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Terminal Doppler Weather Radar Operational Test and Evaluation Orlando 1990

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9 April 1991

Lincoln Laboratory

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16. Abstract

Lincoln Laboratory conducted an evaluation of the Federal Aviation Administration (FAA) Terminal Doppler Weather Radar (TDWR) system in Orlando, Florida during the summer of 1990. In previous years, evaluations have been conducted at airports in Kansas City, MO (1989) and Denver, CO (1988). Since the testing at the Kansas City International Airport, the radar was modified to operate in C-band, which is the intended frequency band for the production TDWR systems. The objectives of the 1990 evaluation period were to evaluate TDWR system performance in detecting low-altitude wind shear, specifically microbursts and gust fronts, at the Orlando International Airport and in the surrounding area; to refine the system's wind shear detection capabilities; and to evaluate elements of the system developed by the contractor, which were new for this C-band system and therefore not available for evaluation in previous years. Some performance comparisons are made among results from the vastly different weather environments of Denver, Kansas City, and Orlando.

The report discusses and presents statistics for the performance of the system in detecting and predicting microbursts and gust fronts. A significant use of the prediction capability is its potential use for air traffic control (ATC) personnel to plan airport operations when hazardous weather is predicted. Issues such as low-velocity ground clutter (from tree leaves, road traffic, and dense urban areas) that affect prediction performance are discussed, along with possible software modifications to account for them. Finally, the ATC personnel and pilots who took part in the evaluation provide the users' perspectives on the usefulness of the system's capabilities.

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ABSTRACT

Lincoln Laboratory conducted an evaluation of the Federal Aviation Administration (FAA) Terminal Doppler Weather Radar (TDWR) system in Orlando, Florida during the summer of 1990. In previous years, evaluations have been conducted at airports in Kansas City, MO (1989) and Denver, CO (1988). Since the testing at the Kansas City International Airport, the radar was modified to operate in C-band, which is the intended frequency band for the production TDWR systems. The objectives of the 1990 evaluation period were to evaluate TDWR system performance in detecting low-altitude wind shear, specifically microbursts and gust fronts, at the Orlando International Airport and in the surrounding area; to refine the system's wind shear detection capabilities; and to evaluate elements of the system developed by the contractor which were new for this C-band system and therefore not available for evaluation in previous years. Some performance comparisons are made among results from the vastly different weather environments of Denver, Kansas City, and Orlando.

The report discusses and presents statistics for the performance of the system in detecting and predicting microbursts and gust fronts. A significant use of the prediction capability is its potential use for air traffic control (ATC) personnel to plan airport operations when hazardous weather is predicted. Issues such as low-velocity ground clutter (from tree leaves, road traffic, and dense urban areas) that affect prediction performance are discussed, along with possible software modifications to account for them. Finally, the ATC personnel and pilots who took part in the evaluation provide the users' perspectives on the usefulness of the system's capabilities.

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1. INTRODUCTION AND EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) Terminal Doppler Weather Radar (TDWR) program conducted an aviation weather hazard measurement and operational demonstration program during the summer of 1990 near the Orlando International (MCO) airport. A principal objective of the 1990 measurement program was to test and refine techniques for the automatic detection of low-altitude wind shear phenomena (specifically microbursts and gust fronts), turbulence, tornados and heavy rain in a weather environment characterized by heavy, daily thunderstorms. The Orlando/Tampa area has the highest incidence of thunderstorm days in the United States. A second important objective of the test was to validate contractor elements of the TDWR system (i.e., C-band operation, user display interface, velocity unfolding, and point target editing algorithms) which had not been used in previous experiments.

The operational evaluation took place between June 18th and August 28th, 1990. The TDWR testbed was located in Kissimmee, FL approximately five miles due south of the Orlando airport. During the hours from 12 noon until 7 pm (local time), the testbed was operated in the TDWR (i.e., unmanned)[1] mode, automatically detecting weather hazard phenomena, generating appropriate weather products and warnings, and transmitting this information to the ATC personnel via various displays in the Tower/TRACON complex.

The specific objectives this year were to evaluate:

1. Microburst detection,
2. TDWR warning functions,
3. Gust front detection and wind shift prediction,
4. TDWR as a planning tool,
5. New products, such as storm movement and prediction,
6. C-band operation, including the use of 0.5-degree beams,
7. Contractor-developed TDWR data quality algorithms (velocity dealiasing and point target rejection), and
8. The TDWR GSD product display formats and user interface.

This report provides a preliminary summary of the results of the measurements and addresses the product evaluation. The objective of the report is to highlight issues that should be addressed in time for the 1991 operations, also to be held in Orlando. Subsequent reports will describe the results of detailed investigations into various issues that arose during the testing.

The remainder of this section summarizes the background of the program, the measurement system (testbed), with important updates for 1990 and the operations results. Sections 2 and 3 describe the microburst and gust front subsystem performances, respectively. Section 4 discusses several data quality algorithms that were implemented for the 1990 operations. Section 5 reports on ATC personnel training, usage, and impressions of the overall system.

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[1]Although the radar operated in a hands-off mode, at least three personnel were present at all times during the operational hours to monitor system performance and to intervene in the event of a system fault.

A. BACKGROUND

Low altitude wind shear has been the cause of several fatal air carrier accidents in the past two decades. In addition, turbulence continues to cause a number of injuries every year to air carrier passengers and flight crews. One of the major goals of the TDWR program is to provide automatic detection and warning of microbursts, the most hazardous form of wind shear for low altitude aircraft approaching or departing from airports. A microburst is produced by a small-scale but powerful downdraft of cold, heavy air that can occur beneath a thunderstorm or a relatively harmless looking cumulus cloud. As this downdraft reaches the earth's surface, it spreads out horizontally, similar to a stream of water sprayed straight down from a garden hose onto a concrete driveway. An aircraft that is flying 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. Figure 1-1 illustrates the effect of a microburst on aircraft. This particular sequence of events has caused at least 30 aircraft accidents and incidents that have killed more than 500 persons in the United States since the mid-1960s. A recent air-carrier disaster caused by wind shear was the 1985 crash of a wide-body jet airliner at Dallas/Fort Worth that took 137 lives.

Based on wind shear measurement programs in Memphis (1985), Huntsville (1986), Denver (1987), and a successful operational evaluation at Denver in 1988, the FAA awarded a contract for the production of 47 TDWR systems. These systems will be used for operational wind shear detection and warning at major US airports, starting in the early 1990s.

B. MEASUREMENT SYSTEM

Figure 1-2 shows the locations of the various ground weather sensing systems used in the 1990 measurement program. The TDWR testbed, developed and operated by Lincoln Laboratory of the Massachusetts Institute of Technology (MIT), was the primary data collection tool for the TDWR measurement program. This radar (designated by the letters TDWR (FL-2C) in Figure 1-2) used a 28-ft.-diameter antenna and a powerful signal processing system to record, process and display the Doppler measurements and wind shear products. The radar was modified prior to the demonstration period to operate at an RF frequency in C-band instead of S-band as in past years. This was necessary in order to evaluate the system in the actual frequency range where the production TDWR will operate. The signal processing techniques used (e.g., digital filters for ground clutter rejection, automatic selection of signal waveforms, etc.) were functionally equivalent to those which will be used in the operational systems which the FAA is procuring. A system of several computers executed the TDWR wind shear detection and product generation algorithms in real time and presented the results on a variety of displays at the FL-2C site and in the Orlando ATC facilities during the demonstration period.

A C-band Doppler radar system operated by the University of North Dakota (UND) also participated in the summer measurement program. This radar (designated UND in Figure 1-2) was located about six miles east of MCO giving coverage of the airport at a 90-degree angle from FL-2C. This provided excellent dual Doppler radar coverage for off-line data analysis. A third C-band Doppler radar, operated by the MIT Department of Earth and Planetary Sciences (designated MIT in Figure 1-2), was intended to provide triple-Doppler coverage for off-line analysis.

The airport surveillance radar (ASR) testbed developed and operated by Lincoln Laboratory was located near the south end of the runways. This S-band (designated by the letters ASR (FL-3) in Figure 1-2) radar uses an ASR-8 antenna and transmitter and a wideband recording system to record all of the data measured by the system from the antenna's upper and lower beams. A Lincoln-developed signal processing system produced estimates of the storm reflectivity and surface wind velocities as well as microburst alarms generated by an experimental algorithm. The ASR provided rapid update measurements (several per minute) on storm reflectivity and on some of the microburst outflows near the FL-3 site. FL-3 operated during August and September in an operational mode with the ATC at Orlando. [1] This was the first time FL-3 operated in this mode.

A network of 30 automatic weather stations (one of which is shown in Figure 1-3) located in open areas collected data on temperature, humidity, pressure, wind speed and direction, and rainfall 24 hours a day. Data were transmitted from each of the stations to the GOES-East geostationary satellite every half hour. The data were downlinked and recorded for later analysis. The wind data from the weather stations is used to validate the wind shear detection performance of the Doppler radars and for the TDWR/Low-level Wind Shear Alert System (LLWAS) integration studies, while the other weather station data is used for meteorological analyses of the wind shear events.

Additional information on the surface wind characteristics during wind shear events was provided by data from six LLWAS anemometers located around MCO. From 1 July to 13 September 1990, National Severe Storms Laboratory (NSSL) personnel made soundings of the atmosphere vertical structure during periods of significant weather using an NSSL-developed weather balloon sounding system.

Between 16 June and 28 August 1990, UND operated its Cessna Citation II jet aircraft equipped with instruments to measure the wind, temperature and humidity conditions near storms as well as the numbers and sizes of cloud droplets and raindrops encountered within storms. This year the Citation was equipped with a miniature version of the TDWR Geographical Situation Display (GSD) to give the pilot a better indication of where the wind shear events were located, thus making it easier to fly precise paths near and into the events. The Citation furnished data on the near surface and upper air environments associated with wind shear events, as well as direct measurements of turbulence to confirm the accuracy of Doppler radar based wind shear and turbulence detection algorithms.

C. OPERATIONAL CONCEPT AND CONTROLLER PRODUCTS

A very important component of the TDWR development program was the refinement of the operational concept to ensure that the TDWR information will meet user needs. Since the characteristics of the weather environment and the wind shear phenomena can differ in various regions of the country and because there are significant differences in airport configurations, it is important that the planned products be operationally evaluated in a variety of environments. The MCO testing permitted further evaluation of the products tested operationally at Denver in 1988 and in Kansas City in 1989.

During the operational period in Orlando, TDWR data were sent directly to the controllers and supervisors via the same two types of displays used in Denver and Kansas City. These displays were:

1. A Ribbon (alphanumeric) display which presents wind shear hazard messages and warnings to controllers for relay to pilots, and

2. A Geographical Situation Display (GSD) which presents weather data in a graphic format to air traffic supervisors for planning purposes.

While the Ribbon display data format was essentially the same as that used in Kansas City, the GSD had several user interface differences from those used in the previous operations. These modifications were implemented in order to make the testbed GSD resemble, as closely as possible, the displays that are being built for the production TDWR systems.

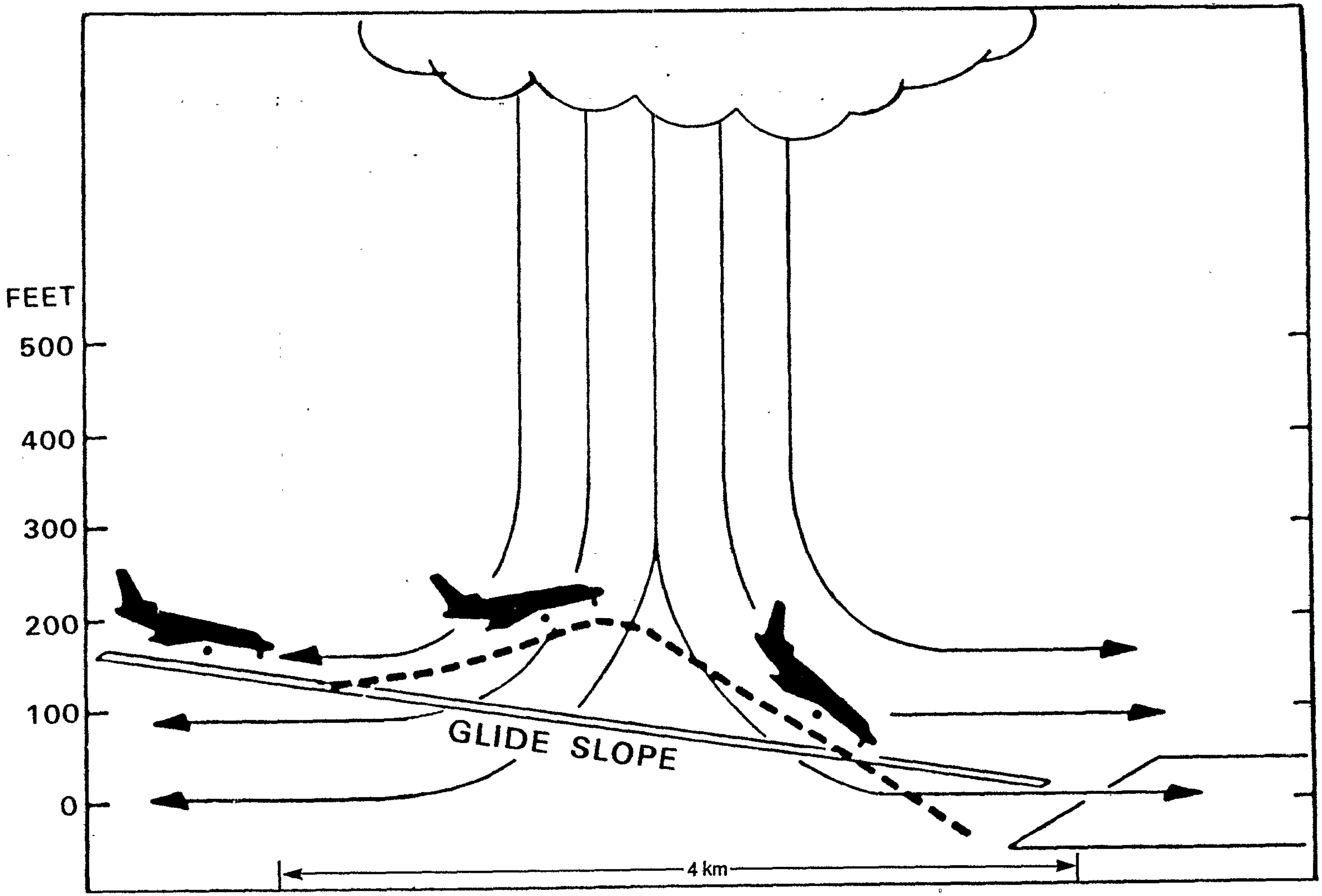


Figure 1-1. Effect of a microburst on a plane flying through it.

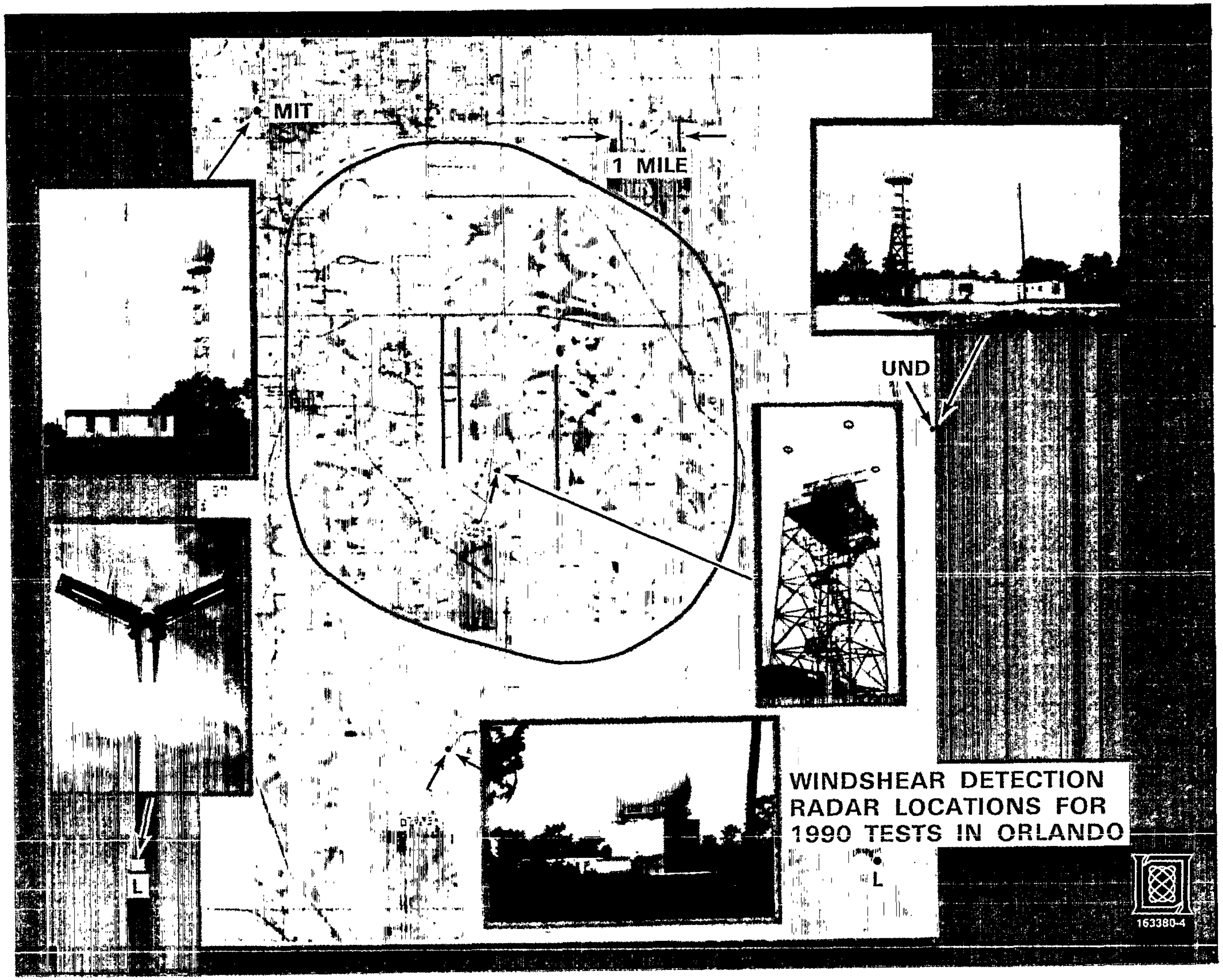


Figure 1-2. Locations of ground weather sensing systems used in 1990 measurement program in Orlando, FL.

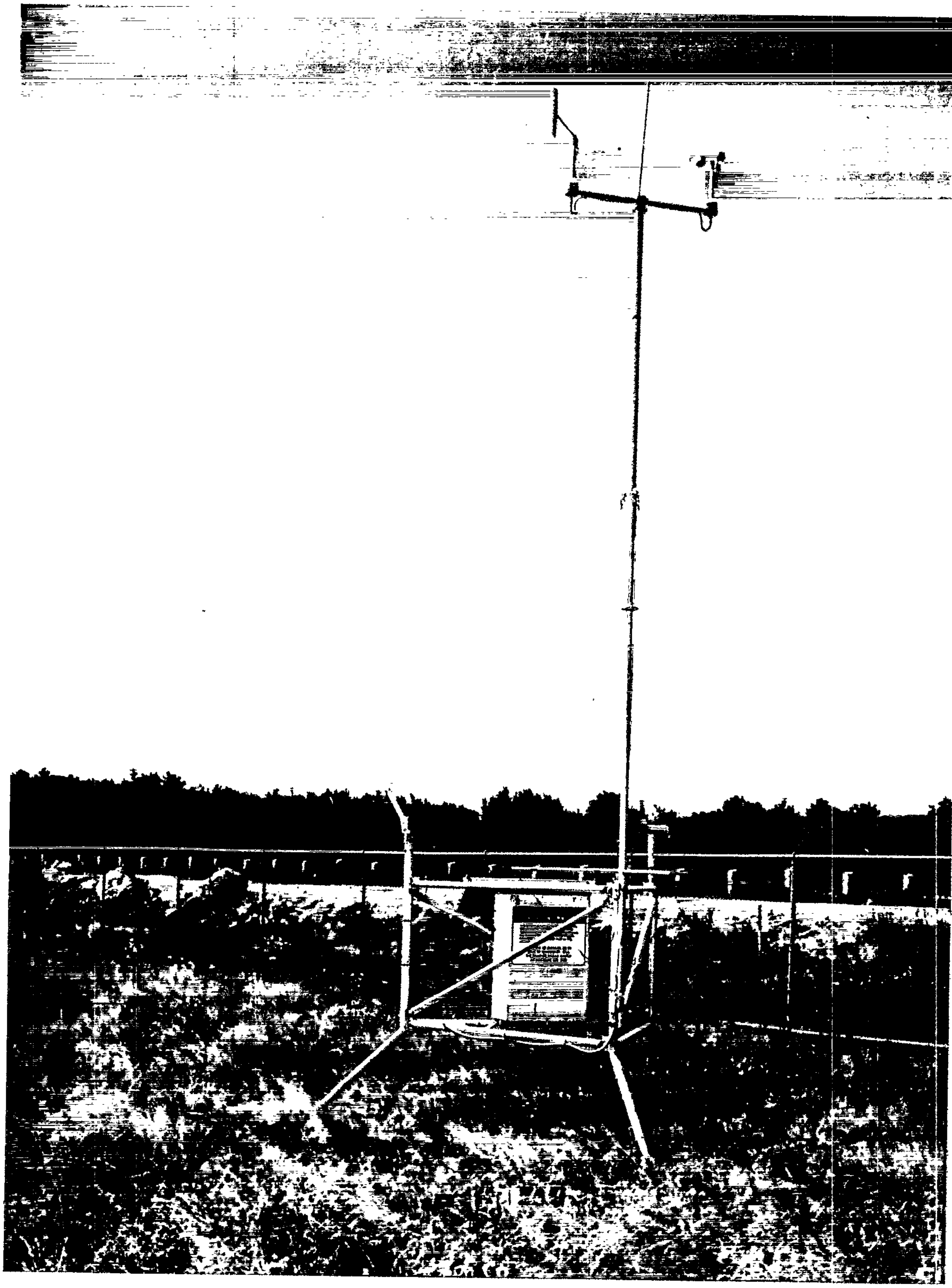


Figure 1-3. Automatic weather stations (also called mesonets) collect data on temperature, humidity, pressure, wind speed and direction 24 hours a day.

1. Ribbon Display

Ribbon displays were provided at several locations in the MCO control tower and at the supervisor's position in the TRACON. Wind shear alert information was presented to the controllers on the ribbon display in alphanumeric format that could be read directly to pilots without interpretation, as shown in Figure 1-4. The alert message describes the affected runway, type of wind shear (strong microbursts were described as a "microburst," gust fronts and weak microbursts as a "wind shear"), the expected headwind change, and the location at which the wind shear will first be encountered along the runway corridor. The specific codes used on the display for alerts were MBA for microburst alert and WSA for wind shear alert.

The hazard location information was quantized into six areas relative to the runway centerline: the runway itself and a series of rectangular boxes along the runway centerline located 1, 2, and 3 nmi from the approach end of the runway and 1 and 2 nmi from the departure end of the runway. A schematic of the safety corridors is shown in Figure 1-5. The width of each rectangle about the extended runway centerline could be varied based on operational experience. A width of 1 nmi was used for the MCO testing. The specific codes used on the display to indicate location were MF for *miles final*, MD for *miles departure*, and RWY for *on the runway*. When a microburst (or gust front) shape overlapped at least one rectangular region (these regions are called Arenas in the operational TDWR), an alert was issued for the location at which the wind shear first would be encountered by an aircraft. Section 2C discusses at length the size of the warning boxes in terms of system performance and reliability.

2. Geographical Situation Display (GSD)

The GSD was available to air traffic supervisors for planning purposes, both in the Tower and in the TRACON. All of the TDWR products (microburst, gust front, wind shift prediction, precipitation intensity, and storm tracking) were available on these displays. The microburst and gust front products were always displayed. Wind shift prediction, various levels of precipitation intensity, and storm tracking were selectable products through the user interface. Other features available through the user interface included range from airport, background maps, and precipitation levels to be displayed. The user interface also provided a means of configuring which runway warning messages would be displayed (and in what order) on the various Ribbon displays. This interface was menu driven and was functionally identical to the contractor-designed TDWR GSD. Figure 1-4 shows the GSD and Ribbon display hardware that was used during the demonstration. These same displays were used in the MCO Tower, Tracon and at the FL-2C TDWR testbed.

D. WEATHER MEASUREMENTS RESULTS

Weather conditions in the Orlando area were substantially different than was experienced in Denver and Kansas City. Statistics indicate that the Orlando/Tampa area has the highest incidence of thunderstorms days in the United States, and strong thunderstorms were almost a daily occurrence throughout the demonstration period. Due to a major failure of the testbed antenna subsystem followed by a lightning-induced system failure, the testbed was inoperable from July 16 through August 19. The problem was caused by an incomplete disconnect from the utility. Although these events caused the radar to be down for over half of the period, 58 individual microbursts were detected within 3 nmi of the airport during the times the radar was operational. This compares with only 14 microbursts detected near the Kansas City airport during all of the demonstration period in 1989 and 54 at Denver in 1988.

Most of the detected microbursts in Orlando were associated with dense rain cores and high reflectivity in excess of +50 dBZ. The high reflectivity was largely responsible for the very low probably of false alarm (PFA), observed to be less than two percent. Figure 2-2 shows graphically the frequency of high-reflectivity cells for Orlando as compared to previous years. It is interesting to note that the distribution of radial shears, Figure 2-1, are relatively constant for Denver, Kansas City and Orlando.

1. Microburst Detection Performance

Table 1-1 compares the Orlando microburst detection performance with those of the two previous years at Denver and Kansas City. The Orlando data includes 55 individually definable events scored on active days. The data includes, for those days, all events that reached the 10 m/s threshold. The significant result here is the very low false-alarm rate due primarily to the high reflectivity of 99 percent of the microbursts.

Although the microburst detection algorithm performed very well, the microburst warning product exhibited a significant "overwarning" condition on certain days. Much of the overwarning issue can be accounted for because of the closely spaced parallel runways. The one-half-mile buffer zone on the side of each runway often caused both runways to be alarmed when a microburst was beside one of the runways (or extensions). When this particular event occurred, it was often exacerbated by the fact that the summer winds in Orlando tend to be light and microbursts often sat relatively stationary for 30 minutes or more, and sometimes caused the entire airport to be shut down. Section 2 discusses the overwarning issue in more detail.

Table 1-1.
Comparison of Microburst Performance
in Denver, Kansas City, and Orlando OT&E Periods.

	Denver 1988	Kansas City 1989	Orlando 1990
POD	.90	.96	.95
PFA	.05	.07	.02

2. Gust Front Detection Performance

Table 1-2 compares the current gust front algorithm detection performance in Orlando with data from Kansas City and Denver. The probability of detection (POD) and PFA are for all truthed events. A more detailed breakdown is discussed in Section 3.

There is little difference in the performance for these three years, except for the higher false-alarm rate in Kansas City. This was due in part to ground-level turbulence caused by strong winds blowing over the irregular terrain. It is expected that an advanced algorithm presently under development will help much of this problem. The advanced algorithm is planned to be tested during part of the operation in 1991.

E. OPERATIONS SUMMARY

The primary objectives of the 1990 Operational Demonstration in Orlando were the same as in the past operations at Denver and Kansas City. These were:

1. To evaluate the format and usefulness of the TDWR hazardous weather messages from the users (i.e., ATC personnel as well as pilots) viewpoints;

2. To assess the usefulness of the TDWR products for air terminal operations and planning; and

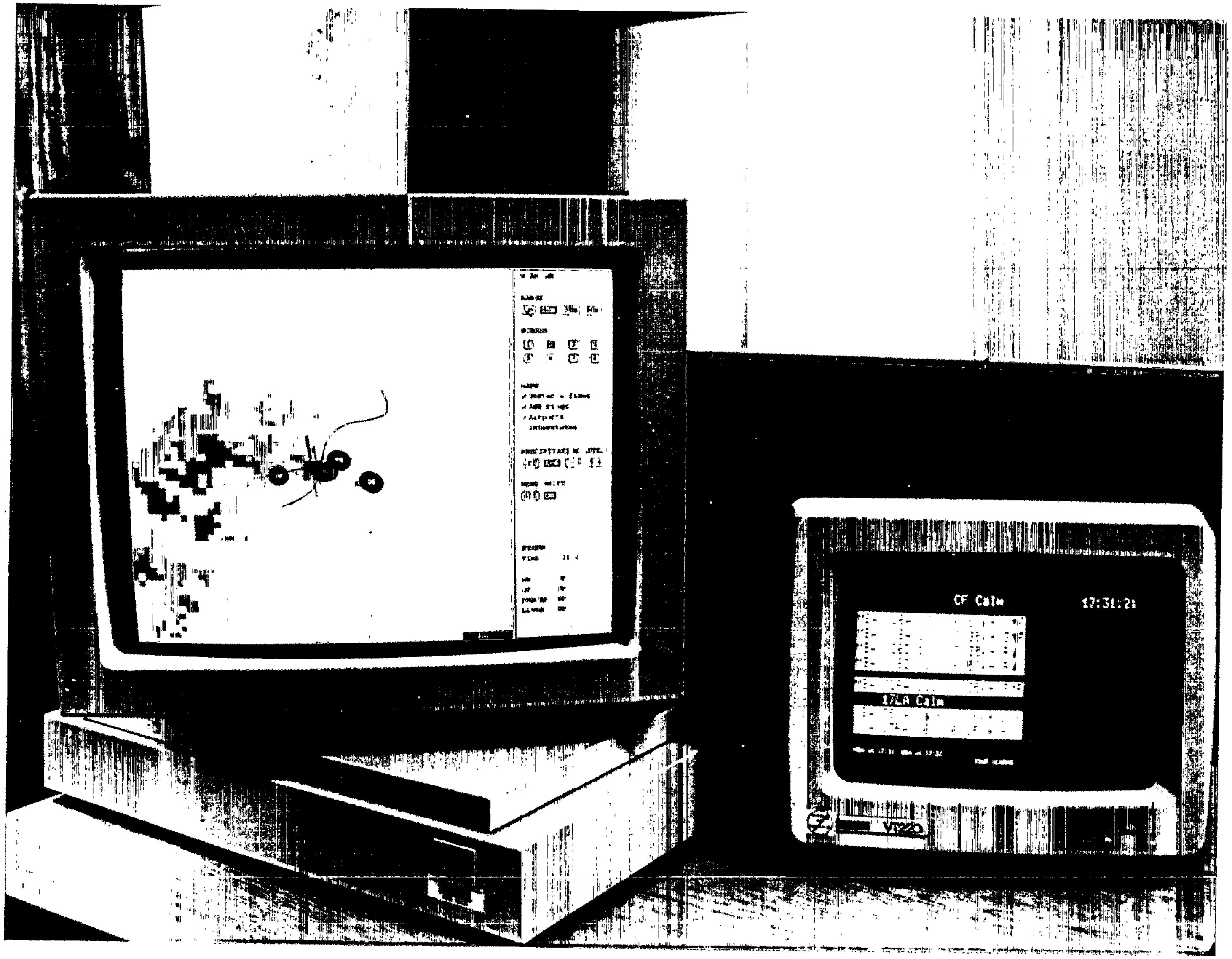
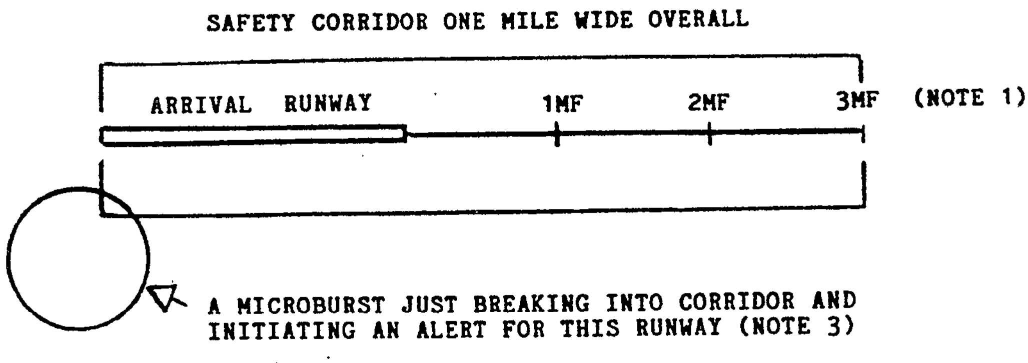
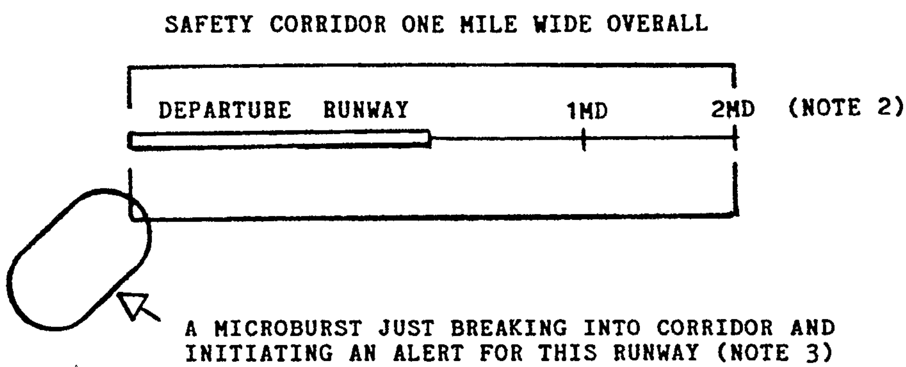


Figure 1-4. Geographical Situation Display (left) and Ribbon display (right) display data in different formats to air traffic control personnel. Information is then relayed to pilots or used for planning runway operations.

FOR ARRIVAL OPERATIONS



FOR DEPARTURE OPERATIONS



NOTES:

(1) 3MF STANDS FOR '3 MILE FINAL'

(2) 2MD STANDS FOR '2 MILE DEPARTURE'

(3) THE SYSTEM SOFTWARE DEPICTED MICROBURSTS IN EITHER OF TWO SHAPES: IN THE SHAPE OF A BAND-AID IF THE SOFTWARE SENSED THAT THE MICROBURST'S OUTFLOW HAD AN ELONGATED AXIS IN SOME DIRECTION AND IN THE SHAPE OF A CIRCLE IF IT DID NOT

Figure 1-5. The safety corridor geometries used during the Orlando 1990 demonstration.

3. To evaluate the TDWR products in the Orlando weather and airport operations environments.

Table 1-2.
Comparison of Gust Front Performance in Denver, Kansas City, and Orlando OT&E Periods.

	Denver 1988	Kansas City 1989	Orlando 1990
POD	.78	.77	.79
PFA	.02	.13	.06

The demonstration in Orlando was similar to the one in Kansas City in that the airport personnel had no previous experience or exposure to the TDWR system, its products, or its operation. Although the basic operational products and procedures were the same as in Kansas City, there were some significant differences that required specific evaluation during the demonstration:

1. The GSD was configured to match that of the actual Raytheon format. This included displayed text, color and shape formats, and menu of display features.

2. The new storm tracking feature was installed and operational during all of the demonstration period.

One problem during the Orlando operation was that the center field wind (CFW) data was to be read from the LLWAS display rather than directly from the TDWR Ribbon display as was done in Denver and in Kansas City. This required the controllers to look at both the LLWAS display and the Ribbon display, a difficult task especially during periods of high activity. On occasion this had a negative impact on the use and evaluation of the TDWR warning products displayed on the Ribbon displays.

In both the Denver and Kansas City demonstrations, the TDWR testbed was operational on a relatively reliable basis during the complete period, giving ATC personnel maximum opportunity to become familiar with the system and its operation. However, at Orlando, the antenna bearing failure and the lightning-induced system failure made the testbed inoperative for approximately half of the total demonstration period. This coupled with the particular Orlando ATC shift configuration, precluded controllers from becoming very familiar with the system. Some controllers were exposed to TDWR operations for only one or two shifts during the total demonstration.

In addition to the radar downtime problems, the system experienced a considerable overwarning condition at times, primarily due to the particular weather environment and system warning thresholds used in Orlando. Unlike Denver and Kansas City, Orlando thunderstorms (and resulting microbursts) were often accompanied by little or no horizontal steering winds. The result was that microbursts often remained relatively stationary for their duration, sometimes as long as 30 minutes. The combination of frequent microbursts, relatively weak advection, and one-half-mile-wide warning buffer zones on each side of the runways and arrival/departure corridors led to several instances of overwarning that the controllers felt degraded traffic operations unnecessarily. The large amount of radar downtime did not allow much adjustment of the warning algorithm during the operational period. Subsequent analysis of the data from the particularly bad events has shown that a modification to the warning algorithm can substantially help the situation. Effort is underway to determine if the modified algorithm can be tested this summer in the 1991 demonstration in Orlando.

Table 1-3 summarizes the results of the testing in Orlando in relation to the test plan objectives. In spite of the significant amount of radar downtime, there was enough wind shear activity to fulfill the principal objectives of performance and product usefulness evaluations. The 55 distinct microbursts detected within the critical area of the Orlando airport during the short time the system was operational provided enough information such that meaningful PODs and PFAs could be compiled. There also was enough data recorded such that substantial analysis of the wind shear algorithms performance in the Orlando environment could be accomplished in time for the 1991 summer experiments. The remainder of this report presents details supporting this summary.

Table 1-3.
Comparison of Test Objectives and Test Results.

Test Objective	Test Results
1. Evaluate microburst detection.	POD = 0.95, PFA = 0.02 for all microbursts that impacted the airport during the period that the radar was operational.
2. Evaluate TDWR warning function.	Message format was easily read and clearly understandable. However, there were several instances of perceived overwarning. Subsequent analysis of the warning algorithm showed an optimization that greatly reduced the overwarning effect.
3. Evaluate gust front detection and wind shift prediction.	POD = 0.79, PFA = 0.06. The gust front detection algorithm performed better than in Kansas City near the airport due to the use of the "overhead tracking" feature that was used in Orlando.
4. Evaluate TDWR planning function.	The TDWR GSD planning products were assessed as "very good" in terms of usefulness. The wind shift prediction and storm tracking functions were particularly useful to the TRACON personnel.
5. Evaluate additional products.	The tornado vortex detection algorithm was implemented during all of the operation, but there were no detections reported from the TDWR or from any other source. No other products were delivered to the Tower operationally.

2. MICROBURST DETECTION PERFORMANCE

This section describes the microburst detection performance of the Terminal Doppler Weather Radar (TDWR) testbed during the 1990 demonstration period in Orlando, FL. Four main topics will be discussed. First, the basic statistics and algorithm performance will be presented, followed by a false-alarm analysis. Next, the issue of microburst alert overwarning, as observed in Orlando, will be discussed. Finally, the Microburst Prediction (MBP) product performance will be presented.

A. BASIC STATISTICS AND PERFORMANCE

In this section, basic microburst statistics are presented for the entire field season and for the performance of the microburst algorithm during the operational demonstration period in Orlando. Prior to discussing the algorithm's performance, statistics on Orlando microbursts are provided to characterize the phenomena to be detected.

Figure 2-1 is a frequency plot of the maximum radial outflow velocity for Denver (1987, 1988), Kansas City (1989), and Orlando (1990) microbursts. The Orlando data set contains a slightly larger percentage of events less than 15 m/s than Denver. However, the percentage of weak events in Orlando is less than that of Kansas City. The distribution of events greater than 25 m/s is similar among the three locales, with the strongest outflows peaking at 40 to 44 m/s. Forty-seven percent of the Orlando events had maximum outflow velocities less than 15 m/s. It is interesting to note the general similarity of the overall distributions for the four years.

Figure 2-2 is a frequency plot of the maximum surface reflectivity in microburst-producing cells for the same data sets used in Figure 2-1. It is clearly evident from the plot that there is a higher percentage of wet microbursts (surface reflectivity ≥ 35 dBZ) in Orlando than in Denver or Kansas City. Approximately 85 percent of the Orlando microbursts were associated with surface reflectivities in excess of 50 dBZ. In comparison to Denver and Kansas City, none of the Orlando microbursts was characterized as dry.

During the 1990 TDWR operational period (June 18 to August 28), there were 58 microbursts within three nautical miles of the airport that were capable of producing wind shear or microburst alerts. The distribution of the maximum velocities for airport events was as follows:

- 10-14 m/s (48 percent)
- 15-19 m/s (24 percent)
- 20-24 m/s (12 percent) and
- 25+ m/s (16 percent).

Over one-half of the outflows were strong enough to produce microburst alerts. The strongest was 40 m/s on August 22. In comparison to Kansas City, there were four times as many airport microbursts, even though the radar operated for a shorter period. All of the airport microbursts had maximum surface reflectivities of 40 dBZ or greater.

The ground truth used in scoring the microburst algorithm is based on single-Doppler radar observations and was developed by analyzing reflectivity and velocity data from the TDWR testbed radar. Each microburst truth entered into the database contains information such as the location, differential velocity, and range across the maximum velocity couplet. The algorithm's performance was determined by comparing alarm boxes with the truth generated by experienced

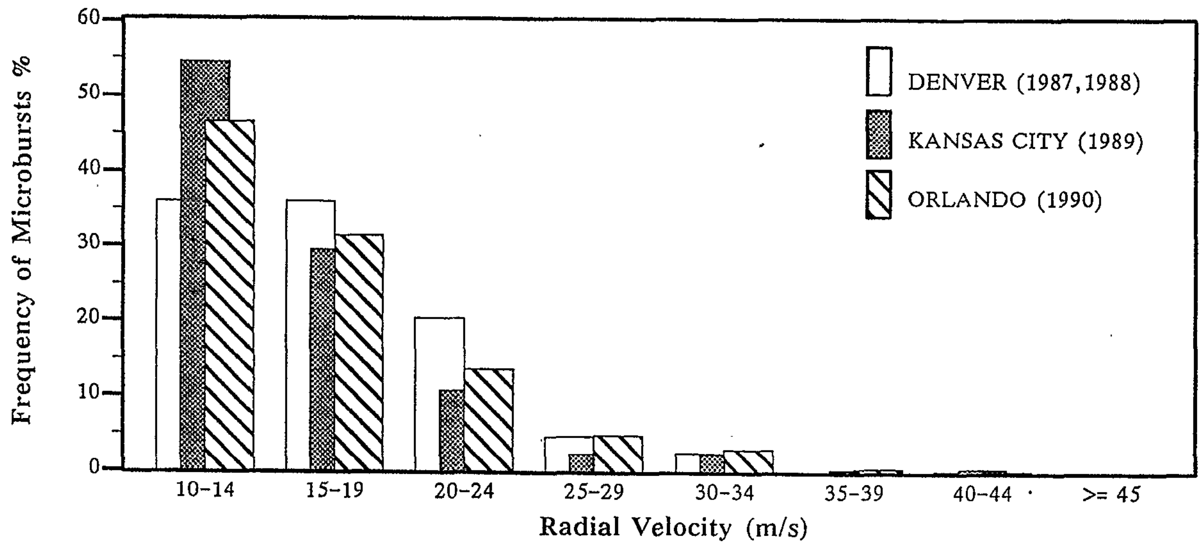


Figure 2-1. Distribution of maximum radial outflow velocity for Denver, Kansas City, and Orlando microbursts.

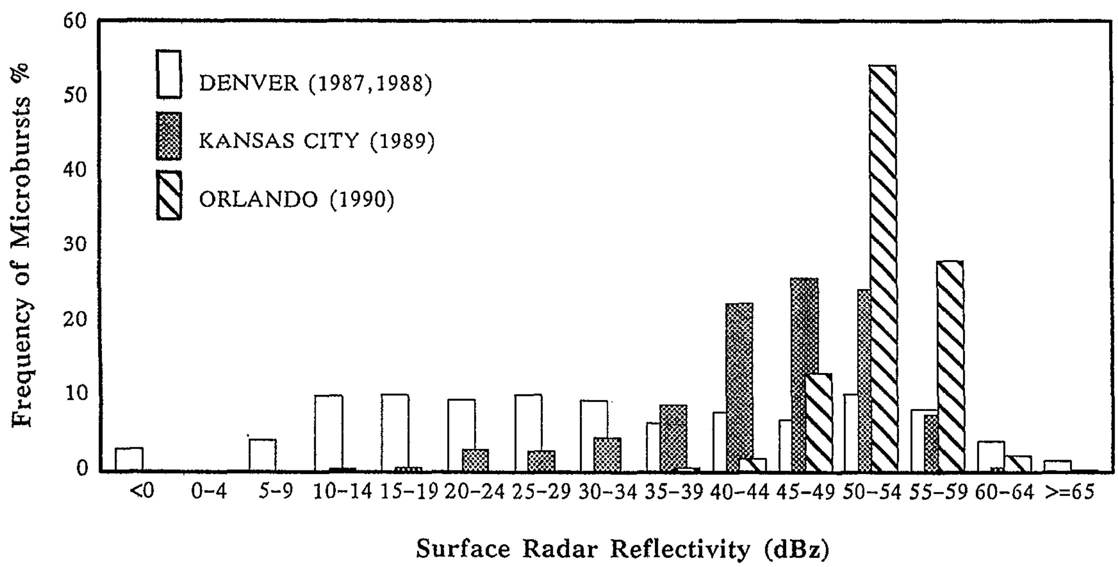


Figure 2-2. Distribution of maximum surface reflectivity in cells that produced microbursts in Denver, Kansas City, and Orlando.

radar meteorologists. Alarms were categorized as either an algorithm detection if the box overlaid a true surface outflow or as a false alarm if there was no surface outflow. A miss was declared if a true surface outflow went undetected by the algorithm. The scoring methodology employed here is similar to that used in Kansas City, and it has evolved over the past four years of experiments in Denver, Kansas City, and Orlando.

For this report, six days from Orlando comprising 52 microburst events were analyzed and formally scored. The probability of detection (POD) is defined as the number of detections divided by the number of true events, while the probability of false alarm (PFA) is the number of false alarms divided by the number of total alarms. As shown in Table 2-1, the algorithm detected 642 out of 677 true events, for a POD of 95 percent. This is similar to the POD in Kansas City and is somewhat better than the results in Denver. On the other hand, the algorithm produced only 12 false alarms over the six-day period, for a PFA of two percent. The PFA in Orlando is lower than for any other locale where the algorithm has been tested, primarily due to the lower incidence of low-reflectivity events.

Table 2-1.
Summary of Microburst Algorithm Results from Orlando.

Date	Microbursts	True Events	Detections	Total Alarms	False Alarms
July 7	3	47	46	46	0
July 8	9	107	96	99	3
July 9	16	163	151	156	5
Aug 16	5	125	122	122	0
Aug 27	13	154	148	152	4
Aug 28	6	81	79	79	0
Totals	52	677	642	654	12

B. SUMMARY OF MISSED EVENTS AND FALSE ALARMS

In this section, the algorithm's performance during the demonstration will be discussed in terms of the maximum velocity and location of the missed events for the entire TDWR operational demonstration period. As shown in Figure 2-3, the majority of the misses (67 of 81) had a velocity differential of less than 13 m/s. There were only three microbursts stronger than 15 m/s which were not detected. Fifteen of the algorithm misses (19 percent) were located within the runway warning region. All of these, except one, would have been classified as a wind shear with loss. The strongest microburst which was not detected was 17 m/s. More than one-third of the misses were at the beginning of the event. In terms of location, the algorithm missed more events outside 25 km than inside 10 km. This is consistent with previous results and is in part due to the height of the beam cutting through a weaker signature at longer ranges.

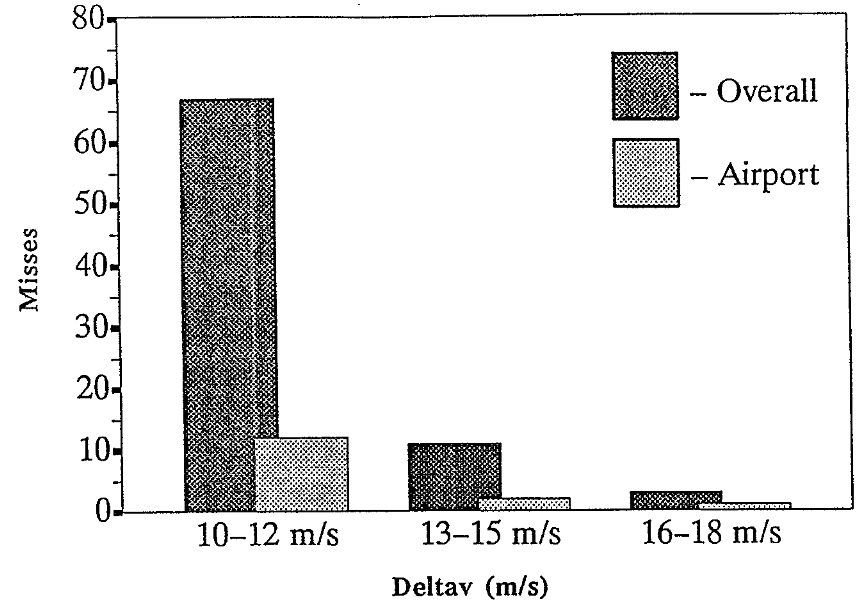


Figure 2-3. Velocity statistics for 1990 Orlando algorithm misses.

While there were few false alarms on the days analyzed for the performance statistics, there was still a perceived overwarning problem with the microburst algorithm during the first two weeks in July. In fact, from July 12 through 14, the algorithm produced an excessively high number of false alarms (45 false alarms in three days). The cause of most of the false alarms was wind velocities which increased with height. This produced a divergent signature of increasing velocities with range along the radial. The algorithm was typically detecting segments longer than 5 km, with shears less than 2.5 m/s per km. A number of these alarms occurred over the airport, resulting in false wind shear warnings.

During the 1988 testing in Denver, a slope test was implemented to trim back the end portion of segments which did not meet a shear threshold of 2.5 m/s per km. The test was applied over the final four gates of the segment and assumed a gate spacing of 120 meters. However, the range gate interval at C-band in Orlando changed to 150 meters. This resulted in an effective shear threshold of 2.0 instead of 2.5 m/s per km. Changing this threshold to the algorithm enunciation language (AEL) value of 2.5 reduced over one-half of the false alarms from this period. Even after this change, there were still false alarms due to long segments with weak shear. The original slope test required a length of four gates over which the shear is calculated. By increasing the size of the window, the test behaves more like an overall shear threshold. It was determined that an eight-gate shear test eliminated 15 more false alarms. The net effect on the POD would be a decrease of less than one percent. All of the misses due to this change were less than 13 m/s and were typically at the end of the event when the shear was weak. The site adaptable parameters were changed to reflect the new eight-gate slope test on August 6.

As shown in Table 2-2, the most common reason for false alarms (other than coasts) in Orlando was weak divergence in the environmental flow (25 percent). Another significant factor was the lack of clutter maps throughout the operational period. Residual clutter contamination produced 20 percent of the false alarms (including coasts). Other causes of false alarms were noisy velocities in the clear-air (13 percent) and false declarations due to features aloft or precursors (eight percent). One of the concerns with the change to C-band was that there would be a high number of false alarms due to range obscuration (second trip). There have been only seven documented cases (six percent) of false alarms from second trip–far below what was expected. During July and August, there were no false alarms of the type observed in Kansas City (due to insects or birds).

Table 2-2.
Causes of 1990 False Alarms.

Environmental Flow	Clutter	Noise	Features Aloft	Second Trip	Weak Shear	Zero Isodop	Coast
25 %	13 %	13 %	8 %	6 %	3 %	1 %	31 %

The influence of clutter maps and site optimization on five of the six evaluation days is reflected in Table 2-3. After site optimization and clutter map installation, recalculation of the data showed that the PFA was reduced from 3.9 to 1.4 percent. There was little difference in POD between the original algorithm and the algorithm with the new shear parameters and clutter maps. During the TDWR testing, there were 117 microburst false alarms. This was reduced to 61 during playback with the inclusion of clutter maps and a more stringent shear test.

Table 2-3.
Comparison of Microburst Algorithm Performance in 1990.

	POD (percent)	PFA (percent)
OT&E	95.3	3.9
After site adaptation parameter optimization and clutter map installation	95.1	1.4

C. OVERWARNING ISSUES

Substantial concerns were raised by air traffic controllers in Orlando about instances of perceived microburst overwarning during the demonstration period. These concerns were substantially greater than previously encountered in Denver or Kansas City. If not corrected, the perception of overwarning by TDWR could lead to a long-term loss of confidence in warnings issued by the system.

There appear to be several sources for the increased concern about overwarning in Orlando. One factor is the much greater thunderstorm activity in Florida compared to previous sites. The central Florida area around Orlando averages 95 thunderstorm days per year, the highest rate in the U.S., so that weather impact at the airport is more likely than in other areas. In addition, microbursts in the Orlando area are likely to be associated with heavy rain shafts which are highly visible to controllers and pilots.

Secondly, the Orlando airport has three runways oriented in the same direction (north-south), whereas the Denver and Kansas City airports have runways oriented at right angles. The parallel runway configuration is more likely to have multiple runways impacted by a single microburst than the perpendicular configuration. For instance, a microburst in the middle of one runway is likely to impact adjacent runways in the parallel configuration, but impact only one runway in the perpendicular configuration.

A third factor in the overwarning issue arose from some initial errors in software implementation and parameter settings for the microburst alerts. These problems primarily affected shear segment formation and microburst shape generation. However, substantial overwarning occurred after these initial problems were corrected and appears to reflect fundamental flaws in the current TDWR microburst alarm and runway message generation methodology.

There are several areas for which algorithm improvements are needed to reduce the incidence of overwarning. These areas include: shear localization, microburst shape generation, runway buffer zone, and loss value computation.

1. Shear Localization

One source of overwarning is incorrect localization of the shear region. As noted in the previous section, the shear regions identified by the divergence regions algorithm were too large because of excessively long shear segments and clutter contamination. The incidence of overly long segments was reduced by parameter adjustments to the shear cropping test. Further reduction of spurious shear regions was achieved with the use of the clutter map feature (note: the clutter map was not used during the operational test).

These changes helped but did not solve the problem of overly long shear segments entirely. It appears that the relatively benign clutter environment of Orlando actually promotes the formation of these long segments since they are less likely to be broken up by clutter. Also, the conversion of the TDWR testbed radar to C-band makes clutter breakthrough less likely since the reduced radar beam width (0.5 degrees) decreases the illumination of surface clutter targets.

It also has been realized recently that the shear segment formation methodology tends to produce a set of segments which are extended in the azimuthal direction more than in the radial direction, even for a perfectly symmetrical microburst outflow. Moreover, the current approach tends to allow the regions of strong shear to be separated in the azimuthal direction, but not in the radial direction. As a result, more work needs to be done to allow better characterization of the actual shear region.

2. Microburst Shape Algorithm

Another source of overwarning was due to to the microburst shape generation process. Initial problems with the parameter settings and software implementation of the Microburst Shape algorithm caused the formation of excessively large shapes under some circumstances. Initially, the parameter settings used during the Denver 1988 demonstration were used in the shape algorithm; these parameters were changed in mid-July to the settings used in Kansas City and Denver during 1989 (along with the adjustments to the shear segment cropping test parameters mentioned above), resulting in a substantial reduction in microburst shape size. Further adjustments were made to the parameters in mid-September, and a further investigation of these parameters is currently in progress.

Several software coding problems also were encountered with the Lincoln implementation of the shape algorithm. One problem not corrected during the demonstration concerned the generation of the loss values associated with the shapes. During the demonstration period, the loss value for any shape was the maximum loss value for the parent microburst alarm.

This loss value was incorrect in two respects. First, the site-adaptable parameters allow the algorithm to assign one of three possible loss values to the shape:

1. The maximum loss value,

2. The next-to-largest loss value, or

3. A percentile loss value (e.g., 85th percentile value), depending upon the number of segments in an alarm.

Second, in the case that the microburst shape exceeds a threshold value, the parent shape can be broken into two or more secondary shapes. In this event, the loss value for each secondary shape should be computed from the subset of segments making up that shape.

To determine the improvement due to these parameter adjustments and software corrections, the data for three days in July were rerun after the demonstration period, and the amount of overwarning was assessed by Lloyd Stevenson of the Transportation Systems Center in Cambridge, MA. Stevenson found that the overwarning was reduced, but remained substantial (i.e., 50 to 75 percent of the runway alerts would be viewed by pilots as false alarms). Thus, TDWR systems could be expected to suffer from substantial overwarning when installed at airports similar to Orlando.

Several improvements are currently being explored for the Microburst Shape algorithm. One is to use a weighted least-squares fit to the alarm segments instead of requiring the shapes to enclose all segments. Another possible improvement would be to use a two-level shape representation for microbursts similar to that used in ELLWAS. In this scheme, a filled-in shape representing the strong shear region would be surrounded by an open shape representing the weaker shear region. This scheme also could be extended to account for the unobserved shear regions resulting from the shear localization asymmetry.

3. Runway Buffer Zone

Another source of overwarning was the buffer zone size used for generating runway warnings. This buffer zone extends 0.5 nmi (1 km) to either side of the flight path to account for such factors as pilotage, microburst advection/growth, and microburst location uncertainty. If a microburst shape touches the buffer zone at all, then a runway warning is generated.

This procedure frequently results in overwarning since aircraft often will pass either through the edge of the outflow or miss it entirely. The pilot in this situation either experiences a cross-wind or does not experience any shear at all, resulting in the perception of a false warning. Repeated experiences of this type tend to erode pilot and controller confidence that the TDWR is producing credible warnings.

Although this problem with the runway buffer zone was noted in the Denver and Kansas City demonstrations, its importance has tended to be discounted in these locations mainly because of its limited effect on operations there. However, several factors make this problem much more apparent in Orlando. First, microbursts move more slowly in Orlando because of light horizontal winds during thunderstorms. Second, visible cues as to microburst location are often ambiguous in Denver, but are very apparent in the Orlando environment and make instances of overwarning highly obvious. Third, as mentioned before, the Orlando airport configuration is more susceptible to impact due to its three parallel runways (a configuration not encountered in previous demonstrations). One approach to the runway buffer problem is to make the size of the buffer zone site adaptable.

4. Loss Value Computation

A final source of both underwarning and overwarning involves the current approach for computing the runway loss value. The current approach is to use the maximum velocity difference for the shape impacting the buffer zone. This approach is flawed for two reasons. First, the aircraft will not encounter the maximum velocity difference unless it flies directly through the center of the entire event. Since this is an unlikely occurrence, overwarning is almost assured.

The other flaw with the current approach is the use of the microburst velocity difference to characterize the microburst hazard. The velocity difference fails to account for the distance over which the shear occurs. Thus, a 30 kt microburst loss over 1 nmi is viewed as equally hazardous as a 30 kt microburst loss over 3 nmi, whereas the shear is clearly three times greater. Moreover, the use of velocity difference rather than shear leads to both underwarning and overwarning. When the initial outflow begins, the shear may be hazardously high; however, the velocity difference may be below the 30 kt threshold and result in underwarning. At the later stages of the outflow, the velocity difference may remain high–but the shear may decline below hazardous levels due to spreading of the outflow–and result in overwarning.

An alternate approach is to make the loss value dependent on the flight path through the microburst shape and on the shear inside the shape. By integrating the shear (delta V / delta R) over the flight path, a more realistic loss value would be achieved. This approach could be extended to account for the buffer zone by computing the anticipated loss on either side of the nominal flight path and taking the maximum value.

D. MICROBURST PREDICTION/FEATURES ALOFT

Previous research indicates that microbursts may be preceded by precursors such as descending reflectivity cores, upper- or lower-level divergence, mid-level convergence, and mid-level cyclonic or anticyclonic rotation. Features such as these have been incorporated into the algorithm to predict a surface outflow prior to a 10 m/s divergence. To do this, the algorithm must detect a descending reflectivity core in combination with a mid- or upper-level velocity feature. The reflectivity core must be above an altitude of 5.2 km, below an altitude of 3.5 km, and have a maximum reflectivity of 57 dBZ. If the core is not descending, the velocity feature must extend below 3.5 km above ground level (AGL). The reflectivity core thresholds were modified in Orlando to be more stringent since there was a high false-prediction rate early in the summer. The ability to predict microburst outflows may provide Air Traffic Control (ATC) with an additional planning tool. For example, a high reflectivity cell which develops over the airport may or may not produce a significant outflow. There would be an increased awareness and an increase in timeliness if the algorithm predicted the wind shear in advance. Providing an estimate of the strength of the outflow may allow ATC to continue operations in the likelihood of a weak event.

Late in July the TDWR scan strategy was modified to include a maximum elevation of 60 degrees. This was required due to the short distance between the radar location in Orlando and the airport. At a range of 10 km, the scan extends to an altitude of 8.7 km AGL, with a worse-case inter-tilt spacing of 1.1 km. There would be coarser resolution with increasing range than the previous scan scenario used in Denver and Kansas City. It was felt that the algorithm would predict more events in the vicinity of the airport with the new scan strategy.

Twelve days worth of data from Orlando in August 1990 were chosen as the database to determine the prediction performance. A prediction was considered valid if a microburst overlapped a prediction box within a 10-minute time period. As shown in Table 2-4, the algorithm successfully predicted 48 percent (22 of 46) of the microbursts that reached 15 m/s. The prediction performance in Orlando is similar to the results from Kansas City. Of the 32 total predictions, 4 or 13 percent were false. In all of these, a microburst was observed after

10 minutes. None of the false predictions was located over the airport. The lead time from a valid prediction to a microburst ranged from one to nine minutes, with a median of five minutes.

Table 2-4.
Orlando Prediction Statistics for Microbursts in August 1990.

Microbursts	Total Predictions	Valid Predictions > 15 m/s	False Predictions	Lead Time (minutes)
46	32	22	4	5.0

Even though the TDWR scan strategy is optimized to detect microburst precursors in the vicinity of the airport, the performance did not increase if only airport events were considered. The algorithm predicted only 41 percent of the microbursts observed within a three- or four-nautical-mile-distance of the runways.

The reason Orlando microbursts were not predicted was determined in order to evaluate improvements to the algorithm (Table 2-5). A microburst may not have been predicted for more than one reason. The most common failure mechanisms were that the reflectivity core was below 5.2 km (14), the precursor overlapped a microburst alarm (9), or there was no velocity feature aloft (8). The algorithm did not detect a reflectivity core in six of the microbursts. Within the algorithm there are site-adaptable parameters which may need to be optimized further to improve the prediction performance.

Table 2-5.
Reason Orlando Microbursts Were Not Predicted.

No Core	Core < 5.2 km	No Velocity Feature	No Association	Velocity > 3.5 km	Overlaps Microburst
6	14	8	2	4	9

The precursor features detected in Orlando microbursts are presented in Figure 2-4. Over 55 percent (26 of 46) of the Orlando microbursts in August were preceded by a descending reflectivity core in excess of 45 dBZ. On average, the bottom of the core descended below 2 km AGL five minutes prior to a 10 m/s outflow. This is similar to the timing for descending cores in Kansas City microbursts. The most common velocity features detected in Orlando microbursts were mid-level convergence and cyclonic rotation (32 and 20, respectively). Upper-level divergence and anticyclonic rotation were detected in less than one-third of the outflows.

In summary, the changes to the reflectivity core thresholds reduced the high false-prediction rate from earlier in the field season. There were no false predictions over the airport. However, the algorithm predicted only one-half of the Orlando events stronger than 15 m/s. While this is similar to the performance in Kansas City, the cases which were not predicted will be analyzed further to determine if the prediction algorithm can be improved with only minor changes to site-adaptable parameters.

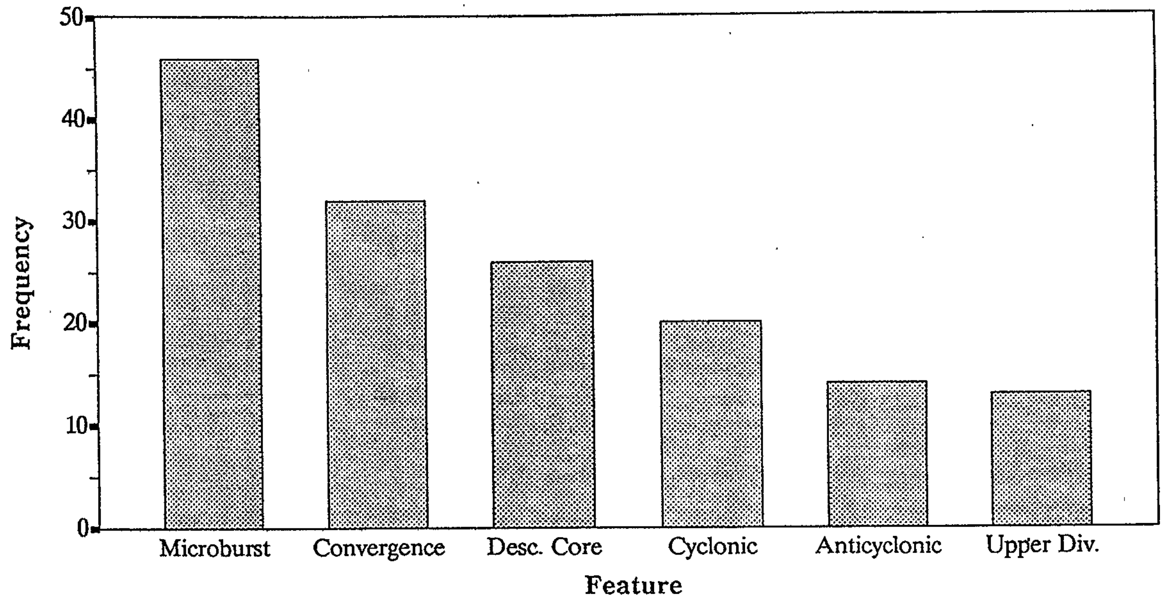


Figure 2-4. Precursor features detected in Orlando microbursts.

3. GUST FRONT/WIND SHIFT DETECTION AND PREDICTION PERFORMANCE

The gust front algorithm serves two functions: warning and planning. Wind shear hazard warnings are issued when a gust front impacts the runways or is within three miles of the ends of the runways. The alarm message consists of the type of hazard (wind shear for gust fronts), the expected gain in wind speed (e.g., wind shear alert, 35 kt gain), and the location (one mile final). The planning function consists of alerting an Air Traffic Control Supervisor when a change in wind speed and/or direction is imminent due to a gust front arriving at the airport. A description of the algorithm and an assessment of its performance during the 1988 Denver and 1989 Kansas City operational demonstrations are found in references [2], [3], [4] and [5].

A. WARNING PERFORMANCE

The ability of the algorithm to produce timely, useful warnings rests upon its detection of convergent shears in the Doppler velocity data. Two basic statistics were used to quantify detection performance: POD and PFA. These statistics are defined as:

$$\text{POD} = \frac{\text{number of detected events}}{\text{total number of events}}$$

$$\text{PFA} = \frac{\text{number of false alarms}}{\text{number of (correct alarms + false alarms)}}$$

An event is a single observation (on the surface tilt) by the ground-truth meteorologist analyst of a gust front in the radar data. A detected event is an algorithmic declaration of a gust front that overlaps ground truth. A false alarm is an algorithmic declaration that does not overlap ground truth. Only those gust fronts that are located within 60 km of the radar are truthed and scored.

1. Gust Fronts Near the Airport

POD and PFA for all truthed Orlando gust fronts as a function of gust front strength is shown in Table 3-1. Gust front strength is determined by the change in Doppler velocity (ΔV) across the gust front. The strength of a gust front is defined as "moderate" for $10 \text{ m/s} \leq \Delta V < 15 \text{ m/s}$; "strong" for $15 \text{ m/s} \leq \Delta V < 25 \text{ m/s}$; and "severe" for $\Delta V \geq 25 \text{ m/s}$. Corresponding POD results from the 1988 Denver and 1989 Kansas City operational demonstrations are provided for comparison. In general, there is little difference in performance between 1988, 1989 and 1990. For the 1988 Denver, 1989 Kansas City, and 1990 Orlando data, the PFA were two percent, 13 percent, and six percent, respectively.

Table 3-1.
Probability of Detection.

	Moderate	Strong	Severe	All	PFA
1988	73%	91%	100%	78%	2%
1989	72%	81%	92%	77%	13%
1990	75%	84%	100%	79%	6%

The POD does not indicate how well a gust front is detected. One measure of the goodness of the detection is the percent of the length of the event that is detected by the algorithm. The average Percent of Length Detected as a function of gust front strength is given in Table 3-2.

Table 3-2.
Average Percent of Length Detected.

	Moderate	Strong	Severe	All
1988	66%	69%	73%	67%
1989	59%	61%	50%	60%
1990	57%	50%	42%	53%

It is possible to apply a minimum Percent of Length Detected threshold such that the length detected must exceed the threshold before a valid detection is declared. POD as a function of the minimum percent of length detected threshold is plotted in Figure 3-1.

The primary cause of missed detections is inadequate convergence in the radial direction. Because the algorithm detects only radial convergence, it is easier to detect gust fronts that are oriented perpendicular to the radar beam. As gust fronts move closer to the radar, less of their lengths are oriented perpendicular to the beam, making them more difficult to detect. An example is given in Figure 3-2.

In Orlando, the TDWR testbed radar was sited such that gust fronts typically were oriented parallel to the radar beam at the same time they were impacting the airport. During the latter part of the demonstration, a function of the algorithm was exercised that provided tracking of gust fronts as they passed near the radar. An example of the performance of this overhead tracking capability is provided in Figure 3-3. A full assessment of algorithm performance using overhead tracking is forthcoming.

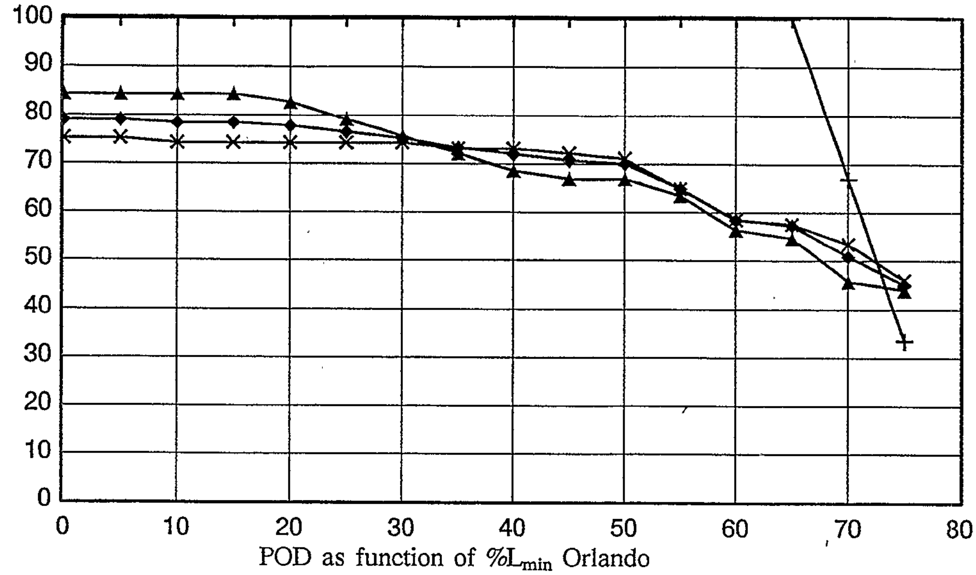


Figure 3-1. Probability of detection as a function of minimum percent of length detected threshold for moderate (x), strong (▲), severe (+) and all (♦) gust fronts.

2. Gust Fronts at the Airport

The gust front algorithm estimates the wind shear hazard associated with each gust front and issues a warning if the gust front is over the airport. The warning is composed of two parts: the location of the wind shear and the intensity. A warning is viewed as correct if the gust front alarm is issued when a gust front is on the airport. The probability of correctly locating the wind shear event is determined by computing the number of gust front alerts issued at the airport divided by the number of gust front alerts that should have been issued. The results of this analysis for 1988 (Denver), 1989 (Kansas City), and 1990 (Orlando) are shown in Table 3-3. For Orlando, the Probability of Correct Forecast (POCF) of 60 percent for moderate gust fronts represents three out of five alerts; for strong gust fronts, three out of six possible alerts. The Probability of False Warning (PFW) is defined as the number of false alarms issued divided by the total number of alarms issued.

Table 3-3.
Probability of Correctly Detecting Gust Fronts at Airport.

	Moderate	Strong	Severe	All	PFW
1988	64%	86%	--	70%	0%
1989	29%	68%	40%	45%	40%
1990	60%	50%	--	55%	0%

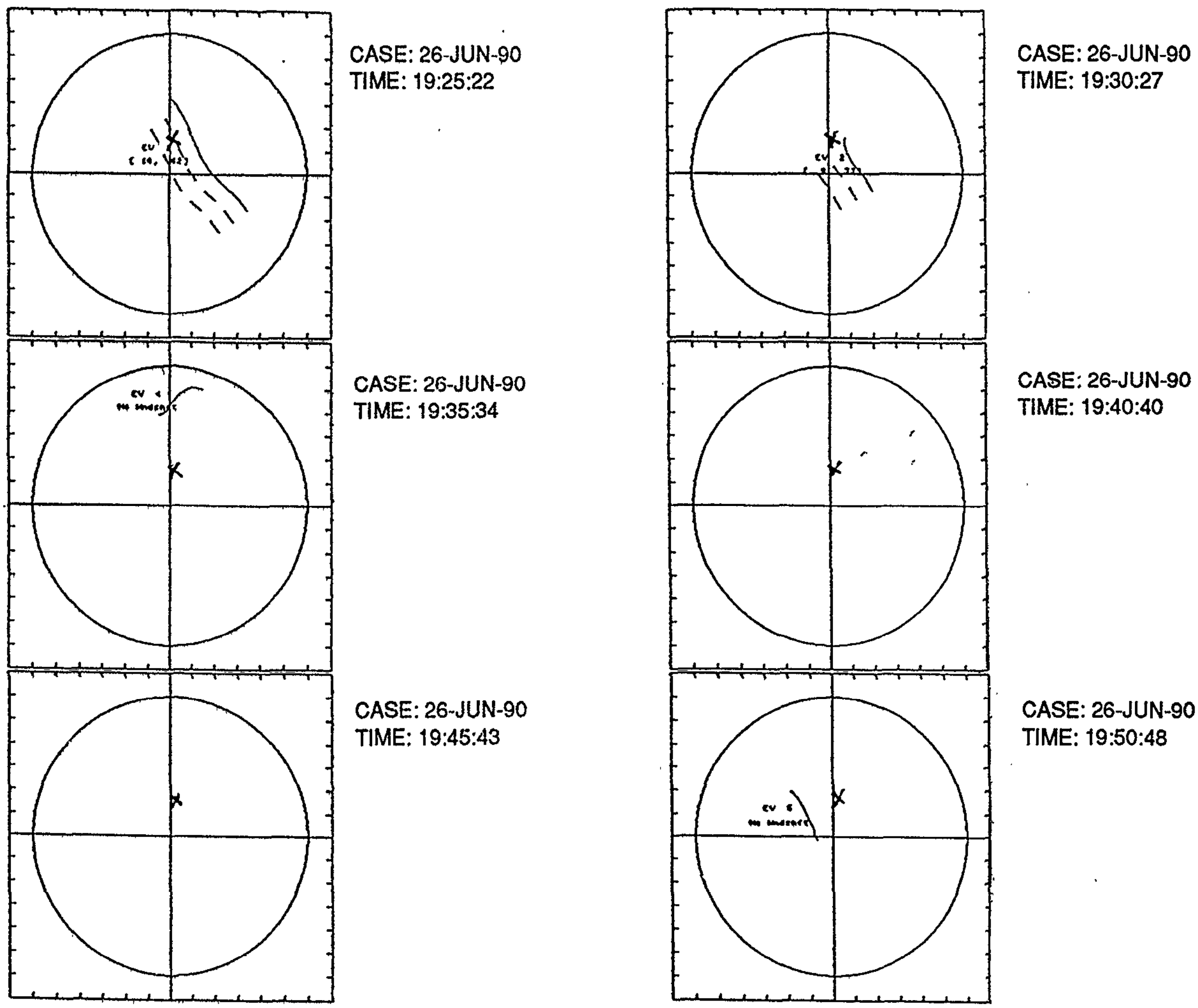


Figure 3-2. Example of the loss of a gust front detection as the gust front passes over the radar and airport. The location of the Orlando International Airport is shown by the "x." The plotting range is 30 km. The solid line indicates the current location of the gust front as determined by the algorithm. The dashed lines are the 10- and 20-minute forecasted gust front locations. The estimated wind speed (m/s) and direction (degrees) behind the gust front are shown in square brackets.

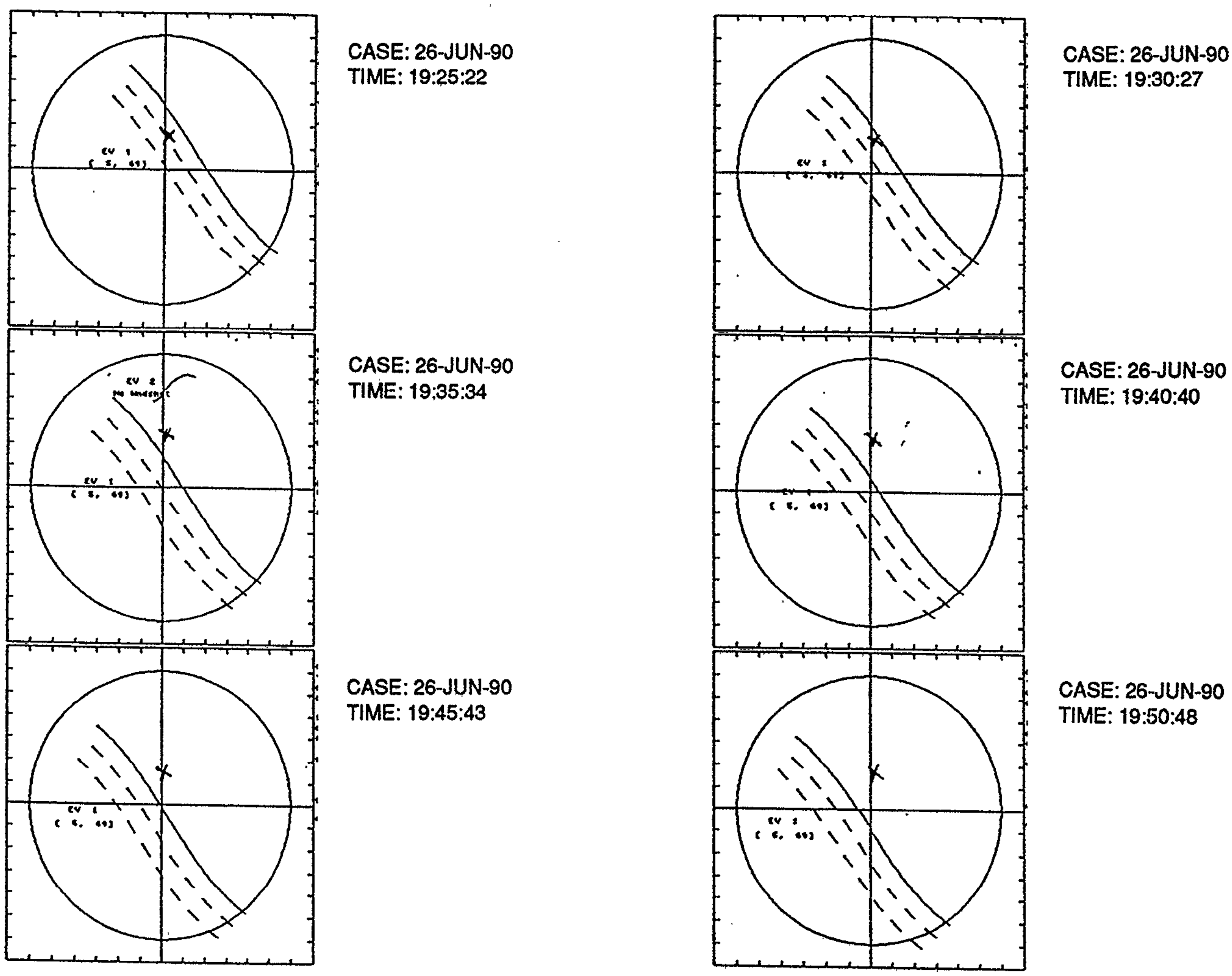


Figure 3-3. Example of a gust front detection that is overhead-tracked as the gust front passes over the radar and airport. The location of the Orlando International Airport is shown by the "x". The plotting range is 30 km. The solid line indicates the current location of the gust front as determined by the algorithm. The dashed lines are the 10- and 20-minute forecasted gust front locations. The estimated wind speed (m/s) and direction (degrees) behind the gust front are shown in square brackets.

The accuracy of the gust front intensity estimates is scored by comparing the intensity expressed in the alert to pilot reports as logged by observers in the tower. In order for an alert to be generated, the estimated gust front wind shear must equal or exceed 15 kts. Orlando gust fronts were typically weak, and there were too few gust front-related wind shear alerts (one) delivered to Orlando pilots to assess the accuracy of the intensity estimates.

B. PLANNING PRODUCT PERFORMANCE

Runway management is improved with the TDWR by alerting an ATC supervisor when a wind shift is expected at the airport (forecasted location), along with the winds that result after the passage of the gust front (wind shift estimate). The forecasted location is scored by determining if a forecast overlaps the truth region for the time at which the forecast is valid. If so, a valid forecast is declared. There are two type of errors in forecasts: forecasts whose locations do not agree with the ground truth (a missed forecast) and forecasts for gust fronts that no longer exist (a false forecast). Forecasts are made for 10 and 20 minutes into the future. The statistics for evaluation of the performance of the forecasting function are the POCF and Probability of False Forecast (PFF) and are given by:

$$\text{POCF} = \frac{\text{number of valid forecasts}}{\text{number of events forecasted}}$$

$$\text{PFF} = \frac{\text{number of false forecasts}}{\text{number of forecasted events} + \text{number of false forecasts}}$$

POCF, as a function of gust front strength, is given in Table 3-4. For Orlando (1990), the PFF for the 10- and 20-minute forecasts were 13 percent and 30 percent, respectively. Forecasts were generated only about 56 percent of the time. The high POCF values show that, when generated, forecasts were very accurate.

The accuracy of the wind shift estimate is determined by comparing the wind shift estimate to the Mesonet data. The average absolute difference in wind speed and direction between the wind shift estimate and the Mesonet data was 2 m/s and 15 degrees, respectively.

Table 3-4.
Probability of Correct Forecast.

	Moderate	Strong	Severe	All	PFF
1988					
10-Minute	97%	98%	100%	97%	11%
20-Minute	82%	84%	--	83%	18%
1989					
10-Minute	95%	100%	67%	97%	18%
20-Minute	95%	93%	100%	94%	21%
1990					
10-Minute	100%	91%	100%	95%	13%
20-Minute	85%	70%	--	75%	30%

4. DATA QUALITY ISSUES

A. CLUTTER SUPPRESSION

1. Clutter Filters

New clutter filters for C-band operation were designed and implemented. The filter specifications were tailored for the range of pulse repetition frequencies (PRFs) to be used in the Raytheon TDWR system (see Table 4-1). Overall, the new filters were found to perform satisfactorily and were used throughout the operational period.

A small anomaly in the velocity product was reported to occur during clear air scans when using the new filters. It was concluded that this problem was a normal consequence of the pulse-pair velocity estimator in use and that the problem would not affect operations. Additional studies using time series data have been planned with the goal of identifying user criteria for "failure" of the velocity estimator.

2. Clutter Residue Maps

Initial clutter residue measurements were taken on May 22. The clutter environment of the Orlando site appears to be much more benign than that of the Kansas City site, but further studies are needed to determine the relative importance of three factors that are new in Orlando: smaller beamwidth, point target rejection, and flatter terrain. It is clear, however, that range-folded distant weather and anomalous propagation (AP) affect clutter measurements much more in Orlando than in Kansas City.

Routine AP in the morning and severe weather in the afternoon prevented clutter residue measurements for map generation prior to the start of the operational period. However, the benign clutter environment combined with the apparent clutter suppression capability of the point target rejection algorithm made it possible to run the operational demonstration successfully without map-based clutter residue removal.

After the end of the operational period a set of clutter residue maps were generated from data collected on September 14. A clear air reflectivity level of 8 dBZ (the 91st percentile) was used. The accuracy of the maps is limited by the relatively high clear air reflectivity in two ways:

1. About nine percent of the clear air returns appear in the maps.

2. About 30 percent of the clutter residue returns below 8 dBZ are absent from the maps.

Figure 4-1 shows a comparison of estimated microburst reflectivity distribution in the core and outflow regions at the time of maximum shear. The figure indicates that two percent of Orlando summer microburst outflow reflectivities at the time of maximum shear are below 8 dBZ.

The detection of microbursts having low-level outflow reflectivities is probably affected by the limited accuracy of clutter residue maps. Despite this, and despite the relatively benign clutter environment, there is evidence that clutter residue editing using these maps does improve data quality, reducing the number of false wind shear detections and improving velocity dealiasing performance.

**Table 4-1.
Raytheon TDWR PRFs.**

PRF Number	Raytheon PRF (Hz)	FL-2 PRF (Hz)	PRI (μ sec)	Unambiguous Range (Km)	(nmi)	Nyquist Velocity (m/s)	Available to PRF Algorithm
1	1930.5	1931	518	77.7	41.9	25.6	
2	1858.7	1859	538	80.7	43.6	24.7	
3	1792.1	1792	558	83.7	45.2	23.8	
4	1730.1	1730	578	86.7	46.8	23.0	
5	1672.2	1672	598	89.7	48.4	22.2	√
6	1618.1	1618	618	92.7	50.0	21.5	√
7	1567.4	1567	638	95.7	51.6	20.8	√
8	1519.8	1520	658	98.7	53.3	20.2	√
9	1474.9	1475	673	101.7	54.9	19.6	√
10	1432.7	1433	698	104.7	56.5	19.0	√
11	1392.8	1393	718	107.7	58.1	18.5	√
12	1355.0	1355	738	110.7	59.7	18.0	√
13	1319.3	1319	758	113.7	61.4	17.5	√
14	1285.3	1285	778	116.7	63.0	17.1	√
15	1253.1	1253	798	119.7	64.6	16.6	√
16	1222.5	1222	818	122.7	66.2	16.2	√
17	1193.3	1193	838	125.7	67.8	15.8	√
18	1165.5	1166	858	128.7	69.5	15.5	√
19	1139.0	1139	878	131.7	71.1	15.1	√
20	1113.6	1114	898	134.7	72.7	14.8	√
21	1089.3	1089	918	137.7	74.3	14.5	√
22	1066.1	1066	938	140.7	75.9	14.2	√
23	326.2	326	3066	459.9	248.2	4.3	

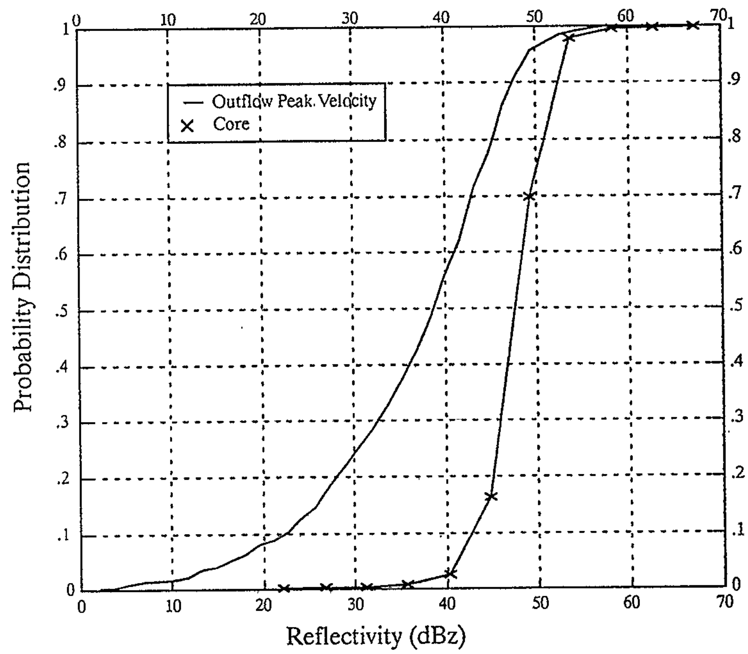


Figure 4-1. Orlando summer microburst reflectivity distribution. Solid line indicates outflow reflectivity at locations of outflow velocity maxima and minima when the microburst had its peak shear.

Lessons learned that will be helpful for the 1991 operation are:

1. Clutter residue measurements must be made before the routine AP and severe weather patterns begin.

2. Time series data should be collected in addition to the standard clutter residue measurements. The time series data can be used to evaluate radar calibration and clutter suppression performance.

B. RANGE OBSCURATION MITIGATION

1. PRF Selection

The PRF selection algorithm used in Orlando was functionally the same as that used in Kansas City and Denver. The distant weather threshold remained at 8 dB SNR, but a number of modifications were made to more closely emulate Raytheon TDWR capabilities:

1. Airport, microburst, and gust front region shapes were defined to match TDWR specifications and Orlando geometry (see Figure 4-2).

2. A set of available PRFs was defined to match the Raytheon TDWR implementation (see Table 4-1).

3. The implementation was enhanced to allow selection of a secondary PRF to support the "dual scan" feature of the Raytheon velocity dealiasing algorithm.

One method of measuring the effectiveness of the PRF selection algorithm is to compare the obscuration levels at the "selected" PRF (the one chosen by the algorithm) with the "average" obscuration levels, where the average level is the arithmetic mean of the potential obscuration levels at each available PRF and can be thought of as the obscuration that would be experienced if the PRF were chosen at random. If the obscuration level at the PRF selected is less than the average obscuration level, then the algorithm is considered to have been effective.

Figure 4-3 contains three histograms, each of which depicts average and selected obscuration levels for one of the obscuration protection regions. The figure shows that the PRF algorithm was effective at mitigating obscuration over both the airport and microburst regions. These regions spent more time at low obscuration levels in the selected case than would have been spent in the average case. For the gust front region, however, average obscuration levels were slightly lower than the selected levels.

The PRF selection process for the gust front region is dominated by the comparatively small airport region. One storm folding onto the airport affects the PRF selected for gust front detection at all azimuths. In satisfying the "low obscuration over the airport" requirement, the algorithm can be forced to select a PRF with higher than average obscuration levels over the gust front region. One solution to this problem might be to divide the gust front region into several azimuthal sectors and select a PRF for each [6]. The selection process for each sector would still be dominated by the portion of the airport region that lies in that sector, but the effects of single storms would be limited to one or perhaps two sectors. Orlando and Kansas City data will be re-analyzed to determine the efficacy of the sector approach.

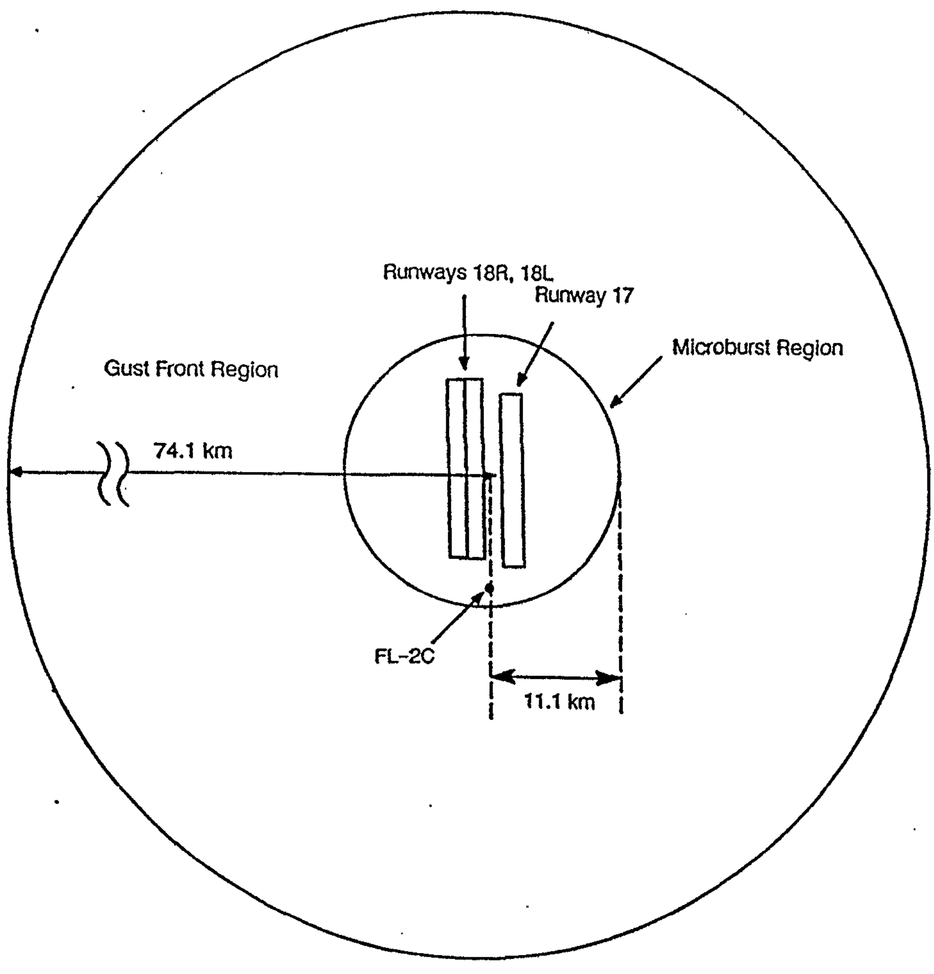


Figure 4-2. Orlando PRF selection regions.

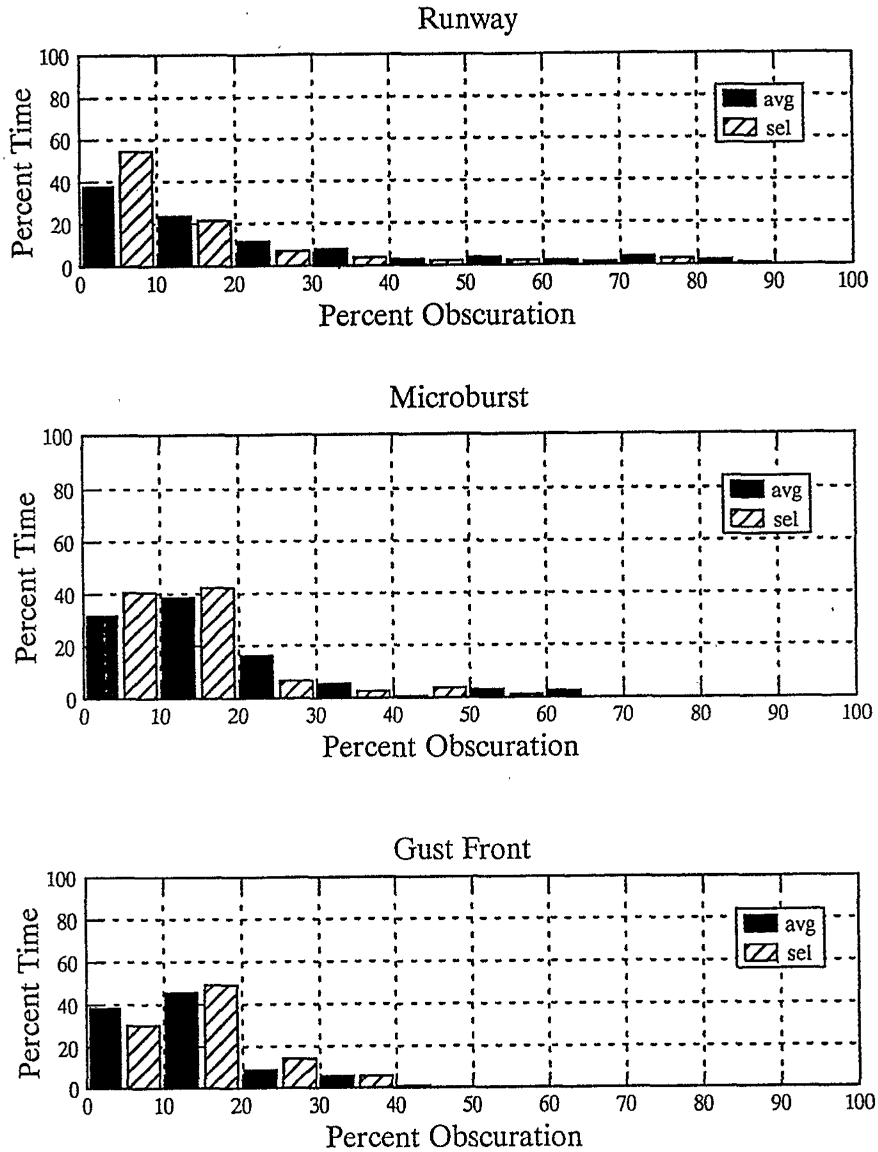


Figure 4-3. Orlando obscuration–10 heavy obscuration days.

2. Range Obscuration Editing

The range obscuration editing capability used in Orlando was functionally similar to that used in Kansas City: long range (low PRF) distant weather information collected once per volume scan is used to estimate the out-of-trip contributions to first trip sample volume measurements; first trip signal strength must exceed the estimated out-of-trip contribution by a site-adaptable obscuration threshold for a sample volume to remain valid. The distant weather threshold remained at 5 dB for Orlando, but the obscuration threshold handling was modified to more closely emulate Raytheon TDWR capabilities:

1. The obscuration threshold was given a nominal value of 3.0 dB. The nominal value in Kansas City was 1.5 dB.

2. The obscuration threshold was not changed with elevation angle or elapsed time. In Kansas City, the threshold was dynamically adjusted in an attempt to account for storm structure variation with altitude and time.

Range obscuration editing was reasonably effective in Orlando despite C-band PRFs and the prevalence (though not to the same extent as in Kansas City) of distant weather. Wind shear detection algorithms, in particular, were well-served by the editing:

1. Only six percent of the microburst false alarms have been attributed to range obscuration.

2. A few gust front false alarms may have been due to range obscuration, but these are still under investigation.

The weather detection algorithm most affected by residual range obscuration was storm motion. This algorithm uses the TDWR precipitation product as input and nominally tracks weather at National Weather Service (NWS) level 2 and higher; the precipitation product was often noticeably contaminated with level 1 and 2 range obscuration, thus causing misleading storm motion vectors to be generated. A mid-demonstration change to track weather only at level 3 and higher significantly reduced the incidence of false vectors and did not adversely affect the usefulness of the storm motion product.

Another portion of the system which could benefit from improvements to range obscuration editing is the Raytheon velocity dealiasing algorithm. The "dual scan" dealiasing, in particular, is sensitive to errors in velocity estimation. These errors, if passed into the wind field model, can persist, especially in areas of sparse velocity data.

C. POINT TARGET REJECTION

The point target rejection algorithm proposed by Raytheon was implemented and used throughout the operational period. The algorithm searches reflectivity data for point targets spanning one, three and five sample volumes in range, using site-adaptable threshold tests to identify discontinuities at each of the three spatial scales. Raytheon has suggested 6, 36, and 60 dBZ for the one, three, and five sample volume tests. These thresholds are based on the theoretical response of their receiver to a "typical" point target. Based on analysis of Kansas City data containing actual aircraft targets, one, three, and five sample volume thresholds of 20, 20, and 40 dBZ were chosen for operational use in Orlando.

Visual examination of the edited data (in the form of resampled images) showed that the signatures of point targets, such as towers and aircraft, were substantially reduced but not always entirely eliminated. There was no evidence of a degrading effect on weather returns. Clutter returns were noticeably reduced; this is not surprising since the clutter environment of the Orlando site is characterized, to a large extent, by isolated and line features which can appear as point targets when viewed one-dimensionally. This clutter suppression capability contributed to the ability to operate without map-based clutter residue removal. Performance of the point target rejection did not seem particularly sensitive to the thresholds used, though further investigation of possible subtle effects on weather returns is warranted.

D. VELOCITY DEALIASING

A major goal of the Orlando demonstration was the evaluation of the Raytheon velocity dealiasing algorithm. This algorithm has some novel features, and so is considered a technical uncertainty in the TDWR systems being built by Raytheon. Those features include:

1. Two successive scans at a given elevation using complementary PRFs, allowing unambiguous velocity determination to several multiples of the Nyquist velocity. Due to scan strategy time constraints, this "dual-scan" method cannot be used at every elevation.

2. Radial and azimuthal velocity continuity constraints, including various quality checks.

3. A three-dimensional wind field model, initialized by the dual-scan process and updated at every elevation. The wind field model velocities are used as dealiasing references when there are insufficient valid data points to determine radial or azimuthal continuity.

A real-time implementation of this algorithm for the FL-2C testbed Concurrent 3280 minicomputer was designed, coded in FORTRAN, and tested. By the start of the demonstration this implementation had been accepted for operational use, pending results of continued observation of the dealiasing quality.

The algorithm performance was evaluated in real time by observation of the base data velocity display. As expected, there were occasional errors made during dealiasing, though most were well contained spatially and temporally. On several occasions, however, the operators concluded that the windfield model had been sufficiently corrupted by errors that the dealiasing quality was compromised and that the wind field model would not self-correct. On these occasions the operators forced re-initialization of the wind field model.

There were two recorded instances of gust front false detections and one instance of a suspect hazard level where dealiasing efforts may have been a contributing factor. These are under investigation. There were no recorded instances of microburst false alarms attributed to dealiasing errors. There was one microburst hazard level which was exaggerated due to a dealiasing error, but this error has been shown to be due to residual clutter (and would not have occurred had clutter residue editing been used during operations).

Data analysis performed concurrently with the operational demonstration identified implementation deficiencies and errors and suggested changes to site-adaptable parameters. The following changes were made during the demonstration:

1. The implementation was corrected so that velocity changes resulting from azimuthal shear minimization would not be discarded.

2. The implementation was modified to work around a compiler flaw which prevented dealiasing during azimuthal shear minimization.

3. The implementation was modified to maintain full dynamic range of velocity information during dealiasing, with clipping to the limits of the real-time system velocity data format occurring only when it would not affect dealiasing quality.

4. The table of PRF pairs used by the PRF selection algorithm was modified to reduce the theoretical probability of false velocity correction during dual-scan dealiasing.

These changes, had they been in place from the start of the demonstration, would have eliminated many errors and would have reduced the number of times the operators had to force wind field model re-initialization.

Additional data analysis has identified a number of improvements which would eliminate almost all remaining errors:

1. Clutter residue editing should be used, even in a relatively benign clutter environment such as Orlando.

2. Azimuthal shear minimization should be invoked as a quality check for all velocities, not just those which have been radially dealiased.

3. Dual-scan-dealiased velocities which are to be incorporated into the wind field model should be required to pass a quality check; this quality check is already required on non-dual scans.

4. Wind field model smoothing, which is accomplished by dealiasing wind field model sectors against azimuthal neighbors, should be used judiciously since it can propagate isolated wind field model sector errors throughout the model. The Orlando environment does not appear to need wind field model smoothing, though some sites might.

Dealiasing algorithm robustness relative to range obscuration is critical to good overall performance. While the changes above make the Raytheon algorithm very robust, there is still the potential for range obscuration to compromise the quality of dealiased velocities. An enhanced ability to flag obscured sample volumes would be desirable since it is unlikely that range obscuration can be significantly reduced.

5. AIR TRAFFIC OPERATIONAL ASSESSMENT

A. AIR TRAFFIC CONTROLLER AND SUPERVISOR TRAINING

It was concluded from the Kansas City operational demonstration that the Kansas City air traffic controllers and supervisors did not receive adequate training on the geographic situation display (GSD) and ribbon display terminal (RDT) prior to the 1990 demonstration. Since the Orlando demonstration was scheduled to coincide with an operational demonstration in Denver, it was decided that Lincoln would train the Orlando International Airport (MCO) personnel. To provide more training for air traffic control (ATC) personnel, a training system was developed. This system consisted of a stand-alone GSD and RDT, with data cases that could be replayed to generate runway alerts. At the beginning of the training period, these alerts were generated by overlaying Kansas City radar data on Orlando runways. The Kansas City data were replaced as Orlando data became available.

Training of the MCO controllers and supervisors was performed over a two-week period. A verbal briefing of the TDWR program took place during the first week. This briefing, which lasted about 45 minutes, covered the following topics.

1. Overview of TDWR,
2. Objectives of the Orlando demonstration,
3. Location of sensors,
4. System performance based upon past demonstrations (Denver and Kansas City),
5. Technique for generating wind shear messages (intersection of alarms and runway boxes),
6. Pilot response to wind shear messages and potential operational impact (avoidance under microburst alert conditions),
7. Overview of GSD products and functions,
8. Function of terminal radar control facility (TRACON) and tower observers, and
9. Role of MCO ATC personnel in operational demonstration

During the second week of the training period, the supervisors and controllers were given the opportunity for hands-on experience with the GSD and RDT training system. The ATC supervisors and controllers were encouraged to become familiar with the functionality of the GSD and to read wind shear and microburst messages aloud to simulate the delivery of the messages to pilots. The training machine was made available to ATC personnel throughout the demonstration period to allow them the opportunity to use the GSD off line or to demonstrate new products before their introduction into the operational ATC environment.

1. Training Effectiveness

Based upon comments and remarks from observers, the training program was not totally effective. Questions that had been addressed in the briefing sessions were asked by controllers repeatedly throughout the demonstration. During operations, ATC supervisors needed help from the observers to change settings on the GSD, and the RDT messages had to be explained repeatedly to controllers.

The ineffectiveness of the training could be attributed to a number of reasons:

1. The training was conducted one to two weeks before the beginning of the operational demonstration, so controllers could not put their training into practice immediately. No follow-up briefings were provided.

2. The emphasis of the training was on describing the TDWR program and its products rather than discussing the impact of the system on Orlando operations. ATC personnel had no clear idea of their role in the demonstration, and as a result assumed the roles of observers rather than as participants in the demonstration. This misconception was reinforced by the inaccessibility (due to location) of the GSD in the tower and TRACON.

3. The training sessions were too informal. The environment in which the training sessions were conducted (a small, noisy room without tables or desks) did not encourage the supervisors and controllers to pay full attention to the information being presented. No hand-outs were provided to allow supervisors and controllers to follow the discussion.

4. ATC personnel did not take full advantage of the facilities provided to become acquainted with the GSD and RDT. Even though the training machine was available to ATC personnel throughout the demonstration, few of the controllers and supervisors used the equipment. In addition, the training machine was located in the training room which was used by ATC personnel only during training sessions.

Training effectiveness should be improved by the following changes for 1991:

1. Training should be conducted in a more-formal (classroom) environment to emphasize the seriousness of the demonstration. The Federal Aviation Administration Technical Center (FAATC) should be involved. This would be seen by ATC personnel as embodying authority.

2. Training should emphasize the role of ATC personnel as the primary participants in the demonstration. The locations of the GSD should be changed to allow easy access by supervisors and controllers as they perform their regular duties.

3. ATC personnel should be re-briefed regularly (bi-weekly) throughout the demonstration. This time would be used to answer questions, explain products, discuss the status of the demonstration, obtain feedback from supervisors and controllers, or discuss new products.

4. The training machine should be located in the conference room or in the break room to encourage ATC personnel to make use of it.

2. ATC Personnel Assessment of GSD and RDT

One of the objectives of having observers in the Orlando tower during the 1990 demonstration was to gather ATC personnel comments on the look and feel of the GSD and RDT. The following is a prioritized list of issues identified during the course of the demonstration. The first four are considered major issues that should be addressed to Raytheon.

"TDWR IMPAIRED" Message on RDT

During the demonstration, if a problem occurred with the radar, communications, or GSD, the message "TDWR IMPAIRED -- SWITCH TO LLWAS" appeared on the RDT. Apparently this message is **not** part of the Raytheon GSD design. If a problem occurs in the Raytheon system and the system monitor does not detect it (i.e., communication line faults), the RDT continues to display the old messages. Controllers have no way of knowing that there is a problem with the system and that the messages they are delivering may be incorrect. It is **essential** that some indication of system status be available to controllers for all situations.

Visual Indicator of Alarms on RDT

When the RDT goes from non-alarmed to alarmed state, an audible alert is sounded. The alerts on the VT220s used during the demonstration were too faint to be heard by the controllers, creating concern about potentially missing an alarm. This resulted in the installation of a visual alert of alarm status, which is not a feature of the Raytheon GSD. This indicator consisted of alternating the video intensity of the messages for runways that were in alarmed condition. During the installation of this feature, the audible alert feature was inadvertently turned off. Although ATC personnel approved of the visual alert, a few controllers and supervisors expressed a preference for the audible alert. The RDT should contain both types of alerts.

GSD Lock-up Due To Open Menu

On one occasion during the demonstration, the range menu was selected and left open. This prevented the GSD from updating the graphics window, although the RDT messages continued to update appropriately. The menu choices should be implemented such that the GSD continues to update even though a menu is open.

Runway Configuration

Upon selecting the runway button, the user is presented with two options: editing the runway configuration or installing a default runway configuration. To *install* a default configuration, the user must move the cursor onto that option and then to the far right to bring up the default options. This is called a walking menu, and it is the only walking menu on the GSD. The cursor must move a great distance to bring up the default menu, and the positioning of the menu (lower right corner) makes it difficult to see the arrow that indicates the presence of the walking menu.

With the default menu exposed, the user is then presented with a list of the numbers 1 through 8. Each number represents a default configuration. If the user is not intimately familiar with the configuration associated with each number, the user will have difficulty making the proper selection. In addition, if the user selects the install option without "walking" to the default configuration menu, the configuration associated with default 1 is automatically installed.

The procedure for *editing* runway configurations is also difficult to use. It allows the user to inadvertently design nonsensical configurations, such as assigning runways to controllers without making the runways active and/or activating runways without assigning those runways to a controller. The software supports eight message lines per RDT, eight RDTs, and eight default runway configurations. All of these are labelled 1 through 8, which is very confusing to ATC personnel and caused some consternation among the observers who at least had experience with a Sun workstation. The mechanism for saving default configurations allows the user to easily write over exiting configurations (i.e., there is minimal write protection). When the install button on the runway menu is pressed, the menu disappears. If a mistake has been made or if the user does not like the newly installed configuration, the user must reopen the menu to make further changes. ATC personnel would like the menu to remain open until they are satisfied with the configuration.

Latency

ATC personnel perceive that the time between making a change to the display (e.g., changing the display range or overlays) and seeing that change reflected on the screen is too long. This latency is particularly long when the GSD is receiving a product update. Putting a message on the screen that indicates to ATC personnel that their command has been accepted would alleviate the problem.

Overlay Menu

When the overlay button is selected, the user is presented with four options (ASR rings, outlying airports, etc.). Selecting an option toggles the overlay on the display (if the overlay is on, it is turned off, and vice versa). This requires that the user know if an overlay is currently on or off in order to determine what impact his selection will have on the display. Also, each time an option is selected, the menu closes. If the user wishes to change three of the overlays, he must open the menu three times. The menu should remain open until the user is satisfied with the overlays and there should be some indication on the menu that the overlays are either on or off.

Microburst Box

When the microburst algorithm declares a detection, a red box containing the word "Microburst" is turned on in the upper right corner of the GSD. The purpose of this box is to indicate to the supervisor that the microburst algorithm has detected an event that may not be visible on the GSD, depending upon the display range. This red box is lighted even if the strength of the detected event is below the microburst threshold of 30 kts. This feature was questioned by a number of supervisors and controllers who did not understand why the box indicated that a microburst had been detected when only wind shears were displayed, even though the meaning of the box had been discussed during the training sessions.

GSD Time

The time shown in the upper right corner of the GSD is different from the other ATC displays. This caused some confusion for the observers and brought comments from the controllers. The time on the Low-Level Wind Shear Alerting System (LLWAS) display and RDT (which is taken from the LLWAS) is Universal time and updates every 10 seconds. The time on the on the GSD is local time and updates every second. So, not only do the displays disagree on hours, but also on seconds. To alleviate any confusion this might cause, the GSD clock should report Universal time.

Other ATC Personnel Suggestions

The microburst shapes should be concentric red band-aids instead of solid red band-aids so that the weather under the band-aids can be seen without using the clear button.

The cursor should not be an arrow. Arrows are used for the storm motion and gust front products. Even though the cursor arrow is different in shape, it causes confusion for controllers and supervisors because it is often located in the Graphics Display Window. To avoid this confusion, the cursor should be identified by a different symbol.

The indicators for storm motion and gust front wind shift should be different. Both products use the same arrows, but of different colors. It is very difficult to distinguish between the colors from a distance, and the arrows (same shapes) represent different information. The gust front arrow indicates the direction of the winds behind the gust front while the storm motion arrow shows the direction of movement of the storm.

The white background on the GSD is too bright for the TRACON environment. The monitor brightness was decreased for the demonstration, which was deemed adequate by ATC personnel. However, a darker background color would be preferable.

3. ATC Personnel Assessment of TDWR Products

ATC personnel were very pleased with many of the products provided during the demonstration, especially those products that aided airspace management. The gust front and wind shift products were frequently used to plan runway changes. In addition, many of the supervisors and controllers expressed a desire for the storm motion product prior to its introduction into the operational environment. Once introduced, the storm motion product was very well received.

The microburst product was considered a problem by ATC personnel because it resulted in reduced operations. Pilots from many of the major airlines were directed by their companies to decline takeoff or abort landing under microburst alert conditions. This had a tremendous impact upon operations. Often in situations where an aircraft penetrated a microburst, there was no confirmation of the hazard. Therefore, whereas the gust front and storm motion products were seen as helpful to operations, the microburst product was often considered a detriment.

On the other hand, pilots (for whom the microburst product was designed) appreciated the product. Although there was an overwarning problem in the early part of the demonstration (see section 2.C., Overwarning Issues) pilots continued to comment favorably on the microburst product. This highlights the conflict between the goals of improving safety for aircraft and increasing airport capacity.

At the conclusion of the TDWR demonstration, the FAATC provided Orlando ATC personnel with an evaluation form. The responses to the questions on the evaluation have been tabulated by the FAATC and are available from Mr. Eric Hess, FAATC, Atlantic City International Airport, NJ 08405. In general, ATC personnel approved of the TDWR products and displays.

APPENDIX A
AVAILABLE FIELD DATA

1. WIND SHEAR EVENTS OBSERVED WITH TDWR TESTBED AND UND RADARS

The following pages (Table A-1) include the events recorded by FL-2C during the OT&E period. Coordinated coverage by the University of North Dakota (UND) and FL-2C began on August 10. The data were recorded in real time; therefore, some reflectivity values are not available. The events with the asterisk next to them are the events for which the UND radar was not operating. Most of these were at the beginning or end of a mission.

Table A-1.
1990 OT&E Wind Shear Event Summary for Lincoln Field Radar, FL-2, Orlando, FL.[2]

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
June 18	MB	1731	8/005	10	50
June 18	MB	1734	17/259	12	45
June 18	GF	1750	9/233	5	5
June 18	MB	1848	26/320	12	45
June 18	MB	2058	17/241	14	50
June 19	GF	2029	33/140	8	15
June 19	GF	2135	10/235	7	
June 20	MB	1818	9/048	10	50
June 20	MB	2048	21/352	10	35
June 21	MB	2017	9/152	14	50
June 21	MB	2101	3/083	12	45
June 21	MB	2117	19/349	16	50
June 21	MB	2123	38/094	18	55
June 21	MB	2137	39/346	10	45
June 21	MB	2146	31/003	16	55
June 21	MB	2205	30/057	11	55
June 21	MB	2208	32/353	13	55
June 21	MB	2208	44/037	16	55
June 21	MB	2214	38/011	21	55
June 21	MB	2215	36/356	13	55
June 22	MB	1854	56/327	20	50
June 22	MB	1901	42/253	19	50
June 22	GF	1916	16/264	14	10

2 Real-time reflectivity data was not available for all events.

**Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.**

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
June 22	MB	1937	24/308	16	50
June 22	MB	1955	12/339	12	45
June 22	MB	2035	26/083	20	55
June 23	MB	1512	24/322	16	55
June 23	GF	1528	8/359	12	5
June 23	MB	1556	2/348	13	50
June 23	MB	1600	5/049	14	55
June 24	GF	1847	19/340	8	10
June 24	MB	1851	16/233	12	50
June 24	MB	1856	14/349	16	50
June 24	MB	1925	5/351	15	55
June 24	GF	1938	4/161	6	
June 24	MB	1939	40/240	12	50
June 24	MB	2001	39/228	16	50
June 24	MB	2017	23/197	18	50
June 24	MB	2032	40/153	15	65
June 24	MB	2147	24/306	16	
June 25	MB	1845	32/119	16	45
June 25	MB	1946	21/144	17	55
June 25	MB	1946	35/153	14	50
June 25	MB	2001	30/125	12	50
June 25	MB	2022	21/116	25	55
June 25	GF	2023	16/093	10	10

**Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.**

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
June 25	MB	2052	19/121	34	55
June 25	MB	2132	6/116	20	50
June 25	MB	2107	6/109	24	55
June 25	GF	2142	13/333	10	10
June 25	MB	2122	30/190	27	55
June 25	MB	2134	17/039	10	45
June 25	MB	2137	8/166	16	50
June 25	GF	2150	48/021	4	15
June 25	MB	2152	15/246	10	45
June 25	MB	2236	17/012	12	50
June 25	MB	2239	25/020	18	55
June 25	MB	2244	22/020	18	
June 26	GF	1952	3/260	11	10
June 26	GF	1759	57/103	12	
June 26	MB	1805	24/337	14	45
June 26	MB	1805	60/341	15	55
June 26	MB	1805	53/006	14	50
June 26	GF	1841	21/058	6	
June 26	MB	1916	24/002	14	55
June 26	MB	1922	14/116	10	50
June 26	MB	1951	21/346	12	60
June 26	MB	2005	17/008	10	55
June 26	GF	2156	12/350	10	

Table A-1 (Continued). 1990 OT&E Wind Shear Event Summary for Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
June 30	MB	1727	39/325	10	55
June 30	MB	1732	17/310	10	50
June 30	MB	1737	34/358	10	50
June 30	MB	1747	41/332	12	55
June 30	MB	1800	8/359	12	50
June 30	MB	1846	52/341	14	50
June 30	MB	1941	34/051	12	45
June 30	MB	2011	38/63	16	50
June 30	MB	2047	74/020	17	50
June 30	GF	2046	22/066	7	5
June 30	MB	2137	42/264	14	55
July 1	MB	1741	3/239	12	55
July 1	MB	1757	5/203	22	50
July 1	MB	1818	9/151	12	50
July 1	MB	1850	30/182	14	55
July 1	MB	1850	39/182	12	50
July 1	GF	2059	32/139	12	5
July 1	GF	1924	38/062	8	
July 1	MB	1929	66/058	20	55
July 1	MB	1937	67/333	14	50
July 1	GF	2011	36/331	7	10
July 1	MB	2023	42/339	13	55
July 1	MB	2043	37/053	25	55

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
July 1	MB	2047	16/059	17	55
July 1	MB	2116	9/043	13	55
July 1	MB	2121	21/058	21	50
July 1	MB	2148	12/072	15	55
July 2	GF	1848	56/092	5	
July 2	GF	1927	25/059	8	0
July 2	GF	1930	37/359	6	5
July 2	MB	1947	50/035	15	50
July 2	MB	1959	35/005	21	55
July 2	MB	2033	23/357	10	50
July 2	MB	2036	22/044	36	55
July 2	GF	2046	10/325	8	
July 2	MB	2116	15/124	18	50
July 2	MB	2226	30/059	12	25
July 4	MB	1929	33/208	17	50
July 4	MB	1952	21/182	22	55
July 4	MB	1955	12/212	20	55
July 4	GF	2019	12/016	10	10
July 4	MB	2020	3/136	20	55
July 4	MB	2020	2/156	18	50
July 4	MB	2046	14/019	17	55
July 4	MB	2047	20/064	10	50
July 4	MB	2049	23/041	16	50

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
July 4	MB	2051	18/033	18	55
July 4	MB	2055	35/326	20	50
July 4	MB	2103	26/031	18	55
July 4	MB	2118	66/206	18	55
July 4	MB	2125	34/033	26	55
July 6	GF	2110	44/077	7	10
July 6	MB	2254	24/090	18	50
July 7	MB	1808	30/088	14	50
July 7	MB	1812	28/043	13	50
July 7	GF	1820	19/100	8	10
July 7	GF	1832	16/020	7	
July 7	MB	1854	14/011	26	60
July 7	MB	1859	30/172	21	55
July 7	MB	1909	21/305	21	45
July 7	MB	1916	22/171	21	55
July 7	MB	1919	30/173	11	50
July 7	MB	1924	16/316	17	50
July 7	MB	1934	15/306	18	45
July 7	MB	2005	21/274	30	50
July 8	MB	1737	8/197	10	55
July 8	MB	1831	5/352	14	55
July 8	MB	1952	9/006	17	60
July 8	MB	1952	5/020	20	55

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
July 8	MB	2000	6/009	14	50
July 8	MB	2002	15/013	14	50
July 8	MB	2009	3/349	23	55
July 8	GF	2022	2/173	6	
July 8	MB	2030	14/359	16	50
July 8	GF	2102	14/196	6	5
July 8	MB	2112	10/320	10	45
July 8	GF	2126	24/052	6	5
July 9	MB	1623	28/099	18	55
July 9	MB	1628	15/006	12	50
July 9	MB	1631	19/355	18	50
July 9	MB	1632	10/044	10	45
July 9	MB	1643	9/080	14	50
July 9	MB	1648	2/136	14	50
July 9	MB	1651	28/065	16	50
July 9	MB	1658	10/202	12	40
July 9	MB	1705	29/047	18	45
July 9	MB	1707	10/056	16	50
July 9	MB	1732	11/000	25	55
July 9	GF	1734	20/280	10	
July 9	GF	2035	26/157	5	20
July 9	MB	2040	31/059	14	55
July 9	MB	2046	30/166	15	55

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
July 9	MB	2101	12/080	15	55
July 9	MB	2150	12/027	18	55
July 11	MB	1739	24/173	14	55
July 11	MB	1805	10/325	16	50
July 11	MB	1819	12/037	10	45
July 11	MB	1819	28/205	18	45
July 11	MB	1826	2/290	17	50
July 11	MB	1830	20/135	18	50
July 11	GF	1832	5/003	6	
July 11	MB	1838	4/034	19	50
July 11	MB	1838	10/025	12	50
July 11	MB	1852	4/008	16	50
July 11	MB	1858	9/028	14	55
July 11	MB	1930	32/342	16	55
July 12	GF	0043	7/031	6	
July 12	MB	1813	15/292	10	55
July 12	MB	1814	79/028	12	55
July 12	GF	1820	19/224	6	
July 12	MB	1837	30/320	10	50
July 12	GF	1846	26/114	6	
July 12	MB	1857	22/126	28	50
July 12	MB	1857	32/054	10	50
July 12	MB	1917	24/070	27	55

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2,Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
July 12	GF	1923	17/059	8	
July 12	MB	1939	34/041	18	45
July 12	MB	1952	32/030	16	55
July 12	MB	1953	9/302	16	50
July 12	MB	2003	25/267	16	45
July 12	MB	2042	34/219	20	50
July 12	GF	2054	21/216	12	15
July 12	MB	2059	33/190	14	55
July 12	MB	2104	24/245	24	50
July 12	MB	2104	24/258	27	50
July 12	MB	2114	23/261	27	50
July 12	MB	2114	26/204	21	50
July 12	MB	2129	29/167	18	50
July 12	MB	2154	16/281	21	50
July 12	GF	2154	19/299	9	
July 12	GF	2159	10/020	13	
July 12	MB	2213	5/039	19	50
July 12	MB	2240	11/023	15	45
July 13	GF	1820	26/132	6	5
July 13	MB	1825	10/260	14	50
July 13	MB	1833	33/029	12	50
July 13	MB	1835	13/299	21	50
July 13	MB	1840	8/254	15	50

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
July 13	MB	1850	19/312	21	50
July 13	MB	1856	18/327	12	40
July 13	GF	1905	8/020	16	15
July 13	MB	1916	16/100	12	45
July 13	MB	1924	11/032	11	50
July 13	MB	1934	20/160	22	50
July 13	MB	1937	58/003	18	45
July 14	MB	1505	21/334	10	50
July 14	GF	1517	19/260	8	
July 14	MB	1520	23/036	12	35
July 14	GF	1524	7/146	12	
July 14	MB	1623	19/199	12	50
July 14	GF	1632	29/072	10	
July 14	GF	1850	29/300	9	
July 14	GF	2117	61/115	15	
July 15	GF	1857	35/308	6	10
July 15	GF	1901	32/115	8	15
July 15	MB	1946	36/60	14	50
July 15	MB	2006	20/268	16	50
July 15	MB	2015	43/044	14	50
July 15	GF	2016	29/231	10	25
July 15	MB	2035	20/251	18	55
July 15	GF	2042	13/170	12	50

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
July 15	MB	2047	25/200	10	45
July 15	MB	2049	5/349	10	50
July 15	MB	2056	8/360	10	50
July 15	MB	2059	8/183	50	50
July 15	MB	2102	2/360	20	45
July 15	MB	2118	16/018	12	40
July 15	GF	2122	6/360	12	35
July 15	MB	2126	17/014	12	40
July 25	GF	1911	42/230	6	5
July 25	MB	1940	80/352	15	55
July 25	MB	1952	39/052	16	50
July 25	GF	1956	26/040	7	10
July 25	GF	1958	52/352	7	10
July 25	MB	2012	30/054	12	50
July 25	MB	2016	45/019	18	50
July 25	GF	2016	39/346	15	25
July 25	GF	2017	22/225	9	10
July 25	MB	2033	20/323	18	50
July 25	MB	2039	29/333	24	55
July 25	MB	2043	27/015	12	50
July 25[3]	GF	2053	18/011	12	10

[3] Lightning strike occurred on July 25.

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
August 10[4]	MB	1822	22/240	14	55
August 10	MB	1837	27/190	16	50
August 10	MB	1905	8/206	16	50
August 10	GF	1920	10/061	4	
August 10	GF	1950	31/108	8	15
August 10	GF	2131	22/083	7	10
August 10	MB	2149	59/328	12	50
August 10	MB	2222	49/304	16	50
August 10	GF	2251	40/279	16	
August 10	MB	2308	23/355	17	50
August 10	MB	2309	24/335	24	50
August 10	GF	2311	14/355	18	
August 10	MB	2311	17/001	13	50
August 10	MB	2321	19/340	36	50
August 10	MB	2346	17/315	18	50
August 10	MB	2349	17/302	23	55
August 10	MB	2349	10/283	15	50
August 10	MB	2349	14/024	26	50
August 10	MB	2356	23/262	20	50
August 10	MB	0014	18/236	16	50
*August 11	MB	1833	34/313	17	50
August 11	MB	1855	17/303	15	45
August 11	GF	1855	8/018	14	15

[4] Coordinated scanning began.

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
August 11	MB	1909	20/243	26	50
August 11	MB	1917	13/092	12	45
August 11	MB	1923	17/213	21	50
August 11	MB	1942	24/046	21	50
August 11	MB	1945	40/022	18	45
August 11	MB	2012	39/056	11	45
August 13	MB	1839	53/137	18	50
August 13	GF	1825	13/049	6	15
August 13	MB	1855	40/080	13	50
August 14	MB	1736	16/105	18	50
August 14	GF	1737	11/092	8	10
August 14	GF	1749	7/353	10	15
August 14	MB	1804	17/310	16	50
August 14	MB	1811	13/066	15	50
August 14	MB	1823	19/331	15	50
August 14	MB	1854	29/089	12	50
*August 14	MB	2004	30/149	12	45
August 15	GF	2138	37/102	6	15
August 15	GF	2212	58/131	12	35
August 15	GF	2232	47/190	9	7
August 15	MB	2247	57/128	18	50
August 16	MB	2055	82/010	18	55
August 16	GF	2110	28/073	7	15
August 16	MB	2143	66/016	12	53

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
August 16	MB	2210	27/086	19	55
August 16	MB	2218	27/106	17	55
August 16	MB	2224	25/021	18	55
August 16	MB	2226	18/007	16	55
August 16	GF	2226	31/011	5	
August 16	MB	2229	29/040	24	55
August 16	MB	2236	21/017	15	55
August 16	MB	2239	29/124	17	55
August 16	GF	2241	25/157	8	10
August 16	MB	2301	32/024	22	55
August 16	MB	2306	31/019	23	55
August 16	MB	2315	18/011	19	55
August 16	MB	2325	38/104	16	50
August 16	MB	2331	37/268	18	50
*August 16	GF	0012	11/270	6	5
August 17	MB	1859	70/050	14	50
August 17	MB	1940	40/078	12	50
August 17	MB	1945	49/057	16	50
August 17	MB	1954	22/115	20	50
August 17	GF	20025	30/122	14	15
August 17	MB	2005	50/114	18	45
August 17	MB	2005	27/129	16	50
August 17	GF	2012	7/021	7	17

**Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.**

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
August 17	MB	2046	38/183	24	50
August 17	MB	2100	48/137	11	50
August 17	MB	2130	35/162	14	50
August 17	MB	2136	40/205	22	50
August 17	MB	2206	44/220	10	50
August 18	GF	1934	34/039	6	20
August 18	MB	1846	70/031	12	50
August 18	MB	1908	54/055	16	50
August 18	MB	1920	31/004	11	45
August 18	MB	1920	54/074	16	50
August 18	MB	1935	26/078	14	50
August 18	MB	1949	19/084	14	50
August 18	MB	1954	41/078	15	
August 18	MB	1956	27/359	23	35
August 18	MB	2011	12/027	17	50
August 18	MB	2011	27/014	16	50
August 18	MB	2017	13/010	30	55
August 18	MB	2019	10/040	18	50
August 18	MB	2036	15/106	19	50
August 18	MB	2036	20/121	13	55
August 18	MB	2045	21/269	20	50
August 18	MB	2045	18/131	12	50
August 18	MB	2100	40/152	16	50

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
August 18	MB	2100	37/184	12	50
August 19	MB	1759	19/109	11	55
August 19	MB	1759	29/113	10	50
August 19	GF	1806	14/139	5	
August 19	MB	2056	13/350	11	50
August 19	MB	2100	12/055	14	50
August 19	MB	2112	10/025	18	55
August 19	MB	2143	4/291	24	55
August 19	GF	2148	10/223	7	
August 19	MB	2158	28/105	10	45
August 20	MB	1920	33/121	13	50
August 21	MB	1703	7/358	14	55
August 21	GF	1952	65/223	5	10
August 21	MB	2002	73/035	10	
August 21	MB	2004	42/008	10	50
August 21	MB	2021	39/007	14	50
August 21	GF	2029	43/262	10	10
August 21	GF	2033	31/003	6	15
August 21	MB	2144	41/277	21	55
August 21	MB	2157	23/310	14	55
August 21	MB	2201	31/347	10	50
August 21	MB	2209	32/321	12	50
August 21	MB	2210	29/352	10	50

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
August 21	MB	2218	17/342	27	55
August 21	MB	2224	13/351	12	50
August 21	MB	2231	22/009	10	50
August 21	MB	2238	17/015	10	
August 21	MB	2243	28/012	14	50
August 21	MB	2248	9/343	10	55
August 21	MB	2254	12/355	10	55
August 21	MB	2256	22/023	12	50
August 21	MB	2308	37/251	12	50
August 21	MB	2346	10/046	20	55
August 21	MB	2347	11/044	14	55
August 21	MB	0011	22/051	10	50
August 21	MB	0018	33/066	16	50
August 21	GF	0019	34/094	16	
*August 22	GF	1909	36/010	5	10
August 22	MB	2042	10/345	40	50
August 22	GF	2049	12/254	9	15
August 22	MB	2100	20/005	30	50
August 22	MB	2101	15/278	14	50
August 22	MB	2101	11/342	14	
August 22	MB	2106	2/348	22	50
August 22	MB	2124	11/244	30	55
August 22	GF	2133	19/133	8	12

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
August 22	MB	2137	26/042	24	50
August 22	MB	2155	36/061	20	55
August 22	MB	2155	37/050	16	45
August 22	MB	2206	20/222	16	45
August 22	MB	2246	23/146	20	50
August 23	GF	1515	10/359	6	10
August 23	MB	1530	25/358	12	50
August 23	MB	1536	29/280	12	50
August 24	MB	1606	30/250	11	50
August 24	MB	1712	26/310	19	55
August 24	GF	1710	5/110	8	5
August 24	MB	1723	4/162	18	55
August 24	MB	1754	30/042	12	50
August 25	MB	1934	26/037	10	50
August 25	MB	1937	5/211	17	50
August 25	MB	1938	16/028	13	45
August 25	GF	1944	21/029	8	15
August 25	GF	1944	12/031	6	15
August 25	GF	2031	27/196	9	15
August 25	MB	2037	21/166	12	50
August 25	MB	2047	28/030	10	45
August 25	MB	2057	18/184	15	45

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
August 25	MB	2107	15/159	14	50
August 25	MB	2148	19/325	21	50
August 25	MB	2158	16/021	13	50
August 25	MB	2158	13/357	20	50
August 25	MB	2204	15/087	14	50
August 25	MB	2234	33/331	13	55
August 26	GF	1929	23/061	7	18
August 26	MB	2114	19/092	10	40
August 26	MB	2137	38/005	14	50
August 26	GF	2158	26/360	6	10
August 26	MB	2200	15/150	14	45
August 26	MB	2217	15/346	10	55
August 26	MB	2225	28/078	16	50
August 26	MB	2245	20/316	12	45
August 26	MB	2249	16/335	18	50
August 26	GF	2312	16/295	16	5
August 27	MB	1620	20/096	12	45
August 27	MB	1653	51/057	14	55
August 27	MB	1700	24/119	10	45
August 27	GF	1744	28/076	10	10
August 27	MB	1753	59/100	12	50
August 27	MB	1756	39/104	10	50
August 27	MB	1806	59/125	12	50

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
August 27	MB	1811	54/024	10	50
August 27	MB	1832	30/096	10	50
August 27	MB	1837	29/157	16	50
August 27	MB	1847	20/077	16	55
August 27	MB	1852	44/100	16	55
August 27	MB	1902	23/280	10	50
August 27	MB	1902	27/185	16	55
August 27	MB	1916	9/075	18	55
August 27	MB	1919	15/039	14	50
August 27	MB	1935	7/046	27	55
August 27	MB	1950	15/174	27	60
August 27	GF	1952	22/031	6	
August 27	MB	2001	5/069	20	50
August 27	MB	2002	31/128	18	45
August 27	MB	2017	4/008	12	55
August 27	MB	2038	30/271	15	50
August 27	MB	2048	25/333	14	45
August 27	MB	2058	36/250	14	50
August 28	MB	1947	33/121	10	50
August 28	MB	2043	25/111	13	55
August 28	MB	2043	21/134	23	50
August 28	MB	2109	19/152	15	55

Table A-1 (Continued).
1990 OT&E Wind Shear Event Summary for
Lincoln Field Radar, FL-2, Orlando, FL.

Date	Event Type	Time GMT	Location Range (km)/ Azimuth (deg)	Delta V m/s	Reflectivity dBZ
August 28	MB	2110	29/330	11	55
August 28	MB	2142	19/313	28	60
August 28	GF	2154	8/297	14	
August 28	MB	2216	10/300	12	55
August 28	MB	2217	11/281	12	55
August 28	MB	2224	30/330	16	50

2. CITATION AIRCRAFT DATA

Table A-2 includes a summary of the UND Citation aircraft operations during the summer 1990 operations in Orlando, FL.

Table A-2.
UND Citation Aircraft Operations at Orlando, FL.

Date	Duration (hrs.)	Number of Microburst Penetrations	Summary
June 16	0.6	--	Shakedown flight
June 18	0.9	--	Shakedown flight
June 21	0.7	1	Weak shear on approach
June 22	0.9	1	Good shear on approach
June 24	0.9	2	Weak shears
June 26	0.7	2	Weak shears
June 27	0.5	--	Datalink shakedown flight

Table A-2 (Continued).
UND Citation Aircraft Operations at Orlando, FL.

Date	Duration (hrs.)	Number of Microburst Penetrations	Summary
June 28	1.0	--	Datalink Shakedown flight
June 28	0.6	--	Cockpit display test flight
June 30	0.5	3	Weak shears
July 1 (two flights)	2.0	4	Weak shears, strong crosswind
July 2	0.5	4	Strong downdrafts at 200 ft.
July 4	1.7	2	Weak shear, gust front
July 6	0.8	--	Cockpit display test flight
July 7	0.8	3	50 kt microburst case
July 8	2.2	7	Moderate and weak shears
July 9 (two flights)	2.1	3	Moderate and strong shears on second flight
July 11	1.4	3	Moderate shear
July 12	1.1	3	Strong downdraft case
July 13	1.3	5	Moderate downdrafts, weak shears
July 15	1.8	6	Strong downdrafts, moderate shears
July 17	1.4	--	Weak shears (no TDWR testbed coverage)
July 18	0.6	--	Citation test maneuvers (no TDWR testbed coverage)
July 20	1.1	--	Weak shears (no TDWR testbed radar coverage)
July 22	0.8	--	Data link test flight

Table A-2 (Continued)
UND Citation Aircraft Operations at Orlando, FL.

Date	Duration (hrs.)	Number of Microburst Penetrations	Summary
July 23	1.4	--	Weak downdrafts (no TDWR testbed radar coverage)
July 24	1.0	--	Good gust front case (no TDWR testbed coverage)
July 25	1.4	(15)	60 kt microburst (no radar during MB penetrations)
September 17	1.7	13	Moderate and weak shears
September 21	1.0	--	No microburst penetrations
September 23	2.0	5	Moderate downdrafts
September 27	2.0	--	Data quality problems
September 28	1.9	14	Moderate shears and downdrafts
Total	39.4	80	Microburst penetrations with TDWR testbed coverage

3. MESONET/LLWAS DATA

Meteorological data were collected by a network of Mesonets and a six-station LLWAS. Barometric pressure, temperature, relative humidity, precipitation, and wind data were collected by the Mesonet stations, while the LLWAS collected only wind information. The Mesonet stations were deployed around MCO, covering an area of approximately 225 square kilometers. Deployment of the stations was staggered, and only three-fourths of the network actually became operational. Figure A-1 depicts the network as it was configured early in September 1990.

A portion of the network was set up to emulate Orlando's enhanced LLWAS (ELLWAS), which is not expected to be operational until some time in 1991. This setup provided that wind data be collected every 15 seconds. To properly emulate the ELLWAS, however, the wind sensors were to be mounted atop 100-ft. towers. This would help eliminate obstruction effects primarily due to tall trees. However, because a number of problems were encountered, only 20 percent of the towers were erected. This was a contributing factor in the incomplete data coverage over the network. Figure A-2 indicates, for each station, what type of meteorological data was collected.

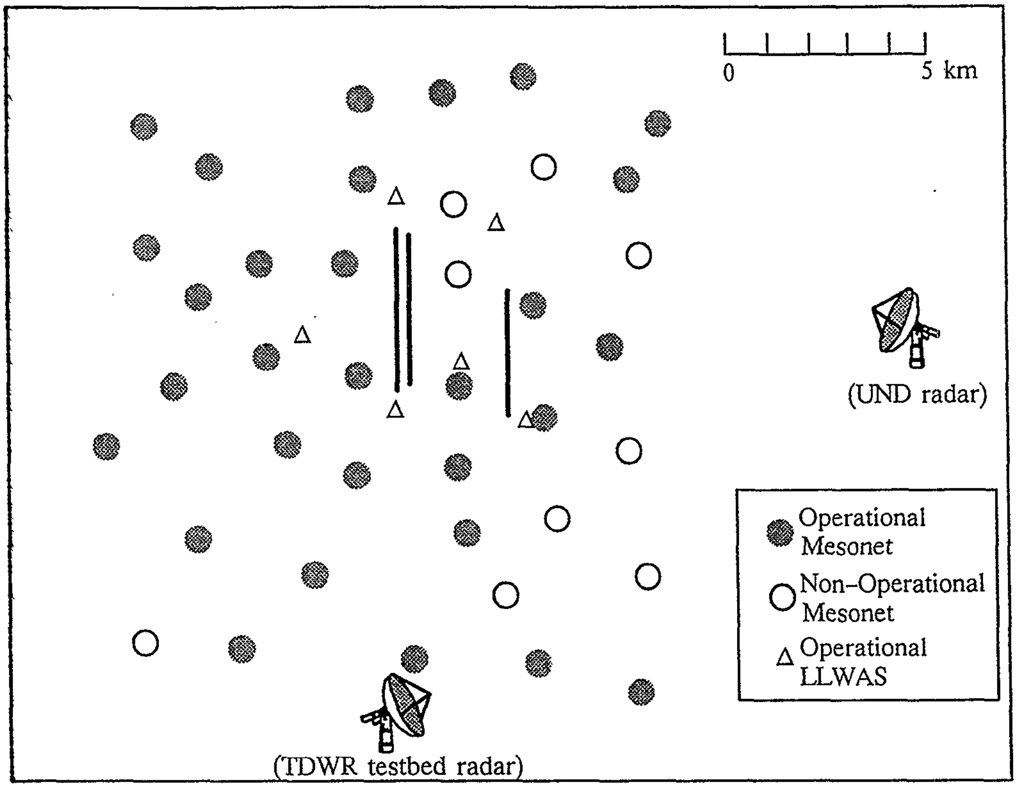


Figure A-1. Configuration and operational status of the Mesonet and LLWAS stations in Orlando, FL during September 1990. North/south lines in the middle of the network represent the runway configuration for MCO.

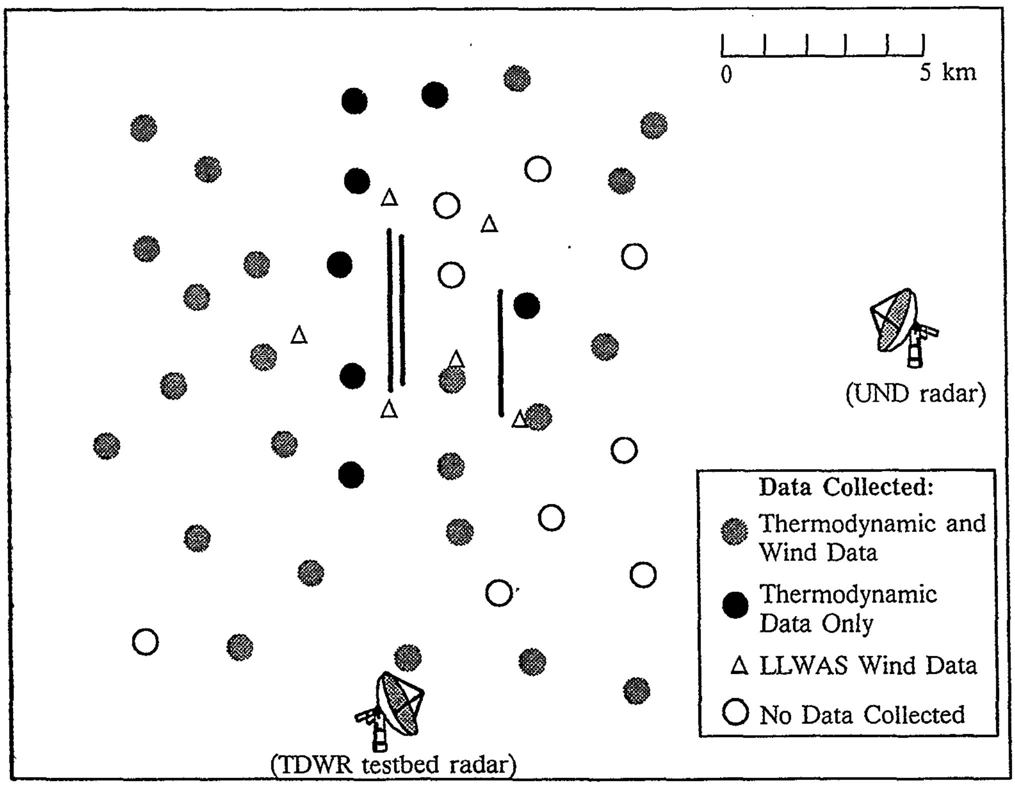


Figure A-2. Same as figure A-1, except that the type of meteorological data collected for each station is identified. Here, thermodynamic data consists of barometric pressure, temperature, and relative humidity. Also, all stations that were operational, except for LLWAS, collected precipitation (rate) data.

It is anticipated that during the 1991 data collection season, only 15 Mesonet stations will be operational. These stations will act to either emulate or supplement the ELLWAS. They will collect thermodynamic and wind data, as well as precipitation rate data. The wind sensors for these stations will be mounted atop 100-ft. towers to eliminate obstruction effects.

4. ATMOSPHERIC SOUNDINGS

Between July 1 and September 13, 1990, NSSL collected data on the vertical thermodynamic and dynamic structure of the atmosphere using the atmospheric sounding system know as M-Class (Mobile Cross-chain Loran Atmospheric Sounding System). The data recorded were 10-second measurements of temperature, dew point, atmospheric pressure, and wind speed and direction. The purpose of this data collection effort was to gather information on the atmospheric environment prior to daily thunderstorm and microburst development.

A total of 172 sounding were launched from a site approximately four miles east of MCO during July and August and from the UND radar site in September. Except for several days when the FL-2C radar was inoperable, launches were made daily at 12Z, 15Z and 18Z. A fourth launch was made later in the day if weather conditions were appropriate. Sounding data is available by request.

APPENDIX B
A PIREP-BASED ANALYSIS OF THE TDWR ALERT SYSTEM EVALUATED AT ORLANDO INTERNATIONAL AIRPORT DURING THE SUMMER OF 1990

During summer 1990 operations in Orlando, FL, the TDWR Program evaluated a system that provided wind shear and microburst alerts to pilots landing at and departing from MCO for a total of 37 days (i.e., from June 25 through July 15 and from August 13 through 28). Pilot reports (PIREPs) of weather-related encounters and observations were obtained for a majority of the alert periods.

This appendix presents a PIREP-based analysis of what took place during the examined alert periods and represents one component of the overall evaluation of the tested alert system and its set of candidate aviation weather products. The analysis is based on PIREPs obtained from two sources: pilots who (a) reported their experiences to Local Control by means of the ATC radio and/or (b) utilized the mail-in questionnaires that were provided in the cockpits of several of the airlines operating out of Orlando. The mailed-in questionnaires have been treated as confidential in the sense that the source of the data has not been identified.

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1. BACKGROUND

Wind shear in general and microbursts in particular are of concern to landing and departing pilots when thunderstorms are in the vicinity of an airport. One FAA activity addressing this concern is the development of the TDWR. The TDWR Program is in the process of conducting a series of operational demonstrations over a period of several years involving a number of airports. These demonstrations are being conducted to define and perfect a set of TDWR-based aviation weather products for operational use, investigate advanced TDWR-related system concepts and products, and do the ground work necessary to assure a smooth start up of the deployed system.

The 1990 demonstration at Orlando represented a test of the basic TDWR system concept in an operational setting, the subtropical climate at MCO. Operational demonstrations also have been conducted in the high-plains climate at Denver's Stapleton International Airport and in the midwestern climate at Kansas City International Airport (MCI).

The following definitions introduce the alert terminology used during the demonstration and in this analysis. Each alert issued to a pilot started off with the alert being identified by Local Control as either a "wind shear alert" or a "microburst alert." Wind shear alerts were of two kinds: positive alerts (e.g., 20-kt gain 2-Mile Final) were used to identify areas of increasing wind speeds associated with such wind shear features as gust fronts, and negative alerts (e.g., 20-kt loss 2-Mile Final) were used to identify areas of decreasing wind speeds associated with weak microbursts. Negative alerts for intensities of 30 kts or more were identified as microburst alerts to highlight the greater potential hazard.

Much was learned from the Orlando 1990 demonstration. The following results look at system performance from a number of operational viewpoints: (a) the number and duration of the TDWR alert periods in the Orlando environment, (b) the number of air crews issued a TDWR alert and the utilization of those alerts for microburst avoidance, (c) the pilot-perceived performance of the alerts in terms of timeliness and overwarning, (d) a characterization of the wind-related situations encountered and reported by pilots that were not provided alert coverage, and (e) pilot reaction to the provided service.

2. A CHARACTERIZATION OF THE ALERT PERIODS

Table B-1 presents a listing of the alert periods that occurred during the demonstration. Alert periods involving the active runway configuration occurred on 15 (i.e., 40 percent) of the days during the 37-day demonstration. The active runways were under alert status for a total of 503 minutes, or about 95 minutes per week on average. The individual alert periods ranged from 2 to 67 minutes in duration and averaged 22 minutes. The distribution of alert period durations shows that the majority of alert periods lasted for less than 20 minutes:

30 percent of the periods had durations from 0 to 9 minutes,

26 percent of the periods had durations from 10 to 19 minutes,

17 percent of the periods had durations from 20 to 29 minutes,

9 percent of the periods had durations from 30 to 39 minutes,

9 percent of the periods had durations from 40 to 49 minutes, and

9 percent of the periods had durations of 50 minutes or more.

Table B-1 also lists the alert periods included in the PIREP-based analysis. For various reasons, the ATC communication tapes were not available for analysis for 6 of the 23 alert periods.

Consequently, the following PIREP-based analysis is based on 17 (i.e., 74 percent) of the 23 alert periods and 387 (i.e., 77 percent) of the 503 minutes during which the active runways were under alert status during the demonstration.

3. A CHARACTERIZATION OF THE ALERTS ISSUED TO LANDING/DEPARTING AIR CREWS AND THEIR UTILIZATION BY PILOTS

With two exceptions, operations paused for portions of all alert periods involving microburst alerts. Table B-2 presents an estimate of those times during the alert periods when landing/takeoff operations paused while aircraft were still waiting to land/take off. These periods started when one or more air crews during an alert period explicitly declined to land/take off and ended when an air crew accepted landing/take-off clearance and then proceeded to complete the landing/takeoff. The periods in which arrival or departure operations paused lasted from 6 to 53 minutes. From the communication tapes, it is clear that heavy rain as well as the potential for wind shear were present during many of these periods of waiting.

Table B-3 characterizes the alerts verbally issued to pilots during the 17 alert periods analyzed in terms of the intensity of wind speed increase or decrease to be expected and the utilization of the alerts by the air crews. Over the 17 alert periods, alerts were issued to 119 air crews. Of these, 57 air crews (i.e., 48 percent) were issued a microburst alert.

Table B-1.
Periods in Which Alerts Were Generated for the Active Runway Operation

Local Date	Greenwich Mean Time of Alert Period	Alert Period Duration (min.)	Maximum Intensity (kts) Neg./Pos. Alerts	Was Alert Period Included in the PIREP-Based Analysis ? *
6-30-90	1801Z-1818Z	17	-35/none	yes
7-01-90	2053Z-2103Z	10	none/+20	yes
7-01-90	2117Z-2123Z	6	-25/none	yes
7-07-90	1850Z-1917Z	27	-50/none	yes
7-08-90	1830Z-1843Z	13	-40/none	yes
7-08-90	1951Z-2030Z	39	-50/none	yes
7-09-90	1625Z-1640Z	15	-25/none	yes
7-09-90	1720Z-1747Z	27	-50/none	yes
7-09-90	2119Z-2121Z	2	-20/none	yes
7-09-90	2143Z-2158Z	15	-35/none	no
7-11-90	1833Z-1912Z	39	-40/none	yes
7-12-90	2155Z-2302Z	67	-35/+25	yes
7-14-90	1624Z-1628Z	4	-20/none	no
8-13-90	2024Z-2030Z	6	-20/none	yes
8-18-90	2003Z-2043Z	40	-55/none	yes
8-19-90	2121Z-2142Z	21	-40/none	yes
8-21-90	1655-Z-1718Z	23	-35/none	no
8-21-90	1734Z-1740Z	6	-25/none	no
8-21-90	2226Z-2231Z	5	-35/none	no
8-22-90	2030Z-2133Z	63	-95/none	no
8-27-90	1920Z-2004Z	44	-60/none	yes
8-27-90	2016Z-2020Z	4	-25/none	yes
8-28-90	2152Z-2202Z	10	none/+15	yes
15 Days	**23 Alert Periods**	**503 Minutes**		

* For various reasons, the ATC communication tapes for six alert periods were not available for analysis.

Table B-2.
Extent that Landing or Departing OperationsPaused During the 17 Alert Periods Examined in the PIREP-Based Analysis.

Local Date	Greenwich Mean Time of Alert Period	Alert Period Duration (min.)	Maximum Intensity (kts) Neg./Pos. Alerts	Extent of any Operational Pauses During Alert Period {1} Departure Operations (min)	Arrival Operations (min)
6-30-90	1801Z-1818Z	17	-35/none	10	0
7-01-90	2053Z-2103Z	10	none/+20	0	0
7-01-90	2117Z-2123Z	6	-25/none	0	0
7-07-90	1850Z-1917Z	27	-50/none	18	18
7-08-90	1830Z-1843Z	13	-40/none	0	0
7-08-90	1951Z-2030Z	39	-50/none	13	6
7-09-90	1625Z-1640Z	15	-25/none	0	0
7-09-90	1720Z-1747Z	27	-50/none	18	6
7-09-90	2119Z-2121Z	2	-20/none	0	0
7-09-90	2143Z-2158Z	15	-35/none	period not examined {2}	
7-11-90	1833Z-1912Z	39	-40/none	0	19
7-12-90	2155Z-2302Z	67	-35/+25	53	50
7-14-90	1624Z-1628Z	4	-20/none	period not examined {2}	
8-13-90	2024Z-2030Z	6	-20/none	0	0
8-18-90	2003Z-2043Z	40	-55/none	21	10
8-19-90	2121Z-2142Z	21	-40/none	7	0
8-21-90	1655-Z-1718Z	23	-35/none	period not examined {2}	
8-21-90	1734Z-1740Z	6	-25/none	period not examined {2}	
8-21-90	2226Z-2231Z	5	-35/none	period not examined {2}	
8-22-90	2030Z-2133Z	63	-95/none	period not examined {2}	
8-27-90	1920Z-2004Z	44	-60/none	0	0
8-27-90	2016Z-2020Z	4	-25/none	0	0
8-28-90	2152Z-2202Z	10	none/+15	0	0
				140 minutes	109 minutes
		20-min. average		8-min. average	6-min. average

{1} The extent of the operational pauses was determined from the ATC communication tapes and represents those periods in which there was a break in landing/takeoff operations and for which it could be determined that operational demand was present.

{2} This alert period was not examined due to the unavailability of the pertinent ATC communication tape for analysis.

Table B-3.
A Characterization of the Alerts Issued and their Utilization by Pilots for Wind Shear Avoidance for the 17 Alert Periods Included in the PIREP-Based Analysis.

		Operational Outcome				
Alert Actually Issued to Pilot	No. Pilots Issued Such an Alert {1}	Pilot Landed	Pilot Executed a Go-Around	Pilot Took Off	Pilot Delayed Takeoff	Pilot Aborted Takeoff Roll
+15 kts	6	3	0	3	0	0
+20 kts	1	1	0	0	0	0
+25 kts	5	1	0	3	1	0
Higher	0	0	0	0	0	0
Subtotal	**12**	**5**	**0**	**6**	**1**	**0**
-15 kts	0	0	0	0	0	0
-20 kts	18	8	2	7	1	0
-25 kts	32	15	1	7	9	0
Subtotal	**50**	**23**	**3**	**14**	**10**	**0**
-30 kts	13	3	2	4	4	0
-35 kts	18	4	4	4	6	0
-40 kts	16	2	3	8	3	0
-45 kts	4	0	1	0	3	0
-50 kts	4	1	0	2	1	0
-55 kts	2	1	1	0	0	0
Higher	0	0	0	0	0	0
Subtotal	**57**	**11**	**11**	**18**	**17**	**0**
TOTAL	**119 {2}**	**39**	**14**	**38**	**28**	**0**

{1} These numbers exclude the runway operations associated with the specially instrumented research aircraft used by the TDWR program during the alert periods.

{2} This number does not include the 17 cases in which local control did not pass on to an air crew the alert in effect; on several occasions, the daily logs maintained during the demonstration noted that there was a problem with the bell being heard on the controller's alert display (i.e., the ribbon display).

Prior to the demonstration, a number of airlines operating out of Orlando instructed their pilots not to continue their landings or takeoffs on receiving a microburst alert, if at all possible. Other airlines left this decision to the discretion of their pilots.

Orlando 1990 represents a snapshot of the attitude of the Orlando pilot population to using these alerts for microburst avoidance as of the summer of 1990. Of the 22 air crews landing at Orlando that received a microburst alert, 11 of the air crews (i.e., 50 percent) did not complete their landing and executed a go around. Of the 35 air crews departing Orlando that received a microburst alert, 17 air crews (i.e., 49 percent) delayed their takeoff.

On the other hand, some pilots declined to take off with a negative alert of less than microburst alert status (i.e., declined to take off with a negative wind shear alert in effect). Of the 24 departing air crews that received a negative wind shear alert, 10 of the air crews (i.e., 42 percent) declined to take off. The communication tapes suggest that some pilots made their no-go decision based entirely on the alert (e.g., a pilot on being issued a -20 knot alert stated: "...OK, that's too much; we are going to wait"). In balancing safety of operations with traffic disruption and aircraft delay, the rigid use of the negative wind shear alert to decline takeoff clearance by some pilots may warrant further study.

Although the sample sizes were small, Table B-4 suggests that pilot utilization of the microburst alert for wind shear avoidance changed over the course of the 37-day demonstration. For trend analysis purposes, the nine days analyzed in which air crews were issued microburst alerts were divided into three-day periods. Near the beginning of the demonstration, 78 percent of the air crews that were directly issued a microburst alert elected to avoid a possible microburst encounter; by the middle portion of the demonstration, the percentage dropped to 46; and near the end, the percentage dropped to 29. A possible explanation of this apparent shift in pilot attitude may be overwarning.

4. OVERWARNING AS AN OPERATIONAL PROBLEM

From the daily logs maintained by the on-site, evaluation team, it was found that overwarning became a recognized operational problem by the watch supervisors on July 8. The following excerpt was obtained from the logs filled out by the Tower Observer for July 8:

> "...Microburst alerts shut down Runways 18L and 17 for about 30 minutes. Supervisors <u>were not</u> happy. One cell could be seen to impact Runway 18L while 17 was unobstructed. This was obvious from the tower. Furthermore, PIREPs did not indicate shear on runways..."

Excerpts from the logs filled out by the TRACON Observer for July 8 were similar:

> "Supervisors concerned (about) overalarming. Pilots elect not to land...'These are weak showers'...forced to work aircraft twice...convinced planes could have landed fine..."

> "...Supervisor was ready to 'shut that thing down' when no PIREPs or LLWAS winds confirmed either wind shear or wind speeds of any strength..."

Due to the concerns expressed on July 8, the system software was checked. By July 12, software changes were in effect reflecting the correction of software errors that had been found and changes to some of the site-adaptable parameters contained in the software. The software changes were expected to significantly reduce the size of the "wind shear areas" declared for surface outflows.

Table B-4.
Pilot Utilization of the Microburst Alert for Wind Shear Avoidance Changed During the Course of the Demonstration.

Three -Day Sets	Number of Air Crews Issued a Microburst Alert During These Three Days	Percentage or Number of Those Air Crews that Sought To Avoid the Microburst {1}
First three-day set (June 30, July 07, July 08)	14 air crews	78% avoidance ratio or 11 of the 14 air crews
Second three-day set (July 09, July 11, July 12)	26 air crews	46% avoidance ratio or 12 of the 26 air crews
Third three-day set (August 18, August 19, August 27)	17 air crews	29% avoidance ratio or 5 of the 17 air crews
	57 air crews	49% average avoidance ratio or 28 of the 57 air crews

{1} The air crews sought to avoid the microburst either by breaking off the approach and going around or by declining takeoff clearance.

No further changes to that portion of the software were made until completion of the demonstration when some additional tuning to the site-adaptable parameters was carried out. However, on a number of occasions after July 12, changes were made to the portion of the software associated with calculating the alert intensity estimate of an outflow's strength.

For analysis purposes, the September version of the software was used to rerun a second set of alerts for July 7, 8, and 9. The alerts were rerun for this three-day period rather than just for the day that overwarning had been identified as an operational problem (July 8) in order to better evaluate the impact of the software changes. The three-day period covered about 60 percent of the 82 air crews that had been issued an alert before the July 12 software changes.

Table B-5 presents a comparison of the original and rerun alerts that were/would have been issued to the air crews for those three days. The table shows that five air crews originally landed/took off with a microburst alert in effect. Of the five air crews, one reported experiencing a 7-kt loss in airspeed, two reported no loss or no fluctuation in airspeed, and two did not provide a PIREP. With the rerun alerts, three of these five air crews would not have received an alert and the other two would have received a wind shear alert versus a microburst alert. Going through the rest of Table B-5, one finds that for those three days that:

> The watch supervisors were correct in their concern about excessive overwarning. With the rerun alerts, there would have been a 40 percent reduction in the 54 air crews originally issued an alert and a 70 percent reduction in the number of air crews issued a microburst alert.

Table B-5.
A Comparison of the Original and Rerun Alerts
for July 7, 8, and 9.

Arrivals/Departures	Number of Such Air Crews with Original Set of Alerts	PIREP Received from the Air Crew, If Any, and the Corresponding Rerun Alert
That either landed or took off with a negative alert in effect:		
A microburst alert	5	<u>Three PIREP cases:</u> No fluctuation — -20 kt alert No loss — -20 kt alert -7 kts — no alert
		<u>Two non-PIREP case:</u> Two cases — no alerts
A wind shear alert	28	<u>Twelve PIREP cases:</u> ±10 kts — -20 kt alert little variation — -20 kt alert no wind shear — -20 kt alert no shear, not bad — -20 kt alert no fluctuation — -20 kt alert ± 5 degree rolls — -15 kt alert 5 kt fluctuations — no alert -10 kts — no alert -5 kts — no alert no wind shear — no alert no wind shear — no alert no shear, smooth — no alert
That either executed a go around or explicitly declined to take off with a negative alert in effect:		
A microburst alert	12	<u>All were non-PIREP cases:</u> four cases — -45 kt alerts one case — -40 kt alert two cases — -25 kt alerts one case — -20 kt alert four cases — no alerts
A wind shear alert	9	<u>One PIREP case:</u> -10 kts — -25 kt alert
		<u>Eight non-PIREP cases:</u> one case — -25 kt alert four cases — -20 kt alert one case — -15 kt alert two cases — no alerts

The air crews did a good job in deciding when to take off and land with an alert in effect. Of the 33 air crews that originally decided to take off/land with an alert in effect, 16 air crews were involved with what turned out to be non-alert situations. For the other 17 air crews, the maximum intensity encounter reported was for ± 10 kts and no air crew would have received a rerun alert of microburst status.

The rerun alerts would not have eliminated overwarning, even though 40 percent fewer air crews would have received an alert.

A primary source of the remaining overwarning or pilot-perceived false alarms was the use of a safety corridor around each of the arrival and departure runway operations. Figure B-1 shows the geometries of the safety corridors used during Orlando 1990. The system monitored these corridors for wind shear features. A runway-specific alert was issued whenever the system software located the edge of a wind shear feature inside one of these corridors. The use of the corridors was an attempt to have the system alert landing and departing pilots of all threatening situations. The rate of overwarning tends to represent those instances in which a nearby wind shear feature in the safety corridor did not move onto the aircraft's path during its landing or takeoff.

5. OVERWARNING REMAINED AT AN UNEXPECTEDLY HIGH LEVEL AFTER THE SOFTWARE CHANGES

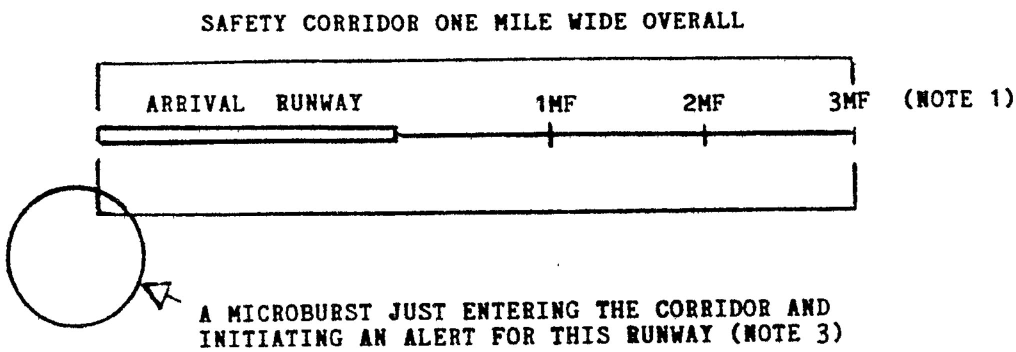
A PIREP-based analysis was undertaken to evaluate the extent of the remaining overwarning from the pilot's viewpoint after the July 12 software changes. For the analysis, the PIREPs were classified according to the scheme presented in Table B-6. The extent of overwarning was taken to be a range of possible values, with the lower limit represented by the first category of PIREPs (i.e., those PIREPs indicating that "nothing was encountered") and the upper limit represented by the sum of the first and second categories of PIREPs (i.e., those PIREPs indicating that "little or nothing was encountered").

Table B-7 presents the overwarning performance of the system after the July 12 software changes. To increase the size of the population available for analysis, the rerun alerts for July 7, 8, and 9 were included. Based on the 19 air crews in this population that received a negative alert, flew into the indicated area, and reported their experience, the rate of overwarning was 58 percent and perhaps as high as 74 percent [i.e., 58 percent of the air crews reported something to the effect that "nothing was encountered" and another 16 percent reported something to the effect that "nothing much was encountered"]. This is much greater than the corresponding rate found by the TDWR Program during the 1989 demonstration at Denver's Stapleton International Airport (i.e., 26 percent and perhaps as high as 56 percent).

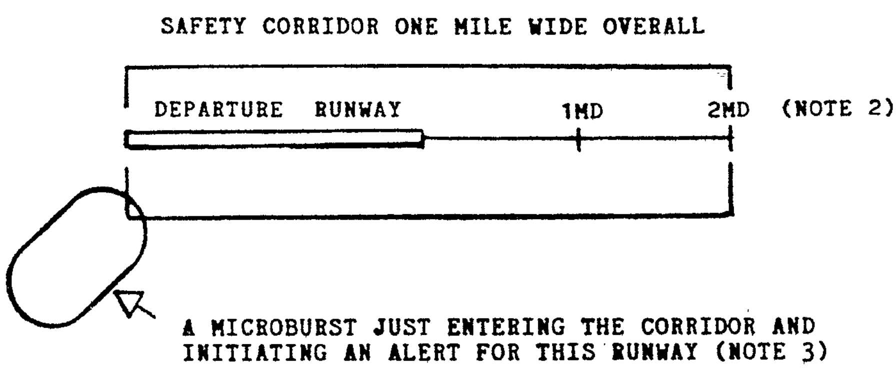
6. A SPECULATION CONCERNING THE HIGH LEVEL OF APPARENT OVERWARNING

A possible explanation of this apparent difference in TDWR overwarning at the two airports (Orlando and Denver) is that pilots may be better able to visually locate thunderstorm-related outflows at Orlando than at Denver. Due to the wet atmospheric conditions at Orlando relative to Denver, the thunderstorm-related outflows at Orlando more frequently occur in close association with rain cells at the surface. The Orlando pilots may be exploiting the closer association of wind shears with rain cells in the Orlando area to decide when to land and take off with an alert in effect than is possible for pilots in the Denver area.

FOR ARRIVAL OPERATIONS



FOR DEPARTURE OPERATIONS



NOTE: (1) 3MF STANDS FOR "3-MILE FINAL"

(2) 2MD STANDS FOR "2-MILE DEPARTURE"

(3) THE SYSTEM SOFTWARE DEPICTED MICROBURSTS IN EITHER OF TWO SHAPES: THE SHAPE OF A BAND-AID IF THE SOFTWARE SENSED THAT THE MICROBURST'S OUTFLOW HAD AN ELONGATED AXIS IN SOME DIRECTION OR THE SHAPE OF A CIRCLE IF IT DID NOT

Figure B-1. The safety corridor geometries used during the Orlando 1990 demonstration.

Table B-6.
PIREP Classification Used in the Overwarning or Pilot-Perceived False Alarm Analysis.

Alerts Considered as Apparent False Alarms:	
Those alerts followed by a PIREP indicating that "nothing was encountered;" example PIREPS:	
No wind shear	No problem
Normal acceleration	No airspeed gain/loss
A normal takeoff	Steady as a rock
Alerts Considered as Possible Additional False Alarms:	
Those alerts followed by a PIREP indicating that "nothing much was encountered;" example PIREPS:	
A little choppy	Nearly normal landing
Just squirrelly	5-knot fluctuations
Slight airspeed hesitation	Mild stagnation
Alerts Considered as Advising Pilots of a Significant Feature Actually on the Flight Path	
Those alerts followed by a PIREP indicating that "something of interest to landing/departing pilots was encountered" (i.e., all PIREPS stating airspeed changes of 10 kts or more {1}, greater than light turbulence/chop, and/or any indication of a downdraft); example PIREPS:	
A sinker	Lost 400 feet in altitude
Pretty good turbulence	A lot of bouncing
Twisting around of aircraft	Gained 10 knots
{1} Numerous pilots have indicated in their mailed-in questionnaires that a wind-related airspeed change of 10 kts was considered a significant wind shear encounter while on final approach or takeoff. To date, only one pilot has indicated that a wind-shear-induced airspeed variation of less than 10 kts was considered to be a significant encounter.	

Table B-7.
Basic Overwarning Performance of TDWR in the Orlando Operational Setting with "Corrected" Software.

Overwarning Rate of the TDWR Alert System with "Corrected" Software	1990 Orlando Performance for the Alert Periods Analyzed {1}, {2}
For all positive and negative alerts	55% and perhaps as high as 75% (sample size: 20 air crews)
For the positive alerts alone	Insufficient data (sample size: 1 air crew)
For the negative alerts alone	58% and perhaps as high as 74% (sample size: 19 air crews)
For the microburst portion of the negative alerts	67% and no weak encounters reported (sample size: 9 air crews)

{1} Of the 23 alert periods that occurred during the demonstration, these results are based on the 14 alert periods for which ATC communication tapes were available for analysis and for which the "corrected" software was used to generate alerts, including the rerun alert periods on July 7, 8, and 9.

{2} The samples consisted of those air crews for which an alert was generated, completed their landing/takeoff, and gave a PIREP.

If Orlando pilots can visually locate thunderstorm-related wind shears, one may ask if TDWR is really needed at Orlando? The evidence at hand suggests that air crews at Orlando are unable to consistently avoid significant wind shear and turbulence encounters:

> On August 3, an air crew executed a missed approach from flare and reported a 30- to 50-kt gain over the runway; this occurred while the TDWR alert service was not in operation.
>
> On August 18, an air crew landed and reported encountering +30 kts at 200 feet; the TDWR alert service was operational at the time, but the air crew encountered a wind shear feature for which TDWR had not been designed to provide alert coverage (i.e., a microburst-generated gust front).
>
> On August 18, a second air crew landed and reported a real rough ride on Short Final; this air crew had received a TDWR alert to expect -55 kts over the runway.

7. OVERWARNING REMAINED AN EXPRESSED CONCERN OF SOME AIR TRAFFIC PERSONNEL AFTER JULY 12–AN EXAMINATION OF TWO SUCH ALERT PERIODS

A review of the daily logs maintained by the on-site evaluation team indicated that ATC personnel expressed concern about overwarning on at least three occasions after the July 12 software changes: on August 19, August 21, and August 27. The ATC communication tapes were available for two of the three cited alert periods and are discussed here in conjunction with the comments made by the ATC personnel and the results of a brief review of the stored TDWR data.

The following excerpts were obtained from the daily logs for August 19. The term "red dots" used in the second excerpt refers to the depiction of microburst outflows on the TDWR GSD.

> "...(TDWR) came up with (a microburst alert) on both runways. Airport was already impacted by (weather) and supervisors were unhappy with the additional delays from the (microburst), which was not perceived as an operational hazard..."

> "Supervisor commented: ' we have been running flights for (the) last hour and now everyone is holding because the system came up and gave red dots'. (Supervisor) feels TDWR is overwarning–too conservative."

Figure B-2 presents a summary of the collected data on the events that took place during the 21-minute alert period cited by the watch supervisors on August 19. The figure shows the position of a microburst on the runways and associated safety corridors at the beginning and midway through the alert period. It should be noted that Runway 18R/36L was out of service during the summer and is not shown in the figure for the sake of clarity. At the beginning of the alert period, the microburst overlaid the two runways in close proximity to a rain shower. Arrivals continued to land during the alert period on Runway 17, while a departure on both Runway 17 and 18L declined to take off with a microburst alert in effect. During the resulting seven-minute period when departures were not taking off, the TDWR data show that both the wind shear area and the rain cell were moving to the south. It appears that the pilots elected to take off once again as the rain cleared the runways. The ATC communication tape indicated that two air crews landed and five air crews departed with a microburst alert in effect during the alert period. Of the five air crews that gave a PIREP of their experience, all stated something to the effect that "nothing was encountered."

To gain further insight into the quality of the pilot go/no-go decision-making process during the alert period and into what the pilots probably experienced when they took off with a TDWR alert in effect, a brief review was made of the TDWR data relative to the wind shear conditions along each of the estimated flight paths. The review was conducted by a Lincoln Laboratory expert in the interpretation of Doppler weather radar data. The results of that review are shown in Figure B-2. For the purposes of this analysis, a significant shear encounter was taken to be one in which the aircraft would experience a wind speed change of 10 kts or more in the direction of flight. From this viewpoint, it is seen that the TDWR data suggest that (a) none of the air crews that landed or took off with a TDWR alert in effect should have experienced a significant wind shear and (b) the go/no-go decision on the part of the pilots was quite good in that the two pilots who elected to delay takeoff would have experienced a modest but significant wind shear (i.e., a 15-kt loss in each case).

In summary, the August 19 case shows that (a) TDWR operated as designed in providing alerts indicating the maximum loss of wind speed that could be encountered if the microburst outflow was completely traversed and the location at which the loss would start to be encountered, and (b) the pilots appear to have done a good job in making their go/no-go decisions, given the reality of the situation, and then in missing or skirting the wind shear area. In this case, operationally meaningful overwarning occurred in that "safe" runway operations would have been lost if these pilots had chosen to follow the "candidate" operational policy of not landing or taking off with a microburst alert in effect. These operations were safe in the sense that the aircraft did not encounter hazardous wind shear conditions or even wind shear conditions of minimal operational concern.

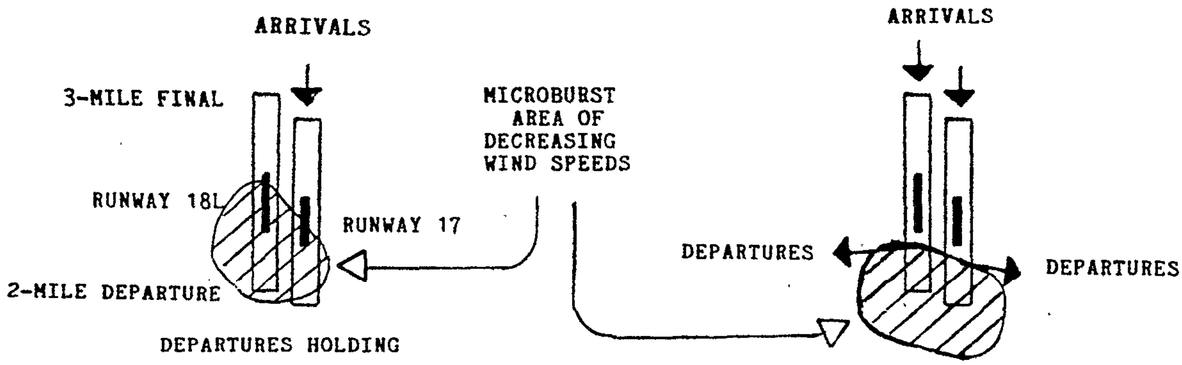
EXCERPT FROM VIEWS EXPRESSED BY THE WATCH SUPERVISORS AFTER A 21-MINUTE ALERT PERIOD AS NOTED IN THE DAILY LOGS MAINTAINED BY THE ON-SITE EVALUATION TEAM

"...TDWR is overwarning - too conservative"

THE SITUATION DURING THE ALERT PERIOD BASED ON A REVIEW OF THE STORED DOPPLER DATA AND THE ATC COMMUNICATION TAPES

NEAR THE BEGINNING OF THE ALERT PERIOD

MID WAY THROUGH THE ALERT PERIOD



ISSUED ALERT	OPERATIONAL OUTCOME	CONTENT OF PIREP	ANY SIGNIFICANT SHEAR ON ESTIMATED FLIGHT PATH BASED ON A REVIEW OF THE STORED DOPPLER DATA?
A TDWR ALERT WAS ISSUED TO 2 OF 11 ARRIVALS DURING THE PERIOD			
1) -30KTS/RWY	LANDED	NO LOSS	NO, A WEAK GAIN
2) -35KTS/RWY	LANDED	NO SHEAR	NO, A WEAK GAIN
A TDWR ALERT WAS ISSUED TO 8 OF 10 DEPARTURES; TWO AIRCREWS DECLINED TO TAKE OFF AND NO DEPARTURES TOOK PLACE OVER A 7-MINUTE PERIOD			
1) -35KTS/RWY	DELAYED	NO PIREP	YES, A 15-KNOT LOSS
2) -35KTS/RWY	DELAYED	NO PIREP	YES, A 15-KNOT LOSS
3) -35KTS/RWY	TOOK OFF	SMOOTH	NO, A WEAK CROSSWIND
4) -35KTS/1MD	TOOK OFF	NO PIREP	NO, SMOOTH RIDE
5) -40KTS/1MD	TOOK OFF	SMOOTH	NO, A 15-KNOT CROSSWIND
6) -40KTS/1MD	TOOK OFF	NO PIREP	NO, A WEAK CROSSWIND
7) -30KTS/1MD	TOOK OFF	NO LOSS	NO, A WEAK CROSSWIND
8) -25KTS/2MD	TOOK OFF	NO PIREP	NO, A WEAK CROSSWIND

Figure B-2. A description of the August 19 alert period when overwarning was an expressed operational concern.

The situation on August 27 was similar. The following excerpt was obtained from the daily logs for that day.

> "...supervisor...commented that either the width of the [safety corridor] should be reduced or the size of the [areas used to depict microbursts] or the airlines should not have a policy of not landing whenever they hear the word 'microburst'. At one point, a [microburst on the GSD] was positioned south of Runway 17. The [depicted microburst area] extended to within 0.5 miles of the southern end of Runway 18 and so set off an alarm...The runways are two miles long and in this case there was plenty of room to land at the northern end [of the runway]...[the supervisor] feels that the [safety corridor] or [areas used to depict microbursts] should be shrunk so that this situation happens less often..."

Figure B-3 presents an overwarning situation similar to the one described in Figure B-2. In summary, operationally significant overwarning occurred during the two cited alert periods in that 16 "safe" landings/departures would have been lost if the pilots had chosen to strictly follow the "candidate" operational policy of not landing or taking off with a microburst alert in effect.

8. PILOT-PERCEIVED ALERT PERFORMANCE

To paraphrase the Timeliness Requirement stated in U.S. Department of Transportation Order 1812.9: the TDWR System is to provide alerts to landing and departing pilots at least one minute before any pilot encounters hazardous wind shear or turbulence while at an altitude under 1500 feet AGL. The requirement does not define the term "hazardous."

During the demonstration, alerts were issued to landing and departing pilots along with landing and takeoff clearance. Operationally, this meant that at least a one-minute warning was given to landing pilots for any wind shear in the critical area inside 1-Mile Final, and almost a one-minute warning was given to departing pilots for any wind shear in the critical lift-off area. The view adopted in the analysis was that an alert would be considered timely if it was issued along with landing or departure clearance.

This viewpoint has two implications. First, alert timeliness had to do with alert startup and restart. For all the following alerts, the key performance issue was alert accuracy and not alert timeliness. An alert startup or restart was considered late only if the first air crew to receive an alert (a) received it some time after landing/takeoff clearance had been issued and (b) reported a wind shear, turbulence, and/or a downflow encounter. Second, an alert was considered late by the number of seconds that elapsed between the time that clearance to land/take off had been issued and the time that the alert was received by the air crew.

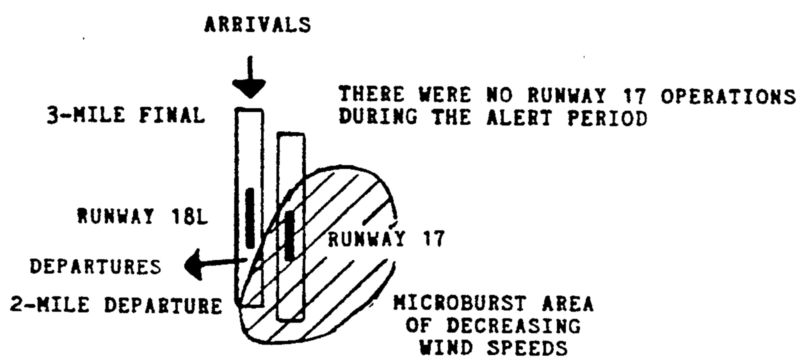
For the 17 alert periods examined in the PIREP-based analysis, there was one late alert. It occurred on July 1 and involved a non-hazardous encounter of the type routinely reported by landing and departing pilots, a 15-kt loss in airspeed. The pilot encountered a developing, short-lived outflow that never exceeded 25 kts in strength. The pilot possibly expected an alert, for he had Local Control verify that the TDWR "was working" about a minute after receiving landing clearance. A few seconds after this pilot-controller exchange, a TDWR alert (i.e., expect a 25-kt loss at 2-Mile Final) was displayed to Local Control for the arrival.

EXCERPT FROM VIEWS EXPRESSED BY THE WATCH SUPERVISORS AFTER A 44-MINUTE ALERT PERIOD AS NOTED IN THE DAILY LOGS MAINTAINED BY THE ON-SITE EVALUATION TEAM

"...either the width of the [safety corridor] should be reduced or the size of the [areas used to depict microbursts] or the airlines should not have a policy of not landing whenever they hear the word "microburst"..."

THE SITUATION DURING THE ALERT PERIOD BASED ON A REVIEW OF THE STORED DOPPLER DATA AND THE ATC COMMUNICATION TAPES

15 MINUTES INTO THE ALERT PERIOD



GENERATED ALERT	OPERATIONAL OUTCOME	CONTENT OF PIREP	ANY SIGNIFICANT SHEAR ON ESTIMATED FLIGHT PATH BASED ON A REVIEW OF THE STORED DOPPLER DATA?
A TDWR ALERT WAS GENERATED FOR 9 OF 22 ARRIVALS DURING THE PERIOD			
1) -35KTS/RWY	LANDED	NO PIREP	NO
2) -25KTS/RWY	LANDED	NO PIREP	NO
3) -30KTS/RWY	LANDED	NO PIREP	NO
4) -30KTS/RWY	LANDED	NO PIREP	NO
5) -35KTS/RWY	LANDED	NO PIREP	NO
6) -30KTS/RWY	GO AROUND	NO PIREP	NO
7) -50KTS/RWY	LANDED	NO LOSS	NO
8) -25KTS/3MF	LANDED	NO PIREP	NO
9) -25KTS/3MF	LANDED	NO PIREP	NO
A TDWR ALERT WAS GENERATED FOR 5 OF 12 DEPARTURES			
1) -35KTS/RWY	TOOK OFF	NO PIREP	NO
2) -25KTS/1MD	TOOK OFF	NO PIREP	NO
3) -50KTS/1MD	TOOK OFF	NO PIREP	NO, A 10-KNOT CROSSWIND
4) -30KTS/2MD	TOOK OFF	NO PIREP	NO
5) -50KTS/2MD	TOOK OFF	NO PIREP	NO

Figure B-3. A description of the August 27 alert period when overwarning was an expressed operational concern.

9. PILOT-PERCEIVED ALERT PERFORMANCE WITH RESPECT TO ACCURACY AS TO THE INTENSITY AND LOCATION OF THE ENCOUNTER

Each alert included a computer-generated estimate of the maximum wind speed change that would be experienced and of the location at which the wind shear feature would be first encountered if the pilot proceeded with the landing/takeoff. In this series of TDWR-related demonstrations, these alert estimates have been compared with the wind shear-induced airspeed variations and encounter locations reported by pilots. Due to the small number of sufficiently detailed PIREPs of actual wind shear encounters reported, this was not done for Orlando 1990.

10. CHARACTERIZATION OF SITUATIONS FOR WHICH PILOTS WERE NOT ALERTED

An operational question of interest is: how well did the tested TDWR-based alert system cover the variety of wind-related situations of concern to landing and departing pilots? Relative to the 17 alert periods examined, it was found that pilots reported four encounters for which an alert had not been issued. A review of the stored TDWR and Mesonet data was conducted in an attempt to identify the types of wind shear features that had been encountered. (The Mesonet consisted of a network of small, automatic weather sensing stations located in the vicinity of the airport.) The results of the TDWR/Mesonet data review are presented in Table B-8. The table provides examples of some of the wind-related situations for which the system had not been designed to provide alert coverage:

1. Wind shear lines that did not satisfy the TDWR software's alert initiation criteria relative to being 10 km or longer in extent and involving wind speed changes of 15 kts or more. The most intense reported encounter with a feature of this type was with a microburst-generated gust front.

2. The outflow area behind a gust front which can exhibit strong surface winds with turbulence.

The encounter with the microburst-generated gust front involved a reported 30-kt gain in airspeed which suggests that these encounters can be substantial. On the other hand, the reported encounters for the other three non-alert situations were for 10- to 15-kt airspeed variations, which are considered as routine and non-hazardous.

11. PILOT REACTION TO THE PROVIDED SERVICE

During the demonstration, pilots could express their opinion of the provided service by means of (a) mail-in questionnaires located in the cockpits of a number of airlines that operate out of Orlando or (b) the ATC radio channel in contact with Local Control. The questionnaires were provided by the National Center for Atmospheric Research as part of the TDWR Program.

Table B-9 summarizes the pilot opinions expressed during the demonstration. The questionnaires on which the table is based were those received from pilots that wrote in response to having been involved in a TDWR alert period. With a single exception, the opinions expressed by these pilots were favorable. In the exception, the pilot expressed concern that the microburst alert is not formatted so as to "adequately get a pilot's attention during a busy approach." A similar concern was expressed by United Airlines as a result of the 1988 TDWR demonstration at Stapleton International Airport.

Table B-8.
Pilot-Reported Wind Shear Encounters Not Provided Alert Coverage During the 17 Alert Periods Examined in the PIREP-Based Analysis.

Operation {1}, {2}	PIREP Content	Alert Situation at the Time of the Operation	"Best Guess" Estimates of Encountered Wind Conditions Based on a Review of the Stored Doppler Radar and Mesonet Data for These Time Periods {3}
7-01/ARR/2046Z	+10 kts at 500 ft	Operation took place 8 minutes before a +20 kt alert period started	The radar data suggest that the aircraft encountered a gust front that had not yet reached alert status.
7-01/ARR/2110Z	±10 kts whole way down, light to moderate chop	Operation took place 7 minutes after +20 kt alert period ended and 7 minutes before -25 kt alert period started.	The radar data suggest that the aircraft flew into the normally turbulent outflow area behind a gust front that had recently swept over the runway.
8-18/ARR/2014Z	+30 kts at 200 ft	Operation took place several minutes before the start of a -55 kt alert period for this arrival runway.	The radar data suggest that the aircraft flew into a microburst-generated gust front.
8-18/DEP/2044Z	-15 kts at 200 ft	Operation took place several minutes after alerts had terminated on the departure runway; alerts for arrival operations on the parallel runway had terminated one minute prior to departure clearance.	The radar data suggest that the "alert" outflow south of the airport had terminated and that there were no wind shear features in the vicinity of the airport; however, the Mesonet data suggest that the aircraft encountered a gust front from a thunderstorm located 4 miles northeast of the airport.

{1} Each operation is identified by the local Orlando date on which it occurred, whether it was an arrival or departure, and the Greenwich Mean Time at which the pilot was issued landing or takeoff clearance.

{2} The results are based on the 17 of the 23 alert periods that were included in the PIREP-based analysis.

{3} Reviews made by a Lincoln Laboratory expert in the interpretation of TDWR data and Mesonet data.

Table B-9.
Summary of Information Available on Pilot Reaction to the Provided Alert Service.

Pilot Reaction Based on Filled-Out Questionnaires	
Five pilots who had been issued a TDWR alert during the course of the demonstration responded:	
All five pilots indicated that the issued warning was considered useful.	
Two pilots commented after waiting to take off during an alert period:	Relative to the lengthy alert period on July 12, one pilot stated: "It is clearly reassuring to know the entire area is scanned before operations are conducted."
	Relative to the alert period on August 18, one pilot observed: "I feel that the microburst warning [is] too 'soft.' [It] does not adequately get a pilot's attention during a busy approach. They are given very causally, e.g., 'American 123 cleared to land, microburst alert.' Even though an actual microburst alert was issued, the significance of it was lost on (a particular landing aircraft was identified) that continued the approach and landed. He then told the Tower that it was so rough below 500 feet that he felt no one else should attempt the approach.... I doubt that they ever picked up the phrase microburst in the warning by Tower. He seemed very surprised at the turbulence encountered."
Pilot Reaction Based on the ATC Communication Tapes	
Two additional pilots commented after waiting to take off during an alert period:	
	Relative to the alert period on July 7, one pilot stated after receiving a microburst alert and declining to take off: "Neat things, those Dopplers."
	Relative to one of the alert periods on July 8, a pilot waiting to take off stated after receiving an update on the microburst alert in effect: "Pretty nifty."

The ATC radio and questionnaires can be viewed as having provided pilots with the means to make their opinions known whenever the system seemed to provide either surprisingly useful or poor quality alerts. From this viewpoint, the response indicated in Table B-9, although not conclusive, suggests that the Orlando pilots, overall, experienced few surprises, had few complaints, and found the general performance of the tested TDWR system concept to have been operationally acceptable.

A small number of questionnaires expressing confusion and complaint were received from pilots that landed/took off during the period from July 16 to August 12 when TDWR was out of service and undergoing emergency repairs.

12. SUMMARY AND CONCLUSIONS

1. There were 23 alert periods that lasted for a total of 8.4 hours over the 37-day demonstration, or for 95 minutes per week on average.

2. The TDWR alert system tested at Orlando in 1990 performed well by a number of measures:

    a. With one possible exception, the stated pilot reactions were favorable.

    b. With one minor exception, the issued TDWR alerts were timely.

    c. Alert coverage of the runways was good in that only one substantial encounter was reported that involved a wind shear feature for which TDWR had not been designed to provide alerts (a reported 30-kt gain with a microburst-generated gust front).

3. The tested system did not perform as hoped in the Orlando operational environment in two areas:

    a. Pilot utilization of the issued TDWR alerts for microburst avoidance was mixed and appears to have declined over the course of the demonstration.

    b. Overwarning persisted even after software changes were made part way through the demonstration. Overwarning was cited by ATC personnel after a number of alert periods as having or potentially having what was viewed as an unnecessarily adverse impact on runway capacity. The results of an analysis of two of the cited alert periods support that viewpoint. Although overwarning was not cited as a concern by pilots, it could explain the apparent decline in the use of the issued TDWR alerts by pilots for microburst avoidance over the course of the demonstration.

13. A FINAL OBSERVATION CONCERNING OVERWARNING

The Orlando results on overwarning, as well as the results from the Denver demonstrations, may justify further study into a number of related issues:

1. Can the current level of overwarning be reduced? (For example, can the safety corridor be reduced in size or eliminated?)

2. If not, what would be the impact of a high level of overwarning on:

a. The full realization of the TDWR safety benefit envisioned for the deployed system? (For example, the worst-case alternative would be if the "candidate" policy of not landing/taking off with a microburst alert in effect was eventually ignored/eliminated; what would be the impact of such a situation on the realization of the envisioned TDWR safety benefit?)

b. Lost runway operations (i.e., arrivals and departures)? (For example, the worst-case alternative in this case would be if the "candidate" policy of not landing/taking off with a microburst alert in effect became 100 percent effective; what would be the cost in lost runway operations in such a situation?) (As a second example, what would be the additional cost in lost operations if the current practice, apparent on the part of some pilots, of rigidly not taking off with a negative wind shear alert in effect became standard practice?)

APPENDIX C
RADAR SYSTEMS SUMMARY

1. SYSTEM FEATURES

The FL-2 Doppler weather radar was designed, built, and is operated by MIT Lincoln Laboratory under contract to the Federal Aviation Administration. This radar has served as a development tool and as an operational TDWR testbed since it was first installed in Memphis, TN in 1985. Since then it has been operated in Huntsville, AL (1986), Denver, CO (1987-1988), Kansas City, MO (1989), and Orlando, FL (1990).

From the time of the initial installation through 1989, the radar was operated at an RF frequency in the FAA-authorized S-band (2.70-3.00 GHz). In anticipation of the C-band (5.60-5.65 GHz) operation of the future operational TDWR systems that will be deployed by the FAA, the FL-2 system was modified to radiate in this band at Orlando. The FL-2 antenna was re-fitted with a C-band feedhorn and waveguide, resulting in a 6-dB gain increase and a 0.5° conical beamwidth. A C-band transmitter was custom built for Lincoln Laboratory by Westinghouse Electric Corporation using technology developed for ASR-9. This was designed to emulate the operational modes of the FAA TDWR transmitter (currently being built by Raytheon). The final amplifier emits one-microsecond pulses with peak power exceeding 250 kilowatts. Although neither efficiency nor stability is as high as desired, the transmitter was installed at Orlando, with most of the functional goals satisfied for the 1990 weather-related operations.

A new receiver/exciter was designed and built by Lincoln Laboratory for C-band operations. This also emulated the principal features of the new FAA TDWR systems. It is controlled dynamically by computers through a new radar controller interface assembly. Faced with the possibility of having to run this year at S-band if the Westinghouse C-band transmitter proved unsatisfactory, the design of this unit was adapted to run either transmitter. This "interim" radar controller is presently being replaced by a unit which is dedicated to C-band operation.

The digital signal preprocessors in the FL-2 system were designed and built by Lincoln Laboratory. These have required only small changes to adapt to the new C-band operations, and little more to meet the TDWR specification goals set for this year. It is important to note that although the antenna beamwidth is 0.5°, the preprocessor still processes dwells of 1.0° in azimuth. A new preprocessor will also soon be installed which will permit testing of the remaining TDWR front-end specifications.

The postprocessors, which make up the subsystems where the weather product and hazardous weather warning algorithms reside, are commercial Concurrent, Sun, and Symbolics computers. The programming of these algorithms and the network configuration of these computers have been further adapted to meet this year's postprocessor TDWR goals.

Current operational capabilities at C-band permit the FL-2 testbed system to meet more closely the requirements of the FAA TDWR system. These include the specified parameters for system sensitivity, scan strategies, weather product computations and weather warning generation, all performed at the required update rates. Since the internal structure of the FL-2 subsystems differs markedly from that of TDWR, FL-2 internal operations do not directly simulate TDWR operations, particularly with regard to system monitoring and data quality assurance.

The C-band configuration of the FL-2 system operated satisfactorily for most of the 1990 weather season at Orlando. Several incidents occurred, however, which interrupted operations for extended periods. These incidents are discussed in the next section.

2. RADAR SYSTEM PERFORMANCE/ISSUES

Two major problems and several minor problems occurred during summer 1990 operations.

During normal operation on July 15, the azimuth bearing in the antenna pedestal seized without warning. The system was shut down for the next 10 days while the bearing was changed, a non-trivial task requiring removal of the radome, antenna, counterweights and the rotating portion of the pedestal. Examination of the bearing was inconclusive. The lubricant appeared to have suffered an unexplained overheating at some time. An attempt was made to reinstall the bearing that had been replaced during the winter. This was unsuccessful because the new pinion gears did not match well enough. The interim fix was to remove, clean, and reinstall the damaged rollers with new grease. This repair allowed the system to function through the remaining operations until a new gear/bearing assembly could be delivered in early December.

On July 25, the same day that operations resumed, the site suffered a lightning strike that damaged virtually every sub-system in the installation. While the phenomena connected with lightning are not widely understood, the evidence suggests that the entire site was raised to a potential considerably above ground. There appear to be no burn marks anywhere, nor is there evidence of high current flow. Through the heroic efforts of everyone connected with the program, the system was again operational on August 13.

a. Radome/Antenna/Pedestal

The rotary waveguide joints in the pedestal were designed with very little internal clearance. During initial installation, the waveguide was not properly aligned and there was a lateral stress on the elevation joint. This eventually caused a bearing seizure which then twisted and destroyed a connecting section of waveguide. The joint was returned to the vendor for repair, including assembly with larger internal clearances.

Both diesel power plants were casualties of the lightning strike, so for a period of several hours there was no power available for the radome inflation equipment. The underinflated dome sagged to one side and became snagged on a light stanchion, causing a three-foot tear in the fabric. Although the radome was delivered with a patching kit, it was decided to have the repair made by a representative of the manufacturer, Chemfab, of Buffalo, NY. A field engineer from Chemfab responded immediately, and the patch was installed within 60 hours.

A second casualty of the power outage was the antenna feedhorn which was damaged by the weight of the radome resting on it. The flange where waveguide connects to the horn is brazed in place, and this union was fractured.

Lightning damage was extensive in the control circuitry for the pedestal drive, including the DC servo amplifiers.

Following the azimuth bearing seizure and replacement, sensors were attached to the pedestal so that vibrations can be monitored spectrally and recorded. Any anomaly should be detected early and rectified before another catastrophic failure takes place.

b. Receiver/Exciter/Transmitter

The transmitter performed very well throughout the experiment and was the only major component that was not severely damaged on July 25. Power was off at the time of the strike due to a failed vac ion pump power supply which was being replaced. The only other problems encountered with the transmitter were coolant leaks in the solenoid and in the water distribution manifold.

The receiver/exciter system required wholesale replacement of integrated circuits after the lightning strike, mostly where there were interfaces between chassis. Otherwise, these subsystems performed as designed throughout the experiment. The circuitry to reduce the effects of coherent local oscillator (COHO) leakage when using phase shift techniques to eliminate second trip weather is much more stable than the comparable circuitry in the S-band receivers. Adjustment is maintained for many hours without re-alignment. Although this is a significant improvement, there are still plans to attempt to dynamically control automation of this adjustment.

c. Signal Processor/DAA Computers

The digitized pulse return range gate data samples that are collected by the receiver are sent to the FL-2 Signal Processor (SP) computer for the first stage of transformation into the "factors" format needed by the Concurrent postprocessor computer algorithms. The second stage of this transformation is performed by the Data Analysis and Acquisition (DAA) preprocessor computers. Both of these preprocessors were designed and built by Lincoln Laboratory as special-purpose computers for weather signal processing. Both operated satisfactorily throughout the weather season at Orlando, except for the damage suffered on July 25.

The signal processor integrates the sample data for each range gate over the dwell time for each 1.0° azimuth sector, forming three lag products. The Data Acquisition and Analysis (DAA) computes the phase angles and magnitudes from these lag products to form "factors" data. Both computers merge various timing and antenna position information with these results to identify them for the Concurrent computer's algorithms. Only minor changes were required to these preprocessors to adapt to the new C-band operations: to the signal processor to match the new data sampling rate (1 MHz rather than 1.25 Mhz) and to the DAA to match the new configuration of range sampling modes.

A major effort before the beginning of the 1990 demonstration period attempted to reduce the frequency and effects of the intermittent failures that occurred in these computers last year. The "speckling" problem has essentially disappeared, as has the problem with occasionally missing radials. The occasional dropout of blocks of data from one of the two DAA processors is also less frequent, but still occurs. Only this last effect has any observable effect on the Concurrent data processing.

Another event relating to the synchronization of the start of an antenna scan with the start of signal processor and DAA processing still occurs infrequently, but the nature of the event changed in the new C-band timing environment. The new DAA processor subsystem that was installed last year at Kansas City shuts down whenever such an event occurs because it makes a stringent check on data quality that the older DAAs does not. The situation could not be resolved before the weather demonstration season began at Orlando; as a result, all of the data gathering is done with the same preprocessors as were used in Kansas City.

LIST OF ABBREVIATIONS

AEL	Algorithm enunciation language
AGL	Above ground level
ATC	Air traffic control
COHO	Coherent local oscillator
DAA	Data acquisition and analysis
dBZ	Decibel (referenced to reflectivity factor z)
ELLWAS	Enhanced Low-Level Wind Shear Alerting System
FAATC	Federal Aviation Administration Technical Center
GSD	Geographic situation display
km	Kilometer
LLWAS	Low-Level Wind Shear Alerting System
M-Class	Mobile Cross-chain Loran Atmospheric Sounding System
m/s	Meters per second
MBP	Microburst prediction
MCI	Kansas City International Airport
MCO	Orlando International Airport
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
PFA	Probability of false alarm
PIREPs	Pilot Reports
POCF	Probability of correct forecast
POD	Probability of detection
RDT	Ribbon display terminal (an alphanumeric display terminal)
RF	Radio frequency
SP	Signal processor
TDWR	Terminal Doppler Weather Radar
TRACON	Terminal Radar Approach Control facility
UND	University of North Dakota

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