Session V.   TDWR Data Link / Display

Integration of the TDWR and LLWAS Wind Shear Detection System
Larry Cornman, National Center for Atmospheric Research

Integration of the TDWR and LLWAS Wind Shear Detection Systems

by

Larry Cornman
National Center for Atmospheric Research*
Research Applications Program

Abstract

Operational demonstrations of a prototype TDWR/LLWAS integrated wind shear detection system were conducted at Denver's Stapleton International Airport during the 1989 and 1990 summer seasons. The integration of wind shear detection systems is needed to provide end-users with a single, consensus source of information. A properly implemented integrated system provides wind shear warnings of a higher quality than stand-alone LLWAS or TDWR systems.

The algorithmic concepts used to generate the TDWR/LLWAS integrated products and several case studies will be discussed, indicating the viability and potential of integrated wind shear detection systems. Implications for integrating ground and airborne wind shear detection systems will be briefly examined.

INTEGRATION OF
THE TDWR AND LLWAS
WIND SHEAR DETECTION SYSTEMS

by

Larry B. Cornman
National Center for Atmospheric Research
Research Applications Program

OUTLINE

- **TDWR and LLWAS as Stand-Alone Systems**

- **Motivation for Integration**

- **Integration Concepts**

- **TDWR/LLWAS Integration Algorithm**

- **Connection to Airborne Wind Shear Systems**

WIND SHEAR COMPONENTS OF CURRENT TDWR AND LLWAS (STAND-ALONE) SYSTEMS

TDWR

o Microburst Detection

-- (One-minute update rate)

-- Event region enclosed in "band aid" shape.

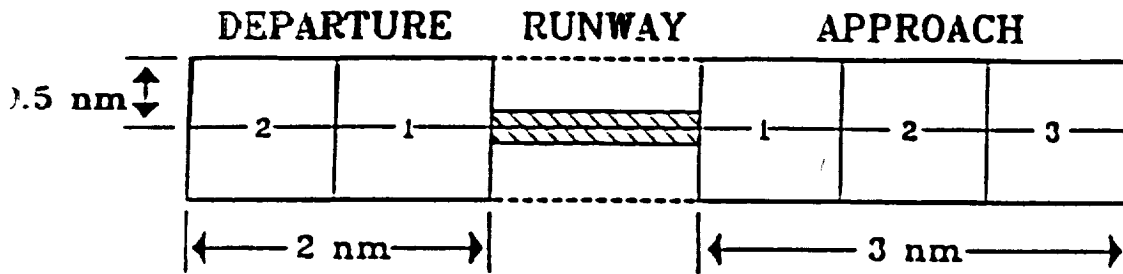-- Alerts generated when shape intersects runway corridor

o Gust Front Detection

-- (5-minute update rate)

-- Event described by solid curve. Alerts generated when curve intersects runway corridor.

o Displays

-- Alphanumeric: runway-specific alerts

-- Graphic: runway-specific alerts and event depiction

RUNWAY ALERT CORRIDOR
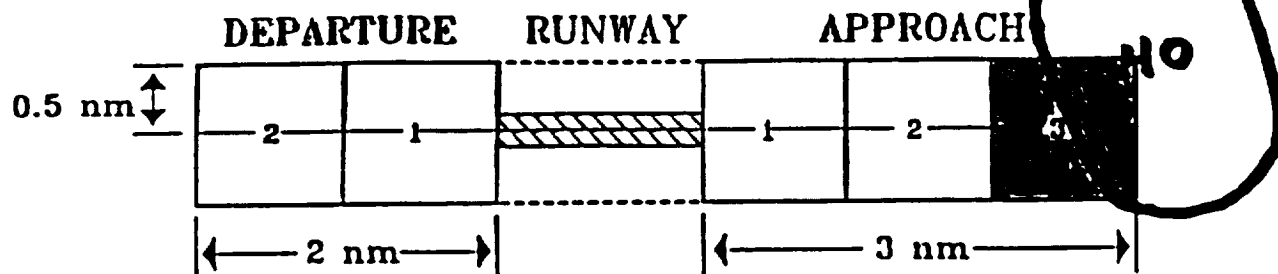
DEPARTURE   RUNWAY   APPROACH

).5 nm

—2——1—   —1— —2——3—

|←——2 nm——→| |←———3 nm———→|

WIND SHEAR WARNING MESSAGE FORMAT

TYPE	WIND SPEED CHANGE	LOCATION	
$\begin{bmatrix} \text{Wind Shear} \\ \text{Microburst} \end{bmatrix}$	$\begin{bmatrix} \text{Loss/Gain} \\ \text{Knots} \end{bmatrix}$	$\begin{bmatrix} 1 \text{ mi} \\ 2 \text{ mi} \\ 3 \text{ mi} \end{bmatrix}$	Approach
		$\begin{bmatrix} 1 \text{ mi} \\ 2 \text{ mi} \end{bmatrix}$	Departure
		$\begin{bmatrix} \ \ \end{bmatrix}$	Runway

RUNWAY ALERT CORRIDOR

DEPARTURE   RUNWAY   APPROACH

0.5 nm

2   1   1   2   3

|← 2 nm →| |← 3 nm →|

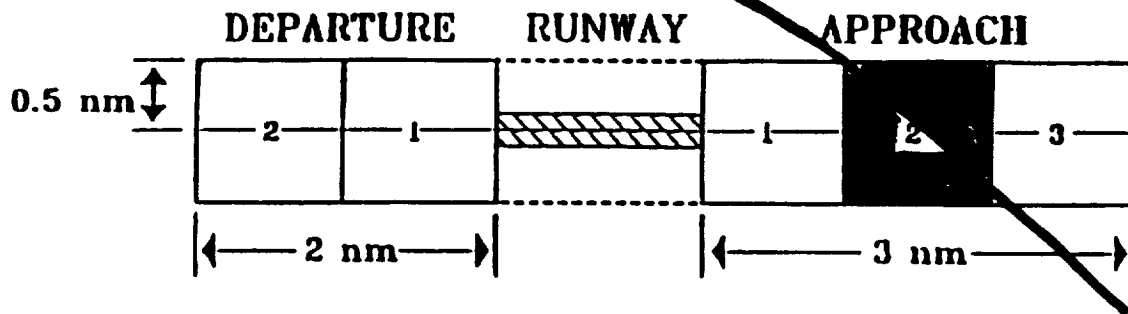# MICROBURST "BAND-AID" SHAPE

IMPACTING RUNWAY
ALERT CORRIDOR

RUNWAY ALERT CORRIDOR

TDWR GUST FRONT CURVE

## IMPACTING RUNWAY
ALERT CORRIDOR

WIND SHEAR COMPONENTS OF
CURRENT TDWR AND LLWAS (STAND-ALONE) SYSTEMS
(continued)

<u>LLWAS</u>

o Phase I: Original "six station".

o Phase II: "Six station", algorithm upgrade.

o Phase III: "Network expansion". Additional stations, further algorithm upgrades: microburst detection, runway-specific alerts.

o Runway extension:"3-mile extensions". Additional stations to protect full runway corridor.

LLWAS ANEMOMETER NETWORK
STAPLETON INT'L AIRPORT

● Original Phase I/II LLWAS
✱ Phase III LLWAS
■ Runway Extension LLWAS
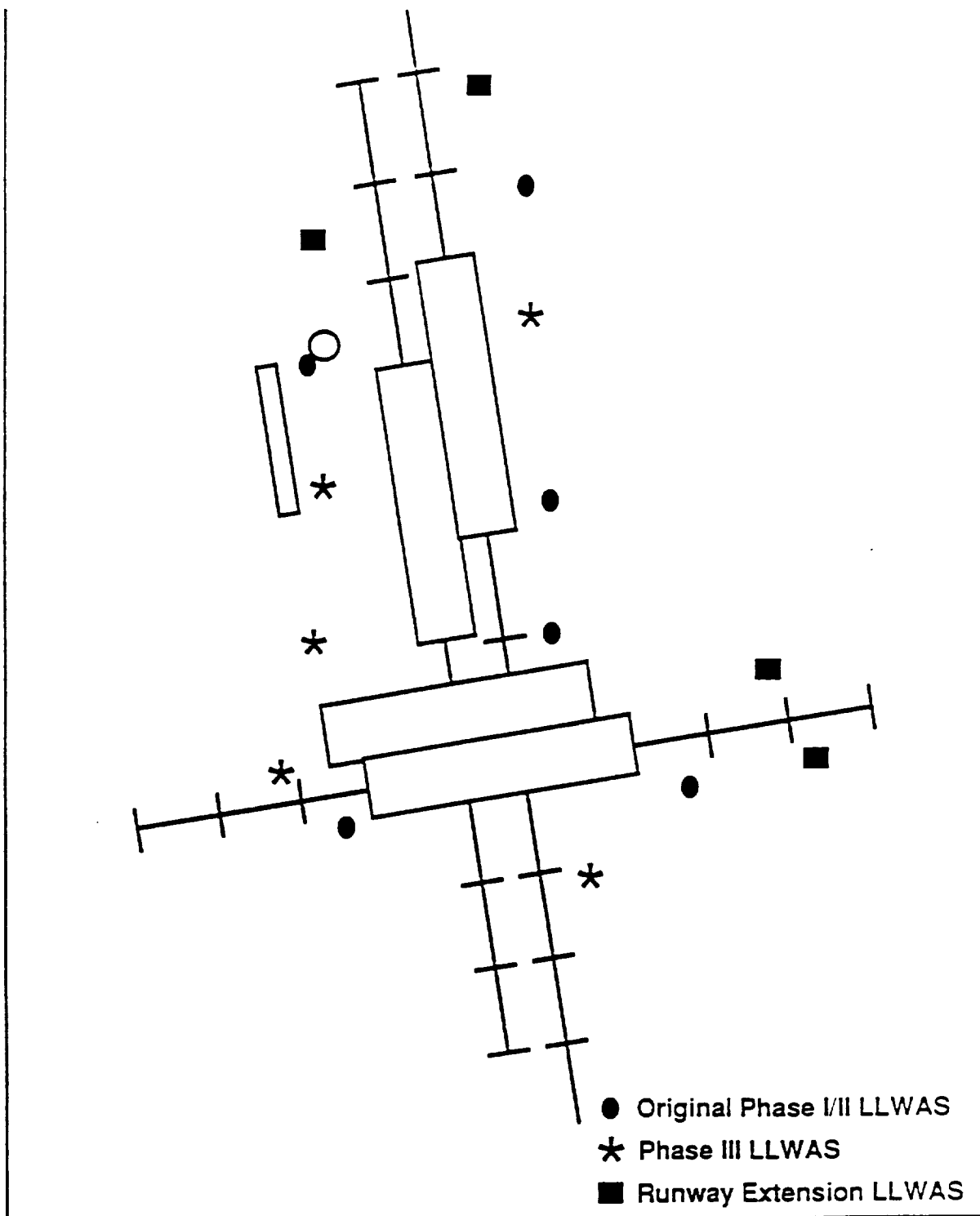
WIND SHEAR COMPONENTS OF
CURRENT TDWR AND LLWAS (STAND-ALONE) SYSTEMS
(continued)

LLWAS (continued)

0 Phase III/Runway Extension:

--Microburst detection

-- Runway-oriented loss and gain detection

-- (10-second update rate)

-- Displays

-- Alphanumeric: runway-specific alerts,
    (identical format as for TDWR)

0 Integration "Add-On":

-- microburst region enclosed in "band aid" shape
   (identical to TDWR)

MOTIVATION FOR INTEGRATION

o Both stand-alone systems do a good overall job detecting wind shear:

-- TDWR and LLWAS have very good microburst probability of detection (POD >90%) and low false alarm rates (FAR<10%).

-- Gust front detection and false alarm values are not quite as good, yet acceptable.

o SO, WHY DO WE NEED TO INTEGRATE?

-- These numbers don't tell the whole story ...

MOTIVATION FOR INTEGRATION
(continued)

0 Cannot have two separate display systems:

   * Physical Space for Displays in ATCT

   * Two, (Potentially Different), Sets of
     Wind Shear Information

   * Users (pilots, air traffic controllers) should not
     have to interpret wind shear information based
     on a variety of sources.

0 Provides Back-Up Capability

   * Each system can continue to operate
     independently.

MOTIVATION FOR INTEGRATION
(continued)

0   The Probability of Detection and False Alarm Rates for Integration Will be Better than Those for the Stand-Alone Systems.

   -- Since the stand-alone statistics are already quite good, the integration benefits might appear to be only marginal.

0   These Numbers Don't Really Reflect the Key "Value-Added" Components of Integration ...

MOTIVATION FOR INTEGRATION
(continued)

Integration "Value-Added Factors:

1. Increased Timeliness

   -- TDWR can detect events moving into airport area.

   -- TDWR can detect microbursts impacting between LLWAS anemometers before the outflow reaches them.

   -- TDWR has predictive capabilities.

MOTIVATION FOR INTEGRATION
(continued)

-- LLWAS has a faster update rate than TDWR (surface scans): 10 sec. vs. 60 sec.

-- So, for rapidly changing events, LLWAS can "monitor" the situation better:

   o first detection

   o increasing/decreasing magnitude

   o event location and size

   o event cessation

278

MOTIVATION FOR INTEGRATION
(continued)

2. Integration Covers "Partial Misses" (Spatial)

O Detection statistics are based on seeing "most" of the event.

*However, pilots need to know what is impacting their specific flight path!

O TDWR can detect events (or portions thereof) impacting runway corridor, yet outside LLWAS network.

O LLWAS can "cover" for TDWR in cases of asymmetry and low-reflectivity.

COVERING "PARTIAL MISSES"

runway alert corridor

llwas

tdwr

true event location
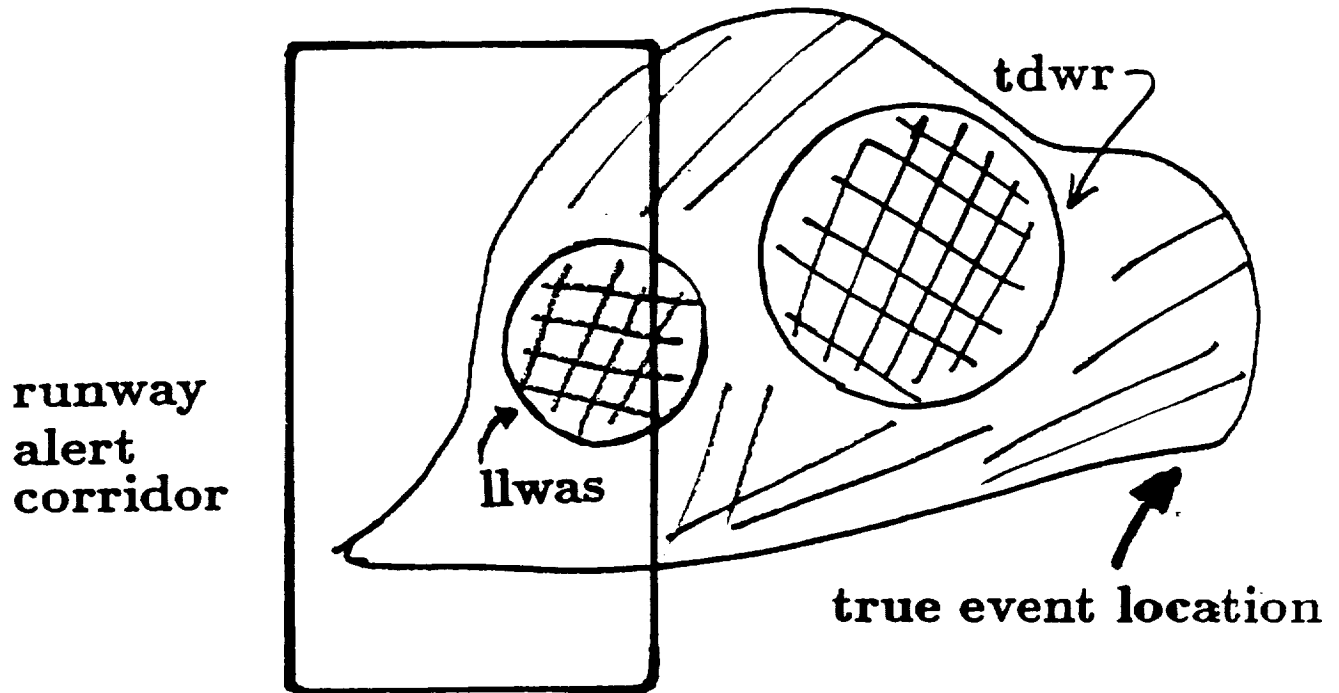
CORRECT DETECTION ??

MISSED DETECTION ??

*** BOTTOM LINE ***

CORRECT RUNWAY ALERT

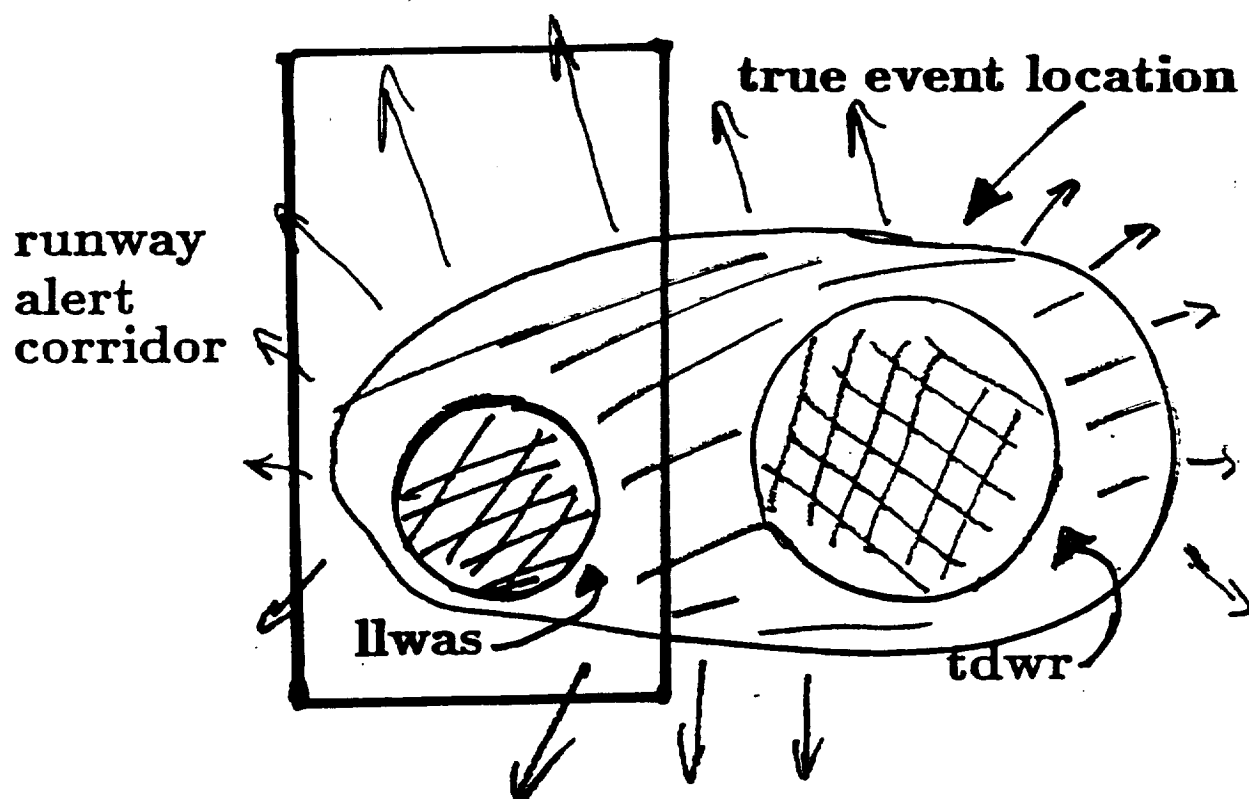# MOTIVATION FOR INTEGRATION
(continued)

3. Runway Component Estimates

o Again, pilots need to know what to expect along their flight path.

o However, TDWR and LLWAS make assumptions as to what the runway shear truly is . . . .
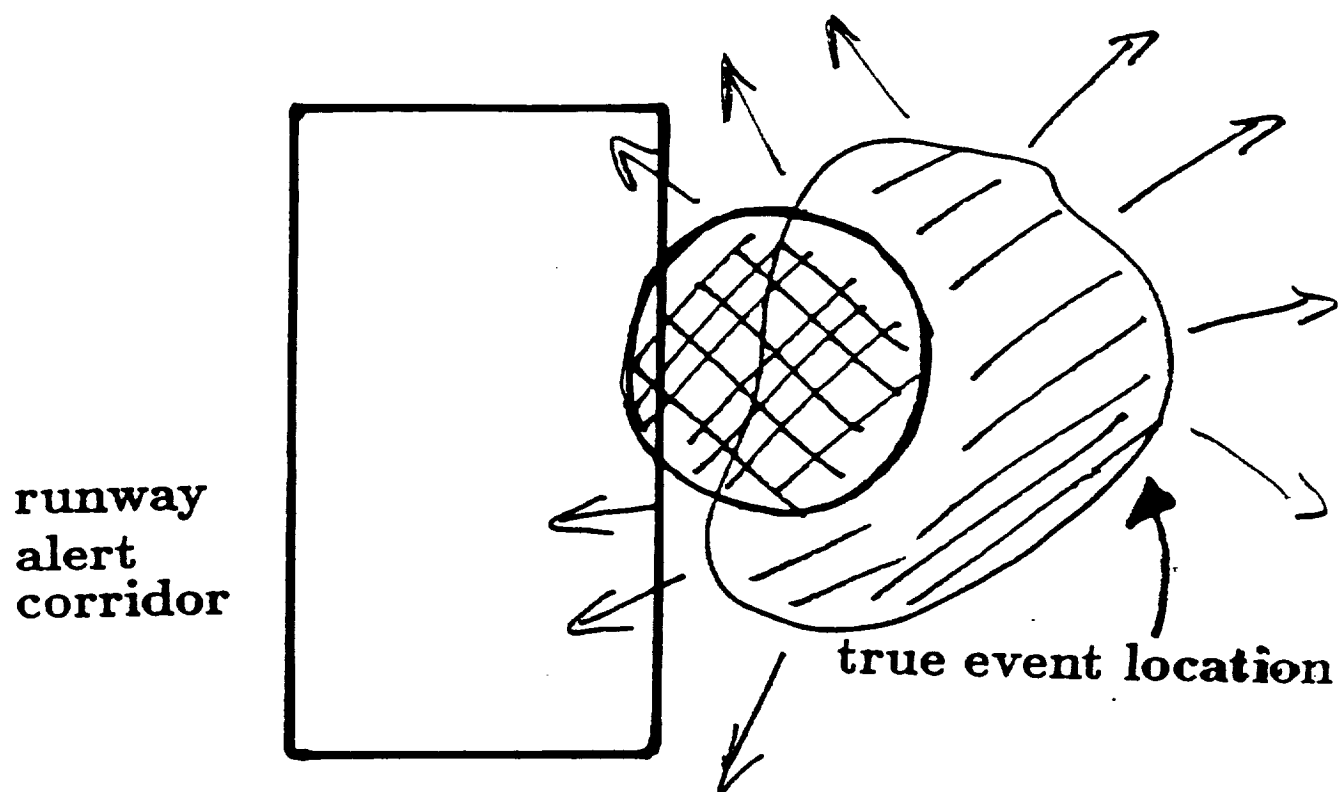
MOTIVATION FOR INTEGRATION
(continued)

O Problems for TDWR can arise in cases of asymmetry, low-reflectivity, rapidly changing event magnitude, and "grazing impact" to runway corridor.

EVENT ASYMMETRY

true event location

runway
alert
corridor

llwas

tdwr

INTEGRATION CAN GIVE
FULL PROTECTION

"GRAZING IMPACT"

runway
alert
corridor

true event location

VIA INTEGRATION,

ONE SYSTEM COULD BE USED

TO "VALIDATE" THE OTHER.

MOTIVATION FOR INTEGRATION
(continued)

0 Problems for LLWAS include: undersampling of wind due to low spatial resolution, underestimates caused by sheltering and/or lack of vertical resolution, and overestimates due to noisy winds.

**However, both systems compliment each other quite well: the strengths of one can often negate the weaknesses of the other.

MOTIVATION FOR INTEGRATION
(continued)

Other Factors:

0 Winter vs. Summer

-- Hazardous wind shear conditions can occur in non-convective weather. TDWR may be unable to detect these events due to lack of reflectors, while LLWAS can.

0 Detection of strong convergence in microburst outflow region. LLWAS can detect these (often very hazardous) situations.

OVERVIEW OF GENERIC INTEGRATION CONCEPTS

0   Exploit Strengths of Stand-Alone Systems

0   Limit Impact of Weaknesses of
    Stand-Alone Systems

0   User-End Products (Graphic and Alphanumeric)
    Should Be Transparent as to Source

OVERVIEW OF GENERIC INTEGRATION CONCEPTS
(continued)

Three Possible Techniques:

1. Alphanumeric-Level
   o Generate consensus of runway alerts by taking "worst case" alphanumeric alerts from stand-alones.

2. Data-Level, "Bottom-Up"
   o Synthesize raw data to then generate end-products.

3. Product-Level, "Top-Down"
   o Utilize intermediate products to generate end-products. "Expert-system".

Description of TDWR/LLWAS Integration Algorithm

o Product-level Technique

o Two basic windshear warning components

  * Windshear-with-loss (MB's, etc)

  * Windshear-with-gain (G.F.'s, etc)

o Generates graphical and alphanumeric displays

Description of TDWR/LLWAS Integration Algorithm (continued)

O <u>Wind Shear-with-Loss:</u>

* Implemented Technique for Generating Microburst Shapes from LLWAS

* To eliminate LLWAS false alarms, a technique for "validating" weaker (15-20 kt) LLWAS microburst detections was implemented using additional meteorological information available from the TDWR system.

* "Union" of TDWR and "Validated" LLWAS Microburst Shapes

Description of TDWR/LLWAS Integration Algorithm
(continued)

o <u>Wind Shear-with-Gain</u>:

   * LLWAS runway-oriented-gain computations used within LLWAS network

   * TDWR gust front used outside LLWAS network

Description of TDWR/LLWAS Integration Algorithm
(continued)

FUTURE (?):

0 Use LLWAS information to address TDWR microburst (spatial and temporal) "overwarning" problem.

0 Modifications to wind shear-with-gain technique with advanced TDWR gust front algorithm.

COMPARISON AND CONTRAST OF
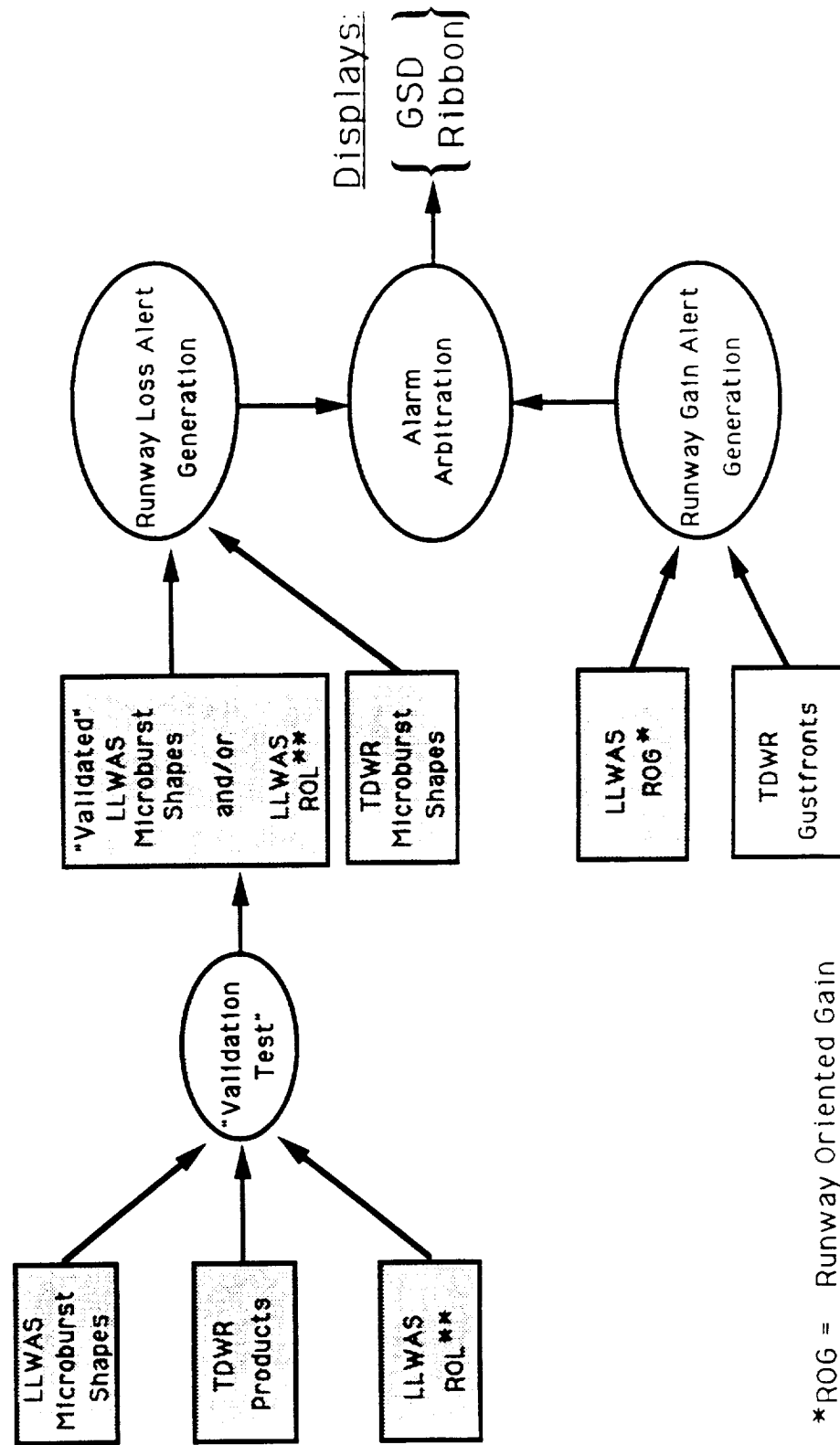## TDWR AND LLWAS DATA & PRODUCTS

Category	TDWR	LLWAS
* Spacial Resolution	High	Low
* Temporal Resolution	Low	High
* Velocity Data Measurements	Radial2-D	
* Reflectivity Information	Yes	No
* Above-Surface Information	Yes	No
* Areal Coverage	Large	Small
* Potential for Microburst Prediction	Yes	No

INTEGRATION ALGORITHM STRUCTURE

FULL SYSTEM
1990

Displays:
{ GSD
  Ribbon }

Runway Loss Alert Generation

Alarm Arbitration

Runway Gain Alert Generation

"Validated" LLWAS Microburst Shapes and/or LLWAS ROL **

TDWR Microburst Shapes

LLWAS ROG *

TDWR Gustfronts

"Validation Test"

LLWAS Microburst Shapes

TDWR Products

LLWAS ROL **

*ROG = Runway Oriented Gain
**ROL = Runway Oriented Loss

Connection to Airborne Wind Shear Systems

o   Data link ground based alarms to aircraft.

o   Must integrate in some form.

o   "Product-level" integration scheme could be applied.

o   NCAR and NASA will begin working on this problem in 1991.

BOTTOM LINE

o With more than one system, we must integrate.

o Integration's "value-added" qualities are very important.

o TDWR/LLWAS integration works very well based on 1989 and 1990 operational demonstrations.

Integration of the TDWR and LLWAS Wind Shear Detection System
Questions and Answers

Q: WALT OVEREND (Delta Airlines) - Are LLWAS sensors located high enough, that is, out of ground effect, to be really sensing the relevant air mass or the prevailing air mass as it effects the runway?

A: LARRY CORNMAN (NCAR) - In a sense there are two parts to that question. One is the sheltering effects and the other is the accuracy of measurements that are that close to the ground relative to what a pilot would see along the glide slope. The first part of the question in terms of the accuracy of measurements form poor locations is something the FAA has dealt with and is part of some of the upgrades to the six stations, certainly the enhance LLWAS system. Sheltering effects are taken care of by either raising the sensors or moving them. The second part of the problem is very difficult. You can only raise the pole so high. The sensor close to the runway surface is probably a very good estimate of what the pilot would see. Out further from the runway, one, two, or three miles, it gets worse. Again, you're limited by the location and the size of the pole that the sensors are on.

Q: GREG HAEFFELE (Boeing) - If both systems alert on the same microburst, but at different intensities, which takes precedence? If detected by both systems, does the "bandaid" size increase to encompass both areas?

A: LARRY CORNMAN (NCAR) - Basically, it's independent. LLWAS and TDWR both produce bandaids independently. The technique for issuing an alert is based on the technique that was developed for TDWR, that is, a bandaid intersecting a runway gives a magnitude and location . If you add more shapes you add extent and potentially larger magnitude. The idea is to pick the largest magnitude in the first potential event encountered.

Q: PAUL ROBINSON (Lockheed) - Complaints from pilots on wind shear reporting have been largely due to too much information. For example, wind speed and direction at different points on the airfield. Is this information from the LLWAS? If not, what information is communicated from ATC to the pilot concerning wind shear on the approach from LLWAS? If so, can the information be compressed into a more manageable form?

A: LARRY CORNMAN (NCAR) - Basically, that's been done. In phase III the alerts are runway specific, and that was part of the TDWR / LLWAS user group work that went into simplifying that data and make it more precise so each runway would have a specific alert.

Q: HERB SCHLICKENMAIER (FAA) - In one of your charts, you showed the product-level integration tests in '90. In it, you used TDWR precipitation to validate LLWAS information. Could the ASR-9 precipitation product be introduced in lieu of the TDWR?

A: LARRY CORNMAN (NCAR) - The product level integration technique that I put together doesn't care what the source is. So, in fact, right now with the wind shear detection program going on with ASR-9 the product output from that system would look identical to the TDWR output. Not only could the precipitation product be used in a similar fashion but the detection of events with a bandaid in a sense would fall through.

Session V. TDWR Data Link / Display

A Status Report on the TDWR Efforts in the Denver Area
Wayne Sand, National Center for Atmospheric Research

A Status Report on the TDWR Efforts in the Denver Area

by

Wayne Sand
Research Applications Program
National Center for Atmospheric
Research

for

17 October 1990
NASA Langley Research Center
Third Combined Manufacturers and
Technologists Airborne Wind
Shear Review Meeting

# A Status Report on the TDWR Efforts in the Denver Area

by

Wayne Sand
National Center for Atmospheric Research*
Research Applications Program

Abstract

A prototype radar developed by Raytheon as part of the NEXRAD program is currently being operated in Denver, Colorado, by the National Center for Atmospheric Research (NCAR). The Federal Aviation Administration has contracted NCAR to use output from the radar to duplicate the wind shear detection capabilitiy of a a Terminal Doppler Weather Radar (TDWR) in an effort to continue development of TDWR algorithms and to protect Stapleton Airport. NCAR's efforts as they relate to the ground-based wind shear detection program will be summarized. The presentation will include a discussion relating in-flight microburst encounters to the severity of the events as detected by the TDWR system. Controllers' and pilots' perceptions of the system, overall detection and false alarm statistics from the system, and microburst alarm threshold logic will be discussed.
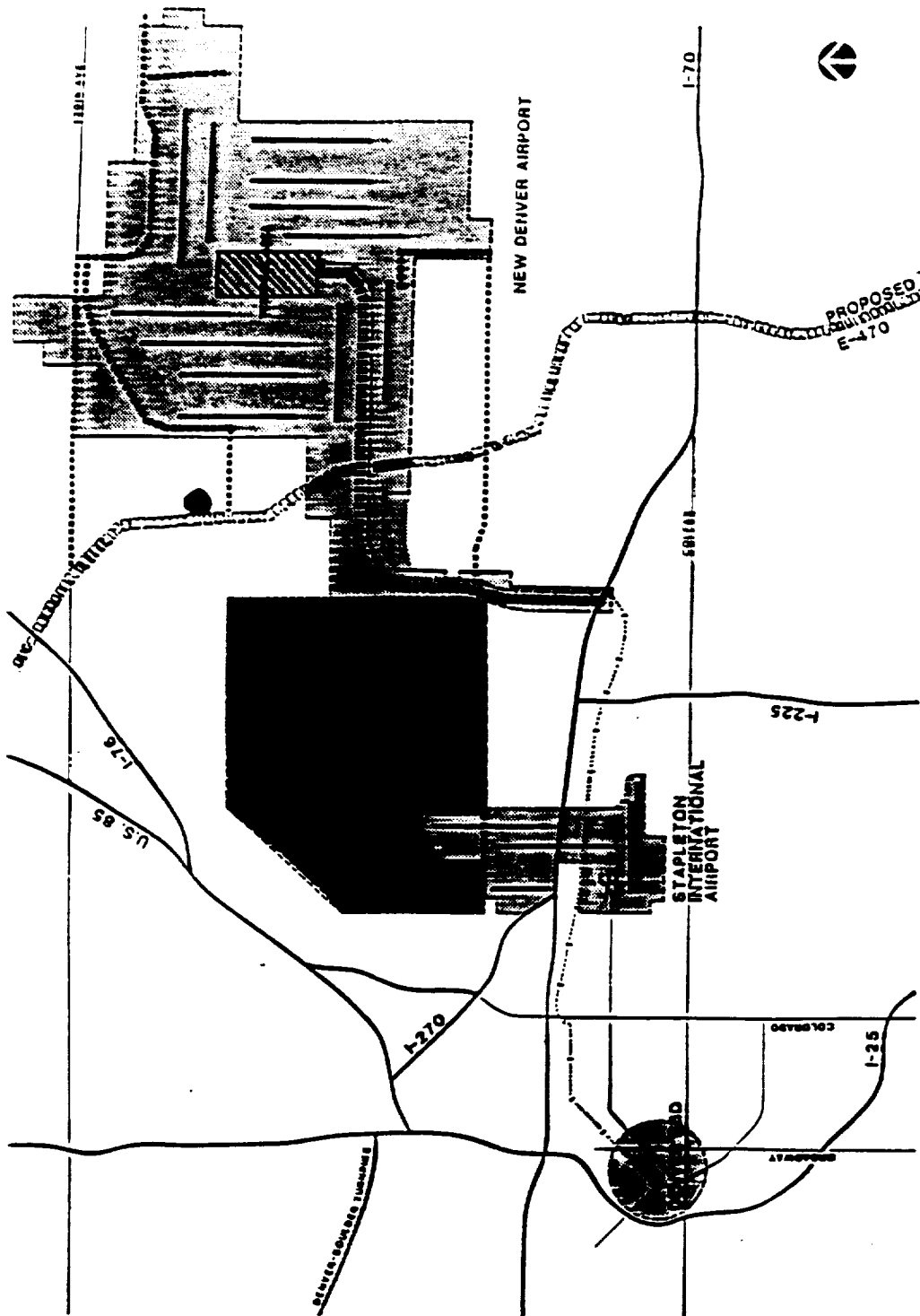
NEW DENVER AIRPORT VICINITY PLAN
JUNE 1988.

302

Denver Terminal Doppler Weather Radar (TDWR)
Geographical Setting

New
Denver
Airport

LONGMONT
ARTCC/CWSU

56 Kb

RAP TDWR
OPS CENTER

MILE HIGH
RADAR

T1

~40 km

BOULDER

~10 km

56 Kb

~17 km

FUTURE
NEXRAD
SITE

Stapleton

Denver
Metro
Area

Height of MHR.5° beam over
Stapleton is 140 m (450 ft)

Edge of
Foothills

303
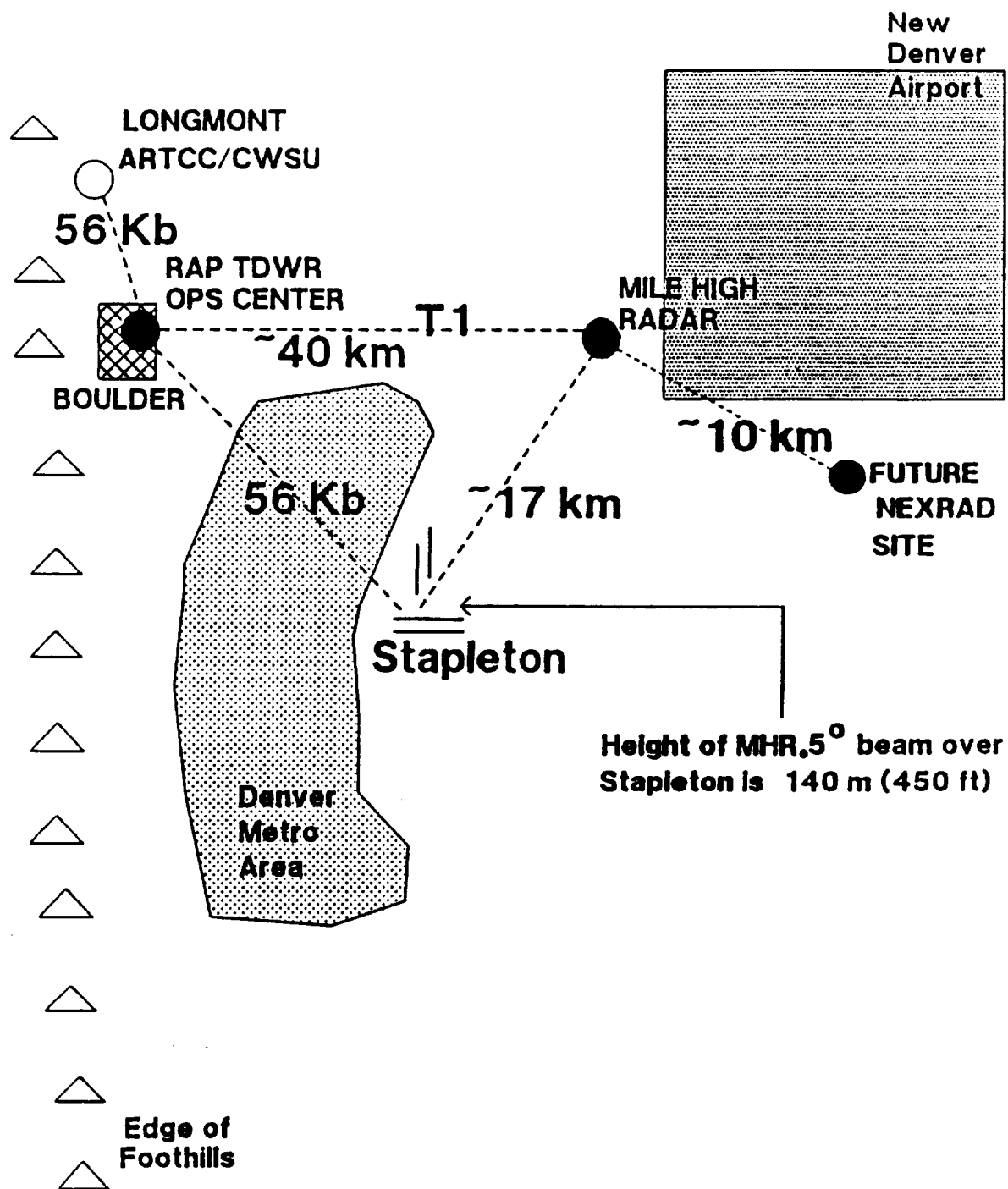
Project Summary
1990 Denver TDWR
Program

Shakedown Period: 1-31 May

Operational Period: 1 June-7 Sept

Products Delivered:

* TDWR/LLWAS Integrated Alarms
* Gust front Detection and Prediction
* LLWAS Operational Winds
* Precipitation (Reflectivity)
* Storm Motion
* Nowcast Product

Operational Summary:

* **Hardware Problems**
  Two days down due to
  Radar hardware failure,
  other minor problems due
  to hardware and software
* **Weather events within <u>5 nm</u>
  <u>of the Airport center</u>**
  > Microburst
    95 Events (30-70 Kts)
    17.6 Hours
    (50 affected the
    airport)
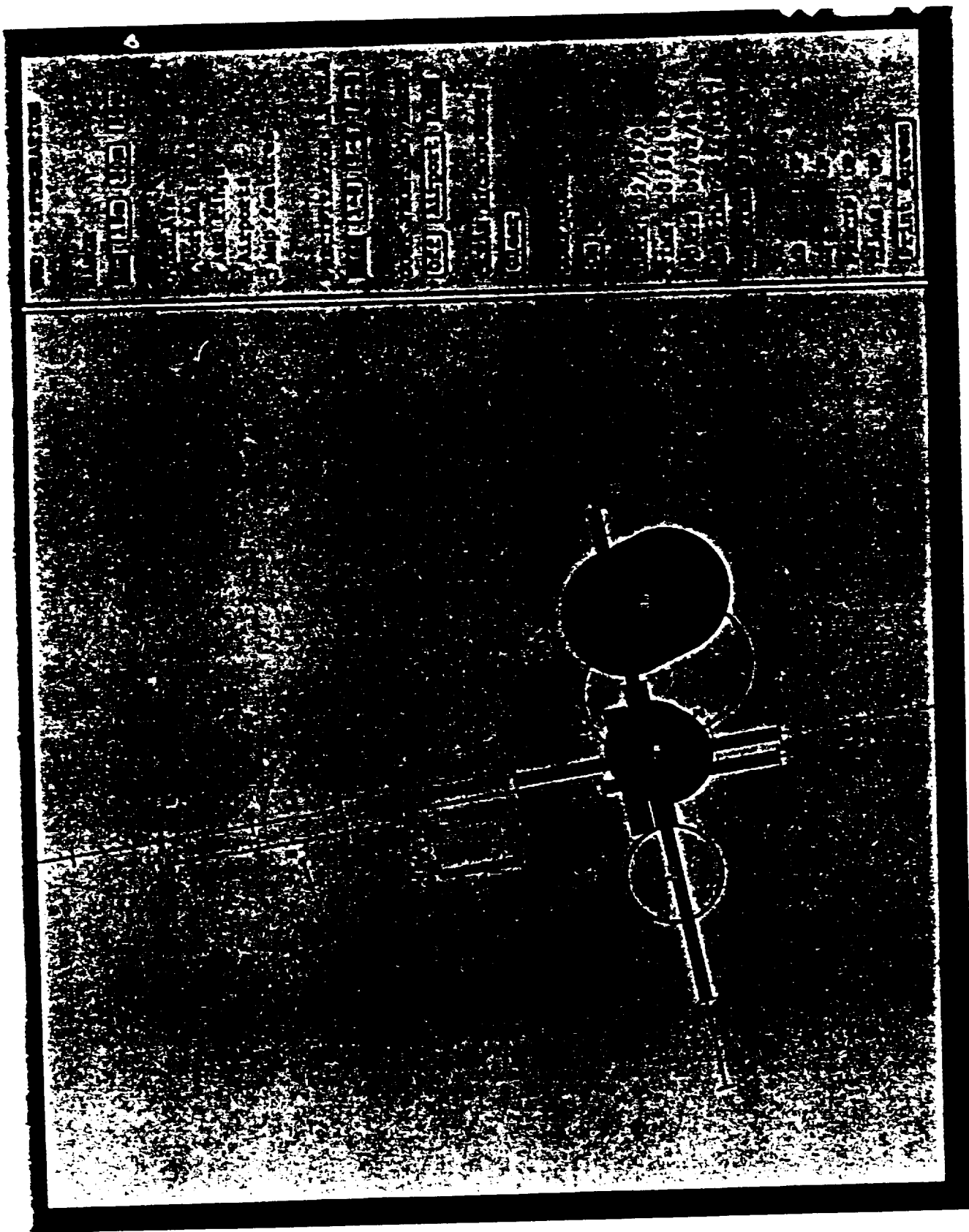 > Wind shear with loss
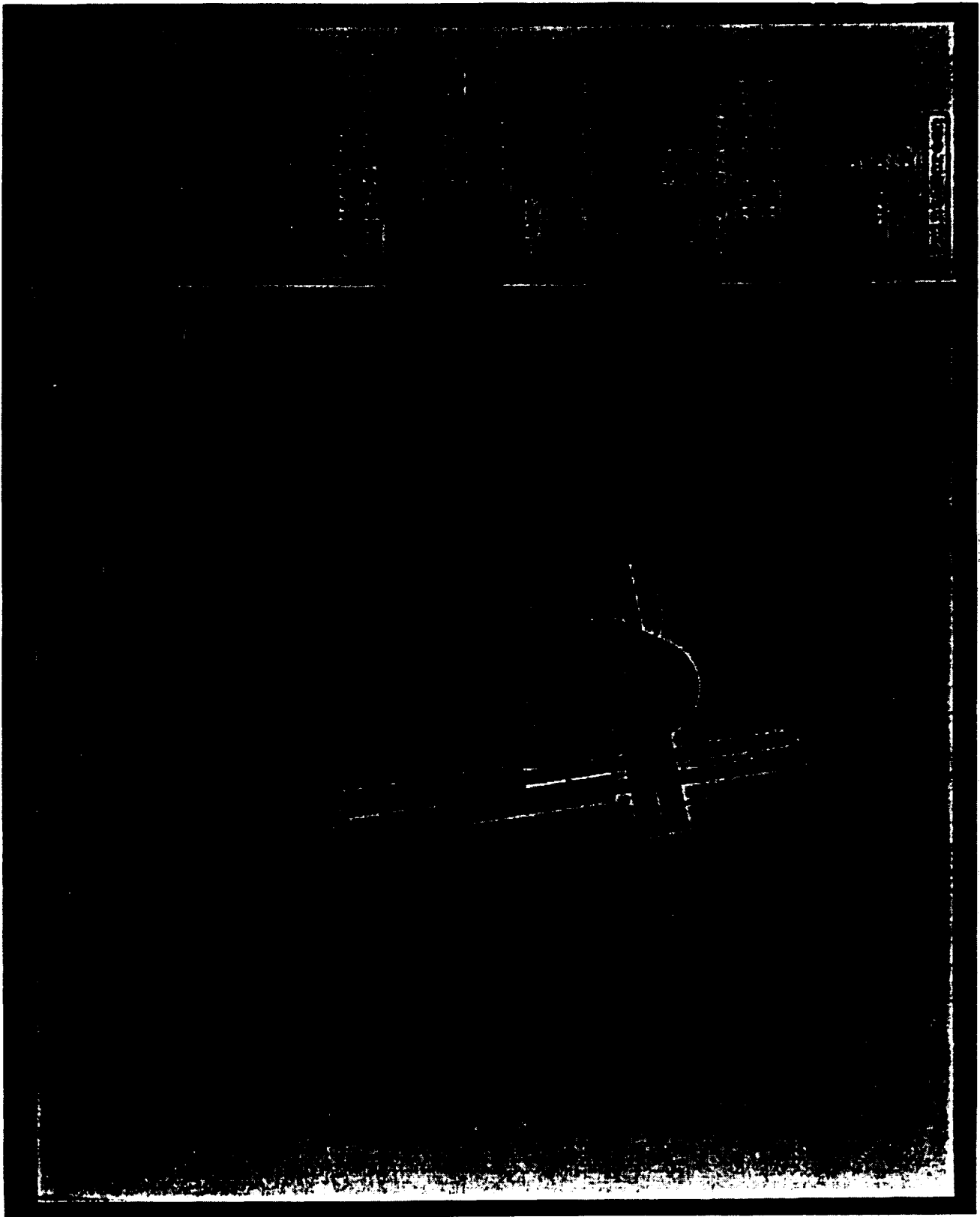   159 Events (15-30 kts)
  > Wind shear with gain
    65 Events (15-45 kts)

* Performance of the system, quick look
    > Greater than 90% POD
    > Less than 5% FAR

307

308

GSD - INTEGRATION

RANGE

5m 15m 30m 50m

Clear Microbursts

Overlays

Products

Configure Runways

NOWCAST: DOWN

DATE: 10/15/90
TIME: 14:48:14
PDATE: 07/01/90
MB TIME: 23:30:43
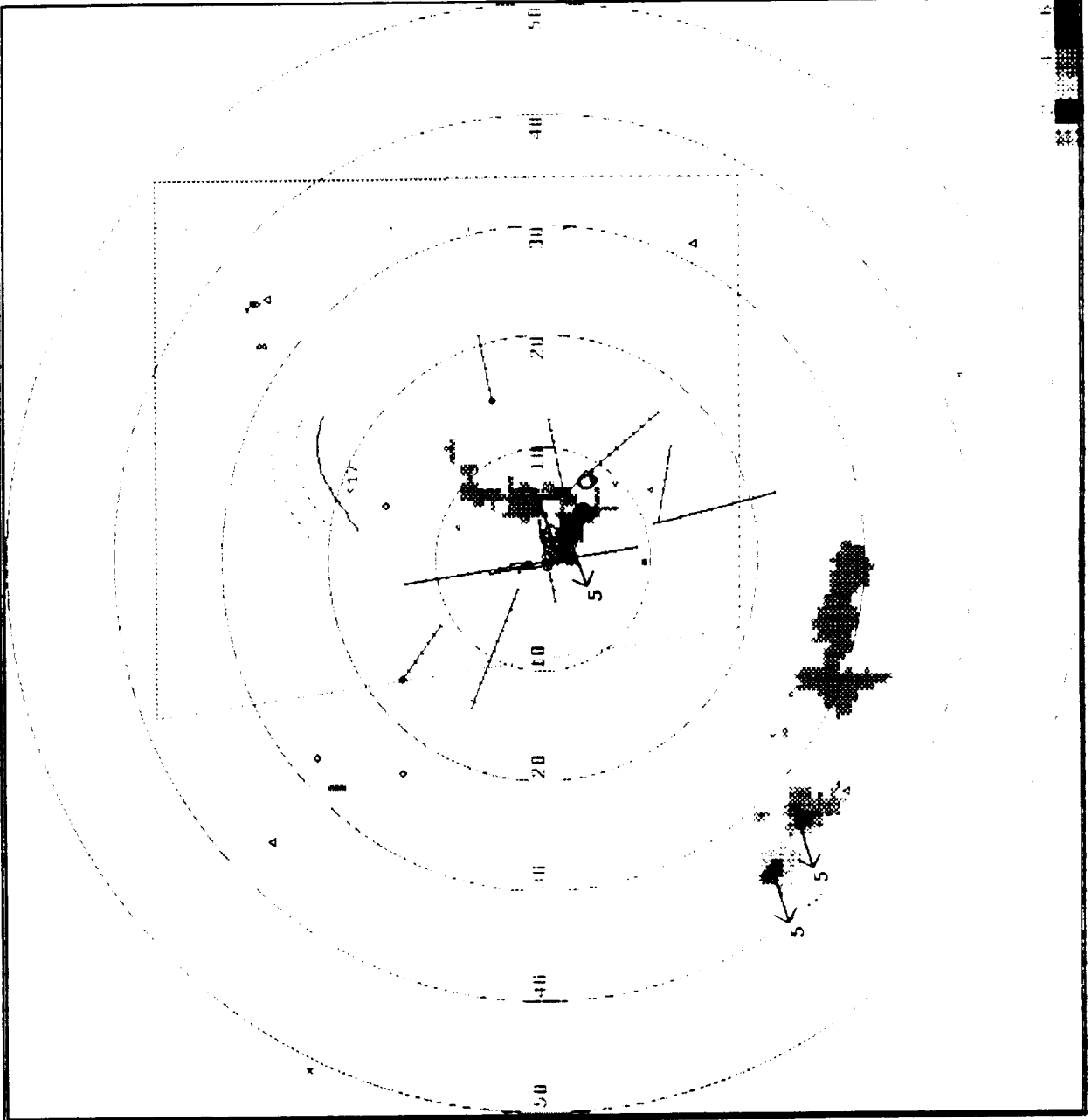GF TIME: 23:30:43

MB: UP
GF: UP
PRECIP: UP
LLWAS: UP
TAP: UP

Print Screen

1990 OPERATIONAL DEMONSTRATIONS

USER INTERFACE ASPECTS

NOTIFICATION OF 1990 OPERATIONAL DEMONSTRATIONS

- PRESEASON AIRLINE BRIEFING
- LETTER TO AIRMEN
- NOTAMS
- PILOT QUESTIONNAIRES
- NOTIFICATION ON ATIS
- ATC TRAINING SESSIONS

PILOT REACTIONS

- FEWER OPERATIONS DURING MBAs; HOWEVER SOME STILL OCCUR
- FEWER TAKEOFFS WITH 15 KT LOSS ALERTS
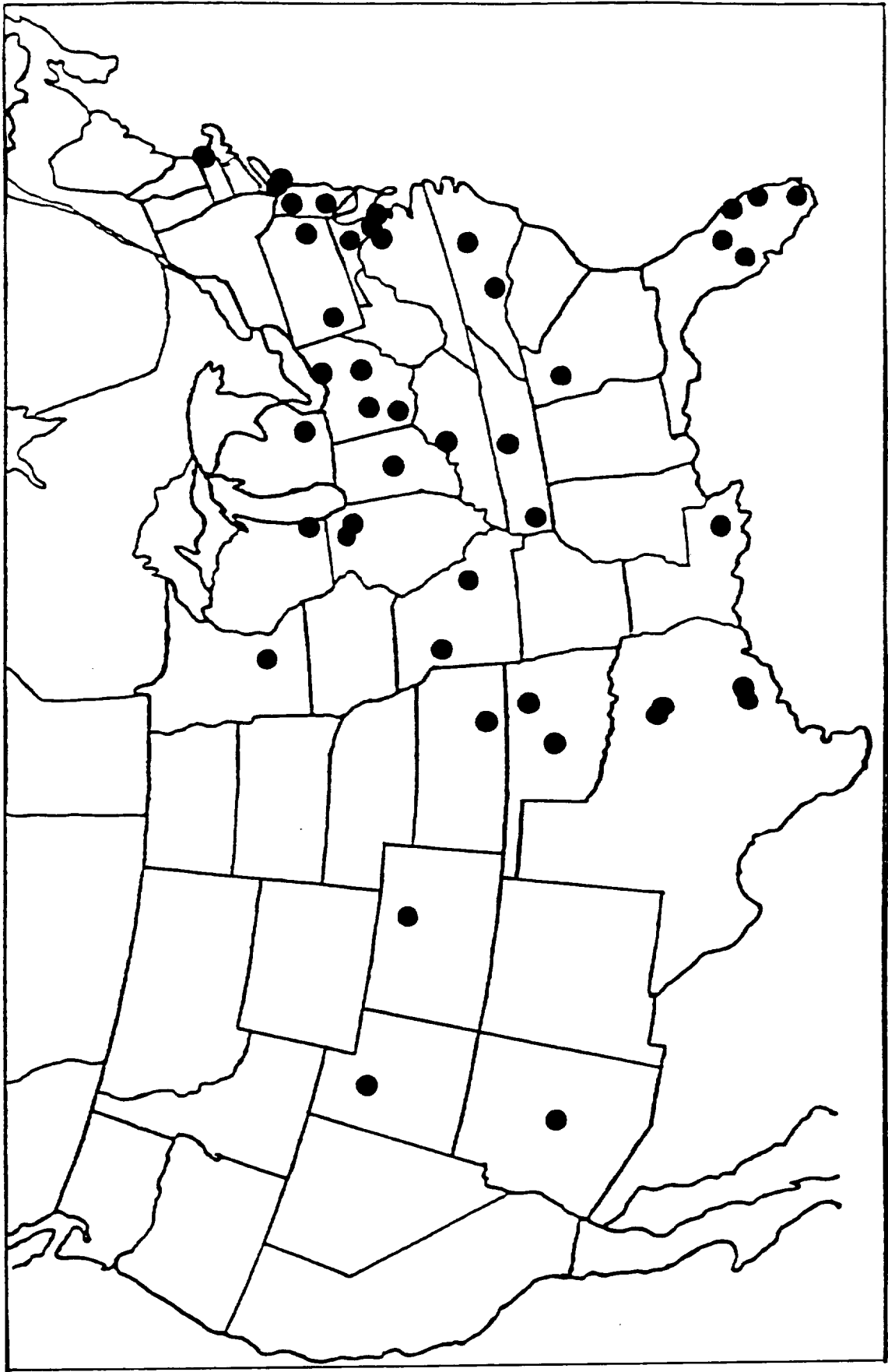
PILOT QUESTIONNAIRES

- PROVIDES PILOTS A MEANS TO COMMENT ON SYSTEM
- VERY SMALL PERCENTAGE RESPONSE
- PILOTS REPORT "SIGNIFICANT" WIND SHEAR ENCOUNTERS BEGINNING AT 10 KTS
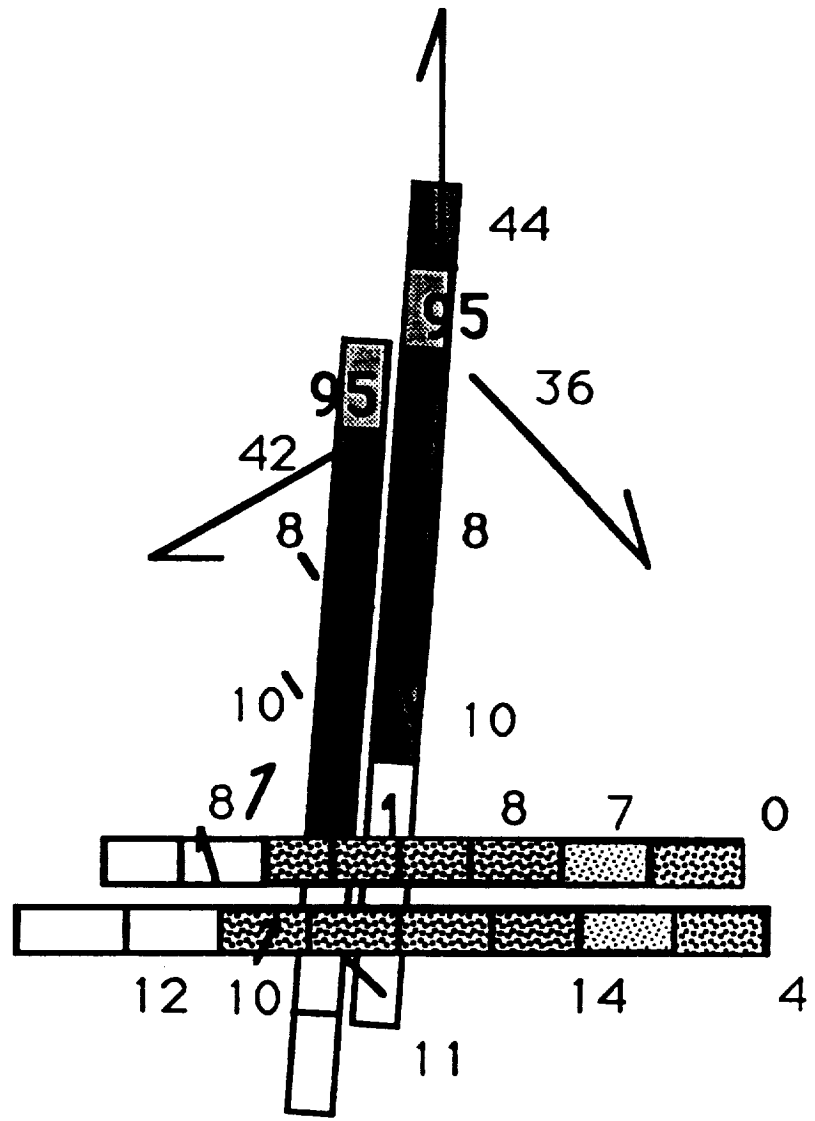
ANALYSIS EFFORTS TO REDUCE "NUISANCE" ALARMS

- 15 KT ALARMS
- MODIFICATIONS TO WIND SHEAR WARNING BOXES
- REDUCTION IN SIZE OF MB SHAPES

TDWR Sites

44

9 5

9 5

36

42
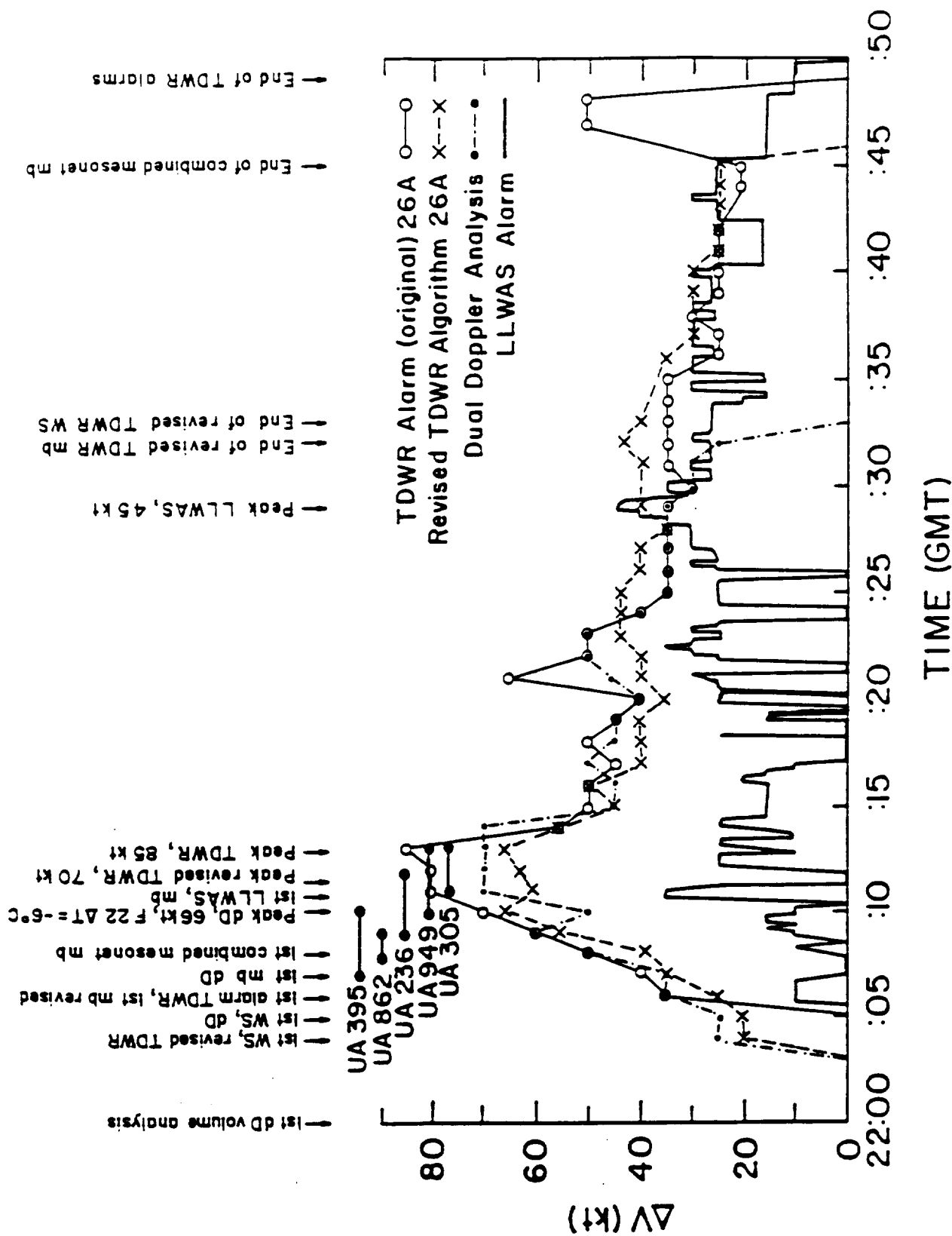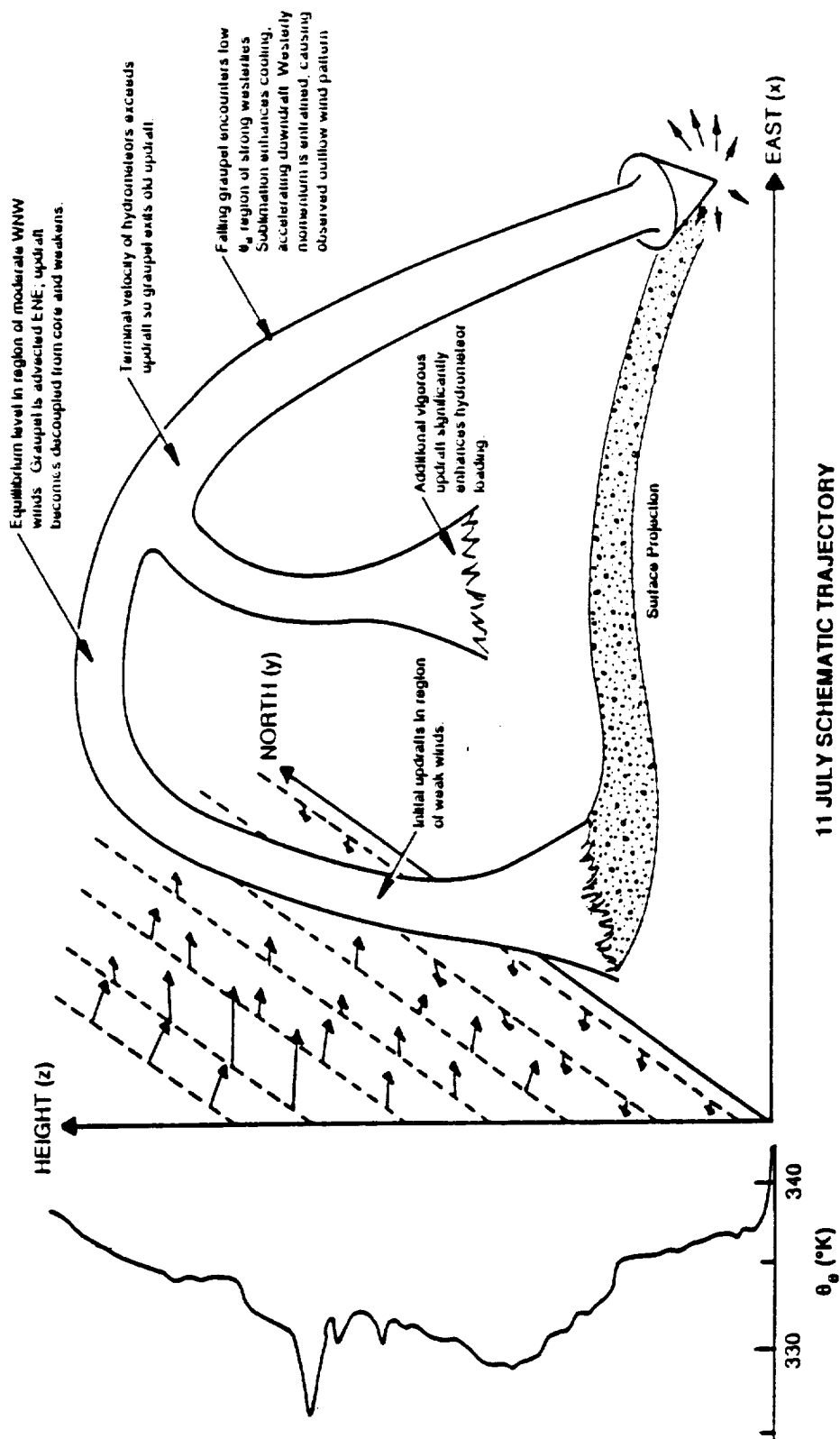
8

8

10

10

8

1

8

7

0

12

10

14

4

11

FIGURE 9. Events plotted against time for the 11 July 1988 microburst. A scale for wind shear difference in knots is indicated on the left. Data sources are indicated.

HEIGHT (z)

NORTH (y)

EAST (x)

θ_e (°K)

330   340

Equilibrium level in region of moderate WNW winds. Graupel is advected ENE; updraft becomes decoupled from core and weakens.

Terminal velocity of hydrometeors exceeds updraft so graupel exits old updraft.

Falling graupel encounters low θ_e region of strong westerlies. Sublimation enhances cooling, accelerating downdraft. Westerly momentum is entrained, causing observed outflow wind pattern.

Additional vigorous updraft significantly enhances hydrometeor loading.

Initial updrafts in region of weak winds.

Surface Projection

11 JULY SCHEMATIC TRAJECTORY

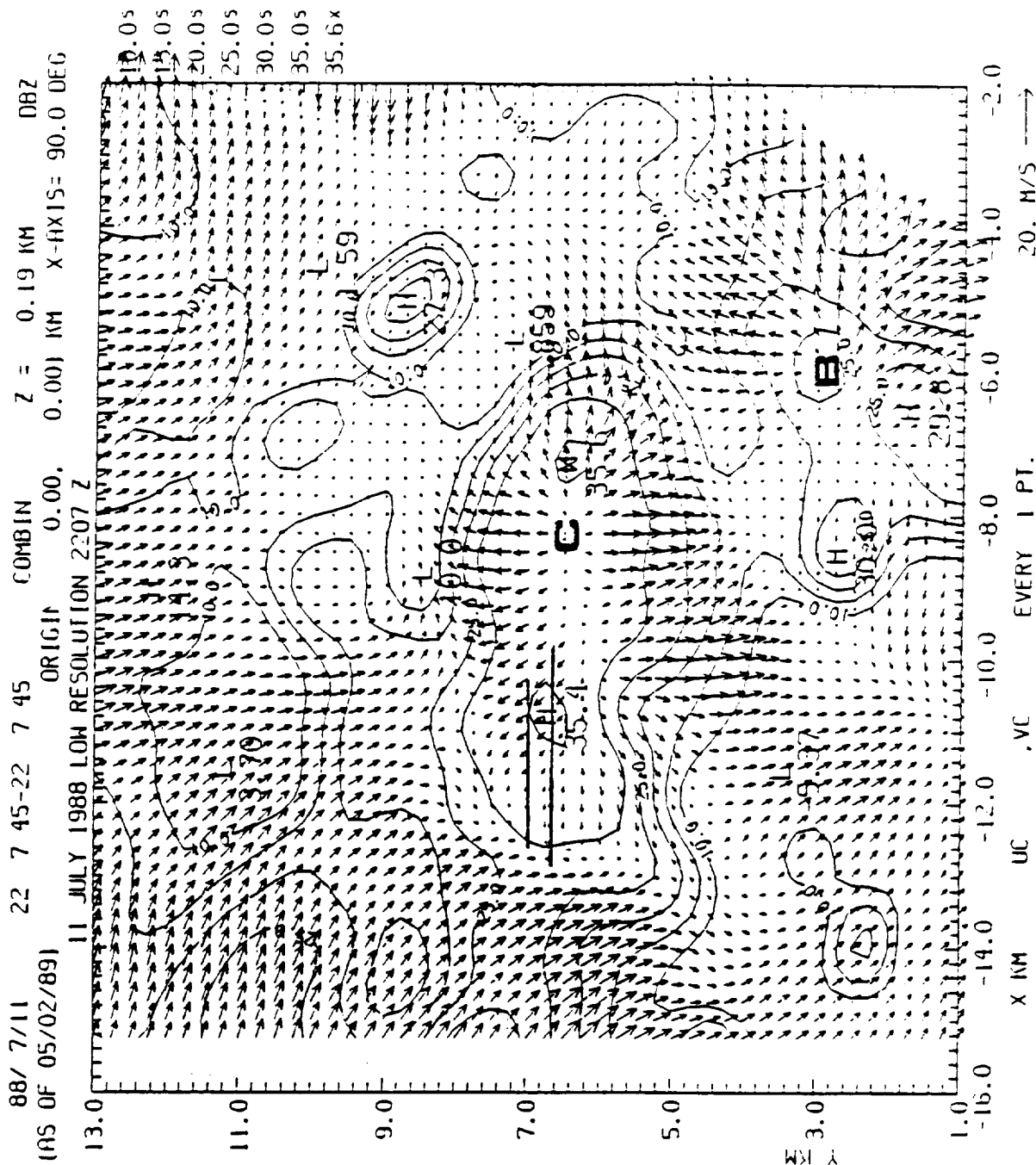FIGURE 17. A schematic diagram depicting the evolution of particle trajectories responsible for the 11 July microburst. The sounding to the left indicates θ_e with height near the time of the microburst. Three-dimensional wind structure aloft may be deduced by the wind vectors on the left-hand side of the figure immediately left of the θ_e sounding.
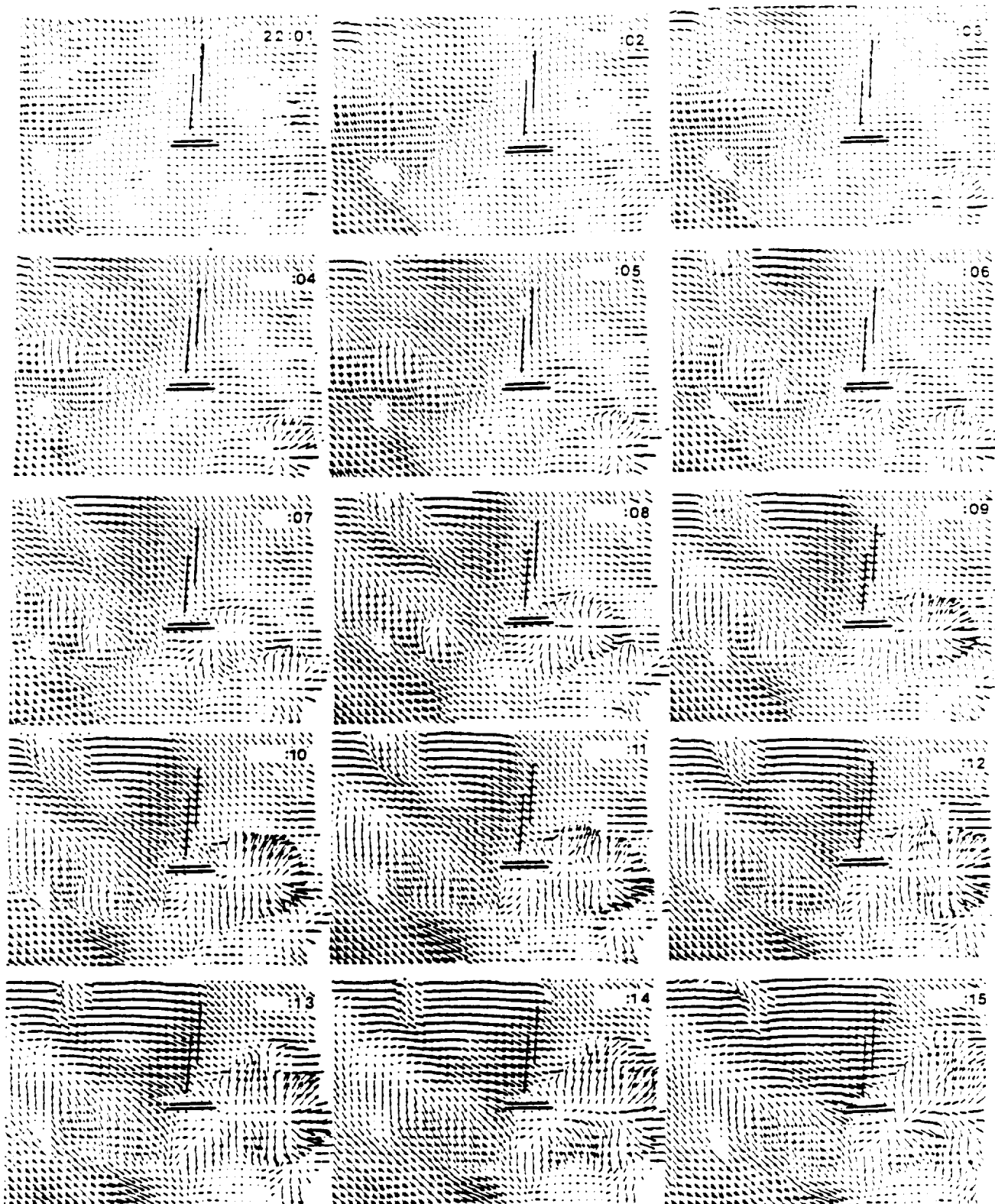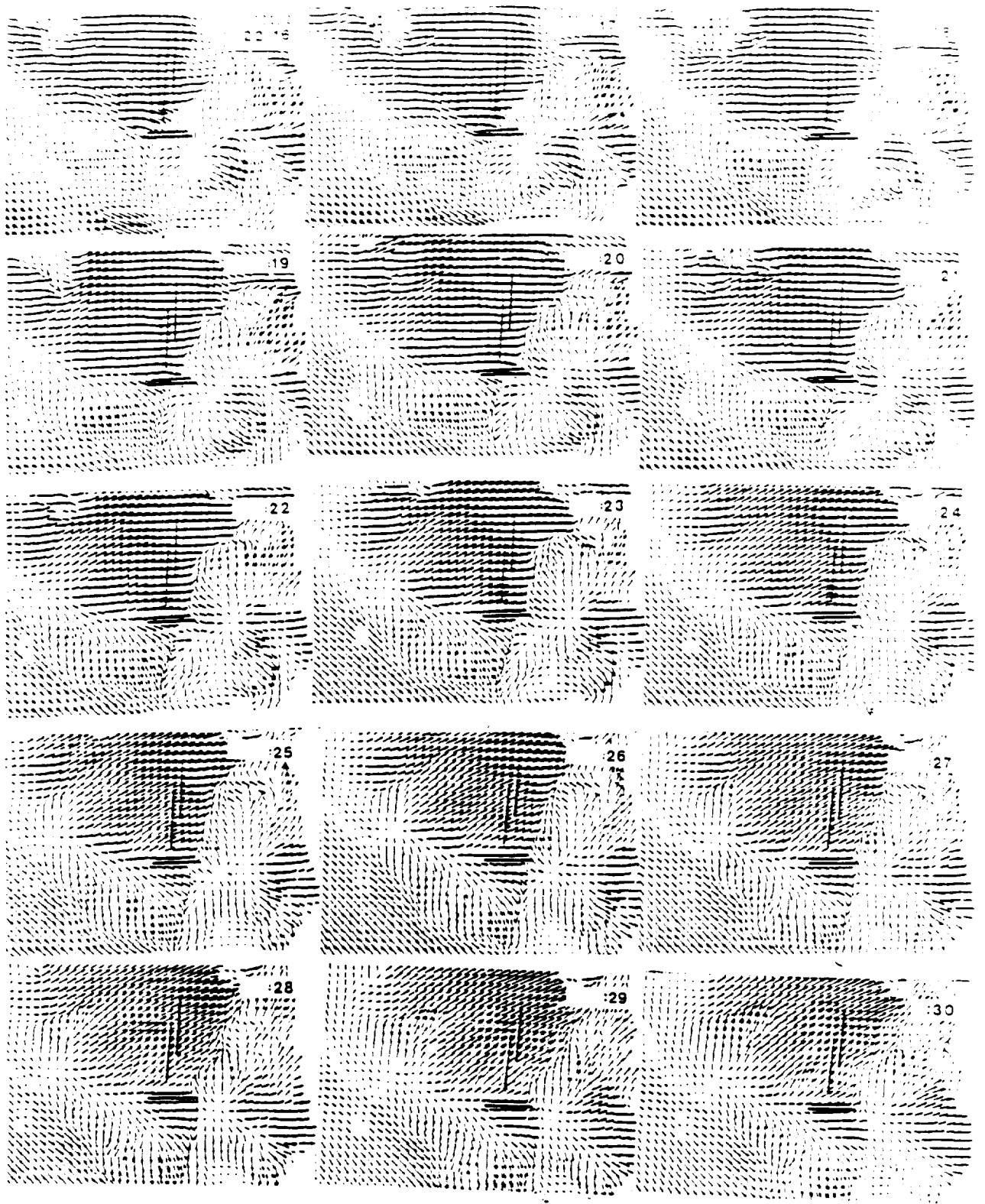
Dual Doppler Velocities
Reflectivity

Dual Doppler Velocities
Vertical Motion

318

f - factor

319

Dual Doppler Velocities
Reflectivity

320
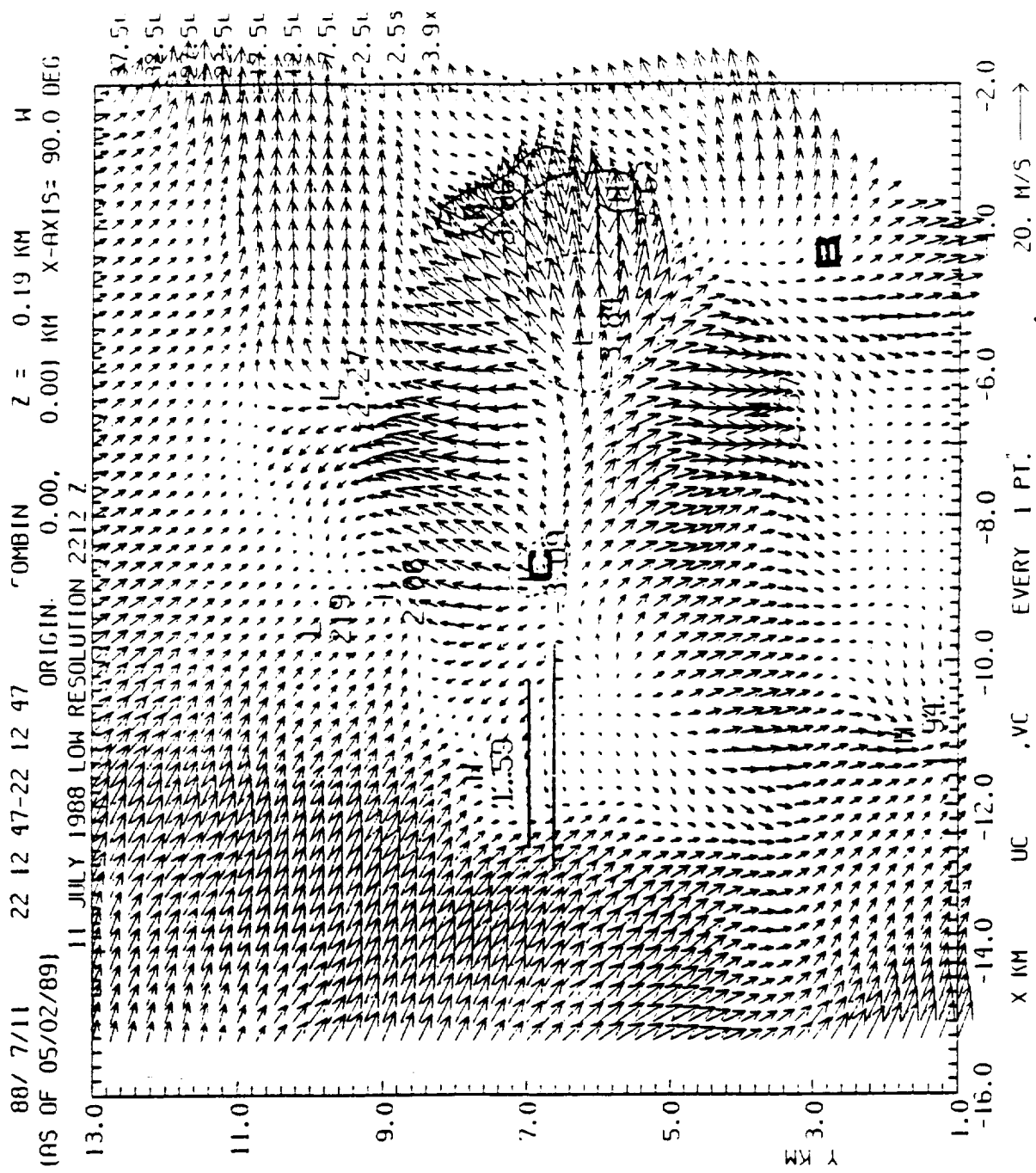
Dual Doppler Velocities
Vectors / Motions

321

322
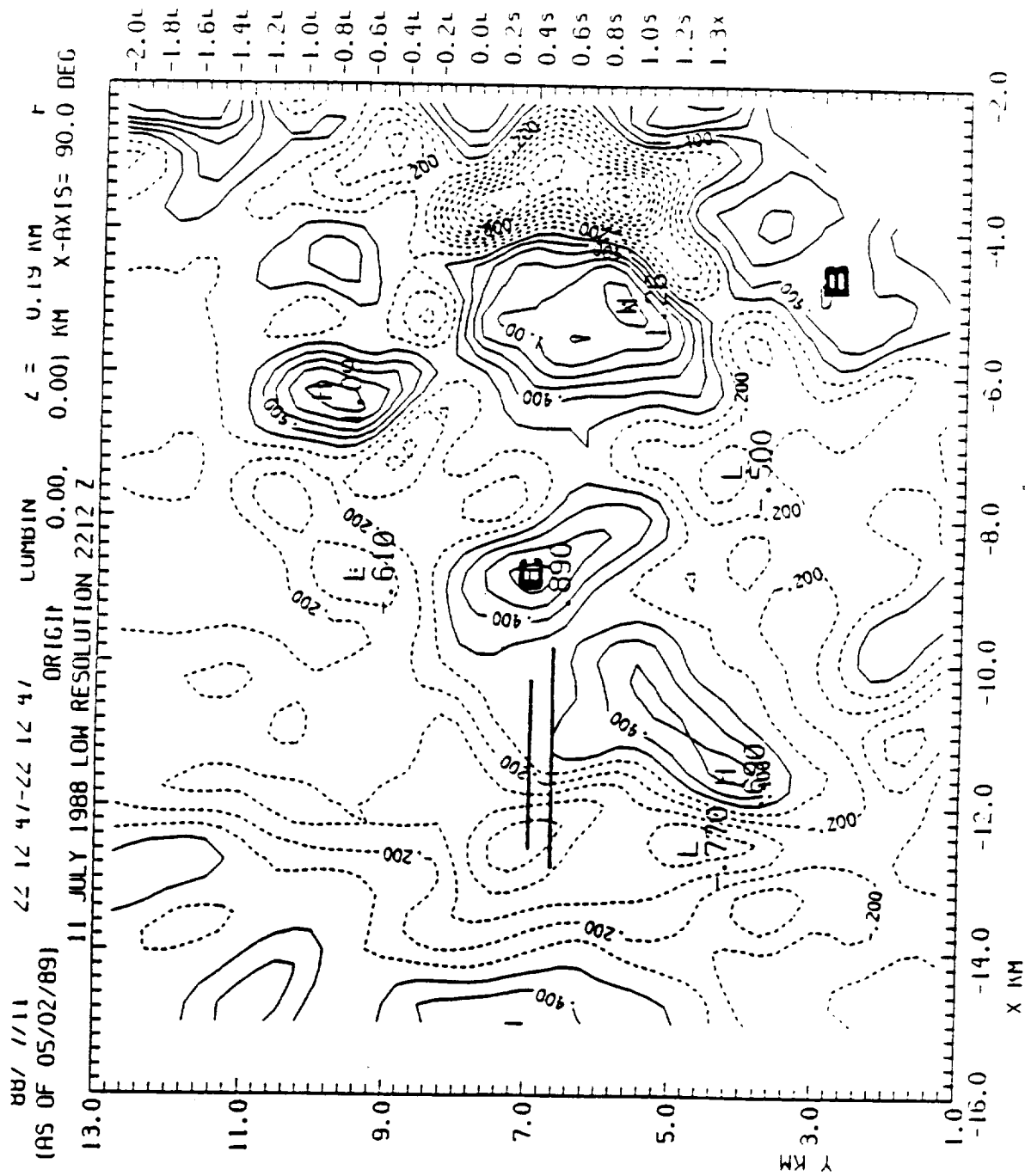
Summary, 89 and 90 Activities at Denver:

1. Continued development and improvement of TDWR/LLWAS Integration

2. Demonstrated Terminal NEXRAD concept in 1989, program canceled

3. Considerable Interaction with other groups for a better understanding of the July 11, 1988 Microburst Case
   > Numerous papers in the literature
   > See DOT/FAA/DS-89/19

4. Reasonably good agreement of f-factor calculations from Radar with those derived from Aircraft

5. Continued development of Nowcasting and Convective Initiation
> **Primary users at Center and TRACON**
> **Prefer Convective Initiation and Storm Motion Vectors**

6. Continued development of Tornado Detection and Forecasting

7. Continued examination of User Interface issues

> Threshold for warnings (15 Kts)
> Size of warning areas (Alarm boxes and alarm shapes)
> Perceived over warning
> Terminology

8. Reliable operations during 1990

9. System performance statistics more than acceptable

10. Runway Extension LLWAS is providing good coverage farther from the threshold

11. Enhanced understanding of the relationships between ground based and airborne systems expected during the 1991 tests with the NASA Aircraft flying in the Denver area

The 11 July 1988 Microburst at
Stapleton International Airport, Denver, Colorado

K. L. Elmore, M. K. Politovich, and W. R. Sand
National Center for Atmospheric Research[1]
P. O. Box 3000
Boulder, Colorado 80307

I. Introduction

During the early afternoon of 11 July 1988, while the Terminal Doppler Weather Radar (TDWR) Operational Test and Evaluation (OT&E) was underway, thunderstorms formed over the mountains west of Denver, Colorado, and moved eastward over the plains. By 2130[2], several cells approached the Denver area. One of the more vigorous of these was located just northwest of Stapleton International Airport. It produced the most intense microburst - 35m s⁻¹ differential - investigated to date using dual-Doppler radar techniques.

The TDWR microburst alarm alerted air traffic controllers to the hazard from 2206–2248. During this time, 4 commercial passenger aircraft penetrated this microburst, fortunately without incident.

The microburst reached the ground several km southeast of the main precipitation shaft of the storm. This behavior differs from that of most microburst case studies reported previously (Fujita 1985). The evolution of the microburst will be examined in this study. Details not contained in this paper will be included in the poster session.

II. Data Sources

The primary data sets used in this study summary come from 2 Doppler radars operated as part of the TDWR OT&E. The Massachusetts Institute of Technology Lincoln Laboratory 10-cm wavelength Doppler radar (FL2) was used as the project test-bed instrument. The University of North Dakota (UND) 5-cm Doppler radar, located about 21 km north of FL2, also gathered data. Scanning patterns of the two radars were coordinated to enable dual-Doppler post-analysis over the airport area (see Fig. 1). Coordinated volume scans were completed every 2.5 min. The lowest effective elevation angle was 0.3° from both FL2 and UND, placing the beam centers approximately 190 m above the center of the airport. Over the airport, both beams were roughly 150 m in diameter.
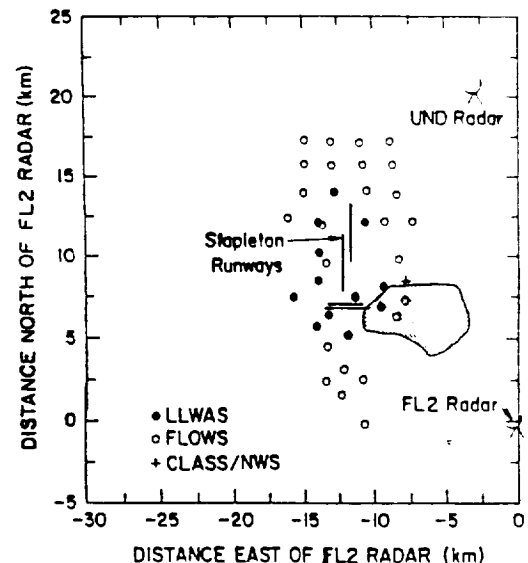
Figure Captions

FIGURE 1. *Locations of radars, surface mesonet stations and the CLASS launch site during the 1988 TDWR OT&E at Stapleton International Airport, Denver, Colorado. The airport runways are also shown. The microburst outline (divergence > 10 m s⁻¹ over a distance ≤ 4 km) near the surface at 2212 is superimposed.*

Surface and upper air thermodynamic and wind measurements were also used in this study. The FAA-Lincoln Laboratory Operational Weather Studies (FLOWS) mesonet (Wolfson et al. 1987), consisting of 22 stations, was in place in and around the airport area. This was supplemented by the 12-station Low Level Wind Alert System (LLWAS), which measured winds near the airport runways. A Cross-chain Loran Sounding System (CLASS) launch site was located at the Denver National Weather Service Office adjacent to Stapleton Airport.

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III. Meteorological Conditions

The major synoptic scale weather feature on 11 July 1988 was a slowly-eastward-moving shallow trough over the western United States. This feature was barely discernable at 70 kPa and vanished above that level. Winds were generally westerly and were less than 10 m s^{-1} at all levels over Colorado, Wyoming and Utah. This westerly flow advected moisture into the Denver area, which increased in a deep layer extending from just above the surface to over 12 km[3]. A maximum of 1.05 cm of total precipitable water was measured by the National Oceanic and Atmospheric Administration's 6-channel microwave radiometer at Stapleton Airport between 2200 and 2230.

Prior to the storm, conditions near the surface were typical of those accompanying microbursts observed in the Intermountain West (Caracena and Flueck 1987). The temperature-dewpoint spread at the surface was 20 - 25°C, with a nearly dry adiabatic temperature lapse rate from the surface to 4.8 km. Above that, a layer of moist air was present. There was marginal moist convective instability, with a Lifted Index of −2.

Equivalent potential temperature (θ_e) is plotted against height in Fig. 2 for 2 CLASS soundings preceding the storm. Above the moist layer, the atmosphere is quite dry and θ_e decreases. At 7.2 km, a sharp absolute minimum θ_e of 326 K is present in the 2004 sounding, and a relative minimum exists between 4.8 and 5.0 km. The minimum θ_e occurs at the level of a 2 °C temperature inversion, the base of which has a temperature of - 20°C. Although saturated parcels originating between 7.4 km and around 4.8 km are potentially cold and will accelerate downward, the coldest parcels will originate around 7.3 km and just below 5 km.

Three basic flow regimes exist: light and variable winds from the surface up to 5 km, westerly winds between 5 and 7 km, and northwesterly winds above 7 km.

IV. Analysis

a. Dual-Doppler Analysis Techniques

The CEDRIC analysis package (Mohr et al. 1986) is used for three-dimensional wind field synthesis and analysis. Fourteen volumes were analysed, from 2148 through 2220. The analysis has 400 m horizontal and 500 m vertical grid spacing. The domain extends from 1.8 -10.8 km (0.19 - 9.19 km AGL) vertically, and 2 - 30 km west, 1 - 23 km north of FL2 horizontally. Stapleton Airport is roughly centered in this grid; the microburst impacted on the southeast edge of the airport, well-centered in the analysis domain (see Fig. 1).

Raw input Doppler velocities were corrected for a deduced storm motion of 10 m s^{-1} from 270°; resulting analyses shows ground-relative winds.
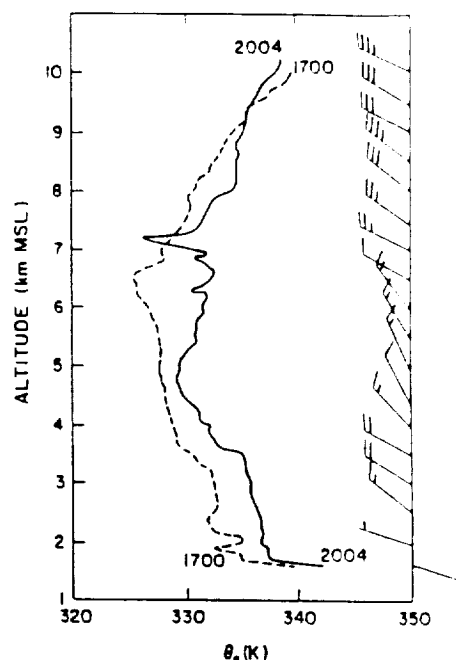

FIGURE 2. Equivalent potential temperature (θ_e) and horizontal winds at 0.5 km resolution plotted against height from the 1700 and 2004 UTC CLASS soundings.

A one-pass Cressman objective analysis scheme was used (Cressman 1959) to map radial velocity components from spherical coordinates to gridded Cartesian space. Before a consistent w component was calculated, the horizontal winds were filtered with 5 passes of a two-dimensional, three-point smoother (Shuman 1955). The resulting analyses have 2 km horizontal spatial resolution at the half-amplitude points.

b. Microburst evolution

The microburst-producing complex originated from two 60+ dBZ$_e$ cells which formed around 2130 over the mountains 34 km west of Stapleton. These cells grew and moved southeastward.

By 2147, a line of convergence aloft was observed near 6.6 km, oriented northwest-southeast and moving to the southeast. Reflectivity at that level increased just west of Stapleton Airport at 2155, and shortly afterwards FL2 detected large-scale cyclonic shear at 4.6 km over the airport. Surface winds during this time were north-northeasterly across the airport with temperatures of 31-32°C across the FLOWS mesonet. The air was fairly dry with 22-25% relative humidity (RH).

As the storm approached Stapleton Airport, the highest radar reflectivity within the storm was above 9.5 km and slightly greater than 40 dBZ$_e$.

[3] All heights are MSL.

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At 2158, 3 reflectivity cores can be identified within the analysis domain, shown in Fig 3a. Core A is the westernmost core extending to the surface. Cores B and C are contained in the comma-shaped region well aloft and southeast of core A (both cores are contained in an area of greater than 33 dBZ$_e$). Core C was associated with the strongest updraft in the analysis domain, 21 m s^{-1}, and was responsible for the strongest microburst. The perspective used for these figures somewhat obscures core C at this time.

A plume of hydrometeors forms a "bridge" of reflectivity which extends downwind (winds near the radar-detected storm top are from the northwest) from the 3 cores. The updrafts within the cores appear to have penetrated into the layer of northwesterly winds above 7 km, carrying the hydrometeors to the southeast.

Although no direct measurements of the hydrometeors are available for this storm, previous studies in northeastern Colorado thunderstorms (e.g., Dye et al. 1974)
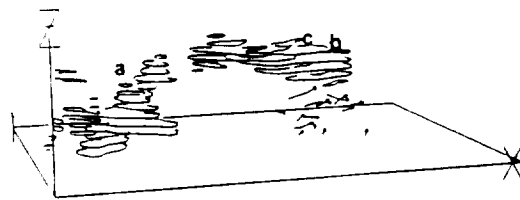

FIGURE 3A. Three-dimensional reflectivity perspective views of the microburst-producing storm of 11 July 1988. The viewer is looking toward the northeast and is located 40 km west and 78 km south of FL2 and is 19.2 km MSL. The 33 dBZ$_e$ is contoured at every 0.5 km AGL. Arrows depict air parcel trajectories during the 2.5 min the volume analysis represents. Analysis time is centered at 2158 UTC.

FIGURE 3B. Same as Fig. 3a, but for 2202 UTC.

FIGURE 3C. Same as Fig. 3a, but for 2212 UTC.

suggest that they were likely graupel. The lifted condensation level from the 2004 sounding has a temperature of -0.5 °C, and the temperature at the echo top level is around -20 °C, both typical of clouds in the area in which ice phase precipitation processes are dominant.

Core A descended to the surface first, well west of the airport area, and represents the main precipitation area of the storm. It produced a weak, large-scale outflow.

By 2202 cores B and C had also extended downward to the surface (see Fig. 3b). Core B produced a small outflow region to the southeast of Stapleton Airport, which was first evident as a 10 m s^{-1} wind speed differential in the dual-Doppler analysis at 2203.

By 2205, the reflectivity bridge, shown in Fig. 3b, filled in and descended. Most of it appears to have emanated from core C. The surface outflow from core C first appeared at 2205. In 7 min, by 2212, it had reached its maximum strength of 32 m s^{-1}. By this time the outflow from core B is no longer evident.

The FLOWS mesonet station closest to the core C microburst exhibited a temperature drop of 6°C (29 to 23°C), a windspeed increase from 7 to 15 m s^{-1}, and a RH increase from 24 to 43% between 2209 and 2210.

The main microburst maintained a wind speed differential above the TDWR microburst criterion (at least 15 m s^{-1} over a distance of 4 km or less) until 2241, according to dual Doppler analysis. By 2254 the differential had decreased to less than 10 m s^{-1}, the criterion for TDWR wind shear regions. Elmore and McCarthy (1989) report an average lifetime for microbursts in the Denver area of 13 to 14 min, with a standard deviation of 7.5 min. This microburst lasted 36 min.

As the storm collapsed and dissipated, the surface outflow became quite complex. A gust front, which had been slowly approaching from the northwest, began to interact with the microburst outflow. Several additional less-intense downdrafts merged with the original main microburst, creating a large, complicated multiple-microburst outflow region.

The highest reflectivities descended to the lowest levels of the storm, unlike earlier analyses where they were generally well aloft. Core C remains identifiable through the last dual-Doppler analysis time centered at 2220:47.

Temperatures continued to decrease slowly throughout the FLOWS mesonet as the storm outflow covered the area. The storm complex eventually developed into a weak line and moved southeast.

c. Air Parcel Trajectory Analysis

The history of the microburst was investigated more thoroughly by computing air parcel trajectories backward in time, starting at the time of the most intense outflow. The CEDRIC analysis software used in the analyses subtracts the fall speeds of hydrometeors from the calculated w values, estimated using the observed radar reflectivities. This approximates the vertical motions of air parcels.

Parcels within the main microburst at 2212, at an altitude of 2.2 km (400 m AGL), were tracked to the beginning of the analysis period, 2148.

Three-dimensional perspective views of resultant trajectory ribbons are shown in Fig. 4. Each trajectory terminus is labelled with a vertical bar, and a short dash indicates where each of those bars intersects the surface. The bars then continue downward until they reach 0 km. Trajectory ribbons are illustrated such that rotation along the path is indicated by twisting of the ribbon. Many more trajectories than those displayed were examined, but these are representative of most parcels within the microburst.
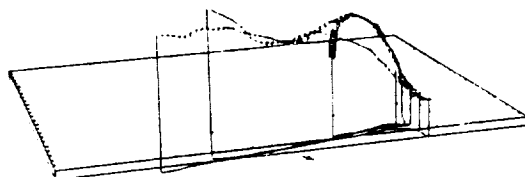

FIGURE 4. *Air parcel trajectories obtained from dual-Doppler analysis. The trajectories are shown in three dimensions with projections on a horizontal plane indicated. Each tick mark along a trajectory ribbon indicates 30 s of travel.*

Air within the microburst at 2212 originates well aloft and to the west of the surface outflow. All air parcel trajectories remain confined to a narrow east-west corridor between about 5 and 7 km. Early in the analysis period, there are 2 groups of trajectories: those at midlevels well west of the airport and those that are slowly ascending further to the east. These groups merge between 2158 and 2200 at a height of 5 to 7 km, where they intersect the developing reflectivity region. By 2202, the air parcel trajectories are clearly within the region of reflectivity greater than 33 dBZ, and have begun to descend, as shown in Fig. 3b. After this time, the region of high reflectivity rapidly descends and the downdraft accelerates until it impacts the surface between 2210 and 2212, creating the microburst.

Other trajectories (not shown) indicated that none of the parcels within the main microburst originated above 6.25 km, or above the minimum θ_e level. Further trajectory analyses, initiated from the first radar volume and calculated forward in time, showed that air parcels originating above about 7.2 km did not tend to descend. In general, it is likely that no actual air parcels originating above the minimum θ_e level descended to the surface during this microburst. Yet, it is quite clear that the hydrometeors did come from above 7.2 km.

The region responsible for most of the cooling and downdraft acceleration is the broad area of low θ_e located between 5 and 7 km. It appears that the hydrometeors were carried ahead of the region of active convection and into this area of low θ_e, where rapid sublimation and evaporation cooled the air within a narrow vertical layer, intensified the downdraft and created the strong, long-lasting microburst at the surface. Visual observations confirmed that the microburst appeared to have descended from aloft and southeast of the main part of the storm, rather than through the most intense precipitation region.

V. Concluding Remarks

Figure 5 shows a simplified schematic evolution of the main microburst, combining the information gained by following the trajectories of hydrometeors and of air parcels, as discussed in the previous section.

Hydrometeors formed and were carried upward in several strong convective updrafts that existed in a region where environmental winds were generally light. The hydrometeors continued to grow until they became too heavy to be supported by the updrafts and began slowly falling. Strong northwesterly winds near the top of the updraft carried the hydrometeor plume southeast of the active convection. Thus, as they descended, the hydrometeors were carried beyond the main precipitation area of the storm into a level of low θ_e air. Liquid water evaporated and frozen hydrometeors sublimated within a relatively shallow layer, causing the air to become negatively buoyant, whereupon the cooling air accelerated rapidly downward to produce a microburst at the surface.

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FIGURE 5. A schematic diagram depicting the evolution of particle trajectories responsible for the 11 July The sounding to the left shows θ_e near the time of the microburst. Three-dimensional winds aloft are displayed a the figure.

Controller and Pilot Decision Making
in Transmitting and Receiving Microburst Wind Shear Alerts
from an Advanced Terminal Wind Shear Detection System

By

John McCarthy and Wayne Sand
National Center for Atmospheric Research (NCAR)[1]
Boulder, Colorado 80307
USA

ABSTRACT

Approximately 650 air carrier passenger fatalities caused by low-altitude wind shear have occurred in the United States over the past fifteen (15) years. The most common form of lethal wind shear is the microburst, a strong downdraft and horizontal outflow that occurs near the earth's surface.

During the past decade, a sophisticated microburst detection and warning system has been developed using Doppler weather (wind-measuring) radar and an array of surface wind sensors either together or independently. This system is capable of measuring the headwind-to-tailwind change that a penetrating aircraft is likely to encounter, and it provides air traffic controllers with a simple hazard alert intended for relay to pilots in the immediate takeoff or approach-to-landing mode. The system is intended to induce an early avoidance decision on the part of the flight crew, thus avoiding a potentially catastrophic wind shear accident. The Federal Aviation Administration (FAA) will place this system at approximately 50 major U.S. airports that experience microburst wind shear on a relatively frequent basis.

Operational demonstrations of this detection and warning system in the summers of 1987, 1988 and 1989 at Stapleton International Airport, Denver, Colorado, provided substantial experience regarding air traffic controller and pilot use of this new system. This paper describes three severe microburst events ranging in total wind speed change from 35 to 95 knots, headwind-to-tailwind. Typical airline policy for flight crews receiving microburst alerts was clear: make an immediate avoidance decision.

Air traffic controller reaction varied from a mechanical recitation of the alert message imbedded in a routine clearance to land (normal procedure) to an urgent relay of a much stronger hazard message followed by a request of the pilot to "say intention," rather than saying "cleared to land." Pilot reactions varied from an immediate decision to avoid the hazardous event (thus totally missing the microburst) to a conscious decision to penetrate the microburst in spite of a clear acknowledgment of the alert.

Human factors related to the ergonomics of these situations are explored, as well as air traffic and flight standards policy issues.

1. INTRODUCTION

Microburst[2] wind shear accidents have been responsible for over 35 air carrier accidents in the United States since 1964, resulting in over 650 fatalities [1]. In the U.S., the most recent such accident was the crash of Delta Flight 191 at Dallas-Ft. Worth Airport in Texas on 2 August 1985, which resulted in the loss of 137 lives. On 3 September 1989, Cubana de Aviacion Flight 3046 crashed on takeoff from Havana, Cuba, with the loss of 115 passengers and crew and 24 persons on the ground. Evidence strongly suggested that the aircraft encountered a severe thunderstorm-induced microburst.

Since the mid-1980s, the FAA, in conjunction with several research organizations, including the National Center for Atmospheric Research (NCAR) and the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, has developed a wind shear detection and warning system that consists of two separate wind sensor systems. First developed in 1976, the Low-Level Windshear Alert System (LLWAS) recently has been upgraded to detect microbursts. This new version of LLWAS, capable of detecting microbursts, employs 11 to 16 anemometer and wind vane wind- measuring sites situated in the runway proximity to detect diverging wind features near the ground.

More recently, the FAA developed the Terminal Doppler Weather Radar (TDWR), which utilizes the wind-measuring capabilities of Doppler radar to detect microbursts in the airport terminal vicinity. Complete technical details of these systems can be found in the references [2,3].

During the summers of 1987, 1988 and 1989, LLWAS and TDWR were tested operationally at the Stapleton International Airport, Denver, Colorado. In 1989, the microburst detection capability of both systems was integrated in a prototype development phase to provide air traffic controllers and pilots with simple, unambiguous hazard alert messages. The TDWR system can detect microbursts with a high degree of accuracy and with a low false-alarm rate. Specifically, for microbursts having headwind/tailwind differences greater than 40 knots, the probability of detection[3] is 98%, while the false alarm rate[4] is 4%. When a

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[2]A microburst is an intense downdraft and associated outflow, located near the earth's surface, that produces strong headwind-to-tailwind changes for an aircraft which penetrates the phenomenon below 1,000 ft. AGL. It is typically situated within thunderstorms but can often occur in less intense convective storms, particularly in dry climates.

[3]The probability that a valid detection will be made by the system.

microburst detection is made, the system automatically generates a microburst alert and provides an alert message to a computer screen situated in front of the air traffic controller; the controller relays the alert to potentially affected flight crews in either the takeoff or landing mode. A typical approach-to-landing alert reads:

UNITED 226, MICROBURST ALERT, EIGHT ZERO (80) KNOT LOSS ONE MILE FINAL THRESHOLD WIND TWO ONE ZERO AT TWO TWO KNOTS

A typical takeoff alert reads:

AMERICAN 330, MICROBURST ALERT FOUR ZERO (40) KNOT LOSS ON THE RUNWAY DEPARTURE END WIND THREE THREE ZERO ONE TWO KNOTS

During the prototype operational tests of the system, air carriers developed company policy regarding flight crew use of these alerts. In most cases, flight crews were provided with flight safety bulletins that typically stated:

FLIGHT CREWS SHALL NOT CONDUCT AN APPROACH TO LANDING OR A TAKEOFF WHILE A MICROBURST ALERT IS IN EFFECT.

In addition, air traffic controllers were instructed to provide all flight crews with the alert message whenever an aircraft might be affected by the microburst. However, since inbound flights normally contacted the air traffic controller at or near the final approach fix, the microburst alert was most often issued in association with the landing clearance. On takeoff, the alert was typically issued at the time of takeoff clearance.

These two demonstrations were prototypical, and while air traffic controllers and pilots generally were aware of the operational capability and associated procedures of the system, it was a new, unique system. Consequently, permanent conclusions about air traffic controller and pilot use of this system are somewhat speculative.

In this paper, three microburst events in which valid microburst alerts were issued by air traffic controllers are examined for the purpose of identifying human factor aspects of these alerts. Conclusions and recommendations for possible actions are addressed at the end of the paper.

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[4]The probability that an alarm is false.

2. EXAMINATION OF THREE MICROBURST ALERT INCIDENTS

Three microburst incidents are described briefly, followed by a description of pertinent human factors elements:

<u>11 July 1988</u>

At approximately 1600 hours (all times are local daylight time), a microburst developed at 1-mile final to runways 26 Left and 26 Right. TDWR was the only operating system; in 1988 the LLWAS and TDWR systems were not yet integrated. The event initially was detected as a 35-knot loss; it then drifted east and intensified to an 80-knot loss at a 3-mile final. The Geographic Situation Display (GSD) for this event is shown in Fig. 1. The situation steadily intensified for approximately 8 minutes until it began to dissipate. Five air carrier jet transports were in various approach locations at the time, and they received a microburst alert outside the outer marker greater than 3 miles from the runway [4]. Figure 2 shows the vertical profile of four of these flights during their go-around sequence. The following is a sequential summary of each flight:

Flight 862 (B-737-200) made an immediate avoidance decision based on 40-knot loss microburst alert. The pilot stated that he did not want to make an approach when a microburst alert was in effect.

Flight 395 (B-737-200) was given a 40-knot loss microburst alert at a 1-mile final. The aircraft continued the approach to a missed approach, reaching its lowest point at 50 ft AGL approximately three-quarters of a mile short of the runway. This aircraft encountered the most severe wind shear.

Flight 236 (DC-8) was given a 50-knot microburst alert and continued the approach; it encountered severe headwind-tailwind fluctuations as seen in indicated airspeed. The flight crew executed a missed approach and descended to near 250 ft AGL.

Flight 949 (B-727) continued the approach but made an early missed approach after receiving a microburst alert of a 70-knot loss 3-mile final. The aircraft did not descend below approximately 500 ft AGL.

Flight 305 (B-727) received a microburst alert indicating an 80-knot loss 3-mile final. The crew elected to miss the approach just inside the outer marker.

The following are the pertinent facts associated with these air traffic controllers microburst alert messages:

The first two flights were handled by one air traffic controller. All alerts were given as appropriate, in the vicinity of the outer marker. In these two cases, the alerts were issued with a clearance to land.

The last three flights were handled by a second air traffic controller who relieved the first controller due to a watch change. The third aircraft in sequence (Flight 236) was issued an alert along with a clearance to land.

The fourth aircraft (Flight 949) was issued a microburst alert in the blind without a landing clearance. In this case, the automatic alert appeared on the controller's display, and the controller issued the alert to all aircraft monitoring the frequency, including Flight 949.

The controller issued the most severe microburst alert (80-knot loss) to Flight 305, followed by "say request" rather than "cleared to land."

There were no additional approaches following these first five aircraft; due to the microburst event, the traffic was diverted from the airport for 30 minutes until the weather improved.

8 July 1989

TDWR was not operational on this day. The Enhanced LLWAS system, utilizing 16 wind-measuring sites, protected Stapleton Airport. This system included additional sensors sited to protect the final approach corridors out to 3 miles from the end of the runway. At approximately 1720 hours, a microburst occurred at the north end of the airport on the approach end of runways 17 Left and Right; this event is illustrated in Fig. 3. The following describes the experience of Flight 531:

After being cleared for a visual approach, the captain heard three microburst alerts. The first one indicated a 60-knot loss on a 2-mile final. He continued the approach. Shortly thereafter, the captain heard a second alert, indicating a 95-knot loss 3-mile final. They initiated a missed approach at about a 3-mile final and did not actually experience the event until about a .5-mile final, when they lost 50 knots indicated airspeed and also lost 400 feet in altitude while experiencing moderate turbulence. The missed approach was initiated at approximately 600 ft AGL; the event was encountered at approximately 1,000

ft AGL with a subsequent loss of 400 ft.[5]

The air traffic controller/pilot interaction can be summarized as follows:

The air traffic controller first had an indication of microburst activity: a 35-knot
loss on a 2-mile final. When he delivered the alert to Flight 531, the captain
asked for substantiating pilots' reports from other aircraft operating these
runways. He queried an aircraft that had just landed on Runway 18 (located
about 1 mile west); the pilot indicated a 30-knot loss on that approach. This
report was heard by the captain of Flight 531 and apparently was used by
Flight 531 to consider a missed approach. The controller continued to
provide microburst reports to Flight 531 and following aircraft.

Approximately 15 aircraft did not land subsequent to the missed approach of
Flight 531. Most aircraft landed at Denver following a hold of approximately 20
minutes; one aircraft diverted to another airport located approximately 60 miles to the
south of Denver.

2 September 1989

On this day, a microburst was detected by the integrated TDWR/LLWAS
system at 1-mile final to Runways 26 Left and Right. The integrated TDWR/LLWAS
system issues consolidated alarms based on products from each independent
system. The following describes the flight sequence for two flights, 914 and 2235:

Flight 914, first in line for the approach, received a microburst alert, for 35-
knot loss 1-mile final. The captain elected to continue the approach. The
event reappeared on the controller's display as a 30-knot loss 1-mile final.
The crew continued the approach after a direct question from the air traffic
controller querying whether the flight wished to continue the approach. The
flight landed with major difficulty, experiencing a 5 g landing that caused
structural damage. The captain, upon exiting the active runway, confirmed the
microburst and further recommended closing of the runway due to unsafe
wind shear conditions.

Flight 2235 followed Flight 914, continued the approach but elected to execute
a missed approach on short final.

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[5]The captain stated in a post-incident debrief that the wind shear equipment was
very good and felt that in this event it probably saved his aircraft.

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The air traffic controller experience is summarized:

The identification of the microburst was clear, and all alerts were issued. The controller, in the case of the first aircraft, queried the flight crew regarding their landing intentions, confirming that they wished to land during a microburst alert.

3. ANALYSIS

Several analyses have been conducted for these three events, although only the first one (11 July 1988) has undergone extensive analysis [5]. NCAR participated in crew debriefings on the 11 July 1988 and the 8 July 1989 events. The following general analytical comments apply:

11 July 1988

1. The microburst was accurately detected and alerts were issued by two air traffic controllers. However, there was a significant difference in the imperative tone between the first and second controller; the second controller used a more definitive tone of voice.

2. The second controller, upon recognizing the urgency of the alert information, used his controller's discretionary function not to issue a clearance to land for the fourth aircraft (Flight 949). He went further for Flight 305 and added "say request." In this case, we believe that the added query was instrumental in the flight crew's subsequent missed-approach decision.

3. The flight crews typically were unfamiliar with airline policy for microburst avoidance and with the airline flight bulletin describing the operational demonstration. In this regard, it must be recognized that this first-of-a-kind operational test cannot be expected to be well understood by most flight crews. However, the first aircraft (Flight 862) clearly was familiar with policy and made an early avoidance decision.

4. Several aircraft used microburst wind shear recovery techniques [6] during the missed approaches, indicating the value of these techniques; this might have saved Flight 395 from disaster.

1. The Enhanced LLWAS performed flawlessly in this event, detecting a very dry environment microburst when there were no visual clues for either the flights involved or the air traffic tower controllers. It should be noted that the 95-knot loss measured by this system was the strongest microburst ever measured by any microburst detection system.

2. The controller exercised good judgment by querying adjacent flights for wind shear reports. His actions serve as a model for controller handling of wind shear events.

3. The crew of Flight 531 exercised outstanding judgement and used flight deck crew coordination (as determined in the crew debrief) to make a consensus avoidance decision upon hearing the 95-knot loss alert.

2 September 1989

1. This microburst event was just above the headwind/tailwind threshold for declaring a diverging shear microburst. The event was well detected just above the threshold that indicates a severe wind shear condition. This is confirmation that a 30-knot threshold is an appropriate one, given that the landing aircraft experienced structural damage.

2. The controller strongly suggested, by his queries, that Flight 914 should give serious consideration to an avoidance action (they did not take the suggestion). It should be noted that the controller did not state "say request" or "say intention" as did the controller on 11 July 1988.

3. The crew of Flight 914 made a clear choice to land the aircraft contrary to airline policy and after informal prompting from the controller. The aircraft easily could have been lost.

4. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

The LLWAS, TDWR and integrated TDWR/LLWAS microburst alert systems are a technical success. Once a divergent wind shear event reaches the microburst threshold of an expected 30-knot headwind-to-tailwind differential, the systems work extremely well and produce alarms which are accurate and timely.

The human factors aspects are less successful, and it is in this domain that considerable additional effort is needed. Flight crews continue to need extensive training regarding the impact of microbursts on aircraft and the inadvisability of

penetrating them; standard procedures are needed to reinforce the training. In addition, improved air traffic controller training is needed to standardize controller response to microburst alerts. From the perspective of the scientists who have examined the basic science of microbursts and helped to develop detection capabilities, air traffic control rules and procedures that dictate avoidance are a required next step. Such rules should be consistent with onboard wind shear avoidance avionics equipment.

Controllers could help sensitize pilots to making time-critical decisions by using terminology that triggers the need for a pilot decision based on the presence of a hazardous weather event. The air traffic service should consider testing a cautionary message of "say request" or "say intentions" to encourage strongly a flight crew avoidance decision. This message will need to be examined to see if it adds to controller workload or has other deleterious impacts.

Finally, accurate and timely microburst wind shear alerting equipment is becoming operational in the U.S. Its international use at airports where microbursts are common would be critical to a major mitigation of this hazard worldwide.

5. ACKNOWLEDGMENTS

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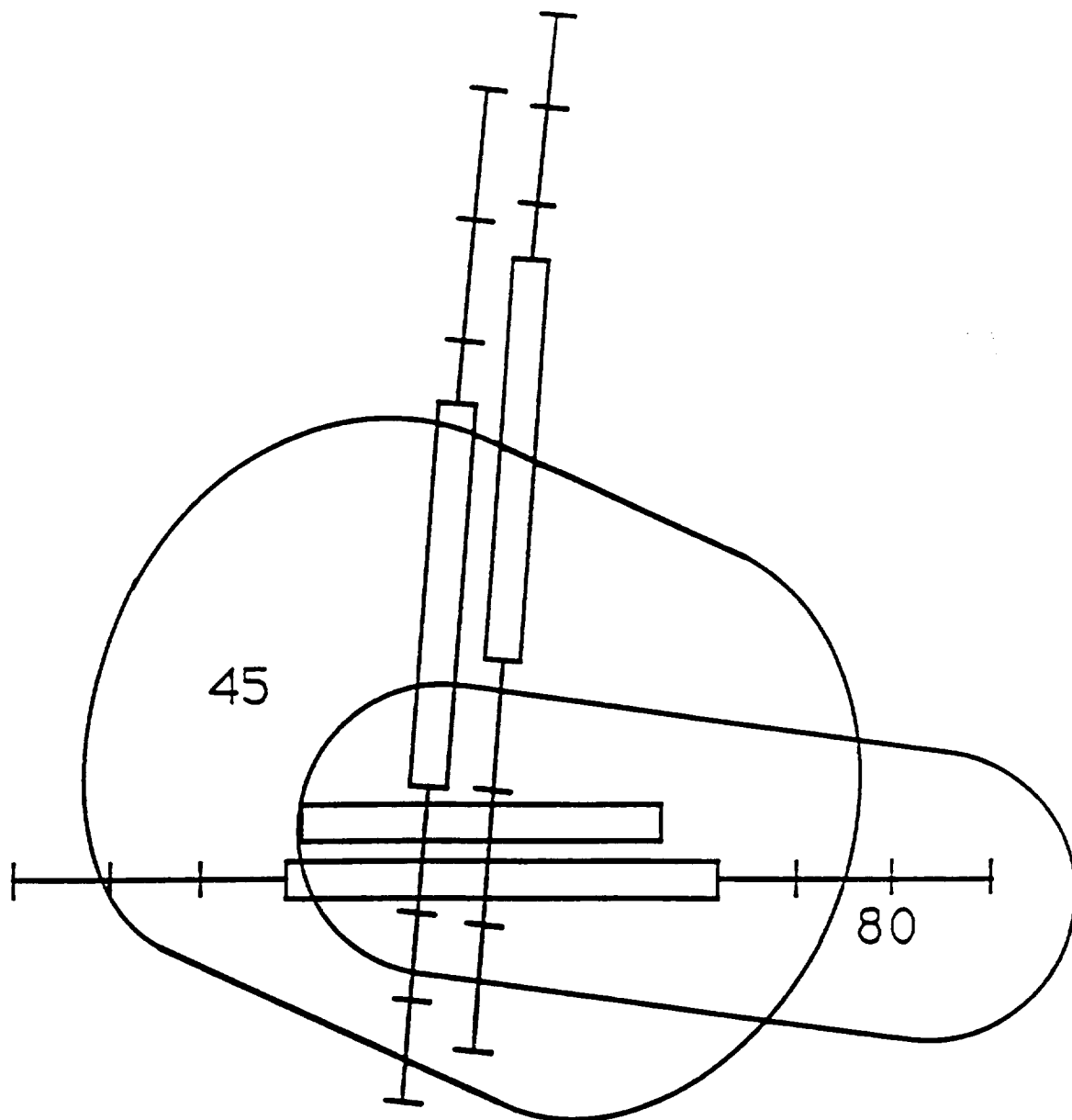
Fig. 1

11 July 1988, 1612 local time, geographic event display of the Stapleton Airport runways with 3 nm extensions off each runway end and microburst events areas shown by ellipses. The 80 knot microburst is shown at it's peak intensity located off the approach end of runway 26.
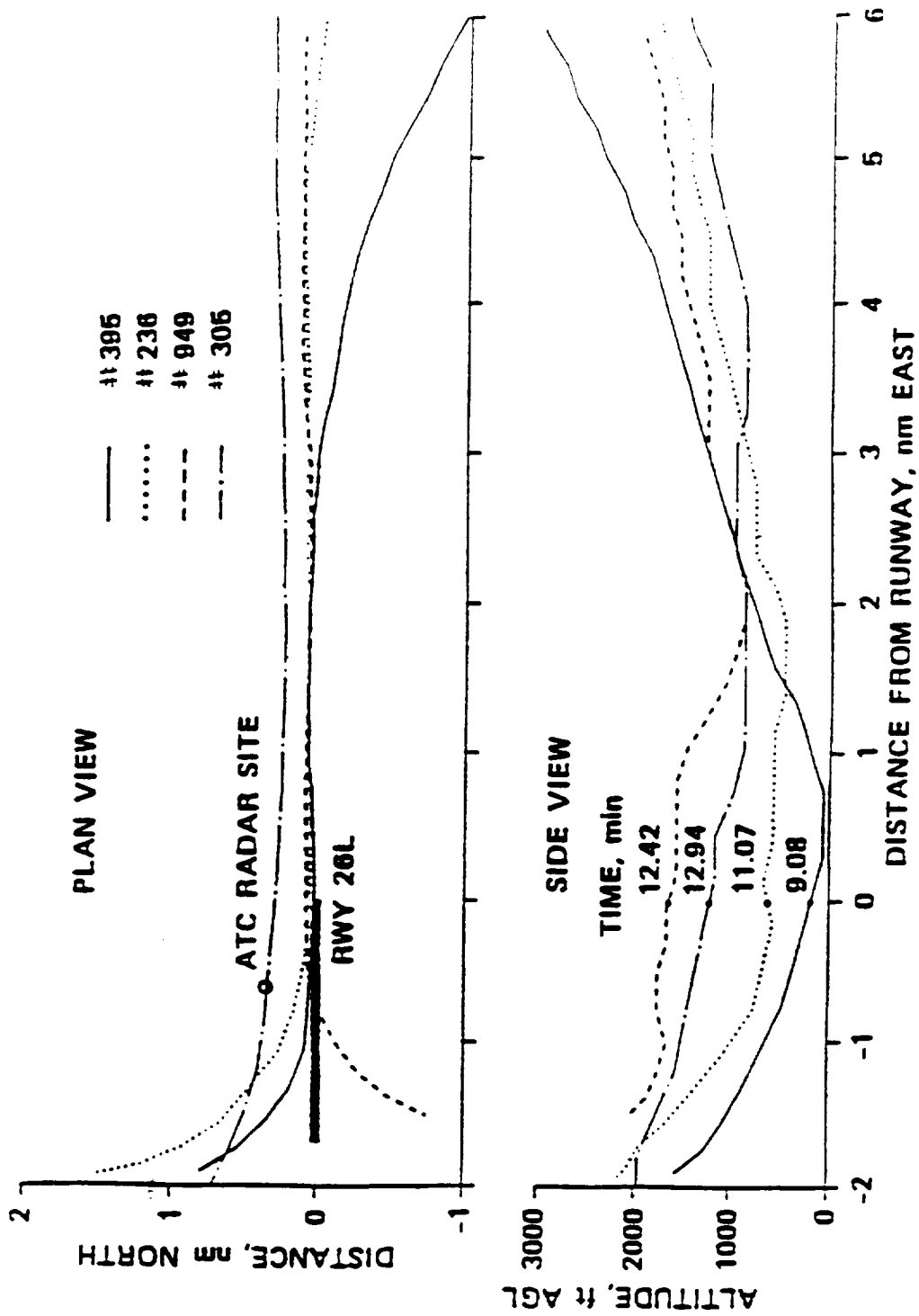
Fig. 2

Aircraft tracks of the four aircraft which penetrated the microburst event on 11 July 1988. The times at which they crossed the runway 26 threshold are shown in the side view with the time being minutes after 1600 local time.

Fig. 3

8 July 1989, 1620 local time, plan view of the runways and three mile runway extensions off all runway ends. The origin of the wind vectors represent the location of the Enhanced LLWAS sensors, the arrows show the direction toward which the wind is blowing and the length and the numbers represent the wind velocity in knots. The 95 knot event on the approach to runway 17 is clearly shown to the north of the airport.

A Status Report on the TDWR Efforts in the Denver Area
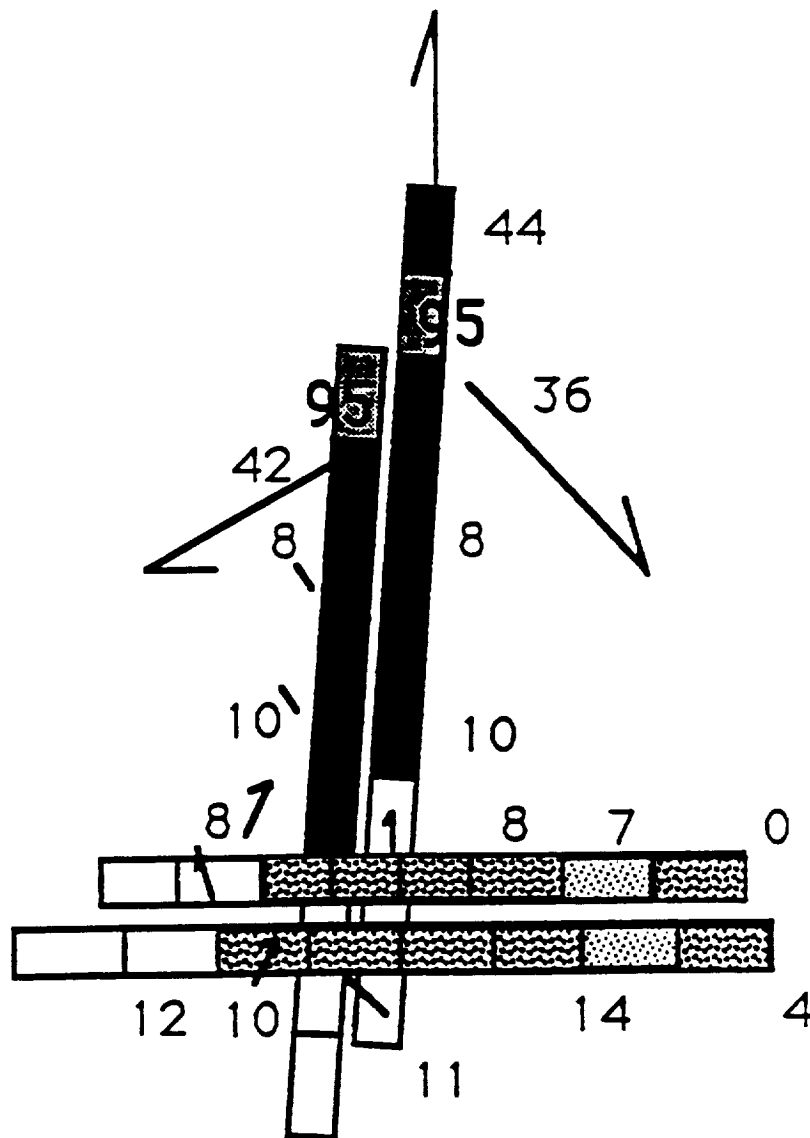## Questions and Answers

Q: ANDY PECZALSKI (Honeywell SRC) - What is the percentage of dry/clear air wind shear and microbursts that are marginally or not detectable by radar at your test site in summer and in winter? Where could I get this information?

A: WAYNE SAND (NCAR) - Try as we could we couldn't recall the exact number and I'm not sure that we have an exact reference for you either. As best we can recall the number is of the order of 5% that were less than -10 dBZ, which went into some of the requirements for the sensitivity on the TDWR specification to build the system. That is part of the answer and some of it is buried away in a lot of different sources that looked at these kind of events. Of course if there's real low reflectivity and you don't have any other evidence you're not really sure you missed the thing. You're not even sure it's there. Of course when you have them right on the airport it's somewhat easier. We have one known event at the airport in '88 that was clearly missed because of low reflectivity. It was detected by the LLWAS system and totally missed by the TDWR. A number of people were standing there watching it, including the chairman of the NTSB. In the TDWR, the spec as I understand it, is -20 dBZ sensitivity at 30 kilometers. That's how the problem is being approached.

Q: DAVE HINTON (NASA Langley) - You indicated that pilots were concerned with a 10 to 15 knot airspeed loss. As Professor Hansman pointed out a 10 knot airspeed loss will require wind divergence of at least 20 knots, more depending on the diameter of the event. Could you elaborate on how you use pilot comments concerning airspeed loss to establish TDWR alarm thresholds that are based on wind divergence.

A: WAYNE SAND (NCAR) - Well, fundamentally this is input from the TDWR/LLWAS user working group which consisted of a number of pilots and controllers and other people associated with the problem. It was counsel received from airline operations, pilots, all of those kinds of people that said they wanted to know when the system detected a 15 knot event. We're still troubling with that threshold value. We're getting feed back from pilots saying they're experiencing what they consider to be significant wind shear events with a 10 knot change. So it's a debatable issue. We set that threshold based on "professional" input from people who thought they knew what they wanted. We continue to assess that threshold.

Q: FRED REMER (University of North Dakota) - I believe that people are avoiding wind shear at Denver but the problem there has been well publicized. How are they responding at other locations?

A: WAYNE SAND (NCAR) - Generally, pretty good. What we're getting back on questionnaires from Orlando this year and from Kansas City last year is generally favorable. The pilots are reacting to that and we see the curve going in the right direction there, at least in our opinion. We have more people avoiding things that are called microbursts everywhere.

Q: FRED REMER (University of North Dakota) - ATC is an active participant in the Denver TDWR program, how would you qualify their participation?

A: WAYNE SAND (NCAR) - They are very active participants. The people in Denver are a good group to work with. The air traffic controllers, supervisors, and the center weather

service unit people are all very interested in what's going on and they all have a lot to say. I'd like to think we listen to all those people and certainly consider all of their input.

Q: FRED REMER (University of North Dakota) - What I found in Florida is that they're not able to handle the situation before a gust front or a microburst occurs. For example, a gust front comes through and all the airliners that were lined up, taxi down to the other end of the runway and get ready for departure. Then the shear is gone and we have environmental conditions again and they taxi back down to the other end of the runway where they were originally. So the question I was asking is, are they able to accommodate that? Do they predict that?

A: WAYNE SAND (NCAR) - In a word, yes. In Denver, they've learned how to deal with that. This 10 and 20 minute wind shift prediction product, which gives them a velocity vector of the wind to be expected behind the gust front, is used by the supervisors to decide when to change runways and if runway changes will be required. They in fact will start taxiing people to different runways. They'll say, hey, we can take airplanes up to this guy, the rest of you guys go to the other runway, whatever it is. In my view they're getting very good at using that wind shift prediction product to reconfigure the airport. Denver, of course, is a little bit different than Orlando, with orthogonal runways.

UNKNOWN - The LLWAS winds are on the GSD for the traffic supervisor at Denver. They were not put on the GSD in Orlando. So that the display of a wind map from LLWAS, which makes the runway management more effective, was not available at Orlando.

WAYNE SAND (NCAR) - That's another word to speak for integration at some level. Putting those wind vectors on the GSD very rapidly builds confidence in the wind shift algorithm.

STEVE CAMPBELL (MIT Lincoln Laboratory) - We did have the wind shift prediction product at Orlando this past summer. Part of the problem may be that the people at Orlando haven't had as much use, or maybe hadn't built up a confidence factor yet, whereas it's been available in Denver for the past couple of years. It's worth noting, one of the main economic justifications for TDWR is the ability to predict these wind shifts. It's one of the things that controllers in general seem very enthusiastic about along with the storm motion.

WAYNE SAND (NCAR) - A lot of these new enhancements that are coming along for the system are pretty well received. I think from day one at Denver, when we started putting up wind shift products they were well received. They figured out right away how to use that. It was very quick. But, as John pointed out, it probably has something to do with the vectors that are on there from all the LLWAS sites. That gives them a lot of confidence in what's going on.

Q: ROBERT OTTO (Lockheed) - It was stated that there is "reasonably" good agreement between calculations of F-factor from radar and those from aircraft. Please clarify. What are the quantitative comparison numbers and how are they determined?

A: WAYNE SAND (NCAR) - There is some arm waving that goes into that. You have to make some assumptions about the vertical motions. What's used to do that is the continuity equation. It's coming down, it's got to change directions and go the other way. So it's a continuity argument used to compare between the two terms in that equation, the horizontal term and the vertical term. There are a number of people who have attacked that problem. We've done some of that at NCAR, the people here at NASA Langley have done quite a bit of it, and the people out at NASA Ames, Rod Wingrove, has done some of those

kinds of things. There is some literature now that discusses those kinds of things. You saw a number of those displays yesterday and today where you're looking at radar computed F-factors versus airplane computed F-factors and generally those track pretty well. I think that was the basis of my comment.

Q: PAUL ROBINSON (Lockheed) - This question relates to operational procedures concerning TDWR procedures on the 11 July microburst encounters. My impression is that the aircraft were only notified about the microburst after being cleared onto the approach and pilot reports seem to be absent.

A: WAYNE SAND (NCAR) - Absolutely true. They were absent. Bob Ireland is here and that was one of the issues that came out of the United report. With that is a very strong encouragement for pilots to give PIREPS. There were none in that event.

Q: PAUL ROBINSON (Lockheed) - Should the shear information have been communicated to the pilots before being cleared onto the ILS?

A: WAYNE SAND (NCAR) - The answer to that is probably yes. In fact, the way the system was working then was that the information was available to the final controllers in the tower and in the TRACON. Those are the people who are talking to them basically before the outer marker. So the flight crews didn't have access to talk to somebody who had the information available right in front of them until they were at the outer marker. Now, based on that case and some additional effort that's gone on since then, there is a little more activity in the TRACON with the supervisors now trying to get that information to controllers. There are more displays of alpha numeric information in the TRACON so that controllers have an option to look at that. But I don't believe there's still any obligation to give that information out from the TRACON positions. It still is the responsibility of the tower controller to give that information to the flight crews once they come over to tower, which at Denver is typically about the outer marker. Were PIREPS available? No, they just weren't available.

Q: ROLAND BOWLES (NASA Langley) - What is the termination criteria for TDWR alerts?

A: WAYNE SAND (NCAR) - It's a relatively simple termination criteria. It's when the system senses that the total wind change across the detected event goes below 30 knots. That is when the event terminates. Now the question is much more complex than it sounds on the surface because by the time it gets to that point the event typically gets somewhat bigger. The real question is, is that waiting too long because the level of shear hazard at that point may be small. It's the delta V over delta R that's important to the airplane. The delta R often times gets quite big. So it's a question of when you cut that off. At the moment we're cutting it off when the delta V goes below 30 knots. That may or may not be correct and that may be one of the ways we can also clean up the time that the system is alarming. It's something that we continue to try and look at and we don't have an answer for yet.

Q: BOB IRELAND (United) - For use in writing SAE-S7 standards for look-ahead systems, please define dry conditions, e.g., dry microbursts, both in terms of reflectivity and other parameters such as relative humidity.

A: WAYNE SAND (NCAR) - I don't know where you draw the line. The ends of the spectrum are pretty easy but where you draw that line I don't know.

UNKNOWN - To call it dry versus wet is arbitrary. You can draw a line anywhere you want. The fact is, the spectra of microbursts go from very dry to very wet and it's continuous.

WAYNE SAND (NCAR) - I'd hate to offer an opinion on that. I would refer back to the analysis of the July 11 case for just a comment. Most of us think of July 11 as being a dry microburst, yet it was raining at the airport and there were reflectivities in the high 30s, which starts to get up to crowding red on an airborne display. In that one we all refer to it as dry, yet on many radars you'd have seen dots of red in that particular event. So, I hesitate to draw that line standing up here on the podium. I don't know where it belongs.

BOB IRELAND (United) - That was probably a little unfair to ask you at the last minute. It just came up last week at the S-7 meeting and we want to say in our document that we want systems to work in both dry and wet conditions. We didn't feel that we had the collective knowledge to draw a line, a reasonable line. We need to say that it's got to work from a certain minimum to a certain maximum.

MARILYN WILSON (MIT Lincoln Laboratory) - The dry microburst was defined as 35 dBZ or lower because we looked at rain gauge measurement in Denver to see when measurable precip was actually detected. For the drop size distributions found in the Denver area, 35 dBZ was most commonly the line. If the reflectivity was lower than that, the rain gauge at the surface measured no rain. But, on a day like July 11, 1988, there was measurable rain. So it's not a hard and fast thing. It depends on what that dBZ is giving you. Those are also surface reflectivities. If you look aloft you could see a higher reflectivity. That's sort of the maximum reflectivity at the surface. What the minimum reflectivity at the surface is, no one has really catalogued.

BOB IRELAND (United) - I guess what I'm concerned about is, in the absence of precipitation, is there still reflectivity? I'm talking about when there is not precipitation but we have a dry microburst, what can we use as a measurement?

MARILYN WILSON (MIT Lincoln Laboratory) - There is precipitation there and there is measurable reflectivity there, it's just that there's a few big drops and it skews this Z number that the radar measures up to a higher reflectivity, like 20 dBZ, even though there is nothing measurable by a rain gauge. There is rain in the air it's just sparse. There is also dust in the air.

UNKNOWN - What we were trying to do on the S-7 committee was to define what an airborne wind shear system must detect. For example, for the IR we picked up some numbers as to the level of rain through which it must look. We needed the other side of the equation for what a LIDAR must do and what a radar must do, in terms of what performance it must meet from an airborne platform to be acceptable. So the question was, if a number like 5% of microbursts are very, very dry, is that something that an airborne radar must detect. Equally, must an IR or a LIDAR look through X rain? That's where we were trying to go with it. We were trying to pick some numbers. Our committee was concerned about what is it that our system has to do. Let's define some system requirements. If people are going to be flying into Denver and if they've got an airborne radar low level wind shear detection system and there are dry microburst, we've got some specs for people to shoot at.

WAYNE SAND (NCAR) - It's certainly a fair question and I would suggest that that's something we probably have to get our heads together between NCAR and Lincoln Labs, at least, and try and provide you with a number. I think it's a matter of, as you say, setting

a definition and somebody has to do it. Maybe we have more data than anybody else between us to try to come up with that number. Let us get back to you for the committee on that. We'll work the problem and see if we can come up with at least our best estimate.

Background

- **Microbursts + other factors**
  - crash aircraft taking off or landing
  - close runways
  - cause delays
  - force alternative airport landings.

- **Microburst detection, location and measurement**
  - will enhance airport usage and safety.

MITRE

Microbursts, streams of rapidly moving, downwardly directed air, are a principal cause of wind shear hazards. The air within a microburst cools rapidly due to water drop evaporation and melting hail, both of which maintain negative buoyancy in the air and propel it to the ground. Microbursts are always associated with clouds and principally with severe convective storms, though microbursts have been observed beneath virga-like precipitation. Microbursts are typically elliptical in shape and initiate relatively high in the atmosphere where heavily water-laden air can have diameters of ten km or more. The negatively-buoyantly maintained rapid downward acceleration of this water-laden air causes a microburst to become narrower as it approaches the ground so that it may have a diameter of less than a kilometer near the ground. When the air in a microburst strikes the ground, it scoots out horizontally in a diverging pattern from a central point (or nadir).

Due to the strongly divergent air, a moving aircraft first experiences a headwind, which increases lift, rapidly followed by a tailwind, which reduces lift by reducing the relative speed of the aircraft. A significant loss of altitude can occur which, depending on the altitude of the aircraft, can cause a crash.