Radar 3D Monitoring of Wake-Vortex Hazards, Circulation and EDR Retrieval/Calibration

SESAR P12.2.2. and FP7 UFO Sensors Trials at Paris-CDG & Toulouse Airports

Frederic BARBARESCO, Patrick BRUCHEC, David CANAL, Philippe JUGE, Mathieu KLEIN
Jéremy MAINTOUX, Fabrice ORLANDI, Cédric RAHATOKA, Yves RICCI, Jean-Yves SCHNEIDER
BU Advanced Radar Concept, Surface Radar
THALES AIR SYSTEMS
F-91470 Limours, France
frederic.barbaresco@thalesgroup.com

***Abstract*—At airports, runway operation is the limiting factor for the overall throughput; specifically the fixed and overly conservative ICAO wake turbulence separation minima. The wake turbulence hazardous flows can dissipate quicker because of decay due to air turbulence or be transported out of the way on oncoming traffic by cross-wind, yet wake turbulence separation minima do not take into account wind conditions. Indeed, for safety reasons, most airports assume a worst-case scenario and use conservative separations; the interval between aircraft taking off or landing therefore often amounts to several minutes. However, with the aid of accurate wind data and precise measurements of wake vortex by radar sensors, 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. This paper presents Electronic scanning radar trials as Safety Net of a wake turbulence system supporting increased throughput as part of the European ATM research program SESAR, and complementary study UFO (Ultra-Fast wind sensOrs for wake-vortex hazards mitigation) funded by European FP7 program, on Radar EDR retrieval & Calibration.**

***Keywords*— wake-vortex hazard, airport capacity, airport safety, X-band radar, wake-vortex circulation, eddy dissipation rate**

I. Introduction

All aircraft naturally generate wake vortices as soon as there is lift. Wake vortices can be considered as two horizontal spiraling tubes trailing behind the aircraft and invisible to the human eye. A trailing aircraft exposed to the wake vortices of a lead aircraft can experience an induced roll moment that is not easily corrected by the pilot or the autopilot.

To avoid jeopardizing flight safety due to encountering wake vortices from the leading aircraft, time/distance separations have been conservatively increased, therefore restricting runway capacity. The concern is higher during the most critical phases of take-off and landing. The wake vortices typically dissipate quickly (e.g., through decay by turbulence or transport by cross-wind), but most airports operate for the safest scenario; this means the interval between aircraft taking-off or landing often amounts to several minutes. To define more efficient intervals, smart planning techniques are integrated in a decision aid tool for the air traffic controller called Wake Vortex Decision Support System (WVDSS). This system relies on both the detection and monitoring of wake vortices and the prediction of their transport by cross-winds, both driving factors to the capacity limitations. Specifically, accurate wind data and precise measurements of wake vortex are required, as well as an assessment of the stability in time of favorable conditions.

Depending on traffic volume, these adjustments can generate capacity gains, which have major commercial benefits for both the airlines and the airport. In particular, the limitation of capacity from wake turbulence is significantly accentuated 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 and complementary wake-vortex detection capability to cover all weather conditions. Furthermore, the use of these sensors can be extended to sense other types of atmospheric turbulence in the airport domain, such as wind-shear and micro-bursts. Their complementarity provides operational coverage for varied weather conditions such as fog, rain, wind, and clear air.

This paper initially paints the landscape for what constitutes wake-vortex hazards and why it is important to mitigate them in the airport domain. The Electronic scanning X-band Radar results for Wake-Vortex monitoring from the first validation campaign at Paris CDG airport in September/October 2012 are discussed in terms of achieved performance and lessons learned, while areas for improvement are highlighted. Recommendations for circulation (wake-vortex strength) retrieval and calibration from these trials are taken into account in the setup of new validation campaign coupled with use of radar simulator developed by ONERA and ISAE. We present new developments for joint retrieval and calibration of EDR (Eddy Dissipation Rate) that characterizes atmospheric turbulence inducing wake-vortex decay. Finally, the paper discusses further use of the Electronic scanning X-band radar for Wind/EDR algorithms validation at Toulouse Airport for FP7 UFO project, in coordination with 12 other partners and 4 associated partners.

II. WAKE-VORTEX HAZARDS

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 the 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, mostly horizontal and of about equal strength.

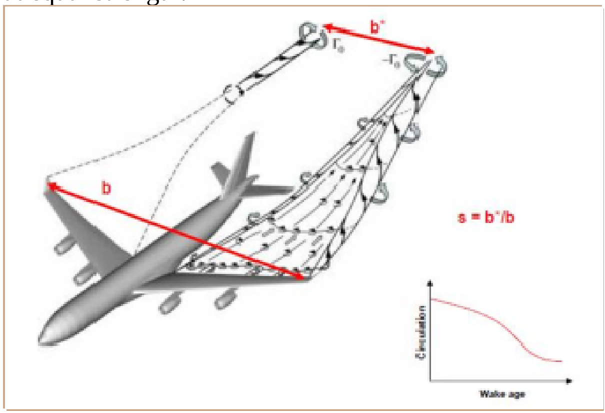

Fig. 1. *Wake-Vortex generation behind commercial aircraft*

Empirical laws model the tangential speed in roll-up: the velocity profile or tangential speed at radius *r*, is defined by:

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

The initial wake vortex circulation strength (i.e., the root circulation in m^2/s) is proportional to aircraft mass *M* and gravity *g*, and inversely proportional to air density ρ, wingspan *B* and aircraft speed *V* with almost $s=\pi/4$[1]:

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

There exist additional factors that impact the dynamic behavior of wake vortices, including wind-shear effect (stratification of wind), ground effect (rebound), transport (by cross-wind), decay (by atmospheric turbulence) and Crow instability.

Critical area of wake-vortex encounter is localized at low altitude. But these areas are also characterized by complex behavior of Wake-Vortex Hazards due to Ground Effect:

- *Wake vortex behavior differs significantly depending on altitude*: in high altitude, out of ground effect, wake vortex behavior is affected by the wind, but remains stable and predictable by "Wake-Vortex Predictor". At low Altitude, Ground effect can lead to unexpected wake vortex behavior. These phenomena are very difficult to predict and to model.
- *In Ground Effect, Wake Vortices Behaviors are driven by very instable causes*: rebound of vortices on the ground, strength enforcement of 1 Vortex due to low level wind-shear induced by airport infrastructure, generation of secondary vortices, and decay of wake-vortex due to low altitude atmosphere stratification

Fig. 2. *Wake-Vortex dynamics and behavior in case of Ground effect*

Because of high severity of Wake-Vortex Encounter at low altitude where wake-vortex have also complex behaviour due to ground effect, it is very important and requested to monitor wake-vortex by sensors in all weather conditions.

III. SESAR TRIALS CAMPAIGN AT PARIS CDG AIRPORT: 3D RADAR MONITORING OF WAKE VORTEX

In the framework of SESAR P12.2.2. XP1 trials campaign, THALES has deployed in September/October 2012, an X-band Electronic-scanning radar at Paris CDG Airport to monitor wake-vortex during airplanes final approach. The X-band radar was localized 830 m perpendicular to the glide slope of runway 26L on the South-East area of CDG Airport. With an update rate lower than *10 s*, Wake-Vortex waveform was instrumented until less than *4 km*, with a spatial resolution of *5 m*, and Doppler resolution lower than *1 m/s*.

Fig. 3. *X-band Radar Deployment at Paris CDG Airport for SESAR*

X-band Radar was remotely controlled, and raw I&Q data were ingested in real-time to test wake-vortex algorithms online.

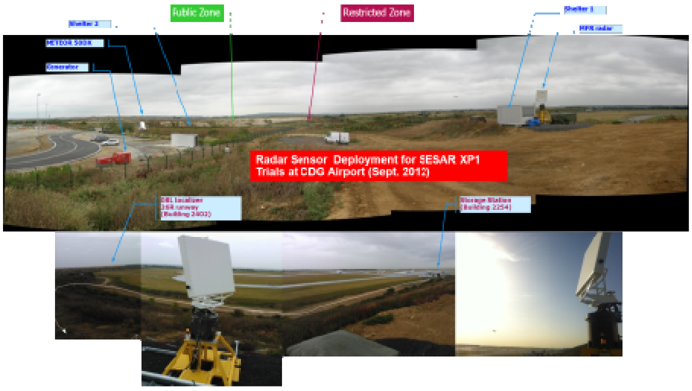

Fig. 4. *X-band Radar Deployment configuration with Remote Control*

Altitude of Aircraft on final approach for runway 26L in the glide slope perpendicular to the radar line of sight was lower than *100 m*, with a final speed around *65 m/s* to *70 m/s*.

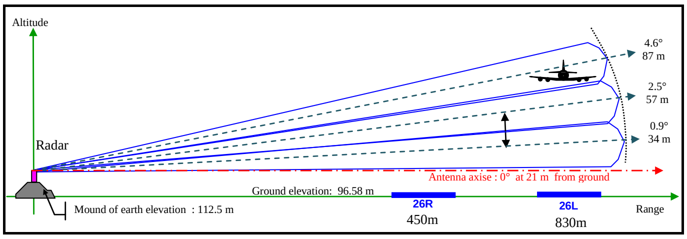

Fig. 5. *X-band Radar Beam steering in Elevation for Wake-Vortex detection*

The wake vortex radar detection is based on a Doppler analysis of raindrops signature, whose raindrops trajectory and distribution are driven by the wind flow induced by the two counter-rotating wake vortices. Raindrops act partially as tracers biased by their terminal speed velocity (size distribution vary with rain rate). For X-band, backscattering cross section of a raindrop is a function of its diameter (Rayleigh approximation). According to the Biot-Savart Law, the local flow velocity could be computed at sum of each roll-up contribution (modeled as Rankine, Lamb-Oseen or Hallock-Burnham velocity profiles). Wake-Vortex transport and circulation decay strongly depends on the atmospheric background such as crosswind, wind shear, ground effect, ambient turbulence and thermal stratification. These weather parameters were provided by Meteo-France MHRPS High Resolution Weather model (grid of *500 m* on horizontal plane).

The radar is able to detect wake vortices in all kind of rain, from drizzle to heavy (which is fully complementary to the Lidar performances), with a detection sensitivity at *2 km* of *–16 dBZ = 0.004 mm/h*. The radar was also able to detect in clear air in weather conditions of high humidity (these cases will be analyzed in future campaign by indexing performances with accurate humidity rate).

Doppler detection algorithm is based on measurement of local radial velocity shifts with Range-Doppler processing, in parallel to ambient velocity retrieval (also estimated by the weather mode). Wake-Vortex flow is characterized by local fast positive/negative Doppler speed transition.

For instance, for an A340 in landing phase, at a scanning azimuth angle of *-22°* (wrt plane orthogonal to the glide) with an ambient wind radial velocity of *–5 m/s*, a maximum local shift of ± *7 m/s* around ambient velocity has been measured, and a distance between two cores of around *45 m* (radial range).

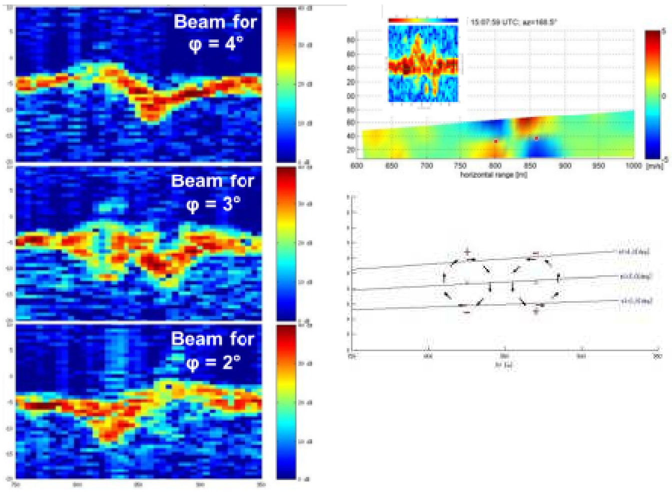

Fig. 6. *X-band Radar Doppler wake-vortex signature for 3 beams*

Results of Wake Vortex detection & localization campaign have proved that these hazards can be monitored in wet conditions with observation duration up to more than *60 s*. It was world first time, that wake-vortex were monitored in 3D on an airport.

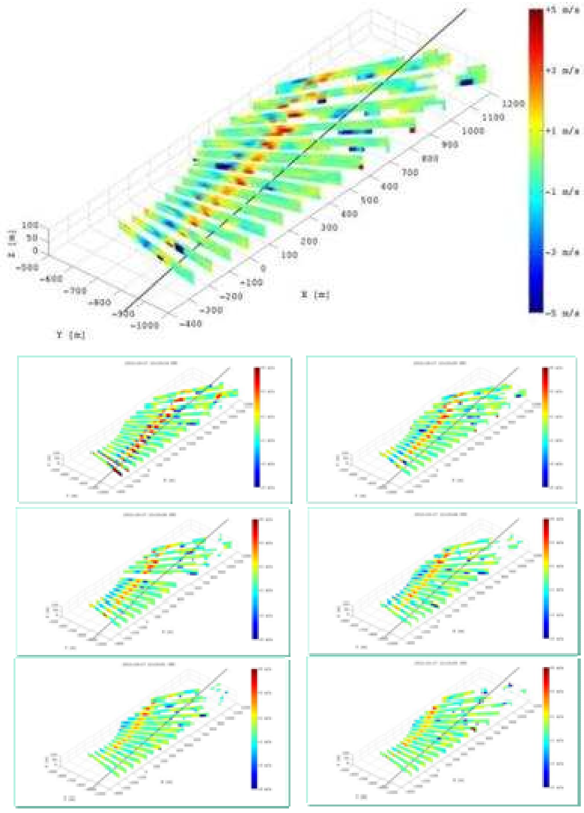

Fig. 7. *3D Monitoring (up) and time evolution every 8 s (down)*

In the following figure, wake vortices detection are displayed in the horizontal plane (position of the glide is given by the black dotted line). The algorithm distinguishes the "left" (in red) and the "right" (in blue) vortex; when not, the vortex plots are displayed in gray. The wake vortices are continuously detected on a length of about *1000 m*, some seconds after the aircraft's crossing. One can observe the important effect of cross wind on vortices.

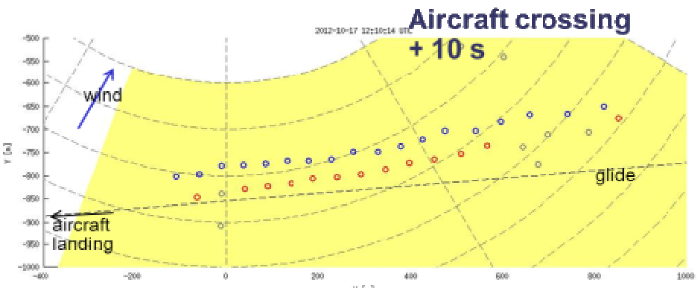

Fig. 8. *Wake-Vortex Radar detections in the horizontal plane*

Next figure is a vertical cut for the azimuth *155°* (i.e. *-20°* with respect to the orthogonal to the glide) displaying the horizontal (XY) range and the altitude (Z) versus vortex age.

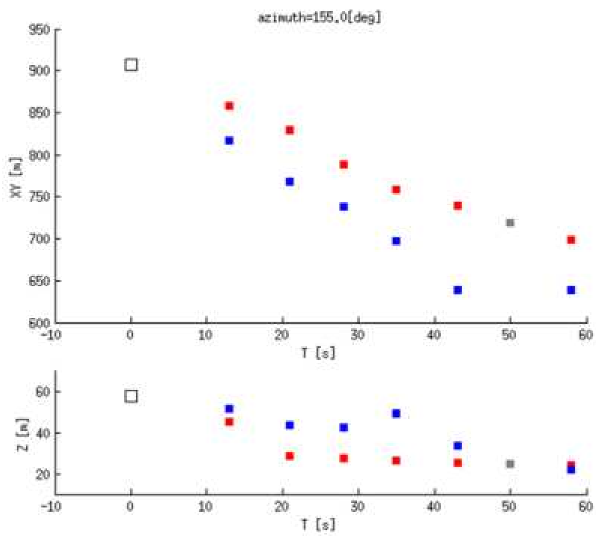

Fig. 9. *Wake-Vortex position in a vertical cut versus vortex age*

Due to the bias induced by raindrops inertia, wind speed flow in the vortex could not be directly measured by Doppler rain signature. Then, the strength of the vortex, the circulation cannot be retrieved directly. Circulation retrieval and calibration should be consequently approximated based on Radar simulation model indexed by rain rate.

IV. Wake-Vortex Circulation Retrieval and Calibration by Simulation

Thales has collaborated with ONERA and ISAE in Toulouse that has developed a Wake-Vortex Radar Simulator in rain. Firstly, the motion of raindrops in wake vortices has been modeled and simulated. The equation of the motion has been derived and the methodology to compute the raindrops trajectory and distribution in the flow induced by the wake vortices has been proposed.

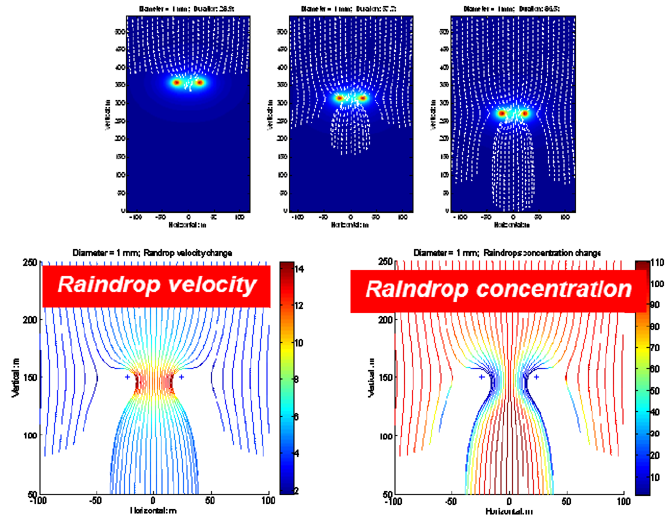

Fig. 10. *Simulation of raindrops trajectories, velocity and concentration*

Secondly, two simulators have been developed for evaluating the radar signatures of raindrops in wake vortices. One simulator is based on the simulation of radar signal time series, by superimposing the radar backscattered signal from each raindrop in the wake vortex region. The other one is based on the raindrops number concentration and velocity distribution in wake vortices, enabling the computation of radar signatures much more efficiently. Those simulators have been used to reproduce experimental configurations of THALES trials and the comparison between measured and simulated signature has shown very good agreement at X band.

Based on the computation of Doppler spectral moments, the radar signatures dependence on rain rate for different vortex circulation has been studied for different aircraft types.

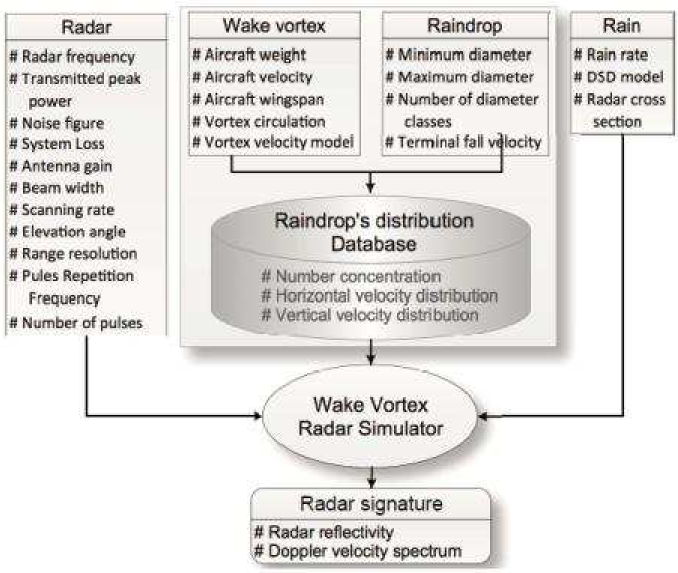

Fig. 11. *Wake-Vortex Radar Simulator in rain developped by ONERA-ISAE*

In the following figure, we illustrate Radar simulation of Doppler Spectrum in 3 successive range cells of *40 m* for 3 elevation angles (*3*°, *5*° and *7*°). We can observe widening of Doppler spectrum in radar cells with vortex.

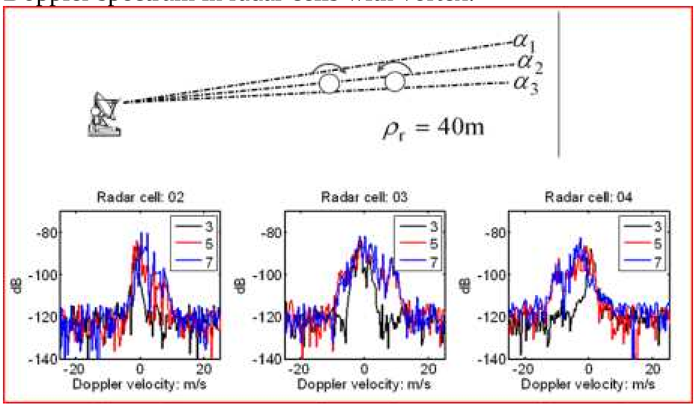

Fig. 12. *Wake-Vortex Radar Simulation at range resolution of 40 m*

We present the Doppler spectrum simulation at *5 m* range resolution, and its comparison with real recorded spectrum. We could observe a very good matching of simulation.

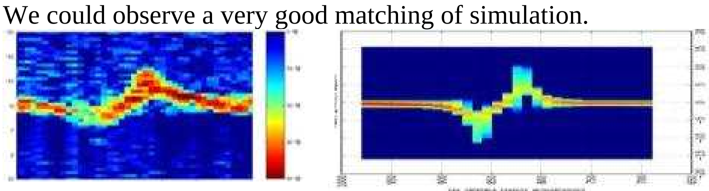

Fig. 13. *Real (at left) and simulated (at right) spectrum at 5 m resolution*

The dependence of raindrops trajectory on wake vortex circulation has been studied, showing that the motion characteristics of raindrops in wake vortices are representative of the vortex strength. In fact, wake vortex circulation has a determinative effect on the wake vortex velocity field, thus determining the raindrops motion and distribution in wake vortices. Therefore, it is very interesting to infer the underlying wake vortex circulation information from the radar signatures, based on analysis of radar signatures dependence on wake vortex circulation.

One of the most attractive conclusion is that the Doppler spectrum width of raindrops is representative of the wake vortex circulation, as vortex circulation decays, the Doppler spectrum width of raindrops is decreasing.

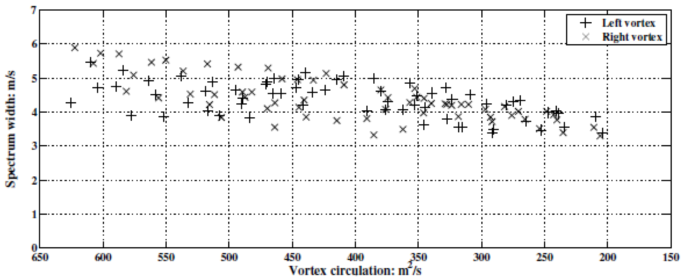

Fig. 14. *Simulation analysis of Doppler Spectrum Width versus Circulation*

V. EDR (Eddy Dissipation Rate) Retrieval and Calibration Study

An EU-funded technology study is conducted by THALES and 12 other European partners to address algorithms for EDR (Eddy Dissipation Rate) Retrieval and calibration . This study called UFO, for “UltraFast wind sensOrs for wake-vortex hazards mitigation” includes live-trials validation exercises at Munich and Toulouse airports. EDR is one the two main factors inducing circulation decay. In calm air (low EDR), wake circulation decreases slowly. On the contrary, in turbulent atmosphere, wake-vortices are rapidly destroyed with fast decay of their circulation.

For wake-vortex hazards mitigation on airport, operational request is to monitor wind and EDR at high update rate and at high spatial resolution in the glide slope at altitude lower than *500 m*. Above *500 m* in altitude, the air is more stable and can be accurately now-casted by new generation high resolution weather forecast system (e.g.: MHRPS from Meteo-France).

There are 3 causes of turbulences in the convective boundary layer:

- ***EDR generated by terrain roughness*** in Prandl layer: The Surface Boundary Layer SBL (Altitude < 100 m) is described by Logarithmic Wind Law (Prandl equation when condition of neutral stability is fulfilled)

$$U(z) = \frac{u_\tau}{\kappa}\ln\left(\frac{z}{z_0}\right), \quad EDR(z) = \frac{1}{\kappa}\frac{u_\tau^3}{z} \tag{3}$$

$$\begin{aligned} &U(z): \text{wind speed at heigh z} \\ &u_\tau: \text{the "friction velocity"} \\ &\kappa: \text{von Karman's constant } (\approx 0.38) \\ &z_0: \text{the roughness length} \end{aligned} \tag{4}$$

- ***EDR generated by obstacles***: Mechanical turbulence is caused by Airport buildings, or other large obstructions. When strong winds are bent around the obstacles, this creates the turbulence. When the wind is strong and pass over a large enough obstacles, they can create turbulent areas as high as 10 time obstacle height.

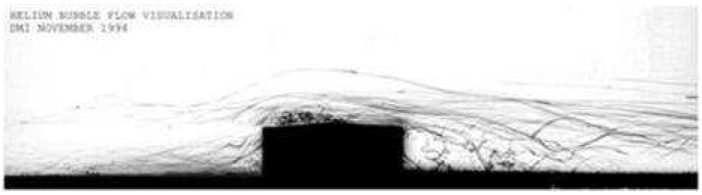

Fig. 15. *EDR/turbulence generated by Obstacles on airport*

- ***EDR generated by Ground Thermal Convection***: When the earth surface is heated by the sun, it will also heat the air directly above it. Since hot air is less dense than cool air, this heated air will rise from the earth surface to a higher elevation. This movement forces a vertical rotation of the air because the cooler air sinks to the bottom as the warm air rises. In the evening, the opposite occurs.

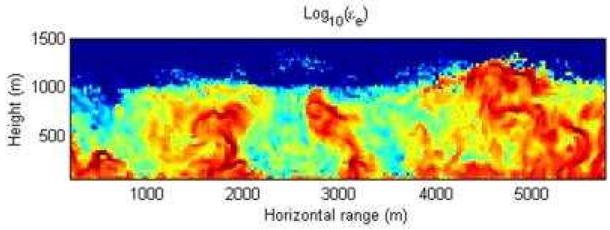

Fig. 16. *4D Simulation of Ground Thermal Convection by ISL (Prof. Cheinet)*

In April/May 2014, THALES has deployed X-band Electronic scanning radar at Toulouse Blagnac Airport for FP7 UFO project. Radar is localized in South of airport at *900 m* perpendicularly from the glide slope.

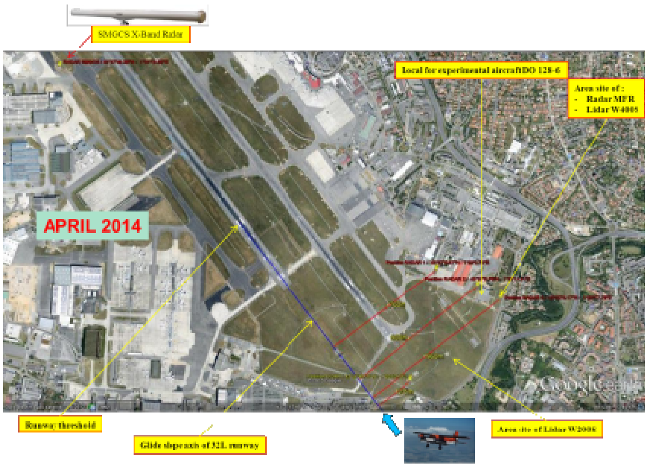

Fig. 17. *X-band Radar Deployment at Toulouse Airport for EDR monitoring*

The X-band radar will be used in rotating/staring modes, with interleaved short/long range waveforms for weather (EDR /Wind) monitoring or wake-vortex detection. In weather mode, the radar will scan *+/-30°* in azimuth and *0°-6°* in elevation in the glide slope until the maximum range of *10 km* (correspond to the requirement of *500 m* in altitude for a slope of *3°*).

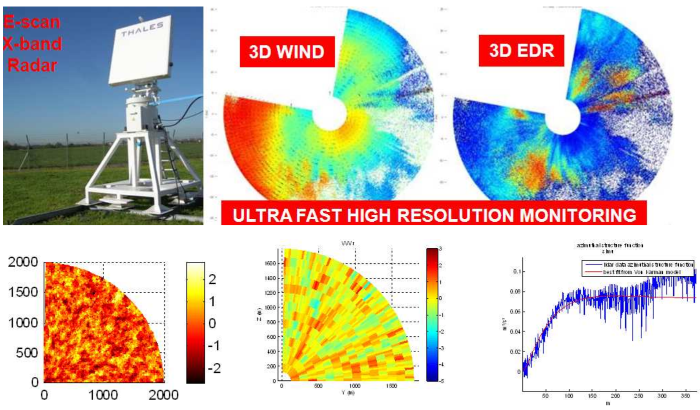

Fig. 18. *Ultra-Fast Electronic-Scanning Solid-State X-band Radar Monitoring of 3D Wind and EDR (by structure function) in the glideslope until 10 km*

For wake-vortex trials, a disdrometer developed by LATMOS has been used for the size distribution of raindrops measurement (up to 0 .1 mm). This reference accurate rain rate will be used to index Look-Up table ("Doppler Spectrum Width/Circulation") generated by radar simulator. These data will be used jointly to calibrate the simulator and define algorithm for Circulation retrieval from LUT based on Doppler signature measurement indexed by accurate rain rate.

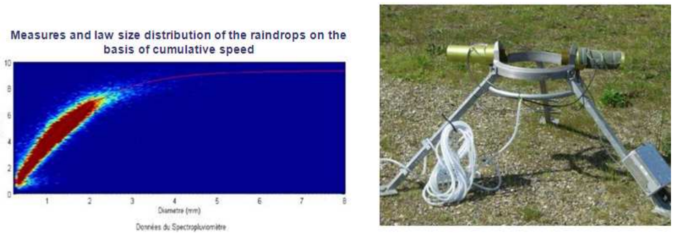

Fig. 19. *Distribution of raindrops (at left) measured by disdrometer (at right)*

VI. Conclusion

X-band radar performances are optimal under rainy/humid conditions. We have observed detection with high sensitivity of the effect of wake vortices on raindrops. Thanks to the good range resolution (*5 m*), we can have an accurate discrimination of the 2 vortices, even for small aircrafts. Radar performances are complementary with Lidar performances, providing capability of wake-vortex detection in all-weather conditions. In September 2014, Thales X-band Radar will be deployed during 1 year at Paris CDG airport to provide statistical figures on Radar performances in different weather conditions.

Acknowledgment

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