Low-Level Wind Shear Characteristics and Lidar-Based Alerting at Lanzhou Zhongchuan International Airport, China

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ABSTRACT

Lanzhou Zhongchuan International Airport [International Civil Aviation Organization (ICAO) code ZLLL] is located in a wind shear prone area in China, where most low-level wind shear events occur in dry weather conditions. We analyzed temporal distribution and synoptic circulation background for 18 dry wind shear events reported by pilots at ZLLL by using the NCEP final (FNL) operational global analysis data, and then proposed a lidar-based regional divergence algorithm (RDA) to determine wind shear intensity and location. Low-level wind shear at ZLLL usually occurs in the afternoon and evening in dry conditions. Most wind shear events occur in an unstable atmosphere over ZLLL, with changes in wind speed or direction generally found at 700 hPa and 10-m height. Based on synoptic circulations at 700 hPa, wind shear events could be classified as strong northerly, convergence, southerly, and weak wind types. The proposed RDA successfully identified low-level wind shear except one southerly case, achieving 94% alerting rate compared with 82% for the operational system at ZLLL and 88% for the ramp detection algorithm (widely used in some operational alert systems) based on the same dataset. The RDA-unidentified southerly case occurred in a near neutral atmosphere, and wind speed change could not be captured by the Doppler lidar.

Key words: low-level wind shear, synoptic situations, alerting algorithm, Doppler lidar

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1. Introduction

Low-level wind shear is considered as sustained headwind/tailwind change $\geq 7.7$ m s$^{-1}$ below 500 m in aviation meteorology. This causes an aircraft lift change, and the consequent deviation from the intended flight path may be hazardous to aircraft landing or taking off from the runway (Fujita and Caracena, 1977; Kessler, 1985). For improved aviation safety, how to automatically and accurately alert low-level wind shear has gained considerable attention.

Low-level wind shear occurs in both rainy weather conditions, such as microbursts and gust fronts associated with severe convection, and non-rainy weather conditions due to terrain effects, sea breezes, low-level jets, dry microbursts, etc. (ICAO, 2005; Shun and Chan, 2008). The wind shear events have some characteristics of meso- and small-scale weather phenomena, such as small temporal–spatial scale and intense change, making it difficult to develop reliable automated wind shear alerting algorithm. Operational low-level wind shear alerts rely mainly on wind information measured by anemometers, Doppler radars, and/or lidars (e.g., Zrnić et al., 1985; Uyeda and Zrnić, 1986; Merritt et al., 1989; Witt et al., 1989; Hermes et al., 1993; Stumpf et al., 1998; Keo-han et al., 2006; Shun and Chan, 2008; Chan, 2012; Augros et al., 2013; Lee and Chan, 2014). Anemometer-based low-level wind shear alert system has been de-
veloped since the 1970s (e.g., Goff, 1980; Wilson, 1993) and Doppler radar was introduced in the 1980s (e.g., Zrnić et al., 1985; Uyeda and Zrnić, 1986; Evans and Turnbull, 1989; Merritt et al., 1989; Witt et al., 1989; Hermes et al., 1993; Stumpf et al., 1998; Augros et al., 2013). Their effectiveness has been well proven for detection and warning of wet shear in rainy weather (ICAO, 2005; Hallowell and Cho, 2010). However, current alerting algorithms based on anemometers and rain-detecting Doppler weather radar data are almost incapable of capturing dry wind shear events during non-rainy weather conditions at higher altitudes (e.g., Gultepe et al., 1990; Shun and Lau, 2002; Keohan et al., 2006), because clear-air returns are not always available from Doppler radar, and anemometers only detect wind shear in the lowest couple of hundred meters (ICAO, 2005; Shun and Chan, 2008).

A complementary method to capture low-level wind shear information uses wind profilers (WPRs), e.g., at Juneau International Airport in the United States (see https://ral.ucar.edu/projects/juneau-airport-wind-system-jaws). The WPRs claim to be capable of capturing wind shear due to terrain effects. However, WPRs are unsuitable for detecting wind shear along glide and take-off paths (ICAO, 2005).

Doppler lidar, a relatively new remote sensing instrument, recently offered a promising alternative way to detect wind shear, particularly under dry conditions, and has been implemented in several international airports, including Hong Kong, Las Vegas, Nice, Tokyo, and Beijing (e.g., Shun and Lau, 2002; Keohan et al., 2006; Shun and Chan, 2008; Boilley and Mahfouf, 2013; Matayoshi et al., 2016; Zhang et al., 2019). Dry wind shear has drawn more and more attention for its frequent occurrence (Shun and Chan, 2008; Chen et al., 2017; Thobois et al., 2019). It was reported that dry wind shear accounts for almost 90% of all wind shear events at Hong Kong International Airport (HKIA; HKO et al., 2010). Hence, our priority is to determine how to develop a wind shear alerting algorithm based on Doppler lidar observations.

Most current operational wind shear alert systems use the ramp algorithm to automatically detect headwind changes, e.g., the lidar wind shear alert system (LIWAS) at HKIA (Choy et al., 2004; Shun and Chan, 2008; Chan et al., 2011). In addition, a lidar-based F factor method was also applied for wind shear alerts at HKIA, in which F factor is calculated directly from the gradient of the lidar-measured headwind profile (Chan et al., 2011; Chan, 2012; Lee and Chan, 2014). Jiang et al. (2016) proposed a wind shear alerting algorithm combining double and single ramp detection algorithms. However, ramp detection and related algorithms identify wind shear depending on wind change along the ramp length and may be contaminated by a single abnormal observation.

Lanzhou Zhongchuan International Airport [International Civil Aviation Organization (ICAO) code ZLLL], located southeast of the Qinwangchuan alluvial–diluvial basin and surrounded by mountains, is in a region of China where wind shear occurs frequently (Dang et al., 2013). Installation of a new coherent Doppler lidar (WindCube400S-AT, Leosphere Co.) in 2016 provided an opportunity to detect low-level wind shear at ZLLL (Thobois et al., 2019). Accordingly, lidar data from May to October 2016 were collected along with 18 wind shear events reported by pilots (PIREPs). By combining the NCEP final (FNL) operational global analysis data, synoptic characteristics of wind shear events were analyzed. Subsequently, we developed a lidar-based alerting algorithm, and verified the algorithm against the PIREPs.

The remainder of this paper is organized as follows. Section 2 introduces wind shear events and associated synoptic circulation background. Section 3 details the proposed lidar-based wind shear alerting algorithm. Section 4 shows the performance of the proposed alerting algorithm in comparison with the ramp detection. Finally, Section 5 summarizes and concludes the paper.

2. Wind shear events and preliminary analysis

2.1 Wind shear events description

In recent years, wind shear events encountered by flights have become more frequent at ZLLL due to rapidly increasing number of flights. Most wind shear events occur in spring and summer, particularly through May and June. For this, a coherent Doppler lidar was installed near a runway at ZLLL from May to October 2016 to evaluate the Doppler lidar capability for detecting dry wind shear at ZLLL. This was supported by a project initiated by the Air Traffic Management Bureau of the Civil Aviation Administration of China (Thobois et al., 2019).

Eighteen wind shear events were reported by pilots during aircraft take-off or landing over the lidar test run period, as shown in Table 1. Figure 1 shows that seven events occurred during 1400–1600 Beijing time (BT), three during 1200–1400, and three during 1600–1800 BT, i.e., 13 of 18 wind shear events occurred in the afternoon and early evening, which was consistent with the previous statistic results (Dang et al., 2013).

2.2 Wind shear classification and preliminary analysis

Wind shear can occur under different weather condi-
tions, so we analyze synoptic characteristics for the 18 wind shear events to understand these occurrences. ZLLL is 1947 m above sea level, and hence this analysis is based on circulation patterns at 500 and 700 hPa, 10-m wind, 2-m relative humidity (RH), vertical velocity, and pseudo-equivalent potential temperature fields.

In general, the upper area above ZLLL airport was dominated by northwest airflow and a trough nearby at 500 hPa. However, synoptic circulation differed for 700 hPa, with different wind shear events exhibiting significant changes in wind speed or direction. Based on spatial distribution of wind field at 700 hPa, wind shear events were classified into four types (see Table 1; final column): (1) strong northerly wind type, where 13 of the 18 reported wind shear events occurred under strong northerly wind conditions; (2) convergence wind type, where three wind shear events (Nos. 5, 10, and 11) occurred under this synoptic situation, i.e., northerly and southerly winds converged around ZLLL; (3) southerly wind type (No. 9); and (4) weak wind type (No. 14). A detailed analysis of circulation background for each synoptic type is carried out for the following four wind shear cases (Fig. 2).

Considering the wind shear event No. 3 that occurred at 1415 BT 8 June 2016 as an example for the strong northerly wind type, Fig. 2a shows that the circulation pattern at 500 hPa was featured with one ridge and one trough. ZLLL was behind the trough, and northwest air-

## Table 1. Pilot reported (PIREPs) wind shear events at ZLLL in 2016 and associated synoptic types

| No. | Occurrence time (BT) | Height (m) | Range from the runway end [nautical mile (NM)] | Wind shear type | Synoptic type |
|-----|----------------------|------------|-----------------------------------------------|----------------|---------------|
| 1   | 1511, 28 May         | 152.4      | 2                                             | H              | N             |
| 2   | 1518, 02 June        | 182.9      | 1.6                                           | T              | N             |
| 3   | 1415, 08 June        | 153        | 0.54                                          | T              | N             |
| 4   | 1427, 08 June        | 400        | 2.16                                          | T              | N             |
| 5   | 1758, 10 June        | 353        | 4                                             | U              | C             |
| 6   | 1441, 12 June        | 121.9      | 2                                             | T              | N             |
| 7   | 1446, 12 June        | 304.8      | 3                                             | U              | N             |
| 8   | 1428, 14 June        | 91.4       | 1.62                                          | H              | N             |
| 9   | 2329, 16 June        | 152.4      | –                                             | T              | S             |
| 10  | 1620, 15 July        | 353        | 4                                             | U              | C             |
| 11  | 1310, 03 September   | 0          | Runway                                        | U              | C             |
| 12  | 1251, 10 September   | 152        | 1                                             | H              | N             |
| 13  | 1256, 10 September   | 0          | Runway                                        | T              | N             |
| 14  | 1617, 20 September   | 152        | 2.16                                          | T              | L             |
| 15  | 1928, 15 October     | 34         | 1                                             | T              | N             |
| 16  | 1931, 15 October     | 182.9      | 2                                             | T              | N             |
| 17  | 2050, 15 October     | –          | –                                             | U              | N             |
| 18  | 1117, 01 July        | 335.3      | 3                                             | T              | N             |

Note: Dashes denote no related information reported by the pilots. Three types of wind shear are presented: headwind shear (H), tailwind shear (T), and unknown (U). Synoptic types include strong northerly (N), convergence (C), southerly (S), and weak (L) wind types.

![Fig. 1. Temporal distribution of low-level wind shear events at ZLLL from the end of May to October 2016.](image-url)
flow dominated over the ZLLL area at 500 hPa. At 700 hPa, strong northwest wind appeared in the northern part of ZLLL, with wind speed up to 7.08 m s$^{-1}$; while weak wind occurred in the southern part of ZLLL, with wind speed of about 2 m s$^{-1}$ (Fig. 2b). Thus, there were changes in wind speed around ZLLL at 700 hPa. Characteristics for the 10-m wind field were similar to those at 700 hPa, and the ZLLL area was in a dry condition with 2-m RH < 40% (Fig. 2c). When this wind shear event occurred, the atmosphere was in convective instability.
stratification. Figure 3a shows that the pseudo-equivalent potential temperature ($\theta_{se}$) decreased with height below 500 hPa, and there were updraft below 300 hPa over ZLLL and significant downdraft over the south side of ZLLL.

Considering the wind shear event No. 10 at 1620 BT 15 July as an example for the convergence wind type. Two ridges and one trough presented at 500 hPa in East Asia, with ZLLL located behind the trough and dominated by northwest airflow (Fig. 2d). A convergence line formed in the east of Gansu Province at 700 hPa (Fig. 2e). At that time, ZLLL was located on the west of the convergence line where the northerly and southerly winds met (Fig. 2e). The 10-m wind field had a similar spatial pattern around ZLLL with wind speed of approximately 7 m s$^{-1}$ in the northeast of ZLLL and only 2 m s$^{-1}$ in other areas (Fig. 2f). Cross-section plots show that $\theta_{se}$ decreased with height below 500 hPa, indicating that the atmosphere was unstable (Fig. 3b). There were updraft below 600 hPa and weak downdraft between 400 and 600 hPa over ZLLL, shown by $\omega$ in Fig. 3b. Moreover, the 2-m RH at ZLLL was less than 30% (Fig. 2f).

The other two wind shear types (southerly and weak wind types) occurred relatively rarely, with only a single instance of each reported over the lidar run period. The wind shear event No. 9 at 2329 BT 16 June 2016 was under southerly wind, and the event No. 14 at 1617 BT 20 September 2016 was under weak wind. Event No. 9 exhibited a “one ridge–one trough” circulation pattern in mid- and higher-latitude areas of East Asia, and ZLLL was located behind the trough, where northwest airflow

![Fig. 3. Latitude–pressure cross-sections of vertical velocity $\omega$ (shaded; Pa s$^{-1}$) and pseudo-equivalent potential temperature $\theta_{se}$ (contour; K) for the four types of wind shear events shown in Fig. 2. Negative (positive) $\omega$ indicates updraft (downdraft). The red triangle indicates the ZLLL site.](image-url)
prevailed above the area around ZLLL at 500 hPa (Fig. 2g). Southerly wind dominated over the ZLLL area at 700 hPa, with wind speed of 6.15 m s$^{-1}$ in northeastern and 1.54 m s$^{-1}$ in northwestern ZLLL (Fig. 2h). The 10-m wind field has similar characteristics to that at 700 hPa, with the wind speed changes near ZLLL (Fig. 2i). The 2-m RH was less than 30% (Fig. 2i), and the atmospheric stability was near neutral, i.e., unchanged $\theta_{se}$ below 500 hPa (Fig. 3c). Vertical velocity pattern shows that strong downdraft occurred over ZLLL and its south (Fig. 3c). In this case, the near neutral stratification and downdrafts may have suppressed the development of convection. For event No. 14 (weak wind type), the trough at 500 hPa was shallower, compared with the other three wind shear types, and ZLLL was located behind the trough (Fig. 2j). Weak wind $<3$ m s$^{-1}$ occurred at 700 hPa and 10-m wind fields, and the 2-m RH was 30%–40% (Figs. 2k, l). This wind shear occurred in a slightly unstable atmosphere below 650 hPa, and there was an updraft over ZLLL (Fig. 3d).

Overall, when the wind shear events occurred, significant wind changes existed at 700 hPa and 10-m wind fields, accompanied by prevailing northwest airflow at 500 hPa above ZLLL. All wind shear events occurred in dry conditions with RH $<40\%$. Except the southerly wind type, most wind shear events occurred in unstable atmospheres with updraft over ZLLL. However, the NCEP FNL data only provide circulation background analysis on these dry wind shear events; more detailed smaller-scale information and identification of dry wind shear events need to be obtained with Doppler lidar, and further analysis needs to be done by use of numerical simulation with lidar data assimilation.

3. Lidar observations and lidar-based wind shear alerting algorithm

3.1 Lidar information

A coherent Doppler lidar (WindCube400S-AT) was installed at the center of ZLLL runway from May to October 2016 for wind shear detection. Observations comprised full azimuthal plan position indicator (PPI) scans at 3° and 6° elevation angles and range height indicator (RHI) vertical scans repeated every 3 min. The lidar had a detection range up to 14 km, with a 200-m resolution, and the PPI scans at 3° and 6° were designed to provide wind shear alerts for aircraft landing and take-off. The RHI scan was configured for detecting vertical wind profiles and higher wind fields. More detailed configurations can be found in Thobois et al. (2019).

The lidar observation area covered ZLLL northern and southern corridors (Fig. 4). Three boxes for wind shear alerts [Fig. 4; squares with 1852-m (1-NM) sides] were located along the extension line of the runway on both sides. The direction of lidar beams along the runway and extension line was consistent with the glide path, and observed velocities were very close to measured headwind and tailwind components.

3.2 New wind shear alerting algorithm

Wind shear at airports refers to wind changes along a take-off or landing path. Divergence (DIV) is an effective physical factor to identify wind shear, which reflects the size of wind change along the runway and its extension line. By using observed velocities from the lidar at ZLLL, DIV along the radial direction can be calculated by the following formula:

$$\text{DIV} = \frac{\partial V_r}{\partial r} \Delta V_r \Delta r; \quad (1)$$

where $V_r$ is the observed velocity and $r$ is radial distance. A similar form has been employed in some alerting algorithms, including DIV calculations in terms of anemometer observations in the low-level wind shear alert system (Goff, 1980; Wilson, 1993; ICAO, 2005) and velocity gradient calculations from a Doppler radar network over France (Augros et al., 2013).

Ramp detection algorithm, widely used in some operational alert systems such as the LIWAS in HKIA, is also used to identify wind shear from wind change $\Delta V$ along the ramp length $H$. In general, a wind shear event needs multiple calculations for different ramp lengths, which vary by a multiplication factor of 2, namely, 400, 800,
... and 6400 m (Shun and Chan, 2008). However, ramp detection algorithm and related approaches (e.g., Jiang et al., 2016) could be affected by a single abnormal observation. Therefore, we proposed a lidar-based regional divergence algorithm (RDA) to identify low-level wind shear.

The RDA comprises two steps: constructing the headwind profile \( (U) \) and calculating regional divergence value \( (RDV) \). Headwind profile was constructed from lidar PPI observations. Since the lidar was located at the center of ZLLL runway, observed velocities \( V_r \) along the runway and its extension line were close to headwind or tailwind components. Velocities were collected from \( N \) beams with angles < 30° between the lidar beam and runway (Fig. 4; shaded area) and used to construct the headwind profile. The determination of \( N \) is discussed in Section 4.1. Finally, \( U \) was obtained by averaging multiple radial velocities from \( N \) beams. Lidar observations were subject to quality control and outlier removal prior to constructing \( U \), similar to Shun and Chan (2008).

The way for construction of \( U \) reduced impacts from local fluctuations of the observed data for a single radial direction on the final results. If lidar beams were not consistent with the runway direction for different installations, the construction of \( U \) can be achieved following Hong Kong’s mode (Shun and Chan, 2008).

The second step of RDA is to calculate RDV and consequently identify wind shear in terms of RDV. Figure 5 shows the way to calculate RDV at any point \( i \). Windows A and B indicate the computational domain and vacant area, respectively. Regional mean velocities \( UI \) are calculated at two A-windows:

\[
UI_{i+D/2+R} = \frac{1}{2R+1} \sum_{k=i+D/2}^{i+D/2+2R} U_k, \tag{2}
\]

and

\[
UI_{i-D/2-R} = \frac{1}{2R+1} \sum_{k=i-D/2-2R}^{i-D/2} U_k, \tag{3}
\]

where \( R \) is the half-width of window A, \( D \) is the width of window B whose unit is multiple of lidar gate interval, and \( U_k \) is the velocity at the \( k \)th gate from the constructed headwind profile. Once UI values are obtained for the windows, RDV at gate point \( i \) can be calculated as

\[
RDV(i) = \frac{1}{(D+2R)\Delta x} \left( UI_{i+D/2+R} - UI_{i-D/2-R} \right). \tag{4}
\]

where \( \Delta x \) is the lidar horizontal resolution (\( \Delta x = 200 \) m at ZLLL). Hence, RDV at each gate along the headwind profile can be obtained, and a wind shear alert is issued if \( |RDV| \) (absolute value of RDV) > threshold at any three continuous gates, where threshold = \( 2.5 \times 10^{-3} \) s\(^{-1} \), converted from the wind shear standard (15 knots) from ICAO. Positive RDV greater than the threshold is regarded as tailwind shear (i.e., increasing tailwind or decreasing headwind), whereas negative RDV lower than the negative threshold is regarded as headwind shear (i.e., decreasing tailwind or increasing headwind). Thus, the low-level wind shear intensity can be represented by RDV, and its position is regarded as the location where \( |RDV| \) exceeds the specified threshold.

4. RDA performance

4.1 RDA parameters sensitivity tests

Parameters \( N, D, \) and \( R \) could affect RDA performance and effectiveness. Therefore, we performed a series of sensitivity tests to obtain appropriate RDA parameters using the wind shear events listed in Table 1. Since lidar data for wind shear event No. 18 were missing, a total of 17 events were used to test the proposed RDA.

The sensitivity of the parameter \( N \) was analyzed first. Considering \( N \) beams with angles < 30° between the lidar beam and runway, \( N \) was therefore set to 3, 5, 7, 9, and 11 for the tests. The residual sum of squares (SSE) between observed velocities and constructed headwind was calculated to assess fitting effects from \( N \) radials. Taking the wind shear event No. 15 at 1928 BT 15 October 2016 as an example, averaged SSEs were 4.04, 3.62, 3.54, 3.64, and 3.80 for \( N = 3, 5, 7, 9, \) and 11, respectively. Thus, fitting headwind has a low sensitivity to \( N \), but \( N = 7 \) provides slightly better fitted headwind profile, and is consistent with quick access recorder (QAR) data (Fig. 6a). The constructed headwind profile can remove “spikes” arising from clusters and local fluctuations from a single radial direction. Thus, \( N = 7 \) is chosen to construct the headwind profiles (Fig. 6a).

Fixing \( N \) at 7, we then designed two groups of experiments to test sensitivities of parameters \( D \) and \( R \), which

![Fig. 5. The schematic diagram of RDA calculation at gate point i, where D and R are RDA parameters.](image-url)
could be performed simultaneously or in any convenient order. Therefore, we set gate intervals $D = 0, 2, 4, \ldots, 18$, corresponding to 0, 400, 800, \ldots, and 3600 m, and fixed $R = 1$ for the 17 wind shear cases. Figures 6b–d
show the test results for wind shear event No. 15, which indicate that the RDA method is sensitive to parameter \( D \) but slightly sensitive when \( D \) is within a range (e.g., \( D = 4 \) or 6; Fig. 6c). Some “spikes” occur in the calculated divergence profiles for smaller \( D \) value (e.g., \( D = 0 \); Fig. 6b), whereas larger \( D \) (e.g., \( D \geq 8 \)) may underestimate RDV, resulting in some missed wind shear alerts (e.g., \( D = 18 \); Fig. 6d).

The results from the 17 wind shear events are consistent with the case No. 15 result (Table 2). Using the identified results from \( D = 4 \) as a reference, wind shear intensity deviations for different \( D \) values for 17 wind shear events were calculated respectively, whose absolute values are listed in the 2nd–6th columns of Table 2. Parameter \( D = 2 \) or 6 produces smaller deviation from \( D = 4 \). In contrast, \( D = 6 \) deviation is smaller than \( D = 2 \). However, \( D = 0 \) or \( D \geq 8 \) causes large wind shear intensity deviations. Thus, RDA is sensitive to \( D \), with optimal \( D = 4 \) or 6.

The sensitivity tests of parameter \( R \) were then done by setting \( R = 0, 1, 2, \) and 3 with fixed \( D = 4 \). Although there is a small difference in wind shear intensity between \( R = 0 \) and 1 (Table 2; column 7), smaller \( R \) (e.g., \( R = 0 \)) resulted in “spikes” in the divergence profile (Fig. 6e), whereas larger \( R \) (e.g., \( R = 3 \); Fig. 6g) led to underestimated RDV, which is not conducive to correctly identifying wind shear (Table 2). Parameter \( R \) has less impact on RDA performance than parameter \( D \). Based on the above sensitivity tests, RDA parameters of \( N = 7, D = 4, \) and \( R = 1 \) are selected to identify wind shear at ZLLL.

### 4.2 Comparison with ramp detection algorithm

We compared the proposed RDA with ramp detection algorithm, which has been widely used previously, including the LIWAS in HKIA, to identify the wind shear events. Based on Shun and Chan (2008), the detecting ramp length \( H \) varies by a multiplication factor of 2, namely, 400, 800, …, and 6400 m.

Ramp detection algorithm was able to identify 15 of the 17 wind shear events listed in Table 1, as shown in Table 3, column 5. Considering wind shear event No. 15 as an example to present the results from ramp detection algorithm (Fig. 7). Ramp detection successfully recognized this wind shear event and identified the location at approximately 0.33–1.5 NM, whereas RDA location was 0.22–1.51 NM (Fig. 6c). Hence, the two methods were consistent. However, ramp detection algorithm requires multiple calculations for each different ramp length to obtain the wind shear occurrence range (Fig. 7), whereas RDA only requires a single calculation. Therefore, RDA can determine wind shear more rapidly and easily than ramp detection algorithm, although in practice the two methods would require similar time given current computational power. Nonetheless, RDA can recognize more wind shear events, as discussed further in next section.

#### 4.3 Verification against 17 wind shear events

To assess the RDA effectiveness and validity in detecting low-level wind shear, we identified 17 wind shear events with RDA parameters \( N = 7, D = 4, \) and \( R = 1 \), and compared these against operational alert and ramp detection algorithm results for the 17 wind shear events (Table 3).

Operational alert information, issued by Rainbow5 software developed by SELEX weather radar company, is shown in Table 3, column 6. Three wind shear events

| Number of wind shear event | \( D = 0 \) | \( D = 2 \) | \( D = 6 \) | \( D = 8 \) | \( D = 18 \) | \( R = 0 \) | \( R = 2 \) | \( R = 3 \) |
|---------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1                         | 2.164     | 0.142     | 0.355     | 1.145     | 3.512     | 0.119     | 0.299     | 0.858     |
| 2                         | 2.590     | 1.117     | 0.156     | 0.450     | 2.883     | 0.147     | 0.440     | 1.166     |
| 3                         | 0.581     | 0.360     | 0.711     | 1.322     | 3.253     | 0.140     | 0.453     | 0.841     |
| 4                         | 1.002     | 0.480     | 0.444     | 0.706     | 3.034     | 0.546     | 0.076     | 0.818     |
| 5                         | 3.770     | 0.462     | 0.878     | 1.484     | 3.413     | 0.505     | 0.051     | 0.593     |
| 6                         | 0.200     | 0.598     | 0.767     | 1.656     | 1.653     | 0.317     | 0.528     | 0.584     |
| 7                         | 1.324     | 0.808     | 0.768     | 1.038     | 1.622     | 0.089     | 0.133     | 0.731     |
| 8                         | 2.212     | 1.019     | 0.583     | 0.922     | 1.529     | 0.174     | 0.024     | 0.368     |
| 9                         | –         | –         | –         | –         | –         | –         | –         | –         |
| 10                        | 0.203     | 1.478     | 0.932     | 2.048     | 3.091     | 0.925     | 0.340     | 1.041     |
| 11                        | 0.343     | 0.135     | 0.616     | 0.926     | 1.688     | 0.073     | 0.425     | 0.622     |
| 12                        | 3.320     | 1.599     | 1.643     | 2.774     | –         | 0.122     | 0.651     | 1.524     |
| 13                        | 2.826     | 1.068     | 0.157     | 0.157     | –         | 0.530     | 0.561     | 1.125     |
| 14                        | 1.463     | 0.533     | 0.111     | 0.604     | 1.890     | 0.398     | 0.382     | 0.583     |
| 15                        | 1.050     | 0.630     | 0.725     | 1.246     | 2.904     | 0.211     | 0.370     | 0.710     |
| 16                        | 0.977     | 0.563     | 1.240     | 2.096     | 4.012     | 0.149     | 0.706     | 1.248     |
| 17                        | 1.083     | 0.404     | 0.859     | 1.762     | –         | 0.278     | 0.470     | 1.019     |
| Mean                      | 1.683     | 0.712     | 0.684     | 1.271     | 2.653     | 0.295     | 0.369     | 0.864     |
were not issued any alerts by the operational system, i.e., 14 of the 17 were identified, whereas ramp detection algorithm identified 15 of the 17 (missing events Nos. 9 and 11), and RDA identified 16 of the 17 (Table 3). That is to say, the alerting rates are 82%, 88%, and 94% with the use of the Rainbow5 software, ramp algorithm, and RDA, respectively. RDA identified two wind shear events that had no operational alerts (Nos. 2 and 11). The wind shear types identified by RDA were consistent with the PIREPs (Table 3), which indicates that RDA can successfully determine wind shear type, including unknown types reported by pilots (Nos. 5, 7, 10, 11, and 17). RDA also determined wind shear location consistent with the PIREPs for most cases (Table 3; column 2). For example, RDA identified wind shear event No. 1 as a headwind shear located at approximately 1.19–1.73 NM from the end of the runway with intensity of about $-4.76 \times 10^{-3} \text{s}^{-1}$ (Table 3), consistent for type and location with PIREPs (Table 1). Location errors of some wind shear events, e.g., No. 11, may have been due to poor consistency between the real flight path and lidar radial direction.

Fig. 7. Ramp detection algorithm results for wind shear event No. 15 at 1928 BT 15 October 2016. Only 5 of 16 panels are shown, for ramp lengths of (a) 400, (b) 1600, (c) 3200, (d) 4800, and (e) 6400 m. Circles denote the headwind change ($\Delta V$) exceeding the threshold (7.7 m s$^{-1}$).
Considering the wind shear event that occurred at 2329 BT 16 June, which was not identified by the RDA, the wind shear was southerly wind type and the synoptic situation at 700 hPa and 10-m wind fields showed a wind change around the ZLLL area, but the wind was weak at ZLLL (Figs. 2h, i). As discussed in Section 2.2, this wind shear occurred in near neutral atmosphere (Fig. 3c), and strong downward flow over ZLLL suppressed convection. Lidar observed velocities along the runway had small velocity gradient (Fig. 8a). For the weak wind type of wind shear event, although there was a weak wind at 700 hPa and 10-m wind fields (Figs. 2k, l), observed velocities showed a large change from −7.25 to 6 m s$^{-1}$ within 2400 m over the south side of the runway and its extension line (Fig. 8b). In addition, the weak wind type of wind shear was in a convective instability condition. Thus, there were considerable differences in small-scale information with weak wind synoptic background conditions. RDA may have been able to identify the weak wind type of wind shear (No. 14), but not the southerly wind type of wind shear (No. 9).

### 5. Summary

Low-level wind shear, particularly that under non-rainy conditions, remains a significant hazard for civil aviation. Therefore, we focused on ZLLL, a region with frequent dry wind shear, to analyze and identify low-level wind shear. Temporal distribution and synoptic situation for 18 wind shear events reported by pilots were analyzed by using the NCEP FNL analysis dataset, and we subsequently proposed a lidar-based RDA to identify wind shear using Doppler lidar observations from ZLLL. The RDA effectiveness and performance were tested for

![Fig. 8. Lidar PPI scans at 3° for wind shear events (a) No. 9 at 2329 BT 16 June and (b) No. 14 at 1617 BT 20 September 2016.](image-url)
17 of the 18 wind shear events (due to lack of observations for one event), with the following results.

(1) Most wind shear events at ZLLL occurred in the afternoon and evening, and generally in dry conditions with 2-m RH < 40%. Northwest airflow dominated around ZLLL at 500 hPa and significant wind speed or direction changes occurred at 700 hPa and 10-m wind fields. Most wind shear events occurred under convective instability conditions accompanied by updrafts, with a few events occurring in near neutral atmospheres. Based on spatial distribution of wind field at 700 hPa, wind shear could be classified into four types: strong northerly, convergence, southerly, and weak wind types. Thirteen of the 18 wind shear events belong to the strong northerly wind type.

(2) Sensitivity tests for RDA parameters showed that the constructed headwind profile obtained with $N = 7$ was consistent with QAR radial velocities, and the local fluctuations from single radial measurements and “spikes” arising from clusters could be removed. RDA was only slightly sensitive to parameters $D$ and $R$ within a certain range. Thus, optimal RDA parameters were derived to be $N = 7$, $R = 1$, and $D = 4$ for wind shear detection at ZLLL.

(3) The proposed RDA performed better than the current operational system alerts and ramp detection algorithm. RDA successfully identified not only the wind shear events identified by operational alerts but also those that were not identified by operational alerts, achieving a 94% alerting rate compared with 82% for the operational system and 88% for ramp detection algorithm with respect to the pilot-reported events.

(4) Since the Doppler lidar system was only in place from May to October 2016, the number of flights at ZLLL was limited during this period; only 18 wind shear events were collected. However, RDA could be applied to other airports with Doppler lidar installed for wind shear detection. It would be beneficial to use more observations and combine numerical simulations to further investigate the proposed RDA’s ability, and to explore the causes for the low-level wind shear and achieve better operational wind shear alerts.

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