

Project Report

ATC-308

**Observations of Non-traditional Wind Shear
Events at the Dallas/Forth Worth
International Airport**

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Radar-based algorithms have shown considerable skill in detecting wind shear events. However, the algorithms were developed to identify features common to the “traditional” events. If the algorithms were modified to detect “non-traditional” wind shear, the corresponding increase in false detections could be unacceptable. Therefore, in this report a new radar-based algorithm is proposed that detects linear divergence, divergence behind gust fronts, and gravity waves for output on the Integrated Terminal Weather System by identifying the radar signatures that are common to these features.

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1. INTRODUCTION

A significant amount of research over the past 20 years has led to a greater understanding of wind shear and its hazard to aviation. Several terms have been introduced that describe the intense downdrafts produced within thunderstorms and the potential hazard they pose to aircraft flying at low altitudes. These include “downrush” (Fawbush and Miller, 1954), “downburst” (Fujita and Byers, 1977), and microburst (National Research Council, 1983). Downbursts were described as “an outburst of damaging winds on or near the ground” (Fujita and Wakimoto, 1981) and a microburst is a similar event on a smaller scale. This type of event, in which the horizontal divergence associated with a downburst comes from a single parent storm cell, is what this report will refer to as a “traditional” wind shear event (Figure 1). By convention, if the airspeed loss experienced by an aircraft is less than 30 knots the event is referred to as a wind shear while losses of 30 knots or greater are termed microbursts.

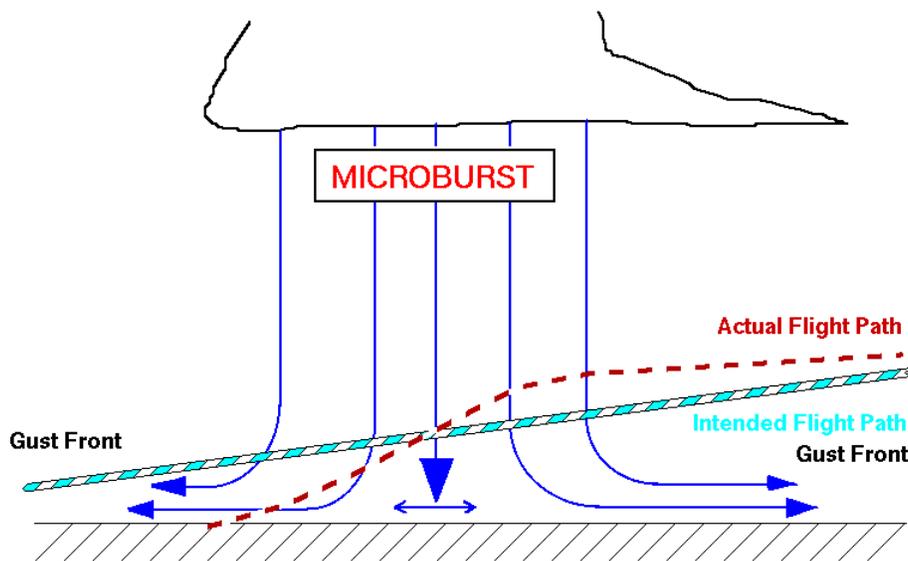


Figure 1. Schematic picture of a traditional microburst. The flight path (red dashed line) shows that the aircraft gains airspeed and lift as it encounters the upwind portion of the event. As the aircraft crosses into the downwind portion of the microburst it loses lift and airspeed and begins to descend. The descent may be exacerbated by pilot over-correction when reacting to the increase in airspeed.

Much attention has been given to the detection of traditional wind shear events using sensors such as the Terminal Doppler Weather Radar (TDWR) and the Low-Level Wind Shear Alert System (LLWAS). The TDWR is a pencil beam radar designed to detect wind shear in the terminal airspace and provide graphical icons and text alerts to air traffic controllers (ATC) for dissemination to pilots (Turnbull et. al., 1989 and Merritt et. al., 1989). The microburst detection algorithms developed using data from the TDWR have shown considerable skill in detecting the horizontal divergence associated with traditional wind shear events. In fact, the requirements for the Integrated Terminal Weather System (ITWS) microburst detection algorithm state that the probability of detection (POD) of wind shear events should exceed 90% while the POD of microbursts must be at least 95%. Performance results at Memphis and Orlando indicate that the detection rate for wind shear and microburst events is 95% and 99%, respectively (Dasey et. al., 1996). However, these values do drop when more-challenging sites are included in the analysis (Isaminger et. al., 1999).

A classic microburst event observed by the TDWR near the Dallas/Ft. Worth International Airport (DFW) is shown in Figure 2. The velocity base data clearly shows the divergence associated with the microburst as a couplet of winds directed towards the radar (greens/blues/purples) and winds directed away from the radar (yellows/oranges/reds). The readily identifiable divergent couplet is the feature that the radar-based algorithm keys on when generating a detection shape.

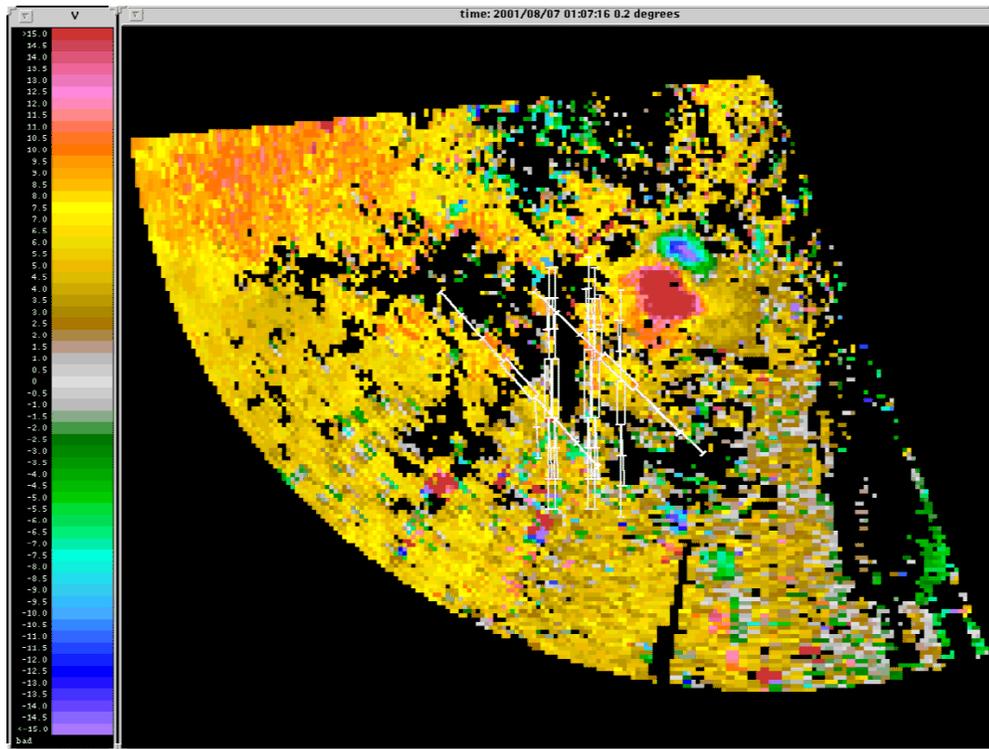


Figure 2. Velocity data from the DFW TDWR showing the signature of a strong microburst (cyan circle) on August 7, 2001. The white lines near the center of the image indicate the location of DFW.

The LLWAS sensor network consists of anemometers located across an airport on towers approximately 100 feet in height. The anemometer locations are strategically positioned near airport runways in order to provide wind shear alert coverage for the Areas Noted for Attention (ARENAS). The location of the LLWAS sensors at DFW in relation to the ARENAS is shown in Figure 3. Depending on the location of wind shear events, relative to the LLWAS sensors, the strength of a wind shear alert is determined from measurements of divergence/convergence on network triangles (three sensors) or edges (two sensors). In either case, the validity of wind shear alerts produced by the LLWAS is dependent on the reliability of individual sensors since the wind is measured directly by each anemometer. At airports that have a TDWR and a Network Expansion of the LLWAS (LLWAS-NE) the alerts are integrated using a set of rules (discussed in Appendix 1 and illustrated in Table 1) and then disseminated to ATC personnel.

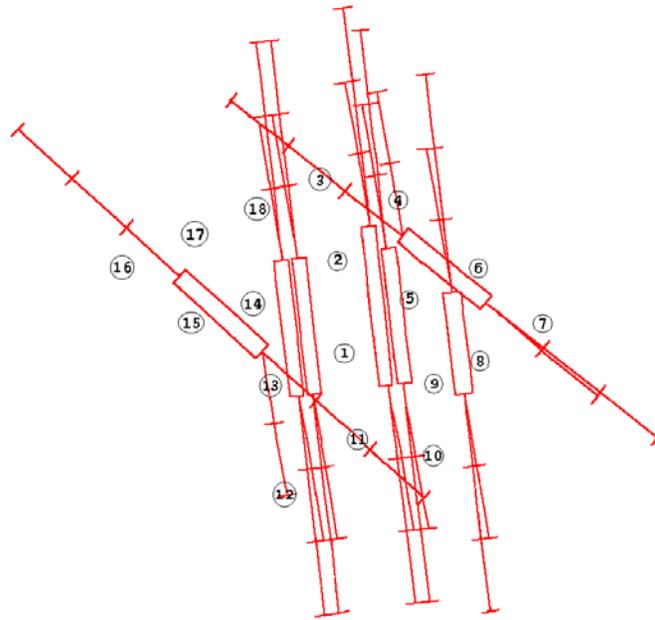


Figure 3. Location of the 18 anemometer sensors that comprise the LLWAS-NE system at DFW. Runways are indicated by the red rectangles with the approach and departure paths (red lines) extending from each runway.

TABLE 1
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

A demonstration ITWS has operated at DFW since 1995. Observations of wind shear events that impacted DFW during ITWS operations indicate that a considerable number of alerts were not generated by “traditional” wind shear events. This report identifies three separate phenomena responsible for producing hazardous wind shear at DFW that are not considered “traditional”. These include:

- Linear divergence associated with line storms.
- Divergence behind gust fronts (DBGF).
- Divergence within a set of low-altitude buoyancy (gravity) waves.

Data from a three-year period from August 1999 through July 2002 was analyzed to determine the frequency of “non-traditional” wind shear at DFW. Each time loss alerts occurred over DFW ARENAS during ITWS operations, the event was classified based on the mechanism generating the alerts. The analysis indicates that during the three-year period, “non-traditional” wind shear mechanisms were responsible for 50% of the loss alert events at DFW (Figure 4).

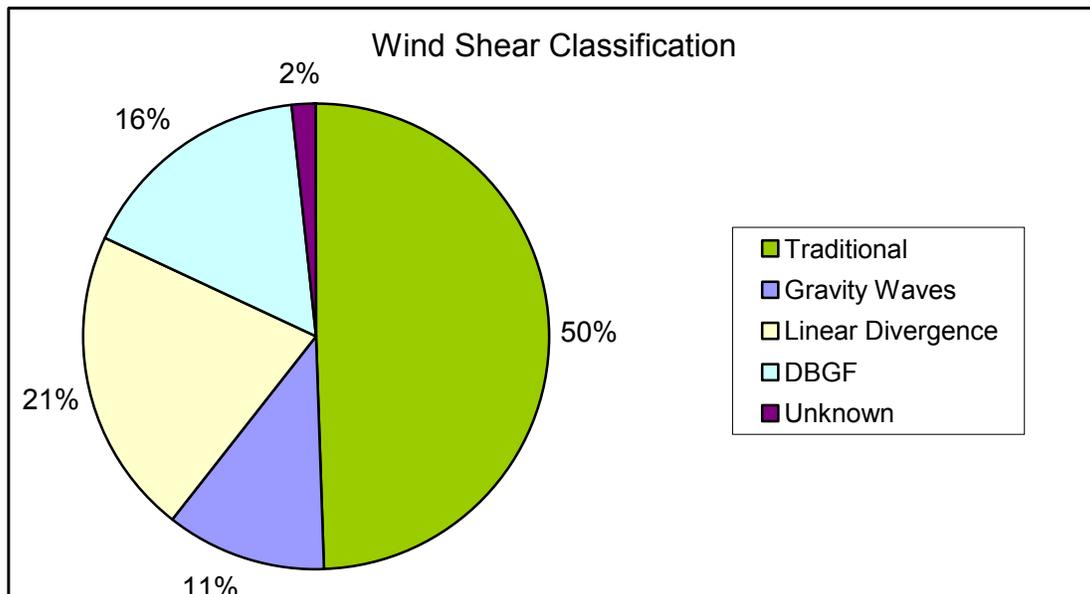


Figure 4. Classification of wind shear alert events at DFW between August 1999 and July 2002.

In addition to the frequency, the strength of each type of event is a useful indicator in determining the importance of detecting “non-traditional” wind shear. However, it should be noted that for a given horizontal loss, the downdraft strength associated with these linear phenomena is less than the “traditional” cylindrical microburst with same horizontal loss. Figure 5 shows the maximum and fiftieth percentile loss alert values for each type of event during the three years analyzed. The figure indicates that the strength of the linear divergence events is comparable to the “traditional” wind shear events. In fact, the fiftieth percentile value is considerably higher indicating that, on average, these events generate stronger alerts. While DBGF and gravity waves tend to be weaker, the maximum loss values for each is still of microburst strength. The strength and high percentage of wind shear loss alerts generated by “non-traditional” wind shear at DFW illustrate the importance of accurately detecting these events. “Non-traditional” wind shear events have been identified before (Wolfson, 1988), but this report describes a new approach to detect and warn ATC of these events using Doppler radar.

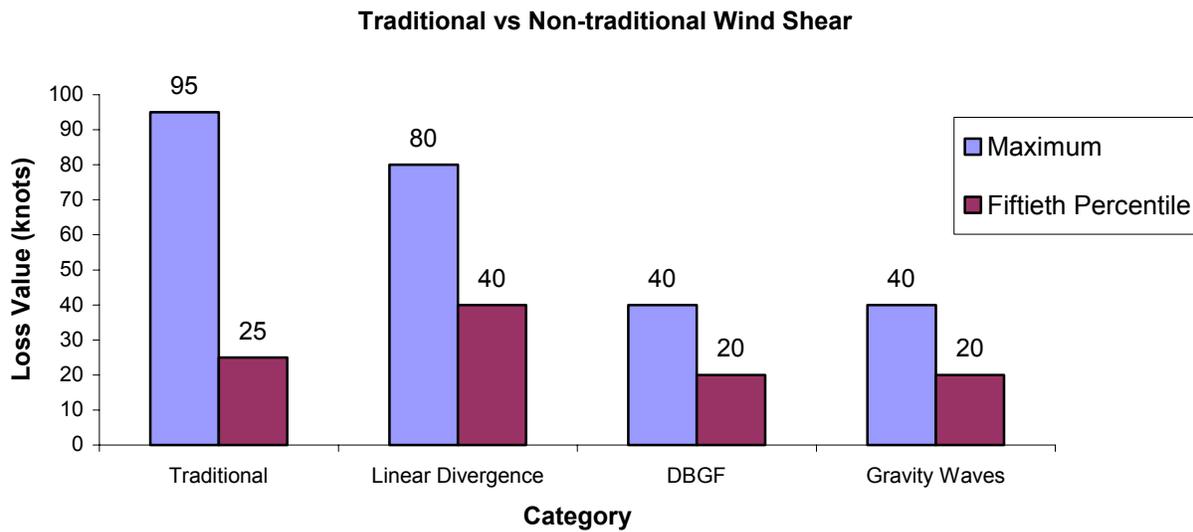


Figure 5. Maximum and fiftieth percentile loss values for traditional, linear divergence, divergence behind a gust front, and gravity wave wind shear events between August 1999 and July 2002.

Section Two describes linear divergence and explains how this type of divergent feature can be hazardous to aircraft at low altitudes. Section Three gives an explanation of divergence behind gust fronts while Section Four examines gravity waves. In the final section, conclusions and recommendations are presented.

2. LINEAR DIVERGENCE ASSOCIATED WITH LINE STORMS

2.1 INTRODUCTION

Linear divergence occurs when a line of thunderstorms produces a linear downdraft within the core of heavy precipitation (Figure 6). The strength of the divergence is usually fairly uniform along the line but may contain discrete microburst events associated with the more intense cells. This phenomenon is the same as the “microburst line” described by Hjelmfelt and Roberts (1985). However, the linear divergence described in this report does not have to be of microburst strength. Figure 5 shows the maximum and fiftieth percentile loss values for linear divergence compared to traditional wind shear. The figure indicates that the maximum value associated with linear divergence during the period studied was 80 knots, which is extremely hazardous to aircraft at low altitudes. The fiftieth percentile loss value for all of the linear divergence events was significantly larger than traditional events. Thus, on average, linear divergence at DFW produced stronger wind shear alerts than the “traditional” events. The majority of time strong linear divergence is associated with intense convection that would not be penetrated by aircraft. However, the following sub-sections illustrate situations in which hazardous linear divergence can go undetected.

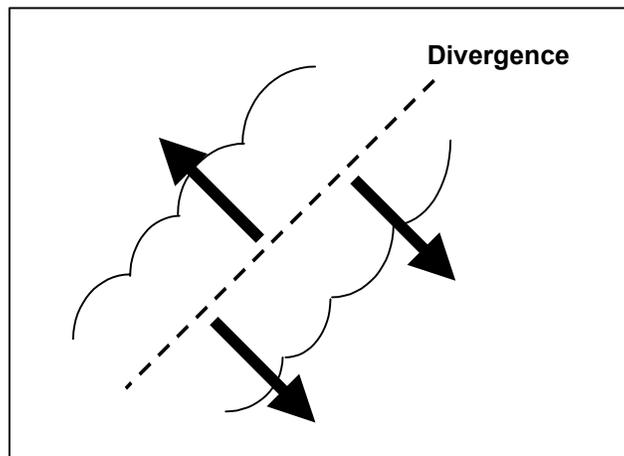


Figure 6. Schematic of the linear divergence associated with a line storm. The scalloped lines show the outline of the convective line while the arrows illustrate the wind direction emanating from the core of the heaviest precipitation.

Observations indicate that there are three situations that can arise that make it difficult for the current TDWR-based wind shear algorithms to detect linear divergence events. The situations are:

- Radial alignment of the divergence, i.e. asymmetry.
- Cell dissipation associated with the divergence line.
- Strength underestimation due to small areal extent.

2.2 RADIAL ALIGNMENT OF THE LINEAR DIVERGENCE

In cases of radial alignment, limitations of the radar data can prevent linear divergence from being detected. This occurs because single radars are only able to detect the wind direction and speed along a radial and not the complete three-dimensional wind field. If the divergence associated with a line storm is orthogonal to a radial then the divergence essentially becomes invisible to the radar-based algorithms. This is exacerbated at DFW because the DFW TDWR is sited 17 km north-northeast of the airport. When a line storm at DFW is oriented northeast-to-southwest it becomes radially aligned with the radar site while it is impacting the DFW ARENAS (Figure 7). During the three-year period analyzed, 50% of the linear divergence events at DFW were oriented northeast-to-southwest.

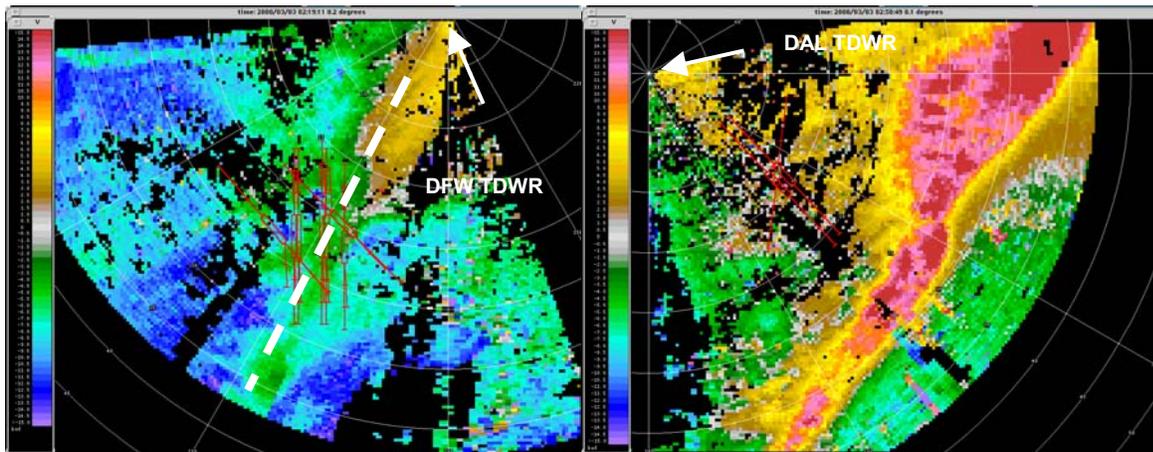


Figure 7. Northeast-to-southwest oriented linear divergence associated with a line storm as viewed by the DFW TDWR (left) at 0219UTC on March 3, 2000 and the DAL TDWR (right) 30 minutes later. Notice that the divergence (white dashed line) associated with the feature is not detectable by the DFW TDWR due to radial alignment but is clearly seen by the DAL TDWR.

2.3 CELL DISSIPATION ASSOCIATED WITH THE DIVERGENCE LINE

Many times, after the cells associated with line storms decay, the divergence field may persist for a significant amount of time. If this occurs, the divergence can be far enough away from the precipitation field that no Vertically Integrated Liquid Water (VIL) is associated with the divergent feature (Figure 8). The ITWS microburst detection algorithm uses VIL as a feature detector test. If a divergent event is not associated with an area of sufficient VIL, the algorithm will classify the feature as being false and not generate a detection shape. Dasey et. al, discuss the use of VIL by the ITWS microburst detection algorithm in detail.

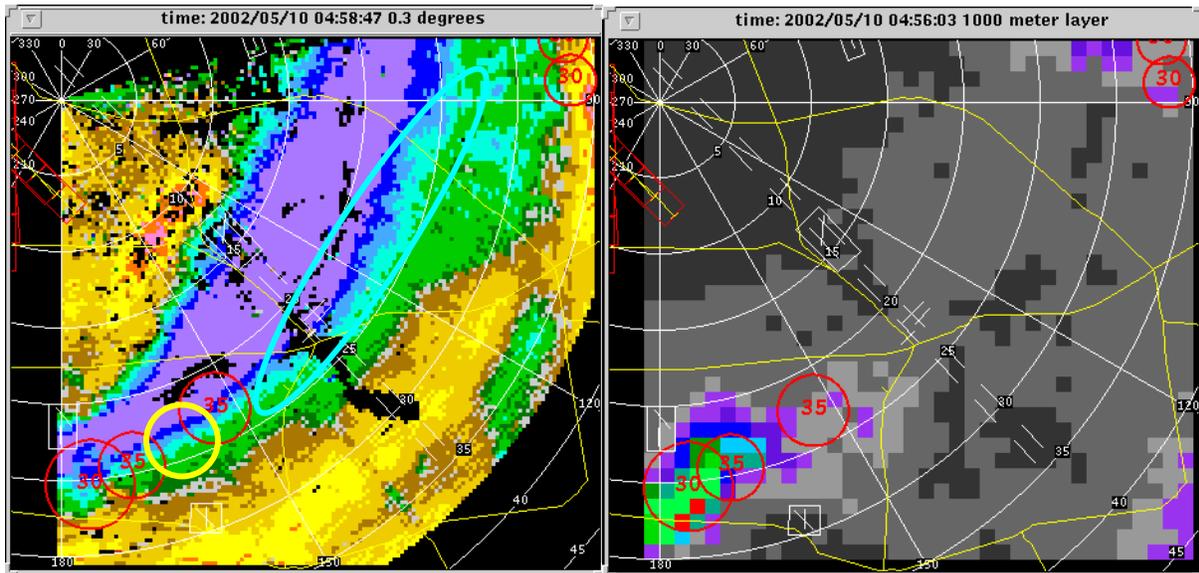


Figure 8. Radial velocity (left) and VIL (right) data from the DAL TDWR on May 10, 2002. Notice that no VIL is associated with the linear divergence (cyan oval) where the convection has dissipated. The yellow circle identifies an area of divergence where no alert shape is generated because of the small areal extent of the microburst algorithms detections.

2.4 STRENGTH UNDER ESTIMATION DUE TO SMALL AREAL EXTENT

Figure 8 also indicates a region of the linear divergence that is not detected (yellow circle) because of the small iconic detection shapes generated by the ITWS microburst detection algorithm. The smaller icons are a result of a stricter shear criterion utilized by the ITWS algorithm. The detection of wind shear events using radial shear was an attempt to mitigate false alarms generated by excessively large shapes. The use of the more stringent shear criterion by the ITWS algorithm greatly reduced the Probability of False Alarm (PFA) in a comparison performance evaluation with the TDWR (Dasey et. al, 1996).

However, the reduced areal extent of detections can cause some areas of valid wind shear along lines of linear divergence to go undetected even in regions that exceed the VIL threshold. This is especially true if the divergence extends over a significant distance.

3. DIVERGENCE BEHIND A GUST FRONT (DBGF)

Whenever the winds behind a gust front quickly weaken or return to the ambient direction, a divergence field may form (Figure 9). In such cases, the divergence can be strong enough to produce wind shear alerts and be hazardous to aircraft at low altitudes. As Figure 4 indicates, 16% of the wind shear alerts that impacted DFW between August 1999 and July 2002 were caused by divergence behind gust fronts.

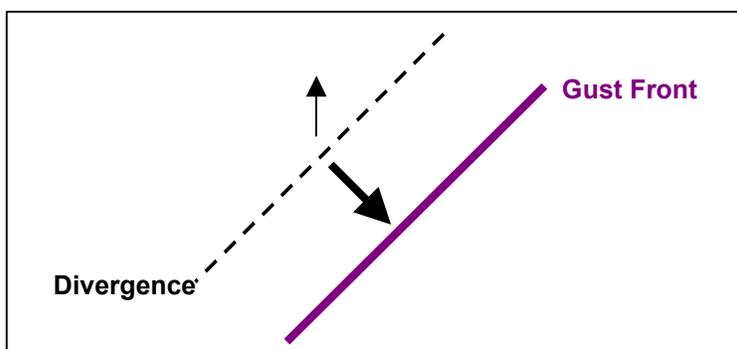


Figure 9. Schematic picture of divergence behind a gust front. The bold arrow indicates the strong wind immediately following the passage of the gust front. The thin arrow illustrates the ambient wind.

Divergence behind a gust front is similar to divergence associated with line storms in that it forms in a linear manner. This implies that the difficulties of detecting DBGF using radar-based algorithms are similar to linear divergence. Radial alignment of the DBGF along with a lack of VIL associated with these events make them difficult to detect with the current algorithm suite. Figure 10 shows the velocity data from the DAL TDWR from July 11, 2002. The figure shows divergence behind a gust front going undetected over the DAL ARENAS due to a lack of VIL. The maximum velocity difference associated with the divergence is 17 m/s.

The strongest DBGF event at DFW in the period analyzed generated loss alerts of up to 40 knots (Figure 5). This is considerably less than the maximum loss associated with “traditional” wind shear events and linear divergence, but is still of microburst strength. The fiftieth percentile loss value for all DBGF events between August 1999 and July 2002 was 20 knots, which indicates that most of the events were relatively weak.

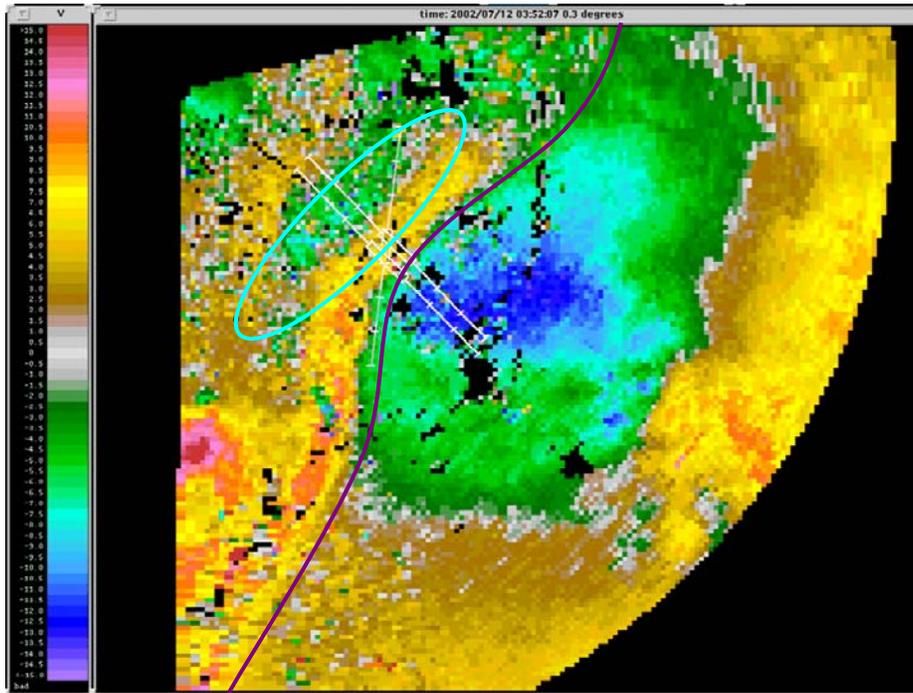


Figure 10. DAL TDWR velocity data showing a divergence field (cyan oval) behind a gust front (purple line) on July 11, 2002. The maximum velocity divergence across the divergent feature is 17 m/s.

4. DIVERGENCE WITHIN A SET OF LOW ALTITUDE BUOYANCY (GRAVITY) WAVES

Gravity waves are alternating lines of linear convergence and divergence that form in a conditionally unstable environment (Figure 11). A set of gravity waves forms a wave train that travels in a direction that is orthogonal to the convergence/divergence couplet. The waves tend to be located in an atmosphere characterized by a temperature inversion, which acts as a duct for the waves to propagate. The inversion is usually the product of cold air near the surface following the passage of a thunderstorm outflow or cold front, but may also be the result of warm mid-level temperatures advected off the higher terrain of the southwestern U.S. Gravity waves are induced by perturbations of air parcels associated with convective elements in response to vertical shear in the horizontal winds (Bieringer, 2002). Many times, these waves are located within a region of stratiform precipitation. However, precipitation is not a condition for gravity wave propagation. Over the past several years there have been several recorded incidents in which commercial aircraft have experienced extreme turbulence and wind shear when encountering gravity waves (Miller, 1999).

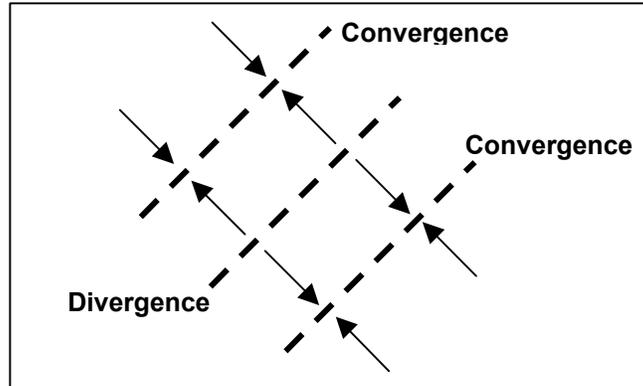


Figure 11. Schematic illustration of a gravity wave train showing the alternating lines of convergence and divergence. Arrows indicate the wind direction along the wave train path.

Figure 12 shows a four-panel image from the ITWS microburst detection display showing from upper-right to lower-left, the DFW TDWR velocity data, shear data, reflectivity, and VIL. The convergence and divergence patterns 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 velocity difference exceeded 20 m/s , the ITWS microburst detection algorithm did not generate alerts at DFW because the VIL threshold was not met.

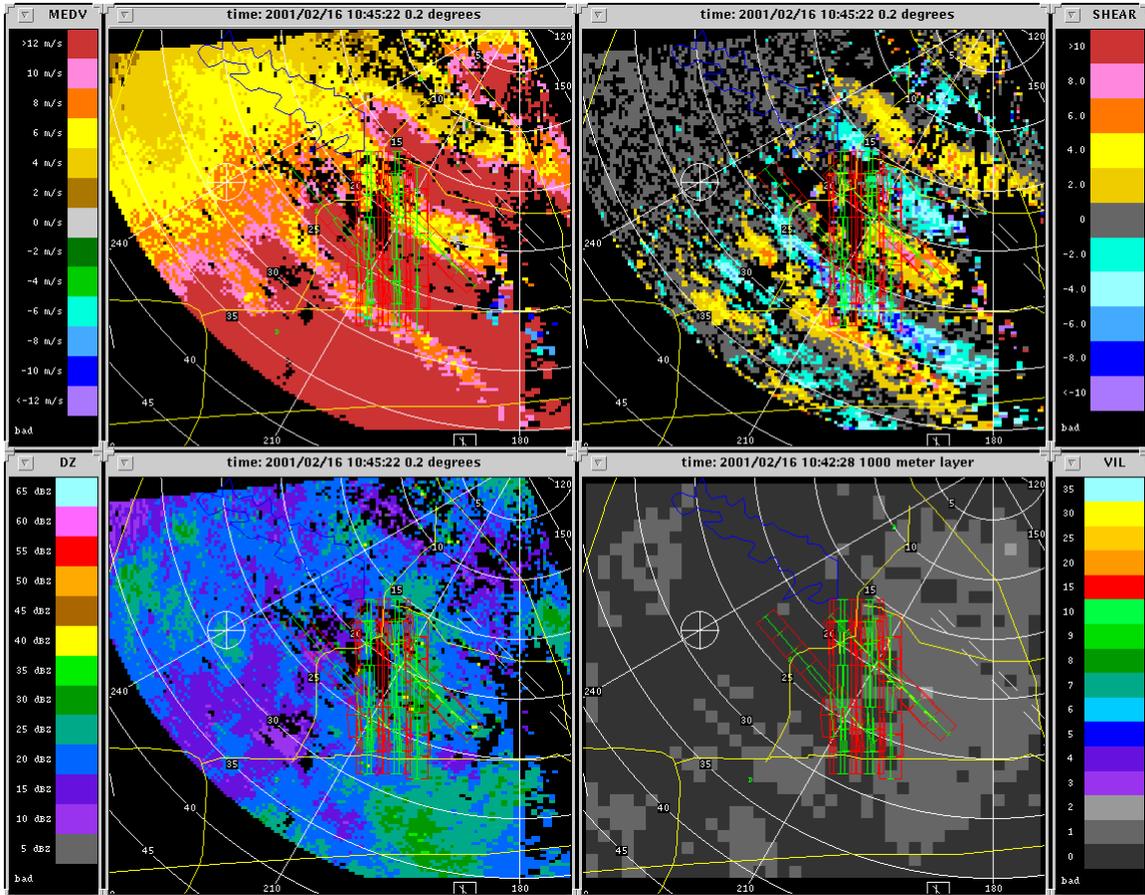


Figure 12. Four-panel from the ITWS microburst detection display showing the DFW TDWR velocity data (upper-left), the associated shear in m/s per km (upper-right), the radar reflectivity (lower-left) and the VIL (lower-right). Notice the pronounced wave feature present in the velocity and shear data. Also note the lack of significant VIL over the DFW ARENAS, highlighted in red and green.

The maximum loss value observed from gravity waves at DFW over the past three years was 40 knots, while the fiftieth percentile loss value during that time period was 20 knots (Figure 5). These values closely correspond to those produced by the DBGF events. Although the losses generated by gravity waves are weaker than those produced by “traditional” wind shear events, interactions between gravity waves at different altitudes can generate rotational couplets that pose an additional threat to aviation (Meuse et. al, 1995, Miller et. al, 2002). Thus, identification of these events would provide additional awareness to ATC in alerting aircraft of potential hazards.

5. CONCLUSIONS AND RECOMMENDATIONS

In this report, three different types of “non-traditional” wind shear events at DFW were identified. Observations reveal that these divergent events have several identifying features in common. These include:

- The divergence is oriented in a linear manner.
- The divergence may or may not be associated with precipitation and corresponding VIL.
- The divergence is easily distinguishable in the radar velocity data if it is not radially aligned.

In addition to the common characteristics, divergence associated with gravity waves may be found at higher levels of the atmosphere.

The results presented herein show that these “non-traditional” wind shear events are common at sites such as DFW. The maximum and fiftieth percentile loss values for these events are also a concern, especially in the case of linear divergence. As previously mentioned, the ITWS microburst detection algorithm was specifically designed to detect “traditional” wind shear. It is a job that the algorithm performs extremely well. By comparison, the “non-traditional” types of wind shear features are not detected as well. There are some potential modifications to the current algorithm that could be implemented to improve the POD for these cases. Each of these would be limited, though, in terms of their overall affectivity. For instance, some would only apply to a particular type of event, while others would only work at a select number of sites.

The most straightforward change to the existing algorithm would be to lower the VIL threshold since many of these “non-traditional” events are associated with marginal VIL. However, this would undoubtedly raise the PFA to an unacceptable level. More substantial changes would involve software modifications. A technique that might work well at sites like DFW would be to merge the detections from multiple radars in order to offset viewing angle limitations. There were several clear examples identified during this study where the DAL TDWR detected the divergence better than DFW due to the different orientation angle. Another upgrade would be to add motion compensation to the VIL product, which is not produced as often as the detection data (2.5 vs. 1 minute). The VIL threshold and the buffer surrounding the VIL field could then be lowered to increase the POD performance, without significantly impacting the PFA. Finally, the atmospheric profile conducive to gravity waves might serve as a means to adaptively select a lower VIL threshold if conditions warrant. The sounding data is already being utilized to modify the VIL based on whether the environment is wet or dry.

However, since these events have strong similarities and several of the distinguishing characteristics are unique to “non-traditional” wind shear, we propose the development of a new algorithm to detect and

warn ATC of these events. The output of the algorithm would be displayed on the ITWS Situation Display in graphical icons and text alerts similar to current wind shear detection algorithms.

We believe that the algorithm should identify “non-traditional” wind shear events by locating lines of divergence/positive shear. The identification process could be similar to the approach used by the ITWS Machine Intelligent Gust Front Algorithm (MIGFA), except identifying regions of divergence instead of convergence as MIGFA does now (Delanoy and Troxel, 1993). The algorithm could use a minimum divergent feature length that would reject small areas of divergence caused by noisy radar data, bird bursts, or “traditional” wind shear events. At sites with more than one TDWR, the data can be combined to produce a merged set of detections. The approach is similar to the Gust Front Mosaic algorithm that tracks difficult to detect gust fronts in large Terminal Radar Approach Control (TRACONS) (Shaw et. al., 2000). Also, in order to detect linear divergent features aloft, the altitude limits will need to be extended in order to sample the lowest few kilometers of the atmosphere.

APPENDIX A

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 approach¹, there is no integration of alerts for this portion of the ARENAS.

Screening

Screening rules are applied when the LLWAS-NE produces a wind shear/microburst alert without a matching alert from TDWR or ITWS. Weak wind shear alerts (below 20 knots) are dropped while strong wind shear alerts (below 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.

Averaging

Averaging is performed when both the LLWAS-NE and the ITWS 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 *ITWS, average of LLWAS-NE and ITWS}, where a and b are nominally set to 0.8.

The formula for determining gain alerts when both systems are producing gain alerts is the same, however, the values of a and b may differ.

¹ 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 with ITWS.

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 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 integrated alert was a loss.

GLOSSARY

ARENAS	Areas Noted for Attention
ATC	Air Traffic Control
DBGF	Divergence Behind a Gust Front
DFW	Dallas-Ft Worth International Airport
ITWS	Integrated Terminal Weather System
LLWAS	Low Level Wind Shear Alert System
LLWAS-NE	The Network Expansion of the LLWAS
MIGFA	Machine Intelligent Gust Front Algorithm
PFA	Probability of False Alarm
POD	Probability of Detection
TDWR	Terminal Doppler Weather Radar
TRACON	Terminal Radar Approach Control
VIL	Vertically Integrated Liquid Water

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