

Airport Radar Monitoring of Wake Vortex in all Weather Conditions

Frédéric Barbaresco

Thales Air Systems, Hameau de Roussigny, F-91470 Limours France

frederic.barbaresco@thalesgroup.com

Abstract— To assess maturity and capability of X-band radars to monitor wake roll-ups in all weather conditions, Radar data were collected on airports, near runway at ORLY airport and just under its ILS Interception Area. Additional trials took place on Paris-CDG Airport to benchmark Lidar & Radar Technologies. Continuous Detection, characterization and profiling capabilities of wake vortices, up to a range of 2000 m, have been proved in clear air and rainy weather. Recorded data have been correlated with electromagnetic and fluid mechanical models of Wake Turbulences for better and more accurate understanding of roll-ups radar cross section (RCS) and Doppler signature. X-band Radar has been proved to be a full-fledged alternative, which can make a significant contribution to a wake vortex alert system, but to achieve as much reliability as possible, collaborative Electro-optical & electromagnetic sensors solution is envisaged encapsulated in a Wake Vortex Advisory System. These sensors could be used to permanently monitor wake turbulence on runways.

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 manoeuvre. 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 after 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 Advisory 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 and the new stretched version of Boeing B747-8.

Radar Sensor is a low cost technology with highly performing wake-vortex detection capability in all weather conditions compared to Lidar sensor that suffers of limited one in adverse weather like rain or fog. Radar is a promising sensor 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 different severe weather conditions like fog, rain, wind, and dry air.

II. PHYSICS OF WAKE VORTEX HAZARDS

In this section, we will describe physics of Wake Vortex hazard and the origin of Wake Vortex radar cross section in clear air. These elements are important to analyze and understand Doppler Radar signature.

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.



Fig. 1 : Wake-Vortex Dynamic & behavior

Fluid dynamic of wake turbulence is modeled by Navier equations, that have been expressed in a new form by Jean Leray [1] that can be used for radar wake vortex signature analysis because new Leray's equation only depends on velocity u and no longer on pressure p . At $t = 0$, if we

assume that $\text{div}u = 0$, then velocity u is driven by :
 $\frac{du}{dt} = -(u \cdot \nabla)u + \nu \Delta u - \nabla p$. Using that $\Delta p = -\text{tr}(\nabla u)^2$,
 Leray has deduced new Navier equation :

$$D_t u(t, x) = \nu \Delta u - C_N \int_{R^N} \frac{x-y}{|x-y|^N} \text{tr}(\nabla u(t, y))^2 dy \quad (1)$$

This last equation drives speed evolution of wake vortices, but cannot be easily exploited to roll-up kinematic characterization. Alternatively, empirical laws will model tangential speed in roll-up. Classically, velocity profile (tangential speed at radius r) is defined by :

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r} \left(1 - e^{-r \left(\frac{r}{B} \right)} \right) \quad \text{where } \Gamma_0 \text{ is called circulation. This}$$

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

$$V [2] \text{ with } s = \pi/4 : \Gamma_0 = \frac{Mg}{(\rho \cdot V \cdot s \cdot B)} \quad (2)$$

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

III. THEORETICAL MODEL OF WAKE VORTEX RADAR CROSS SECTION

During 80's & 90's different Radar trials have been made in UK, France & US for wake vortex monitoring in clear Air with positive results for different bands (VHF/UHF/L/S/C/X bands) at short range (few kilometres). US radar campaigns are detailed by Gilson [8] and in K. Shariff & A Wray [7]. In Europe, joint radar trials have been made: Sheppard (1992)[3] with an S-band Radar, Bertin (1992)[4][5]: with an UHF-band Radar (961 MHz). In Gilson [8], it was observed that Wake Vortex RCS was relatively flat as a function of frequency. Particulates were not involved (they would give f^4 Rayleigh scattering). The frequency dependence was not the Kolmogorov $f^{1/3}$. Furthermore, the RCS measurement 1 Km behind the plane was insensitive to engine thrust and flat setting. In [7], tests have revealed radar echoes from aircraft wakes in clear air. In a turbulent velocity field the presence of mean vertical gradients of potential temperature and humidity lead to fluctuations in refractive index

Two main mechanisms causing refractive index gradients have been considered [7]:

A. Radial density gradient in the Vortex Cores: *The core of each vortex, which has a lower density and therefore lower index of refraction. Radial Pressure (and therefore density) gradient in a columnar vortex arising from the rotational flow. The RCS is due to a density gradient in a vortex arising from a balance of radial pressure gradient and centrifugal forces:*

$$(n-1)10^6 = 77.6 \left(\frac{P_a}{T} \right) + 64.8 \left(\frac{P_v}{T} \right) + 3.77610^5 \left(\frac{P_v}{T^2} \right) \quad (3)$$

B. Transport of atmospheric fluid in the oval surrounding the vortices: *The oval surrounding the vortex pair that transports atmospheric air from one altitude to another. As it descends, the fluid in the oval compresses adiabatically in response to increasing ambient pressure.*

$$[\tilde{n}(z) - \bar{n}(z)]10^6 = -\frac{\bar{\rho}(z)N^2}{g} \Delta z \left[223 + \frac{\overline{RH}(z)P_{sat}(T_z)}{\bar{P}(z)} \left(76.7 + \frac{3.49 \cdot 10^6}{\bar{T}(z)} \right) \right]$$

N : Brünt-Väisälä Frequency

(4)

Other potential causes of wake vortex reflectivity : There is another mechanism which could generate an echo, it is the collective distribution. This mechanism does not require discontinuities but only spatial fluctuations in the index. Spatial Fourier Transform of the optical index field characterizes the fluctuations. The fluctuations which provide the echo are the ones which correspond to a vector of wave \bar{k} of opposite steering to the vector of incident wave \bar{k}_0 and its number of wave is double: $\bar{k} = -2\bar{k}_0$. The turbulence generated by the vortex extends in all the scales up to the dissipation scale. The fluctuations scale that provides the collective distribution is 1.5 cm, a value very superior on the diffusion scale. So a part of the radar echo can be generated by the collective distribution. This effect increases the detectability of the vortex, but it can also change the interpretation of the successful signal, because then an echo can come even if there is no layer of discontinuity normal for the radar line of sight.

IV. X-BAND DOPPLER RADAR SIGNATURE OF WAKE VORTEX

We observe, on the Time/Doppler signature, slopes in Time/Doppler(speed) that can be interpreted by logarithmic spiral structure of wake vortex. Roll-ups are interlacing fences of air from surrounding and from higher altitude (adiabatic transport of fluid within vortex pair). When each roll-up rotates, range of reflecting points at each fence increase. According to Wake Vortex age and tangential speed law, this range evolution induced positive Time/Doppler slopes (young vortex), jointly positive/negative slopes (mature vortex), negative slopes (old & decaying vortices). In the following figure, spiral geometry of contra-rotating vortex roll-ups is illustrated. We can observe that roll-up curvature evolves with radius and time. For "young vortex", wake core is dense with high tangential speed increasing with radius. On the contrary for "old vortex", their cores have been destroyed by diffusion and tangential speed decrease with radius.

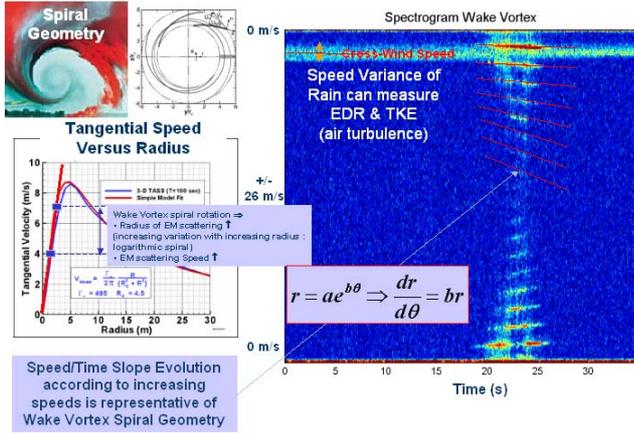


Fig. 2 : Time/Speed Slope Evolution representative of Wake Vortex (logarithmic) Spiral Geometry

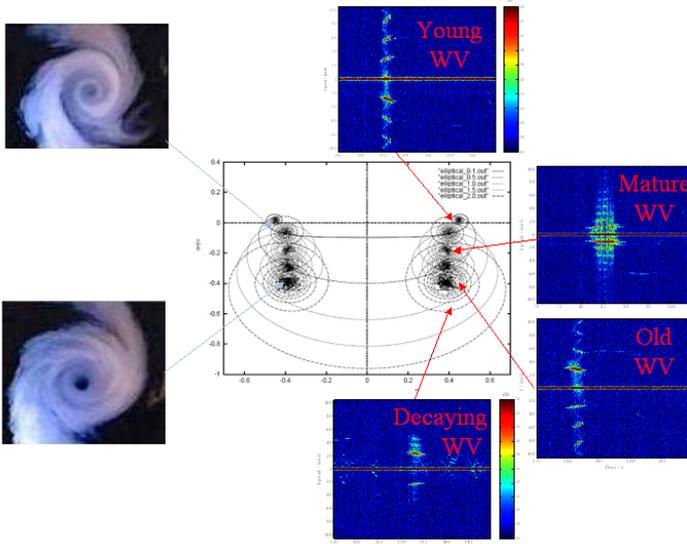


Fig. 3 : Evolution of Roll-up spiral geometry & Doppler spectrum (time/Doppler slopes) versus Age

Following figure shows the Doppler signature of a wake vortex in rainy weather, where we have similar signature for wet and dry air and same kind of reflectivity.

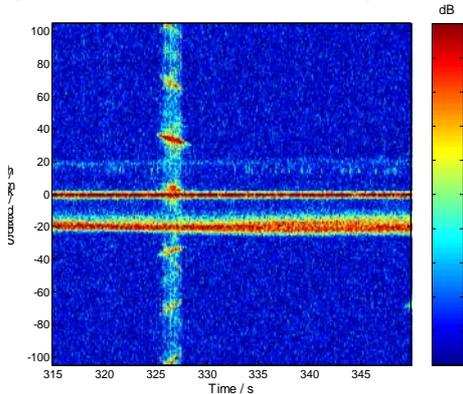


Fig. 4 : Time/Speed Slope Evolution representative of Wake in clear air (at left) and in Rain (at right)

V. ADVANCED DOPPLER PROCESSING CHAIN FOR WAKE VORTEX MONITORING

Based on recording of Doppler complex I & Q data, an advanced processing chain has been developed to:

- **Detect Wake Vortex** (in wet & dry conditions) at short range (<1.5 Km) in Scanning Mode (8°/s)
- **Localize Wake Vortex** in range/azimuth
- **Characterize Wake Vortex:** Geometry (Roll-up Spiral), Age & Strength (Circulation in m²/s)

Wake vortex detection is based on Regularized High Resolution Doppler analysis. For this function, we have developed and tested a highly sensitive detector based on High Resolution Doppler entropy assessment. First, radar cells are localized by a threshold on Doppler entropy, that is defined by mean of information geometry [10,11]:

$$S = \sum_{k=2}^{n-1} (n-k) \left(\frac{1}{2} \ln \left(\frac{1 + |\mu_k|}{1 - |\mu_k|} \right) \right)^2 \quad (5)$$

with $\{\mu_k\}_{k=2, \dots, n-1}$ reflection coefficient of complex regularized Autoregressive model.

For each cell that has been detected with potential hazard, Wake Vortex strength is deduced [6] from circulation computed from $S(V_i)$ the spectral magnitude of a Doppler

velocity bin, after previously applying CFAR on Doppler axis to extract Doppler peaks in spectrum :

$$\Gamma \propto \left[2 \int_{V_{\min}}^{V_{\max}} [S(V_i)]^{2/3} dV_i \right] / \left[\int_{V_{\min}}^{V_{\max}} [S(V_i)]^{2/3} dV_i \right] \quad (6)$$

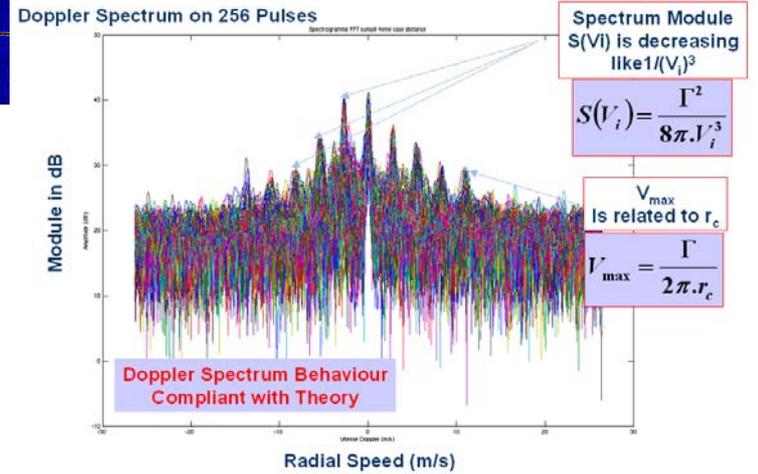


Fig. 5 : Doppler FFT for all radar cells in cas of wake vortex

VI. PARIS ORLY & PARIS-CDG AIRPORT CAMPAIGNS

Before deployment at CDG airport, some tests have been done in Orly by monitoring wake vortex in the glide slope of arrivals. During these first tests, wake vortex at altitude of 1500 m have been clearly detected and tracked from scan to scan in very turbulent atmosphere (capacity that is not available by Lidar).

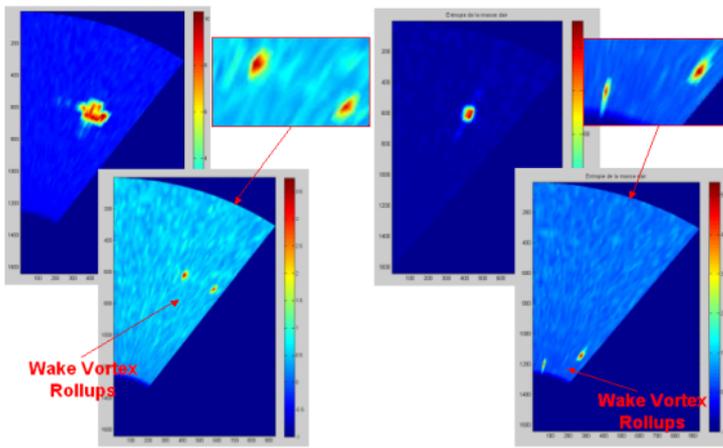


Fig. 6 : Monitoring of clear air wake vortex monitoring at range 1500 m based on High Resolution Doppler

BOR-A radar has been deployed at Paris CDG Airport, and co-localized with a 2 microns Lidar from Eurocontrol.

In a first step, antenna was used in a staring mode for vertical exploration by exploitation of 4° beamwidth. In the following figure, we illustrate wake vortex detection by Doppler entropy in time/range coordinates axes. After each departures on the first nearer runways, wake vortex were monitored.

As soon as a radar cell has revealed presence of wake vortex by its radar entropy, wake vortex circulation is computed as illustrated in following figure.

Doppler Spectrum with Wake Vortex are characteristic of Vortex roll-up geometry as previously explained.

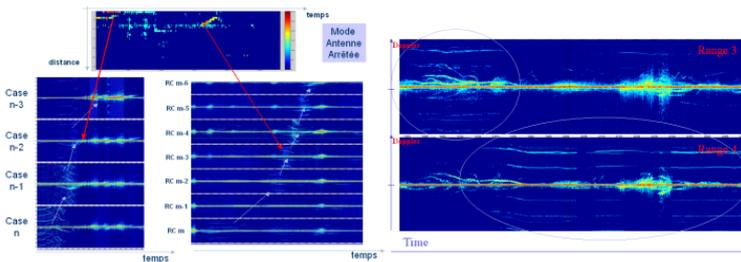


Fig. 7 : Wake Vortex Time/Doppler Spectrum from range to range (at left) and in Range cell 3 & 4 (at right)

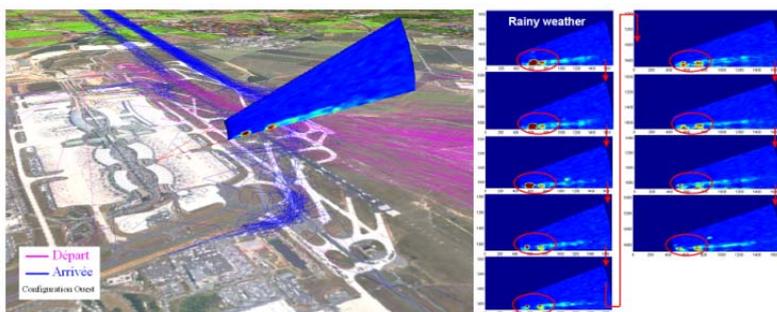


Fig. 8 : wake vortex roll-ups tracking from scan to scan in rainy weather

In vertical scanning mode, we were able to track individual roll-up of each wake vortex in range and elevation axes. In

previous figure, we can observe, above the first nearer runway, wake vortex generated by aircraft during departure. These detection of wake vortex are coherent with classical behavior close to the ground.

We have also proved that we can track each roll-up from scan to scan (with one scan every 5 seconds). Close to the ground, we can finely follow trajectory of each roll-up and estimate their strength by circulation computation.

Based on these elementary detections, results have been exploited to initiate benchmark of Lidar and Radar technologies.

VII. CONCLUSION

X-band radar has proved some capabilities to monitor Wake Vortex for different Weather Conditions (light to heavy rain, fog, turbulent atmosphere,...) with a fast monitoring of very large volume (radar scanning) with high update rate (8°/s with mechanical scanning for BOR-A radar). On these first experiments, Radar seems to have higher sensitivity than Lidar sensor, like capability for monitoring of « medium » aircrafts wake vortex (most common aircraft at Orly, e.g. A320) and not only « heavy / super heavy ». This last capability is needed for traffic mix of « very light jets ».

ACKNOWLEDGMENT

Radar Campaigns were done in coordination with ADP (Aéroport de Paris), DSNA & Eurocontrol.

REFERENCES

- [1] Jean-Yves Chemin , « Jean Leray et les fondements mathématiques de la turbulence », Société Mathématique de France, coll. Un texte un mathématicien, 14 février 2007
- [2] F. Holzäpfel & al., "Analysis of wake vortex decay mechanisms in the atmosphere", Aerospace Science & Technology, n°7, pp.263-275, 2003
- [3] D.J. Shephard, A.P. Kyte & P.D.F. Tait, "Radar measurement of the Wake Vortex of a H.S. 748 and a B.A.C. One-Eleven", Preliminary trials Report, GEC-Marconi Research Center, MTR-92/55A, 1992
- [4] T. Tani & F. Bertin, "Restitution en temps réel du champ de vitesses créé par des vortex d'avions", Convention d'étude CNRS/CRPE & STNA, 1992
- [5] G. Rat & F. Bertin, "Etude théorique de la détection des vortex générés dans le sillage des avions à l'aide d'un radar", CNRS/CRPE, 1992
- [6] William L. Rubin, "Detection and Strength Measurement of Wake Vortices at JFK using Rass", Final Report, WLR Research Inc., Whitestone, NY. FAA Contract DTFAO1-92C-00061
- [7] K. Shariff, "Analysis of the Radar Reflectivity of Aircraft Vortex Wakes", J. Fluid Mech., vol.463, pp.121-161, 2002
- [8] Gilson W.H., "Aircraft RCS measurement", In NASA Contractor Rep. 10139, Part 2, pp.603-623, 1994
- [9] F. Barbaresco & U. Meier, "Wake Vortex X-band Radar Monitoring : Paris-CDG airport 2008 Campaign Results & Prospectives", International Radar Conference, Radar'09, Bordeaux, October 2009
- [10] F. Barbaresco, "Interactions between Symmetric Cone and Information Geometries", ETVC'08 Conf., Ecole Polytechnique, Nov. 2008, published by Springer, in Lecture Notes in Computer Science, vol.5416, February 2009
- [11] F. Barbaresco, "Radar Monitoring of Wake Vortex : Electromagnetic reflection of Wake Turbulence in clear air", Comptes-rendus Physique Académie des Sciences, Elsevier, 2010