LIDAR-based Turbulence Intensity Calculation along Glide Paths

K.M. Kwong * & P.W. Chan

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* Hong Kong Polytechnic University
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K.M. Kwong (a) and P.W. Chan (b)
(a) Hong Kong Polytechnic University, Hong Kong, China
(b) Hong Kong Observatory, Hong Kong, China
pwchan@hko.gov.hk

INTRODUCTION
Low-level turbulence is an aviation hazard. It brings about rapid bumps or jolts to the aircraft. In severe turbulence cases, abrupt changes in the altitude and attitude of the aircraft may occur and the pilot may suffer a momentary loss of control.

For the Hong Kong International Airport (HKIA), on average 1 in about 2000 flights reports encountering of significant turbulence. Terrain-induced airflow disturbance is the major cause of low-level turbulence at HKIA. When winds from the east to southwest climb over the mountainous Lantau Island (an island to the south of HKIA), airflow disruption could occur over the airport area. Such cross-mountain airflow is the most common in spring-time when the monsoon brings east to southeasterly winds to the south China coast, and in the summer when Hong Kong is under the influence of tropical cyclones or the southwest monsoon.

The Hong Kong Observatory (HKO) provides turbulence alerting services at HKIA. Turbulence intensity is expressed in terms of the cubic root of the eddy dissipation rate (EDR). For low-level turbulence, the EDR\(^{1/3}\) value between 0.3 and 0.5 \(\text{m}^{2/3}\text{s}^{-1}\) is taken to be moderate turbulence, and the value of 0.5 \(\text{m}^{2/3}\text{s}^{-1}\) or above refers to severe turbulence.

In addition to anemometer data around the HKIA, the Plan-position Indicator (PPI) scans of the LIDAR were used to generate EDR maps to provide an overview of the turbulence distribution in the airport area\(^1\). This paper is an extension of the previous work to study the possibility of determining the profile of EDR directly along the glide path to be encountered by the arriving aircraft. Since the airflow disturbances at HKIA have rather small spatial scales (in the order of several hundred metres) as illustrated by LIDAR observations\(^2\), the use of LIDAR data for turbulence monitoring is expected to be more precise if the focus is made along the glide path itself instead of an overview of the whole airport area.

CALCULATION OF EDR
The glide-path scans of the LIDAR\(^2\) are used in this study. In this scanning mode, the laser beam of the LIDAR is configured to scan along the oblique line of the glide path by orchestrating the azimuthal and elevation motions of the scanner. For alerting of windshear, i.e. significant changes of headwind, only the radial velocity data collected within prescribed distances from the glide path are utilized to construct the headwind profile to be encountered by the aircraft\(^2\). In calculating turbulence intensity, all the wind data in the measurement sector of the glide-path scan (see, for instance, Figure 2(b)) are considered in a way similar to the treatment of PPI scan data\(^1\). The whole measurement sector is divided into a number of overlapping sub-sectors (each with a size of 10 range gates and 16 azimuth angles, overlapping by 5 range gates and 8 azimuth angles). EDR is calculated in each sub-sector by adopting spatial fluctuation method in the structure function approach\(^1,5\). As such, the two-dimensional distribution of EDR in the entire measurement sector of the glide-path scan is determined and the EDR values along the glide path can be used to construct the turbulence intensity profile to be encountered by the aircraft.

For more accurate determination of the turbulence intensity, azimuthal averaging is minimized by slowing down the horizontal rotation of the laser beam given the time constraint that the LIDAR is also required to perform other scans for operational purposes. With the current setting of the LIDAR, the gate length \(\Delta p\) is 72 m. Based on results of previous studies\(^3,4\), \(\Delta h/\Delta p\) (\(\Delta h =\) range x azimuthal span) should be far less than 1 so that
azimuthal averaging is small compared with range scale length (averaging along the range gate). For real application, this ratio could be set at a maximum value of 0.2 (Frehlich, private communication). Taking the maximum range of 10 km for the LIDAR and the data output frequency of 10 Hz from the LIDAR, the azimuthal rate $a$ should be: $\Delta h = 10000 \times a \times 0.1 = 0.2 \times 72$, which implies that $a = 0.825$ degrees/second. This is a realistic value for the azimuthal rate over a small sector considering operational scanning requirements and laser safety measures. The azimuthal rate of 0.8 degrees/second is implemented for the glide-path scan over the arrival corridor to the west of the north runway of HKIA, viz. the corridor over which most of the aircraft approaches are made. The present study is mainly focused on this glide path.

Each sub-sector in the glide-path scanning area has a size of 10 range gates times 16 radials. For a particular scan $k$, the radial velocity “surface” within this sub-sector (as a function of range $R$ and azimuth angle $\theta$) is fitted with a plane using singular value decomposition method. The velocity fluctuation $\hat{v}$ at each point in the space $(R, \theta)$ is taken to be the difference between the measured radial velocity $v$ and the fitted velocity $\hat{v}$ on the plane:

$$\hat{v}(R,\theta,k) = v(R,\theta,k) - \bar{v}(R,\theta,k). \quad (1)$$

Both longitudinal and azimuthal structure functions are calculated$^5$. The longitudinal structure function is given by:

$$\hat{D}_L(R_1, R_2) = N^{-1} \sum_{\theta,k} \left[\hat{v}'(R_1,\theta,k) - \hat{v}'(R_2,\theta,k)\right]^2 - E(R_1, R_2) \quad (2)$$

where the summation is made over all the possible azimuthal angles and scans over 15 minutes, and $N$ refers to total number of entries in the summation. The error term $E$ is calculated using the covariance method on the radial velocity difference$^3$.

$$\hat{C}(R_1, R_2, n\Delta\theta) = N^{-1} \sum_{l,k} \left[\hat{v}'(R_1,l\Delta\theta,k) - \hat{v}'(R_2,l\Delta\theta,k)\right]$$

$$\times \left[\hat{v}'(R_1,(l+n)\Delta\theta,k) - \hat{v}'(R_2,(l+n)\Delta\theta,k)\right] \quad (3)$$

and the error term is then estimated from the covariance values of different azimuthal changes (the ranges $R_1$ and $R_2$ are dropped in the formula for simplicity):

$$E = \hat{C}(0) - 2\hat{C}(\Delta\theta) + \hat{C}(2\Delta\theta). \quad (4)$$

The azimuthal structure function is calculated in a way similar to Eq. (2), but the radial velocity difference of two azimuthal angles is considered:

$$\hat{D}_A(R \bullet \theta_1, R \bullet \theta_2) = \sum_{R,k} \left[\hat{v}'(R,\theta_1,k) - \hat{v}'(R,\theta_2,k)\right]^2 - E(R) \quad (5)$$

Again, the error term is estimated using covariance method. The covariance of velocity estimate is:

$$\hat{C}(R,n\Delta\theta) = N^{-1} \sum_{l,k} \hat{v}'(R,l\Delta\theta,k) \times \hat{v}'(R,(l+n)\Delta\theta,k). \quad (6)$$

And the error term of velocity difference is taken as two times of the error of the velocity estimate:

$$E = 2\hat{C}(0) - 2\hat{C}(\Delta\theta) + \hat{C}(2\Delta\theta). \quad (7)$$

EDR$^{1/3}$ is determined by fitting the longitudinal or the azimuthal structure function with the theoretical von Kármán model$^5$. The values calculated from both methods are studied in 18 cases and they are found to be comparable with each other (Figure 1). In the following discussions, only the EDR$^{1/3}$ determined from azimuthal structure function would be used.

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**Figure 1.** EDR$^{1/3}$ values determined from the two structure functions
EXAMPLES OF EDR PROFILE

Two pilot reported cases of turbulence encounter are presented. The first case occurred on 25 April 2006, a typical event of terrain-induced airflow disturbance at HKIA during the prevalence of easterly wind in the spring. At 06:47 UTC on that day, an aircraft (B773) landing at the north runway of HKIA from the west reported the encountering of moderate turbulence at a height of about 600 feet. The 1-degree PPI velocity image of the LIDAR around that time is shown in Figure 2(a). It can be seen that the easterly wind was not uniform in the airport area – the sea area to the west of HKIA appeared to be in the wake of the mountains on Lantau Island, with generally weaker winds and even airflow of reversed direction. The turbulence intensity distribution and profile over the arrival runway corridor to the west of the north runway are given in Figure 2(b) and (c) respectively. The EDR\(^{1/3}\) exceeds 0.3 \(\text{m}^{2/3}\text{s}^{-1}\) at 1.5 and 2.5 nautical miles from the western end of the north runway. This is generally consistent with the pilot report.

The second case is a severe turbulence report on 3 August 2006 when Typhoon Prapiroon over the northern part of South China Sea brought gale force winds to HKIA. At 04:06 UTC, an aircraft (A333) arriving at the north runway from the west reported the encountering of “severe turbulence on approach”. The winds in the airport area were very much disturbed due to gustiness of the typhoon winds and airflow disruption by Lantau terrain, as observed in the LIDAR velocity image (Figure 3(a)). The turbulence intensity distribution and profile over the arrival corridor to the west of the north runway are shown in Figure 3(b) and (c) respectively. The EDR\(^{1/3}\) was quite uniform beyond 1 nautical mile from the runway. But it had an increasing trend going from 1 nautical mile to the runway end where the value exceeded 0.5 \(\text{m}^{2/3}\text{s}^{-1}\). The result is consistent with the pilot report.

SUMMARY

The use of glide-path scan data of the LIDAR at HKIA to calculate turbulence intensity distribution is presented in this paper. To minimize azimuthal averaging up to a range of 10 km for turbulence calculation, the laser beam is configured to scan at a rather slow speed of 0.8 degrees/s. As the LIDAR is required to perform other scans for operational applications, the slow scan and thus turbulence intensity calculation is only performed over the runway corridor to the west of the north runway, where most of the aircraft approaches are made. Two methods of determining turbulence intensity are considered, namely, the longitudinal and the azimuthal structure functions. They are found to provide comparable values of EDR\(^{1/3}\).

The application of the turbulence intensity determined along the glide path is demonstrated using two examples of turbulence encounter by the pilots. The LIDAR-determined turbulence intensities are found to be generally consistent with the pilot reports. Future study would include the comparison of EDR\(^{1/3}\) values derived from the LIDAR and the flight data recorder (FDR) data of the aircraft. The methodology presented in this paper has the potential for application in turbulence alerting at the airport.

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REFERENCES

Figure 2  The 1-degree PPI velocity image from the LIDAR (a) at about the time of the pilot report of moderate turbulence on 25 April 2006. The EDR$^{1/3}$ distribution and profile at the arrival glide path to the west of the runway north of HKIA are shown in (b) and (c) respectively.

Figure 3  Similar to Figure 2, but for the severe turbulence case on 3 August 2006.