THE FAA TERMINAL DOPPLER WEATHER RADAR (TDWR) PROGRAM

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1. RESPONDING TO A MAJOR HAZARD FOR U.S. AVIATION

The Federal Aviation Administration (FAA) initiated the Terminal Doppler Weather Radar (TDWR) program in the mid-1980s in response to overwhelming scientific evidence that low-altitude wind shear had caused a number of major air-carrier accidents. The program is designed to develop a reliable automated system for detecting low-altitude wind shear in the terminal area and providing warnings that will help pilots successfully avoid it on approach and departure.

Wind shear has caused more U.S. air-carrier fatalities than any other weather hazard. A 1983 National Research Council (NRC) study (National Research Council, 1983) identified low-altitude wind shear as the cause of 27 aircraft accidents and incidents between 1964 and 1982. A total of 488 people died in seven of these accidents, 112 of them in the 1975 crash of Eastern Flight 66 at New York and 153 in the crash of Pan American Flight 759 at New Orleans in 1982. Since the NRC study was completed, the National Transportation Safety Board (NTSB) has investigated at least three more wind-shear incidents. One of these, the crash of Delta Flight 191 at Dallas/Fort Worth on August 2, 1985, took another 137 lives.

Wind shear is not a serious hazard for aircraft enroute between airports at normal cruising altitudes, but low-level wind shear in the terminal area can be deadly for an aircraft on approach or departure. The most hazardous form of wind shear is the microburst, an outflow of air from a small-scale but powerful downward gush of cold, heavy air that can occur beneath a thunderstorm or rain shower or even in rain-free air under a harmless-looking cumulus cloud. As this downdraft reaches the earth's surface, it spreads out horizontally, like a stream of water sprayed straight down on a concrete driveway from a garden hose. An aircraft that flies through a microburst at low altitude first encounters a strong headwind, then a downdraft, and finally a tailwind that produces a sharp reduction in airspeed and a sudden loss of lift. This deadly sequence of events caused the fatal crash at Dallas/Fort Worth in 1985, as well as a number of other serious air-carrier accidents. Wind shear can also be associated with gust fronts, warm and cold fronts, and strong winds near the ground.

It is important for pilots to be trained in recovery techniques to use if they are caught in wind shear. But a sudden windspeed change of at least 40 to 50 knots, which is not uncommon in microbursts, presents a serious hazard to jet airliners, and some microbursts simply are non-survivable. The only sure way to survive wind shear in the terminal area is to avoid it. However, flight crews do not have adequate information available today to predict or detect wind shear. The primary goal of the TDWR program is to provide pilots with an objective, quantitative assessment of the wind-shear hazard. The TDWR system also will improve operational efficiency and reduce delays in the terminal area by providing air traffic control supervisors with timely warnings of impending wind shifts resulting from gust fronts.

2. GENESIS OF TDWR

Because Doppler radar can produce detailed, three-dimensional pictures of the changing structure of storms, it became a valuable tool for atmospheric scientists during the 1970s. In 1976-78, scientists at the National Severe Storms Laboratory (NSSL) and the Air Force Geophysical Laboratories (AFGL) conducted the Joint Doppler Operational Program, an operational test of a Doppler weather radar system. In 1980, the NEXRAD (short for next-generation weather radar) Program was established by the FAA, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Air Force. The goal of NEXRAD is to deploy a national Doppler weather radar network for observing and predicting severe storms and other weather phenomena.

Doppler radar is a key element of a series of wind-shear research efforts that were undertaken as it became increasingly clear that wind shear was responsible for a number of fatal aircraft accidents. Initially, many scientists believed that gust fronts had produced this wind shear. During the late 1970s, the FAA supported the development by NSSL scientists of the Low Level Wind Shear Alert System (LLWAS), a ground-based instrument network designed to detect gust-front wind shear at airports (Goff, 1980). However, scientific analyses of the 1975 crash of Eastern Flight 66 at New York and two other air-carrier accidents that occurred within the next year suggested that a short-lived, much smaller phenomenon, which came to be known as the microburst, might be responsible (Fujita and Caracena, 1977).

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The first authenticated identification of a microburst with Doppler radar was made in 1978 by University of Chicago scientists using radar equipment from the National Center for Atmospheric Research (NCAR) in the Northern Illinois Meteorological Research on Downbursts (NIMROD) program (Fujita, 1979). The Joint Airport Weather Studies (JAWS) program, conducted in the Denver area by NCAR and the University of Chicago in 1982, produced conclusive evidence on the frequency, radar detectability, and key characteristics of microbursts (McCarthy, Wilson, and Fujita, 1982). Observations of more than 100 microbursts during JAWS established that they typically are a short-lived phenomenon, with an average lifetime of 10 minutes, that can be produced by relatively innocuous-looking convective clouds as well as by thunderstorms. It was found that microbursts typically have a characteristic pattern in the Doppler surface velocity field that is readily identifiable to experienced radar meteorologists. The JAWS researchers also found that, in certain situations, surface outflows in Denver that were identifiable with Doppler radar at ranges up to 50 km occurred where there was not enough rain to wet the ground. These "dry microbursts" exhibited few visual clues for pilots.

These research results led to a recommendation to FAA to develop a wind-shear detection system based on Doppler weather radar. A number of factors were identified that should be addressed, such as suppression of ground clutter, radar scanning strategies to provide adequate measurement rates and storm information, siting compatible with user needs and storm outflow characteristics, automated detection algorithms for various wind-shear hazards, and definition of products that would meet the needs of pilots and air traffic controllers.

It was clear from JAWS data that, although the NEXRAD radars had the sensitivity to detect microburst wind shear, the planned NEXRAD update rate for surface measurements (once every 5-6 minutes) and siting (often many miles from an airport) were inadequate for observing microbursts and surface outflow characteristics. Since the basic NEXRAD mission would have been significantly compromised by the changes required for effective microburst detection, the FAA decided to develop a dedicated Doppler weather radar system for detecting wind-shear in the vicinity of airports.

3. USER NEEDS

The Classify, Locate, and Avoid Wind Shear (CLAWS) project, conducted at Denver's Stapleton International Airport in the summer of 1984, provided important insights into user needs for a TDWR system (McCarthy and Wilson, 1985). CLAWS was a prototype, real-time microburst forecast and warning service operated by NCAR scientists to demonstrate the efficacy of operational Doppler-based wind-shear detection and warning. Air traffic controllers at Stapleton worked closely with meteorologists in the tower and at a radar site northwest of the airport. During six weeks in July and August, the team issued 30 microburst advisories and five warnings of lines of microbursts.

Reports from pilots who received the advisories indicated that their main concern was with wind shear in an approach-and-departure corridor along the runways and up to three miles out from the ends of the runways. The pilots preferred a simple message identifying the nature of the wind shear, its severity, and its location relative to the runway. CLAWS also established that aircraft operational efficiency would benefit substantially if air traffic control supervisors could receive advance warning of wind shifts due to gust fronts that would result in a change in runway operations. This operational benefit means that, in addition to improving safety, TDWR will reduce weather-related delays.

To continue and expand the working relationship that developed between wind-shear researchers and users of their advisories during CLAWS, the FAA established a user working group that included pilots, air traffic controllers, FAA officials, and researchers. This group has worked to define hazardous weather information needs of pilots and controllers and to help develop procedures and terminology for disseminating information and developing products and displays.

4. AUTOMATING THE TDWR SYSTEM

Although CLAWS demonstrated the operational feasibility of a Doppler-based wind-shear warning system, it was clear that it was not practical for an operational system to require the services of meteorologists to translate radar data into wind-shear alerts. As a result, a great deal of research and development has been focused on automating wind-shear detection and warning by using algorithms that allow the computer to recognize radar patterns associated with wind shear and automatically issue a warning of its presence and intensity at a particular location. A major part of the TDWR effort has been devoted to developing and testing an automated system with products that will augment operational efficiency as well as helping pilots avoid hazardous weather (Table 1).

In parallel with JAWS and CLAWS, the FAA carried out studies to identify processing equipment and automatic detection algorithms for TDWR. A transportable testbed Doppler radar (Evans and Johnson, 1984), designed to operate as a NEXRAD or TDWR, was used to collect data at Memphis,

Table 1. Planned TDWR Products

Initial Products

1. Microburst detection--identifies surface outflow divergence pattern that indicates microburst has reached the ground and provides microburst location with respect to runways and runway component wind-speed loss

2. Gust front detection--identifies strong horizontal convergence zone, indicating boundary of large-scale thunderstorm outflow, wind change across front, and location with respect to runways and runway component wind-speed gain

3. Wind shift prediction--predicts when a gust-frontal wind shift will affect the airport terminal and gives wind change after gust frontal passage and predicted time of change

4. Precipitation--Provides graphic display of precipitation for tower and TRACON supervisory positions in terms of six levels of reflectivity

Future Products

5. Storm movement prediction--predicts positions of significant storm cells using a cell tracking algorithm

6. Turbulence--estimates turbulence in precipitation areas, using the second moment of the Doppler spectrum and other storm features

7. Tornado detection--provides the location of tornadoes, using the tornado vortex signature

8. Microburst prediction--gives a warning of microburst impact to the surface, using developing techniques that look at features well above the surface

9. Convection initiation--predicts where and when a thunderstorm cell will form with respect to the airport location, using techniques currently being explored

Tennessee, in 1985; Huntsville, Alabama, in 1986; and Denver in 1987 and '88. The Memphis and Huntsville studies demonstrated that "wet" microbursts occur frequently in these humid southeastern locations with heavy rain from thunderstorms. Compared with the Denver observations, these southeastern observations showed some differences in precursor features and a decreased occurrence of lines of microbursts.

The microburst algorithm development effort initially focused on detecting a characteristic microburst signature in the Doppler ground-level velocity field. An automatic detection algorithm was developed that showed promising results in tests with the Memphis and Huntsville data (Merritt, 1987). However, it appeared that this approach might not be capable of meeting the FAA objective of a 1-minute advance warning to aircraft before encountering hazardous wind shear. Thus investigations were conducted into microburst precursor features that might be used in algorithms to improve the timeliness of warnings. The CLAWS program had shown that, under some circumstances, certain features aloft in a storm indicated that a microburst was imminent at a given location. These features included convergence at 20,000 to 30,000 feet with air flowing into a downdraft, rotation of the downdraft, and water mass descending from the cloud. When these features aloft were observed, warnings were issued as soon as a surface microburst outflow was observed instead of waiting for it to reach a predetermined hazardous level.

These insights from CLAWS, together with results from scientific studies of Denver and Huntsville microbursts, were used to refine an algorithm that identifies microburst features aloft as well as detecting surface outflow (Campbell, 1987). The current version of this algorithm achieves a degree of early warning of microburst outflows by issuing a microburst warning when a less-than-hazardous outflow exists if certain features aloft have been detected. Research is continuing into the time history of various microburst precursor features in various meteorological regimes to determine whether reliable microburst predictions can be issued on the basis of precursors alone.

Although microburst detection is the primary concern of TDWR research and development, wind shear and wind shifts produced by gust fronts are also of interest. Gust fronts may be several miles long and persist over tens of minutes, and they often produce a change in wind direction and/or speed. This change typically occurs over a distance of 1 or 2 miles perpendicular to the gust front. An algorithm developed to detect gust fronts and forecast their future position with NEXRAD has proved effective for detecting gust fronts associated with severe storms in Oklahoma. This algorithm has been adapted for use with TDWR by making adjustments to cope with the TDWR/airport geometry, the characteristics of gust fronts and wind shifts in various geographical areas, and the need for reliable prediction of gust-front wind shifts (Smith et al., 1989). The current algorithm searches for the convergent winds that characterize the leading edge of a gust front and estimates the gust front motion and the anticipated wind shift from the Doppler velocities behind the gust front. By tracking the location of the gust front over time, the algorithm predicts its future location and thus anticipates wind shifts at the airport.

5. RECENT RESEARCH AND DEVELOPMENT

1987 TDWR Testing at Denver. In the summer of 1987, the FAA sponsored an experiment designed to validate the microburst algorithm and provide a product that can be communicated by air traffic controllers and understood by pilots. It was conducted in the vicinity of Denver's Stapleton International Airport by Lincoln Laboratory, NSSL, and NCAR, with participation by the University of Chicago and the University of North Dakota. The TDWR testbed radar, installed at nearby Buckley Air National Guard Base, was the primary detection radar. Objectives of the 1987 test were:

- to refine the algorithms further
- to train scientific staff in use of the algorithms and development of products
- to develop air traffic control displays
- to use dual Doppler radar to further the ground truth information by comparing automatic detection with scientists' independent assessments of microbursts.

The 1987 TDWR experiment was off-line--data were examined in real time, but no operational wind-shear warnings were produced. The algorithms were run on Lincoln Laboratory data to identify microburst events. Data were collected on more than 400 microbursts. The researchers established "ground truth" by examining radar observations from three Doppler systems as well as data from an observing network that included the LLWAS stations, the Lincoln Laboratory mesonet, and other automated ground-based stations. Then the algorithm output was scored against ground truth.

1988 TDWR Testing at Denver. In July and August 1988, FAA conducted an operational TDWR demonstration in the Denver area, with participation by the FAA Technical Center, the Department of Transportation (DOT) Transportation Systems Center, NCAR, Lincoln Laboratory, NSSL, and the University of North Dakota. Four automated products--microburst detection, gust front detection, wind shift prediction, and precipitation--were displayed in real time in the Stapleton control tower and terminal radar approach control (TRACON). Air traffic controllers transmitted alerts to pilots, who provided feedback on their operational usefulness via pilot reports (PIREPS) and pilot questionnaires. Alphanumeric displays (Fig. 1) were provided to tower controllers and TRACON supervisors. Tower and TRACON supervisors also had access to geographical situation displays (Fig. 2).

The radar detected 206 microbursts and 207 gust fronts during the operational demonstration, including 52 microbursts in the warning region around the airport. Very preliminary analyses indicate that the system detected 90% of all microbursts with wind changes greater than 10 m/s and 97% of the microbursts with wind shears greater than 15 m/s.

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 1. Alphanumeric display example. For an aircraft arriving on Runway 35 Left (35 LA), the message is "UNITED 226, MICROBURST ALERT (RUNWAY 35 LA), THRESHOLD WIND 030 AT 23, 55 KNOT LOSS, 1 MILE FINAL, CENTERFIELD WIND 190 AT 16, GUST 25."

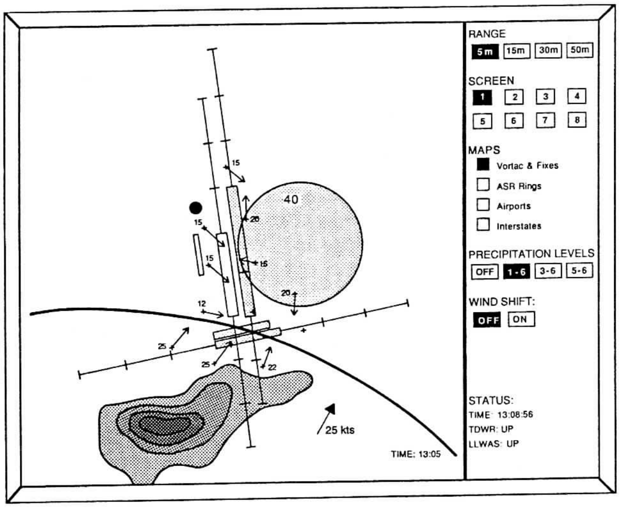

Figure 2. Geographical situation display used in the control tower and TRACON. A microburst is displayed as a circle, impacting Runways 35R/17L. A gust-front wind shift is depicted as a curved line intersecting the east/west runways. Levels of intensity in a precipitation cell to the southwest of the airport are shown in various shadings. LLWAS wind vectors are displayed for each of the 12 sites.

The gust front algorithm provided warnings of 70% of the gust fronts that impacted the airport (i.e., those with wind changes exceeding 10 m/s in locations that called for a wind-shear warning). Warnings were provided for 86% of the strong (wind change of at least 15 m/s) gust fronts that impacted the airport. Approximately 45% of the gust fronts were detected reliably enough to make forecasts of the anticipated location; for these, the probability of a correct 20-minute forecast was 83% (Klingle-Wilson et al., 1989). The reliability of these forecasts allowed the tower supervisors to plan effective runway usage, and the supervisors cited the forecasts as a particularly useful feature of the system.

The operational utility of the system was assessed in terms of both the warnings provided to pilots and its usefulness to air traffic controllers. Preliminary results indicate that, in all cases, warnings of hazardous wind shear were provided to the pilots at least 1 minute in advance of a wind-shear encounter and that the wind-shear intensity estimates were generally accurate. On July 11, when an extremely severe microburst with peak velocity changes exceeding 80 knots occurred off the approach end of runways 26L and 26R, five aircraft received timely warnings and executed missed approaches. However, it was noted in this case and several others that additional avoidance training for pilots and improved communication between controllers and pilots are needed.

On the basis of the successful operational demonstration, the FAA is proceeding with procurement of the initial 47 TDWR systems. Future development work will include fine tuning the microburst algorithm to provide earlier termination of the alert when the microburst becomes large enough so it is no longer hazardous. Flight crew training in responses to microburst alerts will be augmented, and the effectiveness of information transfer from the system to controllers and pilots will be improved.

6. TERMINAL NEXRAD

Although the wavelengths, location, and operation of NEXRAD and TDWR will be different, these two systems will use similar hardware. The TDWR wavelength will be 5 cm. The 10-cm NEXRAD is a long-range system with less attenuation and more penetration power, but that power is not needed for the 50-mile radius to be covered by TDWR.

A contract for the NEXRAD systems was awarded to Unisys Corp. in December 1987. Because of the pressing need for wind-shear detection at major air-carrier terminals, the FAA plans to divert 16 NEXRAD systems for use at airports until TDWR systems are delivered. These "Terminal NEXRAD" systems, which will utilize a special terminal software package, will provide interim wind-shear detection and warning until a network of TDWR systems comes on line.

7. TDWR DEVELOPMENT

The TDWR development effort is addressing a number of issues. The principal ones concern the following performance objectives that the FAA has established for an optimal ground-based wind-shear detection system:

- Detecting most microbursts while having a low false-alarm rate
- Estimating the severity of the wind-shear hazard
- Providing timely warnings of wind-shear hazards
- Automated delivery of products to users.

Detecting most microbursts while having a low false-alarm rate. The TDWR system must detect hazardous wind-shear events with high probability while maintaining a low probability of false alarms. Three basic issues that concern probability of detection are:

- Radar observability--the ability of the TDWR to sense wind-shear events
- Data integrity--the ability of the TDWR to minimize various kinds of measurement errors
- Algorithm performance--the ability of automated algorithms to declare wind-shear events that are sensed by the radar.

The TDWR development program has addressed a number of technical issues for basic Doppler measurements that have been recognized and characterized by radar meteorologists. Ground clutter is a major issue, as radar returns from objects near the airport can be considerably stronger than the return from a wind-shear event. Clutter measurements have been made at a number of airports to verify that the TDWR antenna characteristics and signal processing capability can successfully cope with clutter problems. Many clutter-mitigation techniques developed for FAA air surveillance radars are being applied to the TDWR system. These techniques have been tested further with the FAA TDWR testbed system. Another concern was that radar returns from storms at long range might obscure weather features near the airport. Automatic algorithms are being developed and tested to adaptively choose radar waveforms that will minimize this problem.

A major effort to validate TDWR's capability for wind-shear detection has used data from multiple radars, networks of surface weather stations, and reports from aircraft near the test site. The capability of the radar to measure wind shear was assessed by comparing single Doppler detections with observations made by meteorologists using multiple Doppler and surface network data . All measurements using the TDWR testbed radar have been made at sites with networks of 36 to 80 surface weather-measuring systems spaced approximately 1 to 2 miles apart. The detections made by a skilled meteorologist using single radar data are compared with detections made using data from the surface network as well as two Doppler radars to determine if wind-shear events have been missed due to insufficient sensitivity, asymmetry of wind fields, and/or poor radar siting/scanning. Results from Mephis, Huntsville, and Denver suggest that more than 97% of the microburst events were detectable by a single radar, with most of the missed cases corresponding to weak and generally short-lived events.

The capability of the automated algorithms to detect wind-shear events is assessed by comparing the algorithm results with data analysis by skilled meteorologists. To further ensure the quality and uniformity of the meteorologists' interpretations, a working group from NCAR, NSSL, and Lincoln Laboratory periodically reviews the raw data and interpretations. A variety of storm situations is used, and all available measurements from selected days are analyzed to ensure that all phases of storm development are considered. The current data base for scoring includes more than 100 microburst events from Huntsville and more than 200 microburst events from Denver as well as almost 250 gust-front events from Denver. Table 2 shows the detection results, which indicate that detection is very reliable for the strongest wind shear events, with overall microburst detection performance meeting the FAA requirement of 90% probability of detection (Campbell, Merritt, and DiStefano, 1989; Klingle-Wilson et al., 1989). The 1987 Denver results were obtained before the algorithms (especially the gust front algorithm) had been fully adapted to the Denver wind shear characteristics. The false alarm rate is well within the requirements.

Wind-shear Intensity Estimation. An ideal wind-shear detection system would depict winds over the airport domain in three dimensions, but this would require two or three Doppler radar installations for each airport. Research on aircraft performance suggests that approximately 75% of the microburst wind shear hazard results from the longitudinal component of the wind that the aircraft encounters, specifically an increase in tailwind. About 20 to 25% is caused by the downdraft component, and a small fraction results from the crosswind component. Thus accurate headwind-tailwind measurement will address most of the hazard.

Table 2. Wind-shear detection results

MICROBURST DETECTION

Data	Probability of detection* DV<20 m/s	DV>20 m/s	Total	Probability of false alarm
Huntsville 86	88%	100%	91%	5%
Denver 87	90%	99%	92%	5%
86 & 87 combined	90%	100%	92%	5%
Denver 88*	--	97%**	90%	4%

GUST-FRONT DETECTION

Data	Probability of detection DV< 15 m/s	DV> 15 m/s	all	Probability of false alarm
Denver 87***	54%	73%	58%	44%
Denver 88	73%	91%	78%	2%
88 at airport	64%	86%	70%	0

*preliminary results based on 5 days
** DV > 15 m/s
*** used preliminary algorithm which was then substantially refined for 88 testing

The issue is whether the headwind-tailwind component can be measured accurately with a single Doppler radar that scans all runways and flight paths but can only measure the radial horizontal outflow component. If the radar could be sited so that it could look down the centerline of every runway, it would provide perfect headwind-tailwind measurements in every situation. But the normal configuration of airport runways does not offer such a location; the radar will always have to look at some portions of runways laterally instead of longitudinally. Additionally, an off-airport location allows the radar to scan the mid-levels over the airport for microburst features aloft.

If microburst outflows were equally strong in all directions, this off-axis viewing angle would not be a problem--the outflow in any direction would equal the headwind-tailwind component. Current evidence indicates that most microbursts have some variation in longitudinal velocity difference with viewing angles, with a maximum-to-minimum velocity ratio of roughly 2:1. Table 2 shows that the performance of the detection system improves with the strength (and hence with the hazard level) of the microburst outflow. Although a few microburst events, especially weaker ones, might not be detected by the system because of their asymmetry, the radar observability results discussed above show that this did not represent an operationally significant issue in the tests to date.

Providing timely warnings. The TDWR system must generate timely warnings of hazardous wind-shear events, especially microbursts. The FAA requires that the TDWR provide a 1-minute warning for hazardous wind-shear events. This involves three issues: scan strategy, surface outflow detection, and features aloft.

The TDWR scan strategy produces one surface elevation scan per minute. It also provides a scan aloft of the operational region to an altitude of at least 20,000 feet (6 kilometers) every 2.5 minutes. This strategy is intended to provide frequent updates of surface outflow while monitoring for features aloft that indicate that a microburst is imminent.

Microbursts are recognized primarily by surface outflows. An outflow of at least 10 m/s (approximately 20 knots) will be declared a microburst if it is correlated with a previous surface outflow in the same area or with certain features aloft. The algorithm also can declare a microburst with an outflow below 10 m/s when certain features aloft are detected. When the algorithm recognizes features such as a descending high-reflectivity water mass associated with rotation or convergence aloft, the algorithm may determine that a microburst is imminent even though the surface outflow is weak (7.5 to 10 m/s).

The timeliness of microburst warnings was examined for five days of Huntsville '86 data and five days of Denver '87 data for a total of 124 microburst events. The microburst recognition algorithm declared 91% of the microburst events and the declaration was made an average of 0.4 minutes prior to the point at which the outflow strength reached 10 m/s. Thus the algorithm was timely with respect to microburst outflows reaching this level of intensity. Preliminary analysis of the 1988 operational demonstration test results suggests that the use of information aloft provided an earlier warning for approximately 60% of the observed microburst events than would have been provided using surface features alone (Campbell and Isaminger, 1989).

Full automation of the system. The products required for the TDWR program--microburst detection, wind-shift detection, and wind-shift prediction--will be fully automated. Automated transmission of TDWR products is a long-term goal, as transmission of hazardous weather information by controllers interferes with their other duties. Consequently, the FAA is rapidly developing the capability to transmit weather information to aircraft automatically, using a data link that is part of the Mode-S system, a new transponder and surveillance system that was recently adopted as the standard international air traffic surveillance system. The FAA will receive its first production Mode-S ground stations in 1992 and will complete their deployment by 1996. The initial operational capability of the Mode-S data link will support transmission of alphanumeric messages and locations of windshear events. Research is in progress to develop and secure international agreement on a format for transmitting weather images such as those that appear on the TDWR geographical situation displays. In conjunction with other data link studies, product formats and display options (for example, north at the top of the display versus the aircraft heading at the top) will be investigated, working closely with pilots.

8. FUTURE IMPROVEMENTS IN PRODUCTS

Microbursts. The current algorithm has the ability to recognize microburst precursors for high-reflectivity microburst events. Initial results for 14 high-reflectivity events from Huntsville and Denver showed that the algorithm produced microburst precursor warnings an average of 4.8 minutes prior to the onset of the surface outflow. Work is in progress to improve the performance of the algorithm in recognizing precursors for medium- and low-reflectivity events. A related area involves the prediction of microburst outflow strength. It may be possible to predict the strength of high-reflectivity events on the basis of such indicators as the strength of convergence aloft and the height of the parent storm cell.

Gust Fronts. The gust front algorithm that is part of the initial TDWR capability detects convergent wind shear associated with a gust front. This initial algorithm has achieved good success in detecting strong gust fronts that exceed 40 knots. Research is under way to improve detection of weaker gust fronts that are not a safety hazard but that sometimes require runway changes. This will be achieved by incorporating additional storm features into the algorithm much as has been done for the microburst detection algorithm.

Tornadoes. Tornadoes are hazardous to aircraft in the air and on the ground, as well as to terminal facilities. In 1987, the TDWR testbed radar clearly displayed the characteristic Doppler velocity signature for the vortex of a tornado in Denver at the nominal TDWR-to-airport range of 7 nautical miles. Work is under way to adapt a NEXRAD automatic algorithm for detection of tornado vortices to TDWR.

Turbulence. Turbulence in the terminal area has caused of a number of aircraft accidents. It now appears that most accidents where turbulence was encountered near the surface were primarily due to microbursts, with turbulence as a contributing factor. The FAA has conducted tests of automatic turbulence detection at altitudes above 15,000 feet since the late 1960s, and a turbulence detection algorithm has been developed for NEXRAD. Research on turbulence in the terminal area is under way to identify modifications to the NEXRAD algorithm that will be necessary to provide reliable detection in the TDWR context. This research has included coordinated tests using radar and instrumented aircraft at the TDWR testbed sites at Memphis, Huntsville, and Denver.

Convection initiation. In field research at Denver, NCAR scientists found that about 80% of the thunderstorms observed formed along lines where low-level winds flowing from different directions converge, and that thunderstorms frequently appear soon after convergence develops. The convergence can be detected with Doppler radar, and it should be possible to use Doppler observations to predict the formation of thunderstorms before they appear.

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