29th Congress of the International Council
of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

WAKE VORTEX OBSERVATION CAMPAIGN BY ULTRA FAST-SCANNING LIDAR IN NARITA AIRPORT, JAPAN

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Keywords: *Wake vortex, lidar, and ultra fast-scanning*

Abstract

The Japan Aerospace Exploration Agency (JAXA) is conducting a wake vortex observation campaign at Narita airport, Japan in order to evaluate the probabilistic properties of wake vortex behaviors. Based on the probabilistic properties derived from a large number of observation data, the current safe wake vortex separation minima can be revised and airport capacity is increased without any loss of safety. In our observation campaign, an ultra fast-scanning lidar is used to obtain a large number of wake vortex behaviors with high accuracy and temporal resolution. This paper presents an overview of our observation campaign, collected data, and initial analyses.

1 Introduction

Air traffic demand is increasing worldwide, and there is an urgent need to increase airport capacities, especially for airports serving metropolitan areas. Airport capacity, that is the number takeoffs and landings, can be increased by reducing the distances between two adjacent aircrafts, and revising the current wake vortex separation minima is recognized as an effective measure to achieve this. The International Civil Aviation Organization (ICAO) launched the Wake Turbulence Study Group (WTSG) aiming to revise the aircraft wake vortex separation rules, and the Japan Civil Aviation Bureau (JCAB) is also promoting research and development on this topic in its long-term air traffic management modernization plan, Collaborative Actions for Renovation of Air Traffic Systems (CARATS).

Table 1 ICAO safe separation minima

Leading aircraft	Following aircraft			
	A380	heavy	medium	light
A380	-	6 nm	7 nm	8 nm
heavy	-	4 nm	5 nm	6 nm
medium	-	-	-	5 nm
light	-	-	-	-

As is well known, a wake vortex produced by a leading aircraft is a potential hazard to a following aircraft that flies into it. To avoid such wake vortex encounters, wake vortex separation minima of 4–8 nm between a leading and a following aircraft, which are greater than the radar separation minima of 2.5–3 nm, are utilized (see Table 1.) Although Computational Fluid Dynamics (CFD) analyses and remote sensor observations have indicated that wake vortex persistence varies greatly depending on weather conditions, the current wake vortex separation standards assume the longest wake vortex persistence times regardless of weather conditions and so can be overly conservative. However, in order to reduce aircraft separation distances without any loss of safety, it is important to understand the behaviors of wake vortices in various places and weather conditions, and to provide predicted or observed information in real-time [1], [2], [3], [4], [5].

The Japan Aerospace Exploration Agency (JAXA) is developing a Wake Vortex Advisory System (WVAS) which computes reduced separations according to weather conditions and aircraft wake turbulence categories to realize dynamic wake vortex separation. Because the deformation and transport of a wake vortex are uncertain processes, WVAS applies a

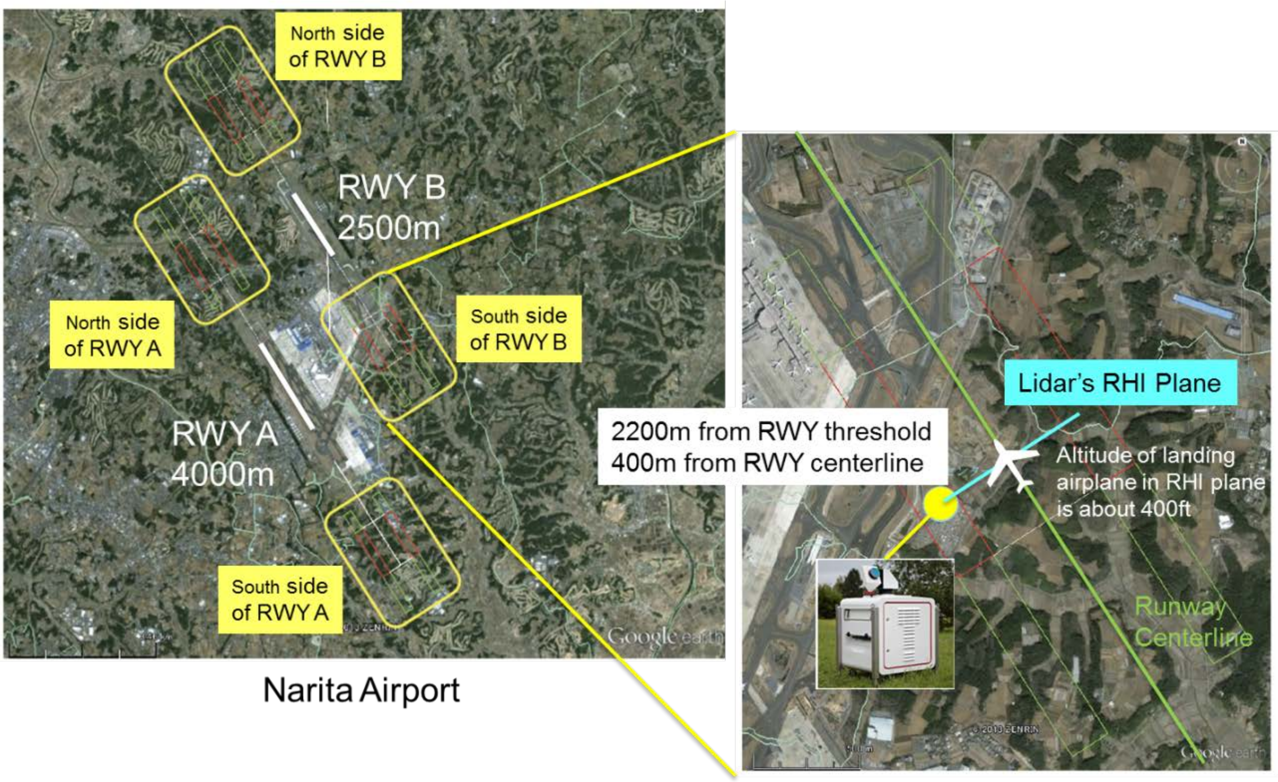

Figure 1 Observation site

probabilistic prediction model that complicate complex phenomena including wake vortex decay, advection, and rebounding processes. In contrast to a deterministic approach such as [6], the probabilistic outputs of the wake vortex prediction can be utilized to assure that the risk of a wake vortex encounter at the reduced separation does not exceed the risk of the current separation standard, which is considered acceptable. This probabilistic characteristic of the wake vortex prediction can be reliably established from a comparison of lidar observations with deterministic predictions for a large number of samples.

This paper describes JAXA's wake vortex observation campaign at Narita airport, Japan, which is being conducted to establish the probabilistic properties of the WVAS wake vortex prediction model. Wake vortex behaviors, that is, time histories of wake vortex physical parameters, are estimated from lidar measurements. An ultra-fast scanning lidar is used in order to obtain a large number of observation samples and to estimate the wake vortex parameters accurately. To establish the probabilistic properties of the wake vortex prediction, the wake vortex parameters are normalized by deterministic wake vortex predictions of D2P and P2P envelopes provided with corresponding flight and weather data which are simultaneously acquired during the observation campaign.

Section 2 of this paper presents an overview of our observation campaign. In Section 3 gives details of the specifications of the ultra fast-scanning lidar, the observation mode, and observed data, and describes the flight and weather data inputs to the prediction models. Section 4 shows initial analyses of the probabilistic property. Section 5 concludes this paper.

2 Observation Campaign in Narita Airport

The observation sites around Narita Airport are shown in Figure 1. Narita airport has two runways, the 4,000 m-long 'A' runway and the 2,500 m-long 'B' runway. Wake vortices are measured using an ultra fast-scanning lidar (Leosphere WINDCUBE 200S) operating in rapid Range Height Indicator (RHI) mode. The observation campaign is mainly focused on

Table 2 Lidar specifications

Lidar	
Type	Pulsed-Doppler
Wavelength	1543 nm
Physical range resolution	25, 50, 75, and 100 m
Range gate interval	1 m (minimum) with range overlapping
Number of range gates	240 (max)
Azimuth angle	0 – 360 deg
Elevation angle	-10 – 190 deg
Angular resolution	0.1 deg
Pointing accuracy	0.1 deg
Radial wind speed	-30 – 30 m/sec
Measurements	CNR, radial velocity, velocity dispersion, Doppler spectrum, range, gazing angle, and time.
Observation modes	Plan Positioning Indicator (PPI), Range Height Indicator (RHI), Doppler Beam Swinging (DBS), and Line Of Site (LOS)
Weight	232 kg
Size (H-W-D)	1365-1008-814 mm
Power consumption	500 – 1600 W
Rapid RHI	
Range sampling	Every 5 m from 100 – 885 m for landing aircrafts, and from 200 – 985 for take-off aircrafts
Physical range resolution	About 50 m
Elevation sampling	Every 0.2 deg from 0 – 40 deg for landing aircrafts, and from 20 – 60 deg for take-off aircrafts
Velocity sampling	Every 3 m/sec from -30 – 30 m/sec
Pulse repetition	18,000 Hz
Number of accumulated pulses	600
Scan duration	6.7 sec (+2 sec to reset scanner head)

wake vortices at low altitudes generated by aircraft landing on RWY B to learn about the complex wake vortex behaviors due to ground effect. The lidar is therefore installed approximately 2200 m from the runway B threshold and 400 m laterally displaced from its centerline. Landing aircraft pass through the RHI plane orthogonal to the centerline at a height of 400 ft. To obtain wake vortex behaviors in the weather conditions of all four seasons, a ten-month observation term is planned from November 2013 to August 2014. We plan to obtain at least 3,000 samples of wake vortex behaviors of at least one minute duration along with data of the weather conditions. The data sets obtained in this campaign are described in the following subsections.

2.1 Lidar Data

The specifications of the lidar and its rapid RHI mode are shown in Table 2. The lidar radiates 1543 nm-laser pulses with a physical length of almost 50 m. These emitted pulses are scattered by aerosols flowing with air, and backscattered light is received and digitally sampled. For each direction, sample data of 600 pulses at a pulse repetition frequency of 18 kHz are processed and accumulated, and measurements of Carrier-to-Noise Ratio (CNR), mean radial velocity, velocity dispersion, and Doppler spectrum are output for each 5 m range bins to a distance of nearly 900 m. In each RHI plane, range profiles are obtained at elevation angles up 40 deg in 0.2 deg increments. Measurements are stored in the lidar storage with a time stamp and position (range, azimuth, and elevation). The scan duration for one RHI is 6.7 sec, and almost a further two seconds are needed to return the scanner head to the initial position of the RHI for the next scan.

Due to the rapid RHI scan rate, the temporal changes of a wake vortex during one RHI scan are almost negligible, and many of the 2-D structures are obtained with a short time step. Figure 2 shows an example of a measured mean radial velocity field plotted on the RHI plane. This measurement was acquired about 6 sec after a Boeing 777 passed through the RHI plane. Two pairs of positive and negative velocities appear at a range of approximately 400 m and a height of approximately 150 m. The wake vortex parameters—range, height, and circulation—are calculated by JAXA's wake vortex estimation algorithm which is designed to extract spatial structures of wake vortices much smaller (about ten times) than the lidar physical resolution of 50 m from the Doppler spectra by assuming a fixed vortex

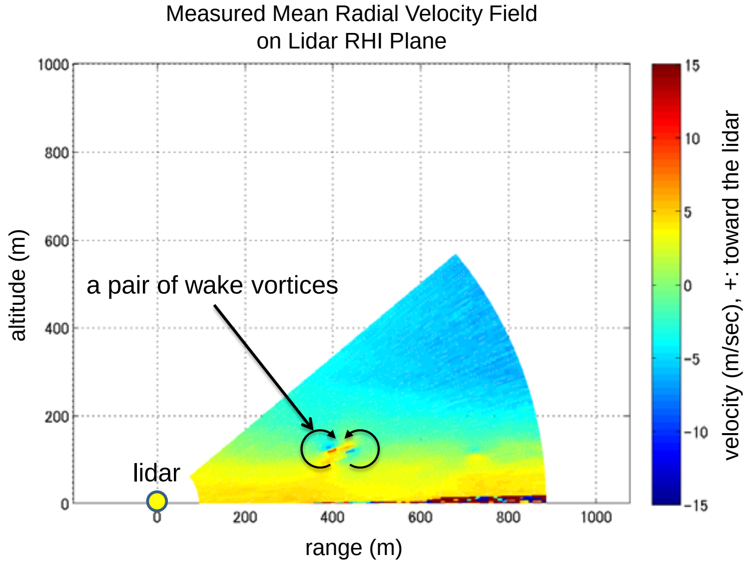

Figure 2 An example of observed wake vortices on the RHI plane

model. Details of the algorithm are presented in another of our papers at this conference, “Detection and Estimation of Wake Vortex on Ultra Fast-Scanning Pulsed-Doppler Lidar”.

2.2 Flight Data

The times at which aircraft pass through the RHI plane are determined using video recordings from co-located cameras which are exactly directed to the RHI plane and time-synchronized with the lidar by NTP (Network Time Protocol). Aircraft types are determined using the video recordings and airport departure and arrival records. Other flight parameters are obtained from recorded Automatic Dependent Surveillance-Broadcast (ADS-B) signals and data from aircraft Quick Access Recorders (QAR) provided by airlines.

Table 3 lists the flight data parameters obtained in this study. Data from the ADS-B recorder (Kinetic Avionics SBS-3) include position and horizontal/vertical path angle. Airspeed, which is not determined solely from the ADS-B data, is estimated using additional wind information from acquired weather data (see the next subsection.) Aircraft weight is statistically estimated by taking into account the aircraft model and flight route. QAR data obtained for some of the flights include all these parameters taken from aircraft on-board systems.

Table 3 Flight data

Data	Source
Aircraft model	Video camera, and record of departures and arrivals
Time	Video camera (NTP synchronized)
Position and horizontal and vertical path angles	ADS-B or QAR
Airspeed and roll angle	ADS-B (with wind data from weather data), or QAR
Weight	Statistical value or QAR

2.3 Weather Data

Since a wake vortex generally moves

Table 4 Specifications of the numerical weather analysis system

Meteorological model	CReSS, version 3.41
Computational area	200 x 200 km (horizontal), 16 km (vertical)
Grid size	500 x 500 m (horizontal), 200 m (> 2 km) and 50 m (< 2 km) (vertical)
Number of grids	403 x 403 (horizontal), 83 (vertical)
Temporal step	2.0 and 0.5 sec
Initial and boundary conditions	JMA’s* Meso-Scale Model and sea surface temperature
Data assimilation	JMA* Doppler weather radar

*Japan Meteorological Agency

downward due to self-induced airflow, weather data are required from ground level up to the height of the generating aircraft. These weather data are obtained and derived from a numerical weather analysis system, QAR data, and lidar data.

Specifications of the numerical weather analysis system are shown in Table 4. The system is based on a numerical meteorological model developed by Nagoya university, the Cloud Resolving Storm Simulator (CReSS) [7], modified to output parameters necessary for wake vortex prediction including Brunt–Väisälä frequency, wind speed and direction, Eddy Dissipation Rate (EDR), and turbulence intensity. The computational area is 200 x 200 x 16 km covering the terminal traffic area of Narita airport with a grid size of 500 x 500 x 200 m. In the lowest 2 km, the vertical axis is further gridded at 50 m intervals.

Weather data are also obtained from observation data such as QAR data and lidar measurements. Brunt–Väisälä frequency is calculated from atmospheric pressure and temperature included in QAR data, which also contains wind speed and direction. The lidar is periodically operated in the DBS mode [8] to obtain vertical profiles of wind speed and direction, which additionally derives EDR and turbulence intensity. The weather data and their sources are summarized in Table 5.

Table 5 Weather data

Data	Source
Brunt–Väisälä frequency	The numerical weather analysis system or QAR
Wind speed and direction	The numerical weather analysis system, QAR, or lidar
Eddy Dissipation Rate (EDR)	
Turbulence intensity	

3 Analyses

Initial analyses were carried out with data obtained between November 2013 and February 2014. About 600 wake vortex behaviors longer than 60 sec are extracted and analyzed using flight and weather data derived from QAR recordings.

An example of observed wake vortex behaviors is shown in Figure 3. The upper left and upper right plots show time histories of circulation and normalized circulation,

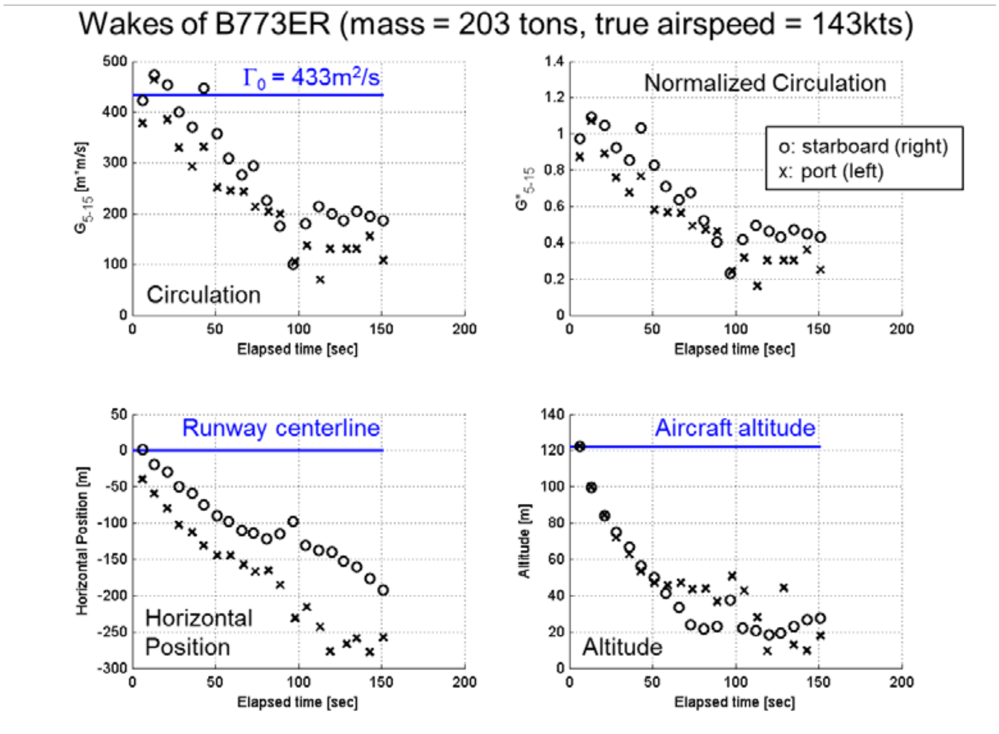

Figure 3 An example of comparison of a pair of wake vortex behaviors

respectively. In this paper, circulation means a radii-averaged circulation from 5 to 15 m from the center of a wake vortex. Circulations are normalized based on [1]. The lower left and lower right plots show horizontal range from the 'B' runway centerline and altitude. In each plot, circles and x symbols indicate lidar port and starboard wake vortices, respectively. In this case, a wake vortex behavior is traced up to about 150 sec elapsed time. In the first RHI, the lidar-estimated circulation is close to a reference theoretical value of 433 m^2/sec derived from the corresponding flight and weather data. From the generation of the vortex to its decay to a circulation of 100 – 200 m^2/sec after 100 sec elapsed, the wake vortex behavior is well resolved at the short time intervals of 8 sec. Horizontal range and altitude are also estimated with high temporal resolution. Comparing the parameter values estimated from lidar observations with the reference values derived from the corresponding flight and weather data during the first few tens of seconds, the standard deviations of the lidar-estimated parameters are 30.2–40.6 m^2/sec in circulation, 13.0–19.1 m in horizontal range, and 4.8–6.5 m in altitude.

Probabilistic properties of the wake vortex parameters are shown in Figure 4. The blue, green, and red lines correspond to circulation, horizontal range, and altitude, respectively. The vertical axis is probabilistic density. The horizontal axis is the parameter value normalized by two deterministic predictions, the D2P prediction and the upper and lower envelopes of the P2P prediction; that is, a value of 0.5 corresponds to the D2P prediction, and values of 1 and 0 correspond to the upper and lower envelopes of the P2P, respectively. These probabilistic properties are considered to be time-independent because time-variant wake behaviors should be compensated by normalization using wake predictions. The line of circulation is almost symmetrical and convex in shape, and is largely broadened compared to the other two parameters. Horizontal range indicates a sharp structure with the smallest absolute bias. In altitude, while there are many samples with negative biases, the highest probability appears at almost 0.5.

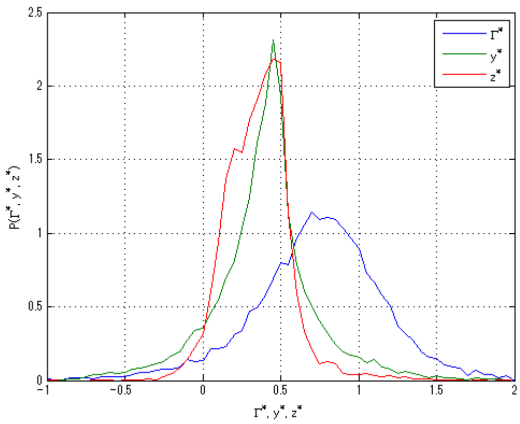

Figure 4 Probabilistic properties of the wake vortex parameters from November 2013 to February 2014.

These trends are similar to results of a previous study by F. Holzäpfel and M. Steen (see Fig. 15 of [6].) One major difference is that the property of circulation has a large bias of about 0.3. This probably means that either the wake parameter estimation algorithm for lidar data tends to overestimate circulation or that the observed wakes decay more slowly than predicted. Regarding the latter explanation, it is possible that the prediction settles into the rapid decay phase too early due to overestimated EDR inputs. Currently, the EDR inputs are estimated from QAR wind data. These EDR inputs will be examined by comparing with another EDR estimate derived from lidar data.

The other major difference is that dispersions of each probabilistic property shown by our observation are about two times larger than the previous research. Normalizing the standard deviations of the lidar-estimated parameters, the contributions of the estimation errors are about 0.32, 0.10, and 0.08 at most in circulation, horizontal range, and altitude, respectively. Because these normalized values are calculated by initial widths of P2P envelopes of 0.4, 4, and 2 in circulation, horizontal range, and altitude, respectively, the three normalized standard deviations are close to the possible maximum values of each. In circulation, the normalized standard deviation of 0.32 is comparable to width of the probabilistic density shown in Figure 4. Therefore, it seems that the contributions of errors from the estimation method are comparable to or greater than those from flight and weather data, and the estimation algorithm needs to be improved. On the other hand, the normalized standard deviations of horizontal range and altitude are smaller than those of the developed properties, and the contribution of errors from the estimation algorithm is small in these two parameters.

4 Conclusion

This paper introduces JAXA's wake vortex observation campaign at Narita airport, particularly its purpose, approach, data collection, and ongoing analyses. The probabilistic properties of wake vortex behaviors, which will be completed in this fiscal year, will be an important resource for later research to determine a new safe wake vortex separation standard. Of course, local characteristics of Narita airport which will be indicated by our database are important, especially in a practical sense. Moreover, it is very significant that the large number of observations will statistically improve wake vortex prediction. We are now pursuing the development of a large database through worldwide cooperation with Ultra-Fast wind sensOrs (UFO) project [9].

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