Optimising Runway Throughput through Wake Vortex Detection, Prediction and decision support tools

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Abstract— **Currently at many airports, runway is the limiting factor for the overall throughput. Among the most important parameters are the fixed wake turbulence separation minima expressed in time for take-off clearance and by distance for arrivals on final approach. This wake turbulence separation limits the arrival and departure flow on many airports in Europe already today. Existing departure and arrival wake turbulence separations are sometimes considered over conservative as they do not take into account meteorological conditions likely to shift, reduce or alleviate their circulations. This paper will present the main aspects of a SESAR project that defines, analyses and develops a verified wake turbulence system according to related operational concept improvements in order to, punctually or permanently, reduce landing and departure wake turbulence separations and, therefore, to increase the runway throughput in such a way that it safely absorbs arrival demand peaks and/or reduces departure delays. This global objective will be achieved by means of developing a wake vortex decision support system able to deliver in real time position and strength of the wake vortices and to predict their behavior and potential impact on safety and capacity, taking in account actual weather information as well as the airport specific climatological conditions, aircraft characteristics (generated wake vortex and wake vortex sensitivity) and airport runways layout. These functionalities will be progressively included in the wake vortex decision support system to be validated and deployed on airports in order to optimize the runway throughput and reduce delays.**

Keywords- airport, wake-vortex, safety, radar, lidar

I. INTRODUCTION

Aircraft creates wake vortices in different flying phases. To avoid jeopardizing flight safety by wake vortices encounters, time/distance separations have been conservatively increased, thus restricting runway capacity. The concern is higher during taking off and landing phases, as aircraft are less easy to maneuver. These vortices usually dissipate quickly (decay due to air turbulence or transport by cross-wind), but most airports operate for the safest scenario, which means the interval between aircraft taking off or landing often amounts to several minutes. However, with the aid of accurate wind data and precise measurements of Wake Vortex, more efficient intervals can be set, particularly when weather conditions are stable. Depending on traffic volume, these adjustments can generate capacity gains, which have major commercial benefits.

Wake vortices are a natural by-product of lift generated by aircraft and can be considered as two horizontal tornados trailing behind the aircraft. A trailing aircraft exposed to the wake vortex turbulence of a lead aircraft can experience an induced roll moment (bank angle) that is not easily corrected by the pilot or the autopilot. However these distances can be safely reduced with the aid of smart planning techniques of future Wake Vortex Decision Support Systems based on Wake Vortex detection/monitoring and Wake Vortex Prediction (mainly transport estimation by cross-wind), significantly increasing airport capacity. This limiting factor will be significantly accentuated soon with the arrival of new heavy aircrafts: Airbus A380, stretched version of Boeing B747-8.

Radar and Lidar Sensors are low cost technologies with highly performing complementary wake-vortex detection capability in all weather conditions compared to others sensors that suffer of limited one. Radar and Lidar are promising sensors for turbulences remote sensing on airport, for all kinds of aviation weather hazards (wake vortex, wind-shear, micro-bursts, atmospheric turbulences) with ability to work operationally in a collaborative way, in different severe weather conditions like fog, rain, wind, and dry air.

II. WAKE VORTEX HAZARDS

The Wake Vortices shed by an aircraft are a natural consequence of its lift. The wake flow behind an aircraft can be described by near field and far field characteristics. In the near field small vortices emerge from that vortex sheet at the wing tips and at the edges of the landing flaps.

After roll-up the wake generally consists of two coherent counter-rotating swirling flows, like horizontal tornadoes, of about equal strength: the aircraft wake vortices.

Empirical laws model tangential speed in roll-up. Classically, velocity profile (tangential speed at radius r) is defined by :

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r}\left(1 - e^{-f\left(\frac{r}{B}\right)}\right) \quad (1)$$

where Γ_0 is called circulation. This Wake Vortex Circulation Strength (root circulation in m^2/s) is proportional to Aircraft mass M and gravity g, inversely proportional to air density ρ, Wingspan B and Aircraft speed V [1] with $s = \pi/4$:

$$\Gamma_0 = \frac{M.g}{(\rho.V.s.B)} \quad (2)$$

Additional factors that induced specific dynamic of wake vortices: Wind Shear Effect (stratification of wind), Ground Effect (rebound), Transport by Cross-wind & Decay by atmospheric turbulence and Crow instability

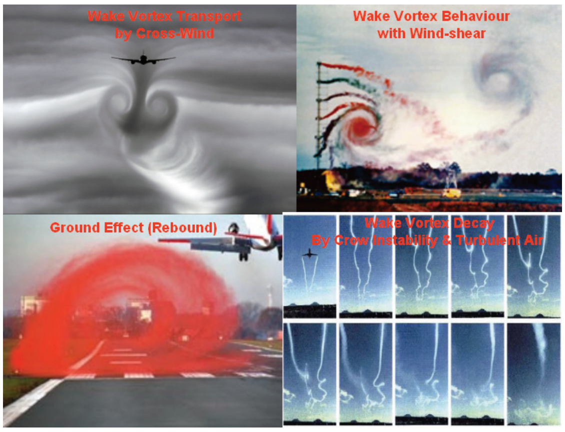

Figure 1. Wake-Vortex Dynamic & behavior

III. Project Phases of Wake Vortex Decision Support System Development

Wake Vortex Decision Support System Architecture will be defined and validated during the following development phases of P12.2.2 SESAR project:

- **Phase 0**

The preliminary system architecture will include wake vortex sensors and weather sensors. During this task, a theoretical study and a sensors benchmark campaign will be performed in Paris CDG airport (XP0 campaign) in order to select the needed sensors set. The recommendations on sensor technology selection and deployment delivered by this task will be used to refine the system architecture in the following phases.

- **Phase 1 - Time-Based Separation (TBS)**

The aim is to verify the position, strength and behavior of the wake vortices depending on headwind strength in arrivals in order to evolve from distance based separation to time based separation. As well, a first release of the Wake Vortex Decision Support System prototype will be developed, which will demonstrate this capability. This demonstration will include an in-situ verification campaign (XP1 in CDG).

- **Phase 2 - Weather Dependent Separation (WDS)**

The system will be updated with all the components linked to weather nowcast and forecast, including real-time prediction of micro-scale terrain-induced turbulence close to the airport. The goal is to assess in real-time the position and strength of the wake vortices and to predict their behavior for both departures and arrivals, in order to demonstrate the possibility to evolve from a time based separation to a weather dependent separation taking advantage of any favorable meteorological conditions (e.g. crosswind). This demonstration will include an in-situ verification campaign (XP2 in CDG). All building blocks regarding weather monitoring will be developed/customized.

- **Phase 3 - Pair Wise Separation (PWS)**

The system will be refined to reach two main goals:

  - Perform a first demonstration of the pair wise separation concept. With a partial aircraft wake vortex characteristics database provided by P6.8.1, it will be demonstrated that the Wake Vortex Decision Support System could determine a dynamic pair wise separation, taking in account the real-time weather conditions as well as the aircraft sensitivity to wake vortex.

  - Demonstrate the system adaptability to other runway layouts.

These demonstrations will be performed in platform tests and verified in an in-situ campaign (XP3 in Frankfurt). Building blocks related to pair wise separation (aircraft characteristics database, algorithms…) will be developed or customized.

IV. Preliminary System Architecture of Runway Wake Vortex Detection, Prediction and Decision Support Tools

The system architecture development is based on SESAR requirements in term of safety & operational use ANSPs & EUROCONTROL Advices & requirements will be also taken into account.

Since no operational Wake Vortex Decision Support System (WVDSS) are currently available, this first framework architecture is based on existing building blocks coming from partners.

The Wake Vortex Decision Support System (WVDSS) receives as main external inputs:

- The information flow (from the **ATC & Airport centers**) describing the current traffic and aircraft data. This function provides the air traffic flow situation to the WVDSS.
- The standard information related to Weather situation (**Meteo Center**) as provided by National Weather Forecast Services. The Meteorological Center provides data from the operational weather forecast model “LM” of national Weather Service (e.g.

METEO FRANCE, DWD…) covering most of Europe.

The system is in charge of elaborating Decision Aids to support:

- the Supervisor,
- the Approach Controllers,
- the Airport Tower Controllers.

HMI towards Supervisor and controllers are considered as outside WVDSS Architecture.

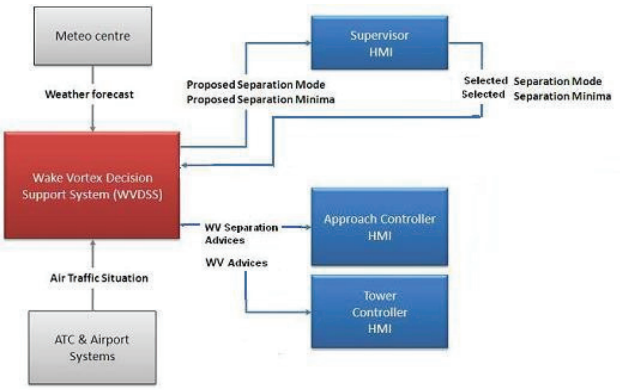

Figure 2. System Overview

Components of Runway Wake Vortex Detection, Prediction and Decision Support Tools are the followings :

A. *Local Meteorological Sensors function*

A combination of sensors, which are typically weather dependent, will be used for wind & air turbulence monitoring.

The local meteorological measurements are used for weather nowcast and forecast, through following parameters:

- Mean wind: three wind components and wind variability,
- Turbulence: measured as the Turbulent Kinetic Energy (TKE) or Eddy Dissipation Rate (EDR) level of the atmosphere,
- Virtual potential temperature: temperature stratification

B. *Wake Vortex Sensors function*

The wake vortex measurements will be performed with two complementary sensors, one X band radar and one 1.5 micron Lidar. The rational is that Lidar sensor performances are limited in adverse condition as in rainy or foggy weathers.

The ability of Radar to detect & monitor Wake Vortices in rainy weather will complement Lidar in adverse weather situations.

Radar and Lidar are good complementary sensors, which can be used for turbulence remote sensing as well. They are able to work in a collaborative way, in different weather conditions like fog, rain, strong wind, turbulent atmosphere and dry air.

C. *Local Weather Nowcast/Forecast function*

Local Weather Nowcast & Forecast function will be able to predict atmospheric state variables within a coverage area of e.g. 100x100 km² centered on the airport with an increasing vertical spacing from e.g. 25 to 50 m throughout the boundary layer. Output variables are vertical profiles of horizontal and vertical wind, virtual potential temperature, turbulent kinetic energy (TKE) and eddy dissipation rate (EDR).

D. *Wake Vortex Advisory System function*

The Wake Vortex Advisory System (WVAS) will be composed of:

- an input/output (I/O) module,
- a separation mode planner module,
- a wake vortex predictor module,
- a monitoring and alerting module

The Wake Vortex Advisory System will be able to:

- Propose the separation mode to the supervisor e.g. ICAO or reduced separation and time applicability of separation mode
- Process wind data including turbulence information and system track to provide spacing (chevron position for display purpose)
- Monitor Wake Vortices (Wake Vortex Predictor output) against system tracks and provide Encounter Advisories to controllers HMI for display purpose in case of actual or predicted danger,
- Manage the wake vortex data (4D data) from Wake Vortex Sensors function. In case of discrepancies between wake-vortex sensors and predictor, an alert is generated.

The Decision Support System functional architecture is described in the following figure:

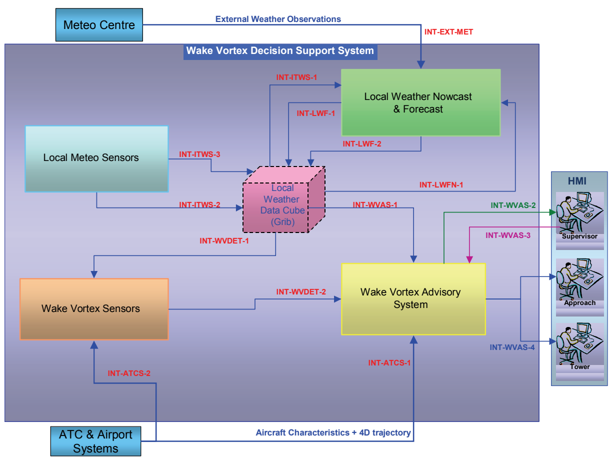

Figure 3. Decision Support System functional architecture

V. SENSORS SIMULATORS

To study best sensor parameters/modes tuning and best sensors deployment on airport, simulators are mandatory. A custumized 1.5 µm Lidar Wake-Vortex Simulators will be developed with UCL (Belgium). Radar Wake-Vortex Simulator activity is relatively new and specific tasks are actively engaged on their development: in collaboration with UCL (Belgium).

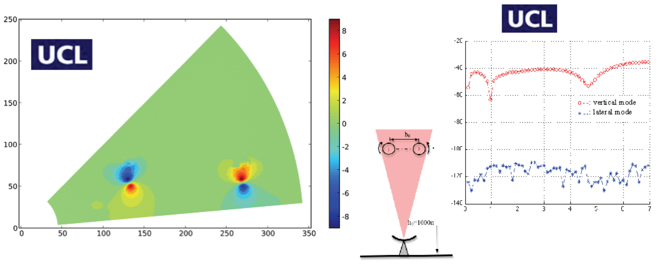

Figure 4. Wake-Vortex Lidar Sensor Simulator (on the left) Wake-Vortex Radar Sensor Simulator (on the right)

VI. WEATHER & ATMOSPHERIC TURBULENCES MODELS

Meteo-France will develop a new advanced Weather Forecast Model (resolution: 500 m) for airport applications :

Meteorological High-Resolution Prediction System (MHRPS)

MHRPS development will be based on the French non-hydrostatic AROME model. The MHRPS will be implemented on the Meteo-France super-computer and will assimilate not only dedicated airport sensors data but also all the routine data coming from the European Meteorological Infrastructure

MHRPS Requirements are the following:

- Required parameters: Horizontal and vertical wind (U, V, W), Temperature (T), Humidity (Hu), Eddy Dissipation Rate (EDR), Surface Pressure (PS);
- Required horizontal resolution: 500 m;
- Required coverage area: 100x100 km² centered on the airport;
- Required vertical resolution: 10 m up to 100 m, 100 m up to 1000 m, 1000 above;
- Required forecast horizon: 3 h;
- Required frequency of forecast outputs: 5';

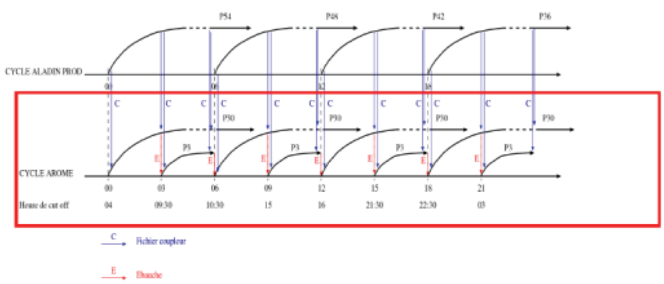

Figure 5. Sensors Data ingestion in Weather Forecast Models

NATMIG will develop Turbulence Forecast Model (grid resolution: 100 m). A Reynolds averaged Navier-Stokes model (SIMRA) has been developed by NATMIG member SINTEF in order to predict local wind and turbulence around airports.

Forecast EDR/TKE model will be adapted for airport infrastructure (buildings,…)

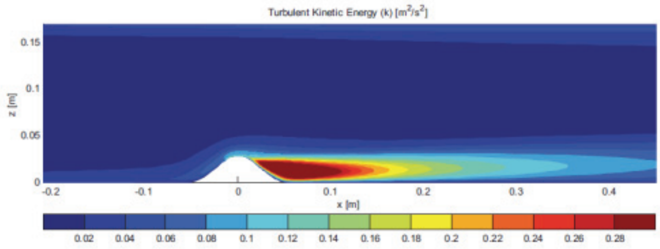

Figure 6. Turbulent Kinetic Energy forcasted by NATMIG model

The MHPRS software of METEO FRANCE and the «Turbulences Calculation» of NATMIG will update the «Local Weather Data Cube». The data stored in « Local Weather Data Cube » are computed by MHPRS within a volume centered on airport containing following areas of interest for all trials XP0, XP1 and XP2:

- Airspace allowed for landing (green color),
- Airspace allowed for taking off (white color),
- Airspace where dense traffic (arrival) is expected (blue color)

Within the volumes, the data are provided by the MHPRS for the grid points whose characteristics are:

- Latitude: 48.6N to 49.4N with a quantum of 0.005° (160pts with an horizontal resolution of 550m)
- Longitude: 2.08N to 2.98N with a quantum of 0.005° (180pts with an horizontal resolution of 360m)

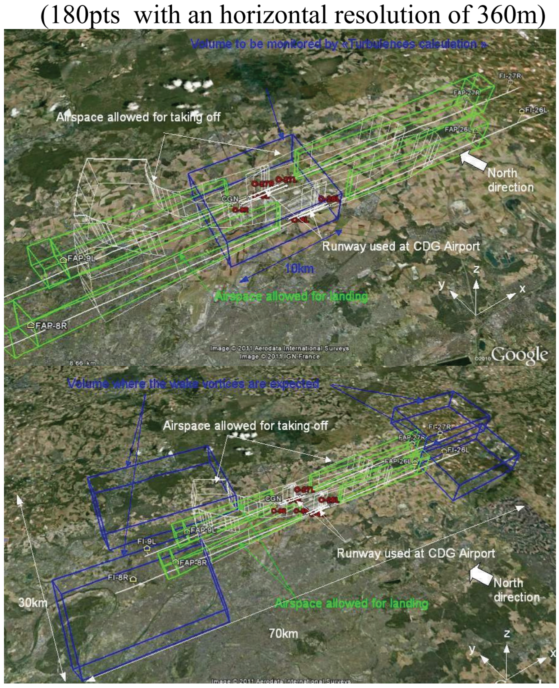

Figure 7. Area of Interests & Volumes of Weather Data Cubes

VII. DERISKING 2008 TRIALS AND SESAR XP0 CAMPAIGN AT PARIS CDG AIRPORT

In derisking phase in 2008 [3-6], THALES BOR-A radar has been deployed at Paris CDG Airport, and co-localized with a Eurocontrol 2 µm Lidar. In a first step, antenna was used in a staring mode for vertical exploration by exploitation of 4° beamwidth. In the following figure, wake vortex detection are illustrated by Doppler entropy in time/range coordinates axes in rainy weather. After each departures on the first nearer runways, wake vortex are monitored.

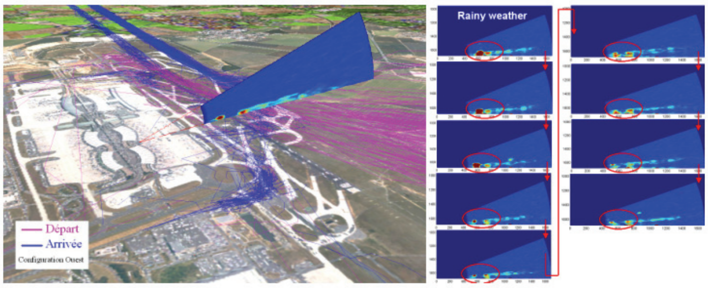

Figure 8. wake vortex roll-ups tracking from scan to scan in rainy weather

In vertical scanning mode, individual roll-up of each wake vortex were tracked in range and elevation axes. In previous figure, above the first nearer runway, wake vortex generated by aircraft during departure can be observed. These detections of wake vortex are coherent with classical behavior close to the ground. Each roll-up from scan to scan (with one scan every 5 seconds) can be tracked as proved by the trials. Close to the ground, trajectory of each roll-up can finely and accurately been followed and their strength been estimated by circulation computation.

More recently, from mid-May to end of June 2011, first XP0 Sensors Campaign of SESAR P12.2.2 have been done at Paris CDG Airport with the following sensors :

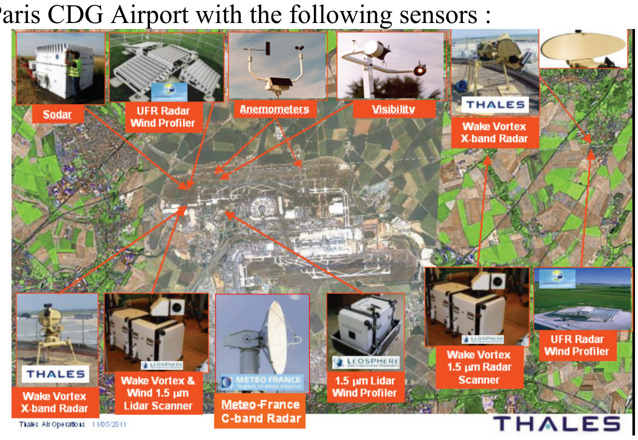

Figure 9. SESAR P12.2.2 XP0 Sensors Campaign at Paris CDG Airport

- **Wake Vortex sensors :** X band radar BOR-A (THALES), Windcube 200S scanner Lidar (LEOSPHERE) [8-9]
- **Weather sensors :** Windcube 70 wind profiler Lidar (LEOSPHERE), C band weather radar (METEO FRANCE), SODAR (METEO FRANCE), UHF Wind Profiler radar-PCL1300 (METEO FRANCE), UHF Wind Profiler radar-PCL1300 (DEGREA)

Figure 10. THALES Wake-Vortex X-band Radar Sensor Deployment

Figure 11. DEGREANE UHF Radar Wind Profiler Deployment

Figure 12. Meteo-France UHF Radar Wind Profiler Deployment

Figure 13. LEOSPHERE Lidar Wind Profiler Deployment

Figure 14. LEOSPHERE Wake-Vortex Lidar Deployment

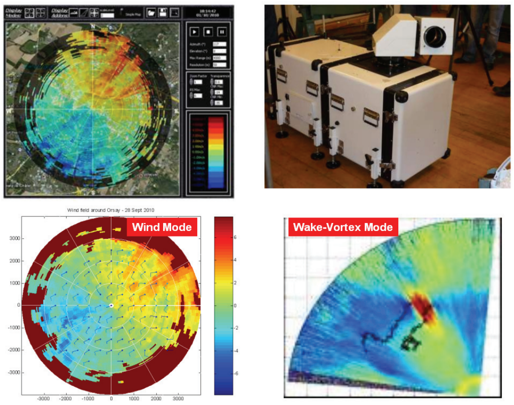

Figure 15. LEOSPHERE W200 Lidar : Wind & Wake-Vortex Modes

In the following figure, Recording coordination during Paris CDG XP0 trials to prepare XP1 are illustrated.

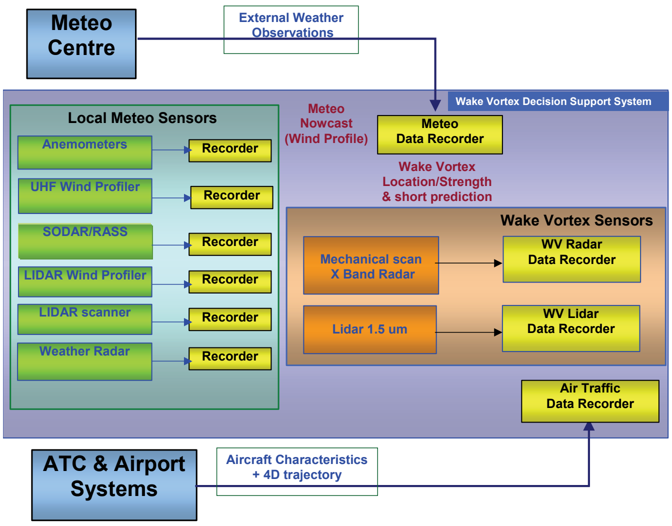

Figure 16. Recordings coordination for XP0

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http://www.sesarju.eu/

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http://www.wakenet.eu/index.php?id=21

http://www.wakenet.eu/index.php?id=125

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