X-band Radar Trials for Wake-Vortex Monitoring in SESAR P12.2.2 Project

Mathieu Klein, Yves Ricci, David Canal
Frédéric Barbaresco & Philippe Juge
Thales Air Systems
X-Band Radar in Wake Vortex Decision Support System

XP1 Trials at Paris CDG Airport

X-Band Radar Description

Experimental Results
- Wake Vortex detection & localization
- Wake- Vortex detection & Wake Vortex Simulation
- Wake Vortex circulation preliminary measurements
- Weather measurements

Works in Progress:
- Validation of Data with UCL Models In Ground Effect
- Radar Simulator Calibration with Radar WV records
- Tests of Extreme Values & Rare Events statistical tools
Operational platform

◆ As Wake Vortex Sensor:
  ○ Real-time wake vortex detection, localization & characterization (strength)

◆ As Local Met. Sensor:
  ○ Real-time wind characterization
  ○ Real-time rain rate characterization

Simulation/test platform

◆ Calibration of the radar simulator
September-October 2012
Operational environment
Focus on aircrafts’ arrivals
● Reuse of existing hardware X-band platform
● Electronic scanning antenna
● Multi-function interleaved waveforms
  ○ Wake-Vortex Detection
    ● 3D scanning on the final part of the glide
    ● Fast update rate: 7.5 s
  ○ Weather Characterization
    ● Radial wind
    ● Rain reflectivity
    ● Fast update rate: 45 s
  ○ Aircraft Detection
● Real-time processing & data transfer
  ○ Computation & visualization in MATLAB
  ○ Linked with WV Tracker & Weather Nowcast/Forecast System
Principles of Wake Vortex detection in rainy/humid weather (1/2)

- **Lateral 3D scan of the final part of the glide**
  - 3 elevation beams
  - Range resolution: 5 m

- **Vortices detected through their effect on raindrops**
  - Detection sensitivity @ 2 km: \(-16 \text{ dBZ} = 0.004 \text{ mm/h (power budget)}\)
    - Clear air with some humidity
  - Maximum observed reflectivity in vortices recordings: \(17 \text{ dBZ} = 0.5 \text{ mm/h}\)

- **Detection of local radial velocity shifts**
  - Range-Doppler processing
  - Ambient velocity (also estimated by the weather mode) = raindrops affected by wind
  - Local positive/negative shift = effect of a vortex
Principles of Wake Vortex detection in rainy/humid weather (2/2)

- **Example:**
  - A346 landing
  - Scan @ –22° wrt plane orthogonal to the glide

- **Doppler analysis:**
  - Ambient wind radial velocity: –5 m/s
  - Maximum local shift: ± 7 m/s around ambient velocity
  - Cores’ separation: ~45 m (radial range)
Results of Wake Vortex detection & localization (1/3)

- Study focus on landing on CDG southeast runway
- Final part of the glide: last 100 m height
- Observation of vortices up to more than 60 s
  - Reduced observation because vortices fall on the ground (< 100 m)
  - And because of the (strong) crosswind during the trials: for an average crosswind of –5 m/s, vortices are out of the instrumented range after only 50 s

- Example: B772
1rst Worldwide 3D Wake-Vortex Monitoring In Ground Effect
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RADAR CAPABILITY TO MONITOR WAKE-VORTEX IN 4D (3D + Time)
Experimental Results: Wake Vortex

Results of Wake Vortex detection & localization (2/3)

- Example: A346
- Headwind: -1 m/s
- Crosswind: -5 m/s
- Rain rate: 0.03 mm/h (light drizzle)

Computed in the Weather mode
Results of Wake Vortex detection & localization (2/3)

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Transport of vortices with the crosswind
Results of Wake Vortex detection & localization (3/3)

- Example: A346
- Headwind: -1 m/s
- Crosswind: -5 m/s
- Rain rate: 0.03 mm/h (light drizzle)

Computed in the Weather mode

Plane orthogonal to the glide

Plane -20 wrt orthogonal to the glide

Vertices falling down
## Experimental Results: Wake Vortex

### Circulation: Preliminary measurements (1/2)

- Comparison of the first estimated values with the theoretical initial circulation:

\[
\Gamma_0 = \frac{(M \cdot g)}{(\rho \cdot b_0 \cdot V_{ac})}
\]

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Wingspan (b) [m]</th>
<th>Max. Take-Off Weight (MTOW) [kg]</th>
<th>Aircraft speed (V) [m/s]</th>
<th>Initial separation (b_0) [m]</th>
<th>Vortex radius (r) [m]</th>
<th>(\Gamma_0 = \frac{(0.6 \cdot MTOW \cdot g)}{(\rho \cdot b_0 \cdot V)})</th>
<th>Theoretical initial circulation (\Gamma_0) [m²/s]</th>
<th>Measured initial circulation (\Gamma_0) [m²/s]</th>
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<tbody>
<tr>
<td>A380</td>
<td>80</td>
<td>560.10³</td>
<td>71</td>
<td>64</td>
<td>11</td>
<td>#600</td>
<td>&gt;550</td>
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<tr>
<td>A346</td>
<td>63</td>
<td>368.10³</td>
<td>75</td>
<td>51</td>
<td>9</td>
<td>#470</td>
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<td>B772</td>
<td>61</td>
<td>247.10³</td>
<td>66</td>
<td>49</td>
<td>8</td>
<td>#370</td>
<td>&gt;410</td>
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</tr>
<tr>
<td>A333</td>
<td>60</td>
<td>230.10³</td>
<td>70</td>
<td>48</td>
<td>8</td>
<td>#340</td>
<td>&gt;370</td>
<td></td>
</tr>
</tbody>
</table>
Experimental Results: Wake Vortex

Circulation: Preliminary measurements (2/2)

- Examples: A380, A346, B772 & A333
- Time evolution of circulation

- Headwind: -1 m/s
- Crosswind: -2 m/s
- Headwind: -3 m/s
- Crosswind: -1 m/s
- Headwind: -1 m/s
- Crosswind: -5 m/s
- Headwind: -1 m/s
- Crosswind: -7 m/s
**Estimation of Radial wind & Rain reflectivity**

- Fast update rate: 3 elevation beams in 45 s
**CDG XP1 Radar Trials**
- Aircraft Type: A346
- Crosswind: -5 m/s

**Example of previous validation of the UCL WAKE4D simulation tool**
- WakeFRA 2004 Lidar database

XP1 Radar database delivered to UCL for comparison with WAKE4D in « In Ground Effect » Configuration (Work in Progress)
Work in Progress: Calibration with Radar Simulation

- WAKE4D Scenario Generator (UCL)
- Radar Simulator in Clear Air (UCL)
- Radar Simulator in Rain (ONERA)

Aircraft trajectory
Simulated time evolution of the 3D wake
Evaluation of the wake vortex properties in the sensor plane

(r, φ)
New Statistics Tools under tests for Extreme Wake-Vortex Behaviors

◆ Wake-Vortex Survival Time and Wake-Vortex Circulation Decay Probability
  Densities are characterized by Heavy Tails

◆ Classical Gaussian Model are no longer compliant (no information is given on heavy tails by mean/standard deviation)

◆ Heavy tails Retrieval Methods:
  ○ Estimation by quantiles to characterize « rare events » or « extreme values »
  ○ Accurate/robust estimation by Extreme Values Theory with very few data available from these extreme behaviors of wake-vortex

⇒ THALES has initiated cooperation with Paris-6/UPMC University (Prof. Paul Deheuvels & Michel Broniatowski, LSTA labs) and UCL (Prof. Grégoire Winckelmans) on « Extreme Values Statistics »

⇒ THALES has initiated cooperation with ONERA (Prof. Vincent Moro) and UCL (Prof. Grégoire Winckelmans) on « Importance Sampling » method to estimate statistical densities heavy tails of « Wake-Vortex Predictor » outputs (sensitivity analysis of LES simulation according to input parameters accuracy)

Prof. Paul René Louis Deheuvels
Member of the French Science Academy
Fellow of the Institute of Mathematical Statistics
Pierre-Simon de Laplace Prize 2007, Société de Statistique de France
Graduated from Ecole Normale Supérieure ULM
(Consultant for TOTAL, ELF, SANOFI,....)
Emeritus Professor of « Pierre & Marie Curie » University
Head of « Laboratoire de statistique théorique et appliquée », PARIS
Conclusions

- X-band radar performances optimal under rainy/humid conditions
  - Detection with high sensitivity of the effect of wake vortices on raindrops
  - Good range resolution (5 m) → discrimination of the 2 vortices, even for small aircrafts
  - Complementary with Lidar performances → all-weather real-time detection system

- Multi-function capability to support WVDSS
  - Real-time 3D wake vortices detection
  - Real-time 3D weather characterization

Perspectives

- Wake vortex processing: Calibration of circulation estimation
- Weather processing: Calibration of rain reflectivity measurement
- WV Radar Simulators calibration with WV Radar data
- Analysis of WV Radar data quality with UCL IGE WV Model as reference

Preparation of next trials (FP7 UFO, SESAR XP2,...)
RADAR CAPABILITY TO MONITOR WAKE-VORTEX IN 4D (3D + Time) Including FREAK WAKE-VORTEX