head-to-tail shear and a warning for 15 knots of shear. Also, it was almost unanimously expressed that decisions about the threat posed by windshear in a particular situation should be made entirely by the pilot, and the controller's role should be to maintain safe separation during avoidance maneuvers. However, it remains to be determined what locations and intensities of microbursts actually constitute a threat in the view of the pilot. It is impractical to plan on distribution of all available windshear information in raw form to all aircraft in a congested terminal area. Some 'threshold hazard level' needs to be defined, based not only on the windshear intensity of the microburst, but including other factors such as the microburst and aircraft locations, aircraft altitude, and desired flight path.

3.4 Current Research

Research to resolve these issues is being conducted with the part-task 757/767 simulation shown in Fig. 11. The simulation uses an IRIS 2400T graphics computer, an autopilot control panel, and an EFIS control panel to duplicate the electronic instrumentation and flight dynamics of the aircraft. Data from TDWR experiments is used to generate simulated airborne weather radar returns and the windfield over the airport.

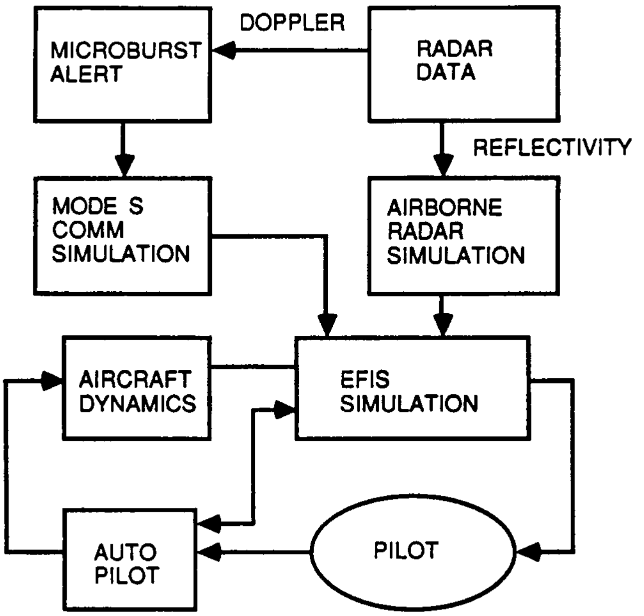

Figure 11: Part-Task 757/767 EFIS Simulation

The initial simulations are based on data provided by NCAR and the Lincoln Laboratory TDWR evaluations. The Stapleton incident is very well documented, and serves as a model for scenario construction. With a suitable sidetask, workload levels will be properly adjusted to get a reasonable range of pilot responses. Once the simulation is validated and a range of scenarios developed, issues of information format can be explored. Simulations of Mode-S transmissions with varying alphanumeric and graphic alert formats can be added, as well as voice communications, and the differences in pilot decision making and reaction time can be measured. If the results are commensurate with the results of the earlier general aviation simulations, more specific tests can be performed. These will center around more specific information issues, such as warning content, timing, and display formats.

4. Conclusions

Based on the above, the following points can be made:

- Technological advances in weather sensors and information transfer will allow development of sophisticated hazardous weather detection and alert systems. Design guidelines, centered around the end user and the available equipment, need to be applied to these systems.

- Microburst windshear is a weather hazard of particular concern and hence provides a good test case for development of user-oriented weather alert displays. Pilot surveys indicate that currently available detection and alert systems are not adequate, and a system for advance detection and alert is needed.

- The events which occurred during the TDWR operational evaluation on July 11, 1988 were analyzed in the context of information transfer issues. The observations included the following: Variability of pilot response to similar microburst alerts. The verbal relay of microburst alerts was found to induce delays. The inclusion of microburst alerts with other routine messages was thought to reduce the sense of urgency of the alerts. Finally, PIREPS have been found to be extremely important in validating the TDWR alerts to the user.

- A review of the current state of microburst detection technology and the analysis of the TDWR operational evaluation leads to the conclusion that the integration of ground-based doppler radar, LLWAS and PIREPS, and of a digital datalink such as Mode-S is the most viable near-term system for reliable advance warning of windshear.

- A simple flight simulator study has indicated that display of windshear information with a graphical display of aircraft and microburst position can result in significantly greater microburst awareness and greatly improve the probability of avoidance when compared with standard voice transmission.

- An opinion survey of air carrier pilots was conducted. Pilots feel that PIREPS and visual clues are the best currently available methods for microburst detection, while LLWAS and airborne weather radar are less effective. Also, pilots were receptive to the idea of displaying windshear information on an EFIS display, preferring the EFIS to ATC voice communications. Alphanumeric information and ATIS were rated poorly for transmission of windshear alerts.

- When asked about microburst alert information content, pilot specified that microburst location and intensity were the most important items, followed by size, movement, and intensity trend information.

- Research is currently in progress to further explore the issues involved. A part-task Boeing 757/767 simulation has been developed to address issues of warning content, timing, and a selection of alphanumeric and graphical display formats.

Acknowledgments

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References

1. National Research Council, *Low Altitude Wind Shear and Its Hazard to Aviation*, National Academy Press, 1983.

2. Targ, R., and Bowles, R.L., "Investigation of Airborne Lidar for Avoidance of Windshear Hazards," AIAA Paper 88-4658, Sept. 1988.

3. Bracalente, E.M., Britt, C.L., and Jones, W.R., "Airborne Doppler Radar Detection of Low Altitude Windshear," AIAA Paper 88-4657, Sept. 1988.

4. Adamson, H.P., "Airborne Passive Infrared System for the Advance Warning of Low-Level Windshear and Clear Air Turbulence: 1988 In-Service and Theoretical Work," AIAA Paper 88-4659, Sept 1988.

5. Wolfson, M.M., "Characteristics of Microbursts in the Continental United States," *The Lincoln Laboratory Journal*, Vol. 1, No. 1, Spring 1988, pp. 49-74.

6. Federal Aviation Administration, *Windshear Training Aid*, 1987.

7. National Center for Atmospheric Research, "Terminal Doppler Weather Radar (TDWR): A Briefing Paper," July 1, 1988.

8. Private Communication with McEachen, A. of Aeronautical Radio, Inc., August 1988.

9. Rucker, R.A., Flathers, G.W., "The Future for Aeromobile Digital Communications," *IEEE/AIAA 8th Digital Avionics Systems Conference*, October, 1988.