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Thunderstorm Impact on Denver Air Traffic Control Operations and the Role of NEXRAD

L. E. Stevenson

April 1984
Final Report

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16. Abstract

This report describes the impact of thunderstorms on the Denver Air Traffic Control (ATC) operation and the potential role of the Next Generation Weather Radar (NEXRAD) in reducing that impact.

The investigation was conducted in two stages. First, data collected at Denver during the summer of 1982 in collaboration with the JAWS Project was used to produce several one- to two-hour case studies. These case studies document specific thunderstorm-impacted ATC situations in terms of traffic disruption, aircraft delay, and pilot-reported encounters with turbulence, wind shear, microbursts, heavy rainfall and hail. Second, these case studies were used as a basis for follow-up discussions with Denver ATC personnel concerning the general impact of thunderstorms on their operation and the role that NEXRAD could play in reducing that impact.

The result of the investigation is a qualitative and, where possible, quantitative description of the impact of thunderstorms on arrivals and departures at Stapleton International Airport. This description covers operations under the control of the following ATC facilities: the Stapleton ATCT, Denver TRACON and Denver ARTCC.

17. Key Words Dopplar Weather Radar, NEXRAD, JAWS Project, Stapleton International Airport, Air Traffic Control Operations, Thunderstorms, Wind Shear, Microbursts, PIREPs, Traffic Flow Disruption

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PREFACE

This study was performed by the U. S. Department of Transportation, Transportation Systems Center, Cambridge MA. The study is sponsored by the Next Generation Weather Radar (NEXRAD) Joint System Program Office.

The purpose of the study was to investigate the impact of thunderstorm activity on the Denver Air Traffic Control (ATC) operation and the potential role in that operation for NEXRAD based aviation weather maps designed for controller use. The investigation was based on data collected during the summer of 1982 that documented the Denver ATC operation during several thunderstorm occurrences.

The data collection activity and follow-up analysis involved the cooperation of a number of organizations and many individuals. The support provided by the: (1) Joint Airport Weather Studies (JAWS) Project of the National Center for Atmospheric Research, (2) The Program for Regional Observing and Forecasting Services (PROFS) of the National Oceanographic and Atmospheric Administration, (3) Department of Geophysical Sciences of the University of Chicago, (4) The Denver Enroute ATC Center and its Center Weather Service Unit and (5) The Denver TRACON is gratefully acknowledged.

TABLE OF CONTENTS

FIGURES

Figure | Page

Figure		Page
4-15(A)	JULY 14 CASE STUDY - DOWNBURST SITUATION BETWEEN 2:30 AND 3:00 PM SHOWN RELATIVE TO THE STAPLETON ARRIVAL OPERATION	49
4-15(B)	JULY 14 CASE STUDY - IMPACT OF A DOWNBURST ON FINAL APPROACH FROM 2:38 TO 2:45 PM	51
4-16	JULY 26 CASE STUDY - DENVER AREA THUNDERSTORM SITUATION NEAR THE BEGINNING/END OF THE STUDY PERIOD	53
4-17	JULY 26 CASE STUDY - REGIONAL WEATHER SITUATION AS OF 7:55 PM BASED ON CONVECTIVE SIGMETS	54
4-18	JULY 26 CASE STUDY - TRAFFIC PATTERN FOR DENVER ARRIVALS DURING THE HOUR	55
4-19	JULY 26 CASE STUDY - KIOWA ARRIVAL CO361	56
4-20	JULY 26 CASE STUDY - TRAFFIC PATTERN FOR DENVER DEPARTURES DURING THE HOUR	57
4-21	JULY 9 CASE STUDY - DENVER AREA THUNDERSTORM SITUATION NEAR THE BEGINNING/END OF THE STUDY PERIOD	59
4-22	JULY 9 CASE STUDY - REGIONAL WEATHER SITUATION AS OF 3:55 PM BASED ON CONVECTIVE SIGMETS	60
4-23	JULY 9 CASE STUDY - ARRIVAL DELAY AND PILOT REPORTED WEATHER ENCOUNTERS	61
4-24	JULY 9 CASE STUDY - DEPARTURE DELAY AND PILOT REPORTED WEATHER ENCOUNTERS	63
4-25	JULY 9 CASE STUDY - EAST GATE DEPARTURE DL262	64
4-26	JULY 9 CASE STUDY - EAST GATE DEPARTURE FL284 THAT DEVIATED TO SOUTH GATE	65
4-27	JULY 21 CASE STUDY - DENVER AREA THUNDERSTORM SITUATION NEAR THE BEGINNING/END OF THIS STUDY PERIOD	67
4-28	JULY 21 CASE STUDY - ARRIVAL DELAY AND PILOT REPORTED WEATHER ENCOUNTERS	68
4-29	JULY 21 CASE STUDY - DEPARTURE DELAY AND PILOT REPORTED WEATHER ENCOUNTERS	69
4-30	JULY 21 CASE STUDY - EAST GATE DEPARTURE UA566	70

1. INTRODUCTION

This report describes the results of an investigation into the impact of thunderstorm activity on the Denver Air Traffic Control (ATC) operation and the role that NEXRAD based aviation weather maps designed for controller use would have in that operation. These maps are the NEXRAD based, weather contour maps envisioned as potential replacements for the uncalibrated, reflectivity - only, weather map presentations available to controllers on their Plan View Displays today.

The investigation was based on: (1) case studies of actual thunderstorm impacted operations in the Denver Terminal Area and the adjacent low altitude enroute sectors and (2) follow-up discussions of the case studies with Denver ATC personnel.

The Next Generation Weather Radar (NEXRAD) is being jointly developed by the National Weather Service, Air Force Air Weather Service, and the Federal Aviation Administration (FAA) by means of a Joint Systems Program Office (JSPO). NEXRAD will be a Doppler weather radar capable of mapping a storm's wind features, such as turbulence and wind shear, as well as its precipitation. It is envisioned that a network of these radars will provide long-range, nation-wide weather coverage by the end of this decade. The JSPO will develop the radar unit and the data processing and communciations network needed to prepare and relay a set of basic NEXRAD weather radar products to the member JSPO organizations.

In parallel to the JSPO activity, the FAA is starting to develop a set of NEXRAD based aviation weather products and a user system to distribute these products to ATC facilities and to the aviation community as a whole. Two issues of particular interest to the FAA are the impact of thunderstorm activity on the overall ATC operation and how NEXRAD aviation weather maps designed for controller use might be used to lessen that impact.

An opportunity to study these two issues relative to the Denver ATC operation presented itself in the summer of 1982. During that summer, the National Center for Atmospheric Research (NCAR) conducted an extensive data collection activity on the structure of thunderstorms using a triad of Doppler weather radars located to the north of Denver's Stapleton International Airport. This activity was part of the Joint Airport Weather Studies (JAWS) Project.

In coordination with the JAWS weather collection activity, the Transportation Systems Center (TSC) collected data documenting the thunderstorm impacted Denver ATC operation. The combined data collection activity produced seven case studies covering eight hours of operations. These case studies focus on the impact of thunderstorm activity on Stapleton arrival and departure operations.

The specific goals set out for this investigation were to:

(1) Measure the impact of thunderstorm activity on Denver ATC operations in terms of delay and weather encounters for several thunderstorm occurrences,

(2) A conservative estimate of the cost of this delay to Stapleton operations over a thunderstorm season is $2M,

(3) Thunderstorm related weather encounters are a common occurrence in the Denver Area. In the eight hours of collected operational data, pilots reported encounters with turbulence, wind shear, downflows, precipitation and hail,

(4) Weather encounters reported by pilots are not all regarded as potentially hazardous and appear to fall into two general groups - those weather conditions that pilots, as a class, would like to avoid:

(a) Provided that the increase in flying distance in detouring around the weather is not operationally significant (e.g., heavy rainfall),

(b) Regardless of the flying distance involved (e.g., hail).

(5) Replacement of the current ATC radar based weather presentations on the controller Plan View Displays with NEXRAD based aviation weather maps, designed for controller use, should:

(a) Improve each ATC facility's ability to manage its airspace/runways in terms of anticipating the weather's operational impact and assessing the operational alternatives available so as to minimize that impact,

(b) Improve the quality of the current controller weather service provided to pilots in terms of advising pilots of the weather ahead and of suggesting flight paths relative to thunderstorm impacted areas,

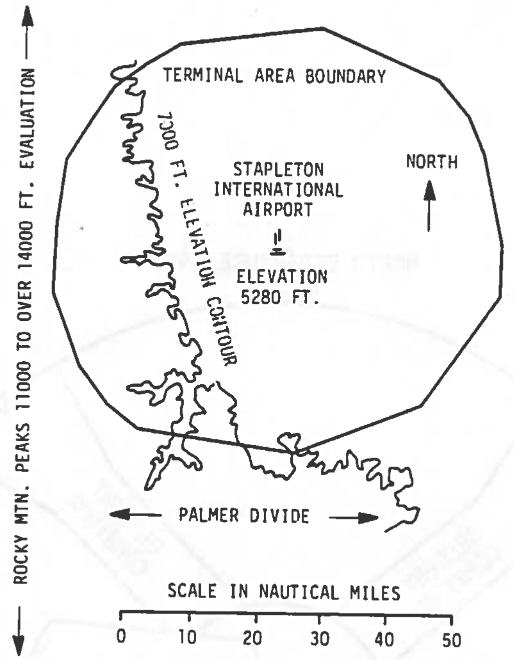
(c) Result in sharply fewer encounters with weather conditions that pilots want to avoid,

(d) Result in an estimated delay savings to Stapleton operations of at least $100K per thunderstorm season.

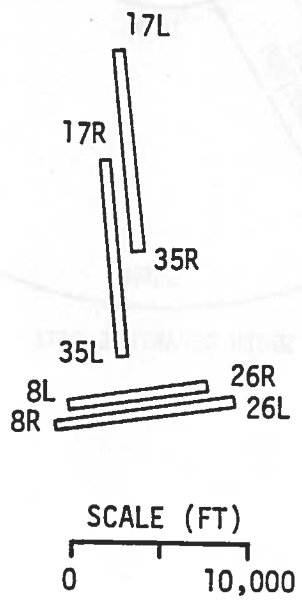
(6) These potential delay cost savings will only be realized if the NEXRAD aviation weather maps, designed for controller use, portray thunderstorm impacted areas so that the useable airspace is clearly identifiable,

(7) The Denver controllers and pilots do a good job of using the limited, real-time weather information currently available to keep the balance between avoiding hazardous weather conditions and keeping the throughput capacity up when operating in the presence of thunderstorm activity. NEXRAD quality, real-time weather information should permit the performance on both sides of that balance to be improved.

The reader may wish to proceed directly to Section 5 and then to Sections 2,3 and 4 if more detail is desired.

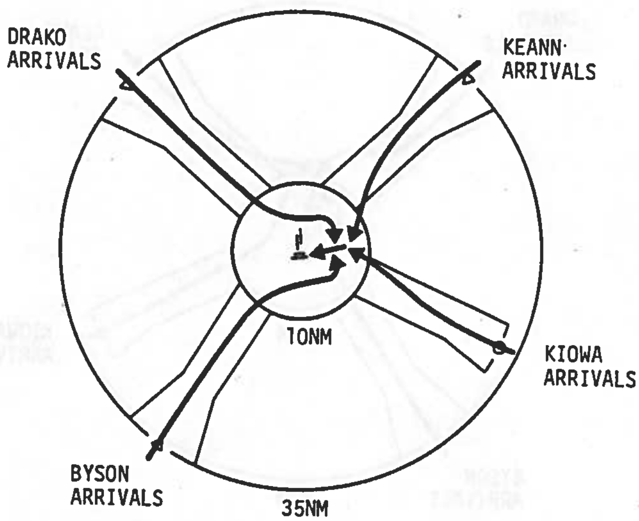


(A) DENVER TERMINAL AREA SETTING

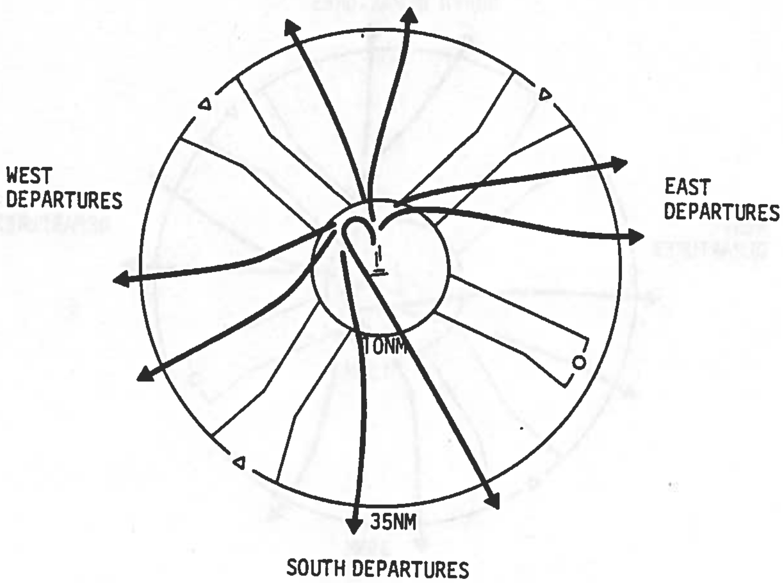


(B) LAYOUT OF PRIMARY RUNWAYS AT STAPLETON INTERNATIONAL AIRPORT

FIGURE 2-1. BASIC LAYOUT OF DENVER TERMINAL AREA AND STAPLETON INTERNATIONAL AIRPORT



A) ARRIVAL TRAFFIC PATTERN



B) DEPARTURE TRAFFIC PATTERN

FIGURE 2-3. TYPICAL GOOD WEATHER TERMINAL AREA OPERATION FOR STAPLETON RUNWAY CONFIGURATION - ARRIVALS FROM THE EAST AND DEPARTURES TO THE NORTH

Figure 2-5 shows the Denver ARTCC sectors that transition the Stapleton arrivals and departures between the terminal area and the enroute ATC structure.

Figure 2-6 shows the regional route structure used by Stapleton departures to certain major cities once they are beyond the Denver transitional sectors. The boundary of the Denver ARTCC is approximately one half hour flying time from the Denver transitional sectors at which time the departures come under the control of other enroute centers. The regional route structure for Stapleton arrivals would appear similar to the departure structure shown in Figure 2-6.

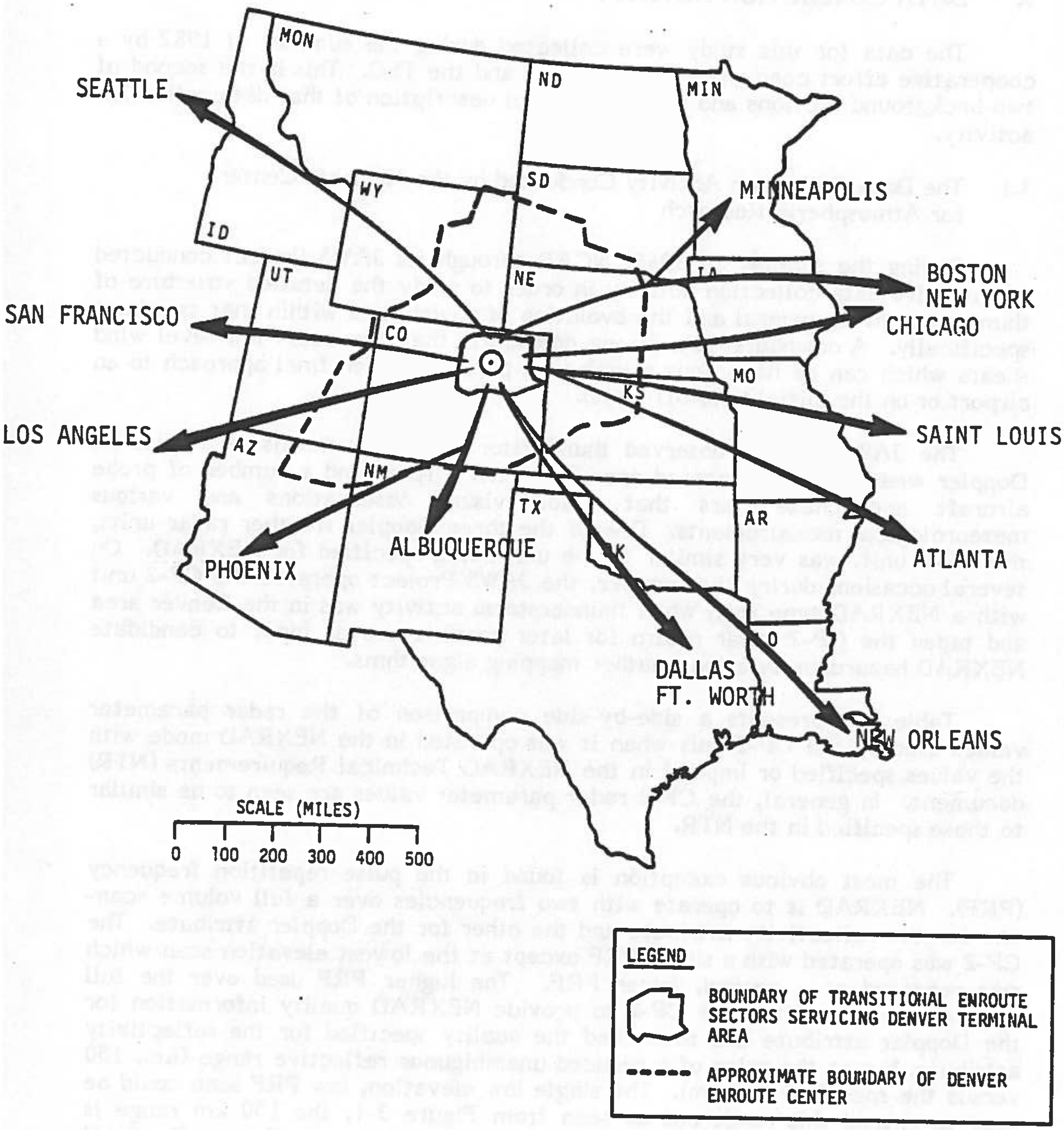


FIGURE 2-6. BASIC REGIONAL DEPARTURE TRAFFIC PATTERN SHOWING ROUTES FROM THE DENVER - ENROUTE TRANSITIONAL SECTORS TO CERTAIN MAJOR CITIES

TABLE 3-1. SUITABILITY OF THE CP-2 WEATHER RADAR AS A SIMULATED NEXRAD NETWORK RADAR

RADAR PARAMETER	NEXRAD AS SPECIFIED IN THE NTR[1]	CP-2 UNIT WHEN OPERATED IN THE NEXRAD SCAN MODE
WAVELENGTH (cm)	10.37 TO 11.10	10.67
AVERAGE POWER (dBm)	>60[2]	59
ANTENNA DIAMETER (m)	7.3[2]	8.5
SYSTEM GAIN (dB)	45[2]	43.9
BEAMWIDTH (deg)	1.00	0.97
BEAM POINTING ACCURACY (deg)	NOT SPECIFIED	0.1
MIN. DETECTABLE SIGNAL @ 10 KM FOR REFLECTIVITY AND VEL.	-22 dBZ FOR 0 dBZ S/N RATIO[2]	-25
AZIMUTHAL SCAN RATE (deg/sec)	3 TO 19.2	15 (I.E. 2.5 RPM)
PULSE REPITITION FREQ (Hz)	1000 [NOMINAL DOPPLER][2] 325 [NOM. REFL.][2]	960 AND 480[3]
PULSE DURATION (μsec)	.75 TO 1.5[2]	1.0
NO. SAMPLES IN ESTIMATE	67 @2.5 RPM[2]	64
MAX. UNAMBIGUOUS RANGE (km)	150 [NOM. DOPPLER][2,4] 460 [REFLECTIVITY][4]	150 AND 300[3]
MAX. UNAMBIGUOUS VELOCITY (m/sec)	± 25[2]	± 25.7 AND ± 12.8[3]
AZIMUTHAL SAMPLE INTERVAL (deg)	1.0	1.0
RANGE SAMPLE INTERVAL -DOPPLER (m)	250	200
RANGE SAMPLE INTERVAL - REFLEC. (m)	1000	200
REFLECTIVITY QUANTIZATION (dBZ)	1.0	.3
QUANTIZATION OF DOPPLER VARS. (m/sec)	1.0	.1

NOTES: [1]NEXRAD TECHNICAL REQUIREMENTS (NTR) DOCUMENT.
[2]NOT SPECIFIED IN NTR BUT DERIVABLE FROM OTHER NTR SPECIFIED PARAMETERS.
[3]ALL ELEVATION SCANS HAVE A 960 Hz REPITITION FREQ. BUT A SECOND LOW ELEVATION SCAN DONE AT A 480 Hz FREQ. EACH VOLUME SCAN
[4]CONTRACTORS WILL PROVIDE A MEANS TO RANGE DEALIAS TO 230 km.

TABLE 3-2. CP-2/NEXRAD SCANNING STRATEGY COMPARED TO THE VOLUME COVERAGE SPECIFIED IN THE NEXRAD TECHNICAL REQUIREMENTS DOCUMENT

EXCERPT FROM THE NTR VOLUME COVERAGE REQUIREMENT (Reference 3-1)

"The RDA shall provide the capability for a volume coverage defined by a rotated triangular section extending in range from the antenna to the specified range, 360 degrees in azimuth relative to the antenna's rotational axis, and from -1 degree to 45 degrees in elevation relative to the antenna's rotational axis and the horizontal plane at the antenna. However, there is no requirement for coverage above 70,000 feet.

A number of automatic antenna scanning programs shall be provided. One scanning program shall provide, for a volume scan time of five minutes, a sample of the coverage volume. This sample shall consist of 14 unique elevation scan levels, from zero degrees to +20 degrees in elevation, with at least the lowest six degrees of elevation having no gaps between the one-way pattern 3 dB points of adjacent elevation scans."

	CP-2/NEXRAD SCAN MODE[1,2,3]	
TILT NO.	CENTER BEAM ELEVATION ANGLE	INCREASE IN ELEVATION ANGLE
1	0.5	
2	1.5	1.0
3	2.5	1.0
4	3.5	1.0
5	4.5	1.0
6	5.5	1.0
7	7.5	2.0
8	9.5	2.0
9	12.5	3.0
10	15.5	3.0
11	19.5	4.0

NOTES:

[1] EACH FULL VOLUME SCAN CONSISTED OF 11 ELEVATION TILTS WITH EACH TILT CONSISTING OF A 360 DEG. SWEEP AND UTILIZING A 960 Hz PRF

[2] EACH FULL VOLUME SCAN WAS PRECEDED BY A 360 DEG. TILT 1 SWEEP UTILIZING A 480 Hz PRF

[3] PERMITTED THE CP-2 TO COMPLETE THE 5 MINUTE VOLUME SCAN WITH A 12 SEC. BUDGET REMAINING FOR BEAM POSITIONING WHEN THE CP-2 OPERATED AT ITS MAXIMUM AZIMUTHAL SCAN RATE OF 15 DEG./SEC. (2.5 RPM).

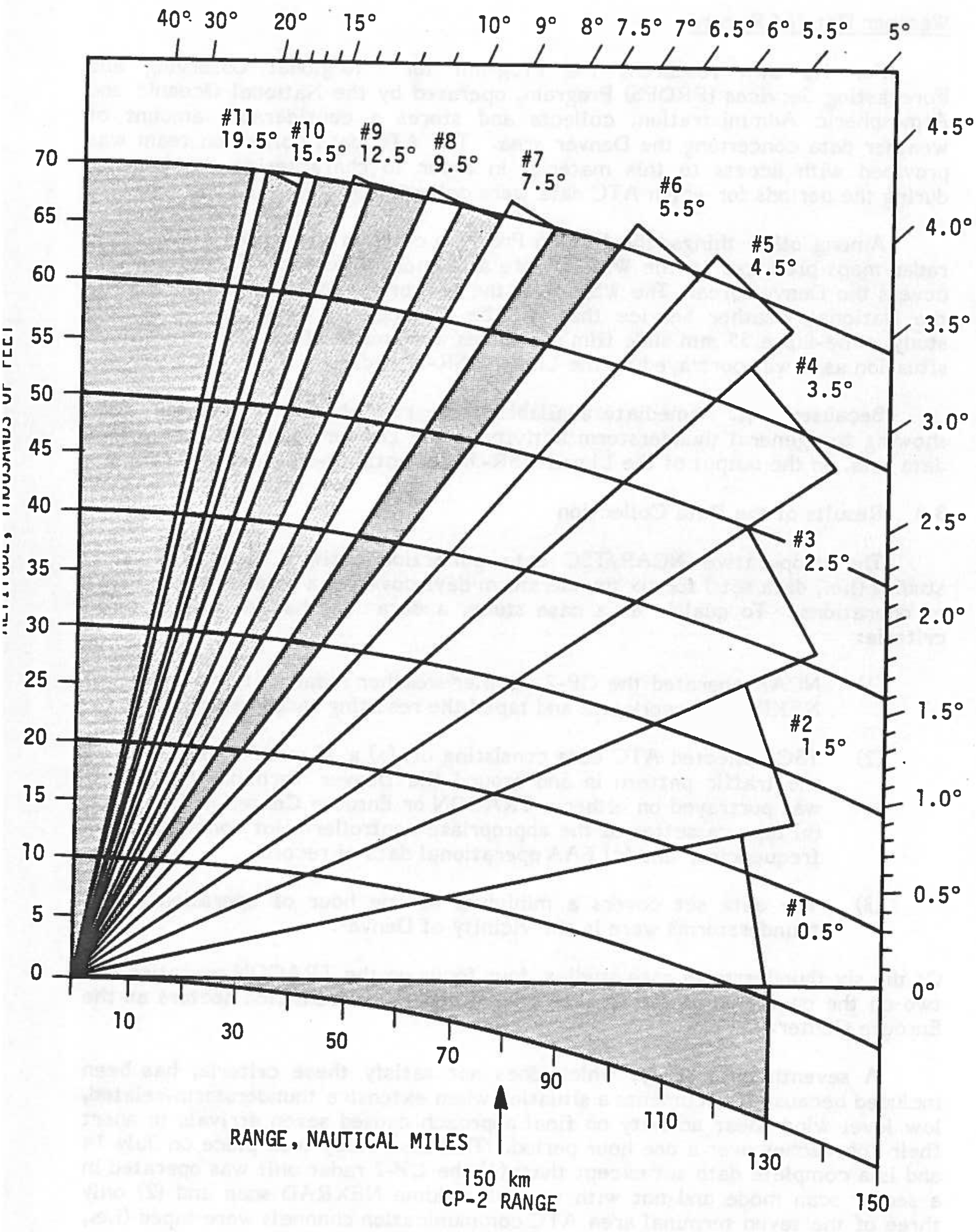


FIGURE 3-2. THE FULL VOLUME NEXRAD TYPE SCAN USED BY THE CP-2 UNIT

4. THE THUNDERSTORM IMPACTED DENVER ATC OPERATION

This section presents: (1) an introductory, qualitative description of the Denver thunderstorm impacted ATC operation, (2) individual descriptions of five of the seven case studies and (3) the results of the case study delay and weather encounter analyses.

4.1 An Introductory Description to the Denver Thunderstorm Impacted Operation

This study focused on two parameters - pilot weather encounters and flight delay due to local Denver thunderstorm activity. Other parameters such as controller workload were not considered.

For both arrivals and departures, delay starts with the development of the first thunderstorm cells in and around the Denver Terminal Area. The delay is in the form of increased flying time and is due to pilots detouring around the individual thunderstorm cells that lie across the standard arrival/departure paths.

For arrivals, the next level of delay occurs when the thunderstorm activity causes the Assistant Chief in the Denver TRACON to reduce the terminal area's arrival acceptance rate (AAR). This can be caused by a number of circumstances, such as the closure of one or more of the terminal area's four arrival gates or the loss of runway capacity due to reduced visibility conditions. A reduced AAR causes the Denver Enroute Center to hold the excess arrival demand.

If it is determined that the airborne arrival delays will exceed some preset limit (e.g., one hour), the Air Traffic Control Systems Command Center (ATCSCC) will insititute the Quota Flow Control (Q Flow) Procedure. The purpose of this procedure is the orderly and safe saturation of the airborne holding points in the arrival and adjacent Enroute Centers in order to provide steady arrival demand to the affected terminal area.

Further, if it is determined that arrivals will experience significant delays for an extended period of time, the ATCSCC will institute the Expanded Quota Flow Control Procedure. In its simplest form, the goal of this procedure is to conserve fuel by holding Denver-bound departures at their departure airports until they can be provided with arrival slots at Denver that will involve acceptable airborne delays.

For departures, the next level of delay beyond simply detouring around individual thunderstorm cells occurs when the thunderstorm activity blocks either: (1) one or more of the terminal area's four departure gates, and/or (2) any of the departure routes leading away from Denver. If departure demand exceeds the capacity of these weather impacted gates/routes, in-trail separations will be increased and the affected departures will take the resulting delays on the ground prior to take off. If the blockage becomes such that

This case study documents the terminal area ATC operation between 3 and 5 p.m. on Wednesday, July 28, 1982. The follow-up discussions of this case involved a controller and watch supervisor at the Denver TRACON.

Thunderstorm Situation

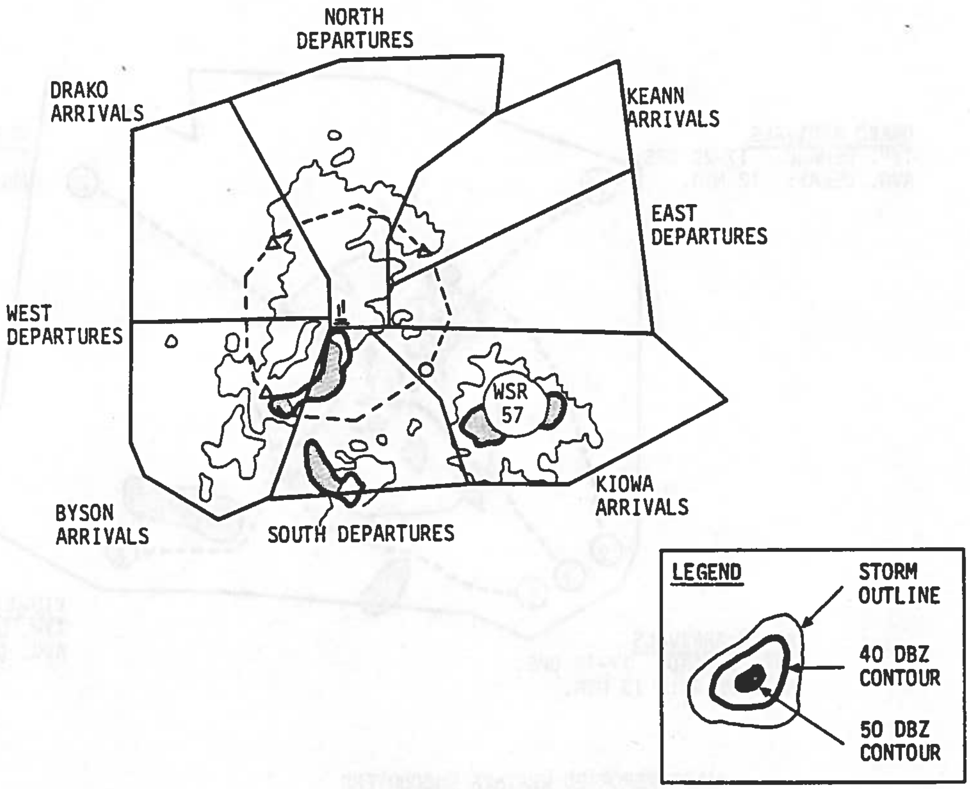
Figure 4-1 (A) shows the thunderstorm situation near the beginning and end of the first hour. The figure shows the : (1) boundaries of the terminal area and the enroute transitional sectors, (2) the storm's general outline of precipitation and 40 dBZ and 50 dBZ contours and (3) the location of the Limon WSR-57 National Weather Sevice radar site that was the source of this weather map.

In addition to giving a direct measure of rainfall intensity, the WSR-57 reflectivity levels tend to also be interpreted as an indicator of the location and possible severity of thunderstorm cells. The 40 dBZ level contains heavy rainfall of .5 inches per hour or more and indicates the presence of a "strong" thunderstorm cell or cells that may contain severe turbulence (reference 3-2). Severe turbulence may cause the pilot of a transport-sized aircraft to lose control momentarily and will cause occupants to be thrown violently against their belts and seats (reference 3-3). The 50 dBZ level contains intense rainfall of 2 inches per hour or more and indicates the present of an "intense" thunderstorm cell that contains severe turbulence and probably contains hail.

On July 28, thunderstorm activity started in the Denver area around 2 p.m. Figure 4-1(A) shows that one hour later at the beginning of the case study that numerous 40 and 50 dBZ cells were building along the Front Range. During the next hour the thunderstorm activity evolved into a line extending southward from Stapleton. Figure 4-1(B) shows that by the end of the second hour this line had moved southward.

Stapleton Arrival Operation

Figure 4-2 shows the Stapleton arrival operation during the first hour of the two hour case study. The figure's format shows: 1) the boundary of the Denver Terminal Area (i.e., the inner perimeter), (2)the boundary of the enroute transitional sectors (i.e., the outer perimeter), (3) the basic thunderstorm situation over the hour (i.e., the areas of precipitation with weather radar reflectivity intensities of 40 dBZ or more), (4) the actual arrival traffic pattern that existed over the hour in the terminal area, (5) the terminal area arrival gates that these arrivals would have used during good weather conditions, (6) the actual gate demand for the hour compared to the typical good weather demand, (7) the estimated average weather related delay experienced by the arrivals and (8) the weather encounters reported by pilots together with the general location of the flights when the reports were made. For example, there were 18 arrivals which in good weather conditions would have entered the terminal area via the Drako Arrival Gate, compared to the typical good weather Drako Gate demand of 17 to 20 operations; these 18 arrivals did enter the terminal area by the Drako Gate and experienced an average weather related delay of 12 minutes and reported five weather encounters.



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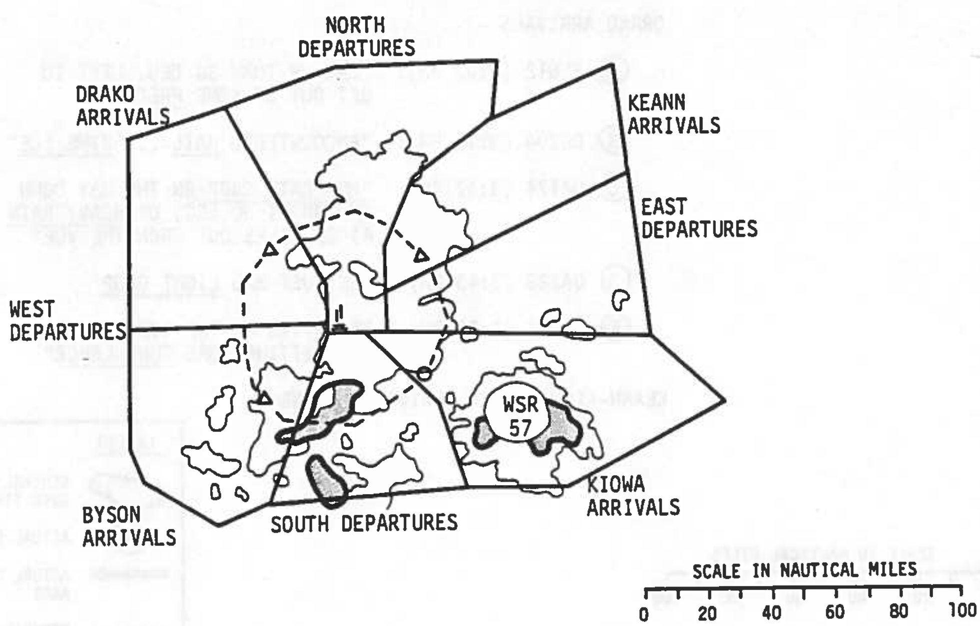


AS OF 5 PM

FIGURE 4-1 (B). JULY 28 CASE STUDY - DENVER AREA THUNDERSTORM SITUATION NEAR THE START/END OF SECOND HOUR OF THE STUDY PERIOD (SOURCE: LIMON WSR57 WEATHER RADAR)

Comparing the traffic pattern in Figure 4-2 with its good weather counterpart in Figure 2-4, it is seen that the primary effects of the weather were the weather encounters reported by the Drako arrivals and the diversion of all but one Byson arrival to other arrival gates. The single arrival to use the Byson Gate was an attempt to open that gate towards the end of the first hour.

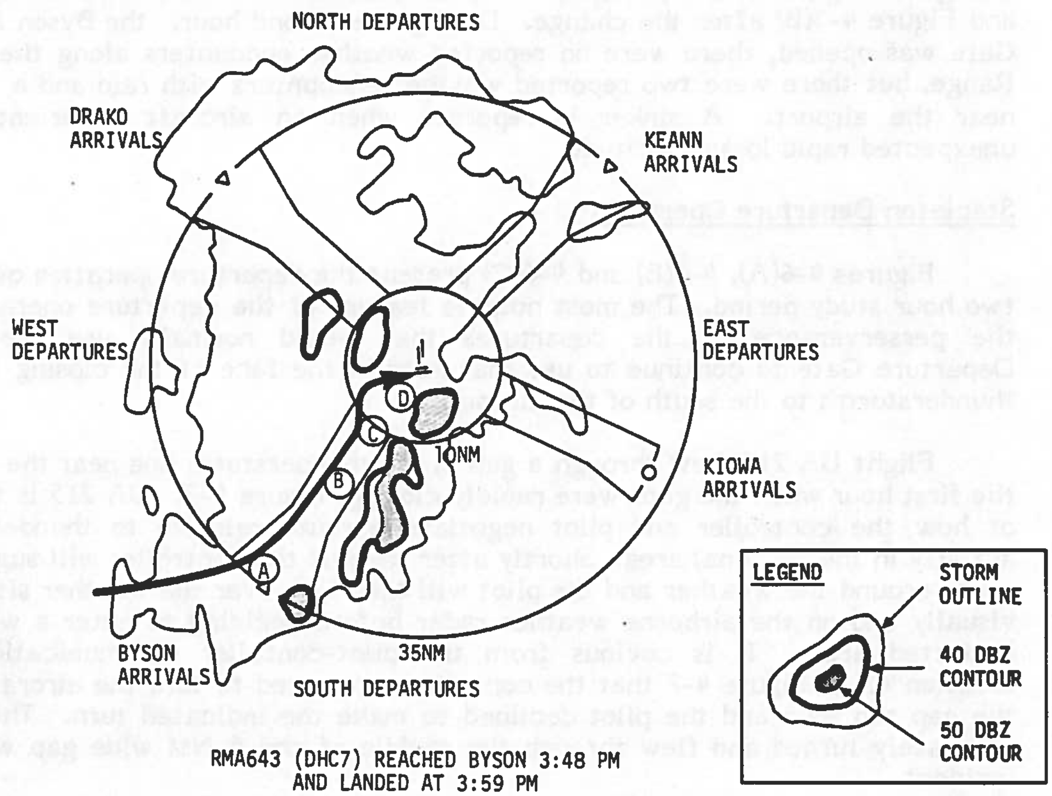
In the follow-up discussions, the dual gate situation of numerous weather encounters by the Drako arrivals and the attempt to open the Byson Gate was used as a basis for a general discussion on gate closure and reopening. Given the multiple weather encounters which included hail, heavy rain, and moderate chop, why wasn't the Drako Gate closed?

The gate closure procedure starts with the controller advising each pilot of the weather situation along his path based on the broadband weather presentation on the controller's ATC display and the comments of preceding pilots. On looking over the weather situation or encountering certain weather conditions, pilots will start requesting deviations around the weather. Drako arrival, FL612, is typical of this part of the procedure, Figure 4-3. The pilot encountered significant rain and requested a deviation that would have taken the flight out of the approach corridor. The controller permitted the requested deviation but indicated that preceding pilots using the approach corridor were having good rides. In this case, the pilot followed the controller's suggestion. Only when two or three consecutive arrivals request wide detours that take the arrivals well outside of the arrival gate/descent corridor is an arrival gate closed. This is done to ensure that a gate is not closed because a particular pilot misses an acceptable way around the weather that would keep the aircraft in the arrival airspace.

Figure 4-1(A) shows that the Byson descent corridor was blocked by 50dBZ cells at the beginning of the hour and only became clear of thunderstorm cells towards the end of the hour. Figure 4-2 shows that the gate was closed and that the arrivals that would have normally used that gate were diverted to the Kiowa and Drako Gates.

The procedure for opening an arrival gate is for the TRACON and ARTCC controllers responsible for the gate to monitor the weather situation as it is presented on their ATC displays. When the blocked approach path looks like it might be clear, the ARTCC controller, in coordination with the TRACON controller, will suggest the option to incoming arrivals. A pilot wishing to shorten his flying time will try the closed gate. In this case, RMA 643 tested the Byson Gate, Figure 4-4. It is seen that the main line of thunderstorm activity had cleared the descent corridor but that the normal downwind leg to Runway 17, the arrival runway, was blocked by two 40 dBZ contours. The pilot reported these cells to the TRACON controller and was advised to land on Runway 8L. The gate remained closed.

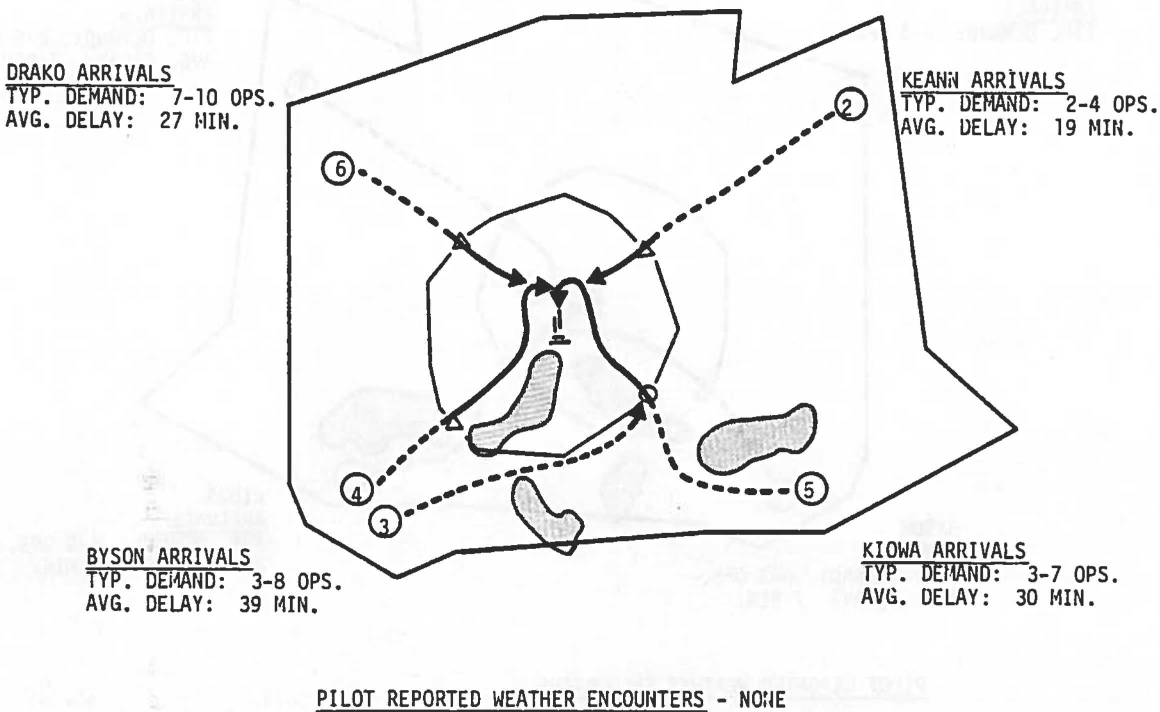
Controller access to a NEXRAD based aviation weather map should permit more timely opening of closed gates. In fact, on seeing the weather situation portrayed in Figure 4-4, one controller said that with that weather map he would have brought RMA 643 over Stapleton, used the downwind leg to the east of the airport, landed the aircraft on Runway 17, and opened the Byson Gate at that point.

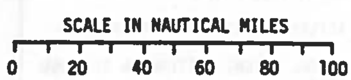


<u>PILOT-CONTROLLER WEATHER RELATED COMMUNICATIONS</u>

Ⓐ	PILOT:	Initial contact with TRACON
Ⓑ	PILOT:	"We are looking at a bunch of low craters along downwind to (Runway) 17."
	CONTROLLER:	"Tell you what, plan (to land on Runway) 8L."
Ⓒ	CONTROLLER:	"Most of this will be to the north of your final to 8L."
Ⓓ	CONTROLLER:	"How was the ride through the weather out there?"
	PILOT:	"Smooth all the way in from Byson."

FIGURE 4-4. JULY 28 CASE STUDY - BYSON GATE ARRIVAL RMA643





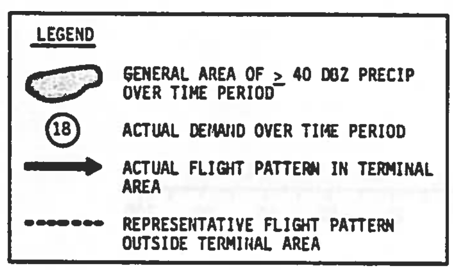


FIGURE 4-5(A). JULY 28 CASE STUDY - WEATHER IMPACT ON THE STAPLETON ARRIVAL OPERATION DURING FIRST 40 MINUTES OF THE SECOND HOUR

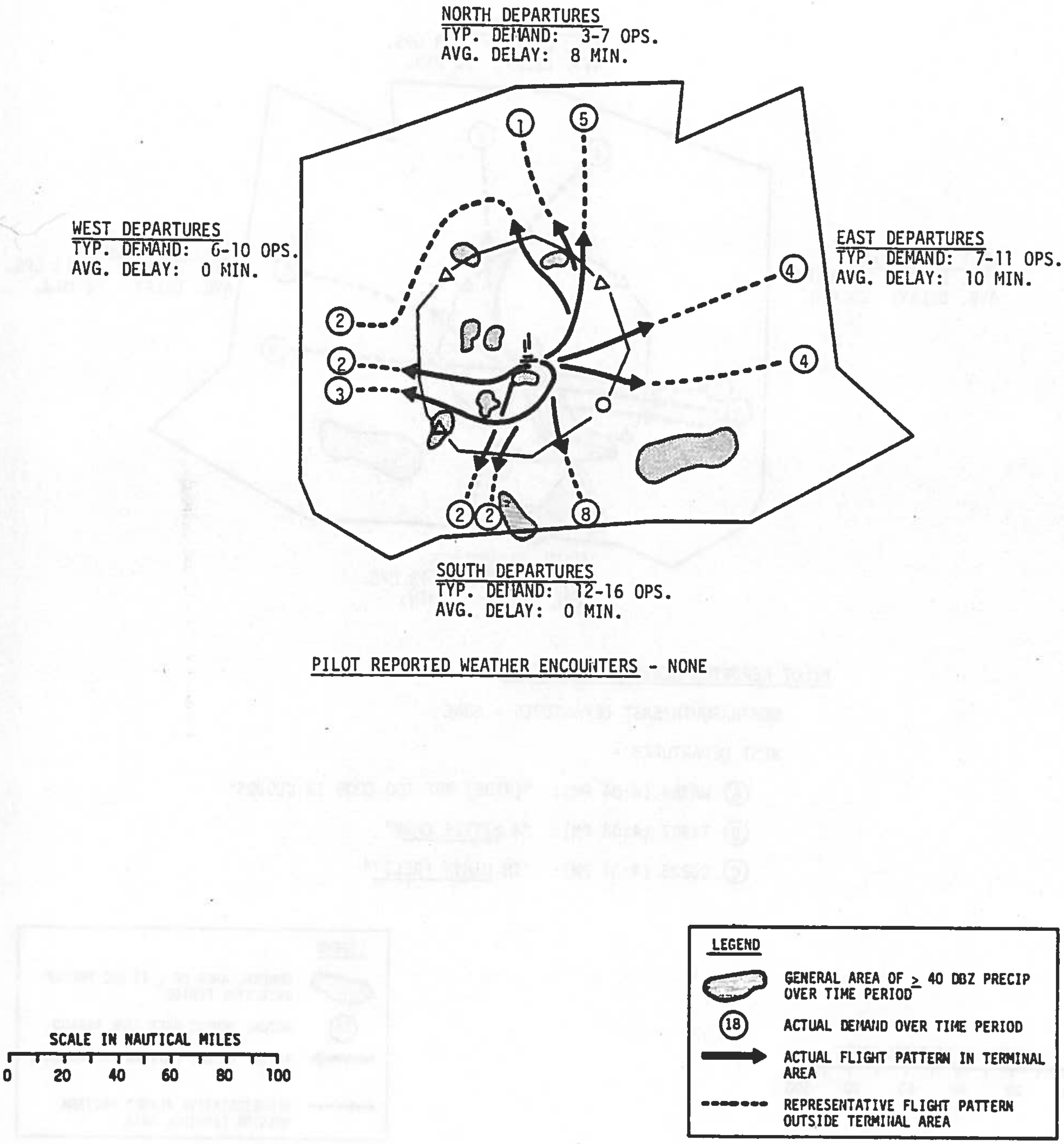


FIGURE 4-6(A). JULY 28 CASE STUDY - WEATHER IMPACT ON THE STAPLETON DEPARTURE OPERATION DURING THE FIRST HOUR

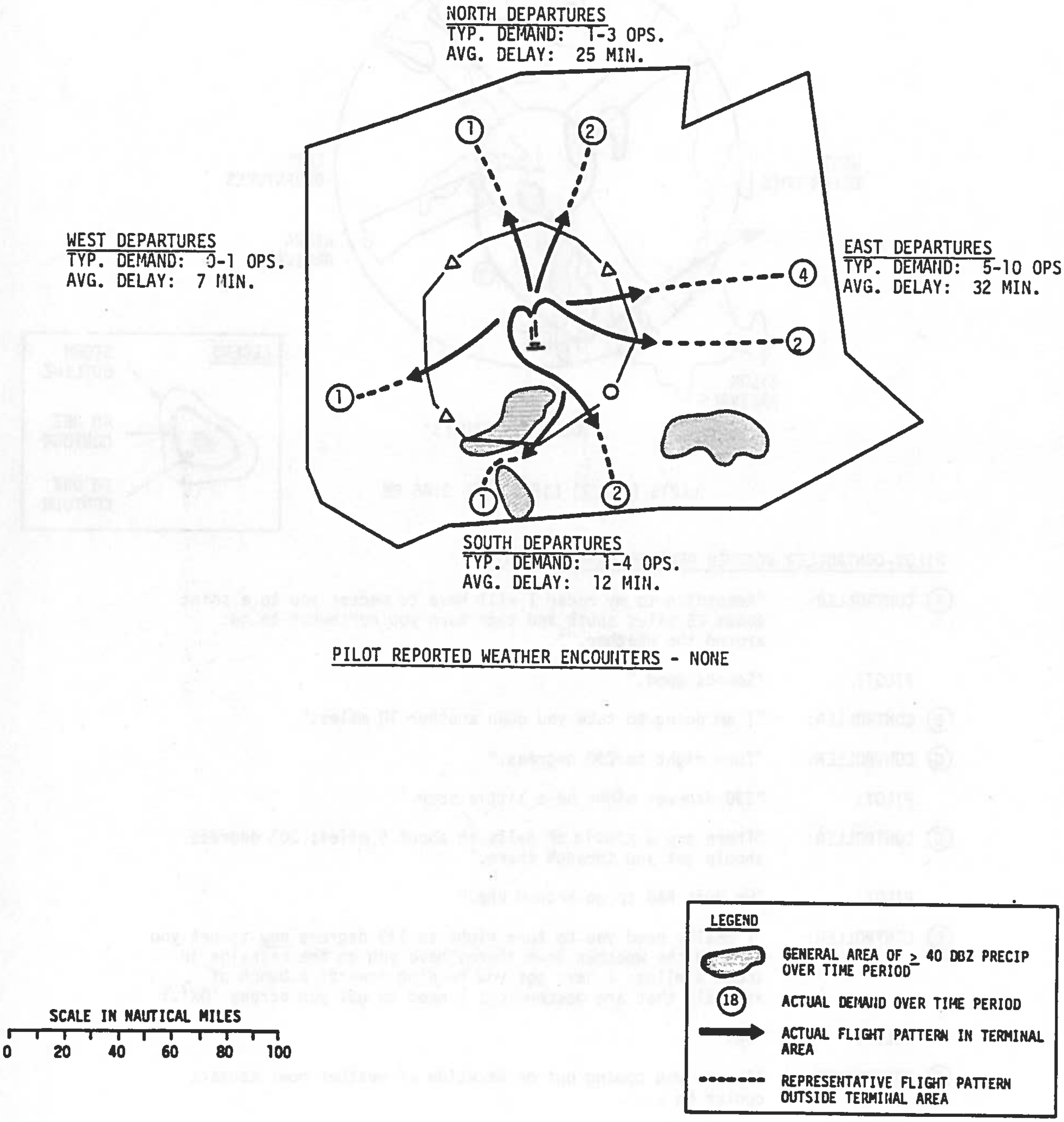
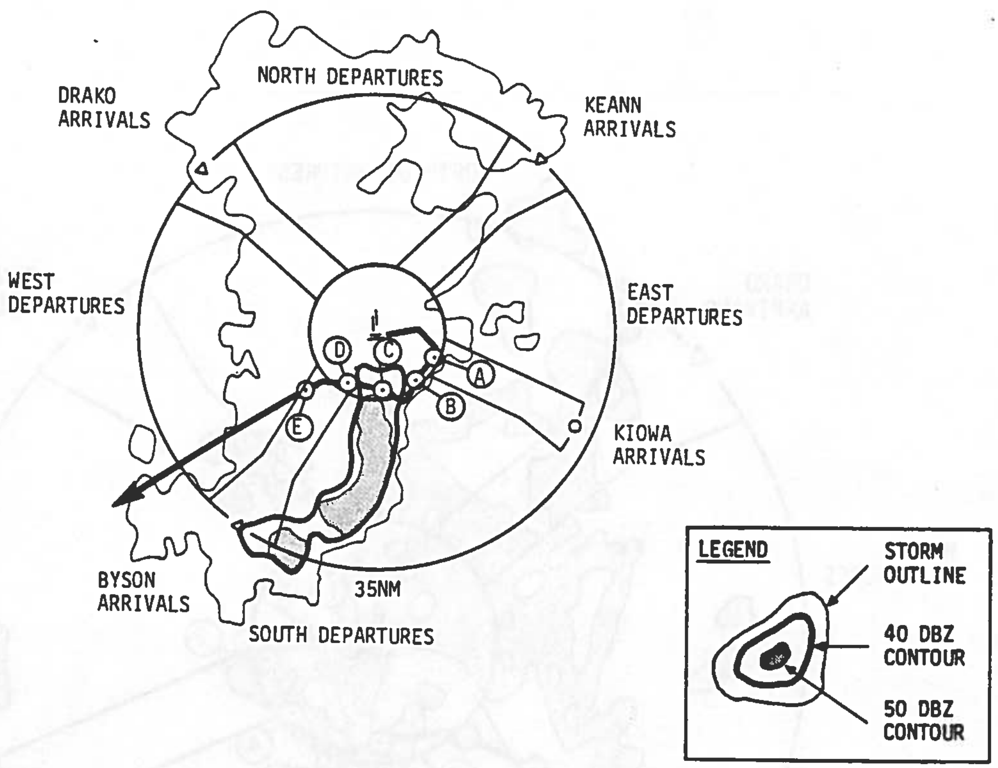


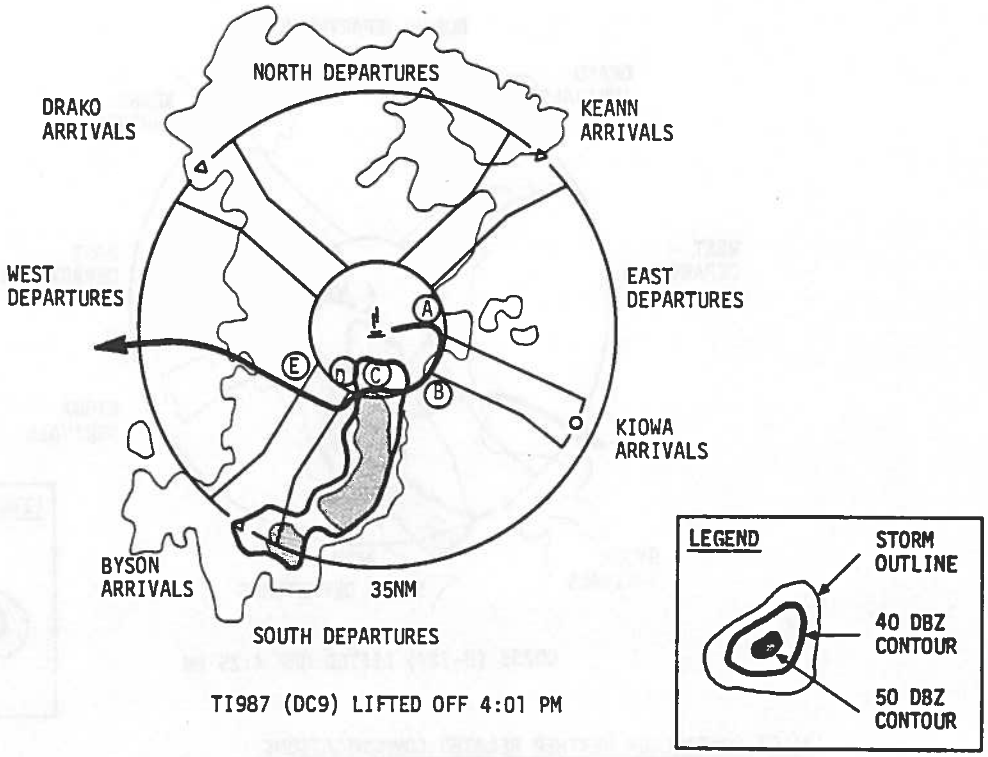
FIGURE 4-6(C). JULY 28 CASE STUDY - WEATHER IMPACT ON THE STAPLETON DEPARTURE OPERATION DURING THE LAST 20 MINUTES OF THE SECOND HOUR



PILOT-CONTROLLER WEATHER RELATED COMMUNICATIONS

(A)	CONTROLLER:	"The line south of airport is tying together to form almost a solid line. About 12 miles south there is a very light area. I plan to take you through that area westbound."
	PILOT:	"Look forward to it."
(B)	PILOT:	"We would like to veer to the southeast, there is a good size cell at 12 o'clock and 25 miles."
	CONTROLLER:	"You have got a cell at 12 o'clock in 8 miles. I plan to turn you to 290 degrees in about 3 miles. It will take you through light air and you will be on the backside in about 4 miles."
(C)	CONTROLLER:	"How is the ride? You're just about ready to come out of the weather in 2 miles."
	PILOT:	"Not too good in the clouds but it looks good ahead."
	CONTROLLER:	"That is the lighest area. Otherwise I would have had to take you 30 to 40 miles south to get you around the weather."
	PILOT:	"This looks good, really."
(D)	CONTROLLER:	"I show you coming out of the backside of it now. How was it?"
	PILOT:	"Not bad, but a little farther north would have been a smoother ride."
(E)		Handoff to the Enroute Center.

FIGURE 4-8(A). JULY 28 CASE STUDY - WEST GATE DEPARTURE WA363



<u>PILOT-CONTROLLER WEATHER RELATED COMMUNICATIONS</u>

Ⓐ PILOT: "Are you going to take us out of this weather?"

CONTROLLER: "We are going to vector you through a light area about 10 miles south."

Ⓑ CONTROLLER: "Turn right to 250 degrees; it will be a little bumpy through there for 2 to 3 miles but a Western just went through there and the pilot said that it looks good on the backside."

Ⓒ CONTROLLER: "You will be coming out of weather in 2 miles. How is the ride in there?"

PILOT: "A little chop."

Ⓓ CONTROLLER: "You should be coming out of it now."

PILOT: "Good work."

Ⓔ CONTROLLER: "That heading ... will take you west of all the weather we are showing; contact center on ..."

FIGURE 4-9. JULY 28 CASE STUDY - WEST GATE DEPARTURE TI987

In the follow-up controller discussions, the aggressiveness shown by these pilots and controller in getting the West Gate departures through the line of thunderstorm activity and out the expected gate was characterized as typical. If the pilots, on examination of the situation with their airborne weather radars, had considered crossing the line of thunderstorm activity as risky, the West Gate would have been closed. The closing of the departure gate would have involved: (1) for the pilots that tried to get through the line of thunderstorm activity, an unknown increase in flying time as they were handed off to the Enroute Center at an unexpected gate, (2) for the ATC personnel at the Denver TRACON and Enroute Center, the need to coordinate the unexpected handoffs of the first few departures and then to initiate the Severe Weather Avoidance Procedure for the following Stapleton departures and (3) for the following west bound Stapleton departures, ground delay in addition to increased flying times if the increased demand on the remaining departure gates and routes exceeded their capacities. Gate closures are avoided whenever possible.

Denver controllers tend to be comfortable with the current FAA weather avoidance policy. The controller, on a time permitting basis, suggests the "best" path through the weather given the weather information available and the pilot makes the final decision on whether or not to follow the suggested path based on what is seen on the airborne weather radar. This approach will be enhanced in the future as the fleet becomes equipped with airborne Doppler weather radars.

This policy emphasizes the role of NEXRAD based aviation weather maps being used by controllers as a weather penetration tool (i.e., to permit a controller to assess the weather situation and to suggest the best route between the thunderstorm cells if such a route exists). As a weather penetration tool, it is important that the weather mapping algorithms used to generate the controller weather maps do not block off airspace unnecessarily.

Delay

This was one of three case studies used in the weather impact delay analysis. The method used to calculate delay and the results of the delay analysis are presented in Section 4.3. The weather related delays experienced in this case study were:

First Hour

Stapleton arrivals experienced an average delay of 12 minutes
Stapleton departures ... 2 minutes

Second Hour

Stapleton arrivals ... 21 minutes
Stapleton departures ... 22 minutes

Example of a Difficult Thunderstorm Situation

One controller, when asked to describe one of the more difficult thunderstorm situations faced by the Denver TRACON, described the situation

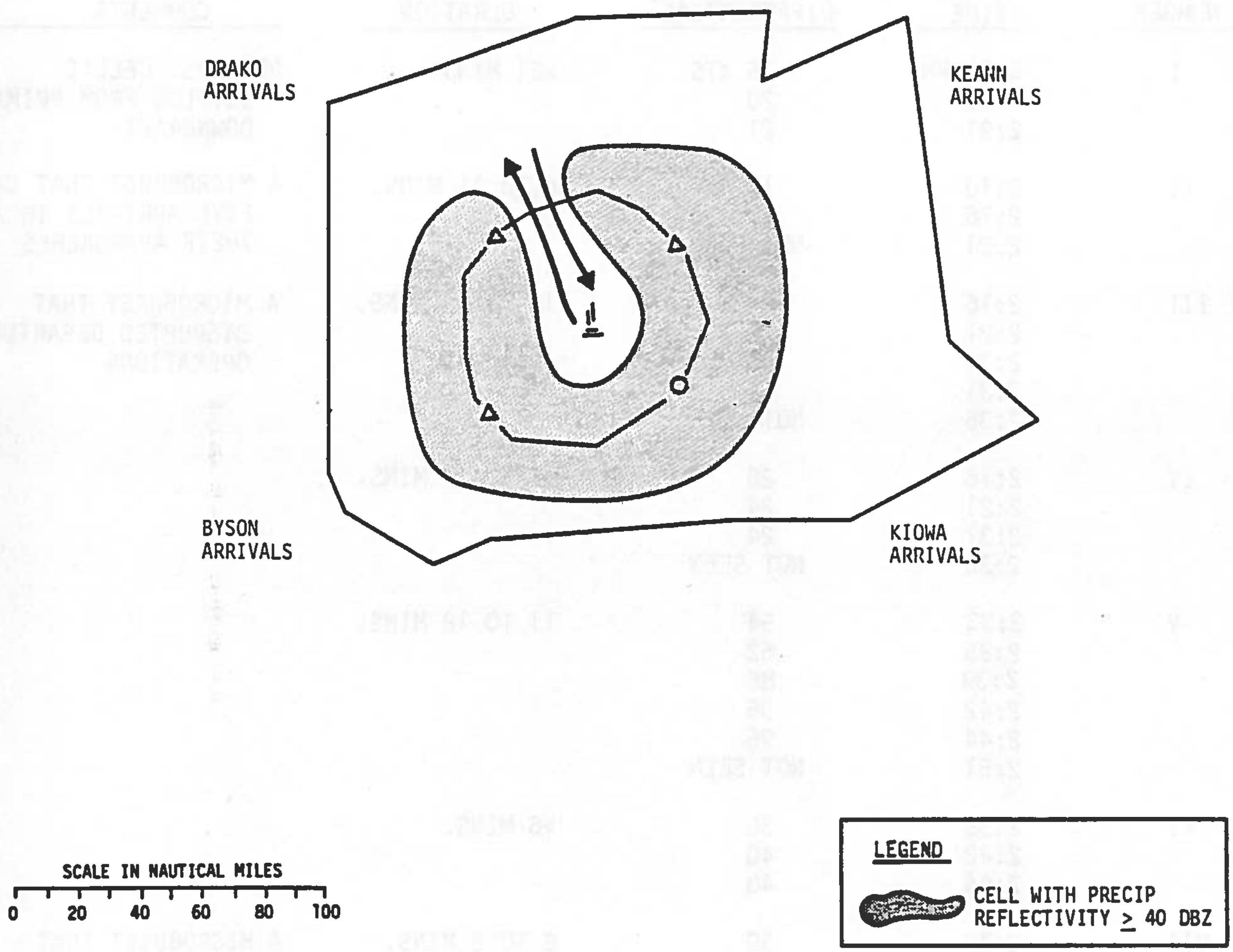


FIGURE 4-11. AN EXAMPLE OF THE WORST CASE THUNDERSTORM SITUATION FACED BY THE DENVER TRACON

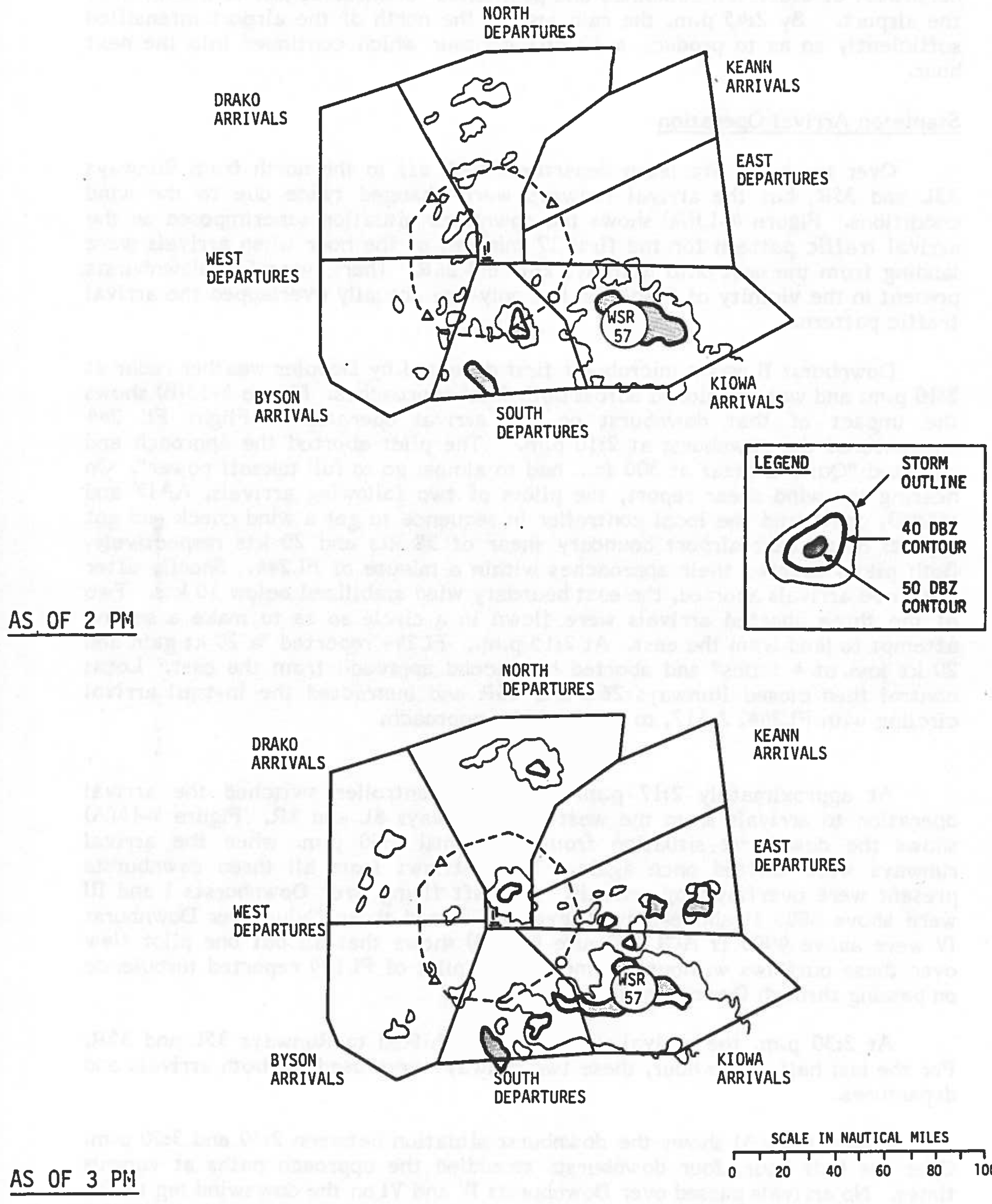
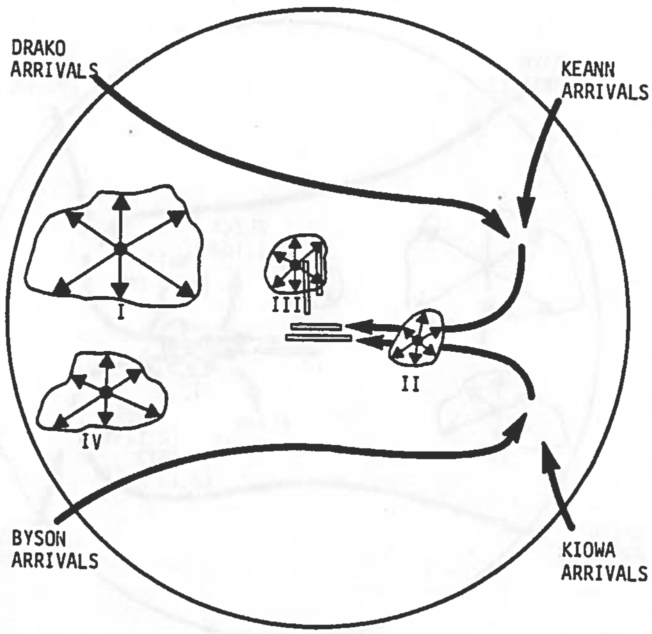


FIGURE 4-12. JULY 14 CASE STUDY - DENVER AREA THUNDERSTORM SITUATION NEAR THE BEGINNING/END OF THE STUDY PERIOD (SOURCE - LIMON WSR57 WEATHER RADAR)



LOW LEVEL WIND FEATURES PRESENT DURING THIS PERIOD

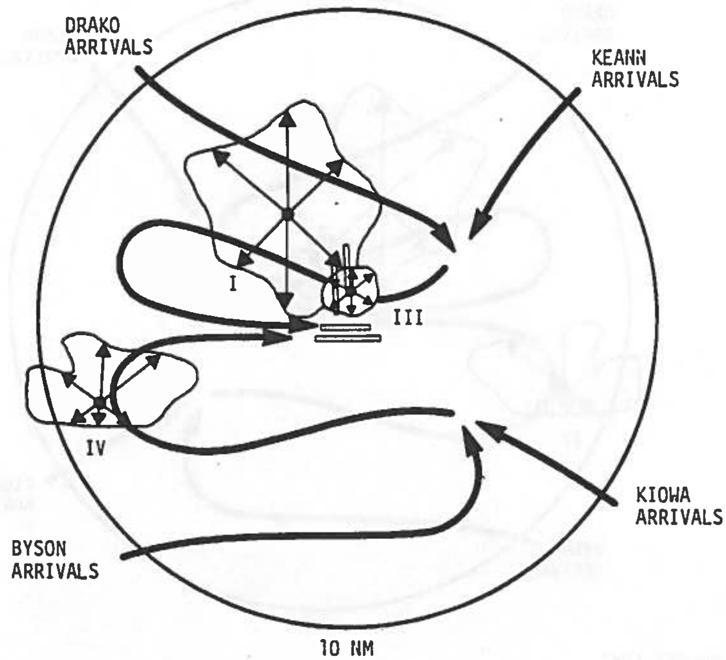
I. DOWNBURST I AS OF 2:00 PM (Δ VELOCITY = 36 KTS)
STARTED: BEFORE 2:00 PM
ENDED: AFTER 2:21 PM
PEAK VEL. DIFF. THIS TIME PERIOD: 36 KTS (2:00 PM)

II. DOWNBURST II AS OF 2:10 PM (Δ VELOCITY = 16 KTS)
STARTED: 2:10 PM
ENDED: AFTER 2:16 PM
PEAK VEL. DIFF. THIS TIME PERIOD: 20 KTS (2:16 PM)

III. DOWNBURST III AS OF 2:16 PM (Δ VELOCITY = 24 KTS)
STARTED: 2:16 PM
ENDED: AFTER 2:31 PM

IV. DOWNBURST IV AS OF 2:16 PM (Δ VELOCITY = 28 KTS)
STARTED: 2:16 PM
ENDED: AFTER 2:31 PM

FIGURE 4-13(A). JULY 14 CASE STUDY - DOWNBURST SITUATION BETWEEN 2:00 AND 2:17 PM SHOWN RELATIVE TO THE STAPLETON ARRIVAL OPERATION



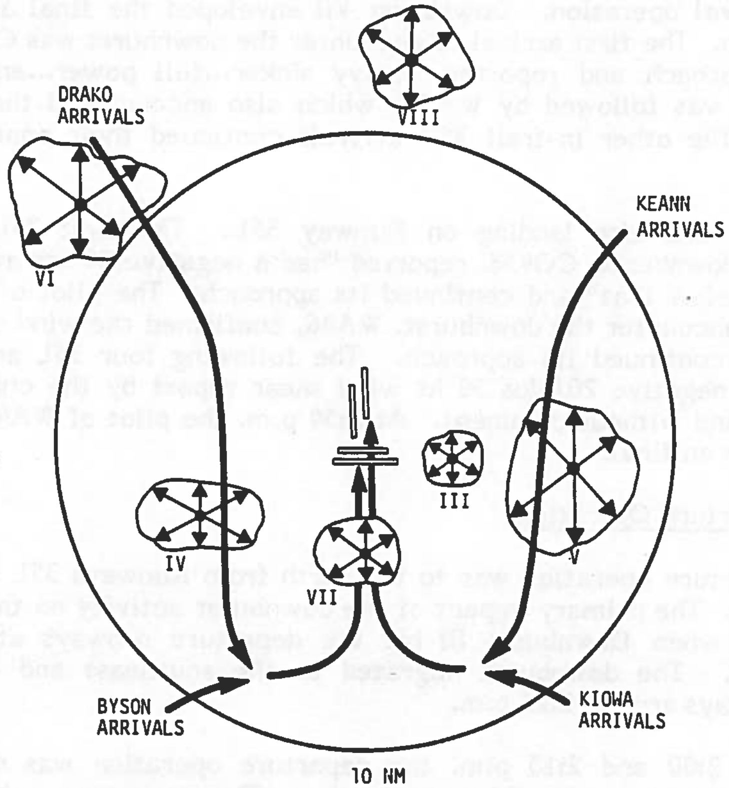
LOW LEVEL WIND FEATURES PRESENT DURING THIS TIME

I. DOWNBURST I AS OF 2:21 PM (Δ VELOCITY = 21 KTS)
STARTED: BEFORE 2:00 PM
ENDED: AFTER 2:21 PM
PEAK VEL. DIFF. THIS TIME PERIOD: 21 KTS (2:21 PM)

III. DOWNBURST III AS OF 2:21 PM (Δ VELOCITY = 24 KTS)
STARTED: 2:16 PM
ENDED: AFTER 2:31 PM
PEAK VEL. DIFF. THIS TIME PERIOD: APPROACHING 44 KTS (2:30 PM)

IV. DOWNBURST IV AS OF 2:21 PM (Δ VELOCITY = 24 KTS)
STARTED: 2:16 PM
ENDED: 2:32 PM
PEAK VEL. DIFF. THIS TIME PERIOD: 24 KTS (ENTIRE PERIOD)

FIGURE 4-14(A). JULY 14 CASE STUDY - DOWNBURST SITUATION BETWEEN 2:17 AND 2:30 PM SHOWN RELATIVE TO THE STAPLETON ARRIVAL OPERATION



LOW LEVEL WIND FEATURES PRESENT DURING THIS PERIOD .

III. DOWNBURST III AS OF 2:31 PM (Δ VELOCITY = 44 KTS)
STARTED: 2:16 PM ENDED: BEFORE 2:36 PM

IV. DOWNBURST IV AS OF 2:31 PM (Δ VELOCITY = 24 KTS)
STARTED: 2:16 PM ENDED: 2:32 PM

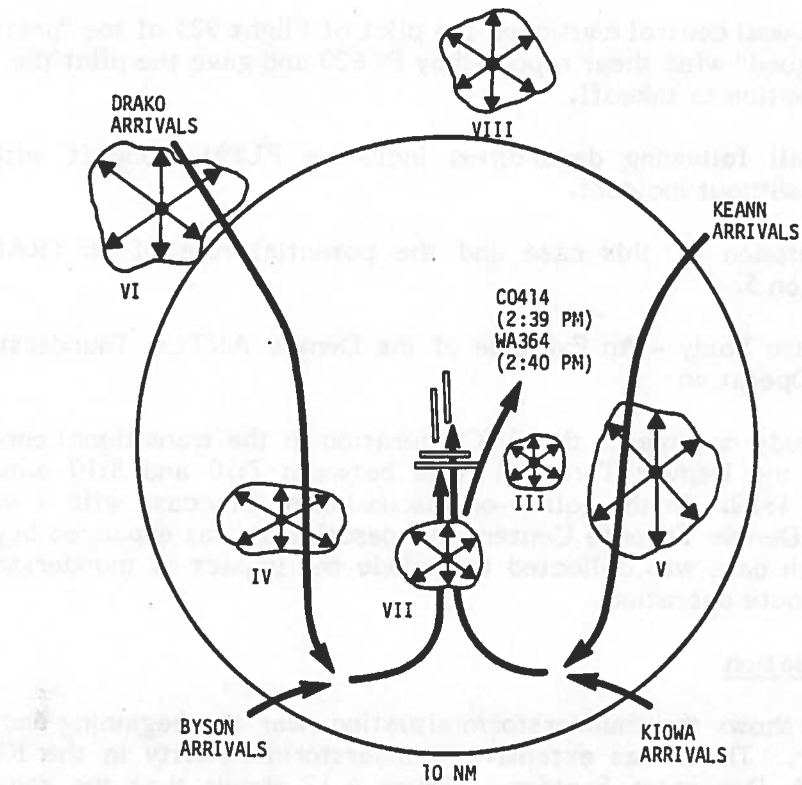
V. DOWNBURST V AS OF 2:33 PM (Δ VELOCITY = 54 KTS)
STARTED: 2:33 PM ENDED: BEFORE 2:51 PM
PEAK VEL. DIFF. THIS TIME PERIOD: 96 KTS (2:43 PM)

VI. DOWNBURST VI AS OF 2:38 PM (Δ VELOCITY = 30 KTS)
STARTED: 2:38 PM ENDED: AFTER 2:44 PM
PEAK. VEL. DIFF. THIS TIME PERIOD: 40 KTS (2:43 PM)

VII. DOWNBURST VII AS OF 2:39 PM (Δ VELOCITY = 54 KTS)
STARTED: 2:38 PM ENDED: BEFORE 2:46 PM
PEAK VEL. DIFF. THIS TIME PERIOD: 60 KTS (2:42 PM)

VIII. DOWNBURST VIII AS OF 2:51 PM (Δ VELOCITY = 45 KTS)
STARTED: 2:51 PM ENDED: FEW MINUTES LATER

FIGURE 4-15(A). JULY 14 CASE STUDY - DOWNBURST SITUATION BETWEEN 2:30 AND 3:00 PM SHOWN RELATIVE TO THE STAPLETON ARRIVAL OPERATION



TIME ARRIVAL AT DOWNBURST (DB) VII	PILOT DB VII RELATED COMMENTS (RESULTING IMPACT)	
	SEQUENCE OF 35L ARRIVALS	SEQUENCE OF 35R ARRIVALS
2:39 PM		C0414: "HEAVY SINKER...FULL POWER... AND STILL SINKING" ABORTED
2:40 PM	C0458: "HAD A NEG. 20 KTS AT 600 FT AND A PLUS 30 KTS BELOW THAT" LANDED	WA364 "WE DID ALSO (PICK UP THE SINKER)" ABORTED
2:41 PM	WA46: "WE CAN CONFIRM THAT (THE C0458 WIND SHEAR REPORT)" LANDED	RC760: "SINKER STILL THERE ON 2 MILE FINAL...12 TO 15 KT LOSS" LANDED
2:43 PM	ASP 434 - NO COMMENT LANDED	TI932 - NO COMMENT LANDED
2:44 PM	C0422 - NO COMMENT LANDED	
2:45 PM	TCE313 - NO COMMENT LANDED	
2:46 PM	WA302 - NO COMMENT LANDED	PI604: "PICKED UP A 10 TO 15 KT. WIND SHEAR ON 2 MILE FINAL" LANDED
2:49 PM	C0402 NO COMMENT LANDED	414MD - NO COMMENT LANDED
2:54 PM	WA481: "WIND WAS STEADY ON FINAL" LANDED	

FIGURE 4-15(B). JULY 14 CASE STUDY - IMPACT OF A DOWNBURST ON FINAL APPROACH FROM 2:38 TO 2:45 PM

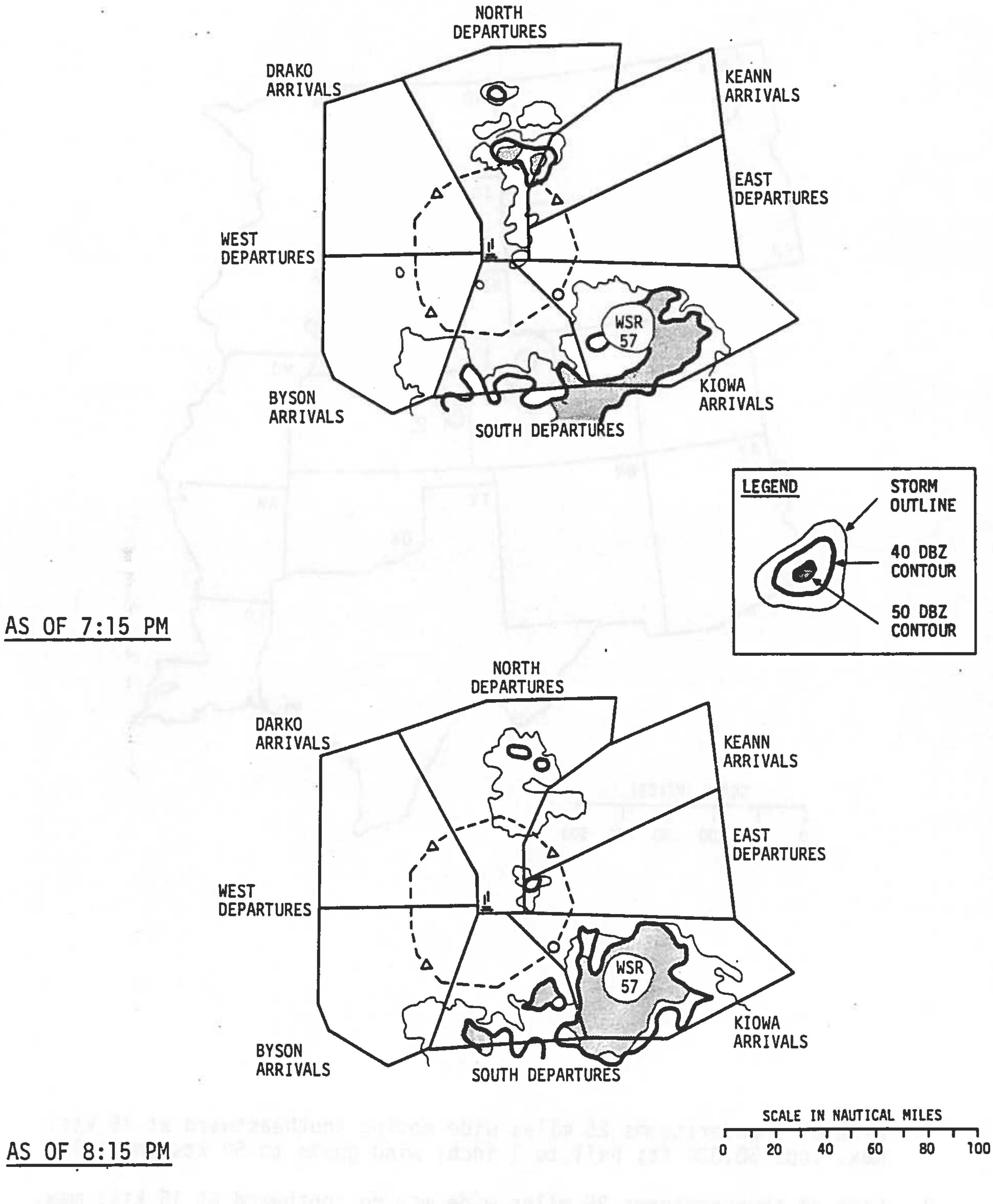


FIGURE 4-16. JULY 26 CASE STUDY - DENVER AREA THUNDERSTORM SITUATION NEAR THE BEGINNING/END OF THE STUDY PERIOD (SOURCE: LIMON WSR57 WEATHER RADAR)

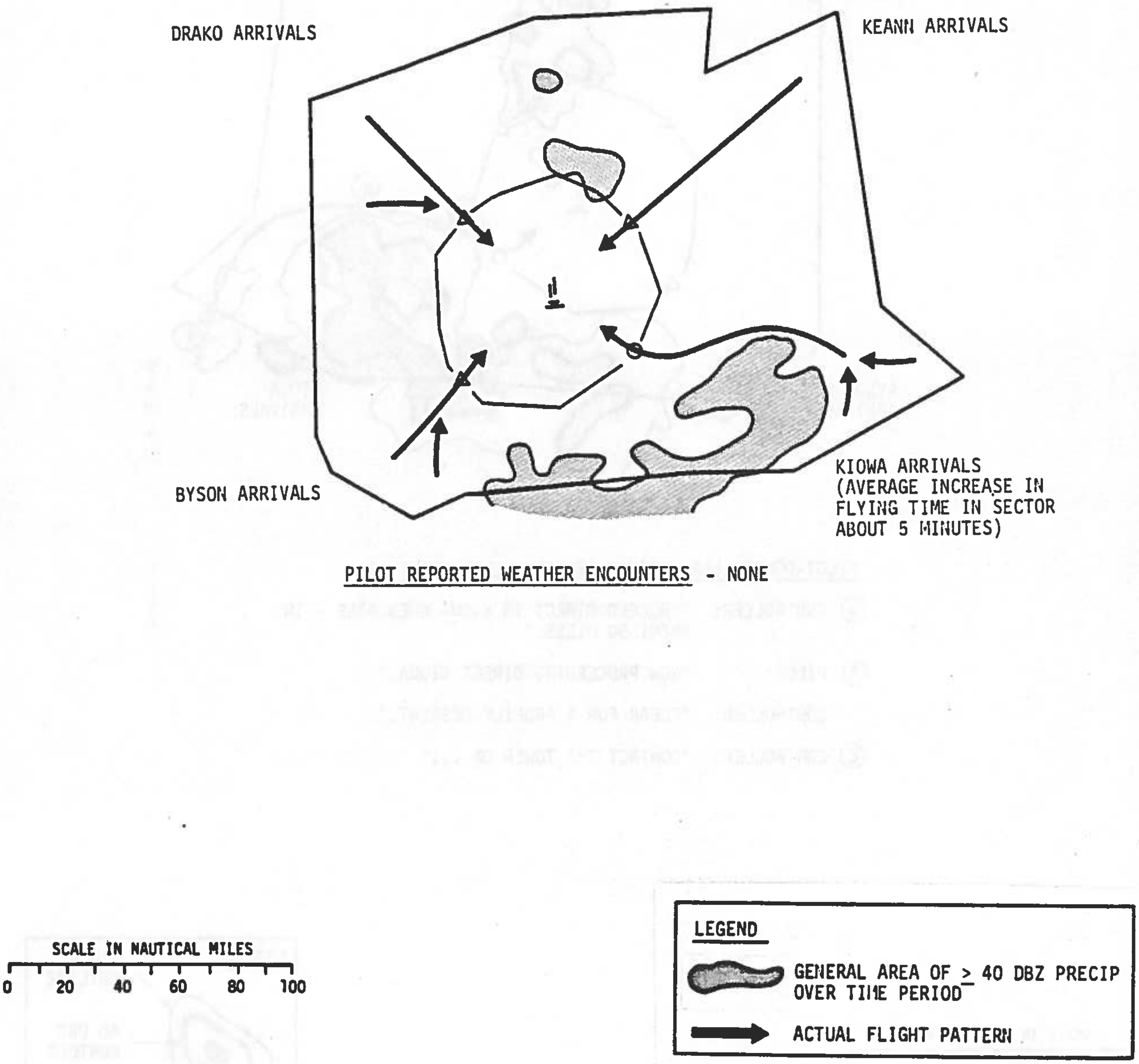


FIGURE 4-18. JULY 26 CASE STUDY - TRAFFIC PATTERN FOR DENVER ARRIVALS DURING THE HOUR

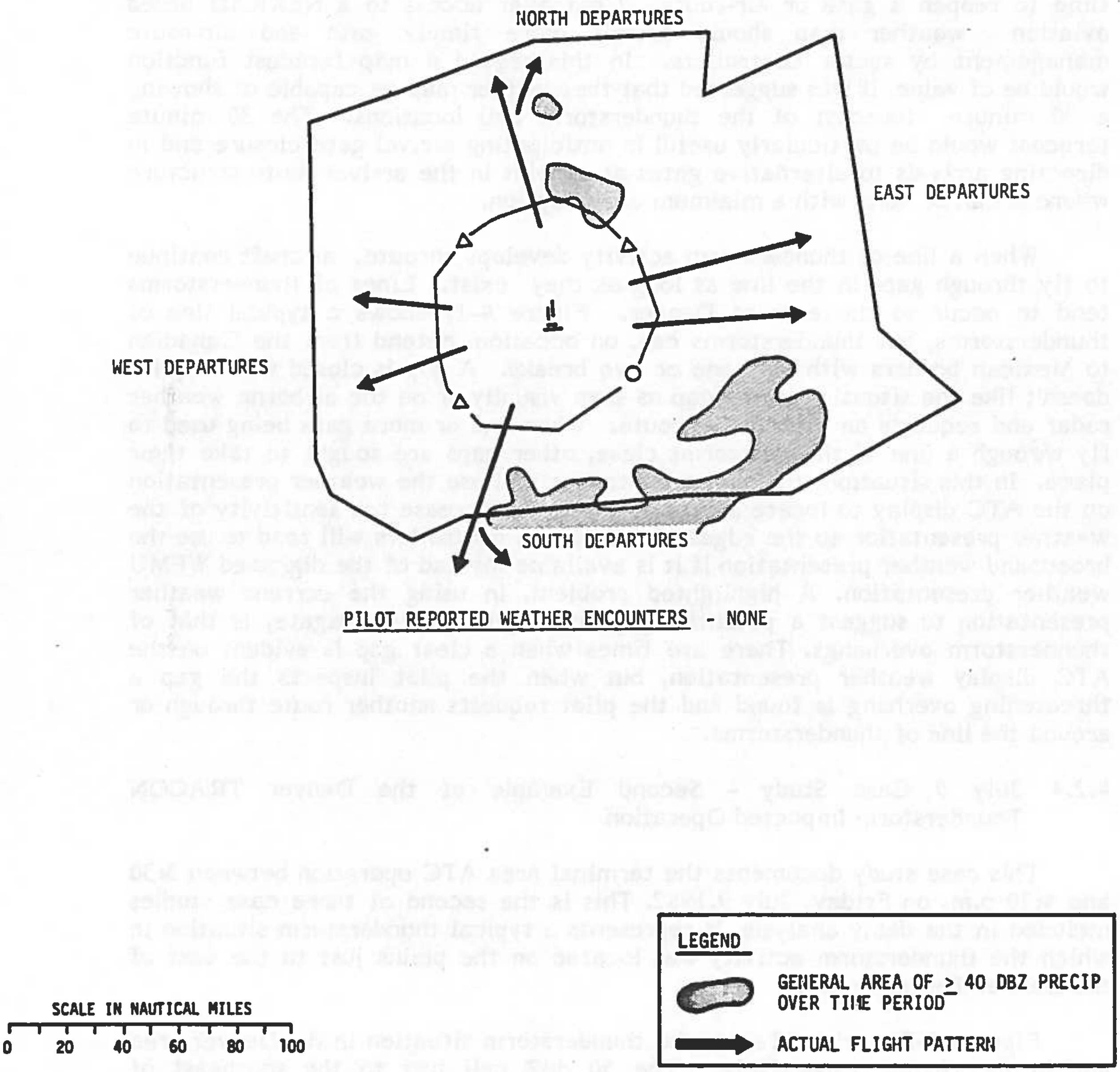


FIGURE 4-20. JULY 26 CASE STUDY - TRAFFIC PATTERN FOR DENVER DEPARTURES DURING THE HOUR

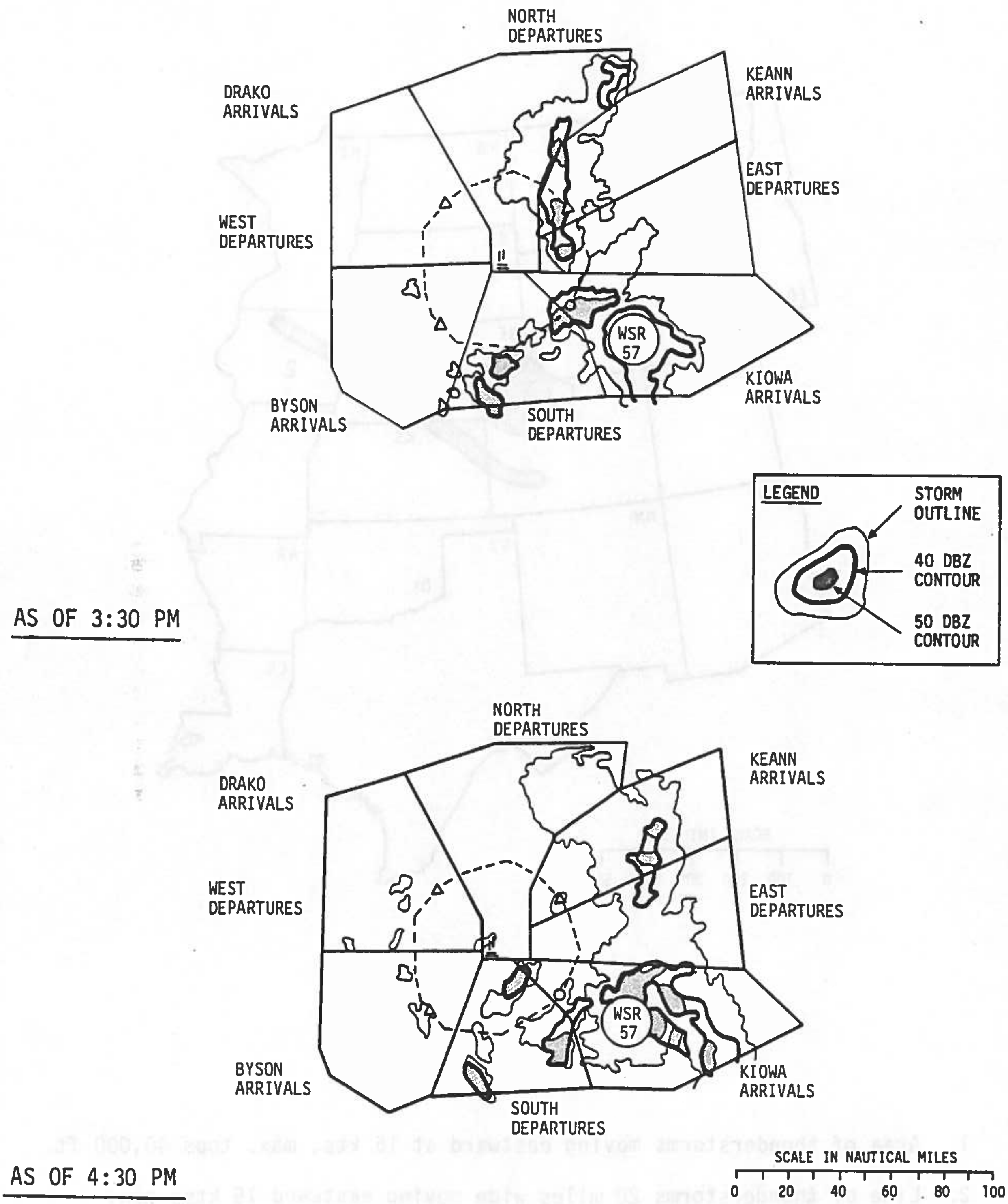


FIGURE 4-21. JULY 9 CASE STUDY - DENVER AREA THUNDERSTORM SITUATION NEAR THE BEGINNING/END OF THE STUDY PERIOD (SOURCE - LIMON WSR 57 WEATHER RADAR)

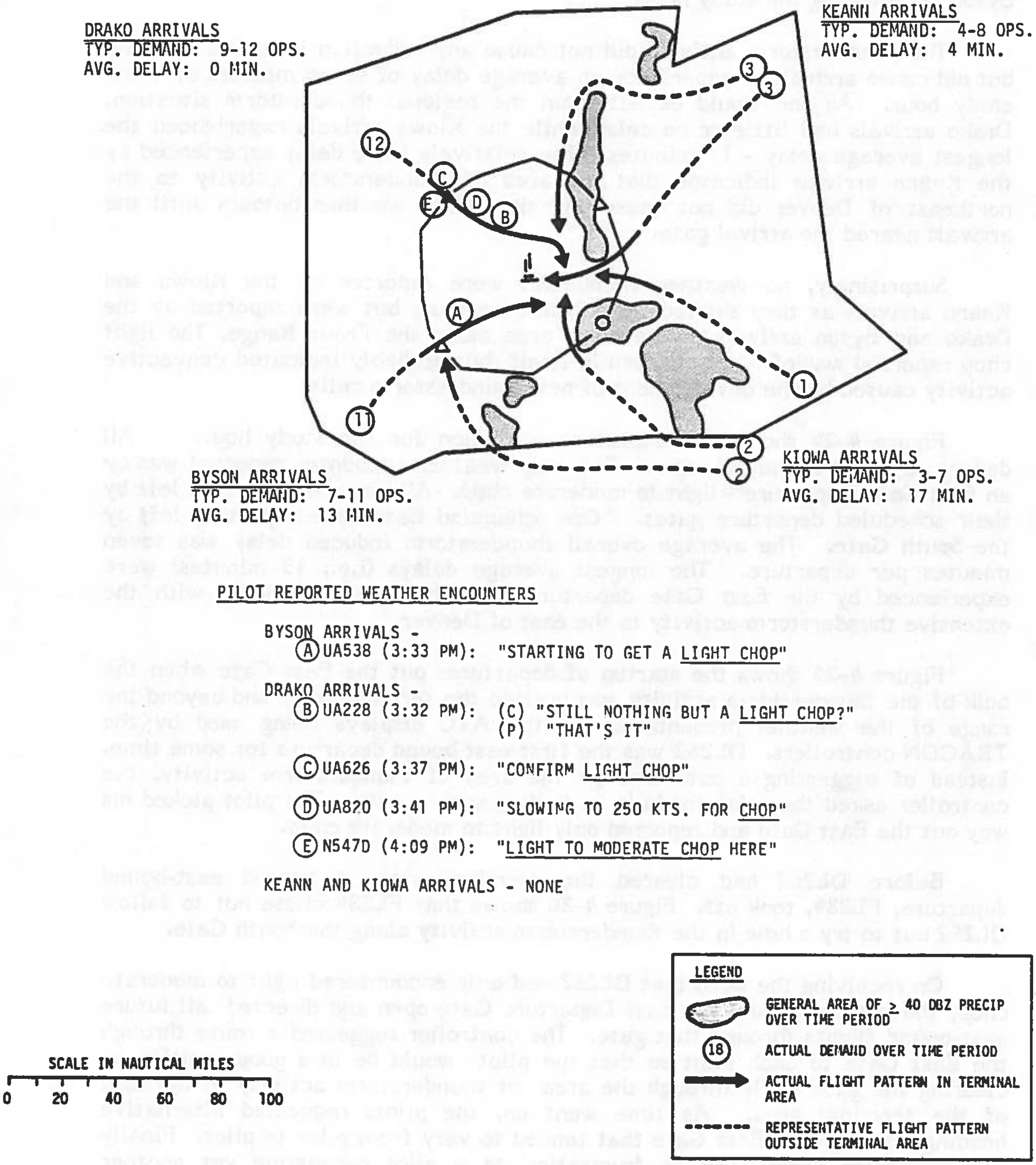


FIGURE 4-23. JULY 9 CASE STUDY - ARRIVAL DELAY AND PILOT REPORTED WEATHER ENCOUNTERS

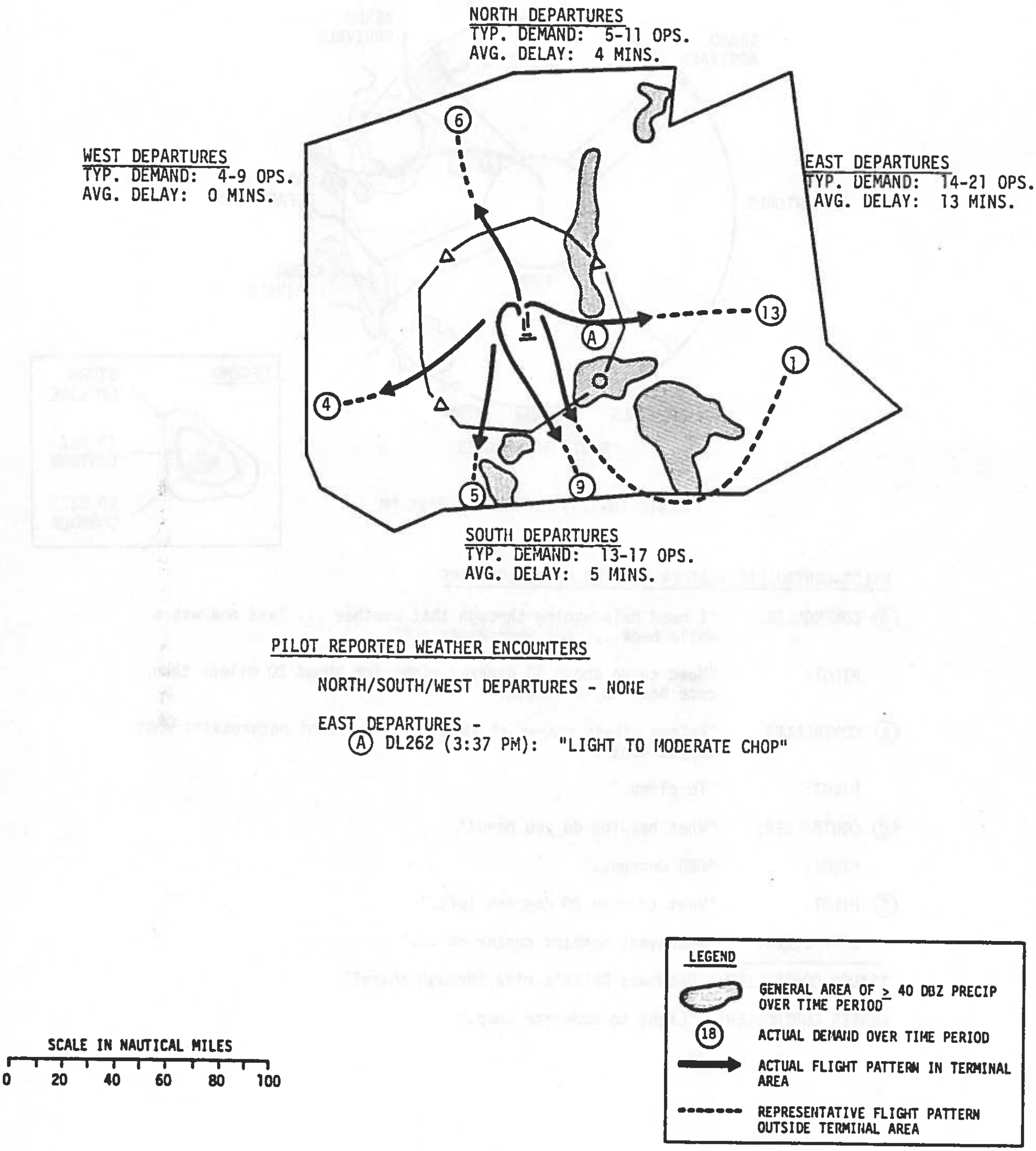
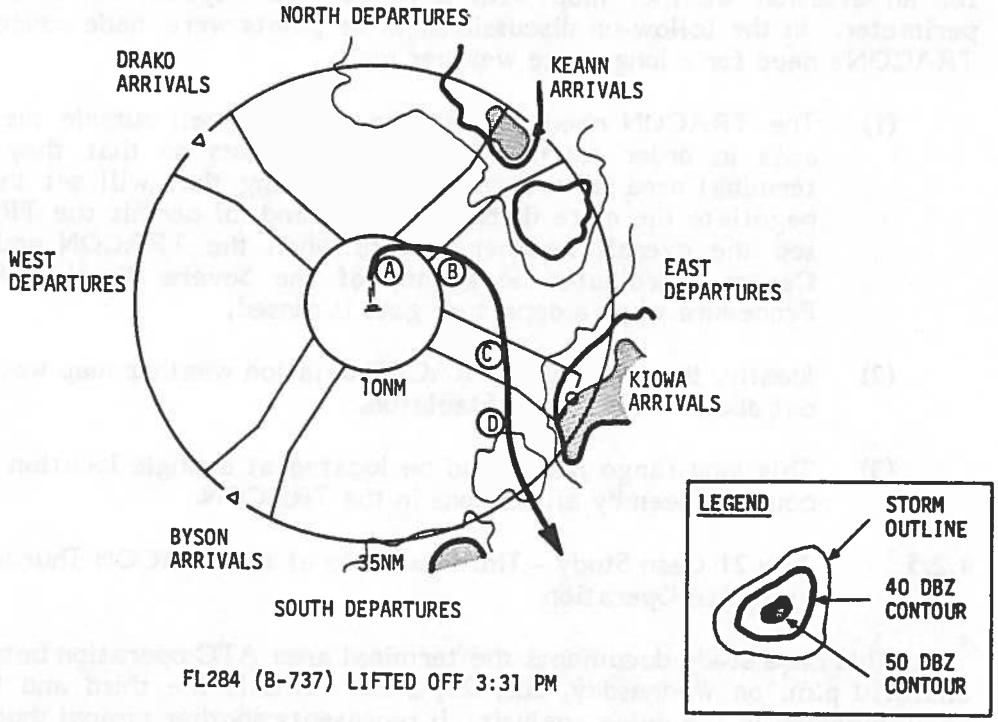


FIGURE 4-24. JULY 9 CASE STUDY - DEPARTURE DELAY AND PILOT REPORTED WEATHER ENCOUNTERS



PILOT-CONTROLLER WEATHER RELATED COMMUNICATIONS

Ⓐ PILOT: "Where is everybody getting through this stuff to the east?"

CONTROLLER: "Have not had anyone going east for awhile; got a Delta out there about 12 miles ahead of you and we are just going to find out."

PILOT: "On our radar, it looks like there are holes to the south."

CONTROLLER: "Last one went south and had to go all the way to Lamar."

Ⓑ PILOT: "We would like a 150 degree heading."

CONTROLLER: "Turn right to 160 degrees."

Ⓒ PILOT: "Want to go to right a mile or so."

CONTROLLER: "Approved."

Ⓓ CONTROLLER: "Contact center on ..."

FIGURE 4-26. JULY 9 CASE STUDY - EAST GATE DEPARTURE FL284 THAT DEVIATED TO SOUTH GATE

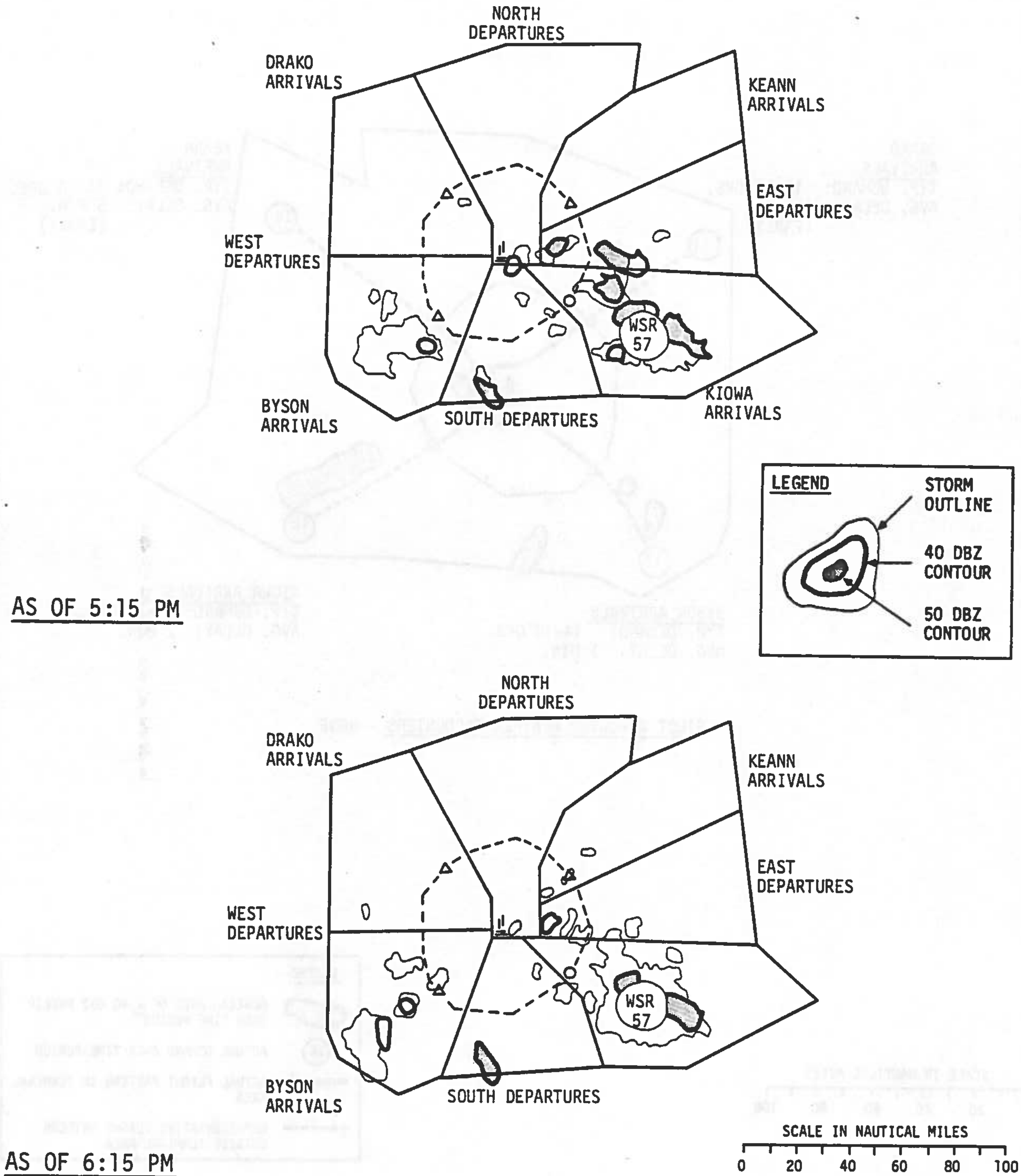
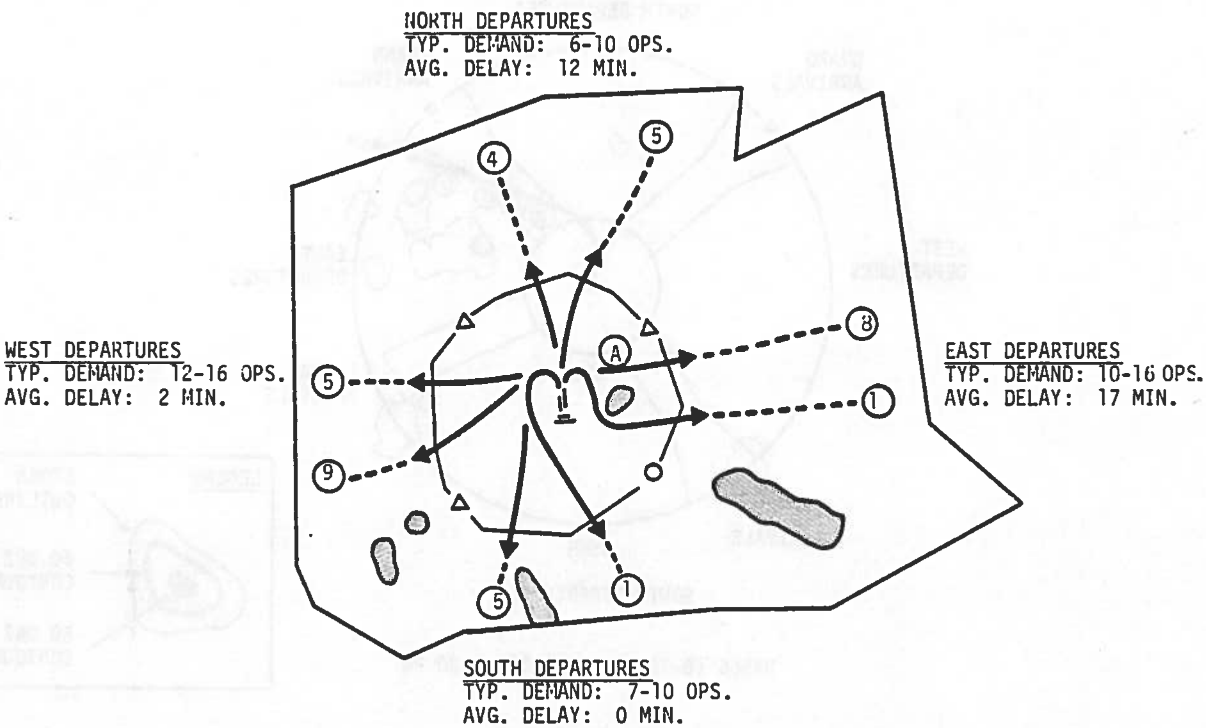


FIGURE 4-27. JULY 21 CASE STUDY - DENVER AREA THUNDERSTORM SITUATION NEAR THE BEGINNING/END OF THE STUDY PERIOD (SOURCE: LIMON WSR57 WEATHER RADAR)



PILOT REPORTED WEATHER ENCOUNTERS

NORTH/SOUTH/WEST DEPARTURES - NONE

EAST DEPARTURES -
(A) UA566 (5:25 PM): "MODERATE CHOP HERE AT 10,000 FT."

FIGURE 4-29. JULY 21 CASE STUDY - DEPARTURE DELAY AND PILOT REPORTED WEATHER ENCOUNTERS

4.3 Thunderstorm Related Delay

Weather related delays were calculated for the July 9, 21, and 28 case studies. To put the results of this limited sampling into a larger context, the results were used as a basis for a general discussion of thunderstorm related delay with a flow controller at the Denver ARTCC. This subsection presents the method used to calculate delay, the results of the delay analysis and the results of the follow-up discussion.

Thunderstorm Related Delays Experienced in Three of the Case Studies

For terminal area operations, the FAA records delay as of touchdown and liftoff. The FAA does not record delays of less than 15 minutes. This missing component of delay had to be estimated from other data sources.

To estimate thunderstorm related delay for departures, the study used the FAA procedure for estimating delay as of takeoff and added any increases in flying times taken to reach the terminal area departure gates due to detours around the weather. The specific means used to estimate departure delay along with the sources of information used in the calculation are presented in Table 4-2. An attempt was made to screen out those flights to such airports as O'Hare and JFK that experienced gate delays at Stapleton on a daily basis due to traffic volume restrictions put into effect at the time of the controller strike.

To estimate the thunderstorm related delays for arrivals, the study estimated the delay of arrivals on reaching the terminal area arrival gates and then added any increases in flying times taken to reach Stapleton Airport due to detours around weather in the terminal area. The means used to calculate arrival delays and the sources of information used in the calculation are presented in Table 4-3.

The three case studies included in the delay analysis span a range of thunderstorm activities. The July 21 Case Study involved the least activity. Figures 4-28 and 4-29 show the arrival and departure operations for that case. There was a little thunderstorm activity in the terminal area but at the start of the study period the thunderstorm situation was worsening some distance to the east of the Denver area. This more distant weather caused the departures out the East and North Gates to be delayed on average by 17 and 12 minutes respectively. The average delay over the hour for all departures was seven minutes. This sudden worsening of the enroute situation had not yet impacted the arrivals coming into Stapleton which experienced no delay on average over the hour.

The July 9 Case Study was characterized by extensive thunderstorm activity along the eastern perimeter of the Denver Terminal Area and farther out on the plains to the east of the Denver area. Figures 4-23 and 4-24 show

TABLE 4-3. METHOD USED TO CALCULATE THUNDERSTORM RELATED ARRIVAL DELAYS

COMPONENTS OF THE CALCULATION	DATA SOURCE
(ACTUAL TIME OF ARRIVAL AT TERMINAL AREA GATE) [E.Q., 0830]*1	o THE TIME LAPSE FILM OF ATC DISPLAY
MINUS (EXPECTED TIME OF ARRIVAL AT TERMINAL AREA GATE IN GOOD WEATHER CONDITIONS) [E.Q., 0825]*1	o PRINTED ON FLIGHT PROGRESS STRIPS*2
PLUS (TIME NEEDED TO DETOUR AROUND WEATHER IN THE TERMINAL AREA) [E.Q., 2 MIN.]*1	o THE TIME LAPSE FILM OF TRAFFIC ON ATC DISPLAY

NOTES: *1 IN THE EXAMPLE, THE ARRIVAL DELAY WOULD BE (0830-0825+2 = 7 MINUTES DELAY)

*2 FLIGHT PROGRESS STRIPS USED FOR THE SAME ARRIVALS BUT FOR DAYS WHEN THE CENTRAL REGION OF THE COUNTRY WAS FREE OF SIGNIFICANT THUNDERSTORM ACTIVITY. ARRIVALS ARE HIGHLY REPETITIVE DAY TO DAY IN CLEAR WEATHER IN TERMS OF SCHEDULE AND TERMINAL AREA GATE USED.

TABLE 4-4. RESULTS OF THE CASE STUDY DELAY ANALYSIS

	STAPLETON ARRIVAL DELAY				STAPLETON DEPARTURE DELAY			
	EST. OVERALL DELAY *1		FAA RECORDED DELAY *2		EST. OVERALL DELAY *1		FAA RECORDED DELAY *2	
CASE STUDY	AVERAGE	TOTAL A	TOTAL B	PERCENTAGE OF TOTAL A	AVERAGE	TOTAL A	TOTAL B	PERCENTAGE OF TOTAL A
JULY 21	<1 MIN. EARLY	44 MIN. EARLY	0 MIN.	-	7 MIN.	289 MIN.	60 MIN. *3	21%
JULY 9	7 MIN.	252 MIN.	0 MIN.	0%	7 MIN.	276 MIN.	108 MIN. *4	39%
JULY 28 *5	16 MIN.	1218 MIN.	210 MIN. *6	17%	14 MIN.	1023 MIN.	240 MIN. *7	23%

NOTES:
*1 INCLUDES ALL PER FLIGHT DELAYS ≥1 MINUTE
*2 ONLY INCLUDES PER FLIGHT DELAYS ≥15 MINUTES
*3 BASED ON TWO DEPARTURES DELAYED AT STAPLETON FOR 30 MINUTES EACH
*4 BASED ON FOUR DEPARTURES EACH DELAYED AT STAPLETON FOR 27 MINUTES
*5 A TWO HOUR CASE STUDY - ALL OTHER CASE STUDIES ARE ONE HOUR
*6 BASED ON NINE STAPLETON BOUND FLIGHTS BEING HELD AT THEIR DEPARTURE AIRPORTS FOR 15 TO 35 MINUTES DUE TO WEATHER CONDITIONS IN DENVER AREA
*7 BASED ON TWELVE DEPARTURES EACH BEING DELAYED AT STAPLETON FOR TWENTY MINUTES

A General Discussion of Thunderstorm Related Delays

Thunderstorm related delays experienced by Stapleton departures primarily occur on the ground. Once airborne, any additional delays are essentially due to increased flying times caused by detouring around the weather. On-ground departure delays occur when:

(1) Lines or areas of thunderstorm activity, mainly to the east of Denver, cause in-trail separations to be increased for Stapleton departures:

- o Frequency of occurrence - most thunderstorm days
- o Typical duration - several hours
- o Operational impact - affected departures can be delayed up to 30 minutes

(2) A departure gate is closed and the Severe Weather Avoidance Procedure (see Section 4.1) is put into effect:

- o Frequency of occurrence - about half of the thunderstorm days
- o Typical duration - two to three hours
- o Operational impact - if this occurs during one of the daily departure pushes at Stapleton, the affected departures can be delayed up to 45 minutes

(3) Stapleton stops all arrival/departure operations due to a thunderstorm cell being directly over the airport:

- o Frequency of occurrence - a few times per year
- o Typical duration - 10 to 15 minutes
- o Operational impact - all operations delayed by 10 to 15 minutes

Delays experienced by Stapleton arrivals due to thunderstorm activity in the Denver area are primarily caused by increased flying times due to detouring around the weather.

The Expanded Quota Flow Control Procedure (see Section 4.1) is not used in the case of thunderstorm activity, which changes too quickly for long-term planning. As in the July 28 Case Study, this procedure is used when long-term IFR conditions are going to exist at Stapleton. Thunderstorm activity in itself does not cause long-term IFR conditions.

4.4 Thunderstorm Related Weather Encounters

The weather encounters reported during all seven case studies have been analyzed. Table 4-6 presents the results of the weather encounter analysis. The analysis of the Denver Terminal Area operation included six hours of operations and 483 flights. Thirty weather encounters were reported to either the Denver TRACON or Stapleton ATCT. The reported encounters with wind features exceeded those with precipitation by a ratio of five to one. The most common encounter reported was with turbulence or chop. The reported intensity varied from light to moderate. The second most common encounter was with wind shear. Wind shear strength was reported in terms of airspeed loss and/or gain and ranged from 10 kts to velocity differentials of 50 kts. The next most frequent weather encounter reported was with rainfall which was always reported as heavy precip. This was followed by reports of downflow encounters commonly reported either as "little" or "heavy" sinkers. Finally, there was one reported encounter with hail.

The types of weather encounter reports received split by the type of ATC facility. The TRACON received all the chop, turbulence, hail, and three of the four precipitation weather encounter reports. The ATCT received all the wind shear and sinker reports and one precip. report. This split is not surprising given the sensitivity of pilots to airspeed and rate of descent changes while on final approach and initial takeoff climb. In the other phases of flight, pilots are more sensitive to the chop/turbulence that accompanies wind shear and downflows, which they and their passengers can sense directly.

The large number of reported wind shear/sinker encounters permits some insight into how pilots operating out of Stapleton regard such encounters on final approach. Table 4-7 lists the strength of the encounters as characterized by the pilots and their resulting ATC impact. The table suggests that pilots tend to continue their approaches when encountering:

(1) Simple wind shears that either add or reduce airspeed by 15 kts or less,

(2) Opposing wind shears with velocity differentials of up to 50 kts that end in a strong gain in airspeed (This is not the signature of a downburst which ends with a reduction in airspeed but may be the result of two separate wind features in close proximity to one another),

(3) Little sinkers (i.e., weak downflows).

On the other hand, the table suggests that pilots tend to abort their approaches when encountering:

(1) Opposing wind shears with velocities of a 20 kt gain followed by a 20 kt loss or more (This is the signature of a downburst.),

(2) Heavy sinkers (i.e., strong downflows).

The second part of Table 4-7 addresses the question of whether forewarned pilots, within five minutes of a position at which a wind shear/sinker of sufficient strength to cause a preceding pilot to abort his approach, will follow the aborted approach in its go-around or will continue their approaches. Of the two separate heavy sinker encounters that resulted in aborted approaches, three in-trial pilots continued their approaches and landed, one pilot continued the approach but aborted on encountering the sinker's outflow, and three pilots followed the lead aircraft on its go-around without testing the sinker's strength.The tendency of some pilots to continue their approaches in such circumstances may be due to the fact that their experience indicates that sinkers and their associated outflows are short-lived features.

Two hours of thunderstorm impacted operations in the the transitional enroute sectors servicing the Denver Terminal Area were also analyzed. Of the 136 flights monitored, no weather encounters were reported.

This procedure makes good use of the available weather information but has obvious deficiencies:

(1) Piecing together and maintaining the real-time, local aviation weather situation adds to controller workload and is done on a time permitting basis,

(2) The controller's mental map of evolving weather conditions is incomplete. (This lack of current, detailed weather information is particularly evident when a new path through a thunderstorm impacted area is being tried.)

Weather Avoidance/Weather Penetration

In general, it is the role of the controller to advise each pilot of the thunderstorm situation ahead and, if possible, to suggest a flight path relative to the weather. Denver controllers routinely utilize the areas between thunderstorm cells when suggesting these paths.

Pilots are responsible for weather avoidance. Each pilot is to look over the weather situation before entering a thunderstorm impacted area along a controller suggested path. If the situation looks questionable, the pilot is expected to request a deviation from the suggested path.

Relative to aviation weather maps designed for controller use, the controller is interested in both the location of thunderstorm impacted areas and the edges of those impacted areas which define the clear areas that can be considered for use.

Aircraft and Severe Thunderstorm Cell Separations Observed in the Denver Terminal Area

Due to the restricted airspace available in a terminal area, the airspace around and between thunderstorm cells is used aggressively at Denver for capacity reasons. The following observations are based on the TRACON case studies:

(1) When thunderstorm cells were embedded in precipitation, aircraft routinely flew through precipitation levels under 40 dBZ,

(2) If detours around the weather only involved a few extra miles flying distance, the aircraft tended to skirt the thunderstorm activity as defined by the 40 dBZ contour and to keep about six to ten miles from the edges of any 50 dBZ cells,

(3) If longer detours were required to maintain these spacings, the pilots and controllers tended to become more aggressive. In a case where a detour involved 30 to 40 miles and perhaps leaving the terminal area through the wrong gate, a series of three aircraft flew across an elongated 40 dBZ contour and skirted the 50 dBZ core of an extended line of thunderstorm activity. From the pilot comments made on clearing the thunderstorm activity, they were satisfied with the tradeoff as were controllers with which this example was discussed in the follow-up discussions.

(5) Encounters with wind shear are seldom reported as such, probably because the pilots in this phase of flight are more sensitive to the chop/turbulence that is normally associated with shear zones.

Not all reported weather encounters are considered hazardous. In the Denver Terminal Area, TRACON controllers would like to be able to:

(1) Caution pilots about to enter areas of moderate turbulence or heavy rainfall,

(2) Keep aircraft out of areas of greater than moderate turbulence/chop, of greater than heavy rainfall, and of hail when suggesting flight paths around or through thunderstorm impacted areas.

<u>Thunderstorm Related Weather Encounters Reported to the Stapleton ATCT</u>

In contrast to the thunderstorm related weather encounters reported to the TRACON, the encounters reported to the Stapleton ATCT consist almost exclusively of wind shear and sinker reports. This reversal in emphasis is because the ATCT is in contact with pilots on their final approaches and initial takeoff climbs when their aircraft are vulnerable to any abrupt change in airspeed or rate of descent/ascent.

In the six hours of case studies covering the Denver terminal area operation, the Stapleton ATCT received 13 weather encounter reports. Eight of these reports involved wind shears, four involved sinkers, and one involved heavy rainfall which obscured the runway.

Ten of these encounters were from one case study - July 14. In the space of one hour, eight downbursts fell within 12 nautical miles of Stapleton center field. Of these, one made a direct hit on the departure runways, and two hit the final approach paths to Stapleton.

The downburst that hit the departure runways caused considerable uncertainty about the low level winds and takeoffs stopped for about six minutes. Takeoffs started on a voluntary basis when the Low Level Wind Shear Alert System indicated that the airport winds were settling down.

The first downburst to hit the final approach path led to three arrivals aborting their approaches. Two of the flights were then brought around to make a second approach to the same set of runways. When the downburst was encountered a second time, the lead aircraft aborted its approach and the arrival operation was shifted to another set of runways.

The second downburst to hit the final approach paths was at least as powerful as the first but its operational impact was less. The first two arrivals to encounter the downburst were caught in a strong downflow and aborted. However, all following pilots elected to continue their approaches and flew through what was a weakening downburst and landed.

In the follow-up discussion with Denver ARTCC personnel, the following observations were made:

(1) In contrast to the lack of weather encounters reported to the ARTCC during the case studies, the Denver ARTCC usually receives multiple reports whenever thunderstorm activity is present in its airspace,

(2) Via the high altitude sectors, the ARTCC receives multiple reports of light or moderate chop/turbulence encounters each thunderstorm day, but little else,

(3) Via the low altitude sectors, the ARTCC receives reports of:

- o Moderate chop/turbulence encounters a number of times each thunderstorm day,
- o Heavy rainfall encounters almost every thunderstorm day,
- o Hail encounters on over half the thunderstorm days,
- o Severe chop/turbulence encounters very rarely,
- o Wind shear encounters rarely (generally reported as chop/turbulence).

A significant difference between TRACON and ARTCC weather concerns exists relative to moderate turbulence/chop encounters. In contrast to the terminal area, moderate turbulence encounters enroute can result in personal injury due to people being out of their seats and food being served. Today an enroute encounter with moderate turbulence located outside or between thunderstorm cells usually results in that aircraft and the in-trail aircraft changing altitude by a couple of thousand feet. This is an avoidance maneuver that minimizes any increase in flying time and one more typical of non-convective winter storms. The typical weather avoidance maneuver used in convective storms is to fly around the particular weather feature of concern. Ideally, any Doppler weather radar map format designed for use by ARTCC controllers would support the controller in both of these weather avoidance maneuvers.

Thunderstorm Related Aircaft Delay

Weather related delay was calculated for Stapleton arrivals and departures in three of the case studies covering four hours of operations. For the purpose of the study, delay was estimated as of touchdown for arrivals and as of clearing the Denver Terminal Area departure gates for departures. The FAA only records delays 15 minutes or longer in duration. This meant that delay data were not directly available as data of record but had to be estimated based on the data collected.

At the Denver TRACON, accurate advisories of weather encounters will have less impact in reducing the number of encounters. While under TRACON control, pilots want to be advised of impending moderate turbulence and heavy rainfall encounters but primarily wish to avoid hail encounters, which are currently reported only a few times each year, and turbulence encounters reported as severe, which are rarely encountered.

The Stapleton ATCT routinely operates in the presence of thunderstorm generated wind shears and downflows. The ability to advise pilots of the location and strength of low level wind features on the final approach paths and the initial takeoff climb paths would be an important service. In order to provide this service, the terminal area Doppler weather radar would have to be sited at or near the airport.

If the airport and terminal area coverages were to be provided by a NEXRAD network site, the radar would operate with a five minute full volume scan cycle. The resulting aviation weather map product for ATCT use may not permit controllers to consistently advise pilots before the initial encounter with the "sudden" appearance of a downburst. The extent that pilots will be forewarned will depend on how early a downburst is detectable in its descent by Doppler weather radar (i.e., at what altitude are downbursts detectable) - an unresolved issue. Regardless of the outcome of this issue, a NEXRAD map product for ATCT use should: (1) permit the controller to advise pilots of gust fronts and wind shifts approaching the airport and long-lived downburst outflows and (2) help the controller to manage the runway operation so as to minimize exposure to wind shear activity.

Ideally, the antenna scanning strategy of a terminal area weather radar would operate at a one to two minute update cycle. The corresponding increase in the update rate of the ATCT aviation weather map would improve the ability of controllers to advise pilots before the first encounters with downbursts take place.

The ability of: (1) controllers to use a NEXRAD aviation weather map to assess and monitor the alternative paths through/around thunderstorm impacted areas contained in their individual airspaces and (2) ATC supervisors to do the same on a larger scale, should result in delay savings in several areas:

(1) At the closure of a terminal area gate or ARTCC air-route, the alternatives could be assessed for the detour that would minimize the increase in flying times,

(2) While the detour is in effect, the alternative paths could be monitored for the creation of one that would permit the detour flying times to be reduced,

(3) To promptly recognize when the detour is no longer required and to reopen the gate or air-route.

There was also one example of using such a map to reopen a terminal area arrival gate sooner. The example involved a total delay savings of 60 minutes. Assuming that the extent of this delay savings to be representative of the arrival gate closure and reopening that typically occurs once per thunderstorm day, then the yearly savings due to this source would be:

(1)	Average savings per incident	60 minutes
(2)	Average number of incidents per thunderstorm day	1
(3)	Average number of thunderstorm days per year in the Denver area	35
(4)	Total reduction in thunderstorm related airborne delay per year	2100 minutes
(5)	Delay savings (assuming $30 savings per airborne minute) (see Table 4-5)	$63K per year

The preliminary estimate of the savings in delay due to a Denver TRACON NEXRAD aviation weather map is $100K per year. This estimate should be considered conservative since it is based on a data set consisting only of typical thunderstorm days.

Of the two case studies covering the ARTCC operation, no examples were found where an ARTCC NEXRAD aviation weather map could have been used to either shorten weather detours or to reopen sooner air-routes closed due to thunderstorm activity. This is due to the small size of the data base in both duration (i.e., only two hours of operational data) and extent (i.e., only seven of the over 30 Denver ARTCC sectors are covered in the data sets). Although an estimate can not be made of the delay savings that an ARTCC NEXRAD aviation weather map would provide, it is expected that the savings would be substantial.

The following statement summarizes the general view expressed by the Denver ATC personnel involved with this study concerning the potential ATC role of NEXRAD. If the operational NEXRAD system lives up to its potential and controllers find that they can rely on the system for their real-time weather information requirements, then NEXRAD will have provided the ATC facilities with a much needed tool for the safe and expeditions handling of aircraft.