Researches towards
Dynamic Wake Vortex Separation

Naoki Matayoshi and Eiichi Yoshikawa
Japan Aerospace Exploration Agency

WakeNet-Europe Workshop 2014
Outline

- Background, Objectives
- JAXA’s Research
  - Wake Vortex Advisory System
    - Wake Vortex Observation
  - Traffic Pattern Optimization System
- Expected Capacity Gain of WVAS
- 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.

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**Current ICAO separation minima**

<table>
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<tr>
<th>Leader / Follower</th>
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*MRS: Minimum Radar Separation*
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 (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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✓ Expected Capacity Gain of WVAS

✓ Summary
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.

**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 second process for all $RF_j$.
4. Calculate WVE risk by repeating the third process for all $RL_i$.

- **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/S2P model developed by DLR.

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

WVE risks in successive landings on RWY22 of Tokyo International airport (about 1000 different weather conditions, 2 minutes 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.

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

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

- JAXA started wake vortex observation in take-off/landing phases at Narita International airport to improve probabilistic wake vortex prediction.
- Over 3000 wake data will be collected together with weather data and flight data of wake generators (including weight, airspeed) by August 2014.
Lidar Location & Scan Pattern

Lidar’s observation plane (RHI)
- Range: 100-900m (5m resolution)
- Elevation: 0-40deg (0.2deg resolution)
- Scan speed: every 8sec (6sec to scan, 2sec to reset)

Altitude of landing airplane in RHI plane is about 400ft

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

Narita International airport

RWY A 4000m
RWY B 2500m

Lidar’s RHI Plane

Altitude of landing airplane in RHI plane is about 400ft
Example of Observed Wakes

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

- Circulation
  - $\Gamma_0 = 433\text{m}^2/\text{s}$

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

- Horizontal Position Altitude
  - Runway centerline
  - Aircraft altitude

Graphs show the circulation and normalized circulation over time, with data points indicating the position and altitude of wakes.
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Concept of TPOS

- **Separation**
  Introduce dynamic separation according to weather condition/aircraft pairwise using wake vortex advisory system.

- **Take-off / landing sequence**
  Optimize sequence to increase the opportunity of successive take-offs/landings of the same category aircraft.

- **Runway allocation**
  Optimize runway allocation to reduce interferences between runways.

- **Flight path**
  Introduce dual thresholds and curved approach to reduce separations by changing flight paths between leading and following aircraft.

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Traffic Pattern Optimization

**Methods**

Optimize traffic pattern by two steps:

1\textsuperscript{st} step: Optimize runway allocation by using non-linear programming method (AIMMS) with relaxed constraints.  
⇒ Optimal, but not executable. Use as initial solution of 2\textsuperscript{nd} step optimization.

2\textsuperscript{nd} step: Optimize aircraft sequence by using constraint programming method (CHIP) with strict constraints.  
⇒ Not optimal, but executable.

**Expected capacity gain of TPOS**

TPOS can increase capacity together with RECAT.

Runway operation at Tokyo International airport in southerly wind condition

Capacity simulation of Tokyo International airport in southerly wind condition
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✓ Summary
Expected Capacity Gain (1/2)

- **Target airport and operation**
  
  Runway operations for southerly winds at Tokyo International (Haneda) airport is chosen because wake vortex separations limit the airport capacity.

<table>
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<tr>
<th>Situation</th>
<th>Wake vortex separation without</th>
<th>Wake vortex separation with</th>
</tr>
</thead>
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<tr>
<td>Successive landings on RWY22</td>
<td>115 sec.</td>
<td>120 sec.</td>
</tr>
<tr>
<td>Successive take-offs from RWY16L/R</td>
<td>95 sec.</td>
<td>120 sec.</td>
</tr>
<tr>
<td>Take-off from RWY16L and landing on RWY23</td>
<td>47 sec.</td>
<td>102 sec.</td>
</tr>
</tbody>
</table>

- **Simulation conditions**
  
  - Only aircraft operations below 2000ft are considered. Cruise-phase and airport surface operation are not considered.
  
  - Approximately 1000 weather conditions where southerly winds prevailed are chosen.
  
  - Two different accuracy levels of available weather information are considered. The poor accuracy of weather information leads to the poor performance of wake vortex prediction.

<table>
<thead>
<tr>
<th>Item</th>
<th>Errors (1σ) case 1 (current)</th>
<th>Errors (1σ) case 2 (ideal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDR [m^{2/3}/s]</td>
<td>0.05</td>
<td>0.025</td>
</tr>
<tr>
<td>Brunt–Väisälä freq. [1/s]</td>
<td>0.005</td>
<td>0.0025</td>
</tr>
<tr>
<td>Wind [m/s]</td>
<td>3.0</td>
<td>1.5</td>
</tr>
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Upper limit of confidence interval (Case 1: large errors in weather information)

Upper limit of confidence interval (Case 2: small errors in weather information)

Original PDD

Lower limit of confidence interval

Probability of existence

Normalized horizontal position of wake vortex

20
Expected Capacity Gain (2/2)

- Major factors affecting capacity gain
  - Target risk level
    Higher target risk level brings larger separation reduction.
  - Weather information accuracy
    Fine accuracy of available weather information increases separation reduction. To improve weather information accuracy is a good tool to reduce separation.

- Expected capacity gain
  We obtained **1.2% - 4.5% capacity gain** with the following assumptions:
  - Consider airport operating condition at the most congested time period (8–9 AM) of the target airport. The ratio of heavy to medium category aircraft was almost one to one.

In addition, the capacity gain can increase up to over 10% if the take-off/landing sequences are optimized.

Simulated separation reductions
(Averaged over approximately 1000 different weather conditions)

<table>
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<th>Situation</th>
<th>Weather information accuracy</th>
<th>Target risk level (cumulative risk level at current separations)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
<td>50%</td>
</tr>
<tr>
<td>Successive landings on RWY22</td>
<td></td>
<td>0 sec.</td>
</tr>
<tr>
<td></td>
<td>Ideal</td>
<td>0 sec.</td>
</tr>
<tr>
<td>Successive take-offs from RWY16L/R</td>
<td>Current</td>
<td>3 sec.</td>
</tr>
<tr>
<td></td>
<td>Ideal</td>
<td>4 sec.</td>
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<tr>
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In addition, the capacity gain can increase up to over 10% if the take-off/landing sequences are optimized.
JAXA develops the following two technologies:

- 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 vortex prediction model used in WVAS, JAXA conducts wake vortex observation campaign in Japan (Narita International airport). Over 3000 wake data will be collected together with weather data and flight data of wake generators by August 2014.