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Results of the Kansas City 1989 Terminal Doppler Weather Radar (TDWR) Operational Evaluation Testing

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J.E. Evans
Editor

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16. Abstract

The ~~Lincoln Laboratory~~ Terminal Doppler Weather Radar (TDWR) testbed was used, ~~to carry out an experimental and operational hazardous weather product evaluation program for the Federal Aviation Administration (FAA)~~ at the Kansas City International (KCI) airport, ~~during the summer of 1989.~~ The objective ~~of the program~~ was to test and refine previous tested techniques for the automatic detection of low-altitude wind shear phenomena (specifically microbursts and gust fronts) and heavy precipitation in a midwest weather environmental, as well as to assess possible new products such as storm movement predictions.

A successful operational evaluation of the TDWR products took place at the KCI tower and terminal radar control room (TRACON), ~~from 15 July to 15 August 1989 and from 15 to 30 September 1989.~~ Several supervisor and controller display refinements ~~that had been determined from the 1988 operational evaluation at Denver~~ were assessed as effective. The system was successful in terms of aircraft at KCI avoiding wind shear encounters during the operational period, and it was assessed as "very good" in usefulness for continuing operation by the KCI air traffic control (ATC) personnel.

The probability of detection for microbursts was substantially better than that in Denver, ~~and was well above the system requirements specifications.~~ However, the false-alarm probability was found to be substantially higher in Kansas City due to a combination of weather and clutter phenomena. By optimizing the site-adaptation capabilities of the TDWR meteorological and data quality algorithms, the required false-alarm probability was achieved.

The gust front performance was generally poorer than in Denver due to a combination of unfavorable radar-airport-gust front geometry of false alarms induced by low-level jets. Gust front algorithm refinements which should provide improved performance are discussed.

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ABSTRACT

The Lincoln Laboratory Terminal Doppler Weather Radar (TDWR) testbed was used to carry out an experimental and operational hazardous weather product evaluation program for the Federal Aviation Administration (FAA) at the Kansas City International (KCI) airport during the summer of 1989. The objective of the program was to test and refine previously tested techniques for the automatic detection of low-altitude wind shear phenomena (specifically microbursts and gust fronts) and heavy precipitation in a midwest weather environment, as well as to assess possible new products such as storm movement predictions.

A successful operational evaluation of the TDWR products took place at the KCI tower and terminal radar control room (TRACON) from 15 July to 15 August 1989 and from 15 to 30 September 1989. Several supervisor and controller display refinements that had been determined from the 1988 operational evaluation at Denver were assessed as effective. The system was successful in terms of aircraft at KCI avoiding wind shear encounters during the operational period, and it was assessed as "very good" in usefulness for continuing operation by the KCI air traffic control (ATC) personnel.

The probability of detection for microbursts was substantially better than that in Denver and was well above the system requirements specifications. However, the false-alarm probability was found to be substantially higher in Kansas City due to a combination of weather and clutter phenomena. By optimizing the site-adaptation capabilities of the TDWR meteorological and data quality algorithms, the required false-alarm probability was achieved.

The gust front detection performance was generally poorer than in Denver due to a combination of unfavorable radar-airport gust front geometry and false alarms induced by low-level jets. Gust front algorithm refinements which should provide improved performance are discussed.

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Important contributions to the Kansas City tests were made by a number of individuals in addition to those identified in the Table of Contents. The dedication of the TDWR testbed operations team (N. Fischer, S. Dajnak and E. Telles) was a key element in the overall success. The University of North Dakota radar operations team (headed by A. Borho), forecasting group (headed by D. Bernhardt), and aircraft crew (headed by R. Tilbury) provided effective measurement support and data analysis assistance.

Major contributions to the real-time software/hardware systems were provided by M. Eby, D. McLaughlin, A. Dockrey, L. Henshaw, M. Maciolek, R. DeMillo, S. Olson, J. Maccini, R. Meuse, D. Piercey, and G. Rappa. G. Weiner (NCAR) adapted the Denver GSD software for Kansas City as well as adding several additional product displays. I. Copeland played a major role in site construction, system movement, and securing local logistical support while M. Couture provided much of the site rigging support.

Much of our success in operational testing was due to the cooperation and interest of the Air Traffic and Airways Facility staff of the Kansas City International (KCI) Airport. D. Hehr and C. Hatem acted as the principal KCI contacts for the ATC operational testing. L. Stevenson (TSC) assisted in the design of the operational data acquisition system as well as participating in the analysis of specific incidents.

L. Neilley had a significant role in both the microburst performance analysis and in various data quality investigations, while M. Donovan assisted significantly in the gust front performance analysis. D. Diskin and S. Stanfill assisted in the extensive clutter residue map generation and evaluation process. The efficiency and dedication of the Lincoln Laboratory computer operators (C. LeBell, P. Mitchell, and P. Morin) enabled the data processing to keep abreast of the data generation.

Staff from the National Severe Storms Laboratory (NSSL), especially M. Eilts and L. Hermes, were at the TDWR testbed site through much of the measurement period for real-time truthing of gust fronts as well as providing site-specific adjustment of the algorithm parameters and rapid analysis of problems identified in the testing. NSSL personnel (primarily L. Showell and B. Curran) also carried out the atmospheric sounding measurements.

Finally, the report preparation, editing, and publication assistance was very ably accomplished by L. Mahn.

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1. INTRODUCTION AND EXECUTIVE SUMMARY
(J. Evans, editor)

The Federal Aviation Administration (FAA) Terminal Doppler Weather Radar (TDWR) program conducted an aviation weather hazard measurement and operational product evaluation program during 1989 around the Kansas City International (KCI)[1] and the other Kansas City area airports. The objective of the 1989 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 Midwest storm environment characterized by squall lines with "supercell" storms and tornadoes.

From 19 June to 15 August and from 15 to 30 September 1989, an operational evaluation of the TDWR products took place at KCI. The TDWR testbed radar located near Leavenworth, Kansas executed the TDWR scanning patterns and automatically generated the TDWR microburst, gust front/wind shift and precipitation products. These products appeared on displays at the KCI control tower and terminal radar control room (TRACON) for dissemination to aircraft landing or taking off at KCI and for the control facility supervisors to better manage the use of the airspace. Additional developmental products (e.g., storm movement forecasts) were tested in the second portion of the operational evaluation period.

The specific objectives were to evaluate:

1. Microburst detection performance,
2. The TDWR warning function,
3. Gust front detection and wind shift prediction performance,
4. The TDWR planning function, and
5. New products, such as storm movement predictions.

This report provides a preliminary summary of the results of the measurement and product evaluation program. Subsequent reports will describe the results of detailed investigations into various issues that arose in the testing. In this section, we provide background information on the measurement program, experimental systems, and present some salient results. Detailed results are presented in the subsequent chapters and the appendices.

A. BACKGROUND

Low-altitude wind shear is a major cause of fatal air carrier accidents, and turbulence causes a number of injuries every year to air carrier passengers and flight crews. A major goal of the TDWR program is to provide automatic detection and warning of microbursts, the most hazardous form of wind shear for 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 [1, 2, 13]. As this downdraft reaches the earth's surface, it spreads out horizontally, like a stream of water sprayed straight down on a concrete driveway from a garden hose. An aircraft that is flying through a microburst at low altitude first encounters a strong head-wind, then a downdraft, and finally a tailwind that produces a sharp reduction in airspeed and a sudden loss of lift. This deadly sequence of events has caused at least 30 aircraft accidents and incidents that have killed more than

[1]The abbreviation KCI is used here to conform to the standard usage by the Kansas City ATC personnel. The official code for the airport is MCI.

500 persons in the United States since the mid-1960s. The most 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), and Denver (1987-1988) and a successful operational evaluation at Denver in 1988, the FAA has awarded a contract for the production of 47 TDWR systems [1, 3, 4]. These systems will be used for operational wind-shear detection and warning at major US airports (including KCI) in the early 1990s.

B. MEASUREMENT SYSTEM

Figure 1-1 shows the locations of the various ground weather sensing systems used in the 1989 measurement program. The TDWR, developed and operated by the

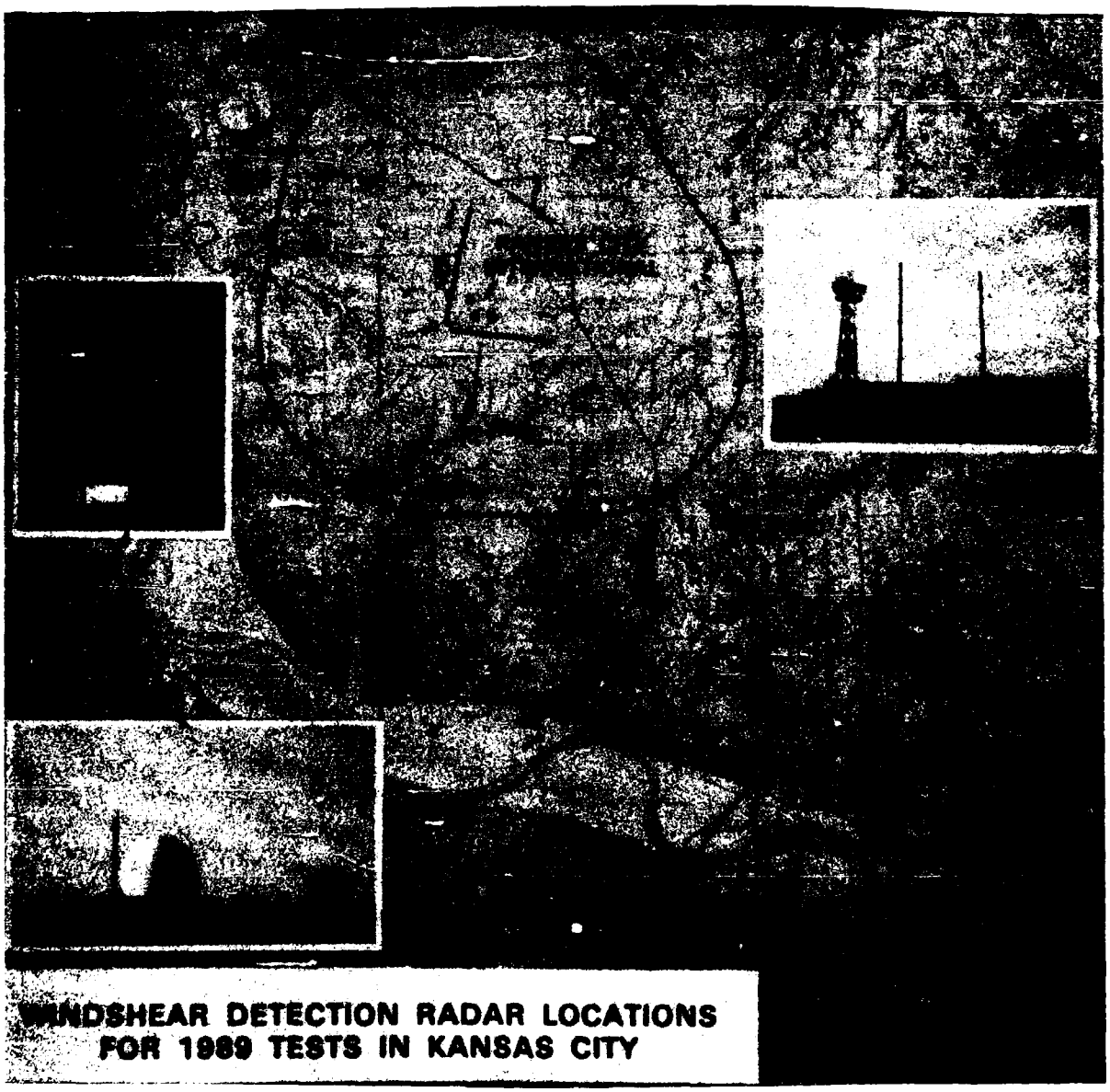

Figure 1-1. Wind shear detection radar locations for 1989 tests in Kansas City.

Lincoln Laboratory of the Massachusetts Institute of Technology (M.I.T.), was the primary data collection tool for the TDWR measurement program. This S-band radar (designated by the letters FL-2 in Figure 1-1) uses a 28ft.-diameter antenna and a powerful signal processing system to record, process and display the Doppler measurements. The signal processing techniques used (e.g., digital ground clutter rejection filters and automatic selection of signal waveforms) are 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-2 site.

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 1-1), located about seven miles east of KCI and five miles northwest of the Downtown airport near Gladstone, Missouri, provided additional confirmation of wind shear events near KCI and the Downtown airport as well as data on the effects of wavelength on the characteristics of various weather phenomena.

The air surveillance radar (ASR) testbed developed and operated by Lincoln Laboratory was located adjacent to the FL-2 sensor near Wolcott, Kansas. This S-band radar (designated by the letters FL-3 in Figure 1-1) uses an ASR-8 antenna and transmitter and a wideband recording system to record all of the data measured by the system on the antenna 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 [14]. The ASR provided rapid update measurements (several per minute) on storm reflectivity and on some of the microburst outflows near the FL-3 site.

A network of 40 automatic weather stations (one of which is shown in Figure 1-2) 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 analysis. The wind data from the weather stations will be 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 will be 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 FAA LLWAS anemometers located around KCI. From 22 June to 15 August, NSSL personnel made soundings of the atmosphere vertical structure during periods of significant weather using the NSSL-developed weather balloon sounding system.

From 1 April to 15 June and 15 August to 4 September, 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. The Citation aircraft furnished the 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.

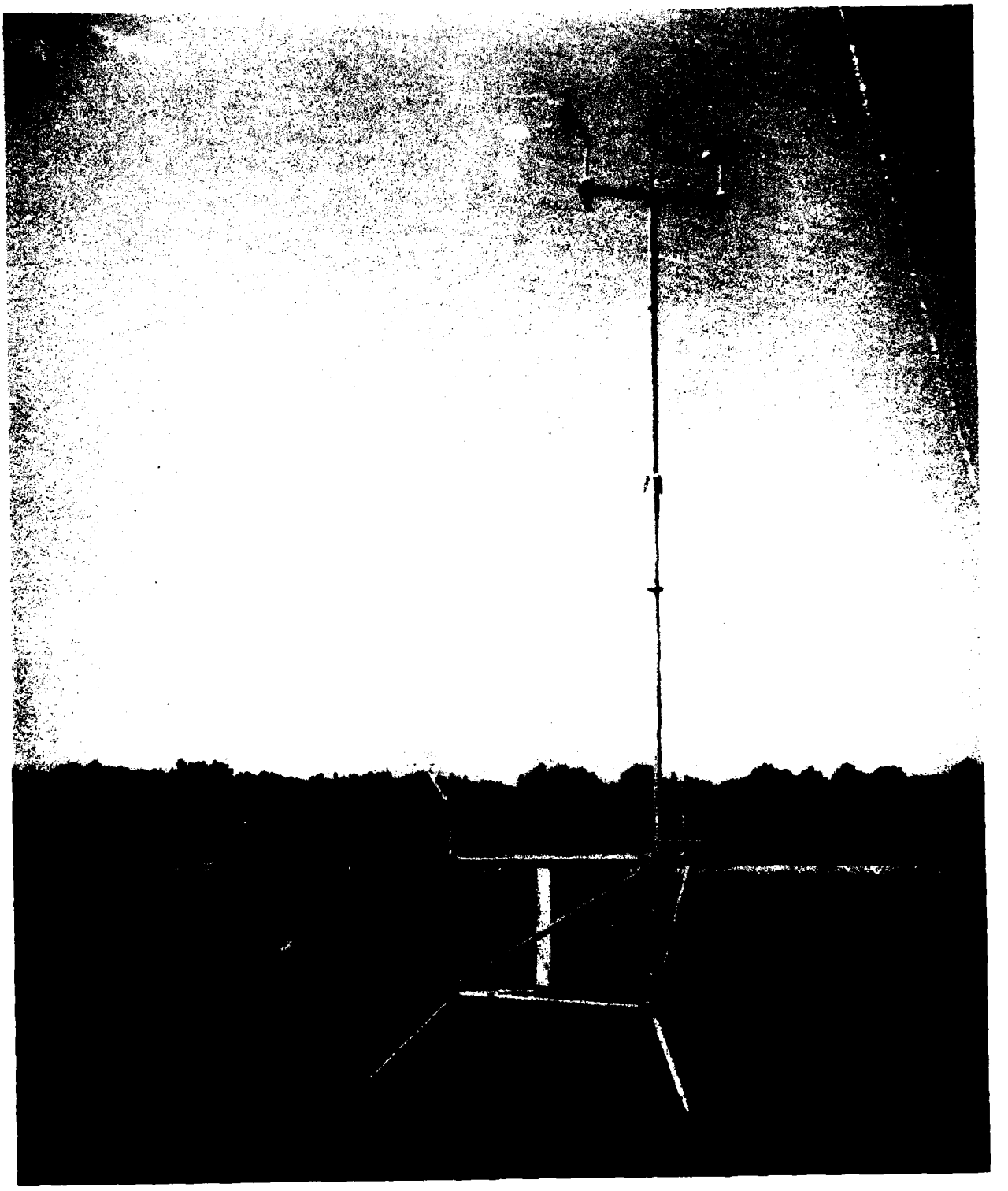

Figure 1-2. Weather radar measurement program surface weather station.

C. OPERATIONAL CONCEPT/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 wind shear phenomena can differ in various regions of the country and there are differences in airport configurations, it is important that the planned products be operationally evaluated in a variety of environments. The KCI testing permitted the evaluation of the products tested operationally at Denver in 1988 as well as the assessment of certain product/user interface refinements that grew out of the Denver tests [5].

In the initial implementation, TDWR data will be directly disseminated to controllers and supervisors using two types of displays. These displays are:

1. A ribbon (alphanumeric) display which displays wind shear hazard messages 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.

1. Ribbon Display

Ribbon displays were provided at several locations in the KCI 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 any interpretation, as shown in Figure 1-3. The alert message describes the affected runway, type of wind shear (strong microbursts are 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 are (1) MBA for microburst alert and (2) WSA for wind shear alert.

Based on the User's Working Group [5], the location information was quantized into six locations: the runway itself and rectangular boxes centered on the runway centerline located 1, 2, and 3 nmi from the approach runway end and 1 and 2 nmi from the departure runway end. 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 KCI testing. The specific codes used on the display to indicate location are (1) MF for miles final, (2) MD for miles departure, and (3) RWY for on the runway. When a microburst (or gust front) shape overlapped at least one rectangular region, an alert was issued for the location at which the wind shear would be first encountered by an aircraft [7].

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, and precipitation intensity) were available on these displays. Selectable features included range from the airport, background maps, and precipitation intensity levels to be displayed. The wind shift product, which can be selected to be either on or off, provided a prediction of the location of a gust front for 10 minutes and 20 minutes in the future. In this way air traffic supervisors could anticipate wind shifts that could change runway usage patterns, rather than reacting to a wind shift that had already impacted airport operations. A GSD also was provided to the Central Weather Service

Unit (CWSU) meteorologist at the FAA enroute control facility in Olathe, Kansas for interpretation of the precipitation display information.

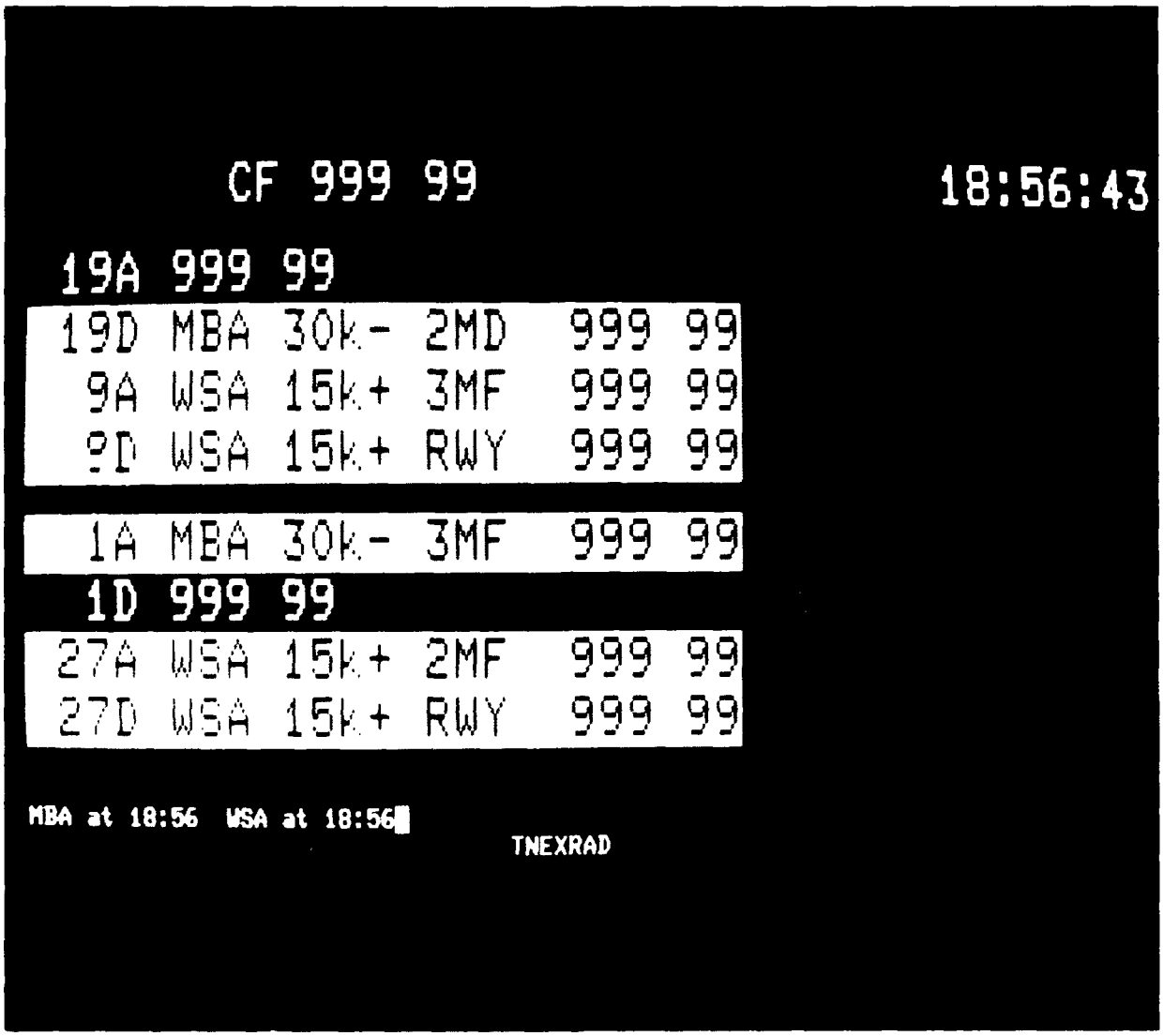

Figure 1-3. Ribbon display for Kansas City testing. The LLWAS winds data (shown as 99 99) are not valid. The message for departures on runway 19D is "microburst alert, expect 30 knot loss at 2 miles on departure."

Figures 1-4 and 1-5 show GSD displays for a wind shear incident which occurred on 24 June during the operational evaluation period. Six microbursts (depicted by open and filled red areas) are active south of the airport. Two microbursts (one with an estimated 30 kt headwind loss) are impacting the N-S runway corridor warning boxes that are 2 and 3 nmi, respectively, from the runway end. These runway corridor regions are shown in red to indicate that they are in a microburst alert status. The leading edge of the outflows from these microbursts have created a gust front (indicated by a purple line) which is impacting the E-W runway corridor (shown in purple to indicate that a "wind

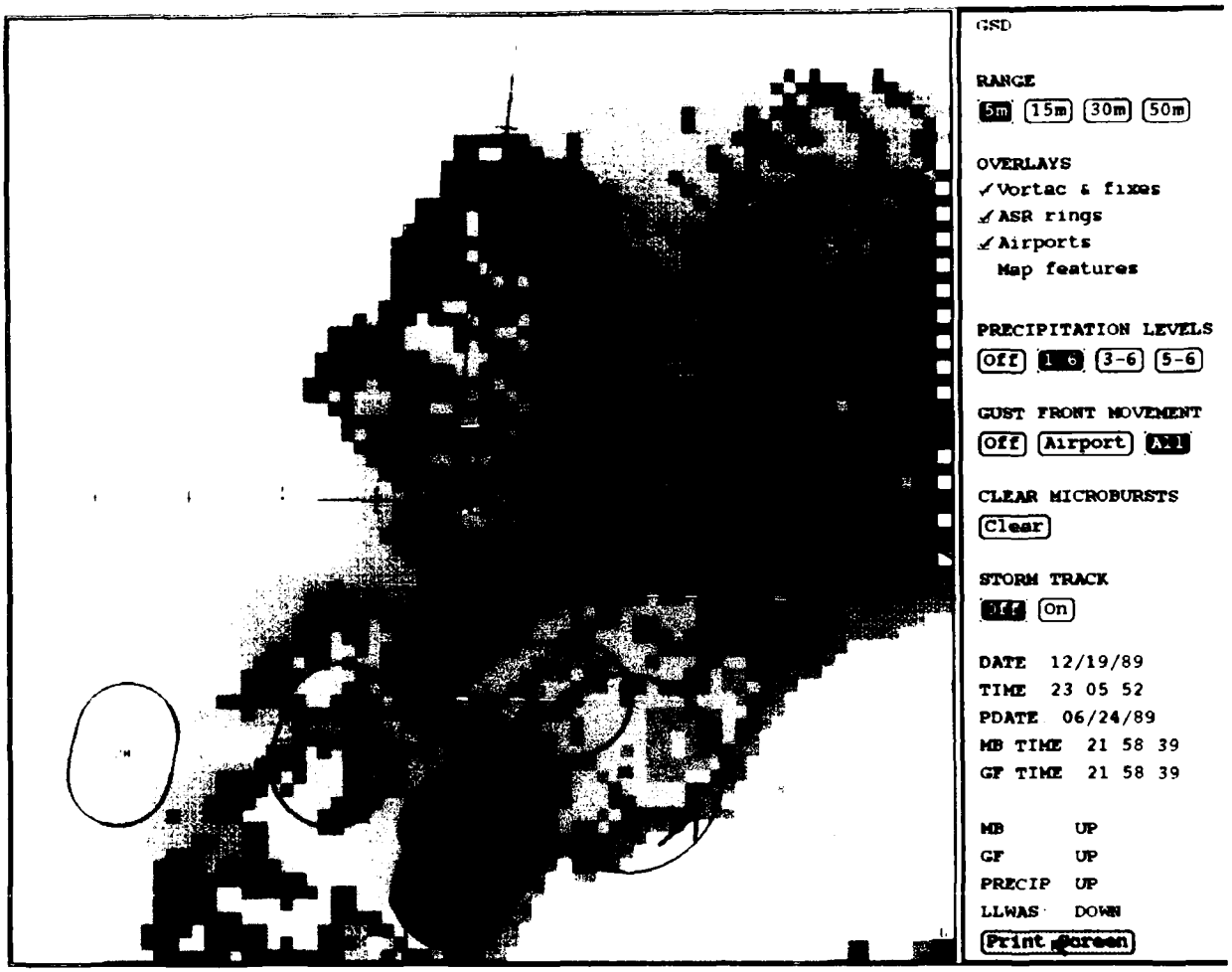

Figure 1-4. Kansas City geographical situation display (GSD) on 5 nmi scale for a wind shear event which occurred on 24 June 1989.

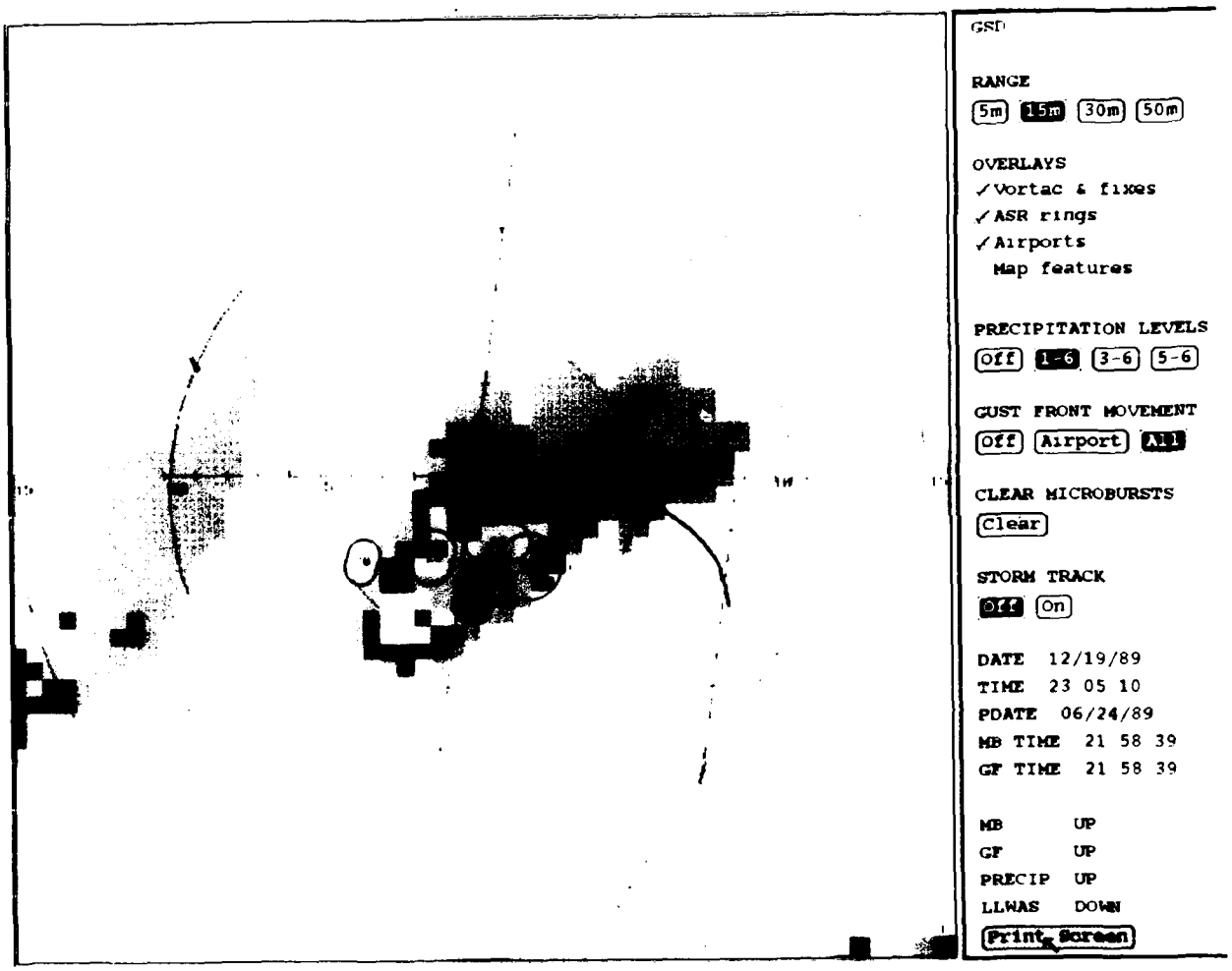

Figure 1-5. Kansas City GSD on 15 nmi scale for wind shear event of 24 June 1989. Navigational fixes, including VORTAC and Kansas City downtown airport, are shown.

shear" alert is in effect for this runway region). The forecasted gust front positions at 10 and 20 minutes are shown as dashed purple lines, and the expected wind shift is shown as a purple arrow. The precipitation levels, depicted by green, yellow, and brown pixels, range as high as National Weather Service (NWS) level 5. Figure 1-5 also shows the optional display of navigational fixes as well as other airports. The downtown Kansas City airport (KCD), approximately 12 nmi southeast of KCI, is seen to be minimally impacted at this time by the KCI storm.

The product/user interface refinements evaluated at KCI included:

1. Reordering the message content on the Ribbon Display to improve wind shear warning comprehension, and

2. Allowing the supervisors to enter the active runways so that Ribbon Display messages are displayed only for the runways in active use.

Storm movement prediction products were displayed on the GSD during the latter portion of the evaluation period to see if this additional planning information for the supervisors was of use operationally. Figure 1-6 shows the GSD with storm movement information for a storm that occurred outside the operational evaluation period.

D. WEATHER MEASUREMENT RESULTS

The weather in the vicinity of the KCI airport displayed considerably less convective activity than is normal during the bulk of the summer, as shown in Table 1-1. As a consequence of this reduced thunderstorm frequency, the microburst wind shear frequency for KCI was considerably less than that observed previously in Denver and Huntsville (see Figure 1-7).

Although KCI is in the center of the "tornado belt," the incidence of severe weather in 1989 was much lower than normal. In particular, there was a lack of major squall lines with supercell storms and/or tornadoes. However, the vast majority of observed wind shear events were scanned in a coordinated dual-Doppler mode by the UND radar. This information, together with simultaneous LLWAS and Mesonet data, will be quite useful for the TDWR/LLWAS integration algorithm development effort.

Prior to the beginning of the operational demonstration, special coordinated aircraft/radar tests were carried out to assess turbulence detection and the ability of the radar to estimate wind shear intensity along a flight path. Approximately 15 turbulence missions and low-altitude penetrations of three microbursts and 10 gust fronts were accomplished (see Appendix A for summary results).

E. HAZARDOUS WEATHER DETECTION PERFORMANCE RESULTS

The Kansas City program provided a good opportunity for assessment and refinement of both the TDWR data quality algorithms and the wind shear detection algorithms in an environment that presented a number of challenges not encountered to a significant degree in the Denver 1987-1988 testing. The environmental challenges included:

1. Spatially contiguous regions of high-level ground clutter near the radar (due to the Missouri and North Platte river valleys),

Table 1-1.
Comparison of Kansas City 1989 Thunderstorm Day Frequency with Long-Term Average Frequency.

THUNDERSTORM DAYS			
	1989	"Normal"	Departure
April	2	5.8	-66%
May	7	7.4	-5%
June*	6	8.4	-29%
July*	3	7.6	-61%
August	11	6.5	+69%
September	5**	5.2	-4%
	34	40.9	-17%

* normal period of severe weather near KCI

** this activity occurred in the first two weeks of September

2. Contamination of data near the airport by range-aliased echoes from distant storms,

3. Strong environmental winds near the surface which could produce velocity signatures similar to those of microbursts or gust fronts,

4. Spatially extended regions of moving clutter sources (e.g., birds and/or insects), and

5. An unfavorable radar - airport geometry for the current gust front algorithm.

The majority of these challenges (1.- 4.) were addressed during and immediately after the demonstration using the site adaptation parameters described in the current TDWR algorithm specifications.

The performance of the algorithms was assessed by comparing the algorithm output with ground truth developed from the FL-2 radar by Lincoln and NSSL analysts. This form of scoring has been used in the past and has given results comparable to those using dual Doppler and/or radar and Mesonet data [4, 6, 7, 8, 9].

1. Microburst Detection Performance

Table 1-2 compares the Denver results with the Kansas City microburst detection performance. The Kansas City results are presented both before and after the microburst algorithm site adaptation parameters were adjusted from the Denver 1988 values to values which are more nearly optimized for Kansas City. Note in particular that 99 percent of microbursts strong enough to generate a "microburst alert" were detected in Kansas City.

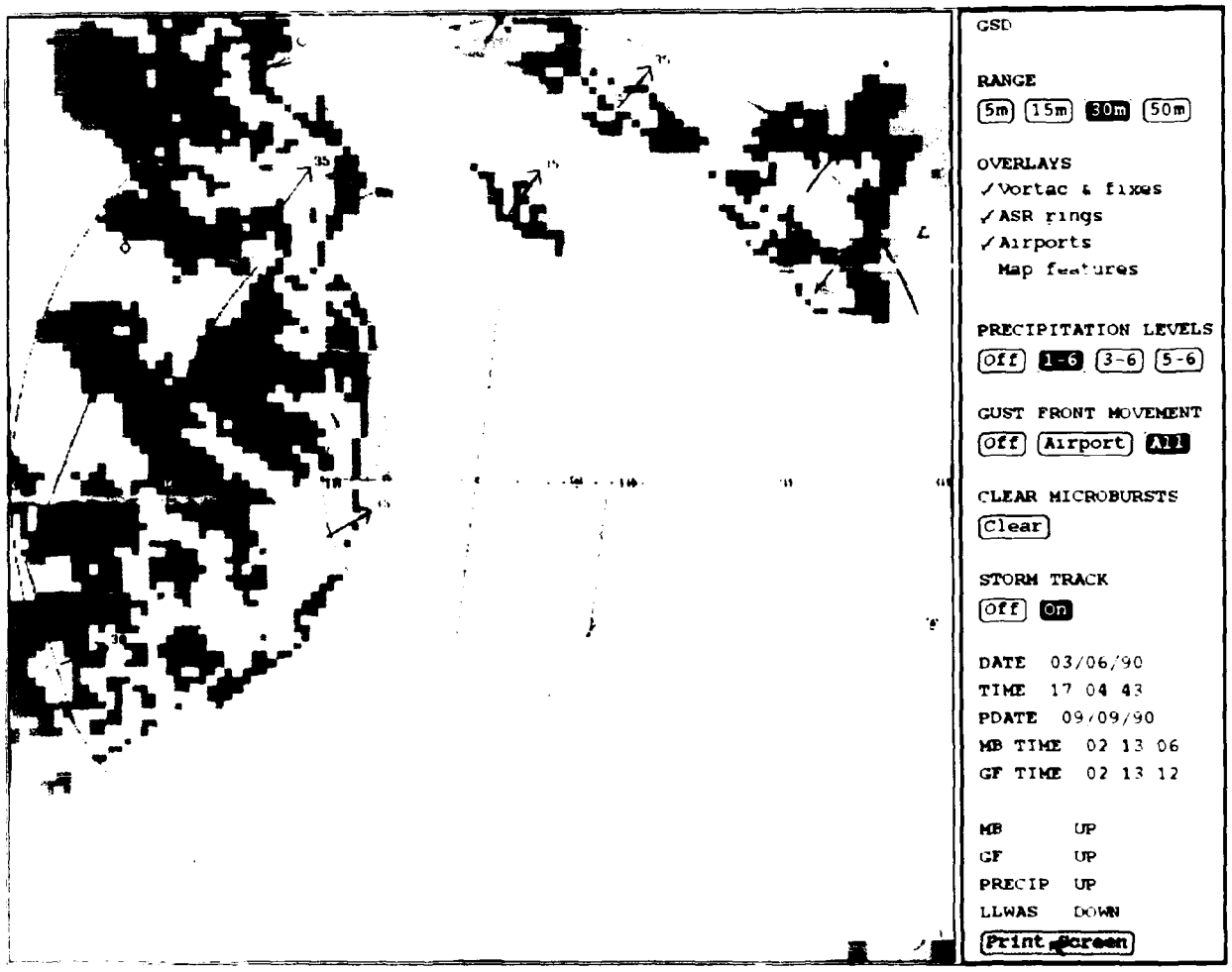

Figure 1-6. Kansas City GSD with experimental storm track vector display for a storm which occurred outside the operational evaluation period. The cells are shown to be moving to the northeast at approximately 35 kt. Approximately 20 minutes after this time, a US aircraft hit a power line on an attempted approach through rain to runway 9A.

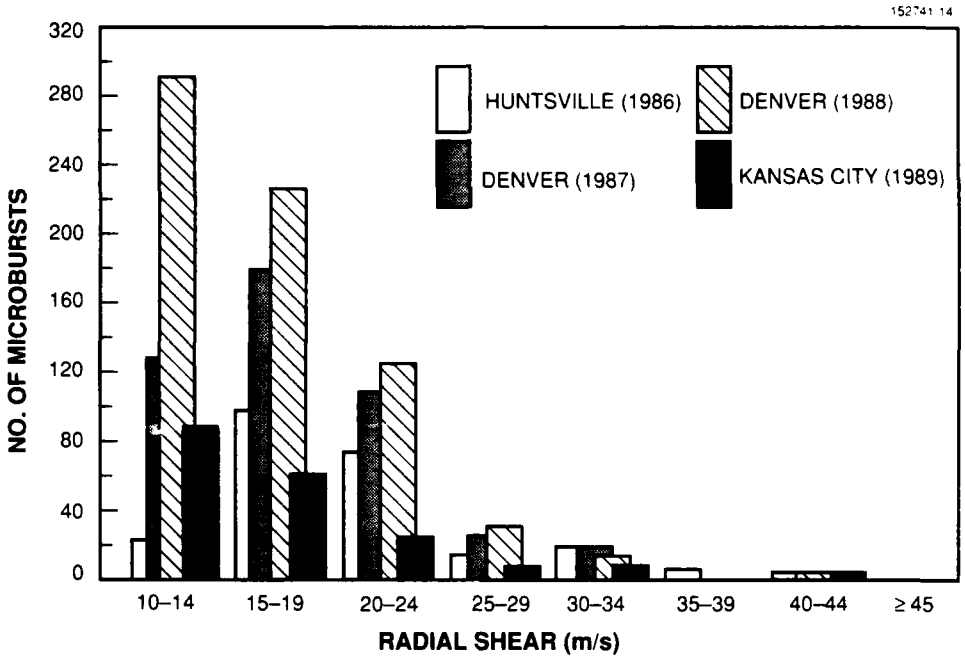

Figure 1-7. Distribution of the radial shear across microbursts.

Table 1-2.
Comparison of Kansas City Microburst Detection Performance with Denver Test Results.

			Kansas City 1989	
		Denver 1988	Initial	After Optimization
Probability of Detection	($\Delta V \geq 20$ kt)	.90	.96	.96
	($\Delta V \geq 30$ kt)	.97	.99	.99
Probability of False Alarm		.05	.11	.07

ΔV = Velocity change across microburst

It was found that 28 percent of the initial Kansas City false alarms arose in cases where there were no cells and that another 12 percent reflected incorrect precursor declarations. By conditioning alarms on reflectivity aloft and making the precursor declaration more stringent, the probability of false alarm (PFA) was reduced to a level less than the TDWR system requirement of 10 percent, while keeping the probability of detection (POD) well above the 90 percent system requirement.

2. Gust Front Detection Performance

Table 1-3 compares the detection performance of the current gust front algorithm in Kansas City with the Denver 1988 results. The POD for all gust fronts within 60 km of the radar is seen to be fairly similar. The higher PFA for Kansas City arises principally from the strong environmental winds (especially, low-level jets) and from unflagged clutter residue along the river banks.

Table 1-3.
Gust Front Detection Performance.

	POD as Function of Gust Front Strength				PFA
	Moderate*	Strong**	Severe***	All	
All gust fronts +:					
Kansas City (1989)	.72	.81	.92	.77	.13
Denver (1988)	.73	.91	1.00	.78	.02
Gust fronts at airport:					
Kansas City (1989)	.29	.68	.40	.45	.40
Denver (1988)	.64	.86	none	.70	.00

* $20 \text{ kt} \leq \Delta V < 30 \text{ kt}$

** $30 \text{ kt} \leq \Delta V < 50 \text{ kt}$

*** $50 \text{ kt} \leq \Delta V$

\+ all gust fronts within 60 km of radar

The POD for gust front wind shear at KCI airport is seen to be significantly poorer than the corresponding figures for Denver. This is because:

1. The current algorithm performs poorly in detecting gust fronts which lie along a radar radial, and

2. FL-2 was situated south of KCI such that gust fronts propagating from the west or northwest would be along a radial when they were near the airport.

In Denver, by contrast, the FL-2 radar was situated to the southeast of the airport such that gust fronts approaching from the northwest were at right angles to the radar radials. This emphasizes the importance of siting for system performance optimization. However, since optimum sites may not be available at some TDWR airports, an intensive effort is underway to develop an improved gust front algorithm whose performance will be less sensitive to viewing angle.

3. Gust Front/Wind Shift Planning Information Performance

Table 1-4 compares the planning information performance at Kansas City with that for Denver. We see that when gust fronts were detected reliably enough to make a forecast, the resulting forecasts were accurate. However, an appreciable number of false forecasts were made. The bulk of these false forecasts were probably of little consequence operationally because a 10- or 20-minute forecast is false if the gust front dissipates before the 10 or 20 minutes has passed.

Table 1-4.
Gust Front/Wind Shift Planning Information Performance.

	Probability of Making a Forecast	Probability of Correct 20-Minute Forecast Gust Front Position as a Function of Gust Front Strength				Probability of a False Forecast
		Moderate	Strong	Severe	All	
Kansas City (1989)	0.50	.95	.93	1.00	.94	.21
Denver (1988)	0.45	.82	.84	none	.83	.18

Average absolute error in forecast wind shift speed and direction was 3 m/s and 30° for both locations.

4. Data Quality Algorithm Performance

An important element of the overall system performance achieved in the Kansas City tests was refinement of the data quality algorithms. In initial Kansas City testing using the data quality algorithms that were successful in Denver, it was found that the microburst false-alarm probability was over 50 percent on three days due to range folded

echoes after the passage of frontal storms. The range obscuration data editing algorithm called for in the TDWR specification was implemented in real time and shown to eliminate over 80 percent of the range-aliased echo false alarms. Additionally, the scan strategy elevation angles for long-range weather measurements were adjusted to provide updates of the pulse repetition frequency (PRF) every five minutes as opposed to the 10-minute update period used in Denver.

It was found that higher than expected ground clutter residue levels occurred along the banks of the Missouri and North Platte Rivers. This residue was largely edited out by the clutter residue map data-editing algorithm. However, wind shear detection performance was adversely affected by the high residue level and by residue breakthrough. Inspection of time series data sets showed anomalous jumps in the waveforms when scanning past high level point targets. These jumps were traced to a malfunction in the automatic gain control (AGC) normalization and compensation system. Correction of this malfunction (prior to the operational demonstration) led to a 10 dB improvement in effective ground clutter suppression. This incident pointed out the validity of the TDWR system requirement for real-time monitoring of the system dynamic response and the utility of time series recording to resolve anomalous performance issues.

F. OPERATIONAL UTILIZATION RESULTS

The objectives of the KCI operational utilization investigations were to:

1. Evaluate the format of the hazardous weather messages on the alphanumeric display and the usefulness of the subsequent controller's messages to the pilots, including the impact of the messages and actions on the terminal ATC system, and

2. Assess the usefulness of the current and possible future GSD products for terminal air planning.

These objectives were essentially identical to those for the 1988 Denver testing. However, there were several differences between the two evaluations:

1. The KCI evaluation involved a terminal facility with no prior experience with wind shear testing or runway-oriented wind shear alerts from LLWAS, whereas the Denver terminal facility has been the location for a variety of wind shear investigations starting in 1984[2].

2. The KCI display systems incorporated several modifications to rectify problems identified in the 1988 testing [5]. These included revising the message content delivery sequence to provide better separation of hazard warnings from routine clearance delivery information (e.g., threshold winds and "cleared to land"), entry of active runways by the tower supervisors to permit reduced clutter on the alphanumeric display, and depicting gust front movement by the expected positions 10 and 20 minutes in the future, and

[2] However, the KCI terminal facilities have had a color NWS weather radar display in the tower and TRACON for several years, and hence the controllers were much more accustomed to a color weather depiction, as on the GSD display, than were the Denver controllers in 1988. We observed that the tower controllers at KCI would, on occasion, use the GSD display to provide weather information to pilots, as opposed to using only the alphanumeric displays.

3. A new planning product, storm movement prediction, as depicted by arrows, was used only at KCI.

These differences should be considered when comparing results from the two evaluations.

The products and displays were presented to the tower controllers and supervisors in a one-hour course[3] held approximately two weeks before the demonstration commenced. During the first month of the operational evaluation, a Lincoln Laboratory or NSSL observer was present at the terminal facility during the operational hours to provide explanations of the product warnings and/or display usage. Subsequently, the observer was present only when significant weather occurred in the vicinity of KCI. At the end of the demonstration, questionnaires were provided to the terminal facility supervisors and tower controllers for evaluation. This was followed by a meeting with representative KCI terminal facility personnel to obtain further feedback on salient issues.

As shown in Table 1-5, the KCI terminal facility personnel generally responded enthusiastically to the TDWR product displays and message delivery formats. The analysis of the impact of the messages delivered and the planning function could not be as detailed as was accomplished in Denver due to:

1. Significantly fewer wind shear occurrences than in Denver. The airport received "microburst" and "wind shear with loss" alerts for approximately 140 minutes during the operational period and "wind shear with gain" (i.e., gust front) alerts for approximately 60 minutes. Most of these alerts occurred on only a few operational days.

2. The traffic density at KCI during the wind shear periods that did occur was significantly less than that at Denver. The density dropped substantially during the operational period as a result of the financial difficulties encountered by the major airline that was using KCI as a hub.

As a consequence of the low frequency of weather and reduced demand on the terminal capacity, the pilots and terminal facility personnel typically reacted very conservatively when microbursts were detected. Moreover, the low frequency of situations in which the warnings would affect operations resulted in much less overall impact on the KCI terminal ATC system than was the case in Denver.

The revised wind shear message format appeared to be quite successful in that there were no situations in which pilots continued an approach or takeoff due to message misinterpretation when a microburst alert was present. This improved clarity in message format, coupled with the conservative reaction to alerts, resulted in virtually no pilot reports available to assess the accuracy of the valid microburst warnings. There were a number of microburst false alarms on cloudless days (before the algorithm site adaptation adjustments were made), and these presented an operational difficulty since the controllers did not want to present to the pilots a warning which they were certain was false.

There were a number of pilot reports in response to gust front warnings. These are being analyzed to determine the accuracy of the warnings. The gust front planning function was not used to a significant degree for two reasons. First, the bulk of the gust

[3] Due to difficulties in scheduling the course participants, the course was repeated approximately seven times over a one-week period so that all of the personnel could participate. In retrospect, the course did not provide adequate "hands on" training.

Table 1-5.
Operational Evaluation Questionnaire Results.

Item	Median Rating*
day time readability of displays	good
night time readability of displays	very good
display readability in glare	fair to fairly good**
display location	
GSD	fair
alphanumeric	fairly good
accuracy of displayed information	good
number of false alarms	good to very good or "do not know"
timeliness of displayed information	good to very good
usefulness of displayed information	very good
freedom from misinterpretation	very good
ease of accessing wind information	very good
information grouping and order	good
aptness of message abbreviations	good
ease of runway selection using GSD	good
usefulness of:	
GSD hazard information	very good
GSD planning information	good to very good
LLWAS winds on GSD	very good
storm motion product on GSD	very good
runway selectability on alphanumeric display	good
usefulness for continued field use	**very good**

* categories were: very good, good, fairly good, fair, fairly poor, poor, very poor, and don't know.
** lowest ratings were for alphanumeric display used which does not meet TDWR requirement for visibility in daylight.

fronts passed over the airport when there was little traffic, so there was little need to anticipate changes in the traffic patterns. Second, the on-airport gust fronts that coincided with high-traffic periods occurred near the beginning of the operational evaluation, a time when the supervisors were still unfamiliar with the performance of the system and reluctant to use the predictions.

No significant operational difficulties were encountered in entry of active runways by the tower supervisors. However, it should be noted that KCI has a small number of active runways, and relatively few situations arose in which active runway changes were made during peak traffic periods. Thus, additional assessment of the impact on supervisor workload is needed for this system feature.

G. SUMMARY

Table 1-6 summarizes the results of the Kansas City testing in relationship to the test plan objectives. All of the principal objectives of the test were achieved, with the exception of:

1. Assessment of the TDWR products and functions during severe midwest storms, and

2. A substantive evaluation of additional TDWR products.

In both cases, a lack of appropriate weather during the test period was the principal obstacle to achieving the test objectives. In view of the interest expressed in the storm motion product in Denver and Kansas City ATC personnel debriefings, it is recommended that this product be evaluated in Orlando and Denver in 1990.[4]

The current plans for the TDWR testing are such that there will not be an opportunity to conduct an operational evaluation of the TDWR products and functions in the presence of severe midwest weather prior to the TDWR deployment. We recommend that a TDWR development group (e.g., Lincoln, NSSL or NCAR) work closely with the first midwest ATC facilities that receive the TDWR to assist in the system usage and site adaptation process.

The Kansas City tests also identified a need for more hands-on training in the system display usage, including practice in delivery of messages in cases where the TDWR is delivered to a facility which has not previously had an enhanced LLWAS. This might include practice in responding to "typical" pilot questions. The tests also identified a need for substantive gust front/wind shift algorithm refinement to reduce the performance sensitivity to gust front viewing geometry. A very active effort is underway to develop a refined algorithm which uses additional features, such as reflectivity thin lines and azimuthal shear, to improve detection performance. Additional work is also indicated in refining the wind shear detection and data quality algorithms to reduce the number of false alarms due to certain features of the midwest weather environment. These weather features include strong surface winds which vary rapidly with altitude and variations in ground clutter residue levels.

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[4] Offline evaluation of a preliminary microburst prediction product (see Chapter 2) showed very promising results. This product also may warrant operational assessment in Orlando in 1990.

Table 1-6.
Comparison of Kansas City Test Objectives and Test Results.

Test Objective (From Test Plan)	Test Results
1. Evaluate microburst detection.	POD=0.96, PFA=0.11 during test. Subsequent site adaptation parameter optimization yielded PFA=0.07 with no decrease in POD.
2. Evaluate TDWR warning function.	New message format was successful operationally in preventing microburst encounters, albeit there were relatively few operationally significant microburst events.
3. Evaluate gust front detection and wind shift prediction.	POD = 0.77 (0.45 at airport) PFA = 0.17 (0.40 at airport) for gust fronts. Forecasts for airport were made for 50 percent of gust fronts and had a 94 percent probability of being accurate for a 20-minute prediction period. Performance was impacted adversely by airport-radar-gust front geometry. Algorithm refinements are underway to improve performance.
4. Evaluate TDWR planning function.	The TDWR GSD planning products were assessed as "good" to "very good" in usefulness. Lack of significant weather occurrences during periods of high traffic significantly impaired the ability of ATC personnel to obtain substantive experience with this function.
5. Evaluate additional TDWR products.	No significant weather occurred during two-week evaluation period for storm movement product. Supervisors assessed its utility as "very good," based on off-line product examples.

H. DESCRIPTION OF REMAINDER OF REPORT

The remainder of the report provides a more detailed discussion of the results which were presented in summary form in this section. In each case, the names of the principal contributors to the section are provided to facilitate follow-up interaction by the reader.

The next chapter discusses the microburst detection performance, emphasizing the basic performance statistics and analysis of false alarm and the results of site adaptation parameter optimization studies. Also included are the results of an off-line study of an initial microburst prediction algorithm. Chapter 3 considers the gust front/wind shift product performance. Chapter 4 considers data quality issues such as ground clutter

suppression, range obscuration avoidance and point target rejection. Chapter 5 describes the operational assessment results, including observations by tower observers.

Many detailed results are presented in the Appendices. Appendix A describes the available field data from the principal sensors (FL-2, UND, the Citation aircraft and the Mesonet/LLWAS system). Appendix B summarizes the features of the TDWR testbed for these tests and compares the functional capabilities with those of the TDWR itself. Also discussed in this appendix are the FL-2 system performance results and issues arising from the FL-2 performance that may be germane for the TDWR system. Appendix C discusses the weather patterns encountered at KCI in 1989 in relationship to the long-term average weather pattern for the KCI area, while Appendix D provides bulk summary statistics for the ATC questionnaires.

2. MICROBURST DETECTION PERFORMANCE
(S. Campbell, editor)

A. BASIC STATISTICS (P. Biron, M. Isaminger)

In this section, basic algorithm performance statistics are presented for the operational demonstration period. The ground truth used in obtaining these results is based on single-Doppler radar observations and was developed by Lincoln Laboratory analysts at the FL-2 TDWR testbed radar. The algorithm was scored by comparing microburst alarm boxes generated by the algorithm with resampled color images of reflectivity and velocity for each surface scan. Alarms were then declared as either an algorithm hit, if the box overlaid a true surface outflow, or a false alarm, if no outflow was declared. An algorithm miss occurred if a true surface outflow was not detected by the algorithm. It should be noted that this scoring methodology differed from the percent overlap scoring applied in 1988; however, the scoring results are considered to be comparable. Also noted in this alarm-logging process were the event location, radial velocities of the microburst couplet, and corresponding surface reflectivity. Accurate detection and false-alarm probabilities were then calculated from the logs on a daily basis. To evaluate the performance of the algorithm, two basic quantities are desired: the probability of detection (POD) and the probability of false alarm (PFA), which are defined as follows:

$$\text{POD} = \frac{\text{Number of Hits}}{\text{Number of Hits} + \text{Number of Misses}}$$

$$\text{PFA} = \frac{\text{Number of False Alarms}}{\text{Number of Hits} + \text{Number of False Alarms}}$$

During the operational period from 19 June through 15 August 1989, 125 microbursts were observed by the radar in the KCI airport sector. These microbursts occurred on just 12 different days during this period, as shown in Figure 2-1, with 30 microbursts logged on 15 July. Of the 125 microbursts, 14 impacted terminal operations at KCI, resulting in alphanumeric alarms being issued by the TDWR system. The strongest potential microburst loss was 40 kt. It is planned to use these microbursts impacting KCI to evaluate issues such as the accuracy of strength measurements and user-perceived alarm timeliness.

Figure 2-2 is a frequency plot of maximum radial outflow velocity for Denver (1987, 1988) and Kansas City (1989) microbursts. The Kansas City data set contains a larger percentage of weak events than the Denver data sets. Fifty-five percent of the Kansas City events have maximum outflow velocities less than 15 m/s. Figure 2-3 is a frequency plot of the maximum radar reflectivity in the parent cell for these same data sets. It is clear from the plot that there is a much higher percentage of wet microbursts ($\geq$ 35 dBz) in Kansas City than in Denver. Approximately 75 percent of the Kansas City microbursts were associated with parent cells in excess of 40 dBz.

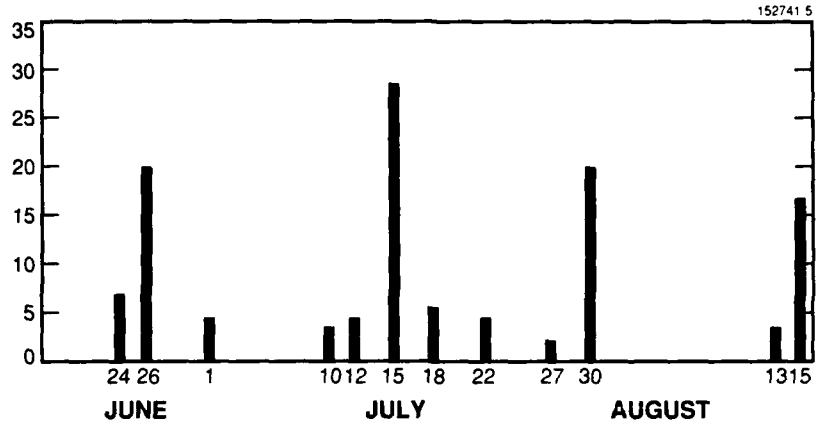

Figure 2-1. Distribution of microbursts by day during evaluation period.

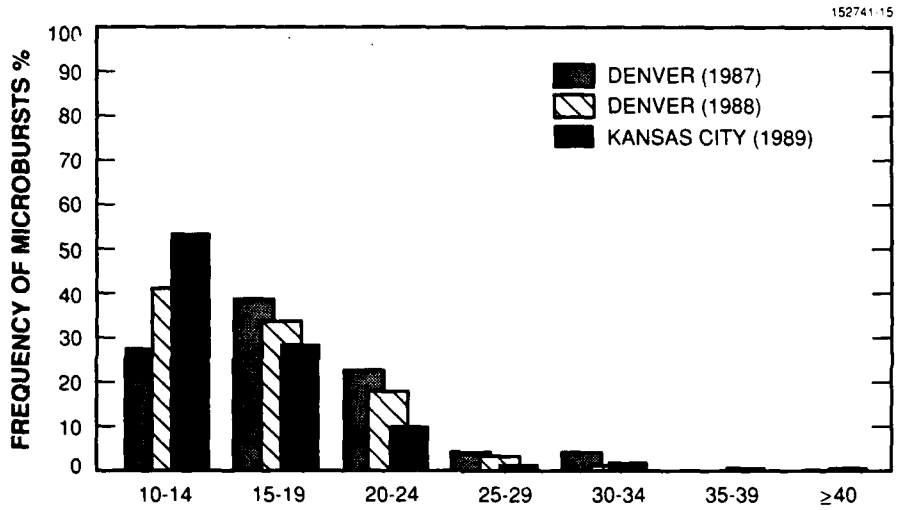

Figure 2-2. Distribution of maximum radial outflow velocity for Denver and Kansas City microbursts.

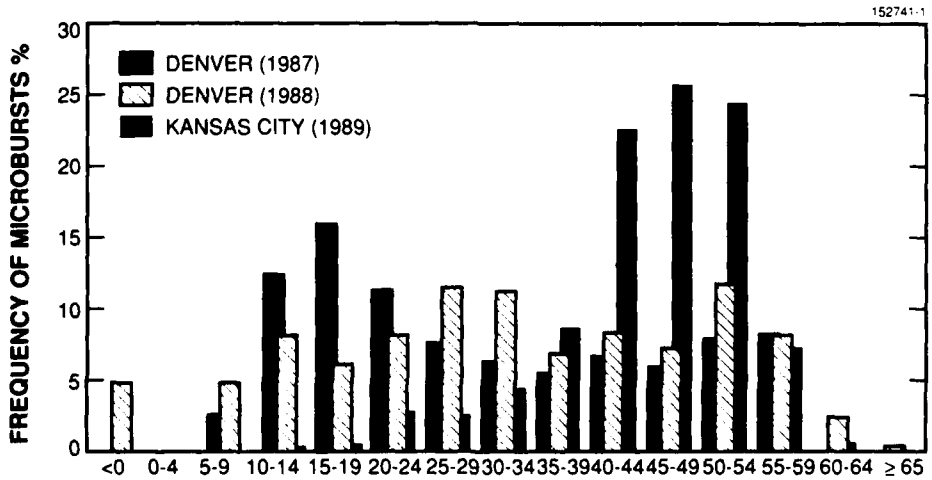

Figure 2-3. Distribution of the maximum surface reflectivity in cells that produced microbursts.

Table 2-1 presents daily algorithm performance statistics for the 1989 Operational Test and Evaluation (OT&E) period. A total of 1262 algorithm hits, 54 misses, and 155 false alarms were issued by the algorithm. No microburst events with differential velocities greater than 15 m/s were missed. For the test period, the POD was 96 percent and the false-alarm rate was 11 percent. The comparable results for the 1988 Denver OT&E were POD of 90 percent and PFA of five percent. The operational requirement for the TDWR is to achieve at least 90 percent POD and no greater than 10 percent PFA. Thus, compared with Denver, the algorithm had a higher detection probability, but also a higher false-alarm probability.

Two factors help explain the high false-alarm rate in Kansas City. First, the site-adaptable parameters used during the OT&E period were the same as those used in 1988 and reflected adaptations to the dry Denver environment. Second, the higher false-alarm rate in Kansas City vs. Denver can be partly ascribed to the 55 percent fewer microburst events which occurred. Assuming that the rate of false alarms is relatively constant (whether wind shears are present or not), then fewer true events will result in a higher false-alarm probability.

Table 2-1.
Daily Kansas City OT&E Microburst Algorithm Performance.

Date	MBs	At KCI	Hits	Misses	False	POD %	PFA %	Storm Cells in Sector
19 Jun 89	0	0	0	0	1	0	100	No
24 Jun 89	7	1	79	3	3	96	4	Yes
26 Jun 89	20	0	162	5	22	97	12	Yes
01 Jul 89	5	1	61	2	0	97	0	Yes
07 Jul 89	0	0	0	0	2	0	100	No
10 Jul 89	4	0	4	0	3	100	43	Yes
12 Jul 89	5	2	45	0	7	100	13	Yes
15 Jul 89	30	2	344	18	34	95	9	Yes
17 Jul 89	0	0	0	0	1	0	100	No
18 Jul 89	6	2	93	0	3	100	3	Yes
19 Jul 89	0	0	0	0	3	0	100	No
21 Jul 89	0	0	0	0	2	0	100	No
22 Jul 89	5	0	35	6	4	85	10	Yes
24 Jul 89	0	0	0	0	2	0	100	Yes
25 Jul 89	0	0	0	0	4	0	100	No
26 Jul 89	0	0	0	0	5	0	100	No
27 Jul 89	2	0	14	0	0	100	0	Yes
30 Jul 89	20	0	262	0	7	100	3	Yes
31 Jul 89	0	0	0	0	2	0	100	No
05 Aug 89	0	0	0	0	2	0	100	No
06 Aug 89	0	0	0	0	2	0	100	No
08 Aug 89	0	0	0	0	2	0	100	No
11 Aug 89	0	0	0	0	4	0	100	No
13 Aug 89	4	0	13	14	7	48	35	Yes
14 Aug 89	0	0	0	0	12	0	100	No
15 Aug 89	17	6	150	6	21	96	12	Yes
Total	125	14	1262	54	155	96%	11%	

It was found that 28 percent of all false alarms occurred on days in which there were no cells in the area. Another 12 percent of false alarms were due to incorrect declarations based on microburst precursors. After off-line adjustment of the algorithm site-adaptable parameters to activate conditioning of alarms based on reflectivity aloft and to make precursor declaration criteria more stringent, the false-alarm rate was lowered to seven percent (Table 2-2). Forty-four false alarms were eliminated by the reflectivity aloft test and eighteen by the more stringent precursor criteria. These changes resulted in three fewer detections, but did not alter the POD.

Table 2-2.
Summary: Kansas City OT&E Microburst Performance.

	Hits	Misses	False	POD	PFA
OT&E	1262	54	155	96	11
After site-adaptation parameter optimization	1259	57	93	96	7

B. ANALYSIS OF FALSE ALARMS (M. Isaminger)

Table 2-3 lists all days in which false detections occurred during the test period and shows the causes of the false alarms. The causes are the best plausible reason, as determined by careful analysis of all false alarms. The primary causes of false alarms were noisy velocities, divergence found across the zero velocity isodop, and birds/insects. Thirty-four percent of these alarms were coasts of a false detection on the previous scan. After modifying the site-adaptable parameters to include reflectivity aloft validation and stricter precursor criteria, the number of coasted false alarms was reduced from 53 to 26. Methods to further reduce these coasted false alarms are discussed later in this report.

False alarms due to range-folded weather echoes were found to be a substantial problem in Kansas City prior to the start of the demonstration period. Range folding had not been a major problem in Denver because the testbed radar was mainly scanning to the west, where an intervening mountain range prevented folding of distant weather. With the installation of TDWR-specified range obscuration editing on 20 June, false alarms due to out-of-trip weather were virtually eliminated, causing only seven false alarms during the OT&E period. Techniques to eliminate false alarms due to birds or insects are still being investigated. This is a particularly difficult problem since reflectivity echoes are sometimes associated with these events. The remaining false alarms in Table 2-3 are due to clutter and divergent signatures in the environmental wind flow. During the OT&E, there were 139 minutes of alphanumeric alerts from microburst outflows, 33 of which were false. After adjustment of site-adaptable parameters, the number of false-alarm minutes was reduced to nine.

Table 2-3.
1989 Kansas City False Alarms.

Date	Zero ISO	Clutter	Noise	Env Flow	2nd Trip	Pre-cursor	Birds/ Insects	Coasts
19 Jun 89	0	1	0	0	0	0	0	0
24 Jun 89	0	0	2	0	0	0	0	1
26 Jun 89	0	0	7	0	4	4	0	7
07 Jul 89	0	0	0	0	0	0	1	1
10 Jul 89	0	2	0	0	0	0	0	1
12 Jul 89	1	1	1	0	0	1	0	3
15 Jul 89	8	1	10	0	0	5	0	10
17 Jul 89	0	0	1	0	0	0	0	0
18 Jul 89	0	0	2	0	0	0	0	1
19 Jul 89	0	0	0	2	0	0	0	1
21 Jul 89	0	1	0	0	0	0	0	1
22 Jul 89	0	0	1	0	0	1	0	2
24 Jul 89	0	0	0	1	0	0	0	1
25 Jul 89	0	0	2	0	0	0	0	2
26 Jul 89	0	0	0	0	0	0	3	2
30 Jul 89	0	1	1	1	2	1	0	1
31 Jul 89	0	0	0	0	1	0	1	0
05 Aug 89	0	0	0	1	0	0	0	1
06 Aug 89	0	0	0	1	0	0	0	1
08 Aug 89	0	0	1	0	0	0	0	1
11 Aug 89	0	0	0	0	0	1	1	2
13 Aug 89	0	0	0	0	0	0	4	3
14 Aug 89	0	0	0	0	0	0	7	5
15 Aug 89	9	0	2	0	0	4	0	6
Total	18 (11%)	7 (5%)	30 (19%)	6 (4%)	7 (5%)	17 (11%)	17 (11%)	53 (34%)

C. RESULTS OF STUDIES TO ADDRESS DETECTION PERFORMANCE ISSUES (S. Campbell, M. Merritt)

Based on the initial statistics and false-alarm analysis, further studies were conducted to address detection performance issues. The areas addressed were: conditioning alarms based on reflectivity aloft, precursor declaration parameters, alarm coasting and other parameter adjustments. The result of the initial work in this area was to reduce the PFA from 11 percent to seven percent with negligible effect on the POD. Additional planned work may lead to further improvement in performance.

1. Conditioning Alarms Based on Reflectivity Aloft

The microburst Algorithm Enunciation Language (AEL) description provides for the optional conditioning of microburst alarms based on reflectivity aloft. When site-adaptable parameter "SWITCH (Storm Test)" is enabled, a microburst alarm must overlap a storm cell or low reflectivity cell in order to be considered valid. The conditions for an alarm and a cell to be considered overlapping are sufficiently lenient

(e.g., centroids must be within 10 km of each other) that rejection of alarms on days when convective activity occurs is prevented.

As noted earlier, 28 percent of the false alarms occurred on days with no convective activity. These false alarms are especially annoying to users since they are readily evident as false. An especially severe case occurred on 14 August when 10 false alarms were observed in a fifteen-minute period.

With the activation of the option for conditioning alarms based on reflectivity aloft, the false alarms on days with no convective activity were eliminated. This adjustment resulted in elimination of 28 percent of the false alarms, with negligible effect on detection probability.

2. Precursor Declaration Parameter Adjustment

The microburst algorithm normally requires a surface divergence of at least 10 m/s in order to declare microburst alarm. If a surface divergence of at least 10 m/s is correlated with either an earlier surface divergence (within two minutes) or a structure aloft (such as a reflectivity core or rotation aloft), then a microburst alarm is declared. However, if a microburst precursor is declared (such as a descending reflectivity core coupled with a convergence aloft), then a microburst alarm can be declared from a weak (< 10 m/s) surface divergence.

The false-alarm analysis for the Kansas City test period showed that a significant fraction of the false alarms (12 percent) were incorrect declarations based on precursors. In order to reduce these false alarms, the site-adaptable parameters for declaring microburst precursors were adjusted. The revised parameters require that the precursor have a reflectivity core which is at least 4.5 km in height and a maximum reflectivity of at least 54 dBz. These revised criteria were based on a study of 24 microbursts observed in Huntsville, AL in 1986 which reached 15 m/s outflow intensity. These criteria were felt to be more appropriate for the wetter Kansas City environment than those used the previous summer in Denver.

Testing with these revised precursor declaration criteria eliminated 12 percent of the false alarms, with no substantial change in POD. These parameter settings may be overly conservative since the Kansas City environment appears to be somewhat less wet than the Huntsville environment. Further examination of these parameters is planned with slightly less stringent conditions.

3. Coast Time Adjustment

The microburst algorithm AEL provides a capability for coasting alarms. When a microburst event has been detected on a previous scan and there is no surface outflow of at least 10 m/s detected for the current scan, then the previous alarm is coasted for one scan. The motivation for this coasting feature is to maintain continuity in the microburst alarms even if the algorithm fails to detect the surface outflow for one scan.

The false-alarm analysis for 1989 indicates that almost 34 percent were coasted alarms. It was therefore decided to examine whether coasted alarms had a net positive or negative effect on overall algorithm performance. The Denver 1988 data set was chosen for this analysis since it has been thoroughly examined for validity. Roughly 23 percent (242) of the total alarms were coasts, and of these coasts only 17 percent were considered false. The results from Denver suggest that removing all coasts decreased the overall

PFA by 2.4 percentage points, but it also reduced the POD by over 10 percentage points. Thus, removing all coasts is not an effective way to reduce false alarms.

While the alarm-coasting feature generally improves microburst algorithm performance, there may be adjustments to the coasting criteria that would be beneficial. Presently, a microburst alarm is coasted if either no divergence is found in the current tilt or if a divergence is found but is less than 10 m/s. One possible modification is to make alarm coasting conditional, based on whether a divergence is found for the current scan.

An additional possibility is to coast an alarm only if the microburst event persists for at least two minutes. An analysis of false alarms during the 1989 OT&E revealed 41 of 55 (77 percent) were coasts of alarms that were detected only once. Another factor to consider is the proximity of true alarms, which might indicate that a coast of the previous alarm is not necessary.

4. Other Parameter Adjustments

There are a number of other site-adaptable parameters in the algorithm which might be tuned to achieve a higher detection rate for Kansas City microbursts. In particular, some of the parameter adjustments for the Denver environment need to be re-examined. During testing at Denver in 1987, it was found that the microburst algorithm missed a significant number of low-reflectivity microbursts. To help alleviate this problem, the signal-to-noise ratio (SNR) threshold for feature extraction was lowered from 10 dB to 6 dB. Also, the minimum length for divergence segments was lowered from 1500 m to 950 m. These changes resulted in an improved POD for dry microbursts in Denver.

However, one-fifth of the false alarms in Kansas City this summer were caused by noisy velocities in low-reflectivity regions not associated with storms. A higher SNR threshold could potentially reduce these false alarms without significantly reducing the probability of detection. This change was evaluated by replaying a subset of the 1989 data (seven days) with the SNR threshold set at 8 dB. The result was that 24 false alarms were eliminated, reducing the PFA to 6 percent, and five fewer detections (5/1024), reducing the POD by 0.5 percent. These misses all occurred in low-reflectivity outflows, which are not typical of the Kansas City environment, and thus 0.5 percent is probably a slightly high estimate in the POD reduction associated with this change. An additional change which may be evaluated is increasing the minimum segment overlap threshold from 0.0 km to 0.5 km.

The performance of the algorithm in recognizing structures aloft and predicting microbursts might also be enhanced by changing the minimum altitude for upper divergence from 7 to 6 km above ground level (AGL). There are examples of microbursts from Denver and Kansas City which exhibited upper-level divergence between 6 and 7 km. This modification should not add to the false alarm-problem.

D. MICROBURST PREDICTION/FEATURES ALOFT (M. Isaminger)

Previous research by the TDWR testbed radar indicated that over 90 percent of the microbursts > 15 m/s were preceded by a descending reflectivity core in combination with a velocity feature such as rotation, convergence, upper divergence, or lower divergence. An advanced warning of the microburst hazard can be provided if these features are detected by the algorithm. Eighteen Kansas City microbursts which reached a maximum velocity of 15 m/s were analyzed to determine which precursors were observed and detected prior to the initial outflow. A reflectivity core accompanied by

rotation, convergence, and/or upper divergence occurred most frequently (Table 2-4). Lower divergence is not a consistent precursor to these types of outflows. In humid regions, the outflow does not diverge significantly prior to surface impact. All of the microbursts except one had a reflectivity core and a velocity feature.

Table 2-4.
Features Aloft Detected for 1989 Kansas City Microbursts of 15 m/s or Greater.

	Rotation	Convergence	Upper Divergence	Lower Divergence	Reflectivity Core
Feature Observed by Expert Radar Meteorologist	16/18 (89%)	15/18 (83%)	11/18 (61%)	3/18 (17%)	17/18 (94%)
Feature Detected by Algorithm	16/16 (100%)	5/15 (33%)	9/11 (82%)	3/3 (100%)	17/17 (100%)
Median Lead Time (min.)	- 7.8	- 5.5	- 9.0	- 0.5	- 4.5

The algorithm detection rate for rotation, lower divergence and a reflectivity core was 100 percent (Table 2-4). Upper divergence occurring below the minimum altitude threshold accounted for the two misses. Mid-level convergence was detected in only one-third of the events. This algorithm is currently being modified to achieve a higher POD.

The median lead time ranged from nine minutes for upper divergence to 0.5 minutes for lower divergence. A mid- or upper-level velocity feature and a reflectivity core were typically detected 4.5 minutes prior to the initial outflow. These results suggest that mid-level features such as rotation and convergence accompany the descent of the core.

The algorithm can provide a five-minute warning of the outflow based on precursor recognition. The performance of the prediction product was evaluated with microbursts from Kansas City. The algorithm successfully predicted one-half (17/34) of the outflows which exceeded 15 m/s. Six of eleven strong (>20 m/s) microbursts were not predicted. Of the three false alarms, two exhibited divergence above the surface tilt. The time difference from a prediction to a 10 m/s divergence varied from zero to nine minutes. A microburst occurred within three to seven minutes of a prediction in two-thirds of the events.

A majority of the microbursts which were not predicted had a reflectivity core and at least one velocity feature. Seven of the cores did not descend prior to the outflow, and ten did not exceed the height (4.5 km) or maximum reflectivity (54 dBz) requirements. There was only one case where the algorithm detected a reflectivity core without a velocity feature.

The thresholds for a reflectivity core are too restrictive for the microbursts encountered in Kansas City. They were developed based on a limited data set of Huntsville storms. An error in the reflectivity equation biased the reflectivity upward several dB. There are examples of strong microbursts in Kansas City from storms between 6 and 8 km AGL which did not exhibit the core development of the Huntsville cases. The algorithm could predict more Kansas City microbursts by lowering the minimum height to 4.2 km and the maximum reflectivity to 51 dBz. These changes will be tested prior to data collection in Orlando. The prediction capability is a new feature which will hopefully be evaluated operationally in 1990.

To summarize, most Kansas City microbursts which reach a differential velocity of 15 m/s were preceded by a mid- or upper-level velocity feature and a reflectivity core. A majority of the events can be predicted in advance if the algorithm detects these features. In fact, data from Kansas City suggests that the algorithm can provide a five-minute lead time to the initial divergence in those microbursts which reach 15 m/s.

3. GUST FRONT/WIND SHIFT DETECTION AND PREDICTION PERFORMANCE
(D. Klingle-Wilson, editor)

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 location and expected gain in wind speed (e.g., wind shear alert, 35 kt gain, one mile final). The planning function consists of alerting an Air Traffic Control Supervisor when a change in wind speed and/or direction due to a gust front at the airport is imminent. A description of the algorithm and an assessment of its performance during the 1988 Denver operational demonstration are found in references [4], [7], [12].

A. WARNING PERFORMANCE (D. Klingle-Wilson)

The ability of the algorithm to produce timely, useful warnings rests upon its ability to detect convergent shears in the Doppler velocity data. Two basic statistics were used to quantify detection performance: Probability of Detection (POD) and Probability of False Alarm (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 a volume scan) by the NSSL ground-truth 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 for all truthed 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. Thus, the strength of a gust front is defined as "moderate" for

Table 3-1.
Probability of Detection.

	Moderate	Strong	Severe	All	PFA
1988	73%	91%	100%	78%	2%
1989	72%	81%	92%	77%	13%

10 m/s $\leq \Delta V <$ 15 m/s; "strong" for 15 m/s $\leq \Delta V <$ 25 m/s; and "severe" for $\Delta V \geq$ 25 m/s. Corresponding POD results from the 1988 Denver operational demonstration are provided for comparison. In general, there is little difference in performance between 1988 and 1989. The largest POD differences are in the strong and severe categories. However, one must take care in interpreting the POD for severe gust fronts since there was only one severe event during 1988.

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. 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.

Table 3-2.
Average Percent of Length Detected.

	Moderate	Strong	Severe	All
1988	66%	69%	73%	67%
1989	59%	61%	50%	60%

POD as a function of the minimum percent of length detected threshold is plotted in Figure 3-1.

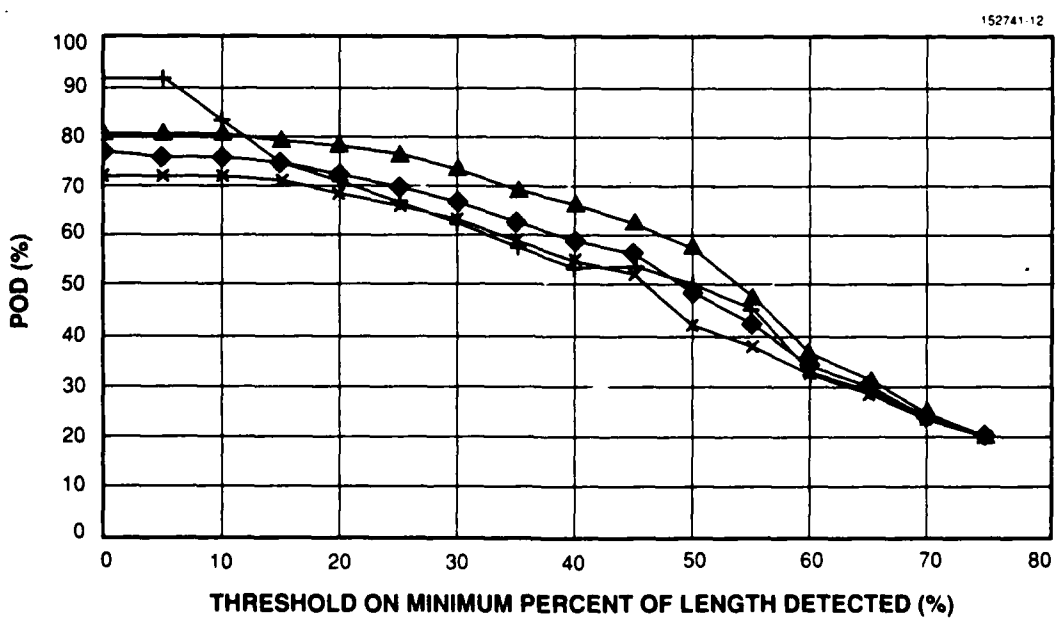

Figure 3-1. Probability of detection as a function of minimum percent of length detected threshold.

The primary cause of missed detections was 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 Kansas City, the TDWR testbed radar was sited such that gust fronts typically passed overhead at the same time they were impacting the airport. The ability to detect reflectivity thin lines and/or azimuthal shears is essential in cases where the TDWR radar site is unfavorable with respect to the local gust front climatology. A study was initiated to determine which feature (azimuthal shear or thin line) will provide the greatest benefit in terms of improved gust front detection.

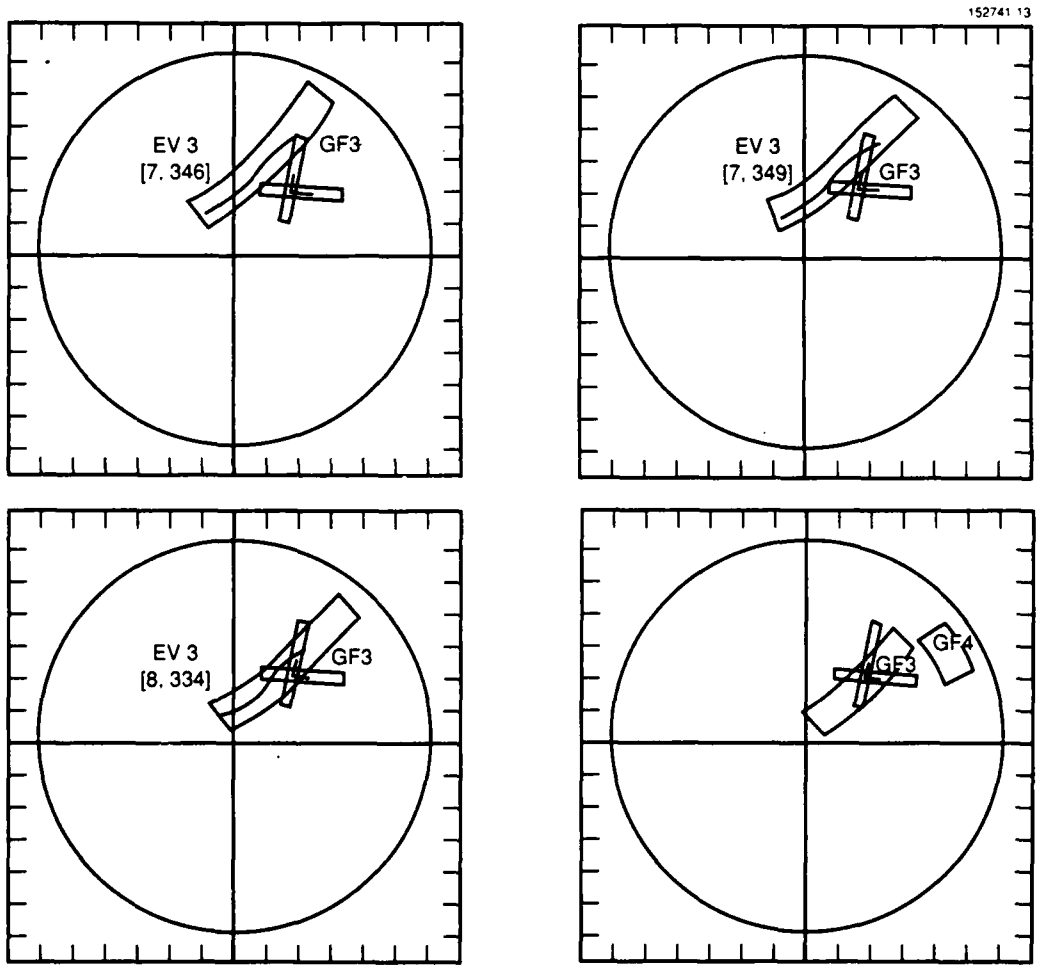

Figure 3-2. Example of the loss of a gust front detection as the gust front passes over the radar. The rectangles represent ground truth and the solid lines represent detections. KCI is located northeast of the radar.

For the 1988 Denver and 1989 Kansas City data, the PFA were two percent and 13 percent, respectively. A common producer of false alarms in Kansas City was the vertical shear in the horizontal wind (i.e., winds increasing, decreasing, or veering with height). This change of wind with height produced an apparent convergence in the

Doppler velocity field that was detected by the gust front algorithm. In addition, the locations of these regions were roughly equal to the range of the airport from the radar, resulting in false warnings to pilots. Techniques for discriminating vertical wind-shear-induced false alarms are under investigation at NSSL.

A second source of false alarms was ground clutter that was not completely removed by the clutter residue editing process. Since ground clutter exhibits a near-zero Doppler velocity, a false convergence is created by winds blowing against clutter. This was observed on the bluffs surrounding the Missouri River.

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) and 1989 (Kansas City) are shown in Table 3-3. The Probability of False Warning (PFW) is defined as the number of false alarms issued divided by the total number of alarms issued. For Kansas City 1989, the PFW was 40 percent versus 0 percent for Denver 1988. The Kansas City false warnings were entirely due to vertical shears in the horizontal winds over the airport.

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%

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. For 1989 and 1988, the average difference between pilot reports and alerts was about 15 kt, with alerts overestimating wind shear relative to pilot reports.

The number of pilot reports available for the analysis of the gust front hazard estimate is quite small (less than 10). There is some evidence in the literature [11] that suggests that the wind shear hazard associated with a gust front may not be appropriately characterized by the simple calculation used in the algorithm. From 1986 through 1989, the UND Citation aircraft performed a number of gust front penetrations. These data will be analyzed to determine if the gust front wind shear hazard estimation algorithm should be refined.

B. PLANNING PRODUCT PERFORMANCE (D. Klingle-Wilson)

Runway management is improved with the TDWR by alerting an Air Traffic Control (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 Probability of a Correct Forecast (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 Denver (1988), the PFF for the 10- and 20-minute forecasts were 11 percent and 18 percent, respectively. For Kansas City (1989), the PFF for the 10- and 20-minute forecasts were 18 percent and 21 percent, respectively. Forecasts were generated only about 56 percent of the time. The high POCF values show that, when generated, forecasts were very accurate.

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%

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 3 m/s and 30 degrees, respectively. The wind shift speed was, on the average, about 2 m/s greater than that determined from the Mesonet data, and the wind shift direction was about 5 degrees counterclockwise of the Mesonet wind direction. These results are nearly identical to the 1988 Denver results.

4. DATA QUALITY ISSUES ANALYSIS
(B. Stevens, editor)

As noted in the introduction, the TDWR data quality algorithms required some site adaptation adjustments to successfully deal with challenges that arose at Kansas City. In addition, new issues arose which are the subject of continuing studies. In this section, we report on three key areas:

1. Ground clutter suppression by MTI filtering and clutter residue editing maps,

2. Range-aliased echo suppression by adaptive choice of PRF and editing of range-obscured data, and

3. Suppression of interference from moving targets (such as aircraft) by a spatial point target recognition algorithm.

A. CLUTTER SUPPRESSION (E. Ducot, T. S. Lee)

1. Clutter Filter Performance

Based on the definition provided in [10] and offline experiments using Kansas City time series data, approximately 45 dB effective ground clutter suppression performance was observed during the KCI testing in situations where 50 dB suppression might be expected. Possible causes of the 5 dB clutter suppression deficiency are spectrum tails outside the clutter filter, stopband clutter residue within the filter stopband, and hardware-related limitations of FL-2.

Distributed clutter and nonstationary clutter targets such as automobiles and trains proved to be a continuing problem. Major distributed clutter sources were found along the Missouri River and North Platte River banks and the 1000-ft. hill just northwest of the airport. It is interesting to note that Route 29 cuts through a sizable hill, and railroad tracks run along both sides of the Missouri river within view of the FL-2 phase center.

The clutter filter performance degradation due to instantaneous AGC (IAGC) jitters was analyzed. The clutter filter error induced by IAGC jitters proved to be controlled by three factors; namely, the frequency of IAGC jitter occurrences, the magnitude of the IAGC jitter, and the receiving clutter power at the jitter occurrence time. The IAGC calibration error has to be much smaller than 1 dB for the clutter filter to be fully effective.

A limited amount of time series data were collected under anomalous propagation (AP) conditions. Although preliminary analysis results indicate that the clutter filter is equally effective, with and without AP in terms of clutter suppression, the usage of the clutter residue map under the AP condition has to be examined further.

As a routine practice, times series data of discrete clutter, such as towers, are monitored for detecting hardware problems of FL-2. However, the bulk of the analysis effort in the future will be spent on issues related to distributed clutter and nonstationary clutter targets.

2. Clutter Residue Maps

Two sets of operational clutter residue maps were generated on 6 June and 3 July. Sample medians of 21 independent clutter residue power measurements were used to generate clutter residue maps throughout the year.

It was observed that false alarms due to unedited clutter residue most frequently occurred in the river bank and high hill areas described above. Two possible causes of unedited clutter residue have been identified:

1. The clear air reflectivity estimate may be too high, such that some clutter residue is ignored in the editing map formation, and

2. The clutter residue in an area may fluctuate about the median level much more than is the case in general.

We are investigating improved clear air reflectivity estimation techniques and the use of polygonal areas of specified clutter residue level to address these problems.

It appears that different clutter residue maps are needed when AP is present. Attempts will be made to generate AP clutter residue maps and study the effectiveness of such clutter residue maps when AP is present at a later time.

B. RANGE OBSCURATION (B. Stevens)

The PRF selection algorithm used in Kansas City was functionally identical to that used in Denver. The distant weather threshold remained at 8 dB SNR, while a number of other site-adaptable parameters were adjusted:

1. The microburst and runway region boundaries were modified for the Kansas City geometry.

2. The scan strategy was modified to achieve a 0.6 degree low PRF sweep once every five minutes. The Denver strategy alternated the 0.6 degree sweep with a higher sweep intended to allow collection of distant weather information which would otherwise have been lost due to terrain blockage. The topography in Kansas City did not require the higher elevation sweep, and the likelihood of faster moving storms suggested that more frequent updates at a single elevation angle would be beneficial.

System testing during actual hazardous weather conditions prior to the operational demonstration period showed a serious problem with out-of-trip weather returns inducing microburst false detections. Based on evaluation of three test cases, it was estimated that approximately 65 percent of the total false detections were due to out-of-trip weather. Consequently, it was decided to accelerate the schedule for implementing range obscuration editing (data flagging) as called for in TDWR requirements [11]. This real-time system feature was ready shortly before the beginning of the operational demonstration and was shown to eliminate approximately 80 percent of the false detections attributed to range obscuration for the three test cases.

Range obscuration editing was performed for each first trip sample volume collected at elevation angles below 8 degrees. The signal strength in each sample volume was compared to the estimated distant weather contribution, the estimate being formed by summing, for all trips out to the maximum range of the distant weather information, and

at range intervals defined by the PRF used to collect the sample volume in question, distant weather signal strengths which exceeded a site-adaptable distant weather threshold. The comparison between the first trip signal strength and the estimated distant weather contribution was made on the basis of a site-adaptable obscuration threshold. The obscuration threshold was dynamically adjusted for the age of the distant weather information and for the difference in elevation angle between the sample volumes being edited and the distant weather information. The time- and elevation-based adjustments were incorporated in an attempt to compensate for the limited distant weather data collection allowed by the TDWR scan strategy, in light of probable distant weather variations with time and altitude.

Although it was not possible to perform a thorough analysis of the site adaptable parameters controlling range obscuration editing, it was determined that the following provided adequate performance:

1. Distant weather threshold was 5 dB. This was lower than the 8 dB used for PRF selection because of the linear interpolation used to resample the 480 m distant weather gate spacing into 120 m gate spacing for use in editing first-trip data[5], and was intended to provide better distant weather information at the boundaries of significant distant weather regions.

2. Nominal obscuration threshold was 1.5 dB. This meant that the first-trip weather had to exceed the estimated distant weather contribution by at least 1.5 dB or it would be flagged invalid.

3. The nominal obscuration threshold was decreased 1.5 dB per 10 minutes of age of the distant weather information and was increased (or decreased) 3 dB for each degree of elevation that the distant weather data were above (or below) the data being flagged.

Post-demonstration analysis of distant weather spatial/temporal distribution was performed on three day's of data collected during the 1989 season. On the days chosen, data contamination due to range aliasing was known to be present and could have affected wind shear detection (significantly biased velocity estimates) at or near the airport.

Figures 4-1, 4-2, and 4-3 represent the actual Kansas City geometry (Sector A), a simulated geometry with a pseudo-airport to the south of the radar (Sector B), and a simulated geometry with a pseudo-airport to the northwest of the radar (Sector C). They show the relationship between the level of potential distant weather contamination (percent of first-trip sample volumes contaminated, quantized in decades), and the length of time (based on the total number of minutes analyzed over the three data cases) a given level of contamination was in present. This relationship is shown for the runway, microburst, and gust front regions, at the optimal S-band PRF for each region. It should be noted that the histograms represent potential, as opposed to actual, obscuration; actual obscuration depends upon the relationship between first trip and distant weather strengths.

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[5] Limitations on the total number of gates which could be processed by the testbed front-end necessitated a minimum range gate spacing of 480m when data collection to 420km was required. The TDWR will use a gate spacing of 150m out to 135 km, and 300m for the remaining gates out to 460 km.

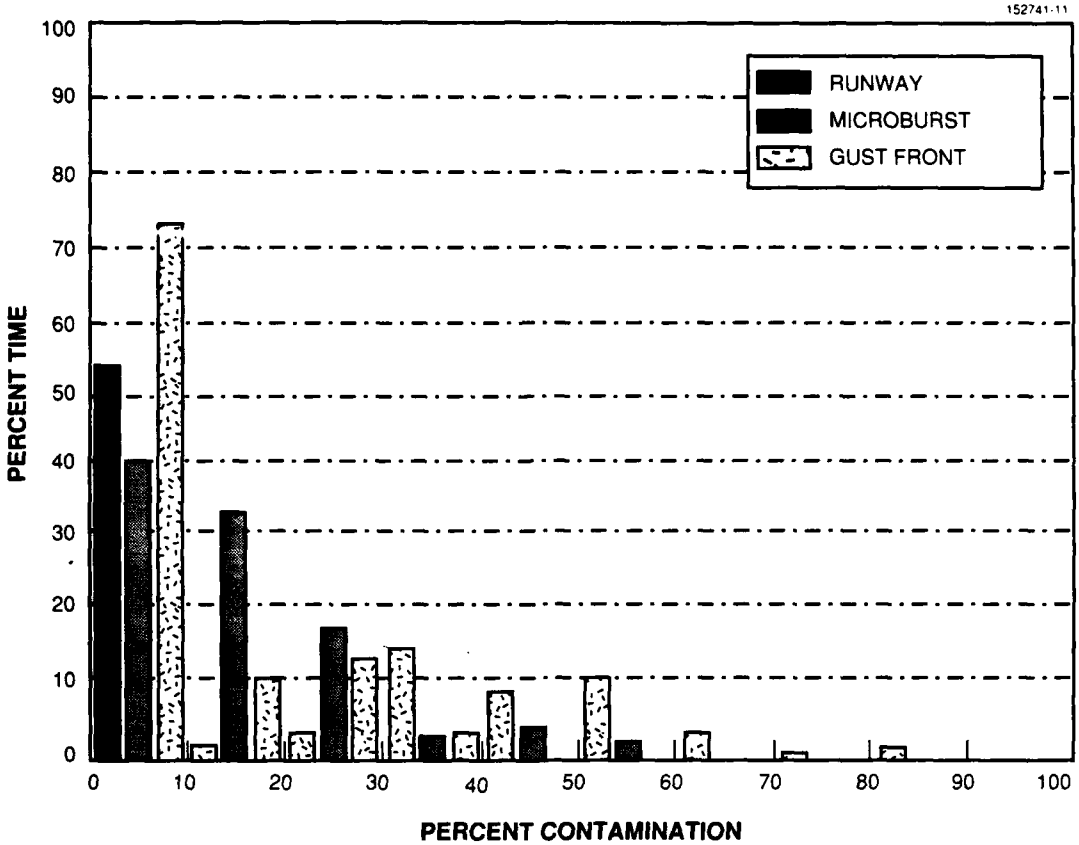

Figure 4-1. Composite contamination levels - Sector A, KCI (airport sector).

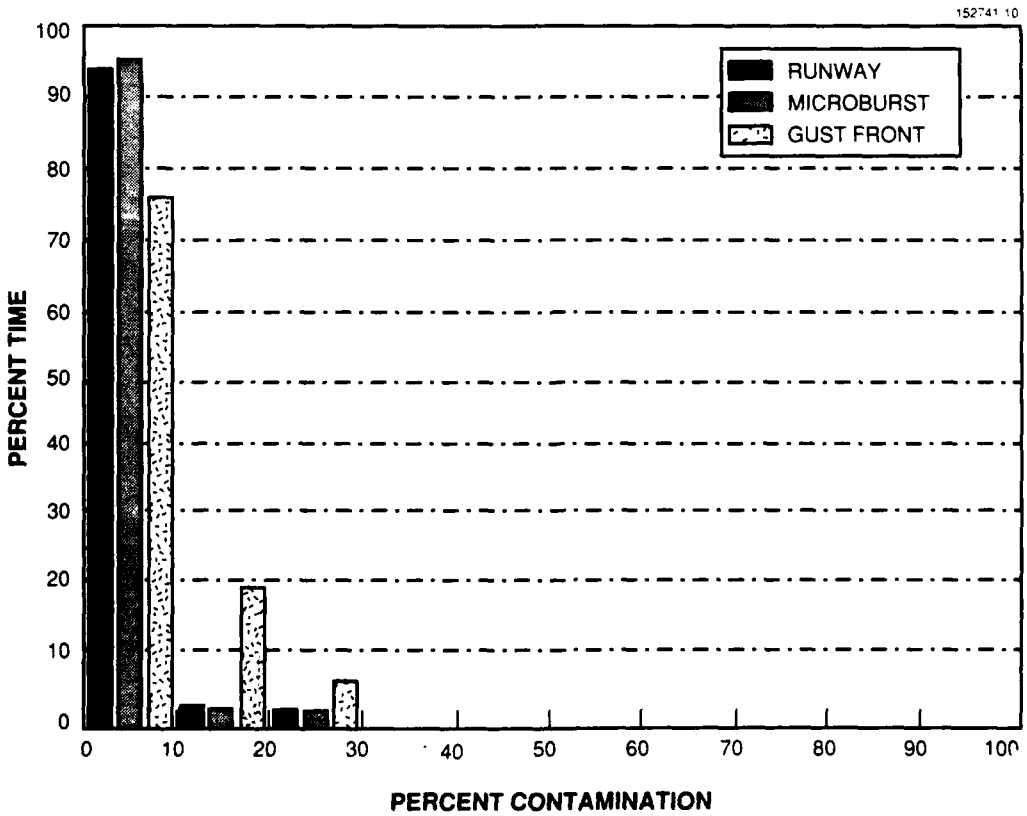

Figure 4-2. Composite contamination levels - Sector B (assumed airport to south).

The figures suggest that a radar location to the north of the airport would have provided the lowest probability for range obscuration, given the weather patterns during the 1989 season. A radar location to the northeast of the airport would probably have had a similarly low level of contamination and would have been better for gust front detection and headwind-tailwind shear estimation.

C. POINT TARGET REJECTION (R. Hallowell)

The point target rejection algorithms developed by the TDWR contractor were tested off line to see if they would be effective in reducing microburst false alarms. This filter processes the reflectivity field, using a one-dimensional spike test to identify the presence of a point target (such as an aircraft). The current Raytheon technique looks at several spatial scales (3, 5, and 7 range gates).

A number of data cases containing obvious aircraft interference echoes were identified for use in evaluating the performance of the two algorithms. The basic characteristics of these aircraft echoes are being characterized to determine the most appropriate spike strength threshold to be used at each spatial scale. Preliminary analysis indicated that a five-gate spike amplitude threshold of roughly 20-25 dB would be quite effective at detecting most aircraft targets, while removing minimal weather cells.

The implementations of the rejection algorithms was used to validate the performance of the techniques against these aircraft cases and will also be applied to a larger set of microburst algorithm scoring cases. These experiments will serve to evaluate the ability of each algorithm to reject typical point target sources without adversely affecting the desired weather event signatures. Processing of these cases and analysis of the results is just beginning and should be ready for formal reporting in 1990.

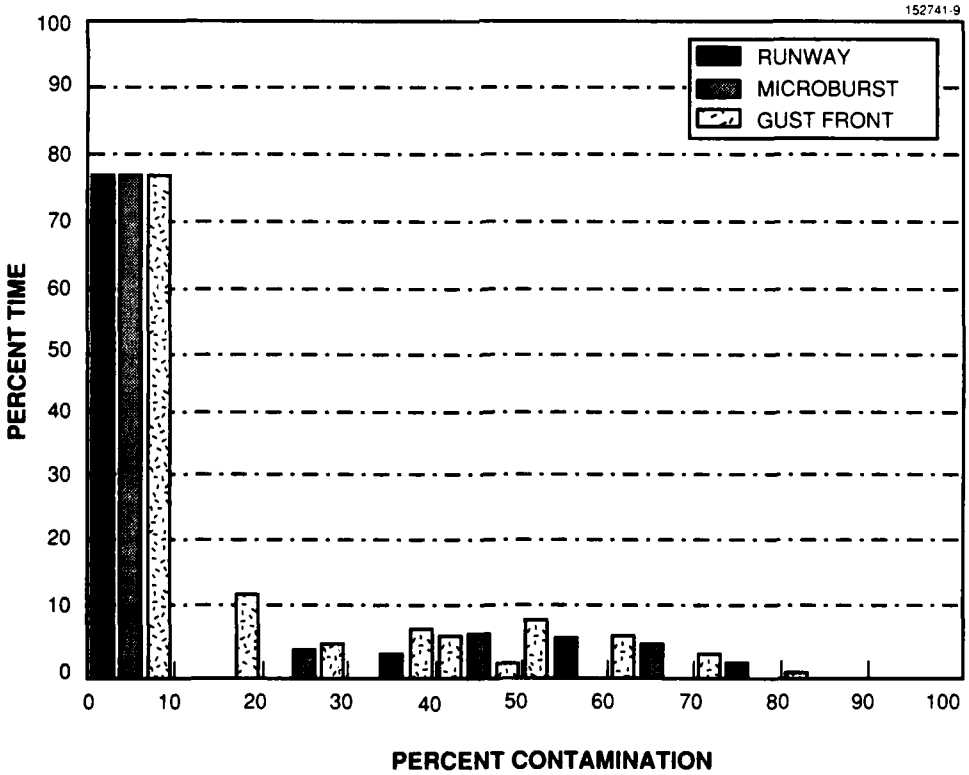

Figure 4-3. Composite contamination levels - Sector C (assumed airport to northwest of radar).

A basic example of the operation of the TDWR point target algorithm is shown in Figure 4-4. This set of images shows the raw radar reflectivity (upper left) and radial velocity (upper right) fields from a radar scan with no significant weather echoes in the vicinity of the Kansas City radar on 15 August 1989. The small-scale interference region from an aircraft can be seen in these images, as indicated by the arrow. The lower two images show the results after the TDWR algorithm was applied. The majority of the aircraft echo was identified and removed from the reflectivity field, and the velocity contamination was filled with data from adjacent uncontaminated range gates. A few gates of residual contamination can be seen in this case, where the interference echo is at rather low signal strength (but still enough to perturb the velocity estimates). Threshold settings for the spike thresholds will require adjustment to achieve the proper balance between target rejection and weather signal degradation.

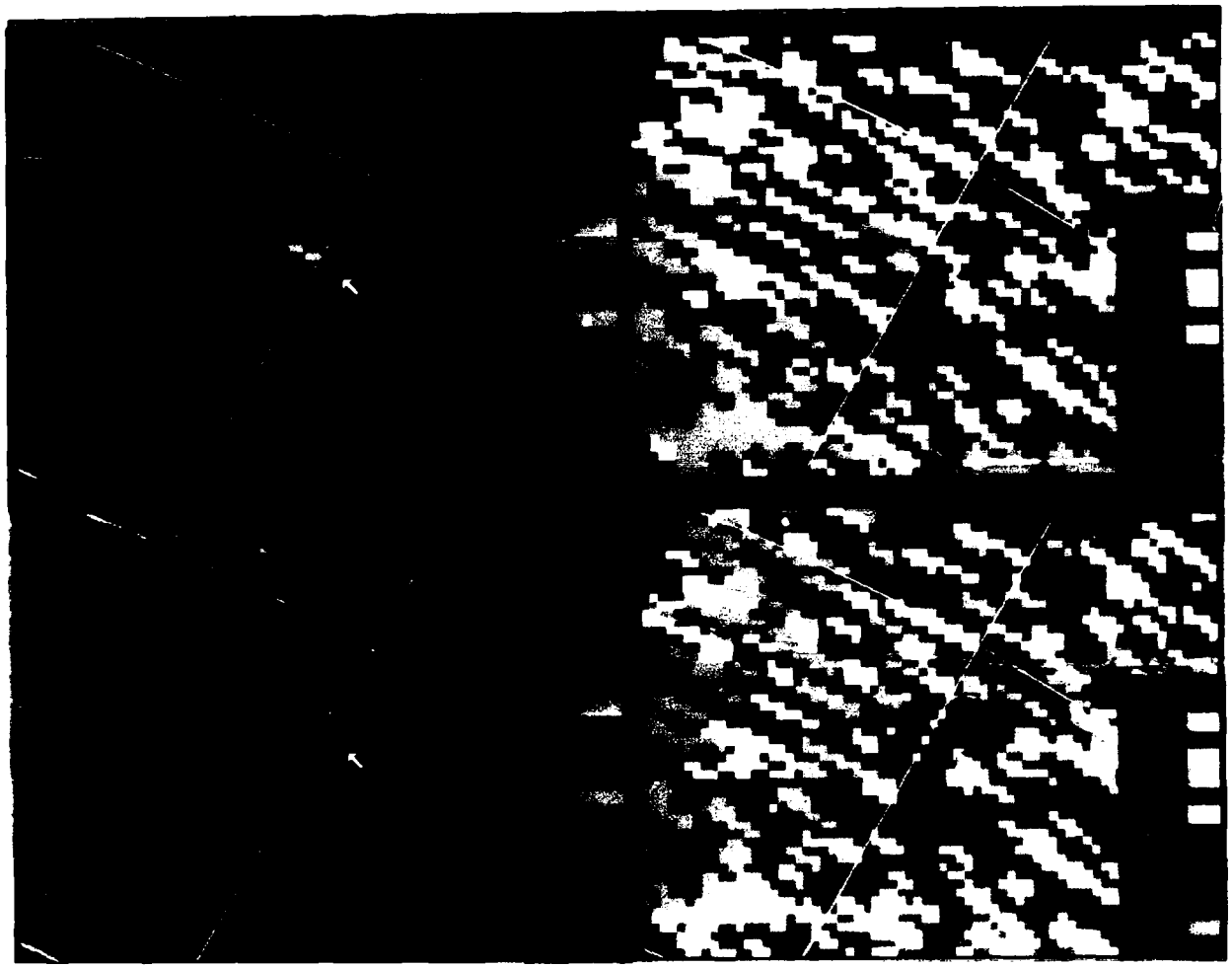

Figure 4-4. Effect of the TDWR point target rejection algorithm on an aircraft signature measured in Kansas City on 15 August 1989. The raw radar data (reflectivity - upper left, and velocity - upper right) show significant perturbations in their respective fields caused by the aircraft (indicated on image with arrows). The bottom pair of images illustrates the same fields after point target rejection. The reflectivity is essentially cleared while the velocity still shows some residual perturbations.

5. AIR TRAFFIC OPERATIONAL ASSESSMENT
(B. Stevens, editor)

A. GENERAL (B. Stevens)

There was relatively little significant weather which affected the KCI area during the 1989 demonstration period. The airport received microburst and wind shear with loss alerts for approximately 140 minutes over the eight-week period; wind shear with gain (gust front) alerts were in effect for approximately 60 minutes. Most of the alerts occurred on only a few of the operational days, and a significant fraction (approximately 23 percent) of the time spent under microburst or wind shear with loss alerts was due to false wind shear detections[6].

Analysis of pilot reports and airport operations during alert periods is underway to determine the accuracy and operational effectiveness of warnings. There are 55 minutes of microburst (or wind shear with loss) alerts and 42 minutes of gust front alerts under investigation, comprising 15 and 5 events, respectively. While the ratio of pilot reports to alerts actually issued by controllers is low for microburst-related events (partly due to missed approaches executed in response to the alerts)[7], the ratio for gust front-related events is quite high and should provide useful information[8].

Gust fronts affecting the airport area were correctly forecast a number of times. While there is no evidence that the controllers chose to reconfigure runway usage on the basis of gust front forecasts alone, with somewhat more experience with the system they may well have. On at least one occasion the supervisor expressed regret at not having heeded the forecast at the earliest possible moment.

B. ATC CONTROLLER/SUPERVISOR FEEDBACK (B. Stevens)

Because of the relative lack of significant weather, controllers were unable to give much meaningful feedback on the usefulness of products or predict what additional products might be desirable. Furthermore, this was their first exposure to the Ribbon Display wind shear message format (the enhanced LLWAS had not been installed at the time of the demonstration); the system and its concept was, consequently, even more unfamiliar to the Kansas City controllers than it had been to the Denver controllers in 1988.

It was clear, however, that the system was universally liked and was given the highest possible expectation of being extremely useful. The few times that local weather conditions were appropriate, the controllers found the information presented to be both

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[6]Analysis following the operational demonstration (see Chapter 2) showed that appropriate adjustment of the site adaptation parameters would have reduced the fraction of time with false alerts to nine percent (i.e., nine minutes), including the elimination of false alerts on all cloudless days.

[7]There was one microburst (as opposed to wind shear with loss) alert issued (the airspeed loss was predicted to be 35 kt); the pilot chose to execute a missed approach and gave no pilot report. Several major airlines operating at KCI issued bulletins to their pilots describing the operational demonstration and the capabilities of the equipment, and advised that warnings issued were likely to be accurate and should not be ignored. As far as we know, however, only United and Continental issued specific instructions not to operate (to decline takeoff clearance or execute a missed approach on landing) when a microburst alert was issued.

[8]Comment: High operational effectiveness in terms of aircraft avoidance of detected wind shear events will result in a reduced number of pilot reports for assessment of the accuracy of warnings issued.

timely and accurate. Microburst false alarms occurred often enough to elicit comments, but did not detract from the overall positive impression made on those using the system operationally.

While a number of comments were made regarding details of displays (e.g., wanting a different color screen) or the information presented (e.g., could current altimeter and ATIS information be displayed on the Ribbon Display), the most important comments were concerned with operational procedure. It was clear that the controllers were uncomfortable with the notion of giving pilots what was obviously a false alarm; they felt they should be allowed to use their judgment as to alarm appropriateness.

For example, occasional microburst alerts would be generated on cloudless days; it was obvious to the controllers that the alerts were false, but they were constrained by the prescribed operational procedure to issue the alerts to pilots. The controllers felt that it did not make sense to knowingly give false information to a pilot who, in response, might abort a landing or takeoff, thereby delaying subsequent operations. Additionally, it was apparent that the local controllers considered the GSD information, used in conjunction with the Ribbon Display information, to be an important element in their ability to effectively use the system and that it should not be restricted to use by supervisors.

C. TOWER OBSERVER NOTES (B. Stevens)

The observations made by Lincoln and NSSL personnel in the tower during the operational demonstration coincide, for the most part, with feedback from the ATC personnel obtained via questionnaire or during debriefing. The tower observer was in a better position, however, to note unusual or unexpected use of the equipment or information. Of particular interest was the use, on one occasion, of GSD information by the local controller to aid in vectoring aircraft around shear zones. In general, the controllers seemed to be most comfortable using the information and equipment flexibly, ignoring (for the most part) the operational concept of relegating the GSD to supervisor use only.

As with the direct controller feedback, the lack of significant weather in the airport area during the operational period limited the usefulness of the tower observations.

APPENDIX A
AVAILABLE FIELD DATA
(J. DiStefano, D. Klingle-Wilson)

1. WIND SHEAR EVENTS OBSERVED WITH TDWR TESTBED AND UND RADARS (M. Isaminger)

Table A-1 lists 42 microbursts (MB) and 33 gust fronts (GF) detected by FL-2 near KCI in 1989. Many of these were scanned in a coordinated dual-Doppler mode with the UND radar. During the OT&E period (19 June - 15 August), there were 10 gust fronts and 14 microbursts detected near the airport. Most wind shear events were weak, with differential velocities (ΔV) of less than 15 m/s. There were only two microbursts and three gust fronts at KCI which exceeded 20 m/s. The strongest microburst was 24 m/s on 14 May. The maximum surface reflectivity for the microbursts ranged from 20 to 55 dBz. A reflectivity thin line was detected in one-half of the gust fronts.

Table A-1.
Wind Shear Events Observed with TDWR Testbed Radar.

Date	Time UT	Event Type	Location range km	Location azimuth deg	Δ V m/s	Surface Reflectivity dBz	Dual Doppler
03/27	0145	GF	14	040	16	----	No
04/05	1925	MB	13	056	12	30	No
04/05	2039	MB	18	016	16	20	No
04/05	1937	MB	9	040	18	25	No
04/14	2135	GF	13	320	7	----	No
04/14	2138	MB	20	043	11	27	Yes
04/14	2150	MB	8	030	16	40	Yes
04/23	2003	GF	30	313	10	----	Yes
04/28	0634	GF	16	039	20	15	No
05/14	1859	MB	19	065	12	25	Yes
05/14	1940	MB	10	020	24	45	Yes
05/18	1850	GF	11	053	10	10	No
05/18	1907	MB	19	054	11	40	No
05/18	1934	MB	9	055	12	55	No
06/03	0634	GF	14	049	15	15	Yes
06/03	0651	MB	11	035	15	46	Yes
06/07	2045	MB	10	097	10	50	Yes
06/18	0255	MB	19	024	15	39	Yes
06/18	0254	GF	10	001	18	20	Yes

Table A-1.
(Continued)

Date	Time UT	Event Type	Location range km	Location azimuth deg	Δ V m/s	Surface Reflectivity dBz	Dual Doppler
06/24	2206	GF	15	045	6	----	Yes
06/24	2158	MB	9	052	13	49	Yes
06/26	2301	GF	12	013	16	10	Yes
06/26	0054	GF	15	044	12	----	Yes
06/26	0111	MB	14	059	14	55	Yes
07/01	2216	MB	12	037	11	42	Yes
07/10	2305	GF	12	025	12	15	Yes
07/12	0636	MB	18	035	12	45	Yes
07/12	0010	GF	20	046	9	20	Yes
07/15	1750	MB	6	100	18	40	Yes
07/15	1802	GF	11	070	14	----	Yes
07/15	1809	MB	11	058	12	45	Yes
07/18	2028	GF	10	090	12	20	Yes
07/18	2012	MB	23	048	17	49	Yes
07/18	2028	MB	14	057	20	41	Yes
07/22	0131	GF	13	046	6	---	Yes
07/24	2122	GF	11	343	6	20	Yes
08/15	2137	GF	16	044	10	10	Yes
08/15	2134	MB	15	047	13	48	Yes
08/15	2140	MB	12	021	11	46	Yes
08/15	2146	MB	8	051	14	43	Yes
08/15	2154	MB	10	049	10	43	Yes
08/15	2205	MB	17	072	18	49	Yes
08/15	2202	MB	16	060	11	47	Yes
08/16	2108	GF	18	056	7	15	No
08/20	1515	GF	19	054	7	---	Yes
08/20	1523	MB	11	039	14	50	Yes
08/20	1533	MB	17	064	14	52	Yes
08/22	0122	GF	18	102	10	10	No
08/22	0534	GF	17	100	12	---	Yes
08/22	0543	MB	19	035	19	47	Yes
08/22	0549	MB	11	045	12	40	Yes
08/22	0553	MB	16	025	11	42	Yes
08/22	0604	MB	13	043	11	40	Yes
08/26	0422	GF	15	060	14	20	Yes
08/26	0601	GF	20	032	15	10	Yes
08/27	2305	GF	15	022	16	25	Yes
08/27	0230	GF	28	056	9	---	No

Table A-1.
(Continued)

Date	Time UT	Event Type	Location range km	Location azimuth deg	ΔV m/s	Surface Reflectivity dBz	Dual Doppler
08/28	0416	GF	15	015	19	---	Yes
08/28	0520	GF	10	047	15	---	Yes
08/28	0527	MB	12	079	14	50	Yes
08/28	2142	MB	10	077	15	47	Yes
08/28	2147	MB	17	070	18	45	Yes
08/28	2210	MB	20	066	11	44	Yes
08/28	2144	MB	13	058	10	45	Yes
09/04	1220	GF	24	027	28	---	Yes
09/04	1207	MB	14	045	12	45	Yes
09/04	1216	MB	17	075	15	35	Yes
09/06	0835	MB	10	065	14	50	Yes
09/06	0850	MB	10	023	18	50	Yes
09/06	0852	GF	16	057	12	---	Yes
09/06	1138	GF	23	028	12	---	Yes
09/08	1433	GF	20	005	9	---	Yes
09/09	0226	GF	14	050	20	---	No
09/09	0229	MB	20	048	15	50	No
10/05	2220	GF	15	039	7	5	No

2. CITATION AIRCRAFT DATA (D. Klingle-Wilson)

An important part of the Doppler weather radar tests at Kansas City was the validation of Doppler radar-based estimates of turbulence and wind shear severity by flight tests using the UND Cessna Citation II jet. The Citation is a twin-engine fanjet instrumented for cloud physics and meteorological research. It is equipped with instrumentation to measure winds, cloud water content, and aircraft dynamic state variables, and an Inertial Navigation System (INS).

The Citation took part in the Kansas City experiment from 1 April through 12 June and 1 August through 8 September 1989. During these periods, 28 missions were flown. A brief synopsis of these missions is provided in Table A-2. The objective of these missions was to collect coordinated aircraft and radar data as the aircraft penetrated regions of operationally-significant turbulence and low-altitude wind shear. The Citation was responsible for collecting in-situ measurements of the events, while the UND and FL-2 provided radar measurements.

A. Turbulence Equipment

The objective of the 1989 turbulence experiments was to fly the Citation in areas around thunderstorms where turbulence encounters by commercial aircraft were likely and where a turbulence product would be most useful in the terminal environment. Most

Table A-2.
Summary of Summer 1989 UND Citation Flights.

Date	Flight Duration (hr: min)	Comments
14 April	1:12	Turbulence mission at 6000 feet. Convective line penetration, moderate to severe turbulence.
20 April	0:55	Turbulence mission at 12,000 feet. Only light turbulence.
23 April	0:57	Turbulence mission at 10,000 feet. Mostly light turbulence.
27 April	0:41	Gust front penetration. No significant turbulence.
4 May	1:09	Turbulence mission at 10,000 feet. Light to moderate turbulence. Computer problems.
5 May	1:32	Turbulence mission at 9000 to 12,000 feet. Light to moderate turbulence, wintery sort of storm.
8 May	1:47	Turbulence mission. Convective cell penetrations at 13,000 feet. Moderate turbulence.
18 May	1:28	Gust front penetrations with moderate turbulence. Approaches at KCI.
18 May	0:59	Attempted turbulence mission -- no turbulence.
22 May	1:01	Turbulence mission along edge of convective line, at 10,000 feet. Moderate turbulence.
24 May	1:32	Approaches, gust front penetrations. Light turbulence.
31 May	1:21	Turbulence mission in convective line, at 11,000 feet. Moderate turbulence.
2 June	1:04	Turbulence mission around convective cells, 11,000 to 13,000 feet. Mostly light turbulence.
3 June	1:22	Turbulence mission through squall line at 17,000 feet. Moderate to severe turbulence. Gust front penetrations at KCI. Moderate turbulence.
7 June	1:06	Gust front mission. Only very light turbulence.
12 June	1:24	Low-level outflow search. Mostly smooth.
30 July	0:41	No significant weather.
14 August	1:01	Weak gust front penetrations. Light chop.
15 August	1:59	Gust front penetrations at KCI. Moderate turbulence. 20 kt airspeed loss.
20 August	0:36	Gust front moved out of range
22 August	0:49	Low approach at KCI, downdraft penetrations. Light turbulence.
23 August	0:16	Storm dissipated.
26 August	1:07	Gust front penetrations at KCI. Some light to moderate chop.
27 August	1:56	Gust front and rain penetrations at KCI. Light to moderate turbulence.
28 August	1:04	Low-level turbulence mission. Moderate turbulence, some severe. Strong thunderstorm.
4 September	1:09	Low approaches at KCI in heavy rain. INS malfunction. Moderate turbulence encountered.
6 September	1:48	Weak gust front and microburst penetrations. Mostly smooth.

of the turbulence missions were flown between 3000 and 25,000 ft above ground level in NWS levels 1 and 2 precipitation. The Citation was vectored by the FL-2 and UND radar crews who used radar information to identify areas of potentially significant turbulence.

As the Citation penetrated the storm, the FL-2 radar executed a volume scan that consisted of three 60° -sector scans. The elevation angle and azimuthal limits of the sectors were defined by the location of the Citation. (Beacon reports from the Kansas City ASR radar were used to locate the Citation.) The first sector scan in the volume was centered on the Citation. The second sector was either 0. 5° or 1.0° above the first, and the third was 0.5° or 1.0° below the first. The elevation angle increment was a function of the range of the Citation from FL-2. If the Citation was from 40 to 60 km (20 to 40 km) from FL-2, the elevation increment was 0.5° (1.0°). This scanning strategy provided high-resolution temporal and spatial data in the immediate vicinity of the aircraft that could be used to validate a turbulence detection algorithm.

The UND radar scanned in a storm surveillance mode, which consisted of PPI scans interspersed with RHI scans. At the time of the experiment, this scanning strategy was used to identify areas where the weather conditions were too hazardous for the Citation and to plan subsequent penetrations. These data provided information on storm development and evolution and the relationship of turbulence to storm evolution.

Fifteen of the 28 Citation missions were in support of the turbulence experiment. Of these 15 missions, the aircraft encountered moderate turbulence on eight and severe turbulence on two.

B. Low-Altitude Wind Shear Penetrations

The objective of the low-altitude wind shear penetrations was to collect data to validate the wind shear hazard estimates produced by both the microburst and gust front algorithms. It was desirable for the Citation to penetrate the wind shear events at altitudes consistent with landing or departing aircraft. This requirement for low-altitude penetrations constrained the Citation to fly approaches to the Instrument Landing System (ILS) at KCI. During these penetrations, the Citation flew the approaches with the landing gear up and well above stall speed. This configuration provided a margin of safety that would allow the aircraft to recover from a possible penetration of a hazardous wind shear.

During these experiments, the FL-2 and UND radars were executing sector scans over the airport. The scanning strategy for both radars consisted of eight scans whose maximum elevation angle was 7.0°. This strategy provided high-resolution, low-altitude radar data of wind shear events.

A total of 12 wind shear penetration missions were conducted. These missions resulted in ten gust front and three microburst penetrations (Table A-3).

3. MESONET/LLWAS DATA (J. DiStefano)

Meteorological data were collected with a network of 40 surface weather stations (Mesonet) and the six-station LLWAS. The Mesonet stations were deployed around the KCI and KCD airports, with the exception of one Mesonet station, which was positioned

Table A-3.
Gust Front and Microburst Penetrations by Citation.

Date	Time (UT)	Type of Wind Shear Penetrated
14 April	2240-2340	gust front
18 May	1825-1925	gust front
24 May	0250-0320	gust front
3 June	0640-0715	gust front
15 August	0500-0540	gust front
15 August	2130-2205	gust front and microburst
22 August	0150-0220	microburst
27 August	2305-2335	gust front
28 August	2255-2320	gust front
29 August	0420-0500	gust front
4 September	1200-1225	microburst

near the FL-2 radar site. Figure A-1 shows the locations of 34 Mesonet and six LLWAS stations in the vicinity of KCI, and Figure A-2 shows those near KCD.

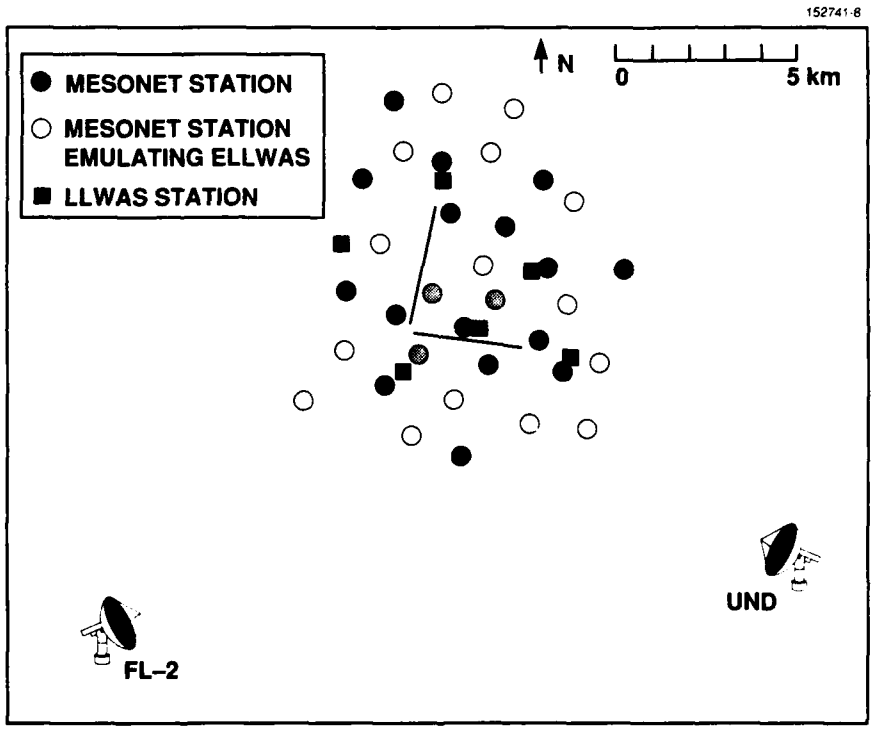

Figure A-1. Configuration of Mesonet and LLWAS stations in the vicinity of the Kansas City International airport.

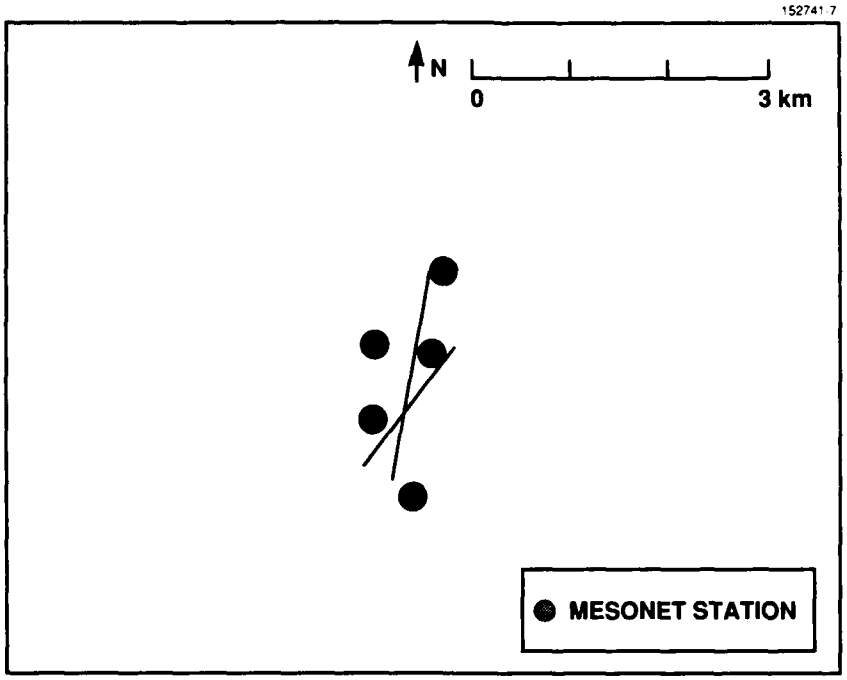

Figure A-2. Configuration of surface Mesonet stations in the vicinity of Kansas City's downtown airport. This airport is located approximately 23 km east-southeast of the FL-2 radar site.

A. Mesonet Data

Data collected from the Mesonet stations consisted of barometric pressure, temperature, relative humidity, precipitation rates, and wind speed and direction. All Mesonet data, other than the wind speed and direction, were collected as one-minute averages. From 25 of the 40 stations, not only was the one-minute-averaged data collected for both wind speed and direction, but the one-minute peak wind value also was collected. The locations of the remaining 15 Mesonet stations around KCI were selected to emulate an enhanced LLWAS (ELLWAS). The data from these stations were collected every 15 seconds.

Mesonet data were recorded during the period of 16 May through 3 October as summarized in Figure A-3. Figure A-4 identifies the Mesonet stations that were operational during that period on a day-by-day basis. Problems, such as delayed shipment of spare parts and lightning strikes, were encountered as we tried to attain 100 percent operational status for the Mesonet. During the first half of September, 60 percent of the stations were intentionally brought down, leaving only the stations that were emulating the ELLWAS up and operational.

B. LLWAS Data

LLWAS station data were collected during the period 18 April through 16 October and consisted of wind speed and direction data only. These data are 30-second running averages, read out every 10 seconds. Two problems, however, were encountered regarding the recording of the LLWAS data. First, data from the northeast LLWAS sensor was lost because of a slight programming error that was not discovered in time. Also lost were all LLWAS data during the period 19 through 28 July. Apart from this, data from the remainder of the period are available.

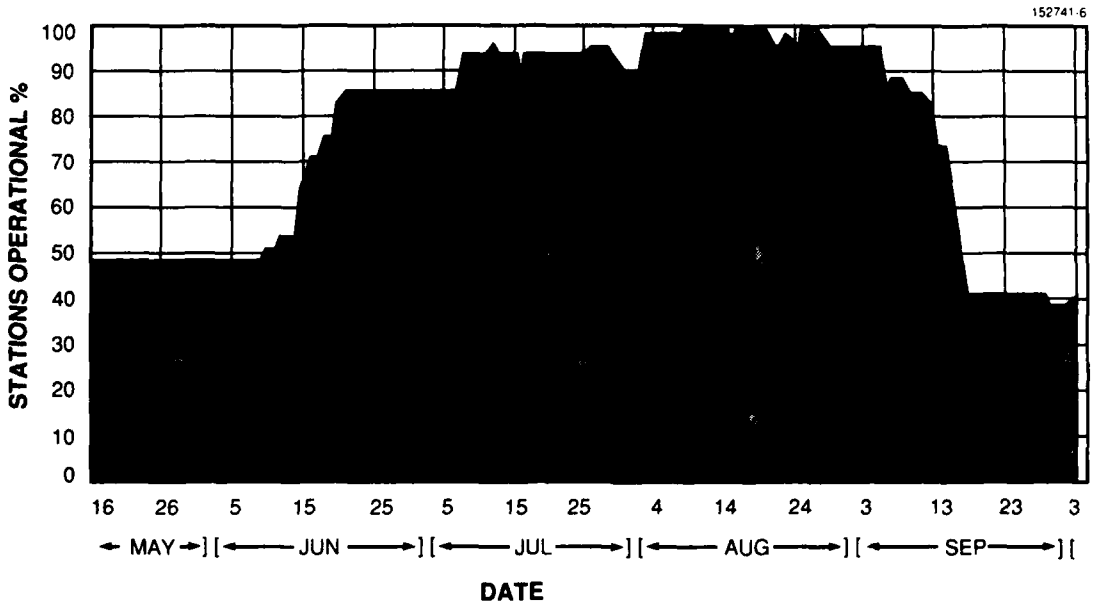

Figure A-3. Percentage of the 40 station Mesonet that was operational during 1989 in Kansas City.

4. ATMOSPHERIC SOUNDINGS (D. Klingle-Wilson)

The atmospheric sounding system know as M-CLASS (Mobile Cross-chain Loran Atmospheric Sounding System) was used during the Kansas City demonstration to collect data on the vertical thermodynamic and dynamic structure of the atmosphere. The weather balloons were launched from the FL-2 radar by NSSL personnel. The data recorded were temperature, humidity, pressure, and wind speed and direction. A description of MCLASS is provided in reference [15].

Table A-4 presents a compilation of the soundings taken at Kansas City. A total of 47 soundings were taken between 22 June and 15 August 1989. The table indicates the reason for the sounding. The purpose of "pre-storm" and "post-storm" soundings was to gather information on the environment before and after thunderstorm and microburst development. "MB storm," "gust front outflow," and "outflow" soundings were attempts to penetrate microburst-producing storms and thunderstorm outflows, respectively. "Low-level jet" soundings were used to forecast the development of the low-level jet, while "lapse rate" soundings were to determine the thermodynamics of the environment.

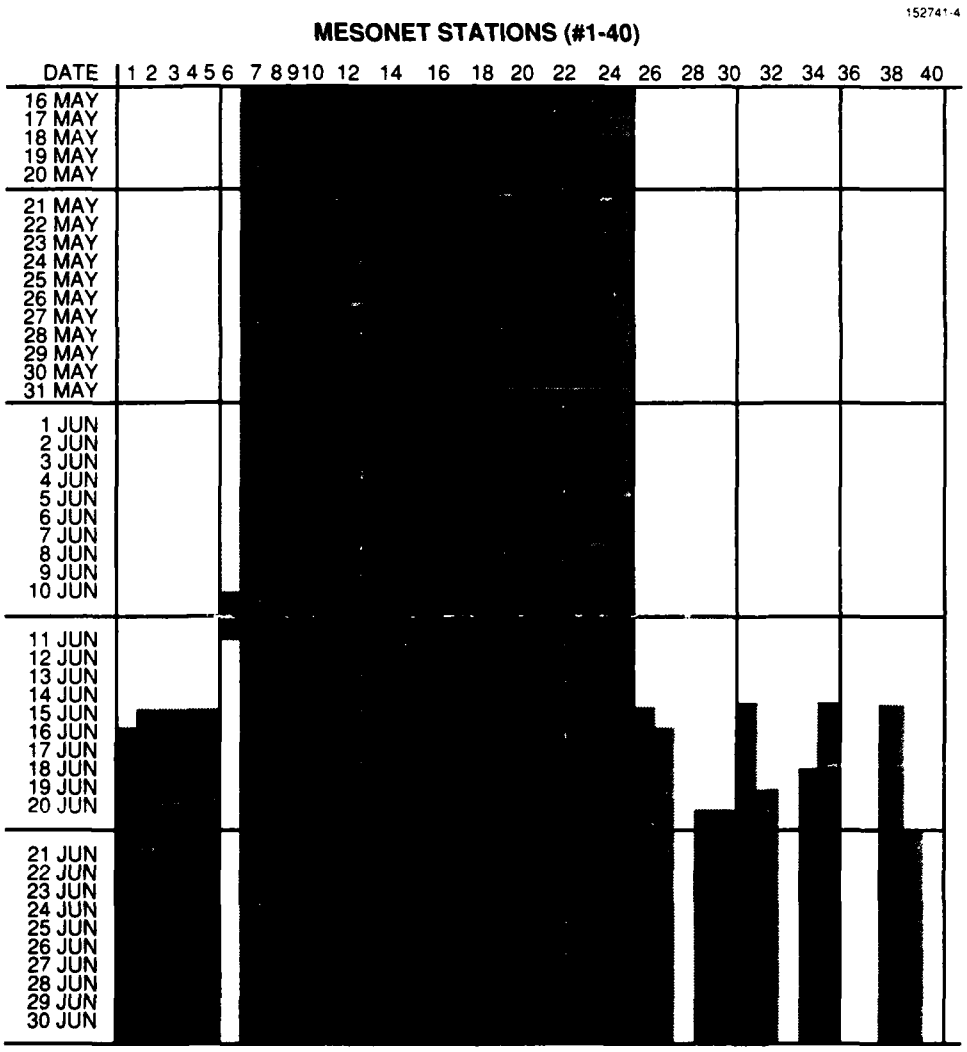

Figure A-4. Daily account of which Mesonet stations, indicated by the shaded areas, were operational during 1989 in Kansas City. Stations 1-5 were located at the KCD airport, station 6 at the FL-2 radar site, and stations 7-40 in the area around the KCI airport. Stations 26-40 were the ones chosen to emulated the ELLWAS.

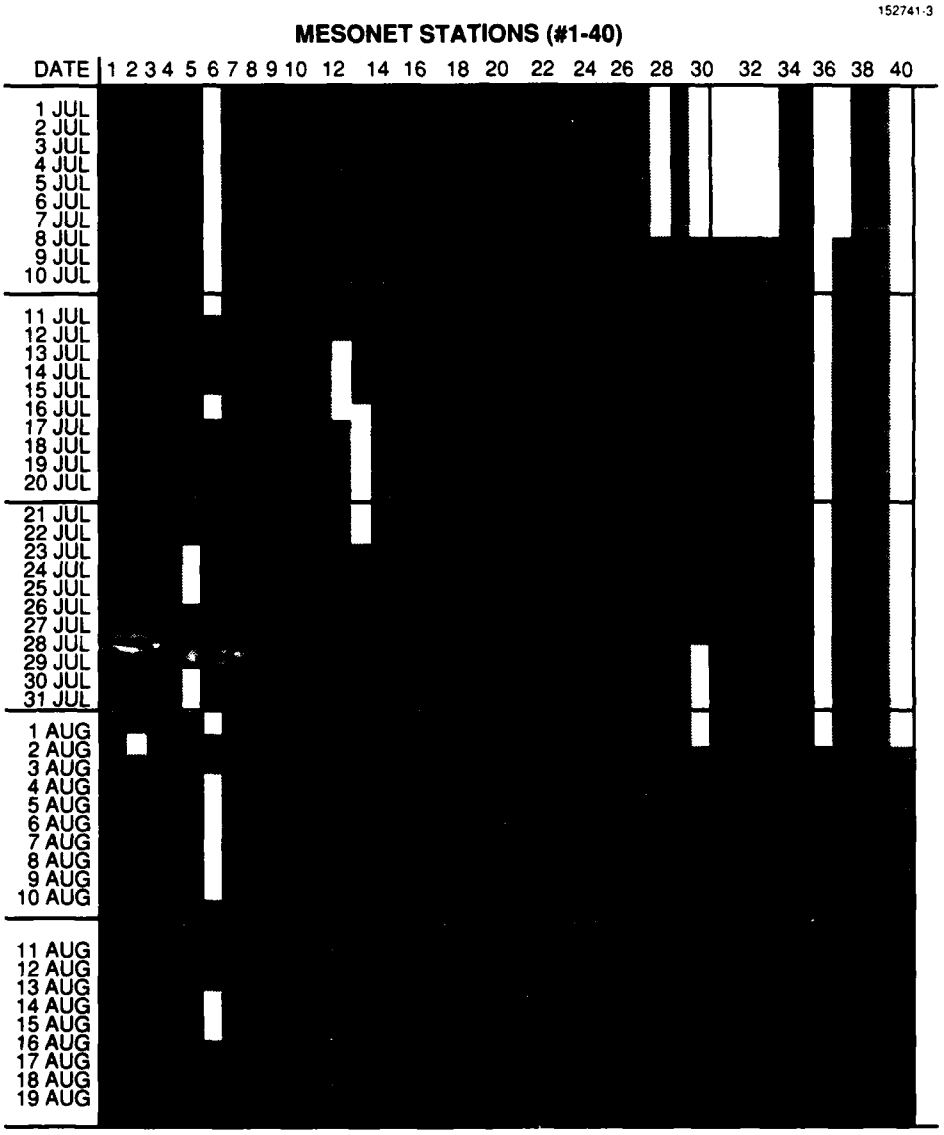

Figure A-4 (Continued).

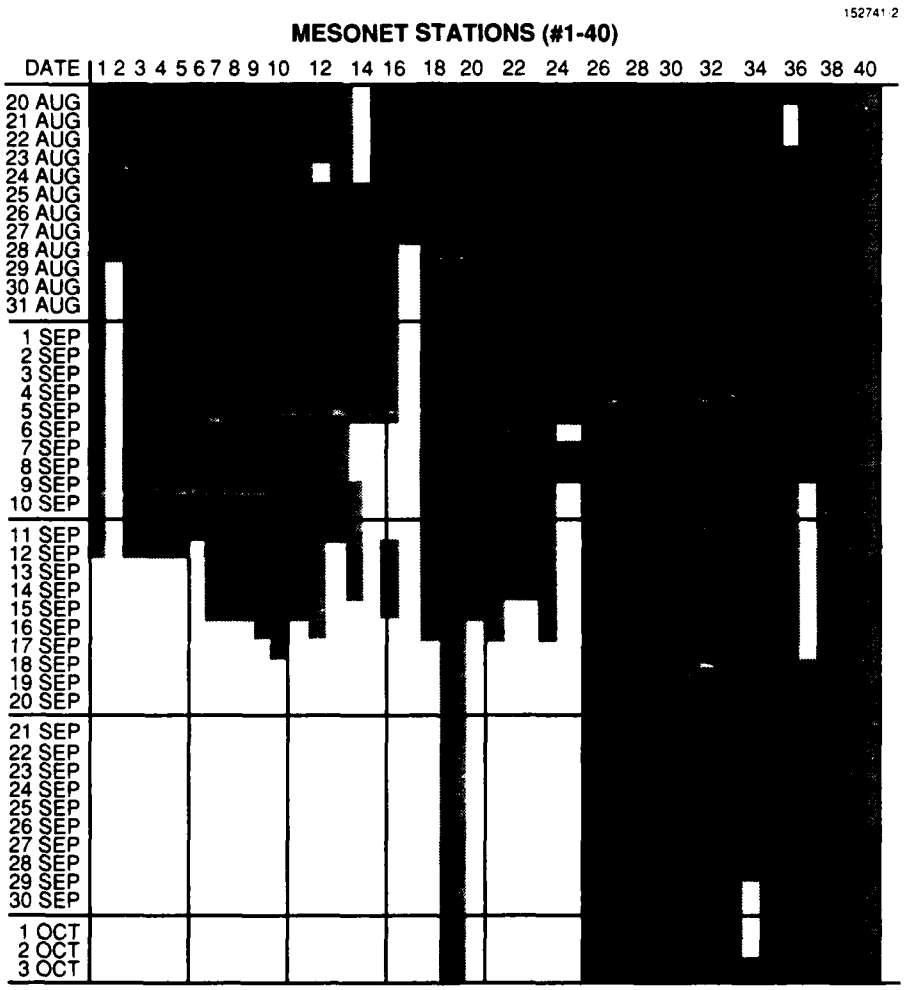

Figure A-4 (Continued).

Table A-4.
1989 Kansas City Soundings.

Date	(Universal) Time	Reason	Type of Event
June 22	1803	Pre-storm	None
June 23	2103	Pre-storm	None
June 24	1959	Pre-storm	Microburst/Gust Front
June 24	2256	MB storm	Microburst
June 25	2000	Pre-storm	None
June 26	2146	Pre-storm	Microburst/Gust Front
June 27	0027	Topeka	None
June 28	2308	Pre-storm	Gust Front
June 29	0000	Topeka	None
June 30	2329	Topeka	None
July 01	2037	Pre-storm	None
July 10	2122	Pre-storm	Microburst/Gust Front
July 10	2323	Gust Front Outflow	Gust Front
July 11	2341	Pre-storm	None
July 12	2206	Pre-storm	Microburst/Gust Front
July 14	2035	Pre-storm	None
July 16	2253	Pre-storm	None
July 17	2112	Pre-storm	None
July 18	0300	Pre-storm	Microburst/Gust Front
July 19	1915	Pre-storm	None
July 22	1829	Pre-storm	Microburst/Gust Front
July 23	1740	Pre-storm	None
July 24	1825	Pre-storm	Gust Front
July 24	2146	Gust Front Outflow	Gust Front
July 25	1929	Pre-storm	None
July 27	1829	Pre-storm	Microburst
July 30	1909	Pre-storm	Microburst/Gust Front
August 02	2030	Pre-storm	None
August 03	1515	Pre-storm	None
August 05	0241	Pre-storm	Gust Front
August 05	0515	Low Level Jet	None
August 05	1700	Pre-storm	None
August 10	2021	Pre-storm	None
August 13	2114	Pre-storm	Microbursts
August 14	1439	Lapse rate	Microbursts/Gust Front
August 14	1532	Lapse rate	Microbursts/Gust Front
August 14	1630	Lapse rate	Microbursts/Gust Front
August 14	1731	Lapse rate	Microbursts/Gust Front
August 14	2000	Lapse rate	Microbursts/Gust Front
August 14	2230	Lapse rate	Microbursts/Gust Front
August 15	0000	Lapse rate	Microbursts/Gust Front
August 15	0208	Lapse rate	Microbursts/Gust Front
August 15	1624	Pre-storm	Microbursts/Gust Front
August 15	2014	Pre-storm	Microbursts/Gust Front
August 15	2223	Outflow	Data no good
August 15	2344	Post-storm	None

APPENDIX B
RADAR SYSTEM SUMMARY
(D. Bernella, W. Drury, J. Frankovich)

1. SYSTEM FEATURES (D. Bernella)

The FL-2 Doppler weather radar was designed, built and is operated by MIT Lincoln Laboratory. This radar has been operated as a development tool and an operational TDWR testbed since its first operations in Memphis, TN in 1985. Since that time it has been operated in Huntsville, AL (1986), Denver, CO (1987-1988), and in Kansas City, MO (1989).

The transmitter/receiver has been operating at an RF frequency in the FAA authorized S-band (2700-3000 MHz). The transmitter was derived from an ASR-8 Airport Surveillance Radar and was modified to increase its stability to permit > 50 dB of near zero velocity clutter suppression. The receiver and digital preprocessors were designed and built by Lincoln Laboratory and have been continuously upgraded as the testbed has been called on to meet more and more of the TDWR system specifications. Several commercial processors (Concurrent and Sun) make up the subsystems where the weather product and hazardous weather warning algorithms reside.

The FL-2 testbed meets most of the functional requirements in the TDWR specifications, including system sensitivity, scan strategy, product and warning generation and update rates, data quality assurance, etc. In addition, the testbed can simulate the T-NEXRAD operation in terms of scan strategy and update rates. However, the actual implementation of the products algorithms and the data quality algorithms are, in most cases, accomplished in different hardware. Furthermore, much of the processing hardware in FL-2 is relatively 'hard wired' and not easily adapted to simulating the T-NEXRAD and TDWR internal processing and system monitoring.

FL-2 in its present form operated satisfactorily during the 1989 season in Kansas City. A few problems were noted and are discussed in the following paragraphs. There were no problems serious enough to halt operations for more than a few minutes at a time.

2. RADAR SYSTEM PERFORMANCE/ISSUES (W. Drury, J. Frankovich)

A. Radome/Antenna/Pedestal

The performance of the radome and antenna was again uneventful during the 1989 testing period. The only maintenance involved was the periodic six-week check of the antenna back structure fasteners where, historically, a few bolts usually need tightening. The antenna pedestal, on the other hand, encountered a few problems during the summer. These are described in the following paragraphs.

Drive Motors. One of the azimuth drive motors developed worn bearings for reasons still unknown at this time. The spare motor was installed and the worn unit was returned to the vendor for repair.

Gearbox Lubrication. Lubrication of the azimuth gearboxes is by forced oil jets. The orifices in one of the gearbox lubing systems showed a propensity for clogging, which continued throughout most of the testing period. Frequent cleaning and the use of lighter-weight oil permitted uninterrupted use of the pedestal, and the problem will be

investigated in depth now that the pedestal has been disassembled prior to shipment to the Orlando site.

Gear Wear. Prior to the move from Denver to Kansas City, the pedestal was disassembled and inspected. Most of the Denver operation involved sector scanning over Stapleton airport, resulting in reversals of direction at two specific angles. When the bullgear was examined, it was found that the area impacted by the driving pinion gears during the reversals was considerably worn. As a result, the gear was redressed at Arch Gear Works and then reassembled such that those particular areas were positioned differently from the ends of scan in the Kansas City scan geometry. The pinions, although not noticeably worn, were replaced at that time.

At the end of the Kansas City experiment, the gears were again examined. Surprisingly, no damage was evident on the bullgear, but one of the pinion gears was severely damaged. All the gears are being carefully examined, and any others showing wear will be replaced. Even though the bullgear did not show the excessive wear of the previous year, plans are to replace it anyway, as it is expected that the system will be operated heavily over the next two years in Orlando. The problem with the damage to the newly-replaced pinion gear is disturbing and is being carefully investigated at the present time. This problem is of particular concern because the TDWR radars will rely heavily on sector scanning, and it is imperative that the pedestal be capable of sustained operation without internal damage.

B. Receiver/Exciter/Transmitter

Receiver/Exciter. The receiver/exciter subsystem experienced one failure during the testing period. An IF amplifier ceased to function and was replaced with a spare unit. Since this failure occurred early in the day, data transmission to the control tower was not affected.

Transmitter. The transmitter exhibited occasional spontaneous shutdowns at a rate of one or two times per week. In each case, the cause was a mystery, as no fault indicator lights came on and the transmitter could be re-started immediately. The downtime of several seconds resulted in a loss of data during part of one tilt on each occasion. Troubleshooting this failure has not been cost-effective since it occurred so seldom and left no clues.

COHO Leakage. Of continuing concern was leakage of the COHO signal into the AGC system, and the drift of that leakage signal as a function of temperature. While using a COHO with constant phase reference, there was no problem because the auto-zeroing circuitry surrounding the analog-to-digital converters compensated for the leakage. When COHO phase-modulation was employed to reduce second-trip clutter, the COHO phase angle was constantly being changed with respect to the unswitched COHO used as a basis for system timing. The result was a low-level DC-offset in the I and Q video signals which changed each time the COHO phase was changed. Although the offsets were only a few millivolts, the signal processing computers were unable to deal with them.

A "hum-bucking" circuit was designed and constructed to inject an added COHO signal of equal amplitude and opposite phase into the IF circuits. This technique worked quite well and would have been a satisfactory solution, except for temperature variation. Although temperature changes appeared to be quite small, in the chassis where the circuitry is located there are components which could provide enough heat to create the observed rise in temperature. The COHO leakage is still a problem because the "hum-

bucker" requires manual adjustment several times a day. As in the case of pedestal gears, this same problem may potentially surface in the TDWR radar systems and should be a concern to Raytheon.

AGC Switching Level. When the system was being assembled following the move from Denver, a check of the AGC switching level was inadvertently omitted. This level is not critical, but it is bounded. If the level is set too low, the resulting reduced dynamic range becomes a minor problem, but is not catastrophic. If the level is set too high, however, the analog-to-digital converters are allowed to limit. When this happens, gross and unpredictable errors are injected into the data. It was this second case that happened in the spring. By early May, the system was checked out to the point of data collection and analysis, and the misadjustment was corrected. This misadjustment resulted in a higher than normal clutter residue level for the data obtained prior to May.

C. Signal Processor/DAA Computers

The two front-end processors in the FL-2 system, the SP and the DAA computers, transform the digitized pulse return range gate samples into the correlation log results[9] for the Concurrent computer. During the summer of 1989, the two processors operated satisfactorily at Kansas City at the full level of performance required for the entire period of the demonstration and experiments.

The enhancements to the SP that were installed for the previous year's work at Denver provided the basis for this year's upgrades in the DAA area. There were no significant changes to the SP this year. The dual DAA (DDAA) configuration of 1988 was used for the bulk of this year's data gathering, and a new DAA (NDAA) with enhanced capabilities was installed in the spring and was operated in parallel with the DAA during most of the summer. Towards the end of the summer it was used operationally for the data-gathering work.

While the two DAA systems were operating in parallel, various tests were made to validate operations. These tests included comparisons of factors data output from both DAAs. These revealed a previously unrecognized bias, apparently due to numerical truncation in factor values from the DDAA. Using input data from a simulated radar source, it was found that the DDAA frequently produced values that were smaller than expected, by counts of 8 to 10 in the LSB. These errors would not affect algorithm computations significantly, but they do show up as a small offset in amplitudes.

For the Kansas City operations, a system change was implemented that permitted the use of the higher update rate beacon reports from the local ASR-8 radar. Occasional errors in the aircraft beacon reports were noted when the higher frequency short range report capability was added. These were fully corrected in the NDAA configuration.

Several other intermittent failures were noted. Prominent background "speckles" occurred frequently in the data displays when the DDAA was used, and to a much lesser extent with the NDAA. These effects have been reduced but not totally eliminated. No algorithm degradation has been noted due to this "speckle" anomaly.

The NDAA not only performed computations with more precision and dynamic range, but also with more internal checking on the validity of the data structures it handled. These internal dynamic tests led to greater confidence in overall system

[9]The correlation lag results are transferred as magnitudes and phase angle of the correlation lags (i.e., "factors").

operations and to the discovery of occasional aberrations. In addition, each radial of factors data and each tilt (sweep) of data outputted from the NDAA included more information to characterize the data and the nature of the radar operation. This information is useful for both archival and real-time data processing.

Both DAA configurations experienced a variety of synchronization problems. With the DDAA, this appeared as a loss of part or all of the data in a tilt from one or both of the DAAs. This problem did not occur frequently enough to be able to isolate and diagnose. The NDAA also indicated synchronization problems, but they did not lead to the significant loss of data. Aside from outright intermittent system equipment failures, these synchronization problems reflect the inherent difficulties of chaining together a number of semiautonomous real-time computers that are loosely coupled and managed by a real-time system controller.

These problems illustrate the need for enhanced diagnostic hardware and program testing capabilities, both for off-line test and for continuous on-line real-time monitoring. One new capability that proved to be especially useful was the Time Series Buffer (TSB). The TSB was developed to capture selected quantities of high-rate raw digitized pulse data for diagnostic purposes. This data was then analyzed, in conjunction with information from archival recordings for verification of system operations. The ability to monitor operational performance and status in these ways with these software and hardware test and diagnostic tools is one of the more important side developments with the FL-2 system.

APPENDIX C
WEATHER OCCURRENCES
(D. Clark)

The weather in the vicinity of KCI from April through September 1989 averaged wetter and cooler than normal, with less than normal convective activity (see Table C-1). Although 25 percent more precipitation occurred than expected, the bulk of the precipitation occurred in August and September, with April through July actually averaging 14 percent drier than normal. This monthly distribution was consistent with occurrence of thunderstorm days reported at the airport. There were 34 thunderstorm days (seven fewer than normal) during the entire six-month period. Eighteen of these occurred between April and July, while 29 were expected. Only August showed more convective activity than normal, with nearly twice as many thunderstorm days as expected.

Table C-1.
Monthly Distribution of 1989 Weather Activity Recorded at KCI Airport.

	Precipitation (Inches)			Thunderstorm Days		
	Actual	Normal	Departure	Actual	Normal	Departure
April	1.50	3.26	-54%	2	5.8	-66%
May	4.57	4.39	+4%	7	7.4	-5%
June	3.43	4.64	-26%	6	8.4	-29%
July	4.76	4.33	+10%	3	7.6	-61%
August	7.40	3.57	+107%	11	6.5	+69%
September	8.86	4.14	+114%	5	5.2	-4%
Total	30.52	24.33	+25%	34	40.9	-17%

The frequency of wind shear events in the vicinity of the airport showed modest correlation with Thunderstorm Day frequency. The most notable feature in the monthly distribution was the marked increase in wind shear activity during August (Table C-2), when convective activity also increased dramatically. The correlation was not as straightforward in late spring/early summer (May - June), which produced relatively few wind shear events, during which time thunderstorm day occurrence was reasonably near normal. Very few strong events ($\Delta V > 20$ m/s) occurred during the entire six-month period. Additionally, none of these occurred in the most active month of August.

Table C-2.
Monthly Distribution of 1989 Wind Shear Events in Vicinity of KCI Airport.

	Microbursts Differential Velocity (m/s)			Gust Fronts Differential Velocity (m/s)		
	10-19	20+	Total	10-19	20+	Total
April	5	0	5	2	1	3
May	3	1	4	1	0	1
June	5	0	5	5	0	5
July	5	1	6	6	0	6
August	17	0	17	11	0	11
September	5	0	5	3	2	5
Total	40	2	42	28	3	31

APPENDIX D
QUESTIONNAIRE RESULTS
(C. Biter, R. Hastie, B. Stevens)

Questionnaires regarding the TDWR products and display issues were created by NCAR and given to KCI tower and TRACON personnel after the operational demonstration was concluded. There were 21 respondents (40 percent of the pertinent personnel), consisting of five supervisors and 16 controllers. The following pages provide the median responses for the controllers or supervisors, indicated by a C or an S, respectively. Questions 5 and 6 are open ended; therefore, actual responses are provided.

A more detailed analysis of the questionnaire responses is being conducted by Prof. Reid Hastie (University of Colorado Center for Research on Judgment and Policy). The results of this analysis and the summary of the debriefing of the FAA supervisors will be reported separately by the National Center for Atmospheric Research.

MEDIAN RESPONSES OF CONTROLLERS (C) AND SUPERVISORS (S) TO DIFFERENT ASPECTS OF THE TDWR

1. Please rate different aspects of the TDWR using the following scale: (Place check marks in appropriate columns.)

+ 3 = Very Good
+ 2 = Good
+ 1 = Fairly Good
0 = Fair
- 1 = Fairly Poor
- 2 = Poor
- 3 = Very Poor
? = Don't Know

ITEM BEING EVALUATED	RATING SCALE							
	- 3	- 2	- 1	0	+ 1	+ 2	+ 3	?
a. Daytime readability of the display								
1) GSD						C S		
2) Alphanumeric						C S		
b. Nighttime readability of the display								
1) GSD							C S	
2) Alphanumeric						S	C	
c. Readability of display in glare								
1) GSD					C	S		
2) Alphanumeric					C	S		
d. Audibility of the alarm beeper								
1) GSD						C S		
2) Alphanumeric						C S		
e. Location of the display								
1) GSD				C S				
2) Alphanumeric					S	C		
f. Accuracy of the displayed info								
1) GSD							C S	
2) Alphanumeric							C S	
g. Number of false alarms (many = -3; few = +3)								
1) GSD						C S		
2) Alphanumeric						C	S	
h. Timeliness of the displayed info								
1) GSD						C	S	
2) Alphanumeric						C	S	
i. Usefulness of the displayed info								
1) GSD						C	S	
2) Alphanumeric						C	S	

ITEM BEING EVALUATED	RATING SCALE							
	-3	-2	-1	0	+1	+2	+3	?
j. Freedom from misinterpretation								
1) GSD						C	S	
2) Alphanumeric						C	S	
k. Ease of accessing needed wind info								
1) GSD						S	C	
2) Alphanumeric							C S	
l. Info grouping and order								
1) GSD						C	S	
2) Alphanumeric						C	S	
m. Aptness of message abbreviations on alphanumeric display						C S		
n. Naturalness of spoken phraseology using alphanumeric display						C S		
o. Usefulness of runway selectability feature on alphanumeric display						C S		
p. Ease of runway selection using GSD						C S		
q. Usefulness of microbursts on GSD							C S	
r. Usefulness of gust fronts on GSD							C S	
s. Usefulness of wind shift prediction on GSD							C S	
t. Usefulness of precipitation on GSD						S	C	
u. Usefulness of LLWAS winds on GSD						S	C	
v. Usefulness of nowcasting product on GSD (Denver only)								
w. Usefulness of storm motion product on GSD (Kansas City only)							C S	
x. Usefulness of GSD for runway management						C S		
y. Usefulness of training received								
1) GSD					S	C		
2) Alphanumeric						C	S	
z. Usefulness for continued field use								
1) GSD							C S	
2) Alphanumeric							C S	

2. Do you see the TDWR/Terminal NEXRAD system as a help or hindrance to you in your job of controlling air traffic? (Please circle one letter below)

Response Choice	Median Response from Controllers or Supervisors (C or S)	
	C	S
a. A great help		
b. A help		
c. A slight help		
d. Neither help nor hindrance		
e. A slight hindrance		
f. A hindrance		
g. A great hindrance		
h. Don't know		

3. Do you see the TDWR/Terminal NEXRAD system as a help or hindrance to the pilot? (Please circle one letter below)

Response Choice	Median Response from Controllers or Supervisors (C or S)	
	C	S
a. A great help		
b. A help		
c. A slight help		
d. Neither help nor hindrance		
e. A slight hindrance		
f. A hindrance		
g. A great hindrance		
h. Don't know		

4. Do you see the TDWR/Terminal NEXRAD system as a help or hindrance to planning and traffic management functions? (Please circle one letter below)

Response Choice	Median Response from Controllers or Supervisors (C or S)
a. A great help	S
b. A help	C
c. A slight help	
d. Neither help nor hindrance	
e. A slight hindrance	
f. A hindrance	
g. A great hindrance	
h. Don't know	

5. What's good about the TDWR/Terminal NEXRAD system? What potential benefits do you forsee for the system?

Supervisors' Responses:

a. Any system that provides storm information is useful to the controller and the pilot.

b. I would like to see the controller be able to disseminate this info quickly which TDWR does help. It helps to give pertinent info about thunderstorms and maybe we can determine what conditions we can ignore.

c. Current valid microburst activity for instant information to pilots.

Controllers' Responses:

d. The accuracy.

e. I never really saw the system function in anything other than VFR wx [visual flight rules weather].

f. None.

g. Planning alternate weather routes and enhancing safety.

h. Runway change anticipation. Forecasting possible problems on landing final.

i. It provides you with information that is very useful to both pilots and controllers. Fewer weather related accidents once everyone understands it properly.

j. It helps in real time weather presentations.

6. What's poor about the TDWR/Terminal NEXRAD system? What problems do you see?

Supervisors' Responses:

a. It puts the controller in the middle of issuing wx [weather] information, when other duties as in separation are higher priority. Why would an aircraft need to fly into, under or near a TSTM [thunderstorm] is beyond me.

Controllers' Responses:

b. The occasional false alarm.

c. N/A.

d. Saw one erroneous readout. We were unable to deviate from the prescribed phraseology. If a pilot reports no wind shear, you should be able to discontinue wind shear advisories.

e. Mis-reading of information until everyone is understanding of the system.

7. Please rate the relative magnitude of benefits and problems of the TDWR/Terminal NEXRAD system by circling the appropriate letter below.

Response Choice	Median Response from Controllers or Supervisors (C or S)
a. Benefits greatly exceed problems	S
b. Benefits exceed problems	C
c. Benefits slightly exceed problems	
d. Benefits equal problem	
e. Problems slightly exceed benefits	
f. Problems exceed benefits	
g. Problems greatly exceed benefits	
h. Don't know	

8. Based on your present knowledge, please rate the TDWR/Terminal NEXRAD system's suitability for widespread operational use in the field. Please circle one of the letters (a) through (h).

Response Choice	Median Response (C or S)
a. Suitable, install and use, fine as is, don't make any changes.	
b. Suitable, install and use, minor adjustments optional.	C
c. Suitable, install and use but some changes beneficial.	S
d. Marginally suitable, proceed with installation but make changes before use.	
e. Unsuitable, don't install, changes definitely needed prior to installation.	
f. Unsuitable, don't install, concept OK, but extensive rework mandatory.	
g. Unsuitable, don't install, entire concept inappropriate.	
h. Don't know.	

GLOSSARY

AEL	Algorithm Enunciation Language
AGC	Automatic Gain Control
AGL	Above Ground Level
AP	Anomalous Propagation
ASR	Air Surveillance Radar
ATC	Air Traffic Control
ATIS	Air Traffic Information System
COHO	Coherent Logical Oscillator
CWSU	Central Weather Service Unit
DAA	Data Acquisition and Analysis
DDAA	Dual Data Acquisition and Analysis
KCD	Kansas City Downtown Airport
DV	Doppler Velocity
ELLWAS	Enhanced LLWAS
FAA	Federal Aviation Administration
GF	Gust Front
GOES	Geostationary Operational Environmental Satellite
GSD	Geographical Situation Display
IAGC	Instantaneous Automatic Gain Control
IF	Intermediate Frequency
ILS	Instrument Landing System
INS	Inertial Navigation System
KCD	Kansas City Downtown Airport
KCI	Kansas City International Airport
LLWAS	Low-Level Wind Shear Alert System
LSB	Least Significant Bit
M-CLASS	Mobile Cross-chain Loran Atmospheric Sounding System
MB	Microburst
MIT	Massachusetts Institute of Technology
MTI	Moving Target Indicator
NCAR	National Center for Atmospheric Research
NDAA	New Data Acquisition and Analysis
NSSL	National Severe Storm Laboratory
NWS	National Weather Service
OT&E	Operational Test & Evaluation
PFA	Probability of False Alarm
PFF	Probability of a False Forecast
PFW	Probability of False Warning
POCF	Probability of a Correct Forecast
POD	Probability of Detection
PPI	Plan Position Indicator
PRF	Pulse Repetition Frequency
RF	Radio Frequency
RHI	Range Height Indicator
SNR	Signal to Noise Ratio
SP	Signal Processor
TDWR	Terminal Doppler Weather Radar
TRACON	Terminal Radar Control room
TSB	Time Series Buffer
UND	University of North Dakota
VFR	Visual Flight Rules
Wx	Weather

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