Project Report
ATC-309

An Examination of Wind Shear Alert Integration at the Dallas/Ft. Worth International Airport (DFW)

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20 August 2003

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16. Abstract

The Dallas / Ft. Worth International Airport (DFW) is one of the four demonstration system sites for the Integrated Terminal Weather System (ITWS). One of the primary benefits of the ITWS is a suite of algorithms that utilize data from the Terminal Doppler Weather Radar (TDWR) to generate wind shear alerts. DFW also benefits from a Network Expansion of the Low-Level Wind Shear Advisory System (LLWAS-NE). The LLWAS-NE generated alerts are integrated with the radar-based alerts in ITWS to provide Air Traffic Control (ATC) with a comprehensive set of alert information.

This study examines the integrated DFW wind shear alerts with emphasis on circumstances in which the detection performance of the TDWR-based wind shear algorithms was poor. Specific detection problems occur in the following situations: when wind shear events over the airport are aligned along a radial to the TDWR, during "non-traditional" wind shear events, when severe signal attenuation occurs during heavy precipitation over the TDWR radar site, and because of excessive TDWR clutter-residue editing over the airport. In all of the cases examined, the LLWAS-NE issued alerts to ATC that would have otherwise gone unreported.

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ABSTRACT

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This study examines the integrated DFW wind shear alerts with emphasis on circumstances in which the detection performance of the TDWR-based wind shear algorithms was poor. Specific detection problems occur in the following situations: when wind shear events over the airport are aligned along a radial to the TDWR, during "non-traditional" wind shear events, when severe signal attenuation occurs during heavy precipitation over the TDWR radar site, and because of excessive TDWR clutter-residue editing over the airport. In all of the cases examined, the LLWAS-NE issued alerts to ATC that would have otherwise gone unreported.

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TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(Continued)

LIST OF TABLES

1. INTRODUCTION

An Integrated Terminal Weather System (ITWS) demonstration system has operated at the Dallas / Fort Worth International Airport (DFW) since 1995. ITWS is composed of algorithms that utilize data from the Terminal Doppler Weather Radar (TDWR) to detect and warn Air Traffic Control (ATC) of dangerous wind shear (Evans and Ducot, 1994). A number of airports that are receiving an ITWS also have a Network Expansion of the Low-Level Wind shear Alerting System (LLWAS-NE). At these airports, alerts from the LLWAS-NE will be integrated into the ITWS to provide ATC with a complete set of alerts.

There has been a considerable amount of effort devoted to developing an algorithm that accurately integrates alerts generated by the LLWAS and TDWR-based wind shear detection algorithms. The initial development was led by the National Center for Atmospheric Research (NCAR) in 1988 (Cornman and Mahoney, 1991). Subsequent efforts by MIT Lincoln Laboratory produced three separate TDWR/LLWAS 3 integration algorithms. A comparative study of each algorithm's performance was conducted in 1991 at Orlando International Airport (MCO) (Cole and Todd, 1994). The study compared the alerts generated by each algorithm to a set of alerts produced from dual Doppler radar data. After analysis of the study results, NCAR and Lincoln Laboratory jointly recommended a message level integration algorithm to the Federal Aviation Administration (FAA). The recommendation led to the FAA procurement of the algorithm for deployment in the existing TDWR systems. An operational demonstration of the TDWR/LLWAS 3 alert integration at Stapleton International Airport in Denver showed significant benefits and improvements in the quality of the alerts (NCAR/RAP1993). The LLWAS was especially helpful in addressing the detection problems associated with "dry" microbursts that are characterized by a low signal to noise ratio. Another operational demonstration at MCO in 1992, showed little improvement when using the message level alert integration.

The development of the ITWS has led to improvements in the detection capability of wind shear algorithms that utilize radar data. The upgrades include a significant improvement in the detection of gust fronts that produce wind shear with a gain in headwind and the introduction of a microburst prediction algorithm. Thus, when an ITWS/LLWAS-NE integration algorithm was developed, these improvements were taken into account. While the ITWS/LLWAS-NE algorithm is based on the previous TDWR/LLWAS 3 findings, there are some differences. A performance evaluation of the ITWS/LLWAS-NE integration was conducted using data from DFW and MCO by Isaminger, et. al., 2000. The evaluation computed the probability of detection (POD) and probability of false alarm (PFA) by examining 1800 truth events from DFW and 1400 from MCO (Table 1). The analysis indicates that the POD for all alert categories increased with the integration of the LLWAS-NE at DFW and remained nearly the same at MCO. Unfortunately, the PFA for wind shear and microburst events at DFW increased with the integration of the LLWAS-NE. However, it should be noted that during the period of evaluation the number 11 sensor at DFW had severe mechanical problems and a high failure rate, which led to numerous false wind shear alerts that biased the PFA results. Thus, the previous studies indicate that the message level alert integration algorithm improves the quality of alerts transmitted to ATC and is especially beneficial in drier climates where microburst detection is more challenging.

TABLE 1
ITWS/LLWAS-NE Integration Performance Statistics for (A) DFW and (B) MCO as computed by Isaminger, et. al., 2000.

(A)	ITWS			ITWS/LLWAS-NE		
	Loss	WS	MB	Loss	WS	MB
POD	.70	.81	.96	.78	.84	.97
PFA		.07	.02		.14	.12

(B)	TDWR			ITWS/LLWAS-NE		
	Loss	WS	MB	Loss	WS	MB
POD	.88	.96	.99	.89	.95	1.0
PFA		.02	0		.05	.04

This report examines the events where integration of the LLWAS-NE has provided improved wind shear alerts at DFW. While the LLWAS-NE has some drawbacks, there are situations in which it can produce valid alerts that go undetected by the TDWR-based wind shear detection algorithms. The five situations identified are:

- Radial alignment of gust fronts.
- Removal of out-of-trip radar echoes.
- "Non-traditional" wind shear events.
- Dome attenuation of the TDWR.
- Aggressive TDWR clutter residue editing.

For each situation, the LLWAS-NE produces alerts that, without integration with the ITWS, would have gone unreported to ATC.

In Section 2, we will offer an overview of the LLWAS-NE network, limitations of the system and the integration process. Sections 3 through 6 discuss each of the above situations and illustrate how LLWAS-NE generated wind shear detections complement radar-derived alerts. The accuracy of the LLWAS-NE generated alerts is examined in Section 7 and in the final section we present conclusions and recommendations.

2. LLWAS-NE OVERVIEW

2.1 INTRODUCTION

The LLWAS-NE at DFW consists of 19 anemometer sensors located across the airport on towers approximately 30 meters in height. The anemometer locations are strategically positioned near the airport's runways (Figure 1) in order to provide wind shear alert coverage for the DFW Areas Noted for Attention (ARENAS). Depending on the location of wind shear events, relative to the LLWAS-NE sensors, wind shear alerts are determined by measuring wind divergence or convergence within triangles (for three sensors) or edges (for two sensors) of the network. In either case, the validity of wind shear alerts produced by the LLWAS-NE is dependent on the reliability of individual sensors.

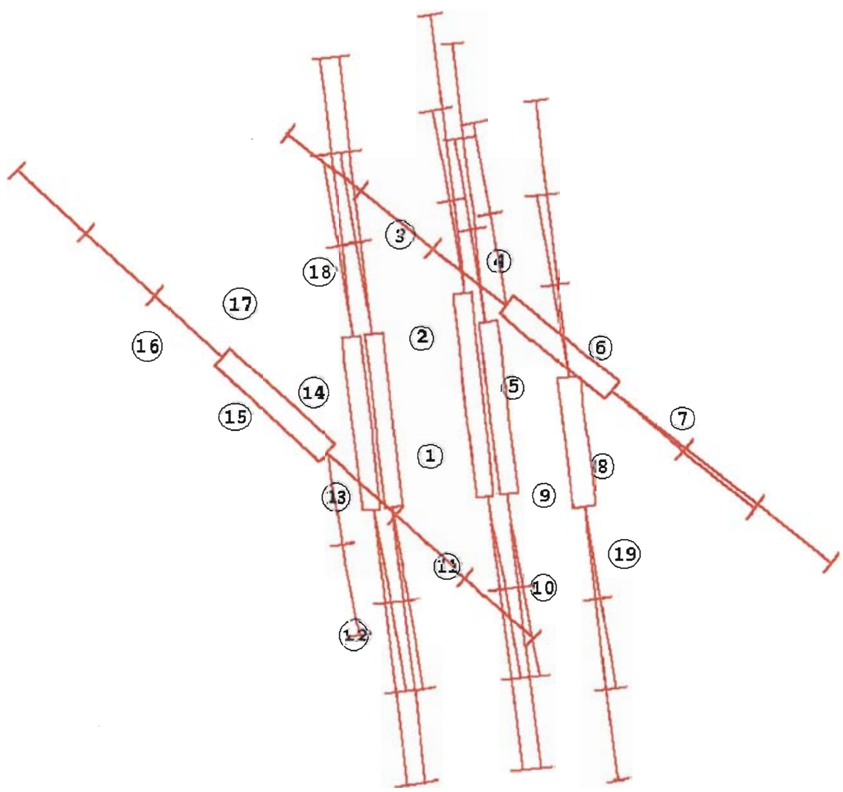

Figure 1. Location of the 19 anemometer sensors that comprise the LLWAS-NE system at DFW. Runways are indicated by the red rectangles with the approach and departure paths extending from each runway.

2.2 LLWAS-NE LIMITATIONS

Several factors can affect the performance of the LLWAS-NE. These include sheltering, sensor failure, overly conservative parameter settings and noise produced from gusty winds. Sheltering occurs when objects such as trees and buildings obstruct the surface winds near a sensor location. This can lead to a wind directional bias or wind speed estimates that are much lower compared to the remaining network. The sensor wind errors associated with sheltering can cause the LLWAS-NE to produce false wind shear alerts.

A second performance issue regarding the LLWAS-NE is a failure of the sensor or its component hardware. As with any mechanical device, an LLWAS sensor is prone to degradation over time. The failure of a sensor can lead to erroneous wind measurements or complete data loss, which can result in false or missed alerts. A sustained preventative maintenance program can help alleviate this problem. In June of 2001, the LLWAS-NE sensors at DFW were upgraded to non-mechanical sonic anemometers, which may help reduce sensor failures.

Another factor that may inhibit the performance of the LLWAS-NE is overly conservative parameter sets used in generating alerts. For all airport ARENAS, the LLWAS-NE uses sensor triples and pairs to construct the triangles and edges required to detect convergence and divergence. The edge length between pairs can be as large as 4.5 km to accommodate sensor outages. In these situations, the computed losses and gains may apply to an area that is much larger than will affect aircraft landing or departing on a specific runway. Figure 2 shows an example of this problem. In this case, a wind shear event is impacting the network across the northern ARENAS with the strongest event occurring near sensor #3, which is reporting a southwest wind of 23 knots. Since the two sensors between #16 and #3 were inoperative, the conservative edge settings associated sensor #16 with sensor #3 (32 knot difference in wind speed) resulting in microburst strength alerts issued over runway 13R. In reality, radar and nearby LLWAS-NE sensor data indicated only 15 knot losses for this ARENA.

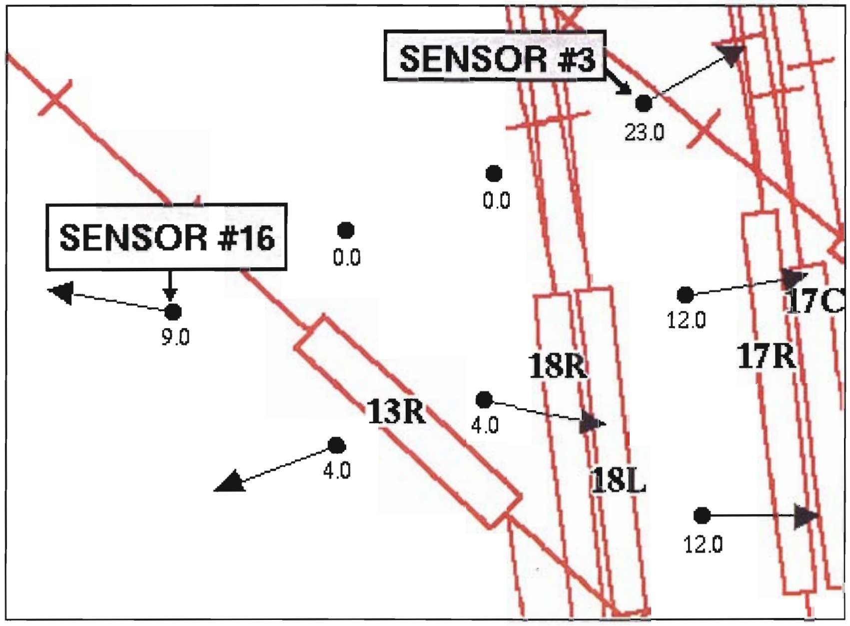

Figure 2. An example of a LLWAS-NE overly conservative sensor pairing for the construction of triangles and edges at DFW.

The LLWAS-NE was designed to be robust to sensor noise[1] of 20% of the wind speed in an individual sensor (Wilson and Gramzow, 1991). However, in very gusty conditions, the noise in the wind measurements rises above this level and may lead to false alerts. This is probably the most common false alert problem experienced at DFW. During the 20 months prior to the sensor upgrade there were 36 separate days with gusty wind alerts. In the first 14 months after sonic anemometers were installed, only 15 days of gusty wind alerts were recorded, of which, only one day had alerts greater than 15 knots[2].

It should be noted that the LLWAS-NE has some advantages to the current radar-based wind shear detection algorithms. The LLWAS-NE has a rapid update rate, with sensor input gathered every 10 seconds, allowing for a much faster detection rate of impending wind shear events. In addition, the LLWAS-NE is not inhibited by viewing angle, radar sensitivity, and ground clutter problems associated with the radar-based wind shear detection algorithms (Evans and Turnbull, 1989).

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[1] Sensor noise pertains to noise caused by rapid changes in wind speed and direction (gusts).

[2] LLWAS-NE alerts < 17.5 knots or less are not reported to ATC.

2.3 LLWAS-NE/ITWS INTEGRATION RULES

The integration of LLWAS-NE and TDWR-based alerts can be categorized into three separate sets of rules: screening, averaging and arbitration. Since the LLWAS-NE does not cover the third mile on approach[3], there is no integration of alerts for this portion of the ARENAS.

2.3.1 Screening

Screening rules are applied when the LLWAS-NE produces a wind shear/microburst alert without a matching alert from the TDWR-based algorithms. Weak wind shear alerts (<20 knots) are dropped while stronger wind shear alerts (<30 knots) are passed through the integration unchanged. Weak microburst alerts (30-32.5 knots) are downgraded to strong wind shear alerts (25 knots) and strong microburst alerts (>32.5 knots) remain unchanged. Gain alerts of less than 20 knots are dropped by the integration. Any gain alert of 20 knots or greater remains unchanged.

2.3.2 Averaging

Averaging is performed when both the LLWAS-NE and the radar-based algorithms are producing similar type alerts (i.e. both loss alerts or both gain alerts). In the case where an ARENA has loss alerts from both systems, the loss values are determined based on the formula:

Loss = Max $\{a$*LLWAS-NE, b*TDWR, average of LLWAS-NE and TDWR$\}$, where a and b are site specific but nominally set to 0.8.

The formula for determining gain alerts when both systems are producing gain alerts is the same, however, the nominal values of a and b are set to 1.0.

2.3.3 Arbitrating Alerts

Arbitrating rules apply when one system is producing a loss alert while the other is producing a gain alert. In these cases, the alert considered most hazardous is issued with the determination of hazard being adjusted slightly to help minimize alerts switching back and forth between losses and gains. A microburst alert is always considered more hazardous than a gain and will pass through the integration unchanged. If both alerts are below 30 knots, the loss is considered to be the greater hazard unless the gain is "enough stronger" than the loss. "Enough stronger" is defined as being 10 knots if there were no previous alerts for the ARENA, 5 knots if the last integrated alert was a gain and 15 knots if the last

[3] Some LLWAS-NE systems may include the third mile on approach, in which case, alerts produced for the third mile of approach would be integrated.

integrated alert was a loss. Table 2 shows examples of how screening, averaging and arbitrating alerts are determined.

TABLE 2
Examples of the three rules for combining LLWAS-NE and TDWR-based alerts (Screening, Averaging and Arbitration).

	LLWAS-NE	TDWR	Integration
Screening			
	No Alert	No Alert	No Alert
	-15kt WSA	No Alert	No Alert
	-20kt WSA	No Alert	-20kt WSA
	-25kt WSA	No Alert	-25kt WSA
	-30kt MBA	No Alert	-25kt WSA
	-35kt MBA	No Alert	-35kt MBA
Averaging			
	-25kt WSA	-35kt MBA	-30kt MBA
	-20kt WSA	-60kt MBA	-50kt MBA
Arbitration			
	-25kt WSA	+30kt WSA	-25kt WSA
	-25kt WSA	+40kt WSA	+40kt WSA

3. RADIAL ALIGNMENT OF GUST FRONTS

3.1 INTRODUCTION

During the DFW ITWS demonstration, it has been observed that gust front detections from the ITWS gust front detection algorithm tend to be degraded over the DFW ARENAS when a gust front is oriented northeast-to-southwest. This occurs because the radial velocity convergence signature used by the algorithm vanishes as gust fronts propagate over the radar site and become radially aligned to the radar. A significant number of dropped and degraded detections are, in large part, a consequence of the location of the DFW TDWR with respect to the DFW airport. Since the DFW TDWR is sited 17 km north-northeast of the DFW airport, when a typical northeast-to-southwest oriented gust front becomes radially aligned with the radar site it is also impacting the DFW ARENAS (Figure 3). Since the TDWR based gust front detection algorithm is used to produce gain alerts for DFW, a missed detection over the ARENAS implies that no radar-based gain alerts are generated.

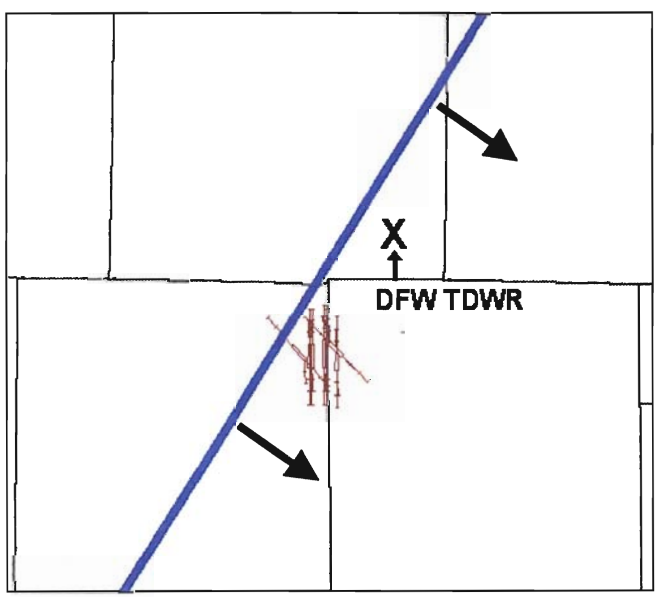

Figure 3. Location of the DFW TDWR with a typical alignment of cold fronts and gust fronts (blue line) as they track across DFW. The red lines are the locations of the DFW runways and their corresponding approach and departure paths while the arrows indicate the direction of motion of the front.

A study of "significant" gust front events that impacted DFW from August 1999 through July 2002 was conducted to determine the extent of the radial alignment problem. Gust front events were considered "significant" if any one of the following three criteria are met: 1) A valid detection was made by the TDWR gust front detection algorithm over the DFW ARENAS. 2) A gain alert was generated by the LLWAS-NE, or 3) The wind shift caused an air traffic flow reconfiguration at DFW. During the three-year period, 302 gust fronts met at least one of the three criteria, of which, 33% were aligned northeast-to-southwest in a manner that could cause a detection to be degraded[4] due to radial alignment (Figure 4).

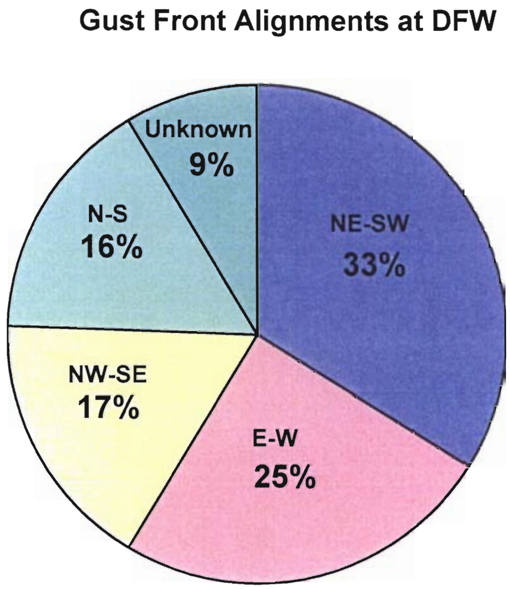

Figure 4. Alignments of "significant" gust fronts at DFW from August 1999 through July 2002.

An examination of the alert origins for each of the northeast-to-southwest oriented gust fronts is shown in Figure 5. The figure shows the total number of cases when alerts were generated by the ITWS gust front detection algorithm and the LLWAS-NE, individually, simultaneously, and the number of cases when there were no alerts. Of the 61 cases in which there were alerts, 51% were produced only by the LLWAS-NE, while in 38% of the cases alerts were generated by both simultaneously with the remaining 11% by the gust front detection algorithm only. This demonstrates that the LLWAS-NE provides an important safety net when difficult to detect gust fronts cross the airport ARENAs.

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[4] Degraded indicates that portions of a front that should have been detected went undetected.

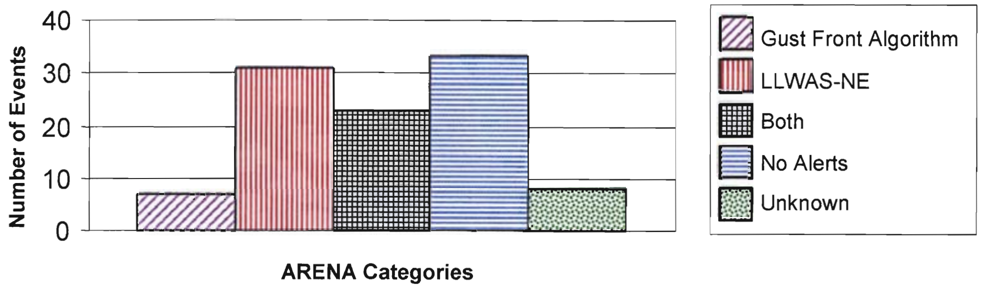

Figure 5. Origin of alerts for each of the northeast-to-southwest oriented gust front cases at DFW between August 1999-July 2002.

3.2 CASE STUDIES

3.2.1 September 21, 2000

A strong, late summer cold front was approaching the Terminal Radar Approach Control (TRACON) area from the northwest during the afternoon of the 20th. The front was oriented from northeast-to-southwest and was tracking southeastward at 20 knots. Initially, as the front entered the range of the DFW TDWR, the ITWS gust front detection algorithm did an excellent job of detecting the frontal position. However, as the front was approaching the radar site the detection became degraded due to the radial alignment of its western most portion (Figure 6a). The detection degradation continued until the front was moving away from the radar site and the velocity convergence signature was re-established. A complete detection was regained as this was occurring (Figure 6b).

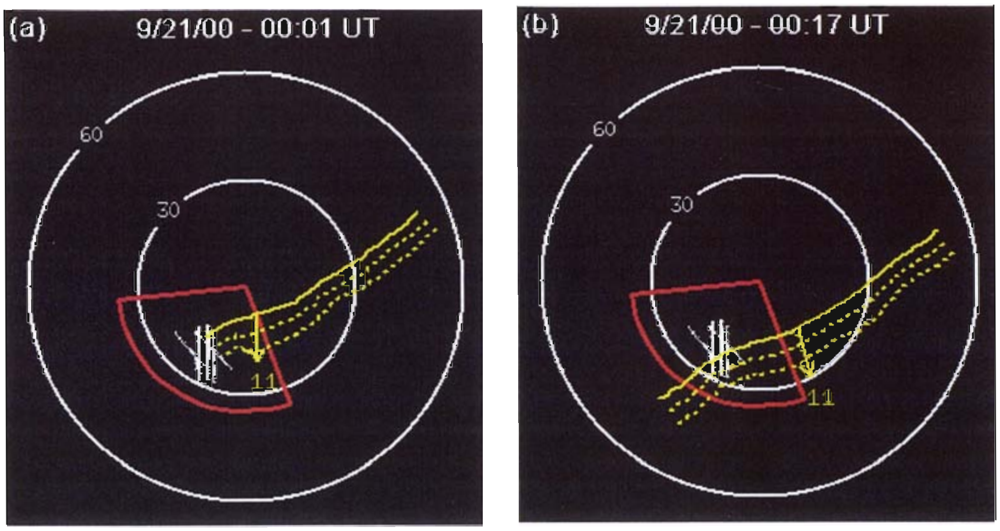

Figure 6. Detection of a strong cold front (yellow solid line) by the ITWS gust front detection algorithm crossing DFW on September 21, 2000. The detection became degraded (a) when the westernmost portion of the front became radially aligned with the DFW TDWR. Later the detection was re-established (b) after the radial velocity convergence increased when the front was no longer aligned along a radial.

Table 3 shows the integrated ITWS wind shear alerts produced between 0001-0022 UT on the 21st. The table shows the origin of the alerts provided to ATC during this event. Gain alert values shown in red were generated by the LLWAS-NE when the gust front was radially aligned and undetected. At 0013 UT, the ITWS gust front detection algorithm was detecting the front and began issuing alerts. However, at this time the LLWAS-NE temporarily drops the alerts for several minutes. With this occurring, the integrated alerts sent to ATC were generated only by the TDWR-based algorithm. By 0016 UT, both the LLWAS-NE and the ITWS gust front detection algorithm were issuing alerts and the values in blue are the integrated alert values produced using the rules outlined in Section 2.3. Also, note that at this time the gust front detection algorithm was generating some alerts on ARENAS that the LLWAS-NE was not (18LD, 13LA, 13LD). The gust front detection algorithm generated the remaining alerts as the front was moving out of the LLWAS-NE network coverage. For this event, the LLWAS-NE alerts are comparable in strength to those alerts produced by the TDWR-based algorithm. The table illustrates the importance of the LLWAS-NE integration since it was allowing alerts to be continuously sent to ATC while the cold front impacted DFW.

TABLE 3
ITWS integrated wind shear gain alerts at 3-minute intervals over the DFW ARENAS on September 21, 2000. Numbers in red are alert strength values (in knots) that were generated by the LLWAS-NE. The values of the TDWR-based alerts are in black and the blue numbers are integrated alert values using the rules illustrated in Table 2.

Time (UT)	13RA	13RD	18RA	18RD	18LA	18LD	17RA	17RD	17CA	17CD	17LA	17LD	13LA	13LD
0001	20	20	20	20										
0004			25	25			25	25	25	25				
0007			20	20			20	20	20	20				
0010							30	30	30	30	30			
0013				20	20	20	20	20	20	20	20	20	20	20
0016						20	20	20	20	20	25	25	20	20
0019				15		15								
0022				15		15		15		15				15

Figure 7 is an image of the radial velocity from the Dallas Love (DAL) TDWR as the gust front is crossing the DFW runways. The DAL TDWR has a better viewing angle of the front and analysis of the velocity data revealed a difference in radial velocity across the front of between 8-12 m/s (~16-24 knots). This corresponds well to the 20-30 knot alerts being generated by the LLWAS-NE during this time.

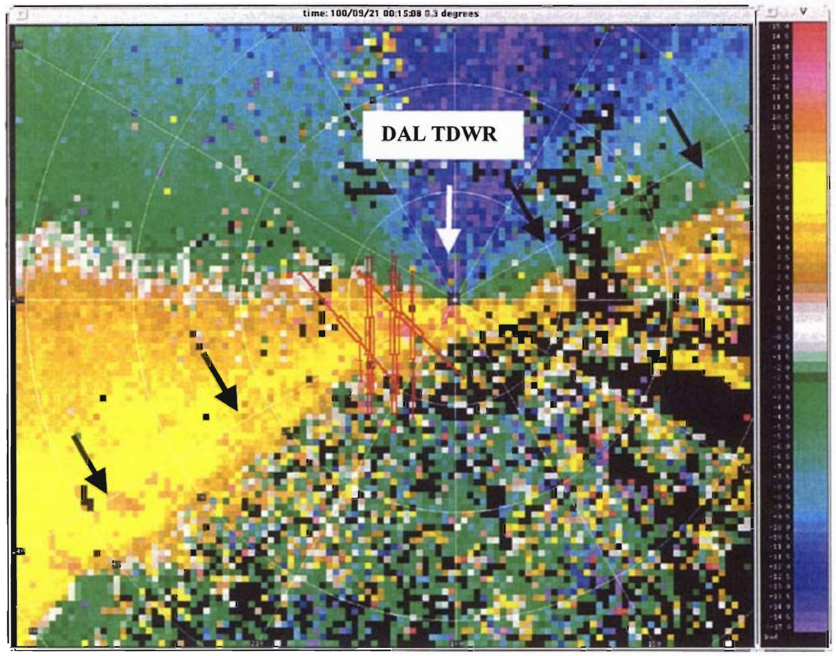

Figure 7. Radial velocity depicted by the DAL TDWR at 0006 UT on September 21, 2000. The black arrows indicate the location of the cold front while the red lines show the location of DFW. The radial velocity difference across the front is between 8-12 m/s.

3.2.2 May 27, 2000

A strong line of thunderstorms was forming ahead of a northeast-to-southwest oriented cold front on May 27, 2000. As the convective line was moving through the western portions of the TRACON, a strong gust front was emanating from the leading edge of the line. The gust front was propagating well in advance of the convection when it began to impact the DFW ARENAS. While it was crossing the DFW ARENAS, the gust front was undetected by the ITWS gust front detection algorithm. Missed detections during this type of weather event are of special concern because many times there will be a heavy push of arriving and departing aircraft before the thunderstorms directly impact the airport. In this case, the LLWAS-NE was indicating gain alerts of up to 40 knots as the front crossed the DFW ARENAS (Figure 8). Since the LLWAS-NE alerts were being integrated into the ITWS, these alerts were reported to ATC.

An inspection of the radar velocity data reveals a lack of radial velocity convergence associated with the gust front (Figure 9). In fact, there is very little evidence in the velocity data that suggests that a significant gust front is affecting DFW. Several factors were contributing to the lack of convergence, including: the location of the radar, the orientation of the front, and the pre and post-frontal wind direction. In this instance, a southerly wind ahead of the front and a westerly wind behind the front both appear as winds directed towards the radar over the DFW ARENAS, and thus, the convergence signature is eliminated.

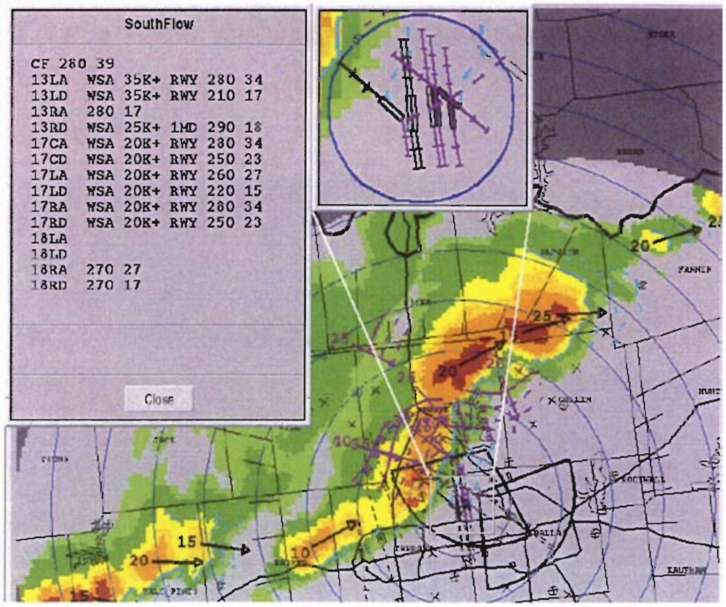

Figure 8. DFW ITWS Situation Display on May 27, 2000 at 2159 UT. The figure shows wind shear alerts being issued for DFW ARENAS (indicated in the exploded area by the purple lines) as a strong, undetected thunderstorm outflow boundary crosses the airport ahead of the convective line. The strength of the alerts and the ARENAS that are being impacted are shown to the upper-left in the Ribbon Display Alerts Window.

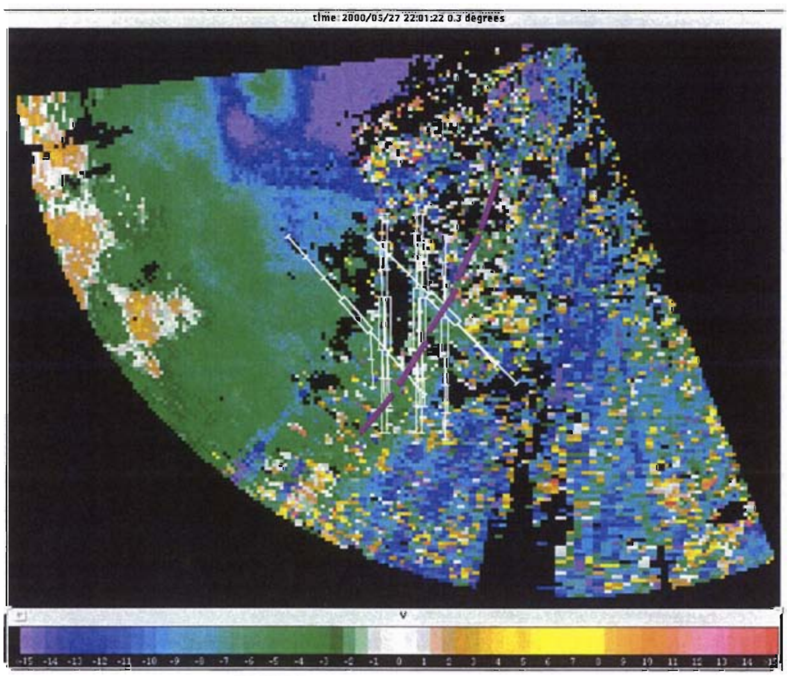

Figure 9. Radial velocity data from the DFW TDWR at 2201 UT on May 27, 2000. The figure shows the lack of a radial velocity convergence signature near the location of the gust front (indicated by the dashed purple line) due in part to the alignment of the front with respect to the radar.

4. REMOVAL OF OUT-OF-TRIP RADAR ECHOES

4.1 INTRODUCTION

A secondary problem in detecting gust fronts occurs when velocity data are removed by out-of-trip editing. The TDWR uses an editing algorithm that attempts to remove the out-of-trip echoes from distant weather that appear within the radar's first unambiguous range interval (Isaminger et. al., 1996). The same storms that are causing data to be edited may also produce a strong gust front that can move ahead of the precipitation and go undetected through the data void region, eventually impacting the airport. Without a valid velocity signature, the ITWS gust front detection algorithm is unable to make a detection and generate wind shear alerts.

4.2 CASE STUDIES

4.2.1 August 22, 1997

On August 22, 1997, a broad area of showers and thunderstorms was located west, north, and northeast of the DFW TDWR. This activity created an outflow boundary, well ahead of the convection, that was moving southeast toward DFW. Much of the velocity data between the precipitation and the radar was being edited to remove the effects of out-of-trip echoes (Figure 10) and as a result, the convergence signature associated with the gust front is practically invisible. Only a thin-line of velocity data showing winds directed towards the radar indicates where the gust front is located. The thin-line alone is insufficient evidence of a gust front, and thus no detection is made. Whenever a gust front approaches the airport from a direction in which distant weather is occurring, there exists the possibility the feature will go undetected over the DFW ARENAS. In cases such as this, the integration of the LLWAS-NE alerts provides an important backup wind shear detection capability to the ITWS gust front detection algorithm.

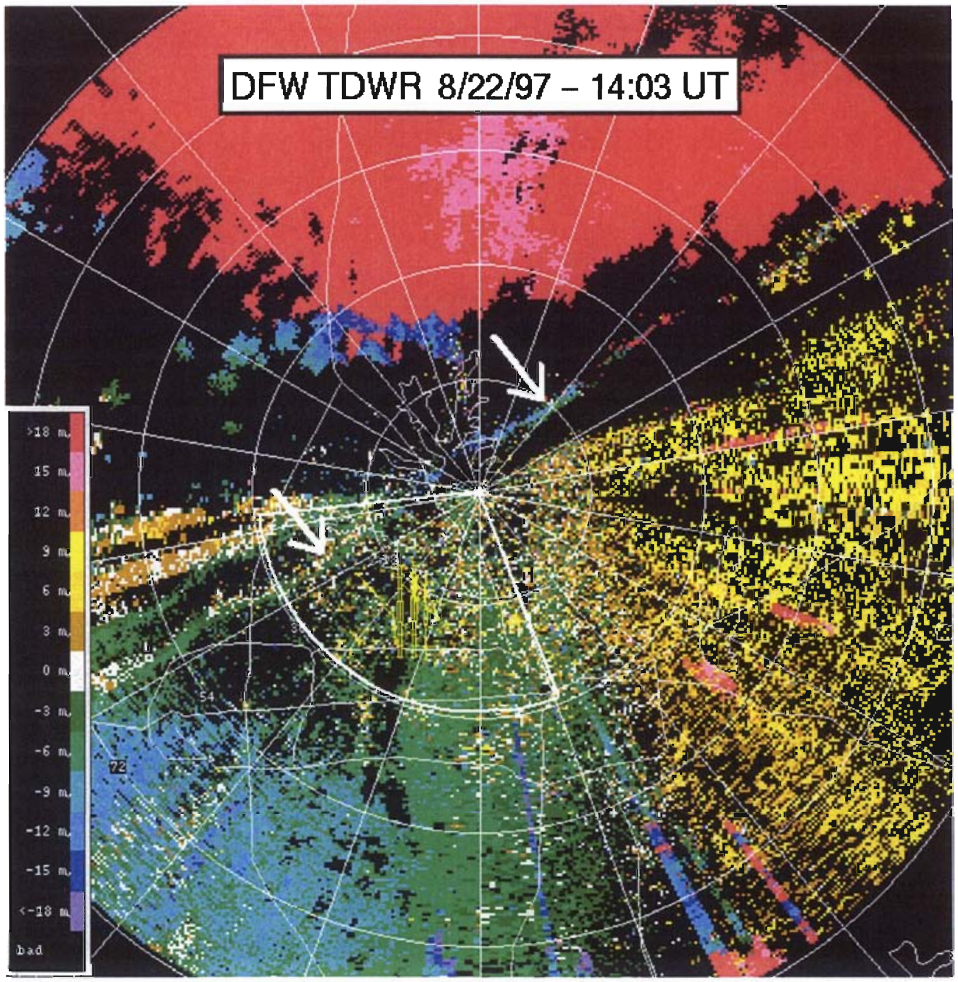

Figure 10. The DFW TDWR velocity data from August 22, 1997 showing the location of a gust front (white arrows) in a data void region. The velocity data has been edited to remove out-of-trip echoes.

5. "NON-TRADITIONAL" WIND SHEAR

5.1 INTRODUCTION

During a three-year period from August 1999 through July 2002, 50% of the wind shear events that produced loss alerts at DFW were generated by mechanisms other than the "traditional" microburst (Shaw et. al., 2000). Although not as dangerous as the microburst, these events still pose a significant threat to aircraft at low altitudes (Miller, 1999). The most common "non-traditional" wind shear mechanisms include: 1) a line of thunderstorms producing linear divergence beneath the core of heavy precipitation, 2) an area of divergence behind a gust front, and 3) lines of divergence within a set of buoyancy (gravity) waves.

The TDWR-based microburst detection algorithms were specifically designed to detect "traditional" wind shear. It is a job that they perform extremely well. Performance results at Memphis and Orlando indicate that the detection rate by the ITWS microburst detection algorithm is 95% and 99% for wind shear and microburst events respectively (Dasey et. al., 1996). However, the design of the TDWR-based microburst algorithms can prevent some of the "non-traditional" wind shear events from being detected.

A line of divergence, rather than circular divergence, characterizes each of the "non-traditional" wind shear events. The divergent line can become radially aligned with the radar in a similar manner as the gust fronts described in Section 3.1. In cases of divergence behind a gust front and gravity waves, the divergence can be far enough away from the precipitation field that there is no Vertically Integrated Liquid water (VIL) associated with the divergent feature. The ITWS microburst detection algorithm uses VIL, which is the amount of water within a given cell in kilograms per square meter (kg/m^2), to confirm that sufficient precipitation is present to force a microburst downdraft. Without meeting a predetermined VIL threshold, the algorithm will classify the divergent feature as being a false detection. The LLWAS-NE is not affected by the alignment of the divergence and does not use a VIL test to validate detections, thus, it is able to detect many of these types of events.

5.2 CASE STUDIES

5.2.1 Linear Divergence – February 25, 2000

During the morning of February 25th, a northeast-to-southwest line of thunderstorms developed west of DFW. As the storms tracked eastward, they have become radially aligned to the DFW TDWR as they begin impacting DFW. The divergence is organized in small linear pockets within the convection. Since the line of divergence is radially aligned to the radar, there is not a detectable divergent signature and the ITWS microburst detection algorithm does not generate any alerts. However, as the storms cross as the storms cross the DFW ARENAS there are several LLWAS-NE generated microburst alerts for losses up to 40 knots. Figure 11 shows the line of storms radially aligned to the DFW TDWR while the eastern DFW ARENAS are being alerted for wind shear events.

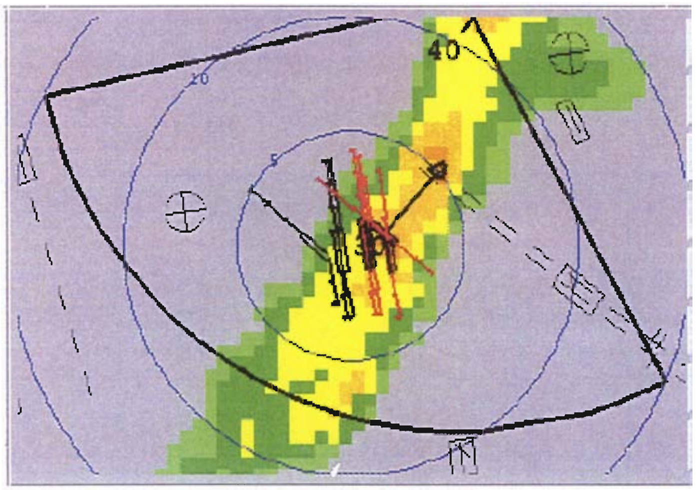

Figure 11. DFW ITWS Situational Display at 1615 UT on February 25, 2000. Red highlighted ARENAS indicate where LLWAS-NE generated wind shear loss alerts are occurring. The DFW TDWR is located at the apex of the pie wedge shape.

Figure 12 shows a comparison of radar velocity data from the DFW TDWR and DAL TDWR at the same time as in Figure 11. The figure demonstrates how a slightly different viewing angle from a Doppler radar can appreciably change the ability to detect wind shear events. Analysis of the DFW TDWR velocity data indicates that there is no evidence of a divergent signature. However, divergence over the DFW ARENAS is noted in the velocity data from the DAL TDWR because of the different viewing angle. Even though the ITWS microburst detection algorithm was unable to detect these features, the LLWAS-NE generated alerts comparable to the divergence strength found in the DAL TDWR base data.

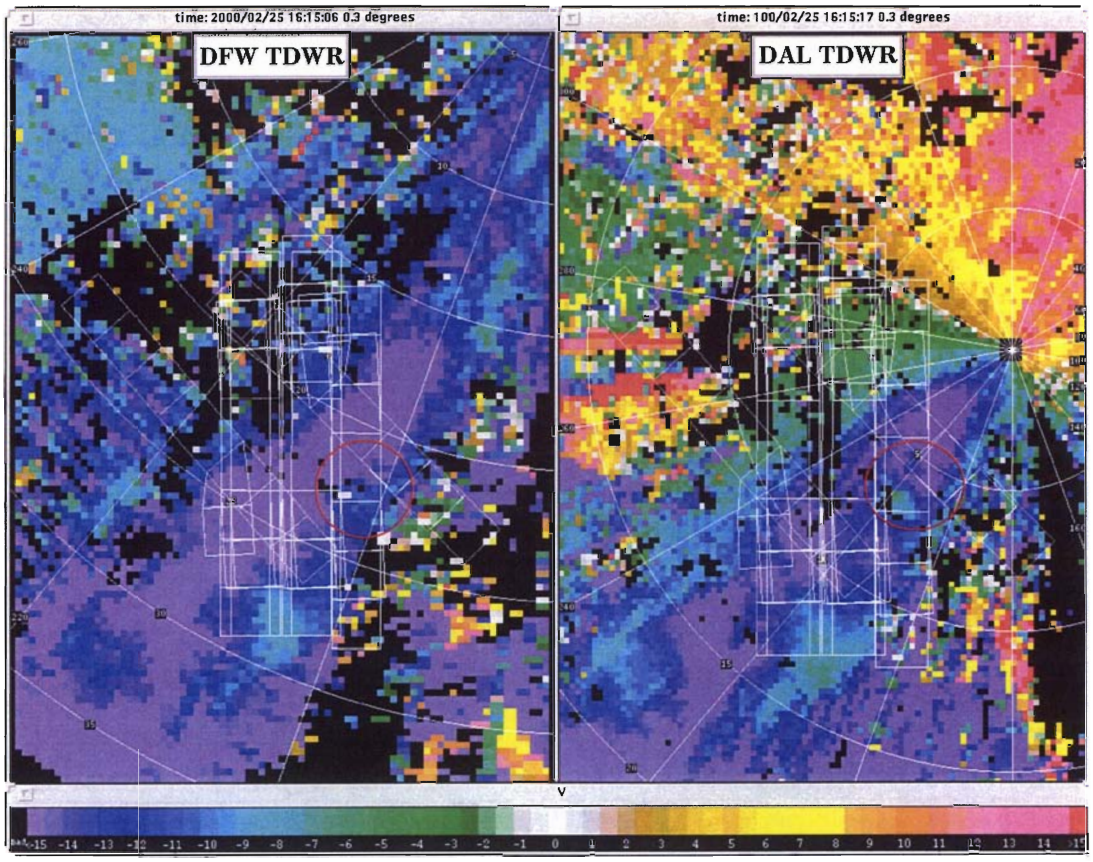

Figure 12. Velocity data from the DFW TDWR and the DAL TDWR at 1615 UT centered over the DFW ARENAS (white lines). The circle indicates an area of divergence over the DFW ARENAS that is detectable from the DAL TDWR but not the DFW TDWR.

5.2.2 Linear Divergence – March 3, 2000

On March 3, 2000, a line of strong thunderstorms orientated in a northeast-to-southwest line was approaching DFW from the west. Again, the line of storms has become radially aligned to the DFW TDWR while impacting the DFW ARENAS. Although no TDWR-based alerts were occurring, the LLWAS-NE was generating loss alerts for up to 50 knots as the divergence embedded within the heavy precipitation crossed the ARENAS. Figure 13 shows a graphical depiction of the weather at 0220 UT.

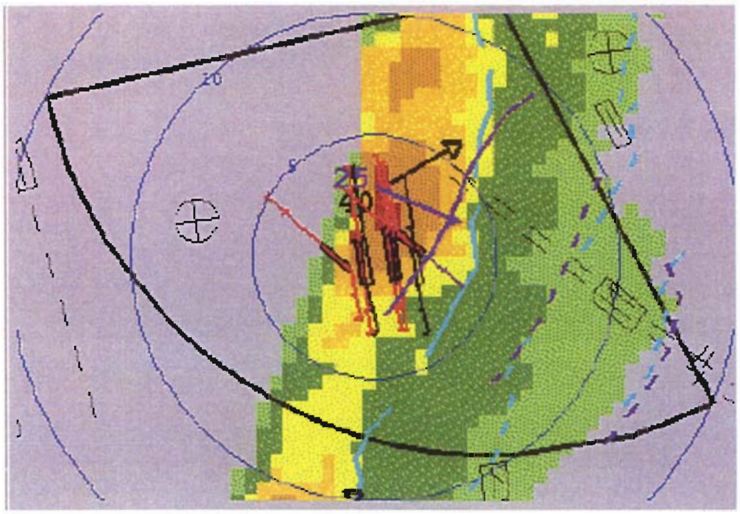

Figure 13. DFW ITWS Situational Display at 0220 UT on March 3, 2000. The red highlighted ARENAS depict where wind shear loss alerts are occurring (produced by the LLWAS-NE). The DFW TDWR is located at the apex of the pie wedge shape.

Figure 14 shows the velocity data from the DFW TDWR at two different times. One time is concurrent with the time in Figure 13 (0219 UT) while the other is 11 minutes later at 0230 UT. The figure shows the dramatic difference in the velocity field with respect to time. At 0219 UT, there is no indication of any convergence or divergence in the velocity data. However, by 0230 UT, both convergent and divergent features are readily apparent.

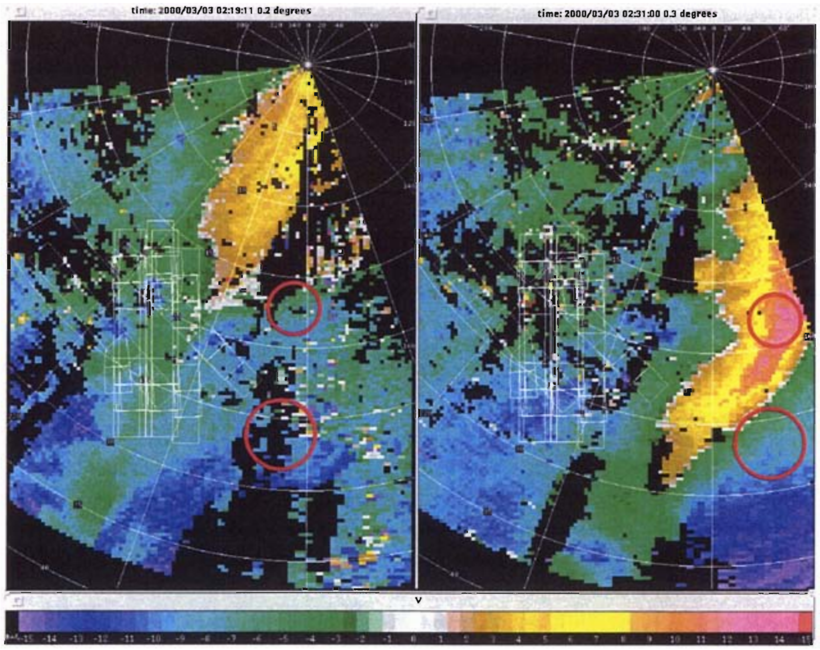

Figure 14. Velocity data from the DFW TDWR at 0219 UT (left) and 0230 UT (right) on March 3, 2000. The image on the left correlates to the time shown in Figure 11 and the circled areas on the right depict detectable areas of divergence.

5.2.3 Divergence behind a gust front – May 27, 2000

On May 27, 2000, a vigorous, northeast-to-southwest oriented squall line developed to the northwest of DFW. As the line approached the TRACON, a strong outflow boundary was present. The boundary moved rapidly to the southeast and impacted the airport well ahead of the convection. Winds along the leading edge of the outflow were out of the northwest at 40 knots, while immediately behind the front the winds weakened and veered to the southwest. This change in wind direction and speed created a divergence field behind the gust front. As the divergence crossed the DFW ARENAS, the LLWAS-NE generated alerts for losses up to 40 knots.

Figure 15 shows the ITWS Situational Display of the weather at 2209 UT with the heavy precipitation northwest of the airport. The lack of precipitation across the airport plays a critical role in defining why there are no alerts being produced by the ITWS microburst detection algorithm. The microburst detection algorithm uses a VIL test to determine the validity of wind shear and microburst detections. In order for a radar velocity divergence feature to be deemed valid by the algorithm, divergence of 7.8 m/s or greater must be detected in close proximity to an area of VIL with a value of 5kg/m^2. This test is an effective way to reduce false alarms. In this case, the divergence is a significant distance away from any precipitation echoes and does not pass the VIL test. Figure 16 indicates that the VIL values over the alerted ARENAS were less than 5 kg/m^2.

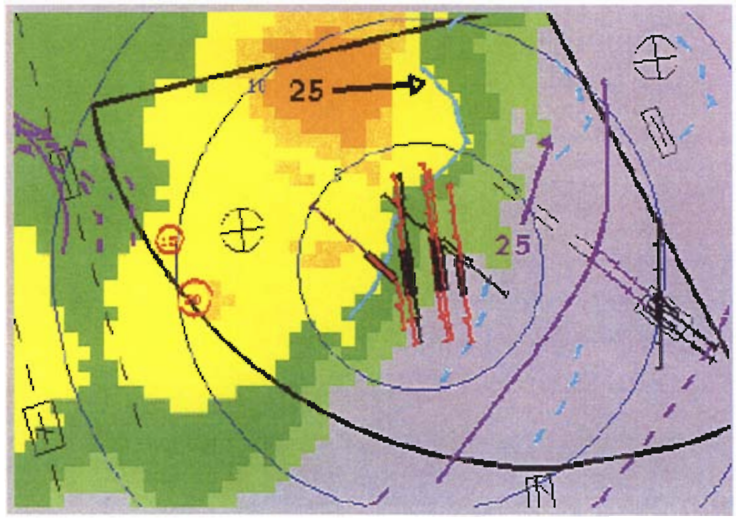

Figure 15. DFW ITWS Situational Display at 2209 UT on May 27, 2000. The purple line indicates the location of the gust front while the red lines show where LLWAS-NE generated loss alerts are occurring on the DFW ARENAS.

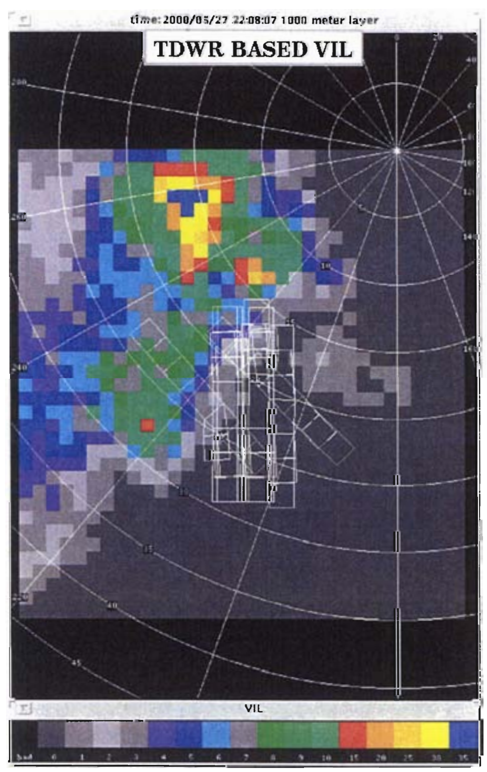

Figure 16. DFW TDWR-based VIL at 2208 UT on May 27, 2000. The VIL values over the alerted ARENAS do not surpass the threshold needed to validate wind shear detections.

5.2.4 Divergence within a set buoyancy (gravity) waves – February 16, 2001

On the morning of February 16, 2001, several sets of gravity waves impacted the DFW ARENAS. Gravity waves are characterized by alternating regions of convergence and divergence. These features usually develop behind an outflow boundary but can also develop in a sheared environment following the passage of a thunderstorm (Miller, 1999). In this particular case, the gravity waves developed following the passage of a thunderstorm.

While several sets of gravity waves impacted DFW throughout the early morning hours of the 16th, the strongest set of waves were generated after an area of heavier precipitation was impacting the airport (Figure 17). Because the precipitation present at the time of impact is so light, the associated VIL is below the detection threshold for the ITWS microburst detection algorithm. However, the shear present in the DFW TDWR velocity data surpasses 20 m/s (~ 40 knots). Figure 18 shows a four-panel image from the microburst detection display showing the DFW TDWR velocity data, shear data, reflectivity and VIL. The convergence and divergence patterns associated with the gravity waves are readily apparent in the velocity data as well as in the shear data. VIL values are very low with a maximum of 2 kg/m^2 over the DFW ARENAS.

Even though the ITWS microburst detection algorithm did not produce alerts in conjunction with the gravity wave train, the maximum loss alerts generated by the LLWAS-NE for this event peaked at 40 knots, which is consistent with shear values found in the DFW TDWR data. The LLWAS-NE continued to generate loss alerts over the ARENAS as subsequent waves crossed the airport from the southwest.

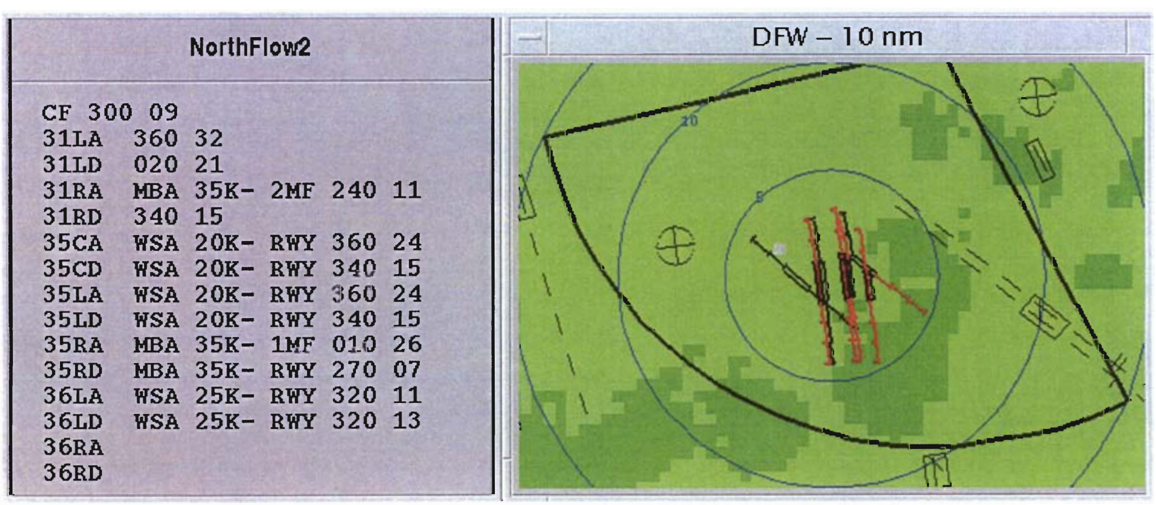

Figure 17. DFW ITWS Ribbon Display Alerts Window (left) and Situational Display (right) at 1043 UT on February 16, 2001. The image shows LLWAS-NE generated alerts being issued for DFW ARENAS (red lines) as a gravity wave train crosses the region.

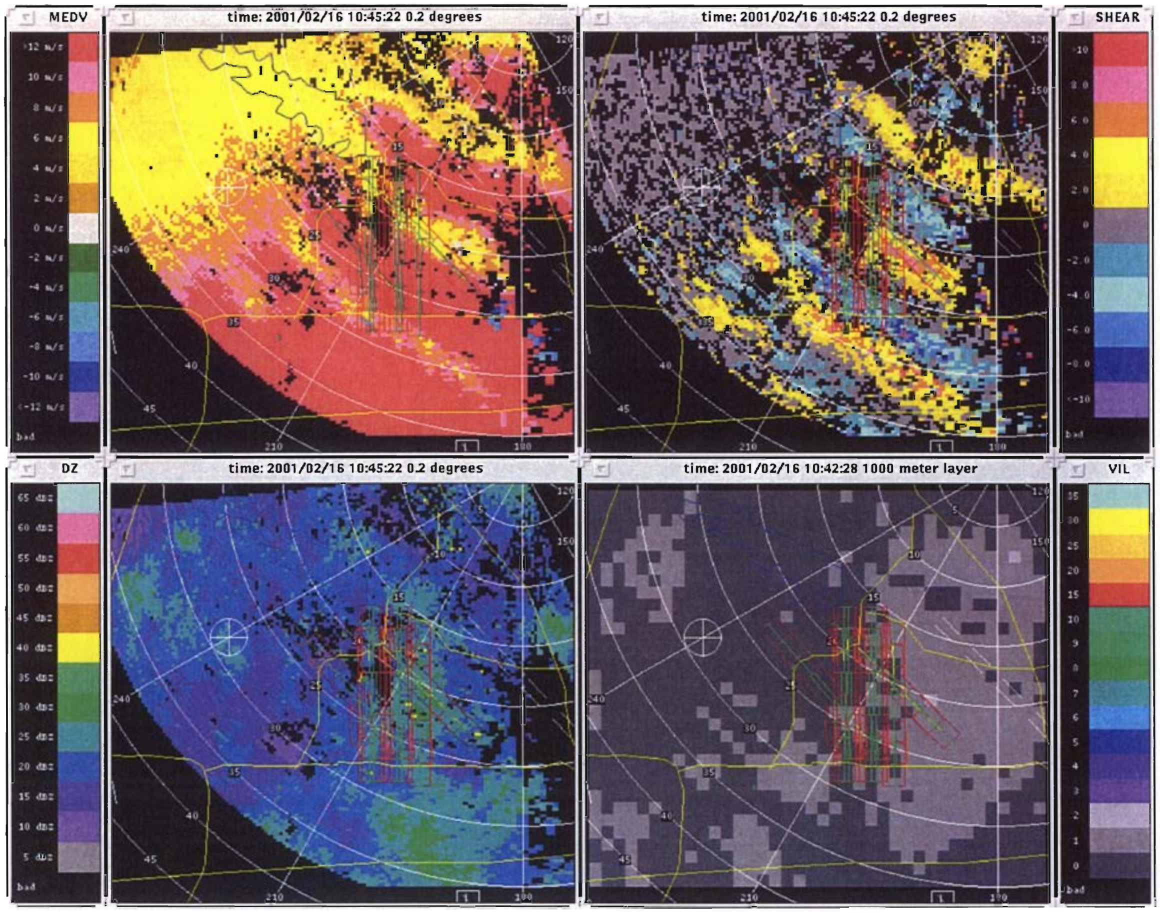

Figure 18. Four-panel image from the DFW microburst detection display showing the DFW TDWR velocity data (upper-left), the associated shear in m/s (upper-right), the radar reflectivity (lower-left) and the VIL (lower-right). Notice the pronounced wave feature present in the velocity and shear data. Also, note the lack of significant VIL over the DFW ARENAS highlighted in red and green.

6. TDWR DATA QUALITY ISSUES

6.1 INTRODUCTION

The data quality issues examined are radome attenuation and clutter editing. Radome attenuation can occur for any domed radar. However the 5 cm wavelength TDWR is more susceptible than 10 cm wavelength radars like the National Weather Service NEXRAD (WSR-88D), because of its shorter wavelength. Dome attenuation occurs when heavy precipitation coats a radome with a layer of water causing lowered radar returns or attenuation. Because the beam is attenuated as it leaves the dome, the radar processing algorithms cannot determine that attenuation is occurring. Therefore, algorithms utilizing base data have no indication that the data are degraded.

In order to detect wind shear events, the TDWR uses a very low elevation scan, typically 0.1 to 0.3 degrees above the horizon. Unfortunately, the low elevation of the radar beam increases the effects of ground clutter residue on the base data, especially in urban areas where most large airports are located. Therefore, the TDWR base data needs to pass through a clutter residue editor. Large buildings located near the center of DFW necessitate editing within the DFW ARENAS. Editing this clutter residue can cause the removal of valid velocity returns, leading to missed wind shear and microburst detections.

6.2 RADOME ATTENUATION

As shown in section 5, the TDWR based microburst detection algorithm uses a VIL test to reduce false alarms brought about by diverging birds, unedited out-of-trip echoes, dealiasing errors or noisy data. However, the computed VIL within a given storm is reduced as radome attenuation occurs and reduces a given power return to the radar. In such cases, a wind shear or microburst event may be detected in the radar's velocity field but not output as a wind shear alert because of a lack of computed VIL.

6.2.1 Case Study – February 26, 2000

On February 26, 2000, a line of severe thunderstorms tracks over DFW and the DFW TDWR site simultaneously. Figure 19 shows the ITWS Situational Display and the DFW Ribbon Display Alerts Window at 0507 UT. As heavy rain impacts the DFW TDWR, dome attenuation occurs. All of the wind shear alerts shown are being produced by the LLWAS-NE. This is evident by the lack of ITWS wind shear detection shapes over the DFW ARENAS.

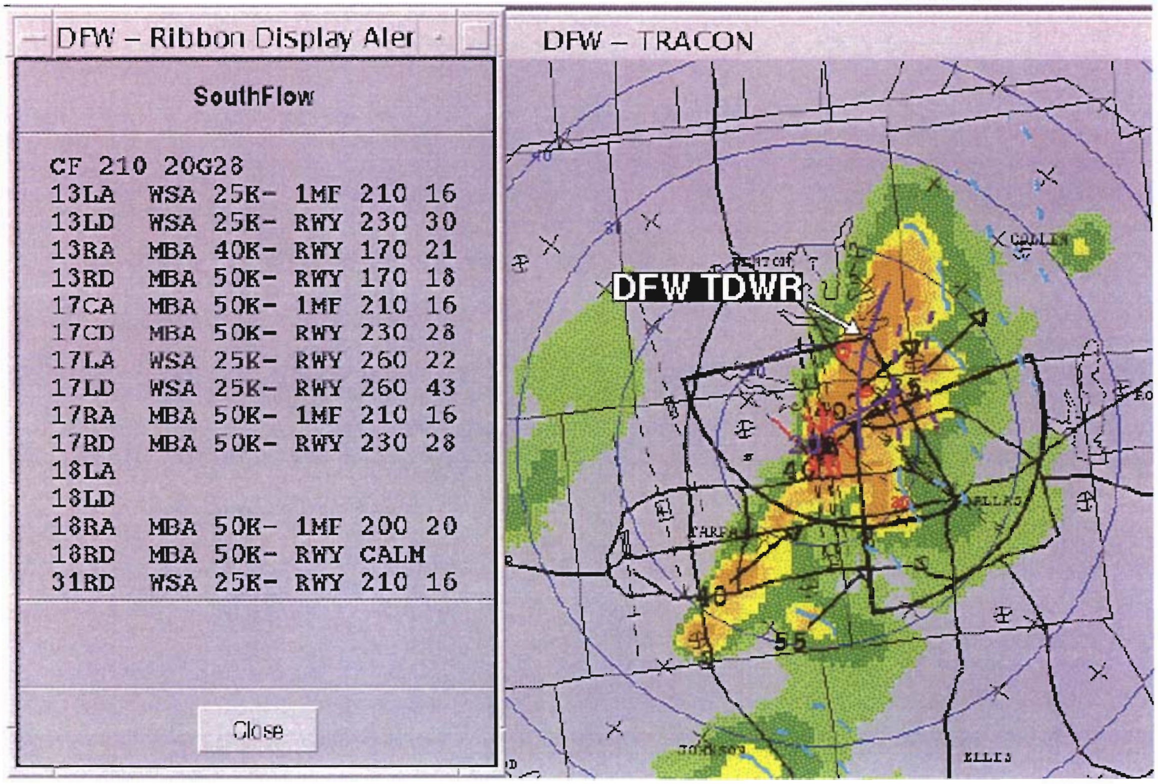

Figure 19. DFW ITWS Situational Display at 0507 UT on February 26, 2000. The image shows the LLWAS-NE alerts from DFW (left) as well as the precipitation data (right). The red highlighted ARENAS (red lines) indicate where wind shear loss alerts are occurring. The pie wedge shapes are the hazard sectors for the DFW and DAL TDWRs.

Analysis of the DFW TDWR velocity data in Figure 20 indicates there is a 26 m/s (~50 knots) microburst event occurring over the DFW ARENAS at 0507 UT. This is comparable to the 50 knot losses generated by the LLWAS-NE at the same time.

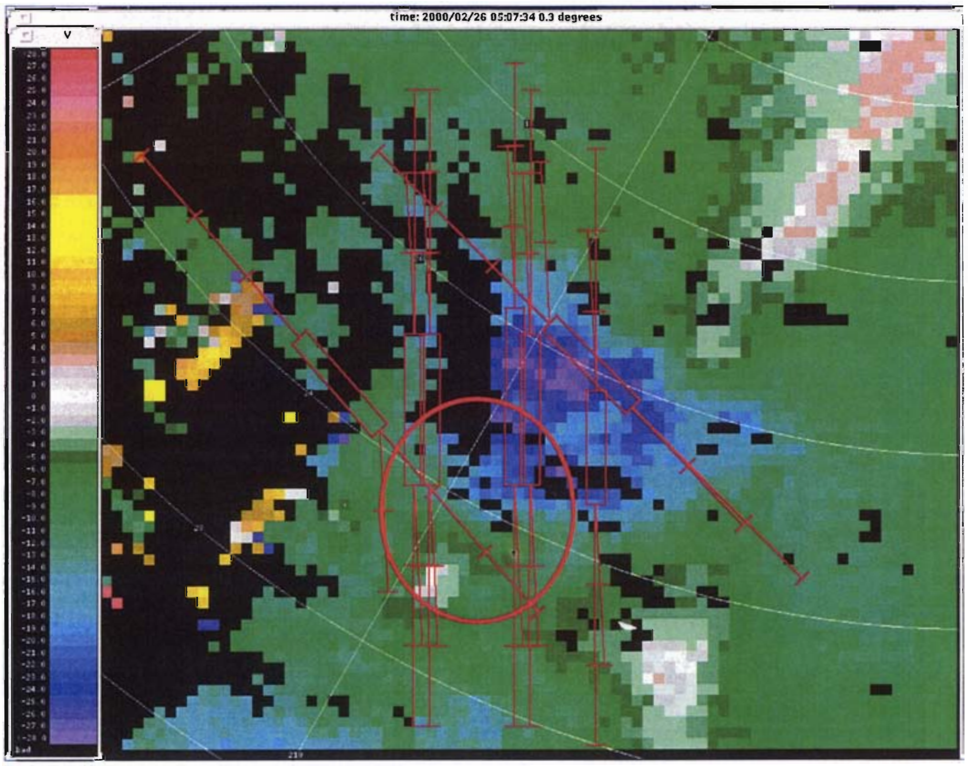

Figure 20. Doppler Velocity data from the DFW TDWR at 0507 UT on February 26, 2000, the same time as in Figure 18. The red lines indicate the DFW runways and approach and departure paths. The velocity data indicates a loss of up to 26 m/s (inscribed in the red circle) over the DFW ARENAS.

Figure 21 shows an example of the degradation of computed VIL data for this case. As the storms approach DFW and the DFW TDWR at 0450 UT, VIL values are greater than 35 kg/m^2. However, as the line of storms reach the radar site and produce heavy rain on the radome, the apparent VIL values drop to only 3 kg/m^2 over the DFW ARENAS. Therefore, the ITWS microburst detection algorithm rejects any wind shear detections over DFW because the VIL threshold test is not passed.[5] An examination of the DFW TDWR velocity data for this event indicates that 17 wind shear alerts (WSA) and six microburst alerts (MBA) are missed due to low apparent VIL values.

[5] The VIL threshold, originally set to 5 kg/m^2, was subsequently reduced to 3 kg/m^2 to account for this type of degradation.

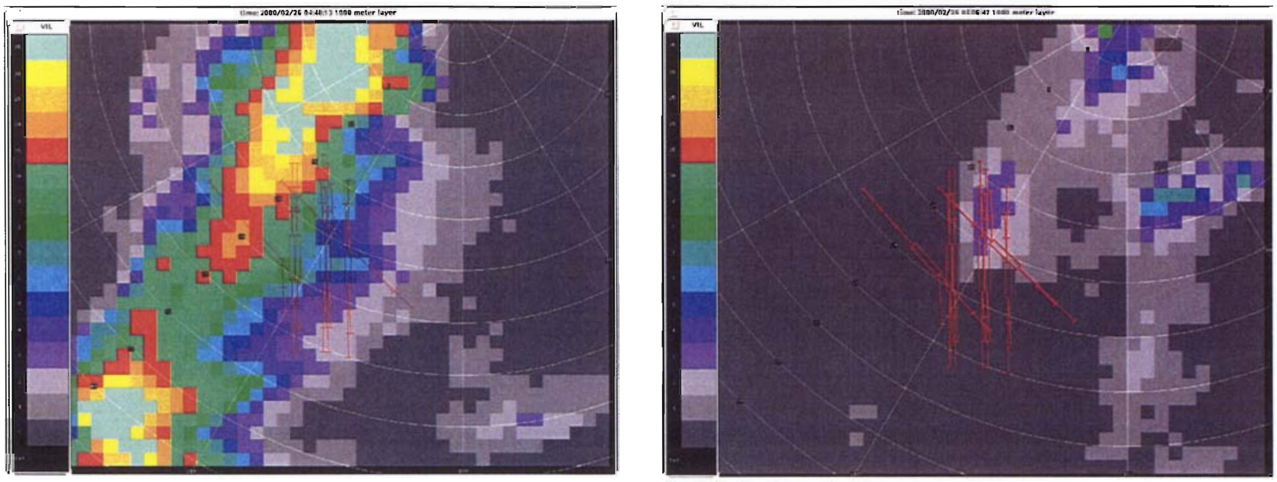

Figure 21. VIL data from the DFW TDWR on February 26, 2000. The image on the left is from 0448 UT, before the line of storms impacted the DFW TDWR.

6.3 CLUTTER RESIDUE EDITING

The removal, or editing, of residual stationary and moving ground targets, or clutter, is a very important feature of the TDWR (Mann, 1988). Without this ability, velocities associated with returns from moving cars could cause a multitude of false wind shear detections and the reflectivity from stationary targets would cause false storm cell detections. Clutter removal from the TDWR base data is accomplished in a two-step process. The TDWR has clutter filters within the signal processor that reject radar returns with near zero velocities. These clutter-filtered returns are then processed to generate "base data" consisting of reflectivity, radial velocities and spectrum width. The reflectivity data for each range, azimuth cell at a given elevation angle is compared to a previously generated Clutter Residue Edition Map (CREM). If the measured reflectivity is less than or equal to the corresponding CREM threshold the base data are flagged as being corrupted by clutter residue. The ITWS algorithms ignore such flagged data and ingest only data in which the reflectivity surpasses the corresponding CREM thresholds.

The CREM is created as follows. First, data are recorded from many scans of the lowest radar tilts on a clear day. Second, the regions of clutter residue are automatically identified and a high-resolution (1° in azimuth, 120 meters in range) map of clutter residue levels is generated. When there is particularly bad clutter that changes position with time (e.g. due to moving vehicles), hand drawn polygons that encircle clutter regions with a human estimated clutter residue level are created. Both the automatically generated high resolution clutter map and the human generated polygon maps are used to create the final high resolution CREM. These are loaded into the TDWR data processor to remove unwanted clutter areas.

The human added polygons have been found to be very effective at reducing false alarms caused by moving targets. However, there is a potential problem when the added polygons are too conservative and cause inappropriate editing of valid base data. Before the latest set of CREMS for the DFW TDWR were installed, a large number of wind shear and microburst events were missed due to very large polygons over the DFW ARENAS. The large number of missed microburst events, and consequently their resulting alerts over the DFW ARENAS, lead to the TDWR Program Support Facility (PSF) taking action and adjusting the CREM to lessen the impact of the polygons. Figure 22 shows a side-by-side comparison of the two revisions of the CREM. Decreasing the strength of the polygons helped reduce the number of missed detections over the DFW ARENAS. However, some regions still exist near the airport where the CREM levels are strong enough to flag base data as clutter residue.

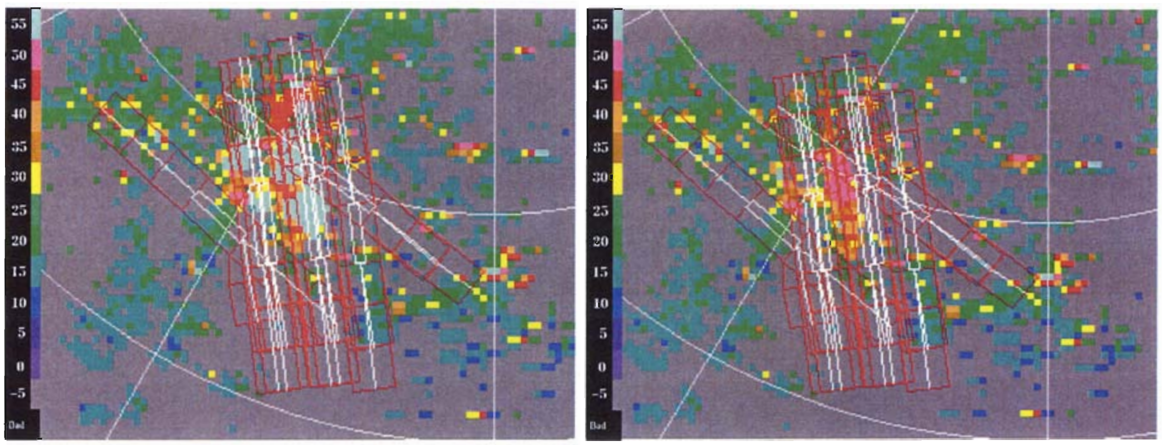

Figure 22. Comparison of the previous version of the CREM (left) and the most recent version (right) over the DFW ARENAS. The color bars show the dBz value of the edited areas. The bright blue regions shown on the left are polygons of greater then 55 dBz, where virtually all data would be edited. Notice these polygons have been reduced but not eliminated in the image on the right.

6.3.1 Case Studies

Two cases are presented as examples of how TDWR clutter residue editing can degrade both microburst and gust front detections. The first case is from May 9, 1998, where microburst detections were missed over the airport. The second case, from May 19, 2000, is an example of degradation of a gust front detection.

May 9, 1998

On May 9, 1998, a severe thunderstorm was impacting DFW and producing a number of wind shear and microburst events within its ARENAS. Figure 23 shows DFW TDWR velocity base data at 0400 UT. The red circles are wind shear events generated by the ITWS microburst detection algorithm. The bad values (black pixels) between the runways correspond to the clutter-edited region. The cyan circle indicates the location of a microburst event that was not being detected by the ITWS microburst detection algorithm. An examination of the data within the cyan circle shows divergence of at least 13 m/s across the data void region. With some extrapolation of the data into the void region, it is likely that the divergence is actually greater than 17 m/s. The LLWAS-NE generated microburst events within the cyan circle of up to 23.1 m/s. Since the velocity data were being edited, the ITWS microburst detection algorithm was unable to detect this feature.

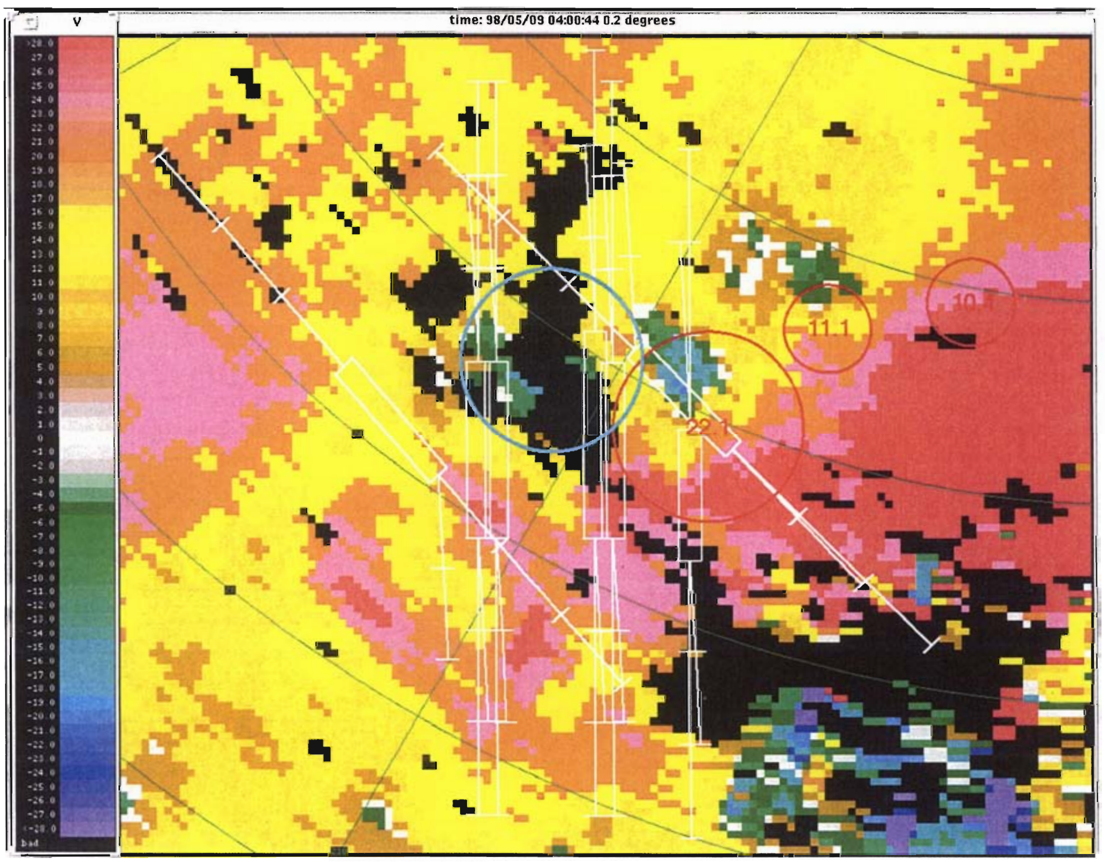

Figure 23. DFW TDWR velocity data on May 9, 1998 at 0400 UT. The red circles indicate locations where the ITWS microburst detection algorithm has detected divergent signatures. The values indicate the strength of divergence in meters per second. The DFW runways and departure and approach paths are shown in white. The cyan circle indicates the area where a microburst was not detected.

May 19, 2000

On May 19, 2000, there is an outflow boundary emanating from a line of thunderstorms approaching DFW. The ITWS gust front detection algorithm has detected the boundary well before the front is impacting the DFW ARENAS. However, as the boundary enters the clutter residue edited region between the east and west runways, a small portion of the gust front detection is dropped due to the editing of the DFW TDWR base data. This creates two gust front detections, one east and one west of DFW (Figure 24A). Figure 24B shows the TDWR base data for the time in question. The convergence is clearly continuous over the DFW airport.

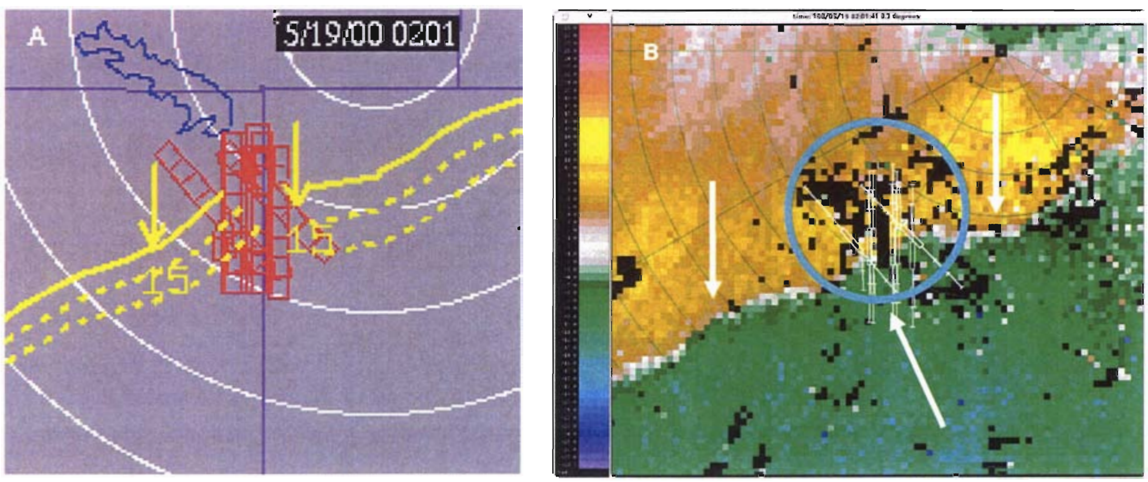

Figure 24. Output from the (A) ITWS gust front detection algorithm and (B) the DFW TDWR velocity data at the same time as A. Note the break in the gust front detection (solid yellow line) over the DFW ARENAS (red lines). The area of bad data (black pixels within the cyan circle) between the runways corresponds to the dropped portion of the detection in A. The convergence associated with the gust front is continuous across DFW and the white arrows indicate the wind direction on each side of the front.

As the front impacts the DFW ARENAS, the ITWS gust front detection algorithm generates gain alerts of 20 knots. As the front tracks over the runways, the detection impacting the ARENAS was dropped and the TDWR-based algorithm no longer generates alerts. However, the LLWAS-NE continues to produce gain alerts of up to 25 knots during this time. Once the front has crossed the airport and is impacting the southern ARENAS, the ITWS gust front detection algorithm has regained a full detection and generated gain alerts for up to 20 knots. The net result of the LLWAS-NE alert integration is a seamless stream of wind shear alerts as the front crossed the DFW ARENAS.

7. ACCURACY ASSESSMENT OF THE LLWAS-NE ALERTS

7.1 INTRODUCTION

The previous sections illustrate how the LLWAS-NE alerts compliment those generated by the radar-based algorithms when situations arise that inhibit radar-based detections. However, the accuracy of the alerts generated by the LLWAS-NE has not been verified. In this section, the validity of the LLWAS-NE generated alerts is examined by comparing the alert values with hand-generated truth from the high-resolution TDWR velocity data.

7.2 EVALUATION METHODOLOGY

The performance results are generated in the same manner as Cole and Todd (1996) in their comparative performance study of TDWR/LLWAS 3 Integration Algorithms. Statistics for probability of detection (POD) and probability of false alarms (PFA) are computed by comparing the alerts generated by the LLWAS-NE and those produced by manually examining high resolution TDWR data. Each arrival and departure ARENA for the parallel north-south runways[6] is in one of three alert states, microburst (MBA), wind shear loss (WSL), or no alert (Null). The alerts produced manually from the radar data are considered truth and the performance results assess the accuracy of the LLWAS-NE generated alerts. The diagonal runways at DFW are not included in the analysis because the line-of-sight of the DFW TDWR is orthogonal to these ARENAS and accurate estimates of the wind shear are difficult to determine from the radar data.

Three different criteria are examined to determine the accuracy of the LLWAS-NE:

1. POD(L|MB) - The probability that the LLWAS-NE will issue a WSA or a MBA when the radar data indicates a MBA.

2. POD(L|L) - The probability that the LLWAS-NE will issue a WSA or MBA when the radar data indicates a WSA or a MBA.

3. POD(MB|MB) - The probability that the LLWAS-NE will issue a MBA when the radar data indicates a MBA.

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[6] Runway 18L is not used because an LLWAS-NE processor limitation only allows coverage for six sets of ARENAs.

In addition to the probability of detection, the probability of false alerts is computed from the contingency tables in order to accurately assess the performance of the LLWAS-NE. Four different statistics are computed, these include:

1. PFA(MB) - The probability a MBA issued by the LLWAS-NE is a false alert.

2. PFA(WS) - The probability a WSA issued by the LLWAS-NE is a false alert.

3. PFA(L) - The probability a MBA or a WSA issued by the LLWAS-NE is a false alert.

4. POW -The probability that the LLWAS-NE will issue a MBA when the radar data indicates a WSA. Thus, while the alert is not false it is an incorrect use of an MBA.

Since the radar data are used to generate the truth, no cases were selected for the dataset in which a poor viewing angle or noisy data biased the radar data. Thus, none of the cases examined in this report are included in the dataset. However, a wide selection of wind shear events was compiled in order to accurately determine the performance of the LLWAS-NE under various conditions. These include: linear divergence, "traditional" wind shear events, and divergence behind a gust front. It is assumed that the accuracy of the LLWAS-NE is similar despite the different mechanisms producing the wind shear events since the system only measures the wind speed and direction at each anemometer. In all, the analysis includes data from six separate days with over 200 minutes of wind shear data truthed.

7.3 EVALUATION RESULTS

The results for the cases analyzed are shown in Figure 25. The figure indicates that the LLWAS-NE shows a considerable amount of skill in detecting losses associated with microbursts but does not do as well when issuing alerts for wind shear losses. When 15 knot wind shear losses that the LLWAS-NE missed are removed from the computations, the POD does increase slightly (maroon bar).

While the probability of detection results are encouraging, the system does have fairly high probabilities of false alerts (Figure 26). The probability of over-warning is also quite high. However, when the 15 knot false alerts are removed and truthed losses of between 10-15 knots are upgraded to a WSA, the statistics improve dramatically. One of the most common types of false alerts occurs when the divergence associated with a wind shear or microburst is completely located on the arrival or departure end of the airport ARENAs. When this occurs, one of the edges connecting the LLWAS-NE sensors used in computing the loss value may narrowly intersect the runway, which results in alerts being issued for both the departure and arrival ARENAs. Additionally, in most cases there is a lag between the time when the radar data indicates wind shear occurring and the time the LLWAS-NE issued its initial alerts. A lag also occurs at the termination of many events when the radar data indicates no alerts and the LLWAS-NE continues to alert for a period of time. This lag time is responsible for some of the reduction and increase in the respective POD and PFA numbers.

Other studies have examined the performance of the LLWAS system (Cole and Todd 1996, Wilson and Gramsow 1991) and produced better performance statistics. Several factors account for the difference in the results. First, Cole and Todd use a margin of error of ±5 knots to account for inaccuracies in the dual Doppler wind field. This removes weak, hard to detect wind shears from their calculations, improving the POD and reducing the PFA. In addition, both studies examine cases of strong microbursts that produce a substantial signal in the wind field. Finally, while the dataset contains a diverse set of data, the number of cases in this dataset is small and may not completely represent the performance of the system. However, it should be noted that in each case examined, the LLWAS-NE generated wind shear and microburst alerts are validated by the radar data. In fact, the high probabilities of detecting the stronger microburst events increases the confidence that the LLWAS-NE is able to detect the more dangerous wind shear events described in this paper.

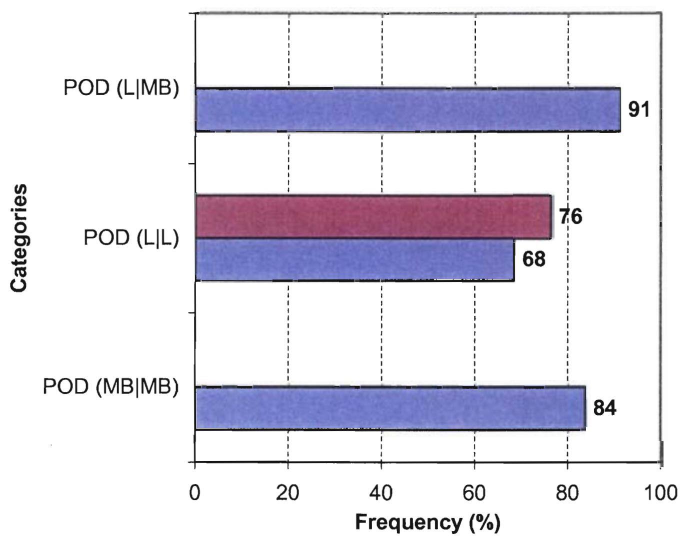

Figure 25. Probability of detection statistics for the DFW LLWAS-NE. The maroon line is the POD(L|L) when 15 knot wind shear losses that the LLWAS-NE missed are removed from the computations.

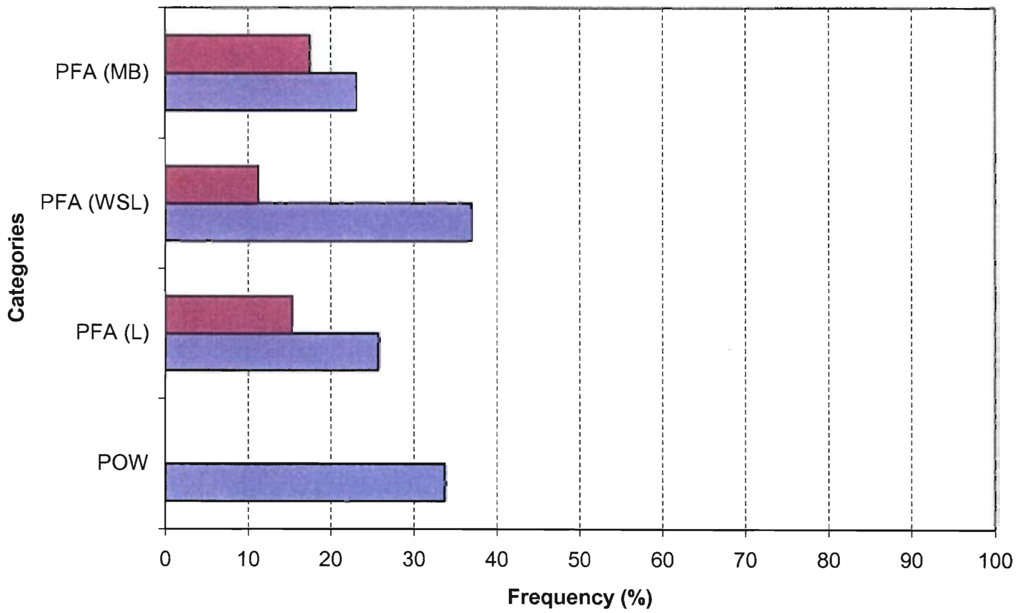

Figure 26. Probability of false alarm statistics for the DFW LLWAS-NE. The maroon lines are the PFA values when weak wind shears are removed and truthed losses of between 10-15 knots are upgraded to a WSA.

8. CONCLUSIONS AND RECOMMENDATIONS

In this report, several cases are presented that illustrate some of the difficulties the TDWR-based algorithms have in detecting wind shear and microburst events at DFW. The principal causes are the location of the DFW TDWR with respect to the DFW ARENAS, radar-based algorithms not designed to detect "non-traditional" wind shear, and data quality issues. Even though we illustrate some of the shortcomings in the performance ability of radar-based wind shear algorithms, the TDWR still provides the most valuable wind shear and microburst information to air traffic controllers and pilots that use the nation's largest airports. However, in the cases that we presented, the radar-based alerts reported to ATC were improved with the LLWAS-NE alert integration. Without the integration of the LLWAS-NE, there would have been potentially hazardous interruptions in wind shear alerts during these occasions.

Airports that have only a TDWR and no LLWAS-NE are potentially vulnerable to all of the wind shear detection issues discussed in this study. There are several areas that are being explored or can be explored to help mitigate these issues at airports with out an LLWAS-NE system:

1. The TDWR could use different waveforms and signal processing to reduce range folding and clutter residue levels. A planned upgrade to the TDWR signal acquisition and base data generator subsystem (the Radar Data Acquisition or RDA) will significantly improve base data quality by improving clutter suppression and largely eliminate out-of-trip editing.

2. The human generated CREM polygons for the TDWR should be carefully reviewed to ensure they are as spatially compact as possible.

3. A new algorithm should be designed to detect radome attenuation.

4. A "non-traditional" wind shear detection algorithm should be developed.

5. At airports with more than one TDWR, the data from each radar should be combined to create a gust front detection algorithm that is less susceptible to radial alignment problems.

Working in concert, the TDWR and the LLWAS-NE systems produce the best possible wind shear detection product available. While there is a propensity for the LLWAS system to false alarm, the TDWR wind shear detection algorithms help to reduce false alarms. Conversely, the LLWAS-NE is able to detect wind shear events that can be missed by the TDWR alone. Therefore, The LLWAS-NE system has proven itself as a valuable tool and should continue to be an input to the ITWS wind shear products generator.

GLOSSARY

ARENA	Areas Noted for Attention
ATC	Air Traffic Control
CREM	Clutter Residue Edition Map
DAL	Dallas-Love Airport
DFW	Dallas Ft Worth International Airport
ITWS	Integrated Terminal Weather System
LLWAS-NE	The Network Extension of the LLWAS
MBA	Microburst Alert
PFA	Probability of False Alarms
POD	Probability of Detection
PSF	Program Support Facility
TDWR	Terminal Doppler Weather Radar
VIL	Vertically Integrated Liquid
WSA	Wind Shear Alert

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