Wake Vortex Measurement Campaign towards Reduced Separation

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Outline

- Background, Objectives
- Wake Vortex Advisory System
- Wake Vortex Measurement Campaign
  - Measurement Setup
  - Measurement Result & Analysis
- Summary
Wake Vortex Separation Minima

- ICAO has defined STATIC wake vortex separation minima between aircraft according to their relative weights.
- Current ICAO separation minima are overly conservative, assuming the worst case.
- Wake vortex separation minima are a major impediment to airport capacity increase.
- Wake vortex life changes largely by weather condition.
- DYNAMIC separation minima according to weather conditions can be an effective solution for airport capacity increase.

Current ICAO separation minima

<table>
<thead>
<tr>
<th>Leader / Follower</th>
<th>Super (A380)</th>
<th>Heavy (≥136 tons)</th>
<th>Medium (≥7 tons)</th>
<th>Light (&lt;7 tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRS</td>
<td>6nm</td>
<td>4nm</td>
<td>MRS</td>
<td>MRS</td>
</tr>
<tr>
<td></td>
<td>7nm</td>
<td>5nm</td>
<td>MRS</td>
<td>MRS</td>
</tr>
<tr>
<td></td>
<td>8nm</td>
<td>6nm</td>
<td>MRS</td>
<td>MRS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MRS</td>
</tr>
</tbody>
</table>

MRS: Minimum Radar Separation (2.5-3nm)
Japan’s Plan to Introduce Reduced Wake Vortex Separation

- Japan Civil Aviation Bureau (JCAB) has compiled the long term vision of the future air traffic system named CARATS (Collaborative Actions for Renovation of Air Traffic System) in 2010. In CARATS, JCAB plans to introduce reduced wake vortex separation to increase traffic capacity as follows:
  1. Introduction of RECAT Phase 2 (2018-)
  2. Dynamic separation taking actual wind data or forecast into account (2022-)
  3. Apply actual wake vortex data or forecast from departure or arrival aircraft (2024-)

- JCAB has participated in ICAO wake turbulence study group (WTSG) from 2013 to support the standardization of the reduced wake vortex separation.
JAXA’s Research Objectives

Establish the following technologies to realize dynamic wake vortex separation:

- Wake Vortex Advisory System (WVAS): calculate safe separation according to surrounding weather condition and aircraft pairwise.
- Traffic Pattern Optimization System (TPOS): optimize separations, take-off/landing sequences, runway allocation and flight paths to increase capacity.

ENRI: Electronic Navigation Research Institute
IFS: Institute of Fluid Science, Tohoku Univ.
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Concept of Dynamic Separation

1. Define target level of wake vortex encounter (WVE) risk within current WVE risks.
   (Assumption: Current separations are practically safe)

2. Reduce separations until the expected risk level at the reduced separation reaches the target risk level, or the separation becomes limited by other constraints.

Reduced separations are acceptably safe as current separations.
To calculate WVE risk, we use probabilistic models that give probability density distributions (PDDs) of aircraft/wake parameters and hazard area model.

**Aircraft trajectory model**
Create JAXA original model based on actual radar track data of target airport and collision risk model (CRM) of ILS approach.

**Wake vortex prediction model**
Employ P2P model developed by DLR.

**Hazard area model**
Create JAXA original model based on flight simulation.

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**WVE Risk Calculation Procedures**

1. Divide regions of leading/following aircraft exist into small sections.
2. Calculate probability that wake shed from $RL_i$ exists within the hazard area of following aircraft that exists in $RF_j$ and the following aircraft also exists in $RF_j$.
3. Calculate probability that following aircraft encounters the wake shed from $RL_i$ by repeating the 2nd process for all $RF_j$.
4. Calculate WVE risk by repeating the 3rd process for all $RL_i$. 
**Example of WVE Risk Calculation**

- WVE risks vary largely by surrounding weather conditions.
  - We can reduce separation at favorable weather conditions.

- WVE risks increase at high altitude (>1500ft) and low altitude (<400ft).
  - GBAS-based curved approach and dual thresholds may be useful to decrease WVE risks.

![Diagram showing WVE risk calculation with altitude of following aircraft (ft) vs. WVE risk (Low risk to High risk)](image)

WVE risks in successive landings on RWY22 of Tokyo International airport (about 1000 different weather conditions, 2 minutes constant constant separation)
Mainly due to wake vortex prediction errors, the following risks ('hazard risk') exist:

- 'TRUE' WVE risks at reduced separations can exceed the target risk level.
- The target risk level can be too high compared to 'TRUE' WVE risks at current separations.

We propose to control 'hazard risk' by under/overestimating WVE risks considering wake vortex prediction errors.
How to control ‘hazard risk’?

1. Define confidence intervals of probability density distributions (PDDs) of wake vortex parameters to quantify wake vortex prediction errors.
2. **Underestimate** WVE risks at current separations using lower limits of PDD confidence interval.
3. **Overestimate** WVE risks at reduced separations using upper limits of PDD confidence interval.

\[ \text{‘Hazard risk’} = 1 - (1 - P_U)^3(1 - P_L)^3 < 3(P_U + P_L) \]

The WVAS probabilistically assures that the WVE risks at reduced separations do NOT exceed those at current separations.
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Wake Vortex Measurement

- JAXA conducted wake vortex measurement at Narita International Airport in Nov. 2013 – Aug. 2014 (140 days) to develop PDDs of wake vortex parameters.
- Wake vortices of aircraft in take-off / landing have been collected together with weather data and flight data (QAR, ADS-B).
Lidar Location

Narita International Airport

Lidar's RHI Plane
Altitude of landing airplane in RHI plane is about 400ft.

RWY B
2500m

RWY A
4000m

2200m from RWY B threshold
400m from RWY B centerline

Lidar

WINDCUBE 200S
Wake Data Acquisition

✔ Lidar
  • Windcube200S, Leosphere
  • Pulsed-Doppler Type
  • Wavelength: 1543 nm
  • Averaged power: 1W
  • Pulse Repetition: 20 kHz
  • Digital Sampling rate: 250 MHz
  • Measurement: CNR, radial velocity, velocity dispersion, Doppler spectrum, range, gazing angle, and time.

✔ Scanning Strategy
  • RHI: 0 – 40 deg for landing aircrafts
    (20 – 60 deg for take-off aircrafts)
  • Scan duration: 6 sec (+1-2 sec to reset)
  • Range sampling: Every 5 m; 100 – 885 m
    (physical range resolution: 48 m)
  • Elevation sampling: Every 0.2 deg
  • Velocity sampling: Every 3 m/sec; -30 – 30 m/sec
Wake Data Example – Lidar RHI Data

Lidar’s RHI Plane

Measured Mean Radial Velocity Field on Lidar RHI Plane

a pair of wake vortices

velocity (m/sec), + toward the lidar

range (m)

altitude (m)
Flight Data Acquisition

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft type</td>
<td>Video camera and records of departures and arrivals</td>
</tr>
<tr>
<td>Passing time</td>
<td>Video camera (NTP synchronized)</td>
</tr>
<tr>
<td>Position</td>
<td>QAR or ADS-B</td>
</tr>
<tr>
<td>Airspeed and roll angle</td>
<td>QAR or ADS-B (with wind data from weather data)</td>
</tr>
<tr>
<td>Weight</td>
<td>QAR or statistical value</td>
</tr>
</tbody>
</table>

- Timing of aircraft passing lidar’s RHI plane was determined by using recorded video image.
- Japan Airlines (JAL) provided QAR data.
Weather Data Acquisition

We derived weather parameters from observation data (lidar, flight data) and numerical weather analysis system.

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brunt–Väisälä frequency</td>
<td>Flight data (QAR) or numerical weather analysis system</td>
</tr>
<tr>
<td>Wind speed and direction</td>
<td>Flight data (QAR), Lidar (DBS) or numerical weather analysis system</td>
</tr>
<tr>
<td>Eddy Dissipation Rate (EDR)</td>
<td></td>
</tr>
<tr>
<td>Turbulence intensity</td>
<td></td>
</tr>
</tbody>
</table>

Numerical weather analysis system

- Meso-scale meteorological model (grid size 500m)
- Weather radar data assimilation
- Analysis error estimation according to weather condition (outputs specific PDDs of analysis error according to weather condition)

![Probability density]

- Analysis error of wind speed (m/s)
- Specific weather condition
- Overall

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

*CReSS: Cloud Resolving Storm Simulator developed by Nagoya University, Japan
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Wake Measurement Results

- 51836 wake data (mainly OGE) of 4189 aircraft in take-off / landing have been collected together with weather data and flight data (ADS-B).
- For 966 aircraft, detailed flight data (QAR) including weight & airspeed have also been collected thanks to the airline.
- By comparing lidar-measured and QAR-derived wake parameters, we estimated the accuracy of our wake measurement.

<table>
<thead>
<tr>
<th>Estimated Errors</th>
<th>Radii-averaged circulation, $\Gamma_0$ (m²/sec)</th>
<th>Horizontal range, $y$ (m)</th>
<th>Height, $z$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_{LDR}$ (bias)</td>
<td>13.3</td>
<td>-1.1</td>
<td>-1.7</td>
</tr>
<tr>
<td>$\sigma_{LDR}$ (random)</td>
<td>22.9</td>
<td>6.0</td>
<td>2.7</td>
</tr>
<tr>
<td>$\sigma_{QAR}$ (random)</td>
<td>17.3</td>
<td>2.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Wake estimation accuracy by our lidar and algorithm

Error in the theoretical equation, $\Gamma_0 = \frac{Mg}{psBV}$, including measurement error of QAR data
Example of Measured Wakes

Wakes of B773ER (mass = 203 tons, true airspeed = 143kts)

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**Circulation**

\[ \Gamma_0 = 433 \text{m}^2/\text{s} \]

**Normalized Circulation**

- o: starboard (right)
- x: port (left)

**Horizontal Position**

- Runway centerline
- Horizontal Position

**Altitude**

- Aircraft altitude
- Altitude

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Using 17404 wake data of 966 aircraft with detailed flight data (QAR), we developed the PDDs of wake parameters for P2P.

Large bias was found in circulation prediction.
- Too rapid decay in P2P
- Updating P2P with DLR support

Normalize measured data by P2P prediction (upper = 1, lower = 0)

Measured wakes
- o: starboard (right)
- x: port (left)

P2P upper/lower boundary
Verification of Reduced Separation

- WVAS calculated reduced separations for 3320 landings using weather prediction data and the developed PDDs of wake parameters.
- WVAS can reduce separations (no wake separations) for 1624 landings (49%) and no wake remained at the reduced separations.
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Summary

JAXA develops the following two technologies to realize reduced wake vortex separations:

- **Wake Vortex Advisory System (WVAS):** calculate safe separation according to surrounding weather condition and aircraft pairwise.
- **Traffic Pattern Optimization System (TPOS):** optimize separations, take-off/landing sequences, runway allocation and flight paths to increase capacity.

To validate and improve wake prediction model (P2P) used in WVAS, JAXA conducted wake vortex measurement campaign in Japan. 51836 wake data (mainly OGE) of 4189 aircraft in take-off/landing were acquired together with weather data and flight data of wake generators. Wake data supported the safety of reduced separation calculated by WVAS.

JAXA plans to improve WVAS using acquired wake data and to conduct additional wake vortex measurement campaign to acquire wake data in IGE.

JAXA is open to share acquired wake data and wake detection algorithm with international society.