Investigation of feasibilities of aircraft wake vortex measurement by a low-energy 1.5-micron pulsed coherent Doppler lidar

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Abstract: In this work the feasibilities of the extraction of information about aircraft wake vortices from data measured by a low-energy 1.5-micron pulsed coherent Doppler lidar (PCDL) are investigated. A strategy of measurement by such lidar at airfield of an airport has been developed and the conditions of applicability of the lidar for wake vortex measurement have been determined. The applicability of the 1.5-micron Stream Line PCDL for measurements of the wake vortices generated by a landing aircraft has been demonstrated in the experiments carried out at the airfield of the Tolmachevo Airport. We estimated parameters of the wake vortices for aircrafts of various types, including Boing-747 cargo aircraft.

Keywords: Coherent Doppler lidar, aircraft wake vortex

1. Introduction

Investigation of aircraft wake vortices is important for development of the flight safety systems. A 2-μm pulsed coherent Doppler lidar [1] with the pulse energy of 2 mJ is used most widely for the measurement of aircraft wake vortices [2]. Relatively large pulse energy of this lidar provides a sufficiently high signal-to-noise ratio (SNR) at ranges up to 2-3 km. In contrast to this lidar, the energy of the probing pulse of a low-energy 1.5-micron PCDL is 100 or more times be lower.

The method of velocity envelopes for estimation of parameters of aircraft wake vortices [2] can not be applied in the case of 1.5-micron PCDL, because too low SNR that is usually realized in practice. As shown by numerical simulations and field experiment with the use of the 1.5-micron Stream Line PCDL (made by HALO Photonics, [3]) with a pulse energy of $14\,\mu\text{J}$, the radial velocity method [4,5] allows us to obtain information about the aircraft vortices, under certain conditions. This paper is devoted to the study of feasibilities of the aircraft vortex measurement by this lidar. Results of estimation of coordinates of the wake vortex axis and the vortex circulation from raw data measured by the Stream Line lidar at airfield of the Tolmachevo airport are presented.

2. Measurement strategy and estimation of wake vortex parameters

The Stream Line lidar can be used to study the spatial dynamics and evolution of wake vortices generated by a landing aircraft at height of no more than 70 m [5]. During the measurement, the scanning by the probing beam in the vertical plane perpendicular to the runway is used, alternately increasing and decreasing the elevation angle φ within the scan sector $[0°, \varphi_{\max}]$. The distance between the lidar and the runway should be about 300 m. The probing beam is focused at 300 m to increase the SNR. The most optimal are the following parameters of measurement and lidar data processing: angular speed of the scanning is $2°s^{-1}$, $\varphi_{\max} = 20°$ (10 s for one scan), and number of pulses used for the data accumulation equals 1500 (for the Stream Line lidar the measurement duration is 0.1 s). From obtained array of the correlation functions of the complex lidar signal the Doppler spectra are calculated and then the radial velocities $V_r(R_k,\varphi_m;n')$ are estimated, where $R_k = R_0 + k\Delta R$ is the range; ΔR = 3 m, $0° \le \varphi_m \le \varphi_{\max}$; $k,m = 0,1,2,3,...$; and n' is the scan number.

Let from the scan number $n' = n_0 + 1$ and to $n' = n_0 + N$ the array of lidar estimates of the radial velocity contain the information about wake vortices. To avoid the influence of the background wind, we obtain the array $V_r'(R_k,\varphi_m;n) = V_r(R_k,\varphi_m;n_0+n) - V_r(R_k,\varphi_m;n_0)$, where $n = n' - n_0 = 1, 2, ..., N$. To obtain estimates of the distance from the lidar to the axis of i-th vortex $R_{Ci}(t_{ni})$, angular coordinate of the axis $\varphi_{Ci}(t_{ni})$, and the vortex circulation $\Gamma_i(t_{ni})$ from the array $V_r'(R_k,\varphi_m;n)$ (indexes $i=1$ for left and $i=2$ for right vortex, t_{ni} is time after over-flight or vortex age) we use the method of radial velocities. Detailed description of this method is given in [4,5].

Using numerical simulation, we calculated the error of estimation of vortex parameters at various SNR and found that acceptable accuracy is possible under the condition: $\mathrm{SNR} \ge 0.04$. But in the simulation we did not take into account that the wind is not homogeneous, aircraft wake vortices move, and the Earth's surface can significantly influence on the spatial dynamics and evolution of wake vortices. Therefore, to fully investigate the feasibilities of lidar sensing aircraft vortices it is necessary a field experiment.

3. Experiment

We carried out first measurements of aircraft wake vortices by the Stream Line lidar at the airfield of the Tomsk Airport in 2014 and obtained results only for a few B737-8 aircrafts [4].

Figure 1. During the experiment at the airfield of the Tolmachevo Airport.

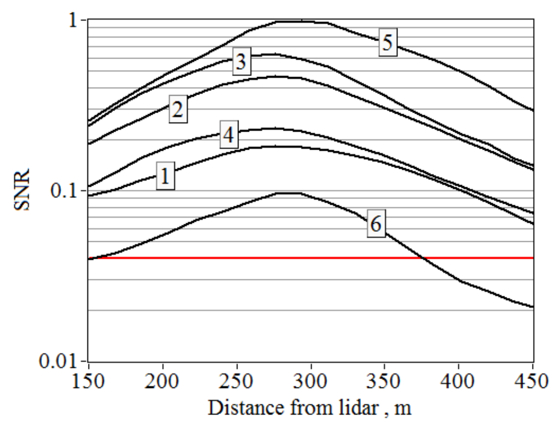

Figure 2. SNR versus range at time moments, when B747 aircrafts crossed the scanning plane.

From 4-th to 6-th May 2016, we conducted an experiment with the Stream Line PCDL at the airfield of the Tolmachevo Airport (near Novosibirsk city). Continuous lidar measurements (see Figure 1) were carried out from 18:00 to 21:00 on May 4, from 00:00 to 13:00 on May 5, and from 00:00 to 10:00 on May 6. During all measurements the weather was always clear without a single cloud. During the day the temperature varied from 12° to 18° above zero, at night and early morning temperatures dropped to 0°. The SNR and the lateral wind velocity V are important factors for lidar observations. For example, if $|V| >$ 5 m/s, the wake vortices can be observed not longer than 30 s (3 scans) at distances R_k from 150 to 450 m. In this experiment, the velocity $|V|$ did not exceed 4 m/s.

The minimum distance between the lidar and a line along the runway was 285 meters. Landing aircrafts crossed the scanning plane at a height of 50 m. During our measurements 44 aircrafts of different types (A319, A320, A321, B737-8, B767, B747-4, B747-8 and a few smaller aircrafts) crossed the scanning plane. Large cargo aircrafts B747 generate very powerful wake vortices.

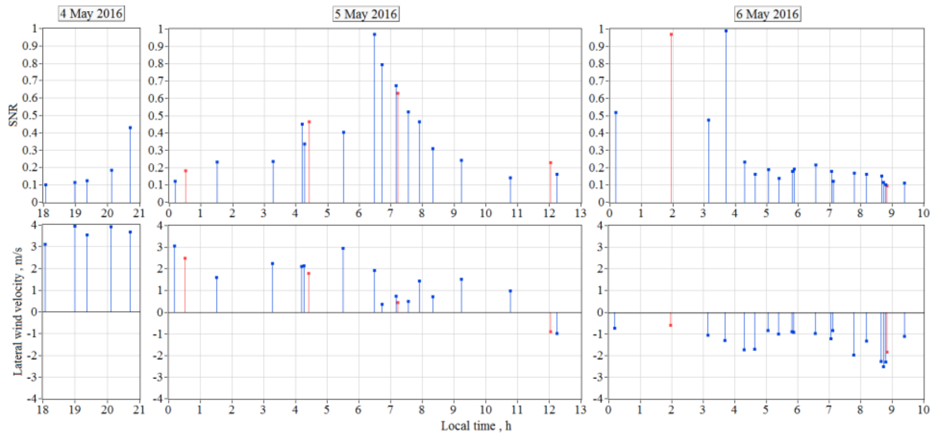

Figure 3. Maximum SNRs and lateral wind velocities at time moments of crossing the scanning plane by B747 cargo aircrafts (red squares) and other aircrafts (blue squares).

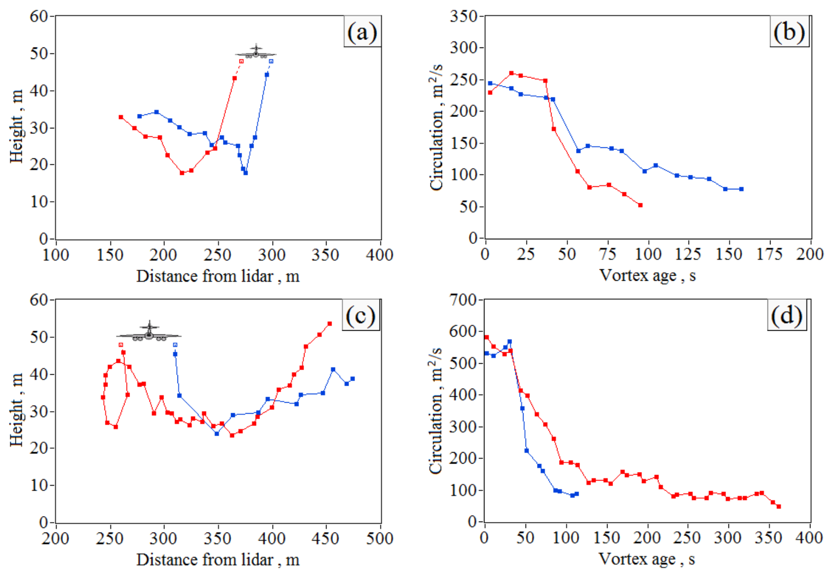

Figure 4. Trajectories of cores (a, c) and circulations (b, d) of wake vortices generated by A320 (a, b) and B747-4 (c, d) aircrafts.

Figure 2 shows 6 profiles of signal-to-noise ratio (data averaged in the interval of φ_m from 5° to 10°), which took place during the observation of vortices generated by B747 aircrafts. It is seen that the maximum signal-to-noise ratio $\mathrm{SNR}_{\max}$ varies from 0.1 to 1. Curve 6 is below the threshold level of 0.04 (red line) at ranges R_k > 370 m. Figure 3 shows $\mathrm{SNR}_{\max}$ and V (if $V > 0$, the lateral wind is directed from the lidar) during our experiment.

Figure 4 shows two examples of vortex core trajectories and vortex circulation versus time, when $\mathrm{SNR}_{\max}$ = 0.5, V = -0.8 m/s (a, b) and $\mathrm{SNR}_{\max}$ = 0.63, V = 0.4 m/s (c, d). Weak lateral wind and a rather high signal-to-noise ratio allow us to observe left wake vortex up to 6 minutes in the case of B747-4 aircraft.

According to theory [7], the initial separation between the axes of the right and left vortex b_0 is determined as $b_0 = (\pi/4)B_A$, where B_A is the aircraft wingspan. Our comparison of experimental (for vortex age not more than 15 seconds) and theoretical values of the b_0 found them almost a full match for all types of aircraft listed above.

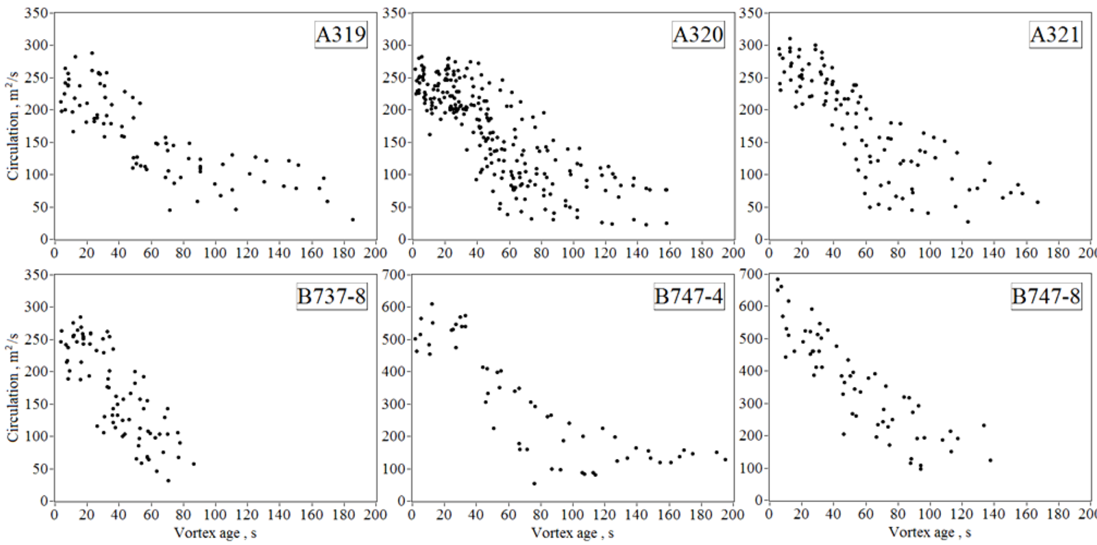

Figure 5. All lidar estimates of the circulation of wake vortices generated by airliners: A319 (5 over-flights), A320 (15 over-flights), A321 (6 over-flights), B737-8 (6 over-flights) and cargo aircrafts: B747-4 (2 over-flights), B747-8 (4 over-flights). These estimates have been obtained from data measured by the Stream Line lidar at the airfield of the Tolmachevo Airport from 4 to 6 May 2016.

Figure 5 shows all the results that we obtained from the lidar measurements in Tolmachevo, for the wake vortex circulation. Using the data of this figure we averaged estimates all circulation in the time interval from 0 to 30 s for each type of aircraft. Comparison of average values of the circulation with the results of calculations by the theoretical equation for the initial circulation [7] $\Gamma_0 = M_A g / (\rho_a b_0 V_A)$, where M_A is the aircraft mass, g is the freefall acceleration, ρ_a is the air density, and V_A is the true speed of the aircraft, yielded similar values.

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4. References

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