MEASUREMENT OF TURBULENCE IN TERRAIN-DISRUPTED AIRFLOW AT THE HONG KONG INTERNATIONAL AIRPORT USING A DOPPLER LIDAR

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Abstract: The Doppler LIDAR of the Hong Kong Observatory was used to measure eddy dissipation rate (EDR) directly for the first time at the Hong Kong International Airport in an experiment in 2004. EDR is a measure of turbulence intensity adopted by the International Civil Aviation Organization. The laser beam of the LIDAR stared in a direction parallel to the runways and radial velocity data were obtained at a range resolution of 60 m. The velocity structure function was computed based on two different estimates of the velocity fluctuation (viz. temporal and spatial methods) and EDR was then calculated by fitting the structure function with the von Kármán model. The two estimtes of velocity fluctuation were found to give comparable EDR values. The LIDAR-derived EDR also turned out to have good correlation with EDR obtained from runway anemometers and a boundary-layer wind profiler. In a case of terrain-disrupted airflow during the experiment, the LIDAR-derived EDR showed that turbulence was present near the centre of a micro-scale vortex to the west of the airport.

***Keywords** – turbulence, eddy dissipation rate, Doppler LIDAR*

1. INTRODUCTION

The Hong Kong International Airport (HKIA) (Figure 1) is located on a reclaimed island to the north of the mountainous Lantau Island with peaks rising to nearly 1000 m separated by gaps as low as 400 m. Turbulent airflow which may affect landing and departing aircraft mostly occurs over the airport when southeasterly winds are disrupted by this complex terrain. Measurement of the eddy dissipation rate (EDR), a measure of turbulence intensity adopted by International Civil Aviation Organization (ICAO), would facilitate the monitoring and alerting of turbulence at the airport.

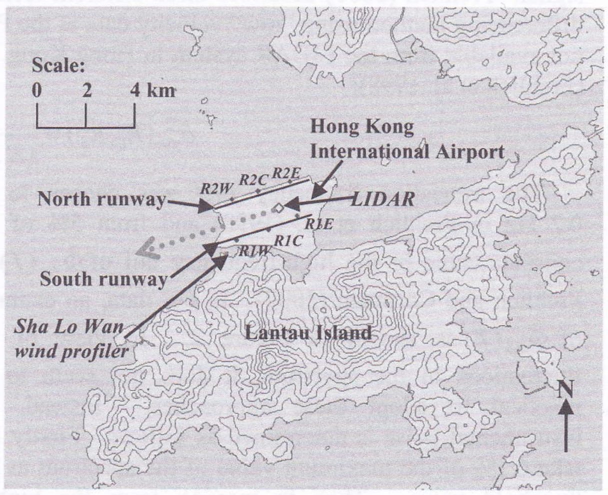

Figure 1. Map of Hong Kong International Airport and the adjacent areas (height contours: 100 m). Equipment labels are in italic fonts. Black dots are the airfield anemometers. The grey arrow is the viewing direction of the staring LIDAR beam.

The Doppler LIght Detection and Ranging (LIDAR) system operated by the Hong Kong Observatory (HKO) at the airport (Figure 1) has been used before to determine the fluctuation of the wind by measuring the standard deviation of the radial velocity and to compare with the aircraft's turbulence report in a typhoon case (Chan and Mok 2004). An experiment was conducted in 2004 to use the LIDAR to measure EDR directly at the airport for the first time. The measurement methodology is described in Section 2. The EDR so determined is compared with the measurements from the conventional cup and vane anemometers on the airfield and a boundary-layer wind profiler (Figure 1) and the results are presented in Section 3. An example of the LIDAR's EDR profile in a southeasterly wind case is presented in Section 4. Conclusions are given in Section 5.

2. CALCULATION OF EDR

The LIDAR is a coherent pulsed system with a wavelength of 2 microns. It has a pulse repetition frequency (PRF) of 500 Hz and outputs radial velocity at 10 Hz. During the experiment, the range resolution was configured to be 60 m, smaller than the 100-m resolution for operational windshear alerting, in order to sample the smaller-scale turbulence. The measurement range was about 6.3 km. The laser beam was made to stare horizontally at a height of about 50 m AMSL towards the 250 degrees direction (from the North), i.e. parallel to the two runways of the airport (Figure 1).

To calculate EDR, the velocity structure function based on the LIDAR radial velocity data is first determined. It could be obtained from two different estimates of the velocity fluctuation associated with turbulence. One way is to follow Frehlich et al. (1998) and use the velocity fluctuation at range R and time t with respect to the temporal mean wind:

$$\hat{v}'(R,t) = \hat{v}(R,t) - \bar{v}(R) \tag{1}$$

where $\hat{v}$ is the radial velocity from the LIDAR, $\bar{v}$ the temporal mean and $\hat{v}'$ the fluctuation component. In all the cases studied below, LIDAR data collected within a period of 10 – 12 minutes would be used to calculate the temporal mean. The velocity fluctuation is determined for each range R of the LIDAR. This first method is called the "temporal fluctuation method".

The second method of determining the velocity fluctuation is to remove the mean wind and the windshear over a certain length L from each radial velocity datum of the LIDAR. For a staring beam, the velocity fluctuation is again expressed as in Eq. (1), but with $\bar{v}$ representing the sum of the spatial mean wind and linear wind change along the length L, i.e. a de-meaning and linear de-trending of the LIDAR velocity data (as a function of range) at a particular time. As a start, L is taken to be 1000 m. This second method is called the "spatial fluctuation method".

Using the velocity fluctuation determined by either one of the above methods, the velocity structure function is then calculated by (Frehlich et al. 1998):

$$\hat{D}_v(R_1,R_2) = N^{-1}\sum_{l=1}^{N-1}\left[\hat{v}'(R_1,l\Delta t) - \hat{v}'(R_2,l\Delta t)\right]^2 - \hat{\sigma}^2_{\Delta e}(R_1,R_2) \tag{2}$$

where R_1 and R_2 are two range gates and N the number of radial velocity data samples. It is calculated over a sliding window of 400 m, which is comparable with the window adopted in Frehlich et al. (1998). The last term on the right hand side of Eq. (2) is an estimation of the error associated with random fluctuations of the LIDAR signal. Frehlich (2001) describes three different techniques for deriving the error and shows that the velocity differencing method using "raw" velocity data at the PRF has the best performance. The "raw" data is however not available from the LIDAR system in Hong Kong. So we use the spectral-based estimate for the error term (Frehlich et al. 1998):

$$\hat{\sigma}^2_{\Delta e}(R_1,R_2) = \frac{1}{(N/2 - j_T + 1)\Delta t}\sum_{j=j_T}^{N/2}\hat{\Phi}_{\Delta v}(j\Delta f, R_1, R_2)\,. \tag{3}$$

The truncation frequency $j_T\Delta f$ was chosen to be 0.2 Hz in Frehlich et al. (1998) and from 5% of the constant value in the high-frequency tail of $\hat{\Phi}_{\Delta v}(f)$ in Frehlich and Cornman (2002). In our data, an example of $\hat{\Phi}_{\Delta v}(f)$ is shown in Figure 2. In view of the fluctuations in the spectrum, it does not seem to be practical to adopt these approaches. Instead, the instrumental noise is determined as follows. Firstly, we take 0.1% of the maximum value of the spectrum as the threshold value. Then in moving from the highest frequency to the lowest frequency in the spectrum, the frequency f_T at which this threshold is exceeded for the first time is taken. All the frequencies below f_T are considered to contain atmospheric signal and those above are associated with instrumental noise.

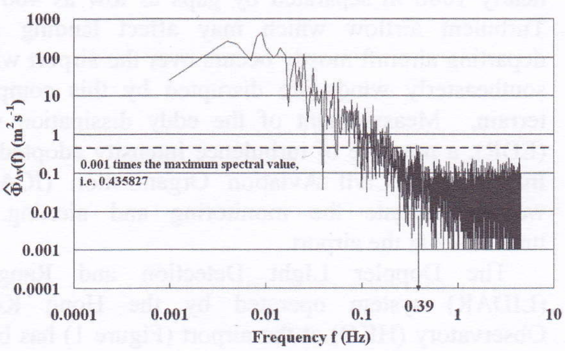

Figure 2. The spectrum $\hat{\Phi}_{\Delta v}(f)$ between the range gates 3 km and 3.3 km from the LIDAR for a 12-minute period starting at 9:57 a.m., 28 August 2004. The frequency indicated by an arrow (0.39 Hz) corresponds to the point where 0.001 times of the maximum spectral value is first exceeded.

The velocity structure function calculated in Eq. (2) is fitted with the theoretical result from the von Kármán model (Frehlich et al. 1998; Davies et al. 2004):

$$\tilde{D}(s,\sigma_v,L_0) = 2\sigma_v^2 G\left(\frac{s}{\Delta p}, \frac{\Delta p}{L_0}, \frac{\sqrt{2\ln 2}\Delta p}{\Delta r}\right) \tag{4}$$

where s is the separation between the range gates, σ_v^2 the variance of radial velocity and L_0 the outer scale of turbulence. Meaning of the other variables and the function G in Eq. (4) could be found in the above two references. The fitting is made by minimizing the weighted error J^2 (Davies et al. 2004), from which σ_v^2 and L_0 are determined. The energy dissipation rate ε is then calculated by (Frehlich and Cornman 2002):

$$\varepsilon = 0.933668\frac{\sigma_v^3}{L_0}\,. \tag{5}$$

EDR used in aviation community and adopted by ICAO is $\varepsilon^{1/3}$.

The fitting to the von Kármán model sometimes could not be made within a reasonably small error, e.g. the velocity structure function still rises rapidly with separation distance between the LIDAR range gates due to windshear, even after removal of linear shear. In that situation, L_0 becomes very large. The fitting resulting in L_0 being larger than 4000 m is not considered. On the other hand, if the resulting L_0 is comparable with the range resolution of the LIDAR (60 m), the quality of the result is also questionable as the LIDAR may not have resolved such fine-scale turbulence. Thus the fitting data with L_0 smaller than 70 m are not considered as well.

3. THE EXPERIMENT AND THE MEASUREMENT RESULTS

The objective of the experiment is to measure EDR at the airport area in terrain-disrupted airflow using a staring LIDAR beam towards the 250-degree direction. However, to study the quality of the LIDAR-derived EDR, measurements were also made in other weather conditions as reference, such as westerly sea breeze and light northerly wind. A total of 12 sets of data were collected on 6 days (in the period 13 July to 11 September 2004), each lasting 10 – 12 minutes.

First of all, EDR values obtained from the temporal fluctuation method and the spatial fluctuation method (Section 2) are compared. They are found to be highly correlated (coefficient of nearly 0.98). On the whole, the latter method gives a slightly larger value of EDR (by about 10%). The length L over which LIDAR data was used to calculate the velocity structure function (1000 m in this study) for the spatial fluctuation method could be varied to see if the resulting EDR values would get even closer to those determined from the temporal fluctuation method. This would be the subject of another study. In the ensuing discussions, only EDR determined from the temporal fluctuation method is considered.

The standard deviation of the LIDAR radial velocity in an azimuthal sector scan has been shown to have certain degree of correlation with aircraft turbulence reports and vertical acceleration fluctuations measured on board aircraft in terrain-disrupted turbulent flow at the airport in a typhoon case (Chan and Mok 2004). Since only a staring beam is employed in the present experiment, the standard deviation (σ_v) values of the LIDAR velocity data over time are calculated. They are found to have good correlation with the EDR values obtained from the temporal fluctuation method, with a correlation coefficient of about 0.83. The least square linear fit equation is:

$$EDR = \frac{\sigma_v}{7.037} + 0.0382\,. \qquad (6)$$

The 1-second wind data obtained from the runway anemometers (10 m above ground, or about 15 m AMSL) to the west of the LIDAR (including R1C, R1W, R2C and R2W, see Figure 1) are also used to calculate EDR for comparison with the LIDAR-derived values. The maximum likelihood method for the wind spectrum was employed. If the mean wind direction measured by the anemometer is within 30 degrees from the runway orientation (070/250 degrees), the EDR determined from the longitudinal spectrum of the wind data is used directly. If it is within 30 degrees from the perpendicular to the runways, the wind spectra from the anemometer are checked for isotropicity (transverse spectrum = 4/3 times the longitudinal spectrum). If this is the case (isotropic within 30%), the EDR determined from the transverse spectrum (corrected for the 4/3 factor) is used. Anemometer data not meeting these critieria are not considered. The anemometer-derived EDR and the LIDAR-derived EDR (at the range gates closest to the anemometers) are found to have reasonable correlation, with a correlation coefficient of about 0.8.

Furthermore, the EDR obtained from the Sha Lo Wan wind profiler (Figure 1), a boundary layer wind profiler with the operating frequency of 1299 MHz, is also used for comparison. Its spectral data are processed by the NCAR improved moments algorithm (NIMA) and the lowest measurement (about 140 m AMSL) is considered. Such EDR values are also found to correlate well with the LIDAR measurements at the range gate closest to the profiler, with a correlation coefficient of 0.88. The profiler-derived EDR values are generally larger (up to 2 times in light turbulence), probably because the airflow could be more turbulent at locations closer to the hills on Lantau Island or the windshear term has not been removed from the profiler EDR estimates.

4. EXAMPLE OF EDR PROFILE IN A SOUTHEASTERLY WIND CASE

In the morning of 28 August 2004, southeasterly winds prevailed over Hong Kong. Strong winds were recorded by anemometers on the hilltops and valleys of Lantau Island. At about 10:10 a.m. (Hong Kong time, 8 hours ahead of UTC), whilst the winds over the airport were mostly moderate east to southeasterly, cyclonic flow was depicted by the wind measurements from the three weather buoys to the west of the airport (Figure 3). The staring LIDAR beam towards the 250-degree direction (Figure 3) revealed a rapid decrease of the radial velocity, from 4.3 m/s (away from the LIDAR) at 3.5 km (range from the LIDAR) to -1.1 m/s (towards the LIDAR) at 4.6 km (Figure 4).

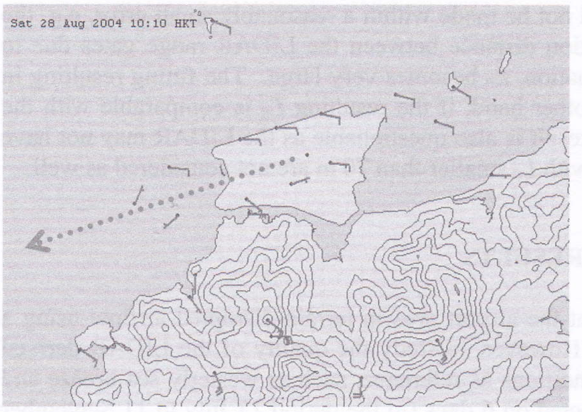

Figure 3. Surface wind observations at 10:10 a.m., 28 August 2004. The grey arrow (in a broken line) indicates the viewing direction of the staring LIDAR beam. Height contours are in 100 m.

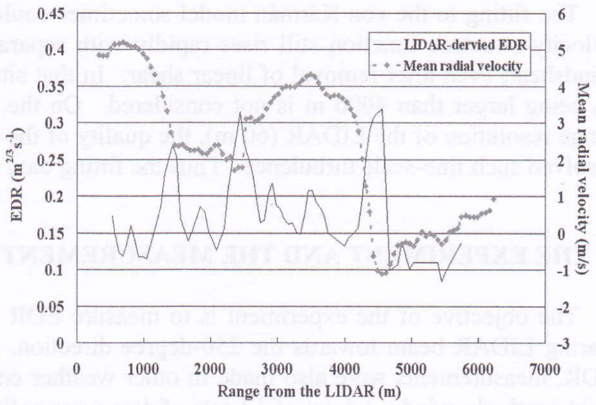

Figure 4. The mean radial velocity and the LIDAR-derived EDR for the 10-minute period starting at 10:10 a.m., 28 August 2004.

The centre of the vortex was located at about 4.4 km from the LIDAR (in the 250-degree direction) as determined from the surface wind data and the LIDAR's radial velocity data (falling to 0 m/s). The LIDAR-derived EDR increased to 0.3 $m^{2/3}s^{-1}$ (moderate turbulence according to ICAO) at this range and continued to rise to about 0.32 $m^{2/3}s^{-1}$ at about 4.6 km. The airflow appears to be more turbulent at the vortex centre and a couple of hundred metres west-southwest of it.

5. CONCLUSIONS

In an experiment in 2004, the Doppler LIDAR at HKIA was used to measure EDR directly by computing the velocity structure function from the radial velocity data and fitting the results with the von Kármán model. The laser beam was made to stare in a direction parallel to the orientation of the runways to provide velocity measurements with the spatial resolution of about 60 m. The LIDAR-derived EDR was found to have good correlation with EDR obtained from runway anemometers and a boundary-layer wind profiler as well as the standard deviation of the radial velocity from the LIDAR itself.

In a southeasterly wind case, the airflow at the airport area was disrupted by the complex terrain of Lantau Island and a micro-scale cyclonic vortex was depicted by surface wind observations over the sea west of the airport. Based on the LIDAR-derived EDR, the airflow was found to be more turbulent near the vortex centre. The experiment demonstrated that the LIDAR is capable of providing very useful turbulence data in terrain-disturbed airflow.

During normal operations at the airport, instead of having the laser beam staring in a particular direction, the LIDAR performs surveillance scans to detect windshear. The next step is to derive "EDR maps" from surveillance scans so that the LIDAR could be used for both windshear and turbulence alerting at the same time.

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