Agenda

1. R-WAKE project (5’)
2. R-WAKE concept (5’)
3. Relation to SESAR 2020 (5’)
4. Achievements vs. Project Objectives (8’)
5. Assessment of Maturity ER -> IR Gate (5’)
6. What next? (proposed way forward to feed IR programme) (5’)

SESAR 2020 - Exploratory Research
R-WAKE Project
R-WAKE – The ER Project
“Wake Vortex simulation and analysis to Enhance en-Route separation management in Europe”

Applications Oriented Separation Management

Consortium Members:

- GTD SISTEMAS DE INFORMACION SA (ES)
- UNIVERSITAT POLITECNICA DE CATALUNYA (ES)
- TECHNISCHE UNIVERSITAT BRAUNSCHWEIG (DE)
- DEEP BLUE SRL (IT)
- M3 SYSTEMS BELGIUM SPRL (BE)
- A-SYST SA (LU)

- 1-April-2016 / 31-Mar-2018
- Grant # 699247

Total Cost: 998,745 €

Website: www.rwake-sesar2020.eu
R-WAKE Research Objectives and Expected Impact

Problem addressed

- Today en-route separation minima is 5NM / 1000 feet for all aircraft,
  - Over-conservative for some aircraft categories,
  - Insufficiently protecting against wake vortex hazards in other cases (e.g., wakes can be sometimes encountered up to 25NM behind a generating airplane).

Expected Impact

- New OIs based on improved en-route separation standards to:
  - Improve wake turbulence safety in en-route operations
  - Improve ATM capacity and potentially enhance flight efficiency, whilst maintaining the same level of safety
- New System & Procedural Enablers to support the OIs
  - On-board / On-ground WEPS (Wake Encounter Prediction System)
  - Dynamic Risk Modelling for safety assessments in sectors or in ECAC
R-WAKE Research Question (application-oriented)

'What Separation Minima Reductions can be applied in specific and clearly defined operational conditions keeping the current safety levels and taking into account the potential En-Route WVE hazards?'

Simulation platform

(tailoring SESAR SRM, to generate quantitative and qualitative safety evidence to support project safety cases)

Safety & Robustness Analysis Method

(traffic trajectories, WV, aircraft upsets & some ATM constraints)
R-WAKE Project Objectives

Research structured in 5 tangible Project Expected Outcomes
(formulation following WP2/MS2 Review with SJU D2.1 assessment)

**01** Absolute Safety Criteria: WVE hazard Severity Characterisation (*Severity Matrix*)

**02** Simulator of (simplified) ATM with WVE dynamic models (*risk quantification*);

**03** Database of Simulation Results that will provide evidence to propose new Separation Standards

**04** Evidence-based proposal for either maintaining current Separation Standards or adopting new ones;

**05** Assessment of the feasibility and impact of the concept on ATM with an initial Validation Strategy and outline Implementation Plan.
R-WAKE Concept
R-WAKE-1 OCD

R-WAKE-1 concept proposal defined as:

“Aircraft Category and Geometry-Wise Wake Separation Minima to improve En-Route Separation Provision Advanced Traffic Services”.

To be presented in the form of a matrix of separation adjustments:

<table>
<thead>
<tr>
<th>RWAKE-1 SEPARATIONS ADJUSTMENTS TABLE</th>
<th>GENERATOR AIRCRAFT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Generator</td>
</tr>
<tr>
<td></td>
<td>Climbing ahead</td>
</tr>
<tr>
<td></td>
<td>Flying level</td>
</tr>
<tr>
<td></td>
<td>Descending ahead</td>
</tr>
<tr>
<td>dV: Vertical separation in FL</td>
<td>C1 (H)</td>
</tr>
<tr>
<td>dL: Longitudinal in NM</td>
<td>C2 (M)</td>
</tr>
<tr>
<td>dO: Offset separation in NM (Over 5NM / 1000feet)</td>
<td>C3 (L)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FOLLOWER AIRCRAFT</th>
<th>Follower Behind</th>
<th>C1 (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C2 (M)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3 (S)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FOLLOWER AIRCRAFT</th>
<th>Follower Opposite</th>
<th>C1 (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C2 (M)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3 (S)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FOLLOWER AIRCRAFT</th>
<th>Follower Crossing</th>
<th>C1 (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C2 (M)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3 (S)</td>
<td></td>
</tr>
</tbody>
</table>

Step-wise roadmap:

Following extensions:
RWAKE-2 Separation Minima Dynamic

1st step: RWAKE-1 Separation Minima Wind-dependent
R-WAKE Separation Standards
(Proposals)

Key assumptions

1. Introduction of Aircraft Categories for En-route separation: RA-RB-RC
   - Initial choice of three categories to minimise complexity for ATCOs (HF criteria)

2. Minimum Wake Separations (MWS) co-existing with Minimum Radar Separations (MRS)
   - The most conservative of both must be applied at any instant

3. Navigation accuracy of RNP-1 for en-route
   - +/- 1 NM error in horizontal & +/- 50 feet in vertical (in cruise)

4. MRS set at 3NM (Horizontal) and 500 feet (Vertical) (current ICAO MRS: 5NM / 1000 feet)
   - Should be robust for RNP-1 capabilities
R-WAKE Separation Standards (Proposals)

Introduction of R-Wake Aircraft Categories for En-Route

Today in en-route: 1 unique category (=no categories)

<table>
<thead>
<tr>
<th>R-WAKE categories</th>
<th>RECAT categories</th>
<th>ICAO categories (for airports)</th>
<th>Category representatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAT RA</td>
<td>CAT A</td>
<td>SUPER HEAVY</td>
<td>A380</td>
</tr>
<tr>
<td>CAT RB</td>
<td>CAT B + CAT C</td>
<td>HEAVY</td>
<td>B744, B764</td>
</tr>
<tr>
<td>CAT RC</td>
<td>CAT D+ CAT E</td>
<td>MEDIUM &amp; LIGHT</td>
<td>A320, F100</td>
</tr>
</tbody>
</table>
R-WAKE Separation Standards (Proposals)

Factors considered in the definition of MWS (Min. Wake. Sep.)

• Multiple possible geometries of the encounter (up to 45: 5H x 3Vg x 3Vf)
• Distinction in three basic separation types
  ▪ Vertical Separation (dV)
  ▪ Lateral (orthogonal) Separation (d0)
  ▪ Longitudinal Separation (dL)
• Combined separations are also considered
• Category considered for the generator aircraft only
  ➔ Unlike in RECAT, the follower will not be considered to compensate for the extra en-route complexity)
R-WAKE Separation Standards (Proposals)

Examples of concept OIs being explored:

- **Vertical separation minima reduced to 500 feet**, e.g. RVSM 2.0, allowing increase airspace capacity by using FL of ..., 285, 295, 305, 315, 325, ...

- **Combined Vertical and Lateral separation minima**, e.g. 500 feet and 1 or 2 NM horizontal separation

- **Wind dependent Lateral separation minima**

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From CVSM (dV = 2000 ft)

- FLs x2
- ATC capacity +20%

![RVSM diagram](image)

- 1000 ft

![RVSM 2.0 diagram](image)

- 500 ft

**FLs x2**

**ATC capacity +20%?**

...further described in next sections
Relation to SESAR 2020
R-WAKE Programmatic context

Relation to SESAR 2020, Related Pj.´s

RWAKE PROJECT
Concept Definition Exploratory Research towards ER/IR gate (PreV1)

RWAKE SYSTEM
RWAKE CONCEPT(s)

Reference Methodology
For Wake Turbulence Hazard Risk Safety Assessment and Separation Improvements
- WV Decay Model (TMA)
- WVE Impact (TMA)
- RECAT & Separations adjustments

RWAKE contribution of New potential CONOPS Or improvement of existing for Pj.10

Reference CONOPS & Systems of En-Route Separation (current & future)

SESAR 2020 Pj.02:
HIGH PERFORMING AIRPORT OPERATIONS – INCREASED RUNWAY AND AIRPORT THROUGHPUT

SESAR 2020 Pj.10:
ADVANCED AIR TRAFFIC SERVICES – SEPARATION MANAGEMENT EN-ROUTE AND TMA

Airport-TMA Operations
Runway Capacity Increase

Advanced Air Traffic Services (ATS) Separation Management In En-Route Operations Capacity (& Efficiency) Increase

RECAT
Concept, Systems, Projects

Conops
TBS PWS D-PWS
WDS

Systems
Ground
ORD WVS-DSS

Airborn
WEPS-ORD WEPS-C

TBS
PWS
D-PWS
WDS
ORD
WVS-DSS
WEPS-ORD
WEPS-C

SESAR 2020 - Exploratory Research
Achievements to project objectives
Achievements to Project Objectives

O1: Absolute Safety Criteria: WVE hazard Severity Characterisation (*Severity Matrix*)

O2: Simulator of (simplified) ATM with WVE dynamic models (*risk quantification*);

O3: Database of Simulation Results that will provide evidence to propose new Separation Standards.

O4: Evidence-based proposal for either maintaining current Separation Standards or adopting new ones;

O5: Assessment of the feasibility and impact of the concept on ATM with an initial Validation Strategy and outline Implementation Plan.
O1: Absolute Safety Criteria
WVE Hazard Severity Characterization
Wake vortex Aircraft Interaction Model (WIAM) tool

- WIAM Cross-Validated against TU-Braunschweig’s model (which in turn it was partially validated with real flights)
- >20,000 simulations performed; a selection assessed by Experts Panel with pilots and ATCOs
O1: Absolute Safety Criteria
WVE Hazard Severity Characterization
Expert Panels

Each selected scenario presented to Experts with a video of the Aircraft PFD:

Upset Example (Climbing)
Scenario Ref. 17404
# O1: Absolute Safety Criteria

to support different safety cases

## Severity Matrix with Upset Parameter Thresholds

- **ΔΦ [deg]** - Max Bank Roll change
- **ΔH [feet]** - Max Altitude loss
- **$V_{z_{max}}$ [feet/min]** - Max Vertical Speed change
- **ΔV [knots]** - Max True Airspeed change

<table>
<thead>
<tr>
<th>Upset parameters</th>
<th>No safety effect</th>
<th>Minor</th>
<th>Major</th>
<th>Hazardous</th>
<th>Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔΦ [deg]</td>
<td>&lt; 25°</td>
<td>25° to 30°</td>
<td>30° to 45°</td>
<td>45° to 60°</td>
<td>&gt; 60°</td>
</tr>
<tr>
<td>ΔH [feet]</td>
<td>&lt; 100 feet</td>
<td>100 to 500 feet</td>
<td>500 to 1000 feet</td>
<td>&gt; 1000 feet</td>
<td>&gt; 1000 feet</td>
</tr>
<tr>
<td>$V_{z_{max}}$ [feet/min]</td>
<td>&lt; 500 ft/min</td>
<td>500 to 1000 ft/min</td>
<td>1000 to 3000 ft/min</td>
<td>3000 to 6000 ft/min</td>
<td>&gt; 6000 ft/min</td>
</tr>
<tr>
<td>ΔV [knot]</td>
<td>&lt; 10 kn</td>
<td>10 to 15 kn</td>
<td>15 to 25 kn</td>
<td>&gt; 25 kn</td>
<td>&gt; 25 kn</td>
</tr>
</tbody>
</table>
Achievements to Project Objectives

1. **Absolute Safety Criteria: WVE hazard Severity Characterisation (Severity Matrix)**

2. **Simulator of (simplified) ATM with WVE dynamic models (risk quantification)**;

3. **Database of Simulation Results** that will provide evidence to propose new Separation Standards

4. **Evidence-based proposal for either maintaining current Separation Standards or adopting new ones**;

5. **Assessment of the feasibility and impact of the concept on ATM with an initial Validation Strategy and outline Implementation Plan.**
O2: Integrated Simulator System

Generator & Follower Trajectory Generator

WV Simulator (WVS)

WV Encounter Prediction System (WEPS) - embeds WIAM and Severity Matrix

- Shown part of the system: configuration for Conditioned Individual Risk (CIR) study.
- Complete configuration includes realistic traffic generation of ECAC-wide or Airspace Sector areas for systemic risk assessment (SER and SAR).

**Generator**

4D Trajectory segment

**WV model:** a 4D tube containing the uncertain WV positions and gammas at 95% CI

**Follower**

4D Trajectory segment

**WEPS**

- Reasonable Worst Case model
- WIAM Upset calculation

**WVE Hazard Severity class**

1: No safety effect
2: Minor
3: Major
2: Hazardous
5: Catastrophic

**WVE Severity Matrix with Upset Parameter Thresholds**

**Wake Vortex 4D tube trajectory segment**

- WV model: a 4D tube containing the uncertain WV positions and gammas at 95% CI
Achievements to Project Objectives

- **O1**: Absolute Safety Criteria: WVE hazard Severity Characterisation (Severity Matrix)
- **O2**: Simulator of (simplified) ATM with WVE dynamic models (risk quantification);
- **O3**: Database of Simulation Results that will provide evidence to propose new Separation Standards
- **O4**: Evidence-based proposal for either maintaining current Separation Standards or adopting new ones;
- **O5**: Assessment of the feasibility and impact of the concept on ATM with an initial Validation Strategy and outline Implementation Plan.
O3: Simulation database
Generation of evidence and openness of results

Simulation Plan (DoE):
Forced/assumed Conditions in multiple experiments exploring different separation distances and encounter geometries)

Risk Maps of Reasonable Worst Case (RWC)
Simplified Hazard Area (SHA):
SHA-YZ (dHO, dV)
SHA-XZ (dHL, dV)
SHA-XY (dHL, dHO)

Public database

Simulations
Upset and severity quantification

Risk Maps of Reasonable Worst Case (RWC)
Simplified Hazard Area (SHA):
O3: Simulation database
Conditioned Individual Risk (CIR)
Suspected Hazard Area (SHA) - Risk Maps

DEMO (2-min)

SESAR 2020 - Exploratory Research
**O3: Simulation database**

**Example of SHA Area boundary Category-Wise Matrix**

per Severity Class = 3 (SC3), having Generators flying at FL280, Mass & Speed = Nominal, and Followers flying Behind with RoCD = levelled, and Atmosphere with Stratification=2, And Turbulence=2

<table>
<thead>
<tr>
<th>Severity Class</th>
<th>Generators conditions</th>
<th>Follower conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>FL280</td>
<td>Heading</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RoCD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Behind levelled</td>
</tr>
</tbody>
</table>

**GENERATORS**

<table>
<thead>
<tr>
<th>Cat A (SH)</th>
<th>Cat B (UH)</th>
<th>Cat C (LH)</th>
<th>Cat D (UM)</th>
<th>Cat E (LM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERT</td>
<td>LONG</td>
<td>VERT</td>
<td>LONG</td>
<td>VERT</td>
</tr>
<tr>
<td>feet</td>
<td>sec</td>
<td>NM</td>
<td>feet</td>
<td>sec</td>
</tr>
<tr>
<td>0</td>
<td>42</td>
<td>5,6</td>
<td>0</td>
<td>33</td>
</tr>
<tr>
<td>100</td>
<td>63</td>
<td>8,4</td>
<td>100</td>
<td>53</td>
</tr>
<tr>
<td>200</td>
<td>84</td>
<td>11,2</td>
<td>200</td>
<td>73</td>
</tr>
<tr>
<td>300</td>
<td>105</td>
<td>14,0</td>
<td>300</td>
<td>94</td>
</tr>
<tr>
<td>500</td>
<td>151</td>
<td>20,1</td>
<td>500</td>
<td>162</td>
</tr>
<tr>
<td>1000</td>
<td>214</td>
<td>28,4</td>
<td>900</td>
<td>180</td>
</tr>
<tr>
<td>1200</td>
<td>226</td>
<td>30,0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cat B (UH)</th>
<th>Cat C (LH)</th>
<th>Cat D (UM)</th>
<th>Cat E (LM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERT</td>
<td>LONG</td>
<td>VERT</td>
<td>LONG</td>
</tr>
<tr>
<td>feet</td>
<td>sec</td>
<td>NM</td>
<td>feet</td>
</tr>
<tr>
<td>0</td>
<td>42</td>
<td>5,6</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>63</td>
<td>8,4</td>
<td>100</td>
</tr>
<tr>
<td>200</td>
<td>84</td>
<td>11,2</td>
<td>200</td>
</tr>
<tr>
<td>300</td>
<td>105</td>
<td>14,0</td>
<td>300</td>
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<tr>
<td>500</td>
<td>151</td>
<td>20,1</td>
<td>500</td>
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<tr>
<td>1000</td>
<td>214</td>
<td>28,4</td>
<td>900</td>
</tr>
<tr>
<td>1200</td>
<td>226</td>
<td>30,0</td>
<td></td>
</tr>
</tbody>
</table>

**FOLLOWERS**

<table>
<thead>
<tr>
<th>Cat C (LH)</th>
<th>Cat D (UM)</th>
<th>Cat E (LM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERT</td>
<td>LONG</td>
<td>VERT</td>
</tr>
<tr>
<td>feet</td>
<td>sec</td>
<td>NM</td>
</tr>
<tr>
<td>0</td>
<td>42</td>
<td>5,6</td>
</tr>
<tr>
<td>100</td>
<td>63</td>
<td>8,4</td>
</tr>
<tr>
<td>200</td>
<td>84</td>
<td>11,2</td>
</tr>
<tr>
<td>300</td>
<td>105</td>
<td>14,0</td>
</tr>
<tr>
<td>500</td>
<td>151</td>
<td>20,1</td>
</tr>
<tr>
<td>1000</td>
<td>239</td>
<td>31,8</td>
</tr>
<tr>
<td>1200</td>
<td>241</td>
<td>32,0</td>
</tr>
</tbody>
</table>

Green indicates reduction from current
Red indicates increase from current

**Altitude Wake Separation per Category**

<table>
<thead>
<tr>
<th>Category</th>
<th>Severity Class</th>
<th>Generators conditions</th>
<th>Follower conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat D (UM)</td>
<td>3</td>
<td>FL280</td>
<td>Heading</td>
</tr>
<tr>
<td>Cat A (SH)</td>
<td>3</td>
<td>FL280</td>
<td>Heading</td>
</tr>
</tbody>
</table>

**Example**

- **Cat D (UM):** Wake separation for Category D (UM) at FL280 with Nominal conditions.
- **Cat A (SH):** Wake separation for Category A (SH) at FL280 with Nominal conditions.

**Wake Separation Values**

- **Cat D (UM):** 100 feet, 21 seconds, 2.7 NM.
- **Cat A (SH):** 100 feet, 21 seconds, 2.7 NM.

**RoCD**

- **Cat D (UM):** 100 feet, 21 seconds, 2.7 NM.
- **Cat A (SH):** 100 feet, 21 seconds, 2.7 NM.
Achievements to Project Objectives

- **O1**: Absolute Safety Criteria: WVE hazard Severity Characterisation (Severity Matrix)
- **O2**: Simulator of (simplified) ATM with WVE dynamic models (risk quantification);
- **O3**: Database of Simulation Results that will provide evidence to propose new Separation Standards
- **O4**: Evidence-based proposal for either maintaining current Separation Standards or adopting new ones;
- **O5**: Assessment of the feasibility and impact of the concept on ATM with an initial Validation Strategy and outline Implementation Plan.
**O4: Separation Standard proposal**

**R-WAKE1 Minimum Wake Separation (MWS)**

Six types of separation improvements proposed:

<table>
<thead>
<tr>
<th>STATIC</th>
<th>WIND-DEPENDENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. MWS Lateral</td>
<td>5. MWS Lateral Wind-dependent</td>
</tr>
<tr>
<td>2. MWS Vertical</td>
<td>6. MWS Combined vertical–lateral Wind-dependent</td>
</tr>
<tr>
<td>3. MWS Longitudinal in same FL</td>
<td></td>
</tr>
<tr>
<td>4. MWS Longitudinal during climbing/descending operations</td>
<td></td>
</tr>
</tbody>
</table>
1. MWS Lateral

Geometries

Separation Adjustements & Benefits

<table>
<thead>
<tr>
<th>MWS required for the follower</th>
<th>Change relative to the current standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 NM (same for all the categories)</td>
<td>-2 NM</td>
</tr>
</tbody>
</table>

Capacity increased
O4: Separation Standard proposal
R-WAKE1 Minimum Wake Separation (MWS)

2. MWS Vertical

Geometries

Separation Adjustments & Benefits

<table>
<thead>
<tr>
<th>Generator</th>
<th>Minimum Wake Separation required for the follower</th>
<th>Change relative to the current standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAT RA</td>
<td>1500 FT</td>
<td>+500 FT</td>
</tr>
<tr>
<td>CAT RB</td>
<td>1000 FT</td>
<td>0 FT</td>
</tr>
<tr>
<td>CAT RC</td>
<td>500 FT</td>
<td>-500 FT</td>
</tr>
</tbody>
</table>

Considerations

- The capacity and efficiency increments will also depend on the traffic mix and on how the traffic is organised in FLs.
O4: Separation Standard proposal
R-WAKE1 Minimum Wake Separation (MWS)

3. MWS Longitudinal in same FL

Geometries

Separation Adjustements & Benefits

<table>
<thead>
<tr>
<th>Generator</th>
<th>Separation required for the follower</th>
<th>Change relative to the current standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAT RA</td>
<td>45 s / 6 NM (35 s / 5 NM if Cat A)</td>
<td>N/A / +1 NM (N/A / 0 NM)</td>
</tr>
<tr>
<td>CAT RB</td>
<td>35 s / 5 NM</td>
<td>N/A / 0 NM</td>
</tr>
<tr>
<td>CAT RC</td>
<td>25 s / 3 NM</td>
<td>N/A / -2 NM</td>
</tr>
</tbody>
</table>

Safety increased
Capacity increased
O4: Separation Standard proposal  
R-WAKE1 Minimum Wake Separation (MWS)

4. MWS Longitudinal during climbing/descending

Geometries:  
Follower climbing/descending behind  
or generator climbing/descending ahead  
or follower crossing below (not separated vertically)

Separation Adjustments & Benefits

<table>
<thead>
<tr>
<th>Generator</th>
<th>Separation required for the follower</th>
<th>Change relative to the current standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAT RA</td>
<td>240 s / 32 NM</td>
<td>N/A</td>
</tr>
<tr>
<td>CAT RB</td>
<td>200 s / 27 NM</td>
<td>N/A</td>
</tr>
<tr>
<td>CAT RC</td>
<td>120 s / 15 NM</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Not defined today:  
Safety increased Capacity?
O4: Separation Standard proposal
R-WAKE1 Minimum Wake Separation (MWS)

5. MWS Lateral Wind-Dependent

Geometries

Separation Adjustments & Benefits

<table>
<thead>
<tr>
<th>Minimum lateral separation (upwind)</th>
<th>Max crossed wind component tolerated</th>
<th>Change relative to the current standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 NM</td>
<td>45 Kts</td>
<td>-2 NM</td>
</tr>
<tr>
<td>4 NM</td>
<td>60 Kts</td>
<td>-1 NM</td>
</tr>
<tr>
<td>5 NM</td>
<td>75 Kts</td>
<td>0 NM</td>
</tr>
<tr>
<td>X NM</td>
<td>15X Kts</td>
<td>+ (X-5) NM</td>
</tr>
</tbody>
</table>

Considerations

- **Exception to nominal wind-dependent offsets (dO):** If the generator is CAT RC, then the distances could be reduced to the half (due to the lower duration of their WV generated)
### O4: Separation Standard proposal
R-WAKE1 Minimum Wake Separation (MWS)

#### 6. MWS Combined Vertical-Lateral Wind-Dependent

**Geometries**

- **H**
  - TOP VIEW
- **V+H**
  - FRONT VIEW
  - FRONT/REAR VIEW

**Separation Adjustments & Benefits**

<table>
<thead>
<tr>
<th>Minimum lateral separation (upwind)</th>
<th>Max crossed wind component tolerated</th>
<th>Change relative to the current standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 NM <em>(only if dV &gt;= 500ft)</em></td>
<td>15 Kts</td>
<td>N/A</td>
</tr>
<tr>
<td>2 NM <em>(only if dV &gt;= 500ft)</em></td>
<td>30 Kts</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Considerations**

- Note that these are *combined separations* (vertical - lateral) that can be useful to apply special procedures, e.g., separating traffic in head-on geometry *(SLOP, as recommended by EASA)*

**Safety increased**
O4: Separation Standard proposal
Subliminal off-sets supported by on-board systems

Idea for new OI:
• aircraft could be equipped with on-board WVE preventing systems (with similar technological basis as Extended-TCAS –not a safety net);
• aircraft over a same track could apply subliminal off-sets (e.g., 100 m or less) in the direction of the wind for the generator and upwind for the follower;
• these offsets would possibly be not perceived by ATCOs (subliminal) but would reduce significantly the risk of WVE (also with today’s separation standard)
Achievements to Project Objectives

**O1** Absolute Safety Criteria: WVE hazard Severity Characterisation *(Severity Matrix)*

**O2** Simulator of (simplified) ATM with WVE dynamic models *(risk quantification)*

**O3** Database of Simulation Results that will provide evidence to propose new Separation Standards

**O4** Evidence-based proposal for either maintaining current Separation Standards or adopting new ones;

**O5** Assessment of the feasibility and impact of the concept on ATM with an initial Validation Strategy and outline Implementation Plan.
O5: Feasibility and Impact Assessment
Cost Benefit Analysis & ATM Roadmap fitness

Concept Definition

Cost Benefit Analysis
- ATM Performance Impact Assessment
  - Safety
  - Capacity
  - Efficiency
  - Environment
  - R&D ROI
- Implement-ability (links to ATM Master Plan enablers)
- R&I Proposal (towards V1 gate & beyond)

Project Methods & Tools
- Study Scenarios
- Safety & Robustness Analysis
- R-WAKE ATM Simulator Framework (Realistic Fast Time Simulation)
  - WEATHER SIM
  - TRAFFIC SIM
  - WV SIM
- Simulation & Analysis Database

Concept Assessment: Defined, feasible, safe?
Technology Assessment: Defined, feasible?
SESAR Alignment: OIS, EN, EATMA?
CBA: Mechanisms Benefit > Cost?
Future Research: Needs, viability, plan/strategy

SESAR 2020 - Exploratory Research
Maturity Assessment to ER/IR Gate
# Maturity Assessment

## Related to App-oriented R-WAKE Concept Definition

<table>
<thead>
<tr>
<th>Separations case</th>
<th>Expected Impact on ATM Performance</th>
<th>Integrity aspects (issues) &amp; confidence level</th>
<th>Further research needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. MWS Lateral</td>
<td>Capacity: +</td>
<td>· No issues identified</td>
<td>· Validate the MRS (3NM)</td>
</tr>
<tr>
<td>2. MWS Vertical</td>
<td>Safety: +</td>
<td>· ATCOs’ radar 2D view (difficult separation provision)</td>
<td>· DSTs for ATCOs</td>
</tr>
<tr>
<td></td>
<td>Capacity: + Efficiency: +</td>
<td>· Risk is sensitive to <em>vertical</em> navigation uncertainty</td>
<td>· WV models to be further validated with real flights</td>
</tr>
<tr>
<td></td>
<td></td>
<td>· Risk is sensitive to <em>vertical</em> navigation uncertainty</td>
<td>· Refine risk models</td>
</tr>
<tr>
<td>3. MWS Longitudinal – same FL</td>
<td>Safety: +</td>
<td>· Risk is sensitive to <em>vertical</em> navigation uncertainty</td>
<td>· Include vertical uncertainties in risk models</td>
</tr>
<tr>
<td></td>
<td>Capacity: +</td>
<td>· Difficult with dense traffic</td>
<td>· DSTs for ATCOs</td>
</tr>
<tr>
<td>4. MWS Longitudinal – climbing/descend or crossing in FL below</td>
<td>Safety: +</td>
<td>· Very large region to protect (while risk of WVE is low)</td>
<td>· WV models to be further validated with real flights</td>
</tr>
<tr>
<td></td>
<td>Capacity: (?)</td>
<td>· Possibly difficult for ATCOs</td>
<td>· DSTs for ATCOs</td>
</tr>
<tr>
<td>5. MWS Wind-dep. – lateral</td>
<td>Safety: + (winds &gt; 75kts) Capacity: +</td>
<td>· Possibly difficult for ATCOs if wind info is not available</td>
<td>· DSTs for ATCOs (incl. wind/weather info)</td>
</tr>
<tr>
<td>6. MWS Wind-dep. – vertical-lateral</td>
<td>Safety: + (winds &gt; 75kts) Capacity: +</td>
<td>· Possibly difficult for ATCOs if wind info is not available</td>
<td>· DSTs for ATCOs (incl. wind/weather info)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>· Difficult with dense traffic</td>
<td>· On-board WEPS</td>
</tr>
</tbody>
</table>
# Maturity Assessment
## Related to the R-WAKE Research System

<table>
<thead>
<tr>
<th>Key system achievements</th>
<th>Relevant features</th>
<th>Further research needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Safety Criteria</td>
<td>· Includes pilot and ATCo perspectives.</td>
<td>· Incorporate Load Factor variations&lt;br&gt;· Further validation (not trivial), with more experts&lt;br&gt;· Find severity for combinations of upset parameters</td>
</tr>
<tr>
<td>R-WAKE Integrated Simulator System</td>
<td>· Based on background enhanced simulators&lt;br&gt;· WEPS partially validated</td>
<td>· WVS models in different weather conditions&lt;br&gt;· More aircraft models in WIAM&lt;br&gt;· Validation with real flights</td>
</tr>
<tr>
<td>Dynamic Risk Models</td>
<td>· Analogue to RECAT to support the en-route safety cases</td>
<td>· Probability Risk models taking into account position uncertainty&lt;br&gt;· Integration with AIM models for SRM&lt;br&gt;· New models to assess the risk in sectors or in ECAC</td>
</tr>
<tr>
<td>R-WAKE Safety and Robustness (SRA) approach</td>
<td>· Fully aligned with the methodologies and requirements of ESSAR4, SAME and SESAR SRM</td>
<td>· Include more effort on analysing Systems, Human Factors and Procedures&lt;br&gt;· Generate evidence and safety requirements for higher maturity levels&lt;br&gt;· Wider systemic approach (including AIMs analysis)</td>
</tr>
</tbody>
</table>
### Maturity Assessment
#### Preliminary Conclusions

<table>
<thead>
<tr>
<th><strong>Potential new OIs:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The <strong>R-WAKE-1 Concept (OCD)</strong> presents good potential for enhancing current <strong>separations</strong>, in terms of safety, capacity and flight efficiency.</td>
</tr>
<tr>
<td>Several OIs can be defined from the baseline proposed (ANSPs could adapt the OIs to their different needs and capabilities)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Potential new Enablers:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The <strong>R-WAKE System as a new safety tool</strong> (e.g., to develop new safety standards)</td>
</tr>
<tr>
<td>The <strong>R-WAKE System as concept-prototype of new real-time DSTs</strong> for ATCOs and/or pilots (dynamic separations)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Maturity:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>We have <strong>identified and quantified some ATM needs</strong> and we propose a Validation <strong>Strategy</strong> (goals of V0).</td>
</tr>
<tr>
<td>Proposed Concept to be formally assessed in ER/IR gate by mid March: <strong>partial V1 expected</strong></td>
</tr>
<tr>
<td>Some R-WAKE elements may be at higher TRL (TRL-2,3) (e.g., <strong>WEPS</strong>)</td>
</tr>
</tbody>
</table>
Way forward in ER/IR programme
R-WAKE Potential Next Steps
Concept development step-wise

Like RECAT, R-WAKE can take a step-wise approach:

- New aircraft category-wise and geometry-wise minima wake separation
  - Static MWS
  - Wind-dependent MWS
- New pair-wise geometry-specific wake minima separation
- And ultimately, dynamic pair-wise encounter-specific wake minima separation

- Need to consider wind and atmospheric conditions from the start (e.g. tropopause altitude)

- **RWAKE-1**: R-MWS-CATwise-GEOMwise
- **RWAKE-2**: R-MWS-CATwise-GEOMwise-WINDdep
- **RWAKE-3**: R-MWS-PAIRwise-GEOMwise-WINDdep
## Way Forward, Strategy/Roadmap

Potential Next Steps to continue the Concept Research, Definition & Validation

1. Further Validation and consolidation of the results by cross-checking them with measured data.

2. Further develop the **Separation OI concepts** for near/medium term implementation
   - This timeframe could **initially** restrict the field of investigation to the **increased separations only**.

3. Further validation of the **reduced separations** (3NM, 500ft) robustness against different atmospheric conditions.

4. Investigate **operating conditions possibilities** including type of Airspace / Network and working Methods
   - Develop the **Unist Safety Case (USC) and Project Safety Case (PSC)** (e.g., adapting the OIs to a specific sector) and assess the **systemic risk** (ECAC/Airspace Sector wide)

5. Continue Research of **longer term concept OIs** (e.g. ADS-B data links and 4D environments) where it might be possible to envisage a cooperative mode ATCO/CREW
   - E.g., Dynamic Pairwise Separations, Avionic Subliminal Offsets, ...
SESAR Solution mapping
Overall preliminary conclusions

• There are no existing Solutions, OI Steps, Enablers etc. that exactly cover the scope of what we are researching.

• R-WAKE provides evidence for the recommendation of adding some OIs and Enablers related to the management of en-route wake vortex hazards.

• More recommendations could be done if the R-WAKE System is further developed as well as more R-WAKE Concept research conducted in the direction of new Enablers and OIs for SESAR Solutions.
Thank you for your attention
BACKUP slides
R-WAKE Partners roles

- **Project Coordination, System engineering & Weather Data**: qtd
- **Traffic and Flight dynamics simulation tools**: UPC
- **WV Simulation**: Technische Universität Braunschweig
- **Safety Analysis**: DEEPBLUE consulting & research
- **WV & ATM Expert**: m3
- **Outcomes Assessment**: CBA, ROI, ATM R&I roadmap
R-WAKE System
# RECAT background reference

Initial assumptions: RECAT-EU methodology as a reference

## RECAT-EU

<table>
<thead>
<tr>
<th>RECAT-EU scheme</th>
<th>“SUPER HEAVY”</th>
<th>“UPPER HEAVY”</th>
<th>“LOWER HEAVY”</th>
<th>“UPPER MEDIUM”</th>
<th>“LOWER MEDIUM”</th>
<th>“LIGHT”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leader / Follower</td>
<td>“A”</td>
<td>“B”</td>
<td>“C”</td>
<td>“D”</td>
<td>“E”</td>
<td>“F”</td>
</tr>
<tr>
<td>“SUPER HEAVY”</td>
<td>3 NM</td>
<td>4 NM</td>
<td>5 NM</td>
<td>5 NM</td>
<td>6 NM</td>
<td>8 NM</td>
</tr>
<tr>
<td>“UPPER HEAVY”</td>
<td>3 NM</td>
<td>4 NM</td>
<td>4 NM</td>
<td>5 NM</td>
<td>7 NM</td>
<td></td>
</tr>
<tr>
<td>“LOWER HEAVY”</td>
<td>3 NM</td>
<td>(*)</td>
<td>3 NM</td>
<td>3 NM</td>
<td>4 NM</td>
<td>6 NM</td>
</tr>
<tr>
<td>“UPPER MEDIUM”</td>
<td>3 NM</td>
<td>3 NM</td>
<td>4 NM</td>
<td>5 NM</td>
<td>6 NM</td>
<td></td>
</tr>
<tr>
<td>“LOWER MEDIUM”</td>
<td>4 NM</td>
<td>5 NM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“LIGHT”</td>
<td>4 NM</td>
<td>3 NM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: RECAT-EU WT distance-based separation minima on approach and departure

(*) means minimum radar separation (MRS), set at 2.5 NM, is applicable as per current ICAO doc 4444 provisions.
RWAKE System: Method view
(flow chart inspired in RECAT’s)

Characterization of Wake Generation
1. Aircraft Characteristics
2. Meteo conditions
3. Dynamic WV Simulation (WVS)

Characterization of Wake Impact
4. Severity Metric: 6DoF upset calculation (WIAM)
5. Determine Vortex Strength under ICAO Standards for Each Aircraft Pair
6. Safety Considerations
7. Establish the Allowed Severity at Potential Encounter for Each Follower

(Re)Categorization Methodology
8. Determine New Separations (V or H) for Each Aircraft Pair (and according to different Encounter Geometry Patterns)
9. Traffic Mix & flow geometries
10. Optimize Aircraft Categories for Capacity Increase
11. Additional Safety Considerations
12. Expert Review and Adjustments
13. Calculate Capacity Increase

Key differences with RECAT
Dynamic model

Severity Metric:
RECAT: 1D (RMC) vs RWAKE: 6DoF

Reasonable Worst Case (RWC) definition with Expert Panels

Vortex characteristic behaviour per Aircraft generator type
Vortex Circulation (Model) [m2/s]
Vortex Age (model) [s]

A310
B744
xxx
xxx

Aircraft Clustering into Categories and Separation adjustments to keep RMC under a limit for all the Aircrafts

(Concept-Development)

SESAR 2020 - Exploratory Research
R-WAKE System: Integrated Simulation Platform
(based on previous background simulation modules)

INPUTS:
- Scenarios
- Conops
- R-WAKE Scenarios to Study:
  Research Questions towards the R-Wake Concept proposal

OUTPUTS (research):
- Separation Standards & Separation Methods to be assessed
- Separation Standards & Separation Methods Assessment & Enhancement proposal

R-WAKE SYSTEM
- Simulation Framework

Traffic Simulator
- Traffic & Traject. Planner
- WVE Region Finder
- WVE Prediction

WIAM: WVE Interaction Assessment Model
- MICRO
- MACRO

Safety & Robustness Analysis
(Metrics & Methodologies)

Results Assessment
(Concept & System Feasibility and CBA)

Database of Simulation Results

Weather Data Provision
- Weather For Flight Dynamics
- Weather Data For WV-Sim
R-WAKE System: framework view

R-WAKE system as a **framework of methods & tools** for the simulation and analysis of safety and robustness of En-route Wake Turbulence Hazard to support the development of new separation standard concepts.

### 3 levels

#### L1

ATM CONOPS

Needs and Opportunities
Scoping and prioritizing the Research Objectives. Business Case

#### L2

CONCEPT SAFETY ASSESSMENT METHOD

#### L3

MODEL & SIMULATION / VALIDATION TOOLING

Evidences Consolidation by background literature, Modeling and Simulation, & Expert Judgement.

---

**Safety & Robustness Analysis (SRA)**

- Project Safety Case
- Unit Safety Case
- Severity baseline And Tolerability Matrix
- Risk Assessment

**Tools (to generate supporting evidences)**

- Fast-Time Simulation Framework
- Micro scale simulation
- Macro scale simulation
- uDB
- mDB
- Expert Judgement (Panels)
- Literature Review

---

**Concept Definition / Standard Development methodology**

- Research Areas (RA)
- Research Questions (RQ)
- Concept Definitions (OCD)
- Study Scenarios (SCN)

**Simulation Plan**

- Design of Experiments (DoE)
- (Role of Concept Validation Plan)

**Results Assessment**

- CBA
- Implement-ability
- Impact on ATM Roadmap

---

**Scoping & Requirements Definition Flow**

**Simulation Data & Validation Evidences Flow**
R-WAKE System: Safety Analysis Approach

**Concept Definition - Standard Development methodology**
- Research Areas (RA)
- Research Questions (RQ)
- Concept Definitions (OCD)
- Study Scenarios (SCN)
- Simulation Plan Design of Experiments (DoE)
- Results Assessment & CBA

**SRA: Safety & Robustness Analysis**
(Based on ESARR4 + SESAR SRM tailored)
- USC "Unit Safety Case"
- PSC "Project Safety Case"

**Mapping to Simulator Use**
- Micro SM Upset Severity Assessment (WIAM)
- Macro CIR Individual Risk (WEPS & WVS)
- DoE Macro SAR Traffic pattern per Area (full integrated simulator)

**Severity Assessment & Matrix**
- Quantitative (Model-based Risk Modelling)
- Qualitative (Experts Panels – Pilots & ATCOs)

**Risk Occurrence Frequency measures**
- (Model based quantitative)

**Benefit (Capacity & Efficiency) measures**

**L1**
- Simulation Plan Design of Experiments (DoE)

**L2**
- USC "Unit Safety Case"
- PSC "Project Safety Case"

**L3**
- Micro Simulation (One Encounter Scenario case)
- Macro Simulation (Traffic per area Scenario case)
R-WAKE System: Risk Assessment and Risk Models

Macro analysis to assess CIR
(multiple experiments reproducing 1 WVE each with different a/c pair and geometries)

Severity-micro assessment:
Wake vortex model used: 4D tube containing all potential vortex positions and gammas within a 95% confidence

CIR Risk Profiles
Find the reasonable worst-case severity for a given WVE (Conditional individual risk probabilistic estimation)

Risk Map of RWCs
Reasonable worst-case severity (at 95% confidence) for each possible WVE condition.

SAR Risk Profile: Frequency assessment (occurrences count)
Find the frequency of each type of WVE in the ATM scenarios simulated, and group by severity class (P-RNAV navigational errors considered)

Macro analysis to assess SAR
(few experiments finding potential WVEs in traffic)
R-WAKE System as a Safety tool
The SESAR SRM broader approach to safety assessment

Minimum achievable risk
Risk with R-WAKE Standards
What we want R-WAKE Standards to do
Risk without R-WAKE Standards

Risk R

Risk to traffic (Without ATS)

Desired risk reduction with new concept

Concept

Induced risk

What we want the new concept to do

What we don’t want the system to do

~1/Integrity

~ Functionality & Performance

Safety improvement with new concept

ATS Risk Reduction (currently)

Current Risk to traffic

A new concept is introduced

Unit Safety Case

Project Safety Case

Risk = f(severity, probability)
R-WAKE System: WIAM tool
Computing the dynamic response of the aircraft interacting with a Wake Vortex: Upset parameters derivation

Lateral and vertical deviations and airspeed changes.

Attitude and rotational velocity changes.

Linear and rotational acceleration changes

Angle of attack, sideslip angle, flight path angle and flight path azimuth angle changes.

Maximum upsets obtained in the coaxial encounter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude change</td>
<td>43 m</td>
</tr>
<tr>
<td>Bank angle</td>
<td>0.65403 rad</td>
</tr>
<tr>
<td>Rate of Climb/Descent</td>
<td>12.471 m/s</td>
</tr>
<tr>
<td>Airspeed change</td>
<td>2.0987 m/s</td>
</tr>
</tbody>
</table>
R-WAKE System: Upset Severity Assessment &
Expert Panel

WIAM Micro-simulation Scenario selection to present the results to

- 20302 scenarios were simulated
- Only 12 presented to pilots and ATCOs
- Every scenario is considered according the following outputs:
  - Maximum change in altitude
  - Maximum change in the bank angle
  - Maximum change in the airspeed
  - Maximum change in the vertical speed
R-WAKE System: Simulators

Trajectory Planner (TP) module

Example of trajectory from EHAM to LEBL

The result is a set of trajectories non deconflicted
R-WAKE System: Simulators
Weather Module (WXM) integrated with the Trajectory Planner

Provide **accurate weather data** to both LPOM and VPOM modules

**Needed data:**
- $W_n(\varphi, \lambda, h, t)$
- $W_e(\varphi, \lambda, h, t)$
- $\tau(\varphi, \lambda, h, t)$
- $p(\varphi, \lambda, h, t)$

- **$W_n$:** north wind
- **$W_e$:** east wind
- **$\tau$:** temperature
- **$p$:** pressure
- **$h$:** altitude
- **$\varphi$:** latitude
- **$\lambda$:** longitude
- **$t$:** time
R-WAKE System: Simulator modules
WakeVortex Simulator (WVS)

Inputs:
• Flight trajectories (in 4D)
• Weather

4D tube
R-WAKE Research Performed Simulations
Simulation-based research process

**R-WAKE Hazard Study**
- **UPSET study**: 6 independent variables, 20,328 scenarios performed
  - WV Circulation
    - WV Gamma
  - Aircraft Follower:
    - AC-f-Type (index)
    - AC-f-Mass
    - AC-f-Speed
    - AC-f-Altitude (FL)
    - AC-f-Heading
- **CIR study**: 15 independent variables, 874,800 scenarios performed
  - Geometries: (3H x 1Vg x 3Vf)
  - Separations: (dL x dHL x dHO)
  - Aircraft pairs: (5 Gen x 4 Follow)
  - Aircraft conditions: (Mass, Speed, Altitude)
  - Meteo conditions: Atmos-Stratification-Id, Atmos-Turbulence-Id
- **SER study**: Unit Safety Case of Current Separation Standard
  - 10 days scenarios ECAC-wide from EVAIR reference
    - Current Separation
      - Flight Profileless
      - FLs Config (AOMs)
- **WV study**: 6 independent variables, 900 scenarios performed
  - Aircraft Generator:
    - AC-Gen-Type (index)
    - AC-Gen-Mass
    - AC-Gen-Speed
    - AC-Gen-Altitude (FL)
  - Meteo condition:
    - Atmos-Turbulenced
    - Atmos-Stratification
- **SAR study**: Project Safety Case of New Concepts
  - 1 scenario of peak traffic flow in UK/Italy route airspace
    - New Separation Rules
      - Flight Profileless
      - FLs Config (AOMs)

**R-WAKE Concept Development**

SESAR 2020 - Exploratory Research
DoE for Micro analysis of Upset

**WV object exploration plan**

- **Generator a/c Type**
  - Values (4): \{ A320-212, A330-301, B772LR, A380-841 \}

- **WV Relative Circulation (%)**
  - Range: [33%, to 100%], step=33%
  - Values (3): \{ 33%, 66%, 100% \}

- **WV Sink Angle (deg)**
  - Range: [-5 to 5], step=5
  - Values (3): \{ -5, 0, 5 \}

- **WV Core Radius (m)**
  - Values (1): \{ 0.035b \}

- **WV Spacing (s)**
  - Values (1): \{ 0.8b \}

**Follower WV-Encounter exploration plan**

- **Follower a/c Type**
  - Values (1): \{ A320-212 \}

- **Follower Rel. Mass (%)**
  - Range: [OEW+0.8MPL, MTOW]
  - Step: \( \frac{MTOW-(OEW+0.8*MPL)}{2} \)

- **Follower airspeed (mach)**
  - Range: \[ M_{MRC}, M_{MO} \]
  - Step: \( \frac{M_{MO}-M_{MRC}}{2} \)

- **Follower Altitude (FL)**
  - Range: [200, ceiling]
  - step: \( \frac{\text{ceiling}-200}{2} \)

- **Follower Rate of Climb (ft/min)**
  - Range: [-1000, 1000], step=500
  - Values (5): \{ -1000, -500, 0, 500, 1000 \}

- **WVE Geometry**: 4 x 3 geometries

  - **Follower Relative Track (deg)**
    - Range: \[ 0, 90 \]
    - step=45; 2 target points when 0°
    - Values (4): \{ 0.a, 0.b, 45, 90 \}

  - **Follower Rate of Climb (ft/min)**
    - Range: [-1000, 1000]
    - step=500
    - Values (5): \{ -1000, -500, 0, 500, 1000 \}

**WIAM UPSET Calculator**

- **Upset**
  - 5 vars:
    - Max Delta Altitude
    - Max Delta Roll (BankAngle)
    - Max Delta Altitude/dt
    - Max Delta Roll/dt
    - Max Load Factor

- **Context Vars**:
  - A/C Thrust Excess

**Micro Data Analysis**

- Expert Judgement Purpose:
  - Upset identification and severity assessment
## DoE for Macro CIR-SHA risk maps generation

### Study Parameters

<table>
<thead>
<tr>
<th>Study Aspect</th>
<th>Study Parameters</th>
<th>Number of Values</th>
<th>Study Values approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WVE Geometry</strong></td>
<td>Geometry H of follower</td>
<td>3</td>
<td>LONGITUDINAL, CROSSING, DIAGONALS</td>
</tr>
<tr>
<td></td>
<td>Geometry V of Generator</td>
<td>1</td>
<td>Generator flying level</td>
</tr>
<tr>
<td></td>
<td>Geometry V of Follower</td>
<td>3</td>
<td>Follower climbing, flying level, descending</td>
</tr>
<tr>
<td><strong>Separation to Test</strong></td>
<td>Longitudinal separation</td>
<td>6</td>
<td>WVE point + sigma (dHL is calculated from WV trajectory and dV)</td>
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<tr>
<td></td>
<td>Cross-track separation</td>
<td>1</td>
<td>Target points (assuming SLOP)**</td>
</tr>
<tr>
<td></td>
<td>Vertical separation*</td>
<td>15*</td>
<td>Scan (From - to - by) (0 to Max-WVV-decay by 100). Depends on WV geometry.</td>
</tr>
<tr>
<td><strong>Aircraft Pair</strong></td>
<td>Generator Aircraft type</td>
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<td>Follower Aircraft type</td>
<td>4</td>
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</tr>
<tr>
<td><strong>Aircraft Condition</strong></td>
<td>Generator Altitude (FL)</td>
<td>3</td>
<td></td>
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<tr>
<td></td>
<td>Generator Mass (% MTOW)</td>
<td>2</td>
<td>NC &amp; RWC</td>
</tr>
<tr>
<td></td>
<td>Generator Speed</td>
<td>1</td>
<td>NC &amp; RWC as function of Mass and Altitude</td>
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<tr>
<td></td>
<td>Follower Mass (% MTOW)</td>
<td>1</td>
<td>NC</td>
</tr>
<tr>
<td></td>
<td>Follower Speed****</td>
<td>1</td>
<td>NC as function of Mass and Altitude</td>
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<td><strong>Meteo Conditions</strong></td>
<td>Atmos. Stratification (Temperature profile)</td>
<td>3</td>
<td>Enumerated list (tabulated)</td>
</tr>
<tr>
<td></td>
<td>Atmos. Turbulence (EDR)</td>
<td>3</td>
<td>Enumerated list (tabulated)</td>
</tr>
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<td></td>
<td>Wind-Horizontal</td>
<td>1</td>
<td>A-posteriori analytic</td>
</tr>
<tr>
<td></td>
<td>Wind-Vertical</td>
<td>1</td>
<td>A-posteriori analytic</td>
</tr>
</tbody>
</table>

**Estimated Expected Total WEPS runs**: 874.800

**Resulted Final Number of WV Encounters scenarios computed (WEPS runs)**: 583.632

Among other variables, we studied different separations.

---

**SESAR 2020 - Exploratory Research**
R-WAKE Separation Standards (Proposals)

Factors considered in the definition of MWS.

In VERTICAL plane:

A. Follower climbing
   A1. Generator climbing ahead
   A2. Generator flying level
   A3. Generator descending ahead

B. Follower flying level
   B1. Generator climbing ahead
   B2. Generator flying level – crossing above level in opposite direction
   B3. Generator descending ahead

C. Follower descending
   C1. Generator climbing ahead
   C2. Generator flying level
   C3. Generator descending ahead

In HORIZONTAL plane:

H.1
H.2
H.3
H.4
H.5

Obtuse
Chasing
Acute
Crossing
Head-on

H.2
H.3
H.4
H.5

V.A1
V.A2
V.A3
V.B1
V.B2
V.B3
V.C1
V.C2
V.C3

dH range: 5-25NM
Concept Development
(OI illustrative use cases)
R-WAKE-1 Concept
Typical ATC radar view

Velocity vector set at 1 min look-ahead time (can be set by the ATCO to other values)

Rough wake trail representation
R-WAKE-1 Concept
Potential applications

- **Combined Separations** in flows to facilitate the quantification of capacity and efficiency that can be obtained, and the link with ATC (integrity analysis)

1) The PSC should *compress traffic in 4D* to increase capacity

2) The risks of PSC will be *benchmarked with historical traffic* (USC) to develop a new standard

3) Still *room for flight optimisation*: "the lighter the higher"
R-WAKE-1 Concept
Potential applications

- Reductions of Vertical separation *(possibly combined with horizontal)*

1) We expect different opportunities for FL reduction depending on the aircraft categories
2) D-VSM opens opportunities to support new ATM concepts to increase capacity and efficiency
3) Could be combined with horizontal separations
4) Explore VS = 500 ft for all FLs
R-WAKE-1 Concept

Potential applications

• Reductions of Horizontal separation (parallel and longitudinal)
  • In the future: **RNP-1** (+/- 1NM max deviation the 95% of the time)
  • **Parallel tracks** (not necessarily following routes, e.g., free-route conops): 3NM could provide a robust separation of 6 sigma with respect to the navigational standard error, and it might be still acceptable for ATC controllability

Note: the use of parallel lanes, since they allow overcomes between flights, can also facilitate the sequencing and merging at the coordination points of the sectors that feed TMAs and airports.

• **Longitudinal:** It may be also interesting to be able to compress the traffic one behind the other, in same level or below.
R-WAKE-1 Concept

Potential applications

- Reductions of Horizontal separation and opportunities to increase capacity
  - In the future: RNP-1 (+/- 1NM max deviation the 95% of the time)

1 upper route – 4 lanes: robust separation of 6 sigma with respect to the navigational standard error, and it might be still acceptable for ATC controllability

1 upper route – 3 lanes: even more robust separation and perhaps easier to manage

The use of parallel lanes, since they allow overcomes between flights, can also facilitate the sequencing and merging at the coordination points of the sectors that feed TMAs and airports.
R-Wake1: Use Case Examples

Horizontal separation

Option 2: 2 sub-upper air route by nominal airway

12 NM

6 NM between different upper air route

6 NM between sub-upper air route

TOP view
R-Wake1: Use Case Examples
Horizontal separation

Option 3: 1 sub-upper air route by nominal airway

12 NM

6 NM between different upper air route
3 NM between sub-upper air route

TOP view
R-Wake1: Use Case Examples

Longitudinal separation
in follower flying levelled
in crossing/diagonal geometries

Flight F should not be at the crossing point earlier than a certain time (TBS). Time can be converted to distance if an average speed is assumed for F.
R-Wake1: Use Case Examples

Longitudinal separation in follower flying levelled in crossing/diagonal geometries

Flight F could be vectored to another point to avoid a potential conflict, but the required longitudinal distance at the crossing point to protect against a potential WVE will be always the same.
R-Wake1: Use Case Examples

Longitudinal separation in follower flying climbing or descending in crossing/diagonal geometries – Case A (head-on descending crossing FL ahead)

Flight G in the same track as F wants to descend and cross the FL used by F. The ATCo should only clear the manoeuvre of G if longitudinal separation for F is guaranteed (if dO = 0)
R-Wake1: Use Case Examples
Longitudinal separation in follower flying climbing or descending in crossing/diagonal geometries – Case B (head-on descending crossing FL behind)

Flight F in the same track as G wants to descend and cross the FL used by G, crossing behind. The ATCo should separate the traffic F longitudinally (if dO = 0)
R-Wake1: Use Case Examples

Longitudinal separation in follower flying climbing or descending in crossing/diagonal geometries – **Case C** (head-on climbing crossing FL ahead)

Flight G in the same track as F wants to climb and cross the FL used by F. The ATCo should only clear the manoeuvre of G if longitudinal separation for F is guaranteed (if \( dO = 0 \))
R-Wake1: Use Case Examples

Longitudinal separation in follower flying climbing or descending in crossing/diagonal geometries – Case D (head-on climbing crossing FL behind)

Flight F in the same track as G wants to climb and cross the FL used by G. The ATCo should separate the traffic F longitudinally (if dO = 0)
R-Wake1: Use Case Examples
Combined separations in dense flows

dV = 500 ft
dO = 1-3 NM
Combined separations in dense flows
One-directional routes

Wind < 50kts

dO = 3 NM & dV = 500 ft
Combined separations in dense flows
Bi-directional routes

Wind < 50kts

\( dO = 3 \text{ NM} \)

\( \& \ dV = 500 \text{ ft} \)
Combined separations in dense flows
Super-High Density flows v1

dO = 3 NM & dV = 500 ft
dO = 6 NM
Combined separations in dense flows
Super-High Density flows v2

dO = 1.5 NM & dV = 500 ft
dO = 3 NM
Maturity Assessment to ER/IR Gate
# The SESAR 2020 ER-IR Criteria

<table>
<thead>
<tr>
<th>Thread</th>
<th>Criteria ID</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPS</td>
<td>OPS.ER.1</td>
<td>Has a potential new idea or concept been identified that employs a new scientific fact/principle? Have the basic scientific principles underpinning the idea/concept been identified? Does the analysis of the &quot;state of the art&quot; show that the new concept / idea / technology fills a need?</td>
</tr>
<tr>
<td>OPS</td>
<td>OPS.ER.2</td>
<td>Has the new concept or technology been described with sufficient detail? Does it describe a potentially useful new capability for the ATM system?</td>
</tr>
<tr>
<td>OPS</td>
<td>OPS.ER.3</td>
<td>Are the relevant stakeholders and their expectations identified?</td>
</tr>
<tr>
<td>OPS</td>
<td>OPS.ER.4</td>
<td>Are there potential (sub)operating environments identified where, if deployed, the concept would bring performance benefits?</td>
</tr>
<tr>
<td>SYS</td>
<td>SYS.ER.1</td>
<td>Has the potential impact of the concept/idea on the target architecture been identified and described?</td>
</tr>
<tr>
<td>SYS</td>
<td>SYS.ER.2</td>
<td>Have automation needs e.g. tools required to support the concept/idea been identified and described?</td>
</tr>
<tr>
<td>SYS</td>
<td>SYS.ER.3</td>
<td>Have initial functional requirements been documented?</td>
</tr>
<tr>
<td>PER</td>
<td>PER.ER.1</td>
<td>Has a feasibility study been performed to confirm the potential usefulness of the new concept / idea / Technology being identified?</td>
</tr>
<tr>
<td>PER</td>
<td>PER.ER.2</td>
<td>Is there a documented analysis and description of the benefit and costs mechanisms and associated Influence Factors?</td>
</tr>
<tr>
<td>PER</td>
<td>PER.ER.3</td>
<td>Has an initial cost / benefit assessment been produced?</td>
</tr>
<tr>
<td>PER</td>
<td>PER.ER.4</td>
<td>Have the conceptual safety benefits and risks been identified?</td>
</tr>
<tr>
<td>PER</td>
<td>PER.ER.5</td>
<td>Have the conceptual security risks and benefits been identified?</td>
</tr>
<tr>
<td>PER</td>
<td>PER.ER.6</td>
<td>Have the conceptual environmental benefits been identified?</td>
</tr>
<tr>
<td>PER</td>
<td>PER.ER.7</td>
<td>Have the conceptual Human Performance aspects been identified?</td>
</tr>
<tr>
<td>VAL</td>
<td>VAL.ER.1</td>
<td>Are the relevant R&amp;D needs identified and documented?</td>
</tr>
<tr>
<td>TRA</td>
<td>TRA.ER.1</td>
<td>Are there recommendations proposed for completing V1 (TRL-2)?</td>
</tr>
</tbody>
</table>
Way forward in ER/IR programme
R-WAKE Potential Impacts on ATM Master Plan – OI steps & enablers

- The current ATM Master Plan has no **Operational Improvement Steps (OI Step)** directly related to en-route wave vortices.

- An **analysis of the current released ATM Master Plan data** (“Dataset 16”) reveals 22 OI Steps dealing with wave vortices of which:
  - 16 relate specifically to arrival and departure management at airports;
  - 1 relates to arrival/departure in TMA;
  - 2 relate to the use of digital data exchange or on-board detection systems for pilot management of wave vortices;
  - 2 deal with the provision of systems to exchange wave vortex related data); and,
  - 1 dealing with wave vortex data being used by Arrival/Departure/Surface Manager systems.

- It is envisaged that **R-WAKE will recommend new OI Steps and related Enablers** for inclusion in future ATM Master Plans. These are likely to be in the area of Conflict Management, for example,
  - “**Static-Category-wise separation management for wave vortex encounters in en-route**”
  - “**Automated controller tools for pre-deconfliction of wave encounter risks in en-route**”.

SESAR 2020 - Exploratory Research
Links to SESAR Solutions, European ATM
Architecture and ATM Master Plan

- SJU identified Operational Improvement Step AUO-0505; Improved Air safety using data exchange via e.g. ADS-B for Wake Turbulence prediction
- This is one of 21 wake turbulence related OI Steps in the Master Plan DS16 – all are in arrival/departure phase of flight and not directly relevant to the R-WAKE scope
- An outcome of R-WAKE is to identify potential new OI Steps and related Enablers for inclusion in future SESAR Solutions and associated ATM Master Plan
- Existing OI Steps give an indication of the types of OI Step we may propose depending on macro-analysis results e.g.
  - Wake turbulence separations (en-route) based on static/dynamic aircraft data;
  - Dynamic adjustment of en-route spacing depending on Wake turbulence;
  - Wake turbulence (en-route) conflict detection and resolution
- Possibly contributes to SESAR 2020 Solutions in some Operating Environments, e.g.:
  - PJ.01-03 Dynamic and Enhanced Routes and Airspace
  - PJ.10-02a Improved performance in Provision of Separation and PJ.10-02b Advanced Separation Management
  - PJ.11-G1 Enhanced Ground-based Safety Nets adapted to future operations
  - Note: PJ.02-01 Wake turbulence separation optimisation is specifically for arrival and departure operations
- The macro-analysis will refine the R-WAKE operational concept to identify associated Enablers (system, procedural and statutory)
- OI Steps and Enablers provide ability to identify traceable links to EATMA data elements (Capability Configurations, Services, Systems etc.) and SESAR Solutions
R-WAKE Potential Next Steps

How to use results in the next phase (ER/IR)

1. The idea of looking for new static standards could be further explored in some regions of interests (also below current RVSM airspace, i.e., below FL290)
2. The system for real-time evaluation of hazards could be further developed, towards dynamic real-time risk evaluation and dynamic pairwise separations
3. The models are key in the safety case, thus they should be further refined and validated (especially WV and WIAM components, and the risk models)
4. The Severity Matrix and the SHAs require further validation and refinement
5. The quantification of system risk at sectors with realistic conditions would be possible with the R-WAKE system and would be compliant with ESSAR4 (ANSPs risk assessment)
6. New opportunities arise with the R-WAKE concept to potentially increase the ATC capacity, the traffic efficiency and the quality of service:
   - New FLAS/FLOS schemes, possibly dynamic, can contribute to organize the traffic and constraints so that capacity and flight efficiency could be optimized
   - The new FLAS/FLOS together with new parallel lanes and/or combined separations give more flexibility (and complexity) in the optimization process
Thank you for your attention