Prediction of Dynamic Pairwise Wake Vortex Separations for Approach and Landing – the WSVBS

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Wake Vortex Advisory System “WSVBS”

- supports weather dependent dynamic separations
  - on closely-spaced parallel runways
  - and single runways
- for weight class combinations
- or dynamic pairwise separations
- demonstration campaigns at
  - Frankfurt airport (winter 06/07)
  - Munich airport
    (summer 10, spring 11)
Wake Vortex Advisory System “WSVBS”

• supports weather dependent dynamic separations
  • on closely-spaced parallel runways
  • and single runways

special thanks for the support go to:
• DFS Deutsche Flugsicherung GmbH
• DWD Deutscher Wetterdienst
  • Fraport AG
• Flughafen München GmbH
• Metek GmbH
WSVBS

meteo measurements
SODAR/RASS USA
3 gates, 0.3 - 1 NM

numerical weather pred.
COSMO-Airport
10 gates, 2 - 11 NM

optionally a/c type comb.
Flight Plan
a/c type, arrival time

wake-vortex prediction
P2P
envelopes for y(t), z(t), Ω(t) in 13 gates
for (individual) heavy/medium pairings

safety area prediction
SHAPe
ellipses for (individual) medium followers

temporal a/c separations
for (individual) heavy/medium pairings

procedures
AMAN
STG, MSR, MSL, ICAO

glide path adherence statistics
FLIP
standard deviations in 13 gates

wake-vortex monitoring
LIDAR
3 planes, 0.3 - 1 NM

conflict detection
validation of vortex predictions

Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft
WSV Topology

13 Gates Along Nominal ILS Flight Path (Δx = 1/3 NM - 1 NM)

<table>
<thead>
<tr>
<th>gate No</th>
<th>$x_{\text{gate}}$ [nm]</th>
<th>$z_{\text{gate}}$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-11</td>
<td>-1077</td>
</tr>
<tr>
<td>2</td>
<td>-10</td>
<td>-979</td>
</tr>
<tr>
<td>3</td>
<td>-9</td>
<td>-880</td>
</tr>
<tr>
<td>4</td>
<td>-8</td>
<td>-781</td>
</tr>
<tr>
<td>5</td>
<td>-7</td>
<td>-683</td>
</tr>
<tr>
<td>6</td>
<td>-6</td>
<td>-584</td>
</tr>
<tr>
<td>7</td>
<td>-5</td>
<td>-486</td>
</tr>
<tr>
<td>8</td>
<td>-4</td>
<td>-387</td>
</tr>
<tr>
<td>9</td>
<td>-3</td>
<td>-289</td>
</tr>
<tr>
<td>10</td>
<td>-2</td>
<td>-191</td>
</tr>
<tr>
<td>11</td>
<td>-1</td>
<td>-94</td>
</tr>
<tr>
<td>12</td>
<td>-2/3</td>
<td>-61</td>
</tr>
<tr>
<td>13</td>
<td>-1/3</td>
<td>-29</td>
</tr>
</tbody>
</table>
Approach Corridor Dimensions

\[ \sigma_{y,fit} = 2.76 \text{ m} + 3.85 \text{ m/NM} \cdot x[\text{NM}]; \quad x < 3.3 \text{ NM} \]

\[ \sigma_{y,FLIP} = 11.5 \text{ m} + 1.23 \text{ m/NM} \cdot x[\text{NM}]; \quad x \geq 3.3 \text{ NM} \]


Approach scenario – WakeScene

(animation)

Numerical weather prediction and meteorological instrumentation

COSMO-Airport:
- meteo conditions along glidepath (output every 10 min)
- assimilation of SYNOP, TEMP, AMDAR and precipitation radar
- time-lagged ensemble predictions with 6 members

SODAR/RASS:
- meteo conditions close to threshold
- wind, turbulence, and temperature
- output every 10 min up to 500 m ($\Delta z = 20$ m)
Comparison of measured and predicted meteo data

40 days

\( z = 100 \text{ m} \)
Representation of individual a/c types – dynamic pairwise

- **a/c pairings according to flight plan in 5 min increments:**

- **HEAVY (15):**
  A306, A310, A332, A333, A343, A346, B744, B762, B763, B764, B772, B773, B77W, IL96, MD11

- **MEDIUM (34):**
  A319, A320, A321, AT43, AT45, AT72, B462, B463, B712, B732, B733, B734, B735, B736, B737, B738, B752, B753, CRJ1, CRJ2, CRJ7, CRJ9, D328, DH8D, E145, E170, E190, F100, F70, MD82, MD83, RJ1H, RJ85, SB20, SF34

- **Γ_{min}:** m = OEW + 1 h fuel + 0,1 PAX 100 kg; V = 200 kts at FAF
- **Γ_{max}:** m = MLW; V = 70 m/s (landing speed)

all relevant a/c types in MUC & FRA
Representation of heavy leader a/c for weight class combinations

<table>
<thead>
<tr>
<th>a/c-parameter combinations</th>
<th>$\Gamma_0$ [m$^2$/s]</th>
<th>$b_0$ [m]</th>
<th>$V$ [m/s]</th>
<th>characteristic time scales $t_0$</th>
<th>descent speed $w_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{0uu} b_{0uu}$</td>
<td>669.2</td>
<td>57.9</td>
<td>73.5</td>
<td>31.5 s</td>
<td>1.84 m/s</td>
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<tr>
<td>$\Gamma_{0uu} b_{0ul}$</td>
<td>669.2</td>
<td>48.2</td>
<td>73.5</td>
<td>21.8 s</td>
<td>2.21 m/s</td>
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<tr>
<td>$\Gamma_{0ul} b_{0uu}$</td>
<td>528.5</td>
<td>57.9</td>
<td>73.5</td>
<td>39.9 s (max)</td>
<td>1.45 m/s</td>
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<tr>
<td>$\Gamma_{0ul} b_{0ul}$</td>
<td>528.5</td>
<td>48.2</td>
<td>73.5</td>
<td>27.6 s</td>
<td>1.75 m/s</td>
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<tr>
<td>$\Gamma_{0lu} b_{0lu}$</td>
<td>448.1</td>
<td>38.4</td>
<td>70.3</td>
<td>20.7 s</td>
<td>1.86 m/s</td>
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<tr>
<td>$\Gamma_{0lu} b_{0ll}$</td>
<td>448.1</td>
<td>27.1</td>
<td>70.3</td>
<td>10.3 s (min)</td>
<td>2.63 m/s (max)</td>
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<tr>
<td>$\Gamma_{0ll} b_{0lu}$</td>
<td>288.2</td>
<td>38.4</td>
<td>70.3</td>
<td>32.1 s</td>
<td>1.19 m/s (min)</td>
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<tr>
<td>$\Gamma_{0ll} b_{0ll}$</td>
<td>288.1</td>
<td>27.1</td>
<td>70.3</td>
<td>16.0 s</td>
<td>1.69 m/s</td>
</tr>
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</table>
Probabilistic Two-Phase Wake-Vortex Transport and Decay model

- P2P accounts for effects of a/c configuration, wind, wind shear, turbulence, stable stratification, and ground proximity
- provides envelopes for $y$, $z$, $\Gamma$ with defined probabilities (based on calibration of model with measurement data)
- validated against data of over 10,000 cases gathered in 2 US and 6 EU measurement campaigns

Envelopes are wider for predicted meteo than for measured meteo input
Wake encounter severity assessment
Simplified Hazard Area (SHA)/
Simplified Hazard Area Prediction (SHAPe)

→ „How close can an aircraft fly safely to a wake vortex?“
→ DLR concept: Simplified Hazard Area (SHA)
  → conservative/ non-hazard approach, safe and undisturbed operations possible outside the hazard area, no go-arounds
  → simple, robust severity criterion
  → roll control ratio: one parameter to cover complete A/C reaction
  → validated with pilot-in-the-loop simulator & flight tests
→ Simplified Hazard Area Prediction (SHAPe) based on MTOW

Roll control ratio RCR
WSV Strategy

- Approach corridor (95.4%)
- Vortex area (95.4%)
- Large follower
- Safety area

State 11 - leader a/c: $\Gamma_{0uu}$, $b_{0uu}$ - separation time = 100 s

Diagram showing the approach corridor, vortex area, and safety areas for large and small followers.
WSV Strategy
Animated
veering light winds
(animation)

• 2004/09/01 08:10
• generator 2 shown
• heavy-medium

25L25L 100 125
25L25R 0 0
25R25L 0 0
25R25R 100 125

staggered approach
WSV Strategy
Animated
strong crosswind
(animation)

- 2004/09/10 19:10
- generator 2 shown which determines sep.
- heavy-medium

25L25L 68 75
25L25R 0 0
25R25L 100 125
25R25R 68 75

- modified staggered left
- reduced sep. single rwy
Potential capacity gain
Frankfurt airport (06/12/20 - 07/02/28)

WSV - CSPR - weight classes

WSV - single rwy - dynamic pairwise
Potential capacity gain offered by WSVBS
Frankfurt airport

<table>
<thead>
<tr>
<th>synthetic meteo data</th>
<th>full year 2004</th>
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<tbody>
<tr>
<td>PROC</td>
<td>MST</td>
</tr>
<tr>
<td>MSL</td>
<td>0 s</td>
</tr>
<tr>
<td>MSR</td>
<td>0 s</td>
</tr>
<tr>
<td>STG</td>
<td>0 s</td>
</tr>
<tr>
<td>ICAO</td>
<td>24%</td>
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<tr>
<td>HM</td>
<td>58 s</td>
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<table>
<thead>
<tr>
<th>WSV 06/07</th>
<th>66 days</th>
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<tbody>
<tr>
<td>PROC</td>
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<td>0 s</td>
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<tr>
<td>ICAO</td>
<td>25%</td>
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<tr>
<td>HM</td>
<td>62 s</td>
</tr>
<tr>
<td>DP</td>
<td>58 s</td>
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CSPR
SGL RWY:
Conclusions I

- The Wake Vortex Prediction and Monitoring System, WSVBS, exists with components: SODAR/RASS/USA/COSMO-Airport/FLIP/P2P/SHAPe/AMAN/LIDAR
- has demonstrated functionality at Frankfurt (12/06 - 02/07) & Munich (6/10 - 9/10) airports
- prediction horizon > 45 min (as required), update every 10 minutes
- predicts the established procedures (WSWS of DFS) for CSPR
- further predicts temporal separations & dynamic pairwise separations also for single rwys
- the LIDAR monitors the crucial altitudes

Frankfurt airport

- potential use of new ConOps (DFS) in 75% of the time
- median durations of procedures amount from 30 min for STG to 90 min for MSR
- potential capacity gain 3 - 4 % (DFS' ConOps only)
- dynamic pairwise (2.8%) almost doubles usage compared to weight class comb. (1.5%)
- the predictions were safe: no warnings from the LIDAR (≈1100 heavy a/c)
Conclusions II

Munich airport (sensitivity analysis dynamic pairwise see AIAA Paper 2011-3037)

- higher sensitivity on heavy leader a/c types than on medium follower a/c types
- WV predictions based on minimum circulation block gates slightly more frequently
- impact of flight corridor dimensions relatively large - improvements of navigational performance may help
- potential capacity gains of dynamic pairwise operations for single runways very small
- WSVBS features very conservative design
- even for perfect weather & WV predictions WV frequently remain in flight corridor
- WSVBS may be further developed as pure warning system