7.8 VERTICAL WIND SHEAR NEAR AIRPORTS AS AN AVIATION HAZARD *

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1. INTRODUCTION

Wind shear has been recognized as a hazard since the beginning of aviation. Before the early 1980's, gust fronts were considered to be the primary hazard. To detect wind shear from gust fronts and warn pilots, the original Low Level Windshear Alert System (LLWAS) was developed. Better understanding of the phenomenology of wind shear in the 1980's led to the understanding that microbursts were the primary wind shear hazard in aviation, and this in turn led to the redesign of the LLWAS (Wilson and Gramzow, 1991) and to the development of the Terminal Doppler Weather Radar (TDWR) (Merritt, et al., 1989), as well as airborne systems. With further field testing of airport wind measurement systems, it is becoming clear that vertical shear in the wind is also a significant aviation hazard. Accurate knowledge of the vertical structure of the wind also increases airport efficiency by allowing for a better optimization of the Airport Acceptance Rate (AAR).

Aircraft on final approach are most vulnerable to wind shear. On approach for landing, a typical aircraft has a 3^{o} glide slope, and a shear of 20 knots per thousand feet of descent gives a shear of 20 knots per 4 km of ground distance. A shear of 15 knots per 4 km is the threshold for a wind shear warning from either the LLWAS or TDWR wind shear systems. If such a shear extends vertically over 1500 ft, the total headwind decrease between the outer marker and threshold (assuming 5 nmi.) is greater than the minimum microburst alert of 30 knots. However, this loss is spread out over a greater distance than in a microburst and thus is less of a hazard. Currently, pilots do not receive a warning for this type of wind shear. In New York and Dallas, wind shears of 20 knots/1000 ft (10 m/s / 300 m) near the ground are relatively common.

The Integrated Terminal Weather System (ITWS) prototypes, being developed by Lincoln Laboratory for the Federal Aviation Administration (FAA), are running a gridded wind analyses, Terminal Winds, in Dallas/Ft. Worth, New York City, and Memphis (Evans and Ducot, 1994; Cole, et al., 2000). In addition, Lincoln is operating a multi-sensor, high-resolution (50 m or finer) wind profiling system to support the NASA Aircraft Vortex Spacing System (AVOSS) prototype at the Dallas/Ft. Worth airport (Perry, et al., 1997). The system developed for the AVOSS work is called the AVOSS Winds Analysis System (AWAS). The Terminal Winds and AWAS are the technological base for designing a system to provide warning of high vertical shear.

2. VERTICAL WIND SHEAR

The site operation logs for ITWS provide a source of preliminary data to determine the extent of days of high shear for both Dallas and New York. The grid used by the prototype Terminal Winds has levels spaced 50 mb apart, or about 1,400 ft near the ground. Due to the large spacing relative to the phenomena, these data tend to underestimate the strength of the shear. Nonetheless, strong vertical shears are regularly seen in these data.

2.1. Dallas/Ft. Worth

The strong shear events in DFW come from the Low Level Jet that sets up overnight. With the Low Level Jet, the wind at the surface is very light, and the wind increases in speed up to an altitude of a few hundred meters, or about a 1000 ft. From May 1996 to April 2000, there were only three vertical wind shear events with shears greater than 20 knots per 1000 ft captured by the ITWS Terminal Winds. However, there were 43 cases in which there was vertical wind shear of greater than 20 knots per 2000 ft. Due to the large spacing of the Terminal Winds grid, it tends to underestimate the shear.

While we do not have a count of strong shear cases as seen in the AVOSS Winds Analysis

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System (AWAS), that system has greater resolution, and thus larger shears are seen more frequently. The low level jets occur on about half the days in Dallas as judged from the AWAS, and typically lasts from 0600 to 1400 UTC. Typical max speeds are 12- 18 m/s, but can reach 25 m/s. A Dallas case is shown in figure 1.

Of the 43 cases of moderate to strong vertical wind shear due to a low level jet seen in the DFW ITWS, in about 2/3 of these cases, the resulting shear was driven by a strong southerly inflow preceding the approach of a synoptic scale low-pressure system. About 1/4 of the cases occurred in strong winds after the passage of a cold front. All but one of the 43 cases showed that the strongest vertical shear occurred during the early to late morning, with a decrease in shear in the afternoon. Nearly half (46.5%) of the cases occurred in the winter months of December through February, with 1/3 (34.9%) occurring in the spring months of March through May. Only two cases occurred during the summer, while six cases occurred in the fall, and no cases occurred in September. Not only did most cases occur during the winter, but the cases during the winter months also tended to be stronger.

2.2. New York

During the winter of 1999-2000, NYC metropolitan airports experienced conditions of shear greater than 20 kts per 1000 ft of descent on final approach on at least eight occasions. Winds above the surface were S/SW on six of the eight cases, with the other two cases featuring east/southeast winds.

It is not an accident that seven of the eight cases had a southerly flow in the lower part of the atmosphere. Since New York City is adjacent to the cool Atlantic waters, there is significant marine influence on the coupling of low-level winds with the surface winds. As warm southerly air flows northward aloft over the cool ocean surface, the stability of the air is enhanced, making it difficult for the strong winds aloft to mix down to the surface. A similar effect may take place when there is a relatively weak but cool surface northeast flow, while at the same time winds veer rapidly with height as a warm southerly flow overruns the shallow but cool surface air. The result is a relatively stable atmosphere. When these winds are unable to mix downward and surface winds remain relatively weak, the result is strong vertical wind shear for aircraft on final approach. The above conditions often exist when northeast coastal storms pass close to the area.

3. AIRPORT OPERATIONS ISSUES

In addition to improving safety, better knowledge of the vertical structure of the wind will also increase airport efficiency by allowing for a better optimization of the Airport Acceptance Rate (AAR). As studies show (Cole, et al., 1997; Evans, 1997), landing even a few extra aircraft per hour at capacity-limited airports provides very large monetary benefits ($17 million/year due to the Terminal Winds product in DFW prior to the construction of the new runway and $27 million/year due to Terminal Winds in NYC). In New York, with strong shears that are properly captured by Terminal Winds, the benefits can be greater than $100K per day (Allan and Gaddy, 2000).

Prior to October 1997, compression issues—regarding aircraft spacing—were of great concern to air traffic controllers at DFW. During this time, controllers used the Terminal Winds product extensively to space incoming aircraft properly, and the controllers would have benefited from a more accurate system. Site operational hours were mandated by the fact that controllers wanted to use the Terminal Winds product at the start of their shifts (6:00 AM local). With the addition of runway 17L/35R in October 1997, the airport is able to maintain a high arrival rate during a broader spectrum of weather events, and therefore compression issues are not as high a priority as they were. However, the experience at DFW shows that improved knowledge of the wind during strong shear events at capacity-limited airports provides large benefits.

In New York, when strong vertical windshear conditions exist at the airports, compression of aircraft on final approach is typically the greatest problem for air traffic managers. The response is usually to institute a Ground Delay Program in which the landing rate is reduced to alleviate holding that takes place when compression becomes a difficulty. As an example, on the strong vertical wind shear case of December 10, 1999, air traffic managers decided to reduce the Ground Delay Program (GDP) Airport Arrival Rate (AAR) from 36 aircraft per hour to 32 aircraft per hour based solely on the wind shear conditions, and at a time when a clearing trend was taking place. That same afternoon, JFK reported three missed approaches because of the wind shear, demonstrating that safety is an issue in strong vertical wind shear events.

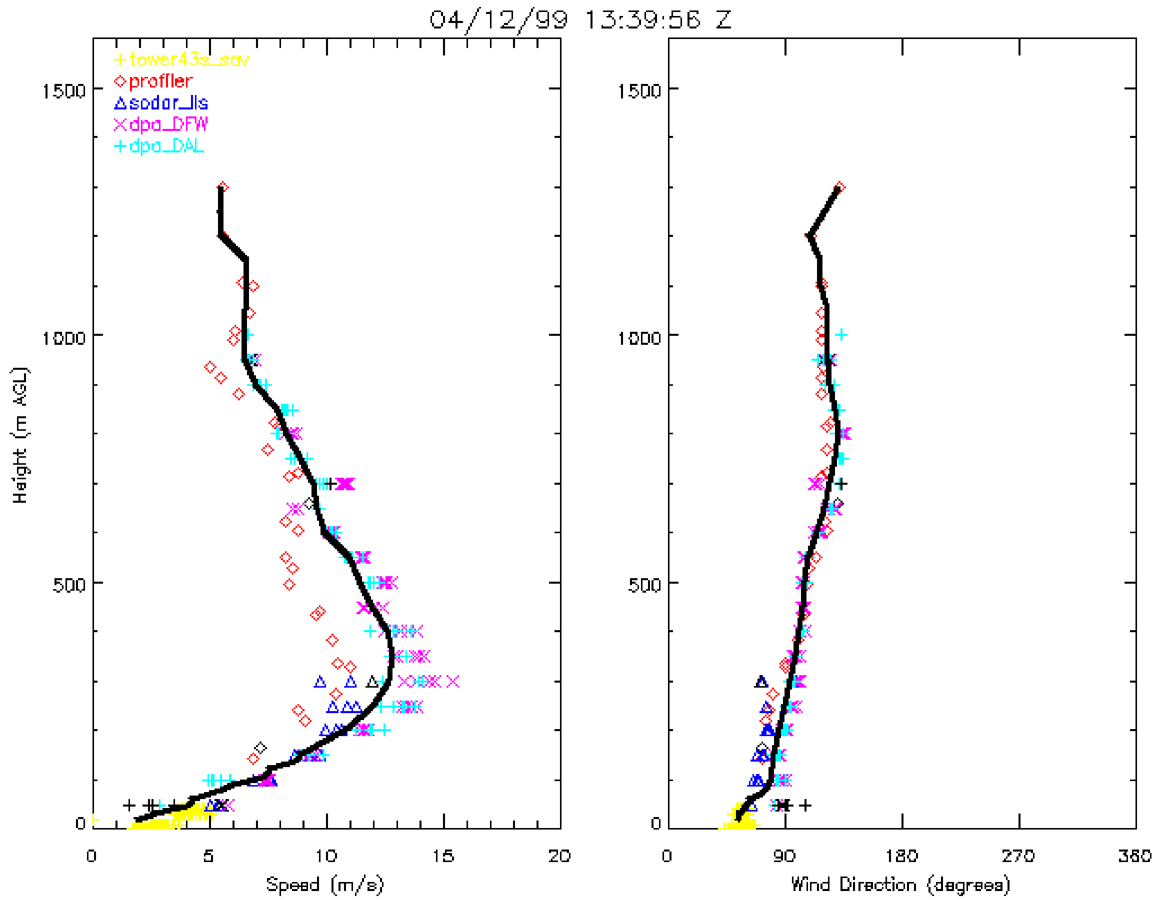

Figure 1. A wind shear case as seen by the AWAS in Dallas. The solid line is the consensus wind profile produced by AWAS, and the sensor measurements are also shown. The AWAS profile shows a wind speed max of about 13 m/s at an altitude of just over 300 m above ground level. The profiler observations, diamonds, show a wind speed maximum of about 10 m/s, while the Dallas Ft. Worth (DFW) and Dallas Love (DAL) TDWR-based Doppler Profile Analysis (DPA) wind profiles show a wind speed maximum of about 14 m/s (three of each DPA are shown, depicting data over the previous 15 minutes).

Greater knowledge of the winds is a help to the New York controllers. Controllers at the EWR tower have expressed a strong interest in knowing the winds below 2000 ft, since below that level they currently have only surface wind information from LLWAS. The TRACON is greatly helped by Terminal Winds, since knowledge of the wind profile helps them make decisions such as what AAR to implement during a GDP. However, when the vertical shear in NYC is especially strong, it leads to errors in the Terminal Winds output.

4. A CANDIDATE WARNING SYSTEM FOR VERTICAL SHEAR

The AWAS provides the basis for developing a Vertical Wind Shear Alert System (Cole, et al., 1998). The AWAS takes in wind observations from towers, sodars, profilers, and TDWRs. The Doppler data are first processed using the Doppler Profile Analysis (DPA), and the resulting wind profiles are then merged in a least squares analysis to produce a vertical profile of wind estimates with a 50 meter vertical resolution. To fit within the current constraints of an ITWS, the system would be modified to ingest data from (one or more) TDWR, LLWAS or airport ASOS, and Meteorological Data Collection and Reporting System [(MDCRS) (aircraft reports)]. The Doppler data support a fine resolution wind profile when enough atmospheric reflectors are available. In New York there are almost always sufficient Doppler data on days with strong vertical shear. In Dallas, due to the large number of winter events, there tend to be fewer Doppler data, and the aircraft reports will be especially important.

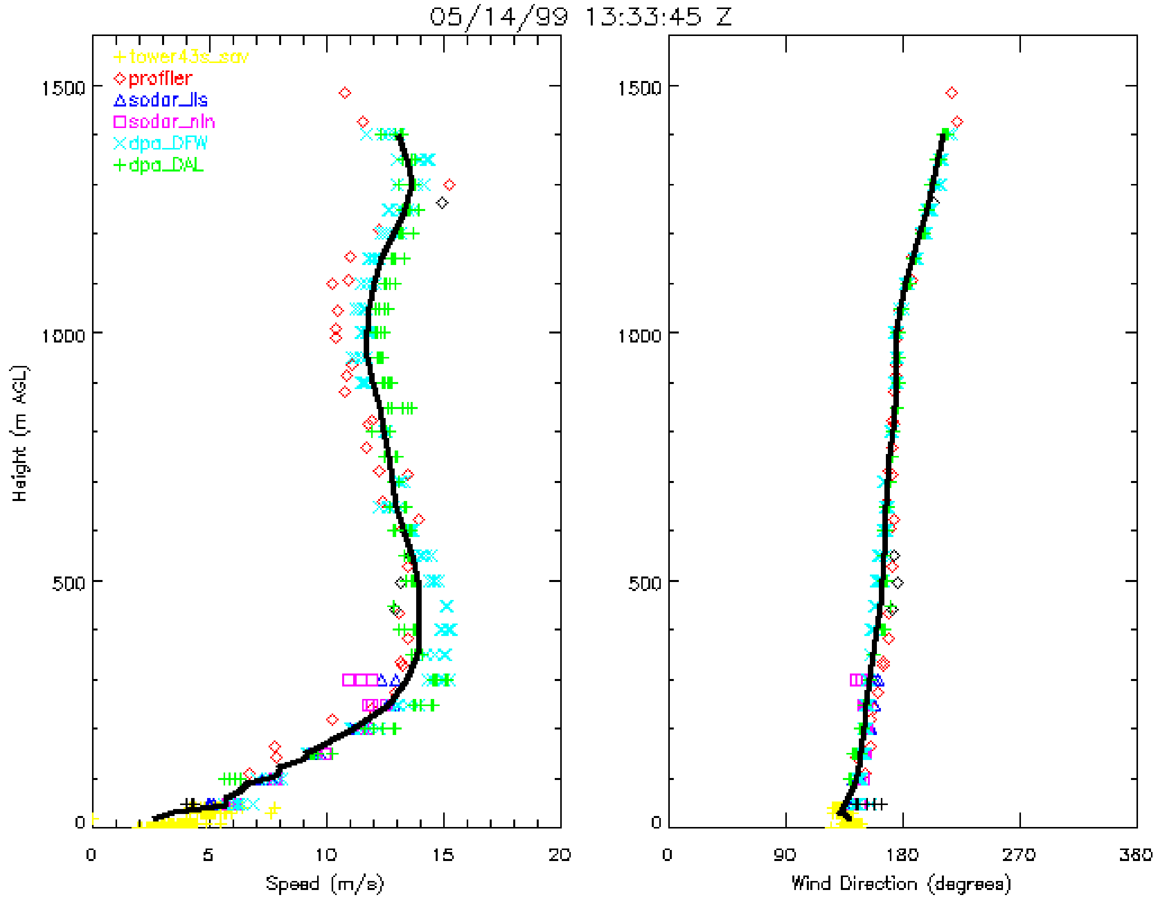

Figure 2. Another wind shear case as seen by the AWAS in Dallas. The solid line is the consensus wind profile produced by AWAS, and the sensor measurements are also shown. In this case the sensors are in very close agreement. The AWAS profile shows a wind speed max of about 14 m/s at an altitude of close to 400 m above ground level. Because the primary runways in DFW are aligned North-South, an aircraft on approach to DFW would experience this wind speed shift as approximately a 23 knot loss of headwind.

The Doppler Profiling Algorithm was developed as part of the prototype AWAS to support the NASA AVOSS program. The DPA is similar in some respects to the common Velocity Azimuth Display (VAD) product in that Doppler radar data at a set of given altitudes are analyzed to produce a wind profile. Typically, a VAD algorithm uses a single tilt of data (data collected on a 360-degree sweep at a fixed elevation angle). A function of the form $A \cdot \cos(\theta - \theta_0)$ is fit to the radial velocity values at a fixed range from the radar, and thus at a common altitude. The value of A gives the mean wind speed, and the mean wind direction is given by θ_0 (equivalently, a sine function can be used, and occasionally a higher-order trigonometric polynomial is used). This works well if data are available over much of the radar sweep and if the wind is uniform over the entire region from which data are collected. Often, a low angle tilt is used, so at higher altitudes the winds must be uniform over a large region.

In contrast, the DPA uses all tilts, from the lowest elevation angle up to some maximum elevation angle. At each altitude in the profile, all the data within a small distance of that altitude are used, resulting in a richer data set than used in a VAD. The mean wind vector, (u,v), is computed using a form of least squares that gives more weight to radial velocity measurements closer to the radar, so that the winds do not need to be uniform over as large an area. The least-squares method also adjusts the weight given each radial velocity value, depending on the data distribution. Due to the nature of Doppler radars, data are often non-uniformly distributed, and data values that are grouped together have correlated errors because the wind is not truly uniform. If this is not taken into account, it leads to errors in the estimate of the mean wind. This method is numerically more stable than fitting a cosine when the data do not cover a large portion of a 360-degree scan. This is especially important since the TDWR currently scans only a 120-degree sector aloft in hazardous weather mode. The specific equations used, along with the method of solution, are discussed in Cole, et al., 1998.

The DPA and AWAS have shown that accurate wind profiles with 50-meter vertical resolution can be generated from TDWR data. The DPA has been run on two different Dallas TDWRs as part of the real-time demonstration of the AVOSS Winds Analysis System in DFW since 1998. Figure 2 shows a wind profile from the DFW AWAS on May 14, 1999. The solid line is the profile output by the AWAS. There are data values from surface sensors, two sodars, a profiler, and the Dallas/Ft. Worth (DFW) DPA and the Dallas Love (DAL) TDWR. As can be seen, all the sensors on this day are in good agreement. The wind direction is largely out of the south, so that the shear is aligned with the approach to the primary DFW runways. Thus an aircraft on approach will experience nearly all the wind speed shear as a loss of headwind. The wind speed goes from 2 m/s to 14 m/s from the ground to an altitude of 350 meters, or approximately 23 knots over about 1200 ft, which is enough to be a hazard to an aircraft on final approach.

In addition to an algorithm to detect and quantify the shear, an algorithm must be designed to format a message for controllers and pilots. Historically, the decision on how this was to be done was made by a users group of controllers, pilots, FAA program managers, and scientists. The messages must fit within the constraints of the current ribbon display that is used for displaying the wind shear alerts from LLWAS, TDWR, and ITWS. One simple method is to format the vertical shear message using the format for Wind Shear With Loss (non microburst) messages. For example, 35RA (right arrival) -20 WSA (20 knot loss wind shear alert) 2MF (2 miles from the runway). There are two difficulties, both of which can be addressed with training. The first is a training issue in that a pilot getting such a message, currently, expects a wind shear due to a downdraft rather than from a shear in the vertical wind on descent, and the pilot's response to the alert may need modification. The second issue is that currently, any loss of 30 knots or greater triggers a Microburst Alert, which is treated very seriously. Without additional training, a non-microburst alert with a 30-knot or greater loss will be confusing. For these reasons, a proper group of users must be put together to decide how the message will be formatted and how the training will be modified.

5. SUMMARY

Rapidly changing winds with altitude are a hazard to landing aircraft when the shear exceeds 20 knots per thousand feet. Shears of this strength are common in both Dallas and New York. Unlike wind shears due to microbursts, vertical shear often occurs in the absence of convective weather or at times of the day when pilots are not expecting wind shear. Vertical shear also is not accompanied by the visual clues that attend microbursts. In addition, these events pose a difficult challenge in maintaining the airport acceptance rate. While shears strong enough that they should lead to issuing wind shear warnings are common, there are no systems to provide alerts for these events.

The technology to detect and quantify these shears has been demonstrated as part of the ITWS and AVOSS field testing. The primary remaining issues are to compile accurate counts of frequency and strength for these events in the DFW and NYC prototype ITWS so that a proper cost-benefit study can be done, to convene a working group to decide on how message should be formatted and on the hazard criteria, and build a prototype demonstration system.

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