# EVALUATION OF PULSED LIDAR WIND HAZARD DETECTION AT LAS VEGAS INTERNATIONAL AIRPORT

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# 1. INTRODUCTION

The Federal Aviation Administration (FAA)<sup>\*</sup> has acquired and maintained several wind shear systems in the United States since a series of wind shear accidents in the 1970s and 1980s. One system, the Terminal Doppler Weather Radar (TDWR), serves 45 major airports based on wind shear climate and air traffic volume. Only 4 of these airports are located in a dry, high plain, or an inter-mountain environment. They are Denver (DEN), Salt Lake City (SLC), Las Vegas (LAS) and Phoenix (PHX). Dry wind shear encounters are more commonplace at these locations. The TDWR does not detect dry wind shear consistently well because of the absence of hydrometers needed for an accurate radial velocity presentation used in detecting wind shear. In addition, these locations are plagued with high clutter values, which demands a higher radar return to detect wind shear.

In order to detect dry wind shear at DEN, a Low Level Wind Shear Alert System Network Expansion (LLWAS-NE++) with 32 wind sensors was installed to complement the TDWR. SLC, LAS and PHX do not have an LLWAS-NE++. The FAA has documented the TDWR dry wind shear detection deficiencies at SLC (SLC TDWR Wind-Shear Detection Performance October 1999). To overcome these deficiencies an LLWAS-NE++ was proposed. However, the cost benefits were marginal and the LLWAS-NE++ was not acquired there. The expense is in large part due to pole construction and land leases for multiple sensor sites.

In addition, the cost benefits methodology (Integrated Wind Shear Systems Cost-Benefit and Deployment Study 1994 – Martin Marietta) places a 10% emphasis on gust front wind shear and a 90% emphasis on microburst wind shear in terms of safety. Air Traffic Control (ATC), however, logged 28 goarounds due to wind shear in 2002 at SLC, all of which were due to gust fronts. In addition, on 24 March 2002, SkyWest flight 3964 clipped a wing on the tarmac at SLC. This CRJ2 narrowly escaped a strong gust front encounter in which the differential lift on the wings resulted in a roll on short final. Therefore, this cost benefits methodology underscores the gust front wind shear hazard and air traffic efficiency in the western environment.

Dry wind shear is also detected by another system, the pulsed Doppler light detection and ranging

(lidar), which only requires a small piece of airport property and is not victim to the clutter plagued airport environment. The lidar reflects off dust particles or aerosols allowing for the detection of dry wind shear. To determine the feasibility of a lidar at airports that have a significant number of dry wind shear events, a lidar demonstration was performed at LAS from 29 July – 14 October 2005. This non-funded demonstration included the FAA for administrative and meteorological support, Lockheed Martin Coherent Technologies for providing the lidar and engineering support, Clark County Department of Aviation for providing airport logistics and land, and the LAS Airways Facilities for providing technical support.

The monsoon season was short-lived, lasting approximately 3 weeks in the Las Vegas Valley. Nevertheless, 6 wind shear cases were captured by both systems. In this paper, a wind shear case is a string of wind shear events. A wind shear performance matrix was generated and results discussed.

## 2. LIDAR and TDWR CHARACTERISTICS

The lidar uses an infrared wavelength of 2022.5 nm with an average transmission power of 1 Watt, pulse repetition frequency of 500 Hz, pulse width of 400 ns and aperture diameter of 10 cm (Hannon 2004). The resulting nominal horizontal range is 8-12 km with a range resolution of 100 m. The azimuth resolution is 0.01°, which results in negligible side lobes minimizing clutter break through. The lidar was located on the southwest side of the airport as indicated in Figure 1.



Figure 1. Lidar, TDWR and LAS geographic layout. The TDWR is NE of the Lidar.

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Plan Position Indicator (PPI) scans were chosen in order to cover the east-west parallel runways and northsouth parallel runways. Two elevation scans of 2° and 4° were chosen to sample just below and above the glide path. For this demonstration, the 2° PPI scan was chosen to produce wind shear products with a 1-minute update rate.

The TDWR uses a 5 cm wavelength and peak power of 250 kW. Both the elevation and azimuth beam widths are 0.55°. The PRF is dynamic in selection to minimize the amount of multiple trip returns over the airport. The PRF dynamic range is from 1066 - 1930 Hz. The TDWR range resolution is 150 m. The TDWR is located 14.8 km to the northeast of the airport (Figure 1). The hazardous scan strategy at LAS consists of 2 volumes per six minutes, which uses a 0.8° surface scan every minute. The surface scans are used in detecting wind shear losses, or microbursts. The first surface scan is also used with a 1.0° scan every 6 minutes to detect gust fronts and associated wind shear gains. Incidentally, a wind shear loss/gain value is the estimated aircraft airspeed loss/gain if the aircraft penetrates the wind shear.

# 3. PERFORMANCE MATRIX DEVELOPMENT

The performance matrix is composed of a wind shear Probability of Detection (POD) and Probability of False Alarm (PFA) for each system for wind shear losses and wind shear gains. The lidar system used a SIGMET wind shear detection algorithm. This matrix contains wind shear performances using the lidar SIGMET and an estimate using a lidar Machine Intelligent Gust Front Algorithm (MIGFA). The latter is the potential wind shear detection rate using the most advanced algorithm that is operational on other systems. For example, when a gust front detected by SIGMET disappeared while traversing over the lidar, it was placed in a potential detection category when calculating the lidar MIGFA performance. The MIGFA overcomes these gust front disappearances when a front has been tracked for several scans. The potential category was not used when a front was well out of the lidar range or if there was a significant data gap between the front and the ambient returns. Experience with the MIGFA would suggest these latter circumstances would not produce a gust front detection. The potential category was also used for fronts located on the west and south final approaches given an optimum placement of the lidar. That is, if a front was missed on 3 Miles Final (MF) for 25L/R because it was out of the lidar range by 1/2 nm, the front was placed into the potential category because the lidar can be placed in a more optimum location 3/4 nm east/northeast of its current position. However, this has a reverse effect on 3 MF on the east and north approaches. The overall gain is minimal, but accounted for in the lidar MIGFA statistics.

Only wind shear that occurred on an AREa Noted for Attention (ARENA), which include 1-mile squares extending out from the runway end to 3 MF and a rectangle of 1-mile width for the runway itself, were used in the performance matrix. That is, wind shear alerts that would be displayed on the Ribbon Display Unit at the ATC positions. Incidentally, the lidar alerts were not displayed to ATC during this demonstration. The TDWR wind shear alerts were sent to ATC because it is an existing commissioned FAA wind shear system.

There were 6 wind shear cases where both systems were operational. Four of these cases were associated with dry gust front gains of 15-25 knots. Two cases were wet microbursts with wind shear losses ranging from 15-35 knots. Both the lidar and TDWR were evaluated using the same truth table. The truth table was developed using the TDWR, lidar, and ASOS.

#### 4. LIDAR / TDWR COMPARISON

There were a total of 347 wind shear ARENA impacts on an ARENA for which both the lidar and TDWR were operational. These wind shear losses and gains were of strength 15 knots or greater. A majority of these wind shears (63%) were wind shear gains associated with dry gust front outflows distant from the source thunderstorms. A minority of these wind shears (37%) were wind shear losses associated with wet microbursts from thunderstorms. These wind shear losses were associated with moderate to heavy rain with corresponding reflectivity values of 45-60 dBZ. The dew point temperatures were in the upper 50s and 60s during these wet microburst events.

#### 4.1 Overall Wind Shear Performance

Table 1 Overall Wind Shear Performance All Wind Shear (Gains and Losses)

	TDWR	LIDAR	LIDAR
		SIGMET	MIGFA
POD	35%	43%	58%
PFA	25%	1%	0%

Table 1 shows the overall wind shear performance of both systems. The overall performance of the lidar was better than that of the TDWR because there were more dry wind shears than wet wind shears (63 to 37%). The LIDAR SIGMET detected 43% of all wind shear, however, if MIGFA were implemented, the LIDAR would detect an estimated 58% of all wind shear alerts. The TDWR captured a total of 35% of all wind shear alerts at LAS during the demonstration. False alarms were essentially absent from the lidar. The TDWR, however, had a 25% false alarm rate for all wind shear events that impacted the ARENAs. These wind shear performance statistics appear anemic; however, a breakdown of the statistics is needed to identify the complementary value of each system.

### 4.2 Gust Front Wind Shear Gain Performance

#### **Table 2 Wind Shear Gain Performance**

	TDWR	LIDAR	LIDAR
		SIGMET	MIGFA
POD	6%	68%	91%
PFA	0%	1%	1%

Four cases contained wind shear ARENA impacts of at least 15 knots gain from distant thunderstorm gust front outflows. The TDWR MIGFA detected 6% of the 219 wind shear gain impacts. The TDWR struggled in detecting these dry wind shear events for several reasons. Two of these fronts came in from the obscured mountainous sector NE of the airport (obscuration from TDWR radial 339-113°). There was no gust front history until the front was near or on the approach corridors. The six-minute gust front update rate resulted in only 2 gust front velocity signatures before reaching the airport. TDWR MIGFA requires 2 detections before an initial detection is made; therefore, 12-18 minutes would have elapsed. The gust front speeds of 20 and 30 knots results in a distance of 4-6 and 6-9 nm displacements before being potentially detected. The airport is 8 nm from the TDWR and thus in the range of not having any advanced warning of a wind shift if a front is moving from the NE to SW at 30 knots.

Furthermore, the gust front is often not detected even after having two frames of tracking because the high clutter values in the airport region require a significant amount of reflectivity to be present for a valid velocity signature (Figure 2).



Figure 2. TDWR 0.8-degree CREM. Reflectivity of 30's, 40's and 50's dBZ are represented by yellow, orange and pink & red.

The typical reflectivity values associated with gust fronts are from -10 to 20 dBZ (Troxel 1994), which are well below the clutter values of 20-50 dBZ that exist on the airport. That is seen in the TDWR velocity field, as many velocities are invalid over the airport (Figure 3). Also note, that a valid velocity can be reduced significantly with the contamination of clutter. That is, range gates in this environment often contain both clutter values and valid velocity values. This caused an underestimation of the radial velocity wind at some gates, further reducing the chance of detecting the gust fronts.

The lidar, on the other hand, is not greatly susceptible to ground clutter and can see the small dust

particles well. As a result, the SIGMET algorithm, which is similar to the original TDWR gust front algorithm, detected 68% of the 219 gust front gain impacts. Again, using a model like MIGFA that has a history feature and azimuthal shear feature would increase the gust front gain detection to approximately 90%. Another 1% improvement occurred by moving the lidar east/northeast <sup>3</sup>/<sub>4</sub> nm from its current position. Fronts from the northeast would be detected a couple minutes sooner on the south and west approaches. The missing 9% of gust front outflows occurred mostly on 3 MF when the front was out of the lidar range even after an optimum location was accounted for. Nevertheless, a substantial increase in gust front outflow detection occurred.

In fact, on 30 July 2005, the lidar began detecting the gust front gain 17 minutes in advance of the wind shift at the airport (Figure 4). A movie loop of the gust front detected by lidar on this day was presented to the Meteorologist In Charge (MIC) at the Los Angeles Center (ZLA) Center Weather Service Unit (CWSU) and the ZLA Traffic Management Officer. Both expressed great interest in the lidar detection of dry wind shear fronts in terms of air traffic management efficiency. The 17-minute lead-time would produce benefits that ripple to the ZLA. Moreover, LAS supervisors can plan a runway configuration change both in the air and on the ground. This reduces delays and is thus an economic benefit to the airlines.



Figure 3. TDWR radial velocity holes (black) over LAS are due to clutter, which contributed to a missed gust front on 30 July.



Figure 4. The lidar detects a gust front approaching the airport from the east on 30 July 2005. Green/yellow shades indicate wind towards/away from the lidar.

# 4.3 Microburst Wind Shear Loss Performance

# Table 3 Wind Shear Loss Performance

	TDWR	LIDAR
POD	83%	0%
PFA	27%	0%

Two wind shear cases contained wind shear ARENA impacts of at least 15 knots loss from wet microbursts. Note that a microburst of at least 30 knots loss is deemed a microburst in terms of a wind shear warning provided by ATC. A weak microburst of 15-25 knot loss is deemed a wind shear in terms of a wind shear warning provided by ATC.

With moderate to heavy rain associated with the wind shear losses, the TDWR was able to detect 83% of the 128 wind shear loss impacts. The 17% missed detections are mostly due to the wind shear being partially located on the edge of the storm where the reflectivity values were marginal relative to the clutter values. The storm edges where moving clutter was quite visible resulted in a high false alarm rate of 27%. Note, the TDWR specification for wind shear detection losses is at least 90% and less than 10% for wind shear loss false alarms.

The moderate-heavy rain associated with these wind shear losses resulted in obscuration for the lidar. In fact, most wind shears were at least half obscured due to the rain. That is, the outflow portion of the wind shear was not observable in these cases. Nevertheless, both the inflow and outflow components of the microburst are needed for proper detection. As a result, the lidar detected 0% of the wet wind shear losses.

The lidar would not have helped reduce the TDWR false alarm rate. This is due to the fact that the false alarms occurred at least partially at a range outside of the lidar or they were obscured by rain.

Not captured in the demonstration was a dry wind shear loss. Undoubtedly, the TDWR has difficulty

detecting this type of wind shear, like the dry gust fronts. Lidar has detected the dry microburst phenomena at other locations such as Jeffco Airport in Broomfield, Colorado.

#### 4.4 Combined TDWR and Lidar Results

Looking at the wind shear performance results separately shows the positives and negatives of each system. The combination of the two systems, using lidar for dry wind shear gust front outflows and TDWR for wet wind shear microbursts optimizes the overall wind shear detection. The current TDWR POD for all wind shear of 35% would more than double to 74% using the lidar SIGMET (Table 4), which is currently available.

The TDWR specification for wind shear detection losses is at least 90% and less than 10% for wind shear loss false alarms, which is not met at LAS. There is no specification on TDWR wind shear gains, but according to the Las Vegas Airspace Users' Council (LUC), all wind shear should achieve at least a 90% detection rate to improve safety and efficiency at LAS. According to the LUC, the goal is to achieve at least a 90% wind shear detection rate and less than a 10% false alarm rate for all wind shear (losses and gains either wet or dry).

### Table 4 Wind Shear Combined Performance using Lidar SIGMET

	ALL	GAINS	LOSSES
		(lidar)	(TDWR)
POD	74%	68%	83%
PFA	14%	1%	27%

#### Table 5 Wind Shear Combined Performance using proposed Lidar MIGFA (estimate)

	ALL	GAINS	LOSSES
		(lidar)	(TDWR)
POD	88%	91%	83%
PFA	12%	1%	27%

# Table 6 Wind Shear Combined Performance with Lidar MIGFA and TDWR RDA Rehost (estimate)

	ALL	GAINS	LOSSES
POD	91%	91%	90%
PFA	5%	1%	10%

Table 5 shows an estimated 88% wind shear detection rate for all wind shear using a lidar MIGFA, which is very near the goal of the LUC of at least 90%. The false alarm rate for all wind shears would be reduced to 12% in this case. A further break down of the statistics shows that the microburst detection rate remains at 83% and the gust front detection rate remains at 91% simply by allowing the lidar to detect and issue dry wind shear events and TDWR to detect and issue wet wind shear events. The microburst false alarm rate remains at 27%, which is unacceptably high. To remedy this component, the Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL) is developing a Radar Data Acquisition (RDA) rehost for the TDWR (Elkin 2002). The false alarm rate is expected to drop to 10% or less for wind shear losses with the implementation of the TDWR RDA rehost in 2007. In addition, the TDWR RDA rehost is expected to increase the probability of detecting wind shear loss events to at least 90%.

Table 6 shows that using the TDWR RDA rehost and lidar MIGFA increases the overall wind shear performance to at least 91% while lowering the false alarm rate to 5% for all wind shear. This would satisfy the LUC request of achieving at least a 90% wind shear detection rate and less than 10% false alarm rate for all wind shear.

# **5.0 OTHER LIDAR ATTRIBUTES**

There are other lidar advantages that may require product development. For example, dust devils were observed on 22 and 23 August. A vortex of 22 knots differential was observed on the parallel east-west runways at 2117 UT. Hazards include differential wing lift and a possible roll of the aircraft and sequencing difficulties as a plane on approach to 25R experiences a tailwind and another on approach to 25L experiences a headwind (Figure 5). A vortex can result from other phenomena, such as intersecting gravity waves (Meuse 1996) as observed at Dallas/Fort Worth (DFW) by American Airlines flight 1352, an MD-80 aircraft, on 12 April 1996. The pilot described this vortex encounter as a severe wind shear and full throttle was necessary to avoid an accident. Since gravity waves have been observed with light or no precipitation, the lidar can detect these sometimes-dangerous phenomena.



Figure 5. Lidar vortex on east-west runways.

The lidar can also detect persistent wind shear from obstacles as it did on 9 September (Figure 6) downwind of the Las Vegas Strip starting with Mandalay Bay (Figure 7). The ASOS wind was from the southwest at 20 knots with gusts to 30 knots. The region of smallscale wind shear, which is displayed as turbulence in Figure 6, remained on the western side of the 19R final approach.



**Figure 6.** Lidar spectrum width where yellow shade represents >4 m/s. The turbulence product is in purple.



Figure 7. Las Vegas Strip adjacent to northern half of the north-south parallels.

During the winter months, inversions occur in the Las Vegas valley. Wind shear often occurs on top of the inversion. These winds are not subject to the effects of friction on the ground and are higher than those deduced from pressure gradients on a synoptic map. The lidar can provide a wind profile to detect the inversion wind shear when it is significant to air traffic efficiency. Also overlapped with this type of wind shear is the low-level jet, which helps transport moisture from the Baja to the Valley.

Another lidar product is wake vortex detection, which is being used in Saint Louis (STL). Currently, however, it is recommended that a single lidar perform either wind shear detection or wake vortex detection. This is due to the time sensitivity of both products. If both products are desired, more than one lidar is needed.

Another possible benefit to an operational lidar is to determine the slant range visibility, often different from that of the horizontal range reported. This difference can result in inefficient airspace use. That is, reduce the LAS capacity from 68 arrivals per hour to 34 based on a horizontal visibility report that is lower than what the pilot experiences on approach. The ZLA CWSU envisions slant range accuracy benefits at LAS and Los Angeles (LAX).

# **6.0 CONCLUSIONS**

(POD/PFA)			
TDWR	Add lidar	Add lidar	Add lidar
	SIGMET	MIGFA	MIGFA &
			RDA
35/25%	74/14%	88/12%	91/5%

#### Table 7 Overall Wind Shear Performance Options (POD/PFA)

In order to satisfy the LUC in achieving a 90% detection rate for all wind shears and lowering the false alarm rate to fewer than 10%, the following actions need to be performed. A dry wind shear detection system, lidar, needs to be installed at an optimum location and utilize the latest gust front technology, MIGFA. The TDWR RDA rehost needs to be implemented. This study shows that the lidar well qualifies to be a reliable dry wind shear detection system.

At the request of the LUC, a lidar demonstration to the LAS ATC is recommended. An immediate advantage (without algorithm improvements) using the lidar display in the tower will provide a 68% gust front gain detection rate, up from the current 6% gust front gain detection rate from TDWR. The overall wind shear detection rate in this case will more than double from 35% to 74% (Table 7), but will still be below the desired LUC goals. Therefore, while a short-term gain is obtained by using the system as it is, longer-term improvements are needed to meet the LUC goals.

That is, fully exploit the lidar by using MIGFA to detect gust fronts, optimize the lidar site location, and implement the TDWR RDA rehost. The result is an estimated 91% wind shear detection rate and 5% wind shear false alarm rate for all wind shear (Table 7). In order to produce one set of wind shear alerts, the lidar should simulate the LLWAS-NE++ output format needed to integrate the TDWR and lidar alerts. The integration logic should allow the lidar to dictate gust front gain

alerts and allow both the TDWR and lidar to issue microburst alerts. The latter will naturally provide wet microbursts from the TDWR and dry microbursts from the lidar. In cases where both systems provide a microburst alert, the average will be taken, but will not be reduced to below 80% of the maximum loss value. These improvements will meet the LUC goals in the next 2 years.

This study has applications beyond LAS (i.e. SLC, PHX) and can be considered at other non-TDWR airports (i.e. Albuquerque, NM, Tucson, AZ, Ontario, CA, and El Paso, TX where WSP is located) where dry wind shear detection remains a challenge. Other benefits mentioned in section 5 can be exploited based on the users' needs at a particular location.

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