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AIRCRAFT WAKE VORTEX MEASUREMENT WITH COHERENT DOPPLER LIDAR

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ABSTRACT

Aircraft vortices are generated by the lift-producing surfaces of the aircraft. The variability of near-surface conditions can change the drop rate and cause the cell of the wake vortex to twist and contort unpredictably. The pulsed Coherent Doppler Lidar Detection and Ranging is an indispensable access to real aircraft vortices behavior which transmitting a laser beam and detecting the radiation backscattered by atmospheric aerosol particles. Experiments for Coherent Doppler Lidar measurement of aircraft wake vortices has been successfully carried out at the Beijing Capital International Airport (BCIA). In this paper, the authors discuss the Lidar system, the observation modes carried out in the measurements at BCIA and the characteristics of vortices.

1. INTRODUCTION

Wake vortices are generated by the lift-producing surfaces of the aircraft[1]. The lifting surfaces of all aircraft produce wake vortices to some extent[2,4]. The vortex created by a large aircraft can have a catastrophic effect on a small airplane following closely behind[3].The variability of near-surface conditions (temperature, humidity, wind shear, etc.) can change the drop rate and cause the vortex cell to twist and contort unpredictably[4]. Wake Vortex behaviors very close to the ground have very complex causes that could change abruptly and need for real time monitoring[5].

The CDL(Coherent Doppler Lidar) system is a useful tool that can measure wind, turbulence, aircraft wake vortices, and so forth[5-10].The pulsed Coherent Doppler Lidar Detection and Ranging is an indispensable access to real aircraft vortices behavior which transmitting a laser beam and detecting the radiation backscattered by atmospheric aerosol particles[11]. The Line-Of-Sight (LOS) velocity component of the air motion could get by analyzing the Doppler shift in the frequency of the backscattered signal[12]. From the LOS velocities and the broadening process of the backscattering spectrum the characteristic of the aircraft vortices can be deduced.

The pulsed CDL system (Fig.1) is based on all-fiber laser technology and fast digital signal processing technology. The laser equipped in the CDL system is 1.5-μm eye-safe fiber laser which has an adjustable pulse length of 100ns to 800 ns and a pulse repetition frequency of 10 kHz. The measurement range of the CDL system is ±50m/s, while the speed measurement uncertainty is 0.1 m/s. The scanner and detection range of 3000m enable the system to detect the aircraft wake vortices. The fiber-based optical circuit works stable even under vibrating environment and temperature variation. The Fast Fourier Transform (FFT) spectral estimates are processed with FPGA in real time. All these design of the pulsed CDL system make it stable, reliable and high-integrated [13].

2. METHODOLOGY

Fig.1. the Coherent Doppler Lidar at BICA airport

The OUC Lidar team developed and carried out aircraft wake vortex field observation on the final approach to test out the performance of LOS velocity measurement in RHI (Range Height Indicator) and in ATOM (Along Track Observation Mode) configurations.

For tracking the wake vortices of a landing aircraft in RHI mode, the laser beam scanned in a plane perpendicular to the flight path of the aircraft. Fig. 2 shows the transverse observation mode of the pulsed coherent Doppler Lidar. However, the spatial precision of wake vortex core is limited due to the pulse duration and the data sampling rate.

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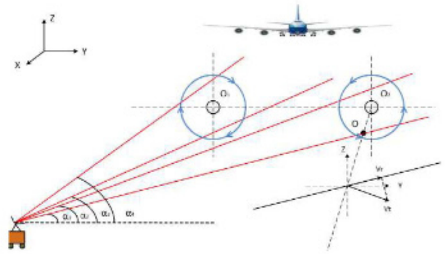

Fig.2. Transverse Observation Mode by Lidar.

In the axial detection or so-called ATOM setup, the Lidar was installed below the taking-off/landing slope in front of the runway. The aircraft were flying towards the Lidar beam passing the detection volume. The Lidar made a number of scan measurements to form a probing area covering the wake vortex corridors. (As shown in Fig.3)ATOM was designed to evaluate the feasibility of improving the localization accuracy of the vortex core.

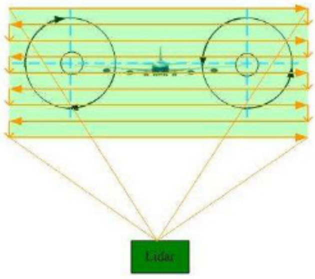

Fig. 3. Along Track Observation Mode (ATOM).

3. RESULTS

During the trial field test, a simple Doppler spectrum subtract method was applied to confirm the Doppler broadening behavior by wake vortex and to define an initial architecture which has been adopted in the BICA field experiment.

For each elevation angle in a scan measurement, Lidar obtained range-resolved signal with a resolution of 30 m. In each spatial sampling point, the backscattered signal is detected and spectrum is then calculated by a Fourier Transform.Fig.4 shows the frequency spectrum of one range bin with a LOS pointing through the vortex in core vicinity. It consists of three adjacent elevations. The blue plot shows a symmetrical and Gaussian-like spectrum from background wind, whereas the red and green plot indicate the spectral broadening up to around 10 point, approximately 10 MHz due to the wake vortices when Lidar probe beam cross the fraction of it. The difference between each two adjacent plots (shown as magenta and olive dashed line) had a zero-crossing pattern which could be used to locate the vortex.

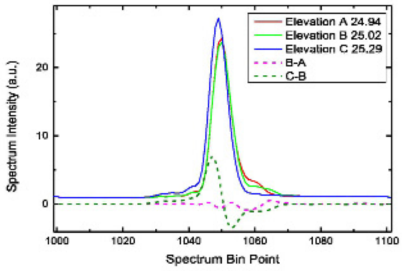

Fig.4. Power spectrum from three adjacent elevation scan in one range bin.

In the Lidar scan patterns such as Fig.5, the red and blue colors indicate positive (away from Lidar) and negative (towards Lidar) movement of the air mass along the laser beam, respectively. It should be noted that the color of the plot is the volume speed of the detected air mass. If there is no wake vortex generated, the color indicates the background atmospheric wind speed projection on the direction of laser beam. If there is wake vortex, the color shows the weighted sum of wake vortex and background wind, which means the color is shifted by the wake vortex, so the wake vortex could be extracted from the background.

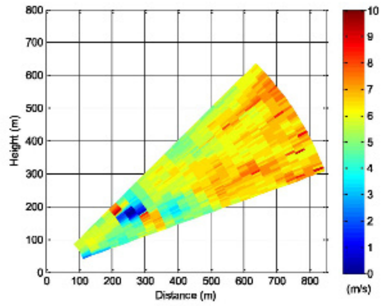

Fig.5. Volume averaged LOS velocity shows positive and negative velocity pattern of vortices.

Fig.5 shows the volume averaged LOS velocity, from which a pair of wake vortices were observed with characteristics of positive and negative velocity pattern at a height of about 200 m and a horizontal distance of 200m to 300m. The color inside the vortex region has a physical meaning of averaged tangential speed in one detection volume. The center of the pair of positive and negative velocity shows the core position of each wake vortex.

In order to investigate the characteristics of wake vortex, the envelopes of both positive and negative

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velocity have to be extracted. To obtain the envelope representing the sum of the tangential velocity of the vortex and the radial wind velocity, the threshold has to be chosen in accordance with the measured Doppler spectrum.

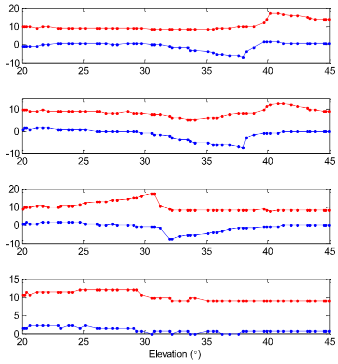

Fig.6. Envelops of velocity along elevation within 9-12 (from top to bottom) range bins. The red and blue curves show the maximum and minimum velocities in each bin.

Fig.6 shows the velocity envelops along four range bins where wake vortices can be captured. The characteristics of a pair of wake vortices can be found in the top figure (bin 9) with elevation around 39 and in the third figure (bin 12) with elevation around 31.In addition, time dependence of the vortex circulation can be achieved as shown in Fig.7.

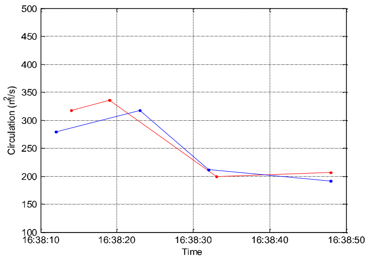

Fig.7. Circulation of a pair of vortices.

As the vortices usually move downwards, an ascending laser beam scan with increasing elevation goes across the pair of vortices faster, which means the vortices are compressed. So the detected radiuses of the vortices are less than their real values. Consequently, the value of vortex circulation is underestimated. On the contrary, when the Lidar scans downwards in a descending scan, the feature of the vortices are expanded and the vortex circulation is overestimated.

Since the movement of the core position can be obtained by a series of descending and ascending scans, the trajectory and speed of vortices can be estimated. Consequently, this information can be used to correct the expanded wake vortex to obtain its exact dimension and circulation. Fig.8 shows the corrected distribution of vortex velocity with radial distance.

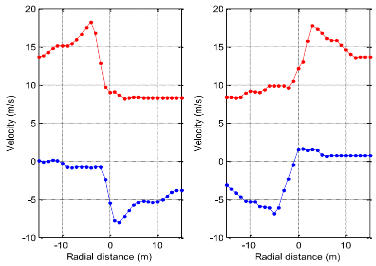

Fig.8. Corrected velocity envelops around vortices core.

Consequently, the time series of the circulation can be calculated from the corrected velocity distribution as shown in Fig.9 Compared to Fig.7, the expansion and compression of circulation value due to alternate scanning direction was calibrated.

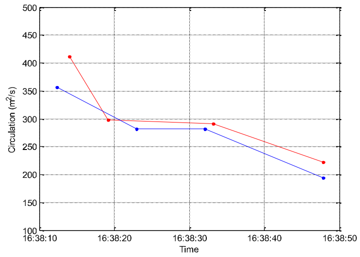

Fig.9. Circulation after scanning effect calibration.

In the ATOM, for tracking the wake vortices of a landing aircraft, the laser beam scanned in a volume along the flight path of the aircraft. To find out the feature of wake vortex, quick-look figures of radical velocity and spectrum widening were generated by processing all data measured in ATOM. Compared to the spectrum of background wind, the intensity of wake vortex is weaker. The wake vortex will generate Doppler frequency shift and extend the width of frequency spectrum. Fig.10 shows the LOS velocity and velocity dispersion measured in ATOM.

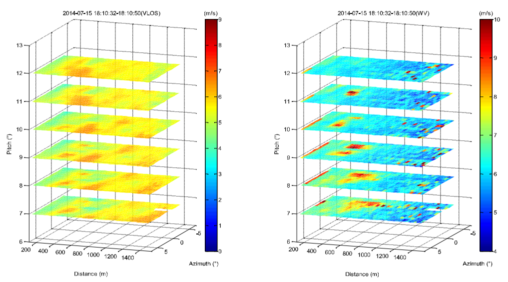

Fig.10. LOS velocity (left) and velocity dispersion (right) measured by Along-Track-Observation-Mode.

For each aircraft flew over, a time series of LOS velocity and velocity dispersion volume scans can be obtained by Lidar system. Analyzing the velocity dispersion is an indispensable access to study the evolution of the wake vortices generated by aircraft.

4. CONCLUSIONS

Wake vortex in clear air can only be derived from Lidar measurements up to now. It is possible to detect the wake vortices generated by aircraft as a consequence of lift with different Lidar observation mode. From series of field tests at BCIA and TAO, our research team estimated the circulation, the position of wake vortex core and the velocity dispersion.

The indispensable access to real wake vortex behavior is provided by Lidar measurement that traces full-scale wake vortices in the free atmosphere. The paper shows that the 1.5-μm pulsed CDL is a practical tool for aircraft wake vortex research. The system can detect the intensity of wake vortex which has impact on setting efficient interval and securing the lifting aircraft.

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