ANALYSIS OF THE 12 APRIL 1996 WIND SHEAR INCIDENT AT DFW AIRPORT*‡

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1. INTRODUCTION

Wind shear detection algorithms that operate on Doppler radar data are tuned to primarily recognize the velocity and reflectivity signatures associated with microbursts and gust fronts. Microbursts produce a divergent pattern in the velocity field that is associated with a descending column of precipitation. Gust fronts produce a convergent pattern that is often associated with a thin-line reflectivity feature.

On April 12, 1996 at Dallas-Fort Worth International Airport (DFW) three pilots reported encounters with wind shear in a five minute period (2329-33 GMT). The third pilot (AA 1352) reported an encounter with "severe wind shear", which we refer to as "the incident" throughout the paper. He used maximum throttle to keep the MD-80 in the air and reported that it was only "by the grace of God" that the aircraft did not crash (Dallas Morning News, 4/19/96). The plane, originally bound for Pittsburgh, was diverted to Tulsa where the passengers were offloaded to another aircraft, the black box was removed, and the engines were checked according to procedures required whenever maximum throttle is utilized.

At the time of the incident (2333 GMT), the airport was under the trailing stratiform region of level 1 precipitation associated with a line of thunderstorms 20 miles to the east. Preliminary review of the available data indicates neither a microburst nor a gust front in the velocity field at the time of the incident. We hypothesize that two separate groups of gravity waves intersected over the DFW airport. In addition to their inherent wind shear, their intersection plausibly led to zones of strong vorticity which we believe explain some of the evidence pointing to rotational wind shear associated with the incident.

In this paper we discuss the wind shear encounters from the air traffic perspective, and have included the Airport Surveillance Radar (ASR-9) data and partial transcripts of the radio communications around the time of the incident. Next, we include some limited visual observations from witnesses at the time of the incident. To understand the meteorological setting, we study the environmental conditions at the time, using the National Weather Service (NWS) surface chart and Ft. Worth sounding, and the GOES-8 satellite data. We then look for evidence of low altitude wind shear in the data from the Dallas Love Terminal Doppler Weather Radar (TDWR), the DFW Low Level Wind Shear Alert System (LLWAS), and the DFW Automated Surface Observing System (ASOS). Figure 1 shows the location of these sensors. The DFW TDWR, located to the north, was not commissioned or in service at the time of this incident, so no data from this sensor was available for analysis. The Fort Worth NEXRAD (KFWS) was operational and the data was examined, but the sensor was too far from the airport (45 km) to provide any additional information on the low altitude wind shear.

2. WIND SHEAR ENCOUNTERS

DFW operations were severely impeded on April 12 by a line of severe thunderstorms that ploughed through the DFW airspace, as well as a four-hour problem with the air traffic control (HOST) computer at the Fort Worth Air Route Traffic Control Center (ZFW). Delays exceeded four hours for some aircraft.

The airport was operating in a "south flow" (planes taking off and landing towards the south) before the storms reached the airport. The line of storms approached from the west and prevented arrivals starting at 2205 GMT (Fig. 2). Departures continued until 2227 GMT. The thunderstorms caused a wind shift at the airport which necessitated a change in runway configuration with nearly 100 aircraft on the ground waiting to depart. The first post-storm departure occurred at

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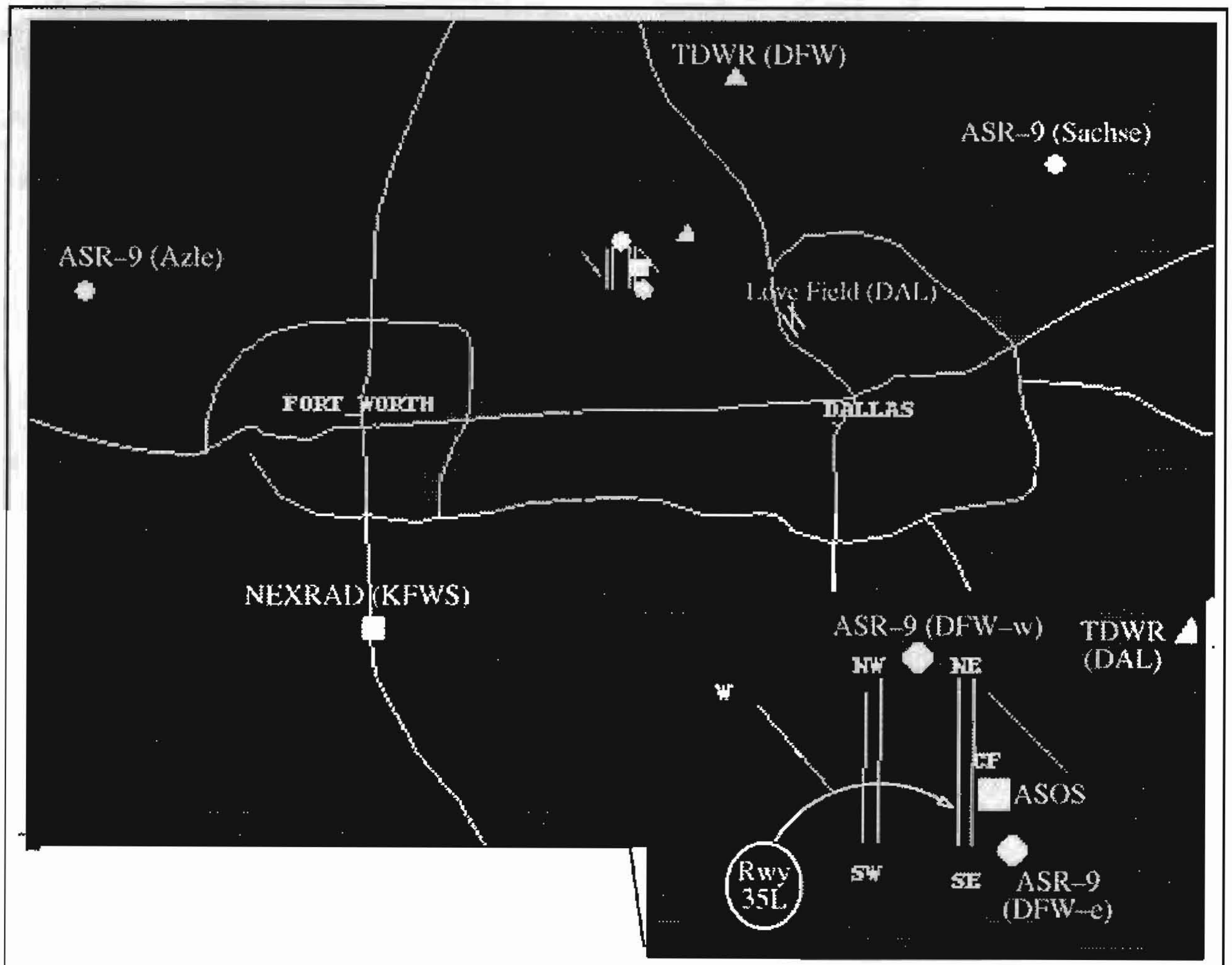

Figure 1. Map showing location of the Dallas/Ft. Worth airport, the sensors around DFW, and the Dallas Love Field. The Low Level Wind Shear Alert System (LLWAS) stations at DFW are denoted by their geographic identifiers (W, NW, SW, etc.), the Automated Surface Observing Station (ASOS) at DFW is shown as a square, the Love TDWR (DAL) is shown as a triangle, and Runway 35 Left (35L), on which the incident aircraft was taking off (toward the north), is also labelled.

2257 GMT in a "north flow" with miles–in–trail restrictions due to ongoing computer problems at ZFW.

By the time the departures resumed in earnest, precipitation at the airport had diminished to level 1 and the line of thunderstorms was approximately ten miles east of the airport moving eastward at 30 knots (Fig. 2). Approximately 15 aircraft took off to the north without incident before two aircraft on the west side of the airport reported wind shear encounters at approximately 2330 GMT. (Figure 3 shows a transcript of the weather–related transmissions on the west and east side tower frequencies for the period of reported wind shear.) Three minutes later the pilot of AA 1352 taking off on Runway 35L on the east side of the airport reported an encounter with severe wind shear. Reportedly, the winds gusted to 40 kts from the southwest (a tailwind), "the plane was rocked ...violently to the right" (Dallas Morning News, 4/20/96), and the right wingtip banked down toward the runway. The aircraft was so low in altitude, there was concern that the wingtip might actually impact the runway. He used full throttle to keep the plane airborne and advised the relevant air traffic controller to halt departures.

3. METEOROLOGICAL DATA

3.1. Witness Observations

At the time of the incident, personnel at the prototype Integrated Terminal Weather System site operated by MIT Lincoln Laboratory at DFW could see turbulent low clouds moving in different directions over the airport. The clouds were described as looking "like the top of a meringue pie". The cloud base was approximately 250 m (820 ft) AGL.

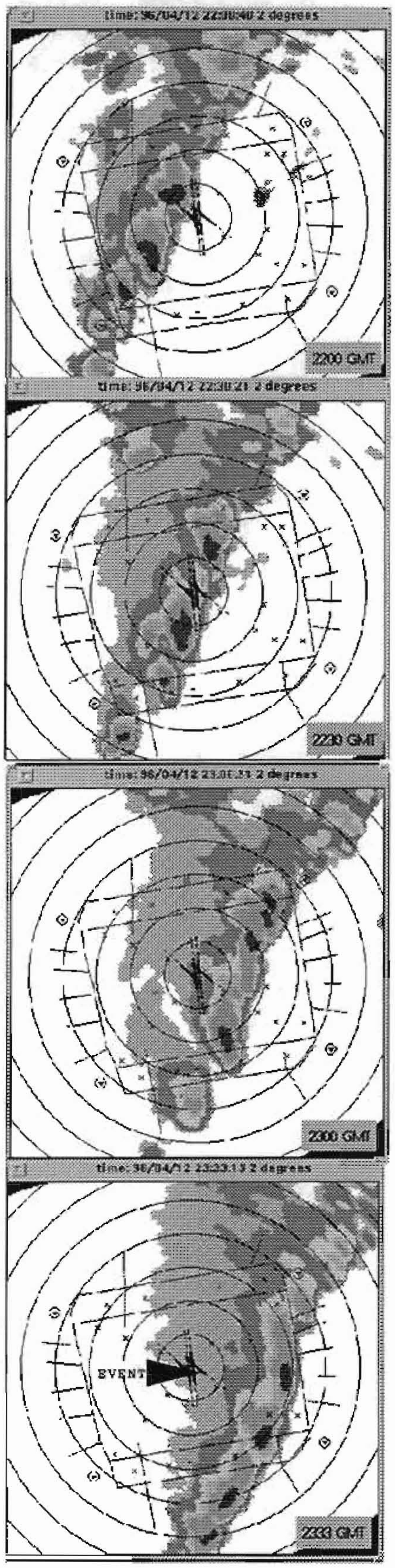

Figure 2. Data mosaiced from three of the four Airport Surveillance Radars (the "DFW–w" ASR–9 is not routinely included in the mosaic) is shown at half hour intervals leading up to the wind shear event. The range rings are drawn at 10 nm (18 km) intervals. The approximate location of the wind shear event is shown in the final panel, at the tip of the black arrow. The wind shear encounter took place in the stratiform region trailing the squall line.

Several airport workers on the ground reported watching a rotating cloud cross the airfield into the flight path of the incident aircraft. The eyewitnesses were reportedly skeptical that the aircraft would remain airborne after encountering the cloud.

3.2. Environmental Conditions

The surface synoptic chart around DFW at 0Z on 13 April is shown in Figure 4. A low pressure center of 999.9 mb is just south of Ft. Worth, where the pressure reads 1004.5 mb. The temperature at Ft. Worth is 60°F and the dew point is 58°F, after the passage of the line of thunderstorms. The heavy dashed vertical line depicts the location of the dry line, a line of density contrast with much drier air to the west. The cold front is not shown, but is associated with the northerly winds shown at Ft. Worth, Oklahoma City, and Dodge City, KS. It's orientation is approximately E–W through the low pressure center. The strong line of thunderstorms was triggered by the dry line, and the development was supported by the presence of the cold front and the broad lifting associated with the low pressure center.

The NWS sounding taken at 0Z on 13 April (30 min after the incident) shows the characteristics of the environment behind the line of thunderstorms, in which the wind shear incident took place (Fig. 5). The most prominent feature is a strong surface inversion that is 1.0 km (3300 ft) deep. The air at the surface is cold and saturated due to the thunderstorm outflow, but the air at the top of the inversion is extremely dry, characteristic of surface air behind the dry line, with a dew point depression greater than 25°C. This extremely stable boundary layer provides an excellent "duct" for supporting buoyancy oscillations, or gravity waves. As we shall see, these play a prominent role in creating the low altitude wind shear conditions at DFW.

The sounding wind profile at this time also shows large vertical shear of the horizontal wind. The winds in the stable boundary layer are northwesterly, but shift to southwesterly at speeds >50 kts above the inversion. The large vertical wind shear throughout the atmosphere is due in part to the low pressure center situated just south of DFW.

West side tower frequency for the parallels (124.15)

2310 – 2326: 11 aircraft depart without incident

[...some assorted wx reports reported by controller from LLWAS CF:
	2311	winds	310 13
	2315	winds	300 15
	2316	winds	300 16
	2327	altimeter	29.65]

2327 *Tower:* "Sun Jet 610 fly heading 345 runway 36R clear for take–off"
(SJ 610 is an MD80)

2329 *Tower:* "American 1526 fly heading 345 runway 36R clear for take–off"
(AA 1526 is a Fokker100)

[We never heard a report from AA 1526 on the scanner but were told by AT that pilot reported shear; it may have been reported on the departure frequency (which was not recorded).]

2333 *SJ 610:* – – too garbled to understand – –

Tower: (repeats SJ 610 report to all) "Attention all aircraft...ah... aircraft reported wind shear at 1000 feet on departure."

2334 – controller clears Delta 243 Heavy for take–off on 36R.

[In the next few minutes the next departure waits on the ground for a report from the Delta Heavy.]

2338 *Tower:* "...the Delta heavy jet....ah....said just before he released the breaks to go he got notice of some [wind shear] but he didn't get any on departure."

[Next departure goes.........]

East side tower frequency for the parallels (126.55)

2320 – 2331: nobody departs

2331 *Tower:* "Winds 360 @ 20"

2332 *Tower:* "American 1352 fly heading 360 runway 35L clear for take–off winds 360 @ 20"
(AA 1352 is an MD80)

2333 *AA 1352:* "Don't let anybody depart on 35"
Tower: "Say again."
AA 1352: "Hold the departures."

[There are nearly 50 planes on the east tower frequency and the controller doesn't know who's talking]

AA 1352: "....we had severe wind shear on departure, American 1352. . we thought we were gonna lose it. I would hold the departures."
Tower: "American 1352 contact departure on 118.55"
AA 1352: "And I'm not kiddin', that was severe on departure, American 1352, good–day."
Another pilot on the ground somewhere: "Tower, do you see the clouds are swirling around down here?"
Tower: "Stand–by please"

[conversation between tower & the next pilot]

2337 *Tower:* "[your route is] probably gonna change here shortly but ah, no one's gonna depart right now because the last one to go...here...ah...reported a 40 kt loss on departure."
AA 1830: "OK"
Another pilot: "You said 40 kt loss?"
Tower: "40 kt loss, yes."

2340 *Tower:* "...winds are 340 @ 22"
Aircraft waiting to depart at south end of 35L: "Down at this end of the runway the winds seem to be calm."

2345 *Tower:* "...winds 360 @ 12"

Figure 3. Partial transcripts of the West side and East side tower frequencies at DFW on 12 April 1996 around the time of the incident. All times listed are in GMT. Comments that included meteorological information were selected from audio tapes of the scanners.

GOES–8 was under Super Rapid Scan Operations (SRSO) on April 12. The SRSO scan strategy has an update rate of 1 minute interspersed with 5 minute updates at a resolution in the visible band of 1 km. The dry line crossing the Dallas/Fort Worth area was clearly visible. At the time of the incident, the airport was covered by thick anvils (Fig. 6), so it is impossible to determine what was going on at the airport by the satellite data. However, the visible cloud motion from 2258 to 2339 indicates a strongly sheared and unstable atmosphere. The anvil tops of the convection associated with the dryline were blown off to the northwest by strong upper level southeasterly winds. The system as a whole was moving eastward.

At 2223, wave fronts (low rolls made visible by cloud bands) emerged behind the line of thunderstorms. They are located 75–100 km southwest of the airport moving to the southwest in Fig. 6, at 2332. The fronts intersected a cloudy region to their north and triggered another patch of wave clouds moving in a different direction, still clearly visible at 2332 in Fig. 6. This satellite data provides further evidence that the atmosphere was supporting abundant low altitude gravity wave activity.

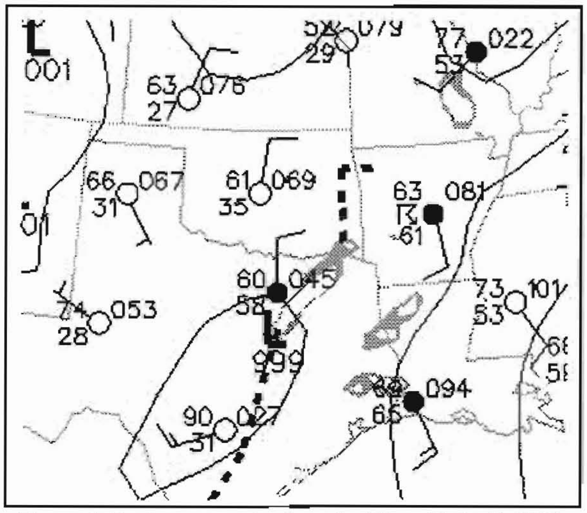

Figure 4. Surface synoptic chart for 0Z on 13 April 1996.

3.3. Dallas Love TDWR data

At the time of the incident the Dallas Love (DAL) TDWR was scanning in Hazardous Mode. The TDWR Hazardous scan consists of five 360° low elevation tilts and twenty–eight sector tilts, ranging from 0.1° to 39.7° elevation, providing full volume coverage over the Dallas Love airport (located approximately 10 nm southeast of the DAL TDWR). Unfortunately the DFW incident did not occur in the DAL TDWR Hazardous sector, so our analysis is limited to the 360° tilts with elevations of 0.3°, 1.0° and 2.6°, which update every 5 minutes. The altitude coverage provided by these tilts over Runway 35L is listed below. The radar beamwidth is 0.5°, giving a vertical resolution over the runway of 52 m (170 ft).

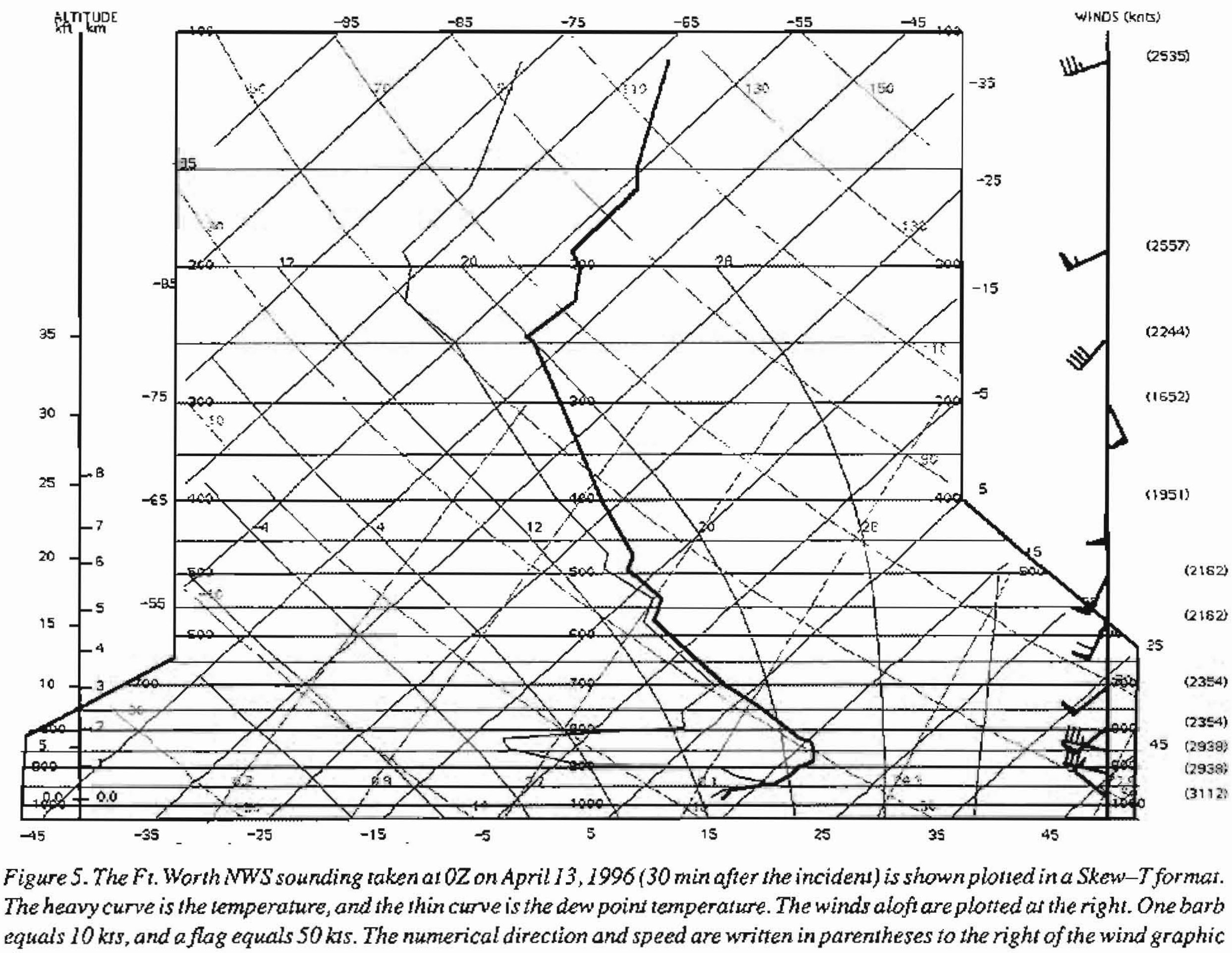

Figure 5. The Ft. Worth NWS sounding taken at 0Z on April 13, 1996 (30 min after the incident) is shown plotted in a Skew–T format. The heavy curve is the temperature, and the thin curve is the dew point temperature. The winds aloft are plotted at the right. One barb equals 10 kts, and a flag equals 50 kts. The numerical direction and speed are written in parentheses to the right of the wind graphic [(1652) = 160° at 52 kts]. The vertical scale is in pressure (mb), but the conversion to altitude (in Kft and km) is given by the vertical scale at the left. The primary horizontal scale is temperature (skewed from lower left to upper right) labelled in °C across the bottom of the plot. Notice the sharp surface inversion 1.0 km (3300 ft) deep.

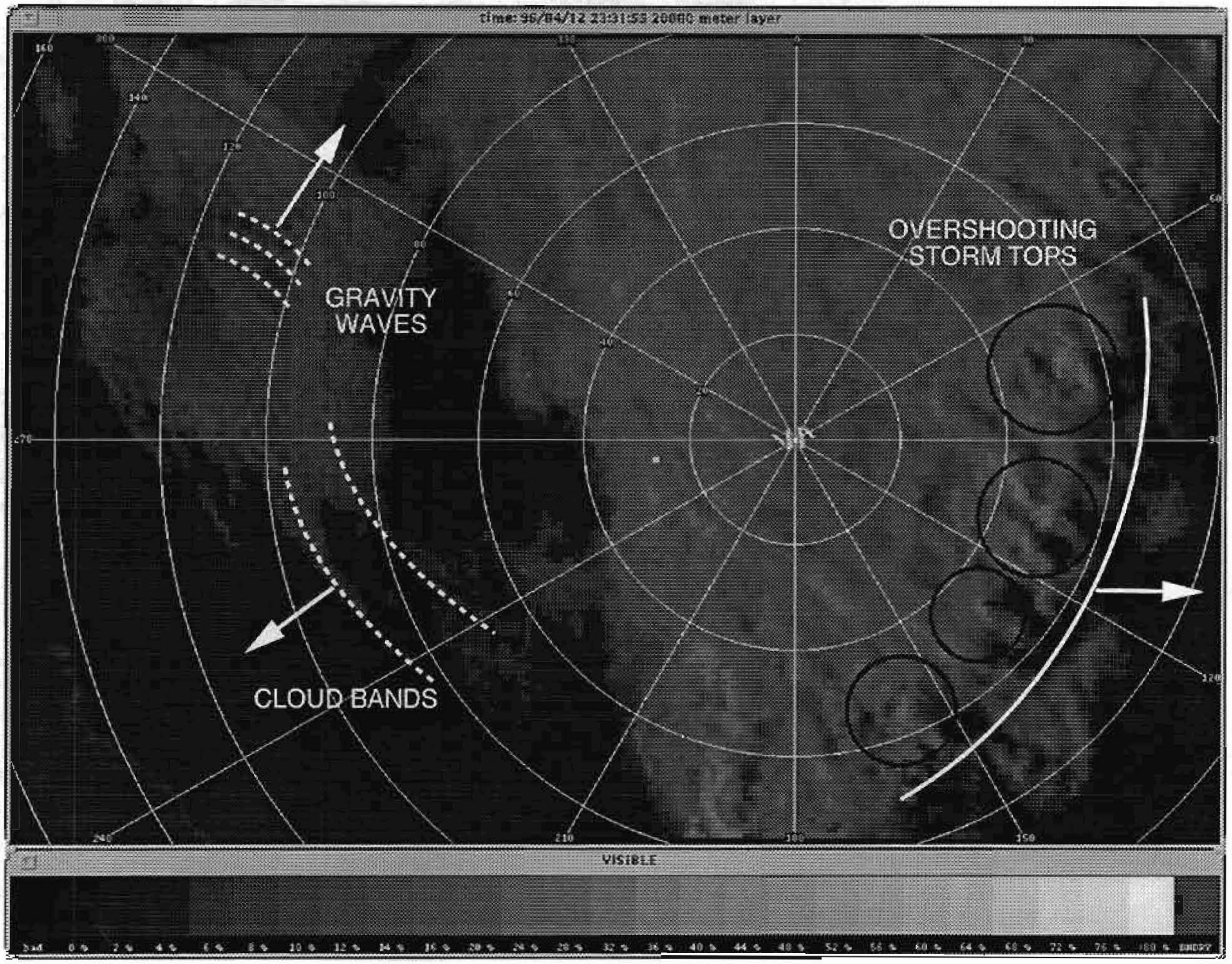

Figure 6. GOES–8 visible satellite image taken at 2332 GMT on 4/12/96. The DFW runway pattern is shown at the center of the range rings, which are spaced at 20 km intervals. The high tops of the strong convection in the squall line are shown east of the airport between 40 and 60 km range rings. The atmosphere behind the front supports gravity wave activity, as evidenced by the visible waves oriented NW to SE in the patch of cloud west of the airport between 100 and 120 km range, and by the cloud bands to the southwest.

TILT ANGLE	ALTITUDE OF TDWR BEAM OVER RUNWAY 35L
0.3°	32 m (105 ft)
1.0°	100 m (328 ft)
2.6°	257 m (843 ft)

At 2320 GMT, a northwest–southeast orientated convergent boundary is apparent off the southern end of the four parallel north–south runways in the 0.3°(not shown) and 1.0° tilts (Fig. 7). This boundary was one in a series of gravity waves which were observed in a 0.3° surface tilt five minutes earlier southwest of DFW. The maximum observed velocity differential across this feature is 13 m/s (25 kts) at an altitude of 140 m (460 ft) AGL. The wind direction behind this feature is southwesterly which is consistent with the LLWAS and ASOS data discussed later. The reflectivity data at this time shows a finger–like echo of 15 to 25 dBz, on the backside of the main precipitation region, which is associated with the velocity feature. On the 2.6° tilt approximately two minutes later, there are a series of azimuthal shear features at an altitude of ~ 500 m (1643 ft) AGL located directly above the convergent boundary. These likely represent the return flow aloft of the gravity wave, or roll structure moving in from the southwest.

Surface winds remain northerly around 20 kts at 2329 GMT, 4 minutes prior to the incident. The radial velocity plot in Figure 8 shows a banding structure of weak winds bordered by strong winds blowing from north to south, which is indicative of more gravity waves. These bands are oriented west–southwest to east–northeast, and the northerly wind gusts are extremely shallow (100 m [330 ft] deep). The observed western

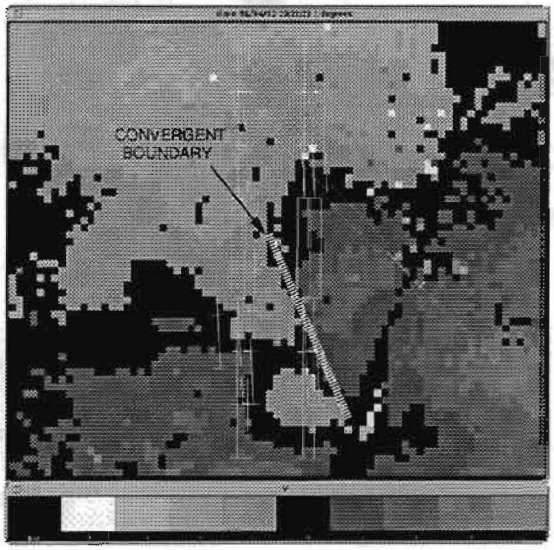

Figure 7. DAL TDWR Doppler velocity data from the 1.0° tilt at 2321. A zone of convergence can be seen approaching the east side of the DFW airport.

end of one of the bands is over the south end of the incident runway (35L) at 2329 GMT. Although it is not shown, this patch of gravity waves over the airport was within, and made visible by, the back edge of the weak reflectivity region trailing the squall line. The gravity waves may also exist in regions outside of the weak precipitation, but the radar is unable to see them because there are too few scatterers in the clear air.

Careful analysis of the two time periods shown in Fig. 8 reveals that the average gravity wave wavelength is approximately 5.4 km (3.4 mi). The waves were moving relative to the ground at 14 m/s (27 kts) toward 75° azimuth (ENE). At this speed it would take approximately 4.5 minutes for the successive wave crests to cross a point on the ground. The LLWAS anemometer data from the CF sensor (discussed later) appears to also show evidence of this wind pattern.

Strong banded azimuthal shear features, both cyclonic and anticyclonic, are evident in the 2.6° tilt at 2331 GMT (Fig. 9). The strongest winds toward the radar are located almost directly above the strongest northerly winds at the surface, and probably are part of the

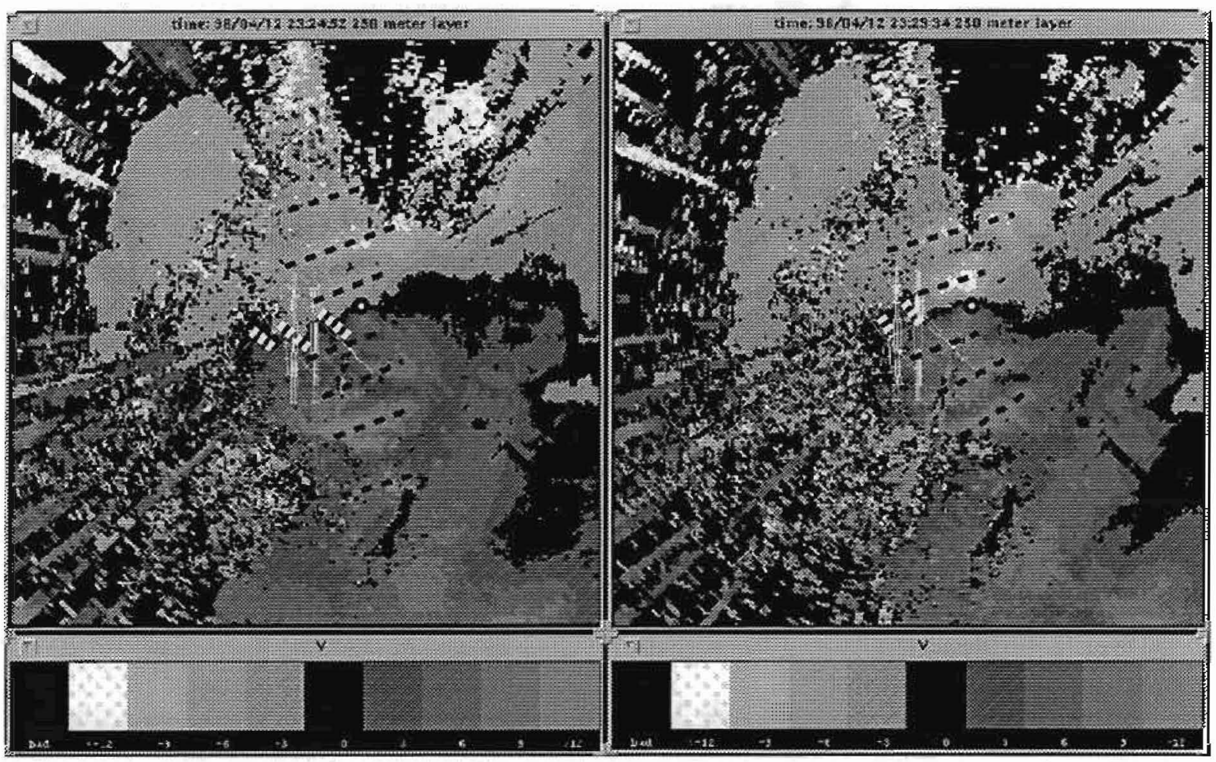

Figure 8. Surface layer (125 m [400 ft] AGL) of Doppler radar data from DAL TDWR at 2324 GMT (left) and 2329 GMT (right). The dashed black lines highlight the bands of high velocity associated with a short train of gravity waves moving east–northeastward (relative to the ground). The thicker, hatched white lines highlight the bands of convergence propagating in from the southwest. The west end of the middle (third) wave is approaching the south end of the incident runway (35L) at 2329. The white dot northeast of DFW shows the location of the DAL TDWR.

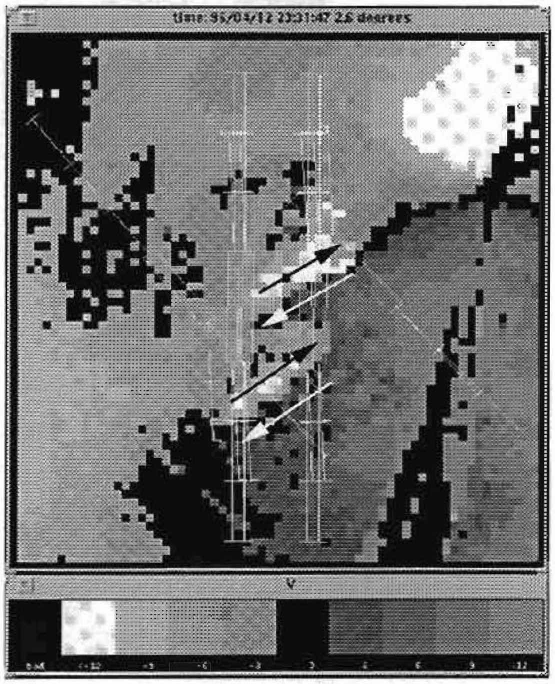

Figure 9. DAL TDWR Doppler velocity field from 2.6° tilt at 2332 GMT. Azimuthal shear in a banded pattern can be seen. One particularly significant shear zone is located over the east runways. This feature is approximately 250 m (820 ft) AGL.

return flow of the gravity wave rolls. The azimuthal shear was particularly strong over the north end of the east runways, with a 32 m/s (62 kts) velocity differential (+10/−22) over an azimuthal distance of about 4 km (2.5 mi). Some shear at this altitude (250 m [820 ft]) was likely present over the west runways as well, and may account for the pireps of "wind shear at 1000 ft" reported on the west runways (Fig. 3).

Since observers noticed a "rotating cloud crossing the airfield" and a pilot mentioned the clouds "swirling around down here", we attempted to locate a rotational feature in TDWR data near the surface. There was no clear rotational couplet visible in the lowest TDWR tilt at the time of the incident. However, faint remnants of the convergent boundary (gravity waves) coming from the southwest are still visible in Fig. 8. (Since there is very little precipitation, the radar signal of this feature is weak and noisy.) One boundary, oriented at approximately right angles to the main series of gravity waves (oriented southwest to northeast), is crossing the north end of 35L at 2329, and so is likely to be intersecting these waves. The wind maxima in Figure 9 at 250 m (820 ft) AGL associated with the main group of gravity waves, do appear coincident with the wave crests in this second "southwest" group of waves.

If these two groups of gravity waves did intersect, the surface winds gusting from the southwest might combine with northerly wind gusts from the main gravity wave train to create zones of vorticity, which could spin up into tight, rapidly spinning vortices. The intersection of gravity waves at nearly right angles, with winds blowing in nearly opposite directions, we believe represents a plausible hypothesis for a mechanism to create zones of vorticity and dangerous low altitude rotational wind shear. There is some evidence for strong rotational shear over the airport around the time of the incident in the LLWAS and ASOS data, described in the following section.

3.4. DFW LLWAS and ASOS data

The DFW airport has an LLWAS-2 network consisting of six sensors: CF, NE, NW, W, SE and SW. LLWAS stations report only wind speed and wind direction, but do so at 10 s intervals. The wind data from all six sensors is plotted in Figure 10.

The CF sensor shows a wind pattern which is consistent with a gravity wave crossing the airport at the time of the incident. The winds begin as northerly and somewhat gusty around 20 kts. Just before the incident, they shift in direction through easterly, where the wind speed drops to less than 10 kts, then to southerly through westerly at the time of the incident, where the winds pick up again (20 kts), back around to northerly where the wind gusts to 30 kts and then settles back to the former approximately 20 kt speed. (Notice that the wind direction scale on the CF plot wraps around at 340°). The CF wind speed first peaks from the north at 2330:10 (360° at 22 kts) and again at 2334:40 (340° at 30 kts). These points are illustrated by dashed vertical lines on the CF plot in Figure 10. The time difference is 4.5 min, matching the time estimate for successive gravity wave crests to cross a point on the surface, based on TDWR gravity wave wavelength and motion estimates. The northerly wind direction at the time of the peak wind speeds also matches the pattern found in the TDWR velocity data.

The SW station also shows a significant wind shift prior to the time of the incident. The wind direction backs from 20° to 200° in advance of the incident, gusts from 5 to 14 kts, and then veers to 290°. It is interesting to note that this station shows a backing wind pattern with a wind gust from the southwest, while the CF sensor shows a veering wind pattern with gusts from the north. This could be evidence of the two different gravity wave trains we found in the TDWR data.

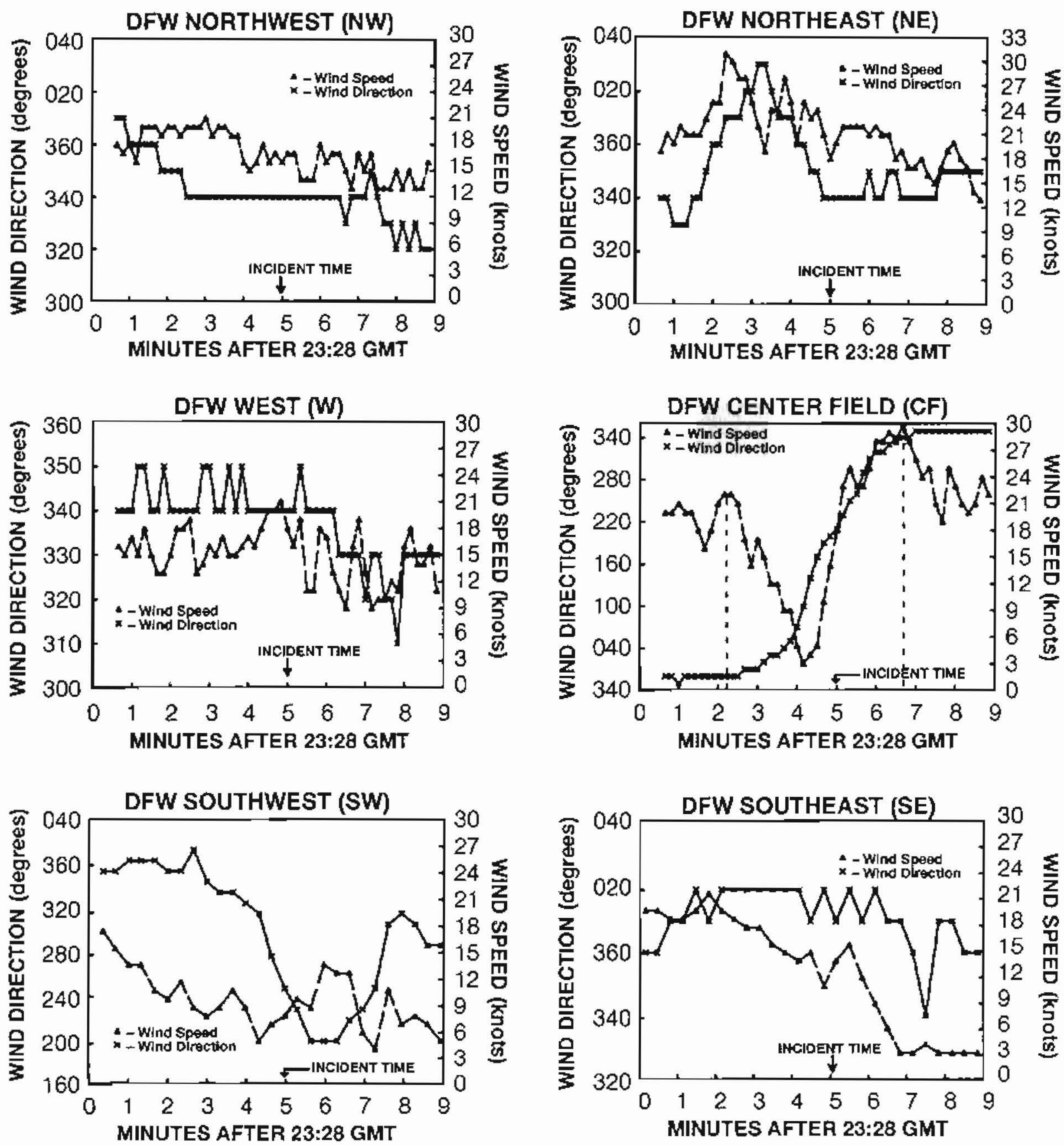

Figure 10. Plots of wind speed and direction from six LLWAS stations surrounding DFW airport. Refer to Fig. 1 for locations of the LLWAS stations relative to runways. Note that the scales on each plot are different in order to capture the wind profiles.

Other evidence of the gravity wave(s) in the LLWAS data is somewhat less clear. The NE sensor shows some peak wind gusts from the north at an earlier time, which may have been due to a wave crest. The W, NW and SE LLWAS sensors show little deviation in wind speed or direction in the time period leading up to the incident.

DFW ASOS data is available for the 90 minutes prior to and the 35 minutes following the incident. The observations from 2210 GMT to 0009 GMT are shown below in Table 1. The NWS employs a contractor who augments the ASOS data with comments about the significant weather, and who issues special observations (off-hourly) when conditions warrant.

Table 1. ASOS data

TIME (GMT)	PRESSURE (mb)	TEMP (deg F)	DEWPOINT (deg F)	WIND SPEED (knots)	WIND DIR (degrees)	SIGNIFICANT WEATHER
2210	1002.7	74	66	18G32	230	occasional lightning
2222	1003.1	70	60	19G23	260	occasional lightning
2236	1003.2	63	60	15	300	occasional lightning
2253	1004.0	62	60	15G20	290	occasional lightning
2308	1002.9	61	60	14	330	pressure falling rapidly
2317	1003.8	61	60	16	300	occasional lightning
2332	1001.1	60	60	18	10	pressure falling rapidly
2334	1001.3	60	60	13G27	140	pressure jump at 2333*
2336	1001.9	60	60	27G33	330	peak wind @ 2335, 33 knots
2343	1003.7	60	59	16G33	350	occasional lightning
2353	1004.5	60	58	10	360	
0009	1004.2	58	57	14	350	

*Comment "pressure jump at 2333" appeared in ASOS observation at 2353 GMT.

The gusty winds in association with the squall line passage can be seen prior to 2317. At 2332, the wind becomes gusty again and shift to the east, then southeast at 2334 (27 kts) and northwest at 2336 (33 kts). It has returned to its northerly direction by 2343.

A small plot of the LLWAS and ASOS winds one minute after the incident, at 2334, is shown in Figure 11. The north end of the airport is clearly under the influence of northerly surface winds, with the strongest gust reported at CF. However, the ASOS station (and SW) show more southerly wind gusts. Figure 11 provides definite evidence of small-scale vorticity in the surface wind field on the south and especially east sides of the airfield near the time of the incident.

The pressure trace near the time of the incident is also interesting. At 2332 GMT, the pressure has fallen to 1001.1 mb, dropping 2.7 mb within 15 min. We cannot tell if the abrupt change in pressure is due to the gravity wave(s) or a small low pressure area associated with a vortex (or both), but the change itself provides evidence of strong wind perturbations and low altitude wind shear. The aircraft departed runway 35L at the time of lowest pressure recorded by ASOS, and during the rapid windshift.

4. CONCLUSIONS

On April 12, 1996 at 2333 GMT, AA 1352, an MD–80 aircraft, experienced severe wind shear while taking off from Runway 35L at DFW. The LLWAS and ASOS data both showed a significant wind shift to a tailwind during the time of the incident. Our analysis of the

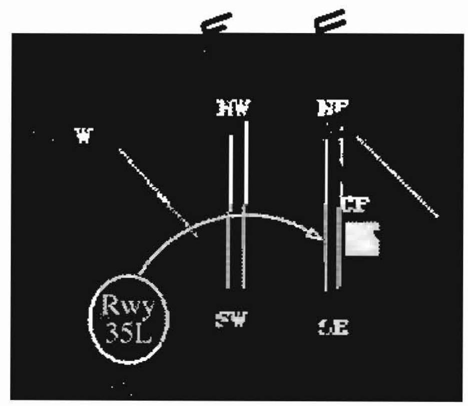

Figure 11. Plot of winds at 2334 GMT, one minute after the incident. The white square is the ASOS station, the others are LLWAS stations. One long wind barb equals 10 kts; a short barb equals 5 kts.

DAL TDWR data revealed that two separate groups of gravity waves, oriented at nearly right angles to each other, were present at the airport between 2325 and 2335 GMT. Passage of the gravity waves was also evident in the LLWAS data.

The visual observations definitely suggests a rotational feature crossed the path of the incident aircraft. Our hypothesis for the generation of rotational shear over the airport is that two gravity wave trains intersected, where the northerly winds from one group combined with the southwesterly winds from the other to create a large amount of vorticity. The lack of a strong southwest surface wind or a rotational signature in the

TDWR surface data is evidence against this hypothesis, but such a signal might also not have been visible due to data contamination and/or feature resolution. The surface wind observations, though, showed clear evidence of rotational shear. If one or more vortices did develop, they could have enhanced the wind shift associated with the gravity waves at low altitudes.

One more piece of evidence that may support the intersecting gravity wave analysis is the visual appearance of the clouds as "like the top of a meringue pie". The interference pattern of the two sets of gravity wave rolls might be expected to give a complicated pattern of vertical motions, leading to a similarly complicated pattern of peaks and troughs in the cloud base. This could, in fact, resemble a meringue pie top!