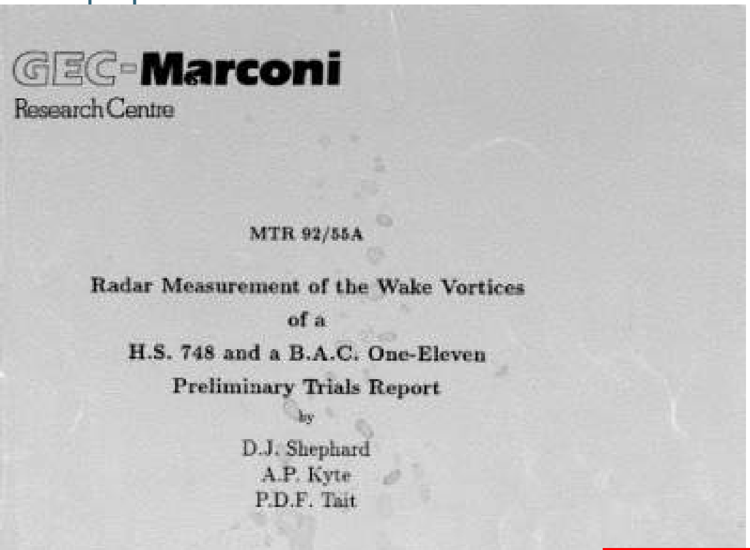
# High Doppler Resolution X-band Wake-Vortex Radar : CDG Airport Trials

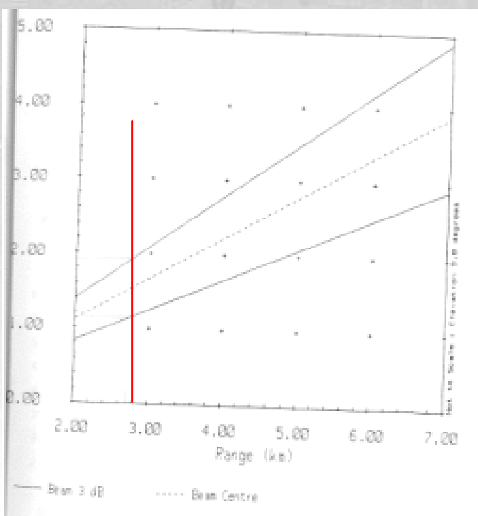
F. BARBARESCO

# Brieve History of Wake Vortex Radar Campaigns


GEC-Marconi
Research Centre

MTR 92/55A

Radar Measurement of the Wake Vortices
of a
H.S. 748 and a B.A.C. One-Eleven
Preliminary Trials Report
by
D.J. Shephard
A.P. Kyte
P.D.F. Tait




**Radar Beam Position**

**GEC-MARCONI DX 04 Radar (S Band)**

**Wake Vortex have been clearly detected (measured RCS : -80 dBsm to –90 dBsm) at 2.8 Km by radar (radar beam perpendicular to the aircraft's flight path)**

**DX Radar Figures :**

**3 GHz ($\lambda$=9 cm)**

**PRI = 100 $\mu$s**

**$\tau_c$= 4 $\mu$s (B=0.25 MHz, 600 m) to 13 ns (B=77 MHz, 2 m)**

$\tau < 400 . \tau_c$

**$P_c$ = 10 KW**

**$\tau$/PRI < 2.5 %**

**$G_{Em}G_{Rec}$= 33 dB**

**Weather conditions :**

**Cloud base : 2500 feet**

**Humidity : 85%**

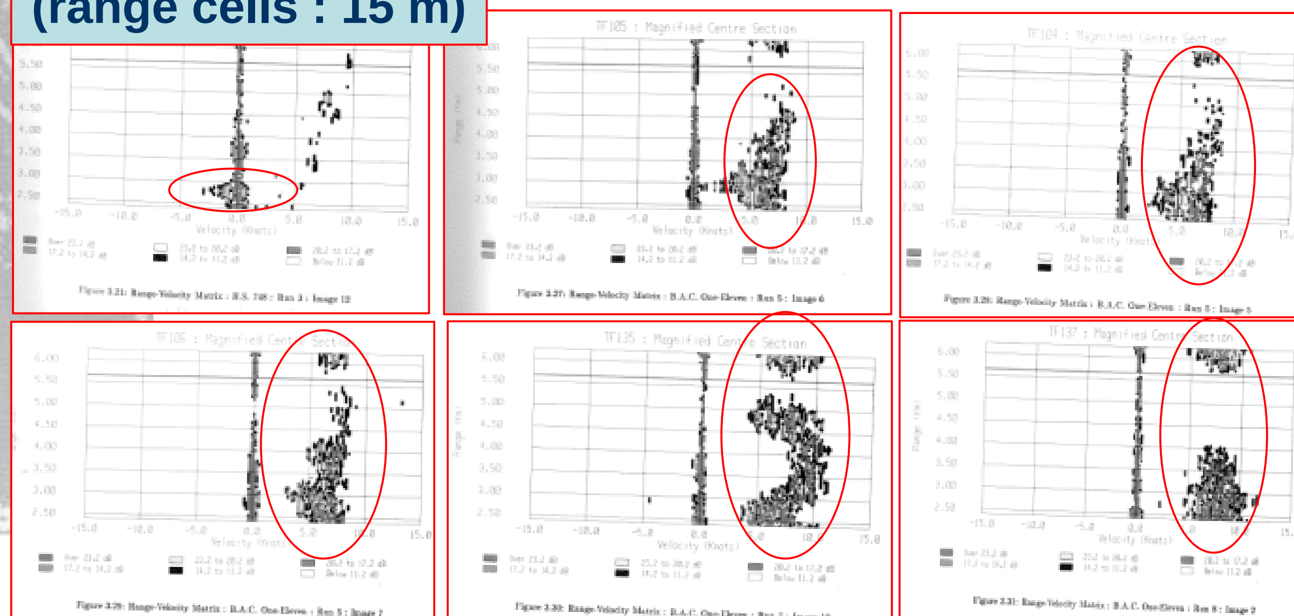
**HS-748 Plane :**

**Width : 30.02 m**

**Weight : 40000 LBS**

**Speed : 138 kts (69 m/s)**

**Doppler Spectrum (range cells : 15 m)**



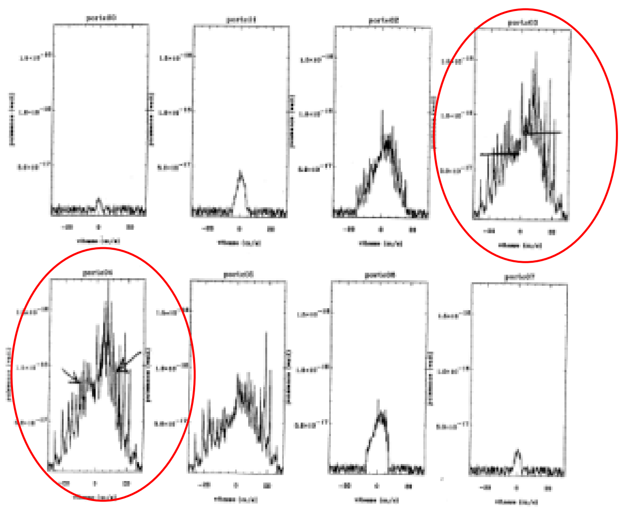
# CNRS/CRPE, CNET & STNA (France) : 1992

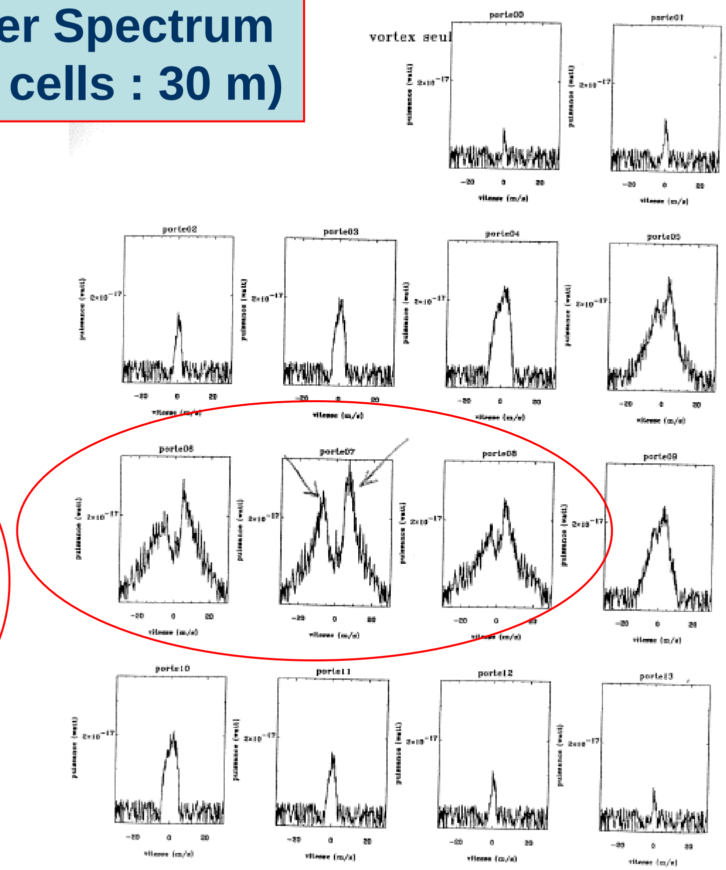
Figure 1 : L'antenne de 4.6 m de diamètre du radar PROUST à l'aéroport de Coulommiers.

**PROUST Radar**
**Frequency : 961 MHz**
**Wavelength : 31.2 cm**
**PRI = 156.4 μs**
**$\tau$ = 1 μs**
**$P_c$ = 4.5 KW**
**$Res_{range}$ = 150 m (without pulse compression)**
**$\tau$/PRI < 2.5 %**
**Beamwidth : 5°**
**$G_{ant}$ = 29 dB**
**$Range_{amb}$ = 23.4 Km**

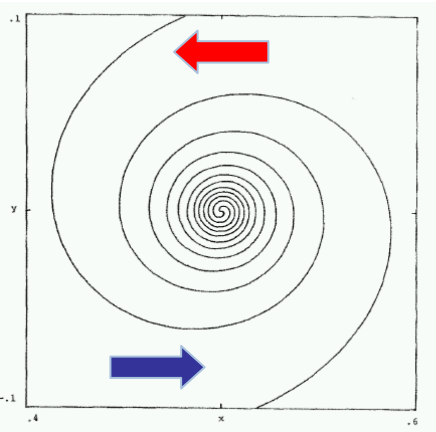
**Doppler Spectrum (range cells : 30 m)**

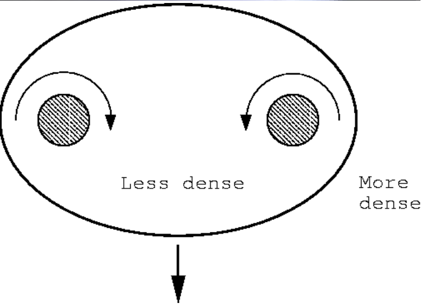
Un profil de 8 portes de 30 m (espacées de 10 m) obtenu dans le cas d'un seul vortex (Modèle N° 5)






Un profil de 14 portes de 30 m (espacées de 10 m) obtenu dans le cas du modèle N° 7




# Tests have revealed radar echoes in clear air.

- **Two mechanisms causing refractive index gradients are :**
  - **Radial Pressure (and therefore density) gradient in a columnar vortex arising from the rotational flow :**

$$(n-1).10^6 = 77.6\left(\frac{P_a}{T}\right) + 64.8\left(\frac{P_v}{T}\right) + 3.776.10^5\left(\frac{P_v}{T^2}\right)$$

$$\text{with} \begin{cases} n : \text{refractive index of humid air for frequencies below } 20\ GHz \\ P_a : \text{the partial pressure (mb) of dry air ;} \quad P_v : \text{the partial pressure (mb) of water vapour} \\ T : \text{the temperature (K) ,} \quad T_\infty = 288K \end{cases}$$

  - **Adiabatic transport of atmospheric fluid within a descending oval**

$$[\tilde{n}(z) - \overline{n}(z)].10^6 = -\frac{\overline{\rho}(z)N^2}{g}\Delta z\left[223 + \frac{\overline{RH}(z)P_{sat}(T_z)}{\overline{P}(z)}\left(76.7 + \frac{3.49.10^6}{\overline{T}(z)}\right)\right]$$

$$\text{with} \begin{cases} N : \text{Brünt-Väisälä Frequency (stratification parameter)} \\ \text{at Sea Level : } N = 0.014s^{-1} \text{ (in Summer) } N = 0.02s^{-1}\text{-}0.03s^{-1} \text{ (in Winter)} \\ \Delta z : \text{Descend Altitude, and } P = P_a + P_v \end{cases}$$

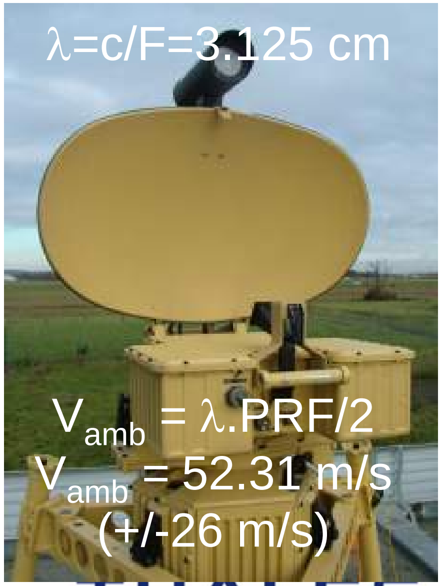
- **Particulates were not involved (not $f^4$ Rayleigh scattering) .**
- **The frequency dependence was not the Kolmogorov $f^{1/3}$**
- **The role of Engine Exhaust :**
  - **RCS doesn't change when the engine run at idle or full power**
  - **Exhaust diameter yields a partial pressure of vapour and a contribution which is much smaller than that due to temperature.**

# THALES RADAR WAKE VORTEX PROCESSING CHAIN

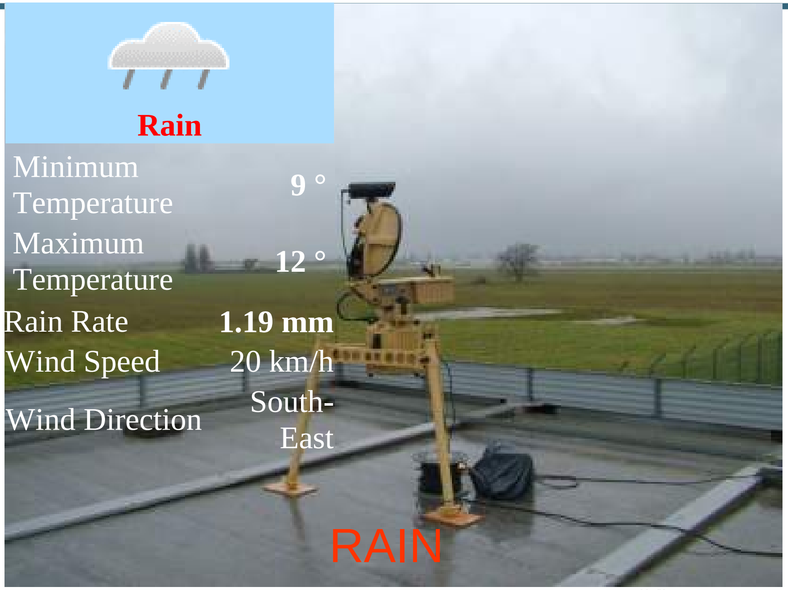
# CHARACTERISTICS OF THALES X-BAND BOR-A550 RADAR

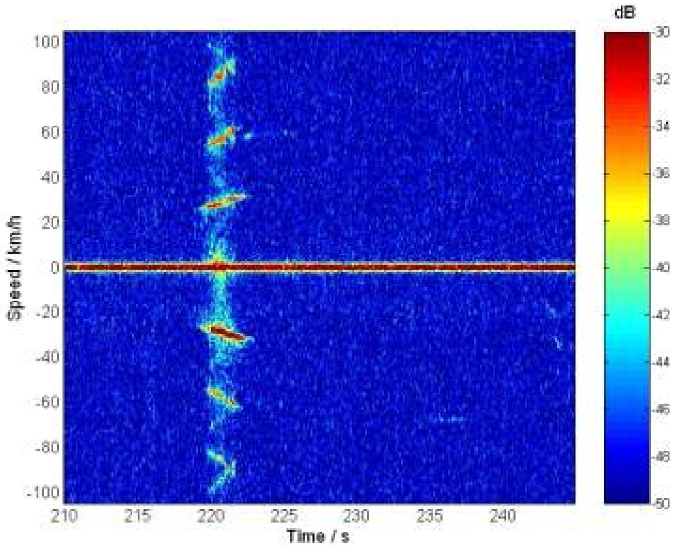

**Main Figures**

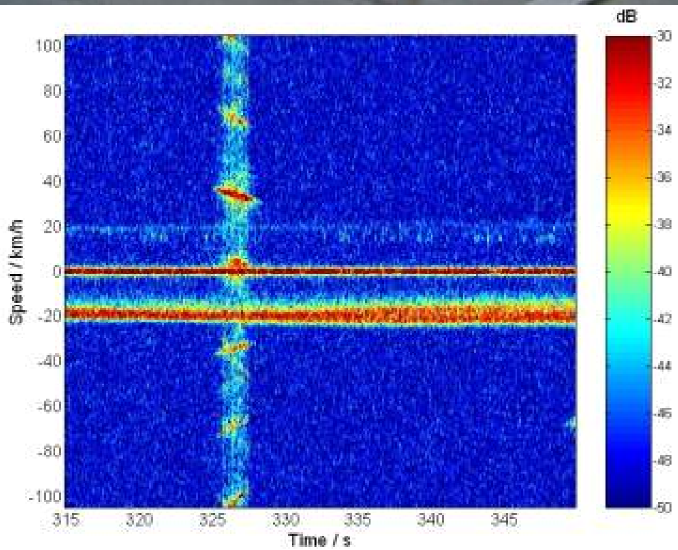
- Frequency : X Band (**9.6 GHz** for ORLY Campaign)
- Minimal Range : **400 m**
- Maximal Range : **40 Km**
- Range Resolution : **40 m**
- Mechanical Tilt : **+/- 24°**
- Beam Width (elevation/azimut): **4°/2.7°**
- Radial Velocity Range : **+/- 26 m/s**
- Doppler Resolution (& High Resolution) : **0.2 m/s** **(0.04m/s)**
- Mechanical Scan Rate : **8°/s** (sur **45°** pour ORLY)
- Peak transmit power: **75 W**
- Data Link : RS232 (x2), RS432 (x2), **Ethernet**
- Recording System : **All range cells**
- external link Ethernet 20 Gb/s



# Wake Vortex Detection in All weather Conditions

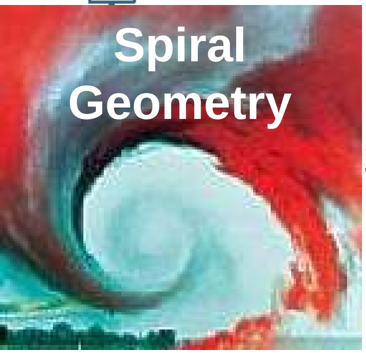



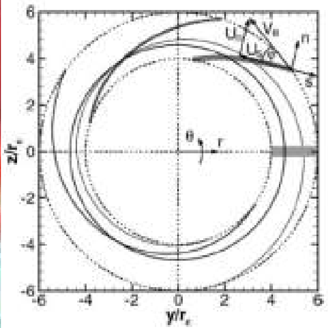




**RCS of Medium Aircraft Wake Vortex : 0.01 m$^2$**

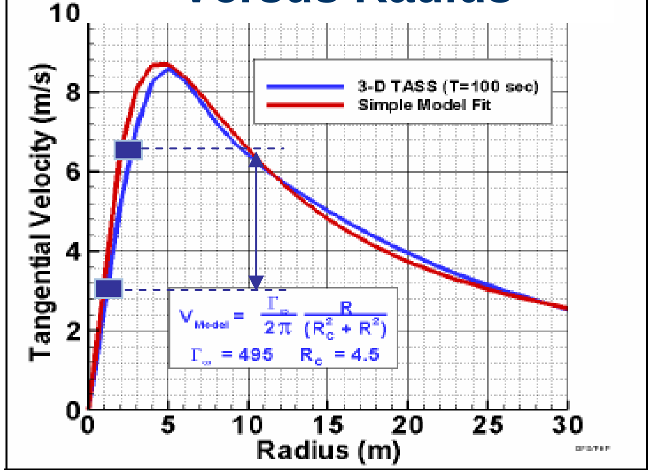
**S/N ≈ 15 dB (Range = 600 m)**

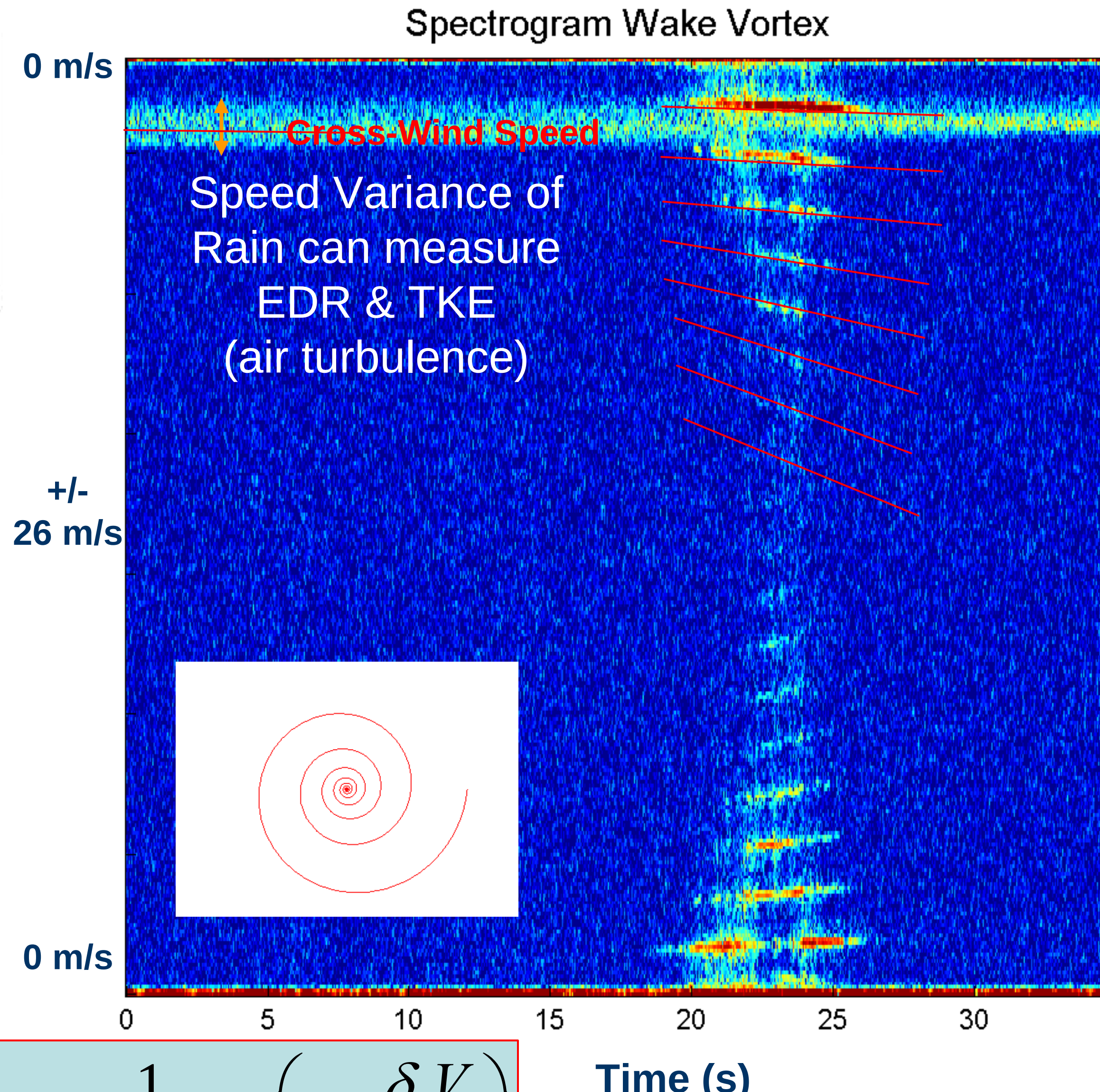
# WAKE VORTEX PROFILING : RADAR DOPPLER ANALYSIS




## Tangential Speed Versus Radius




$$r = ae^{b\theta} \Rightarrow \frac{dr}{d\theta} = br \Rightarrow b = \frac{1}{2\pi}\log\left(1 + \frac{\delta_r V}{V}\right)$$

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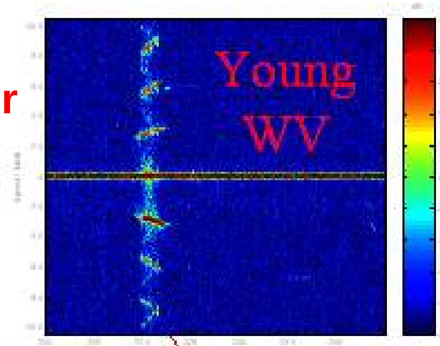
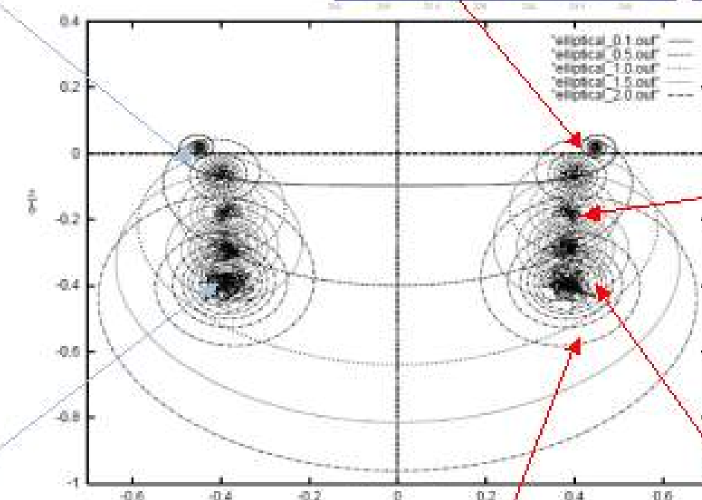
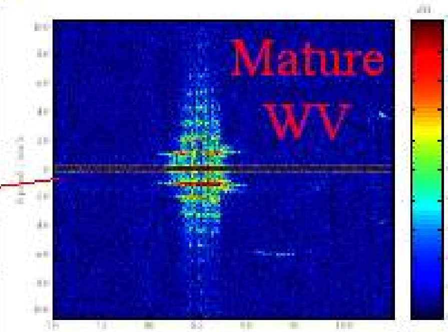
# WAKE VORTEX PROFILING : WAKE VORTEX AGE

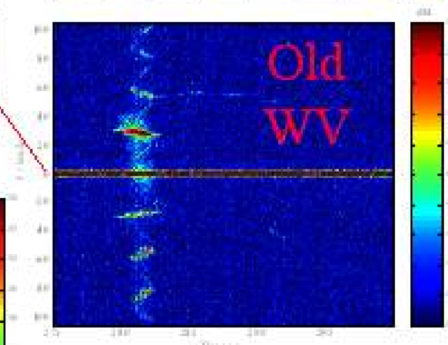
**Positive Time/Doppler slopes**



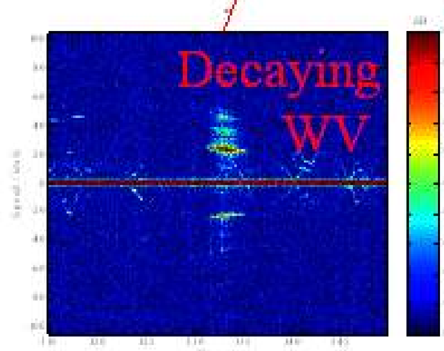




**Zero Time/Doppler slopes**




**Negative Time/Doppler slopes**




**Low speed Negative Time/Doppler slopes**



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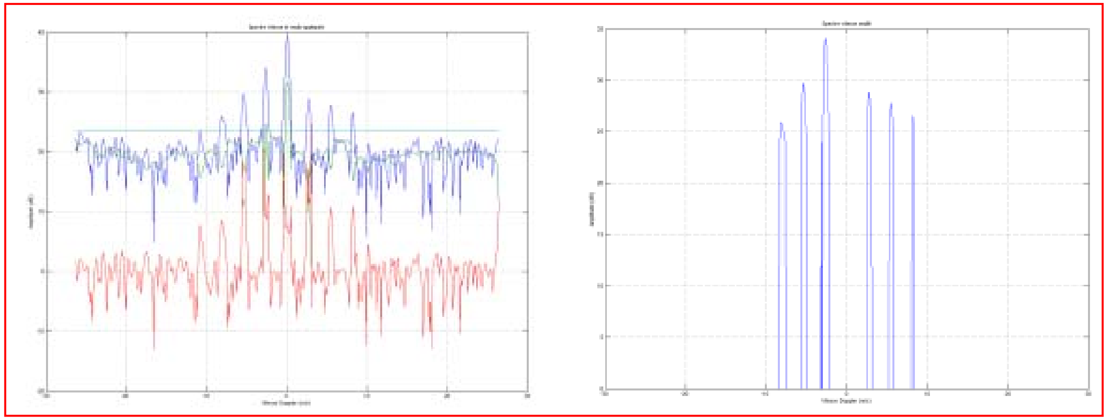
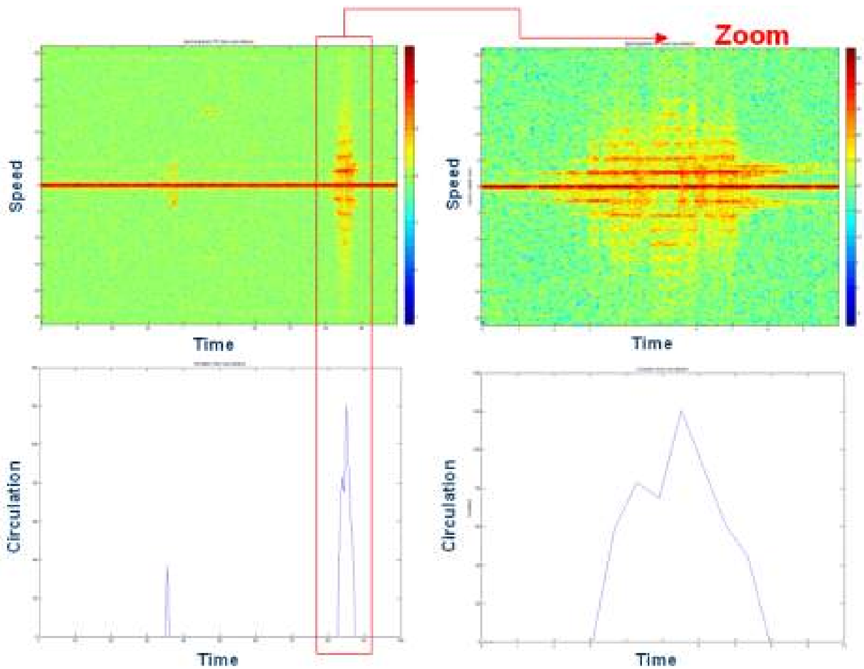
# Wake Vortex Circulation Computation



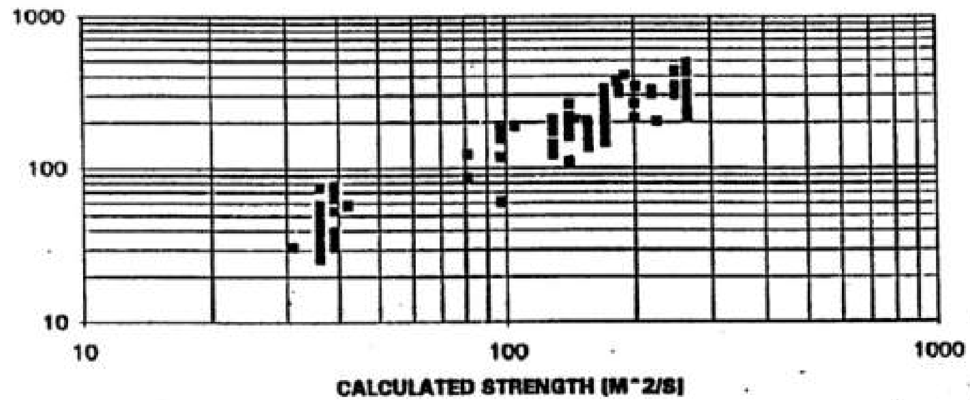
**Wake Vortex Doppler Frequencies Extraction**
(Pre-Processing : CFAR on Doppler axis)

$$\Gamma = k_3.2nd\ moment\left[S(V_i)\right]^{2/3}$$

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




Rubin, W. L., "Detection and Strength Measurement of Wake Vortices at JFK Using RASS," Final Report, WLR Research Inc., Whitestone, NY. FAA Contract DTFAO1-92C-00061, March 1995 (Proprietary).




Comparison of Observed and Calculated Vortex Strengths



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# Wake-Vortex Detection based on Doppler Entropy criteria

- In the framework of Affine Information Geometry, Kähler metric is given by Hessian of Entropy, considered as Kähler Potential Function :
  - Entropy of Multivariate Gaussian Law of Zero Mean :

$$p(Z_n / R_n) = (\pi)^{-n} . \left|R_n\right|^{-1} . e^{-Tr\left[\hat{R}_n . R_n^{-1}\right]} \Rightarrow \tilde{\Phi}(R) = -\log(\det R) - n\log(\pi e)$$

$$\text{with} \quad \hat{R}_n = (Z_n - m_n).(Z_n - m_n)^{+}$$

$$\text{et} \quad E\left[\hat{R}_n\right] = R_n$$

$$g_{ij} \equiv \frac{\partial^2 \tilde{\Phi}}{\partial H_i \partial H_j} \quad \text{et} \quad H = -R$$

  - Entropy can be parametrized by reflection coefficients of complex AR model

Doppler Spectrum shape → ... ← Doppler Spectrum Power

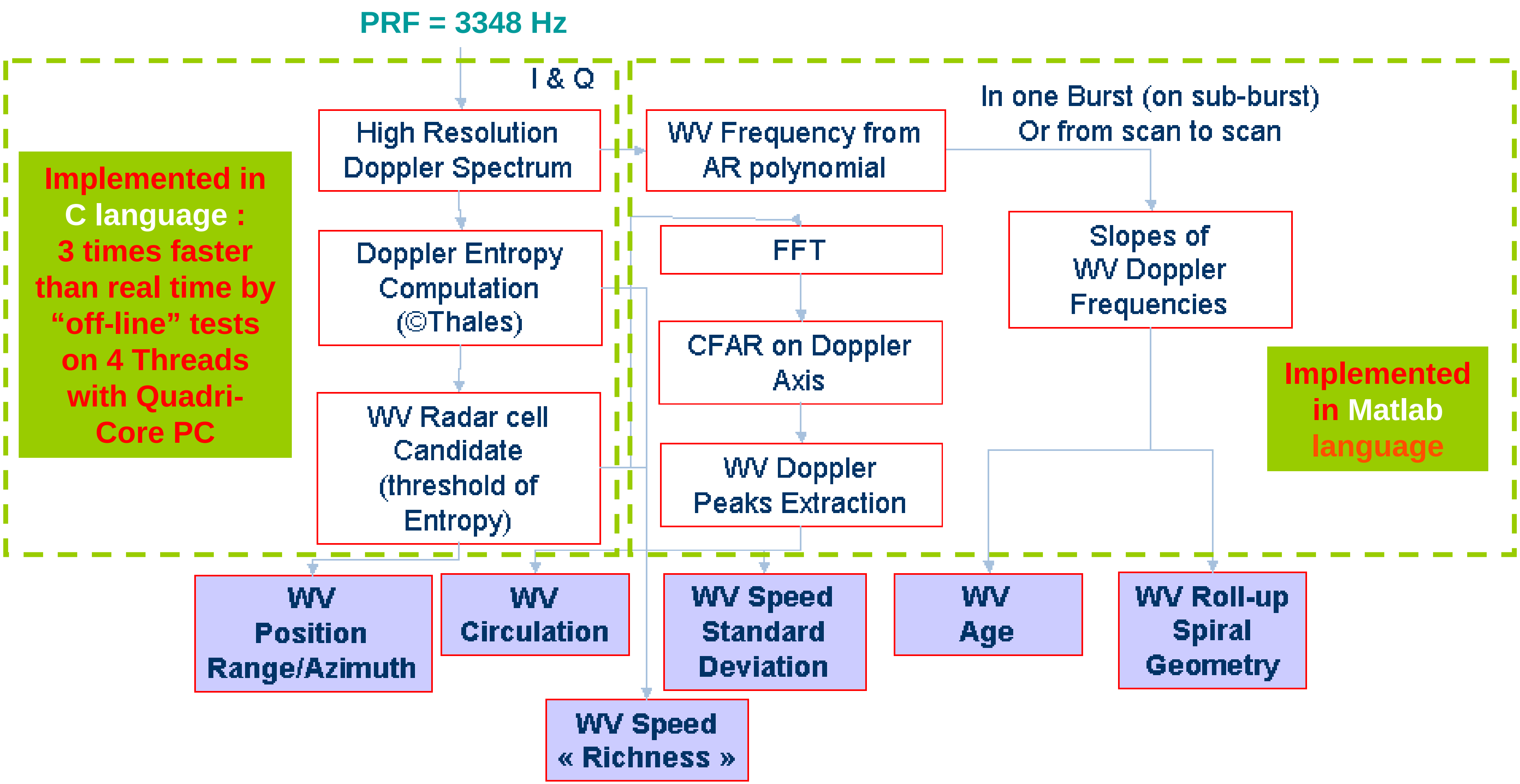
$$\tilde{\Phi}(R_n) = \sum_{k=1}^{n-1} (n-k).\ln\left[1 - \left|\mu_k\right|^2\right] + n.\ln\left[\pi.e.P_0\right]$$

$$\alpha_n^{-1} = \left[1 - \left|\mu_n\right|^2\right] \alpha_{n-1}^{-1}$$

$$\det(R_n) = \prod_{k=0}^{n-1} \alpha_k^{-1} = \alpha_0^{-n} \prod_{k=1}^{n-1} \left[1 - \left|\mu_k\right|^2\right]^{n-k}$$

$$\text{avec} \quad \alpha_0^{-1} = P_0 = \frac{1}{n} \sum_{k=1}^{n} \left|z_k\right|^2$$

# Thales Advanced Processing Chain: 3 Patents





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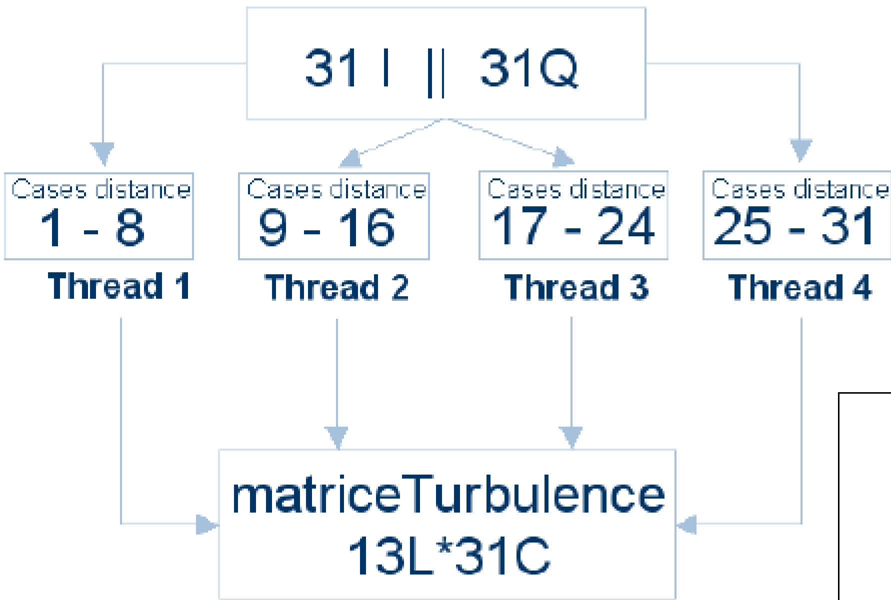
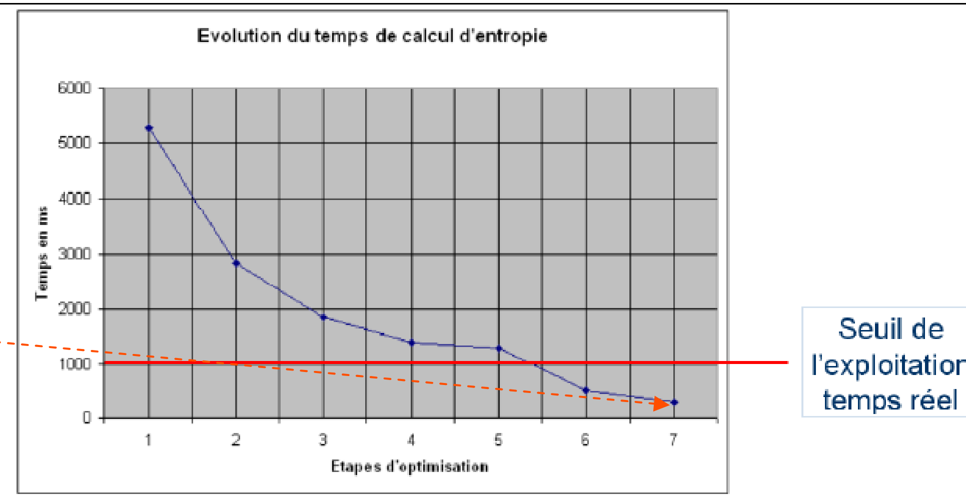
# "Off-Line" Tests on 4-threads quadri-Core PC




- C-Code Code has been parallelized on 4 threads by divided 31 Range cells in 4 Domains (1.2 km)
- Each Range Domain is processed on 1 thread
- Range Cell resolution : 40 m

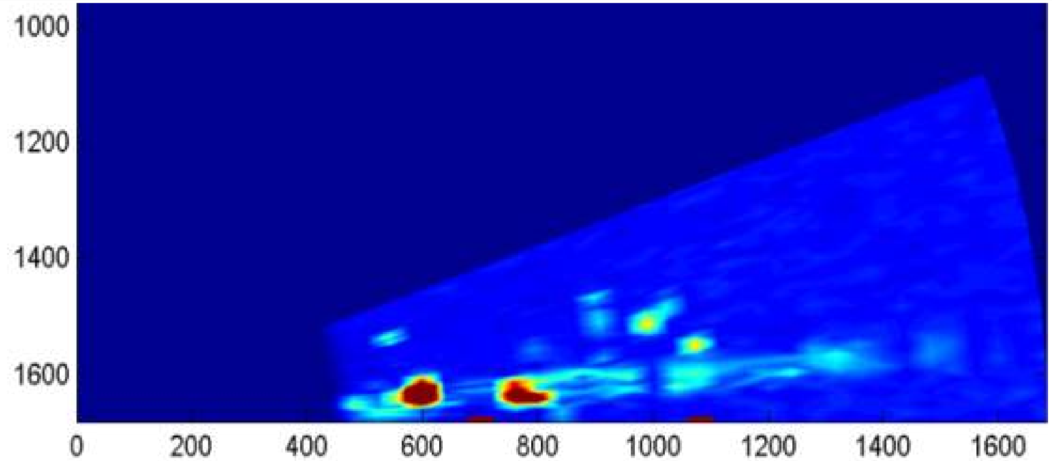
C-Code implemented on 4 Threads is 3 time faster than real time :

1 second processed in 300 ms

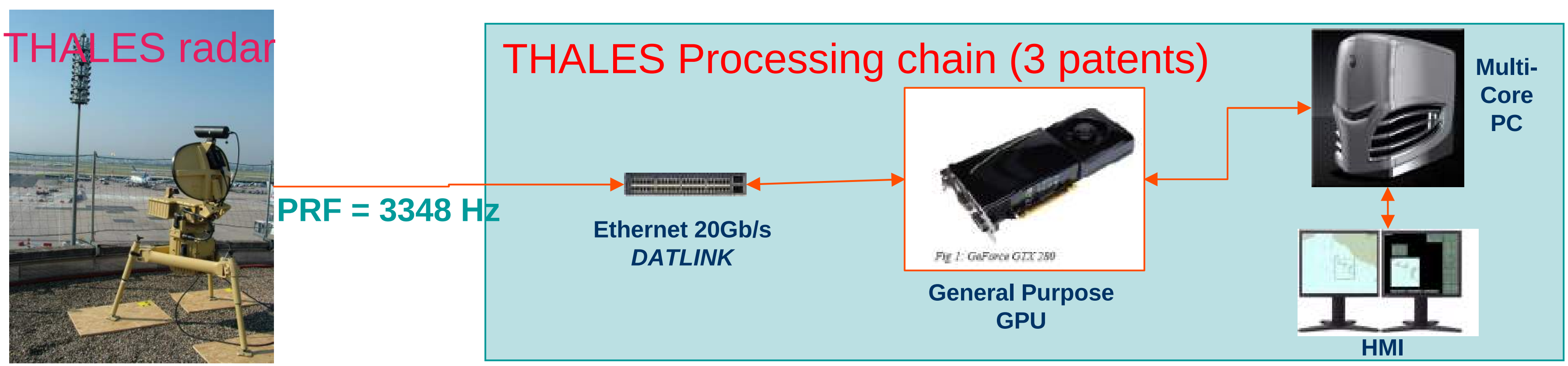



**Etape 1 :** Passage du code Matlab au code C
**Etape 2 :** Optimisation des boucle et suppression des calculs parasites
**Etape 3 :** Utilisation de 2 Thread : exploitation du DuoCore
**Etape 4 :** Utilisation d'une fonction de chauffe (allocation mémoire)
**Etape 5 :** Utilisation de 2 Thread
**Etape 6 :** Utilisation de 4 Thread : exploitation du QuadriCore

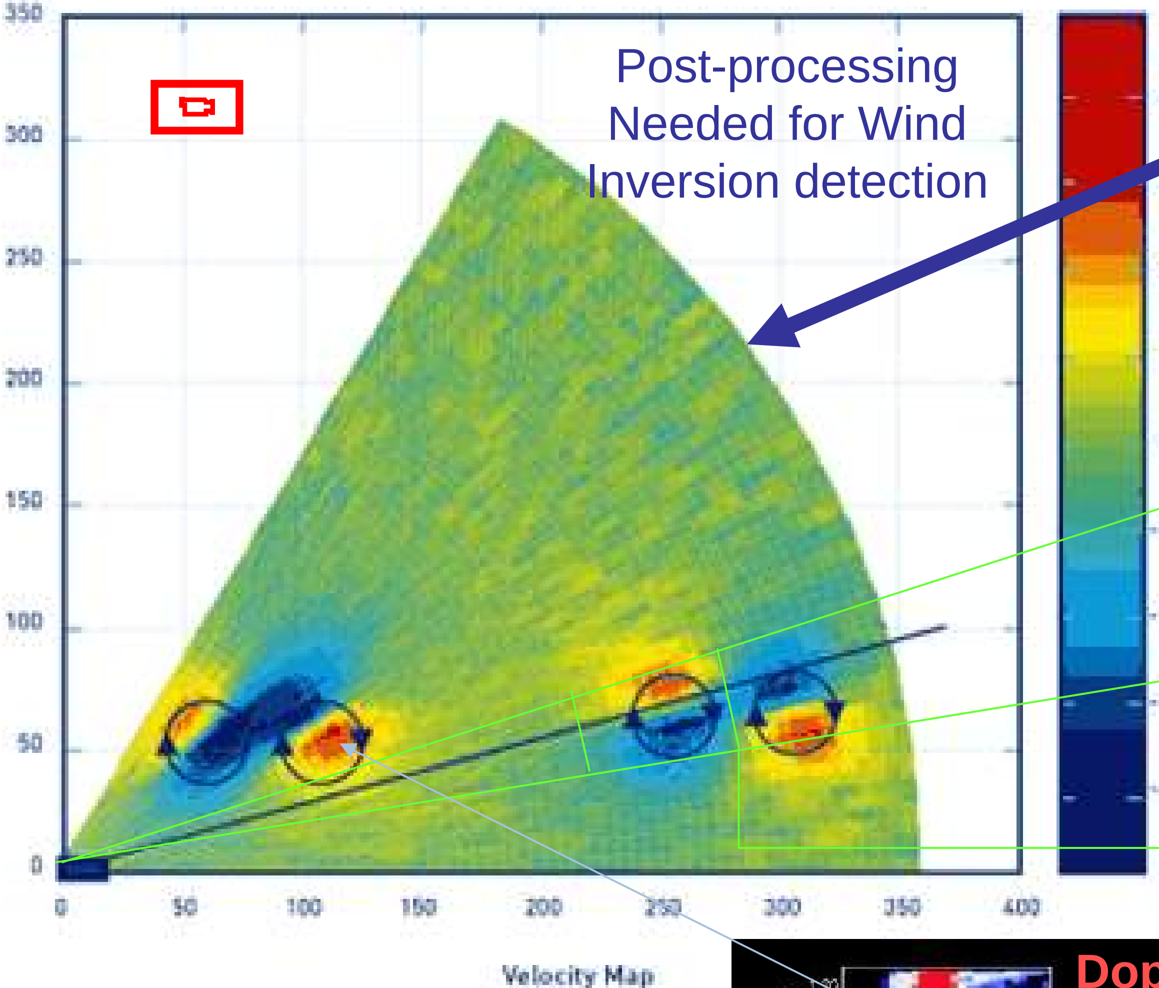
# In Progress : Real-Time THALES Processing Chain




- Real-Time Implementation of THALES “Wake Vortex” Algorithms (e.g. : General-Purpose computing on Graphics Processing Units)

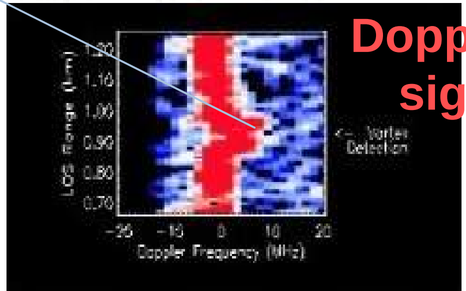


## LIDAR WAKE VORTEX DETECTION

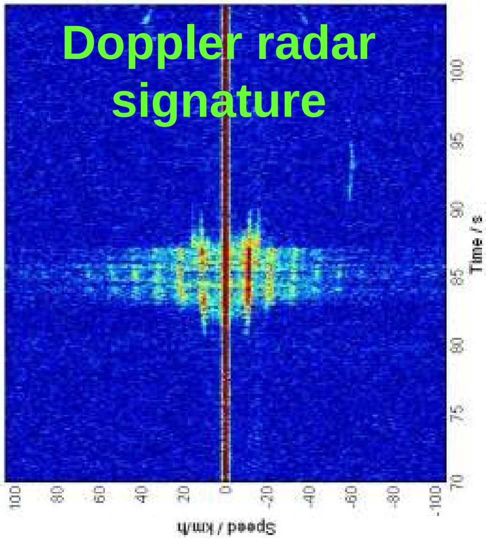



Post-processing Needed for Wind Inversion detection


Angular Radar resolution




Doppler Lidar signature




Doppler radar signature



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# Paris Airport Radar Trials

# Radar Sensor Campaigns funded by THALES

- **2006 : Paris Orly Airport**
  - From Mode S site (500 m from runway)
  - Wake Vortex Monitoring during departures
  - Weather conditions : Winter (clear air, rain)
- **2007 : Paris Orly Airport**
  - From Thales Limours Testbed Tower
  - Wake Vortex Monitoring during arrivals (ILS Interception)
  - Weather Conditions : Autumn (highly turbulent atmosphere)
- **2008 : Paris CDG Airport**
  - From Kbis Tower co-localized with Eurocontrol Lidar (2 mm Windtracer)
  - Wake Vortex Monitoring during arrivals/departures on Closely Spaced Parallel runways
  - Weather Conditions : Summer (very hot, rain)




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# BOR-A550 Radar View at Paris ORLY Airport Site



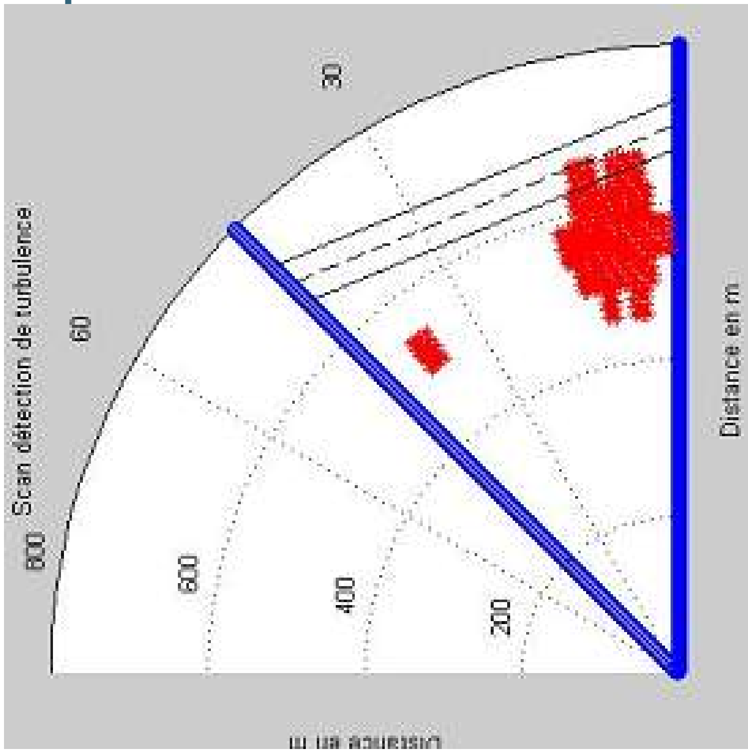





# PARIS ORLY WAKE VORTEX RADAR CAMPAIGN (2006)



# Orly Airport 2006 (runway monitoring for departure)





Recording Conditions

- 27th of November : without Rain
- 28th of November : with Rain (1.19 mm/h)

Recording only on Small & Medium Aircrafts (as heavy aircrafts have longer take-off threshold, they have not been recorded)



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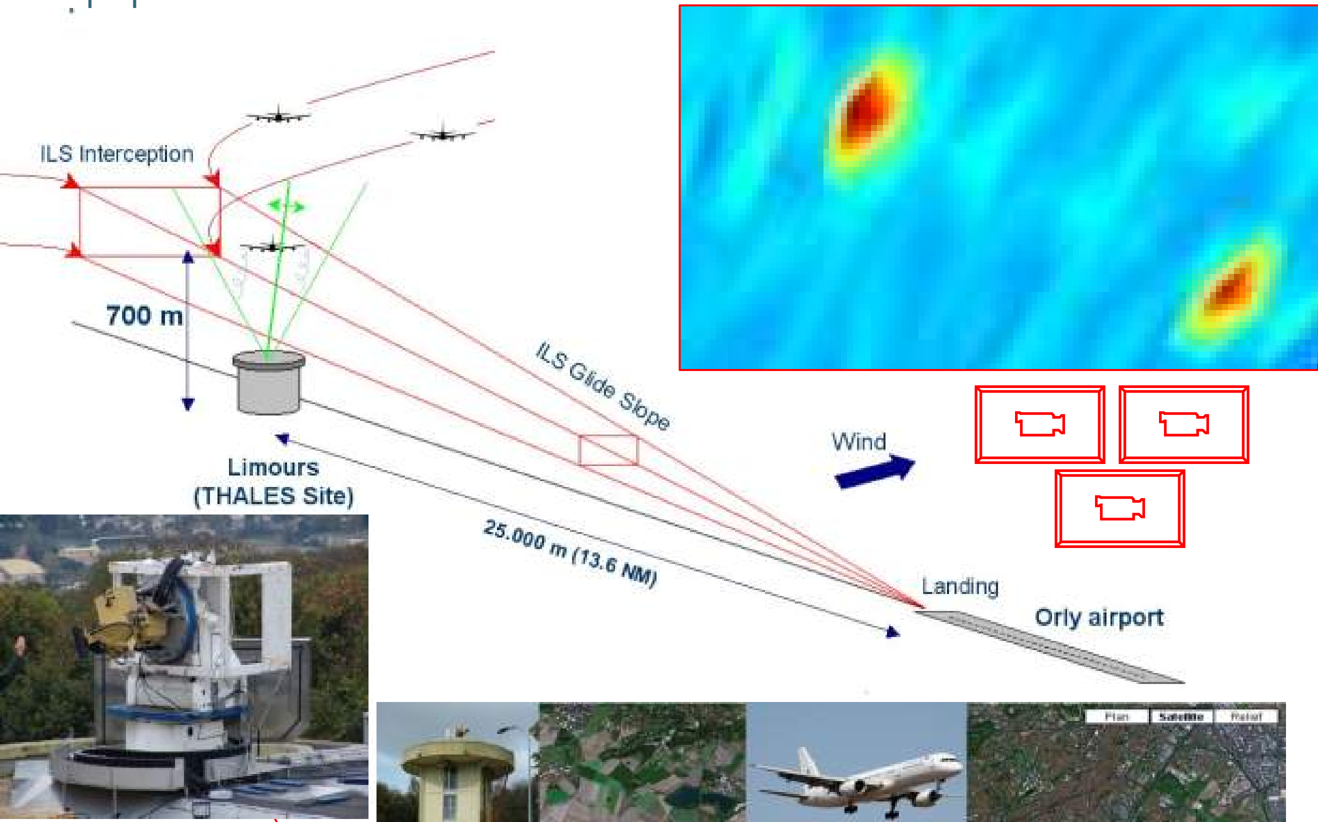
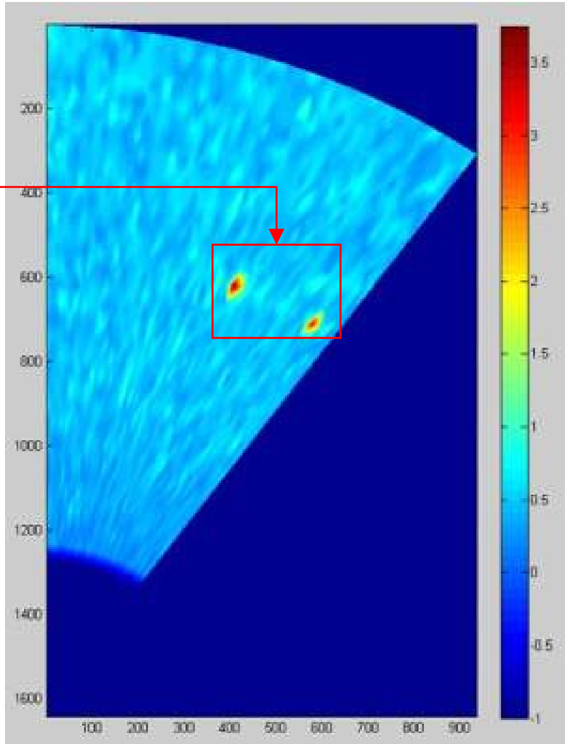
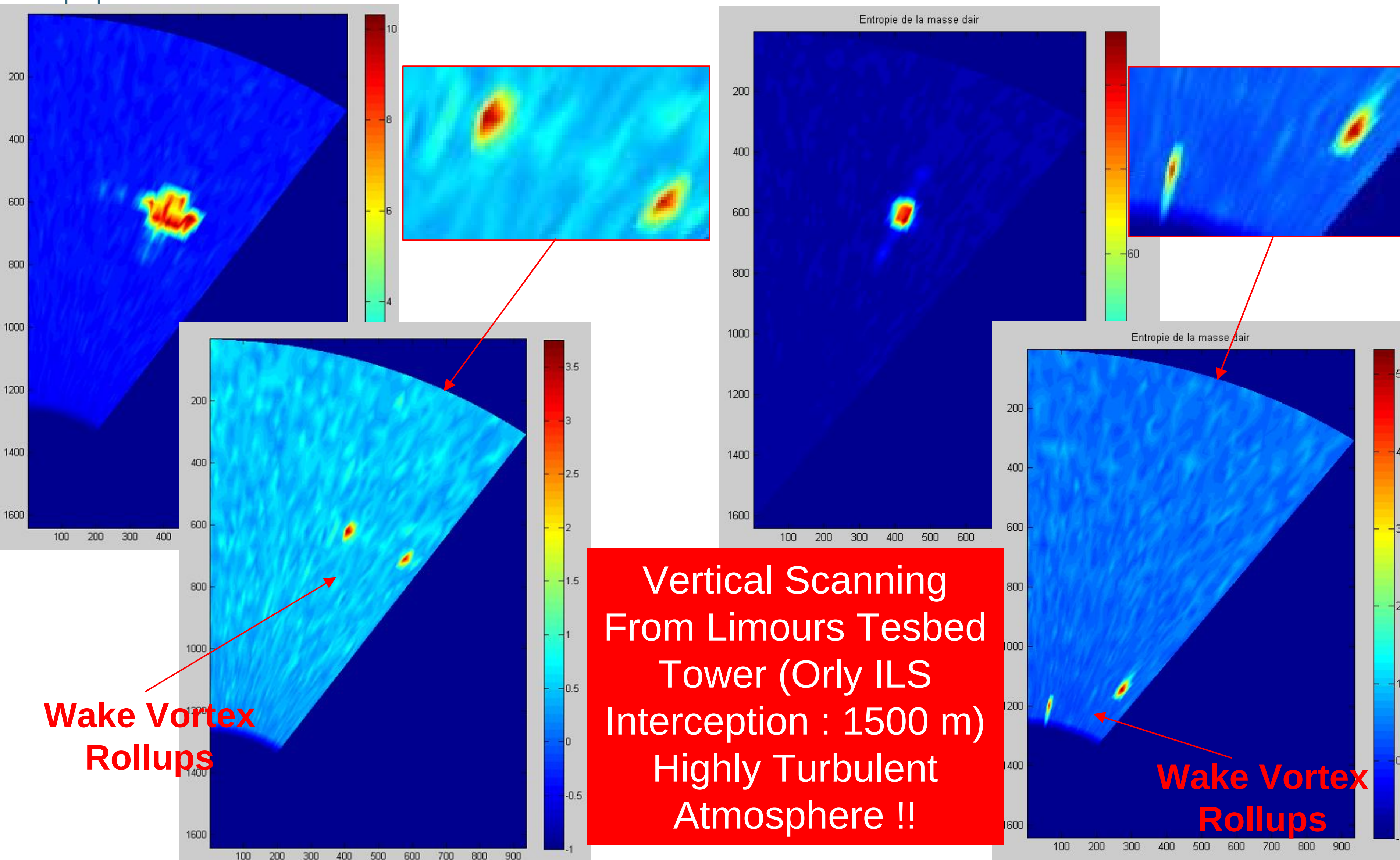
# Orly Airport 2007 (ILS Interception monitoring for arrival)





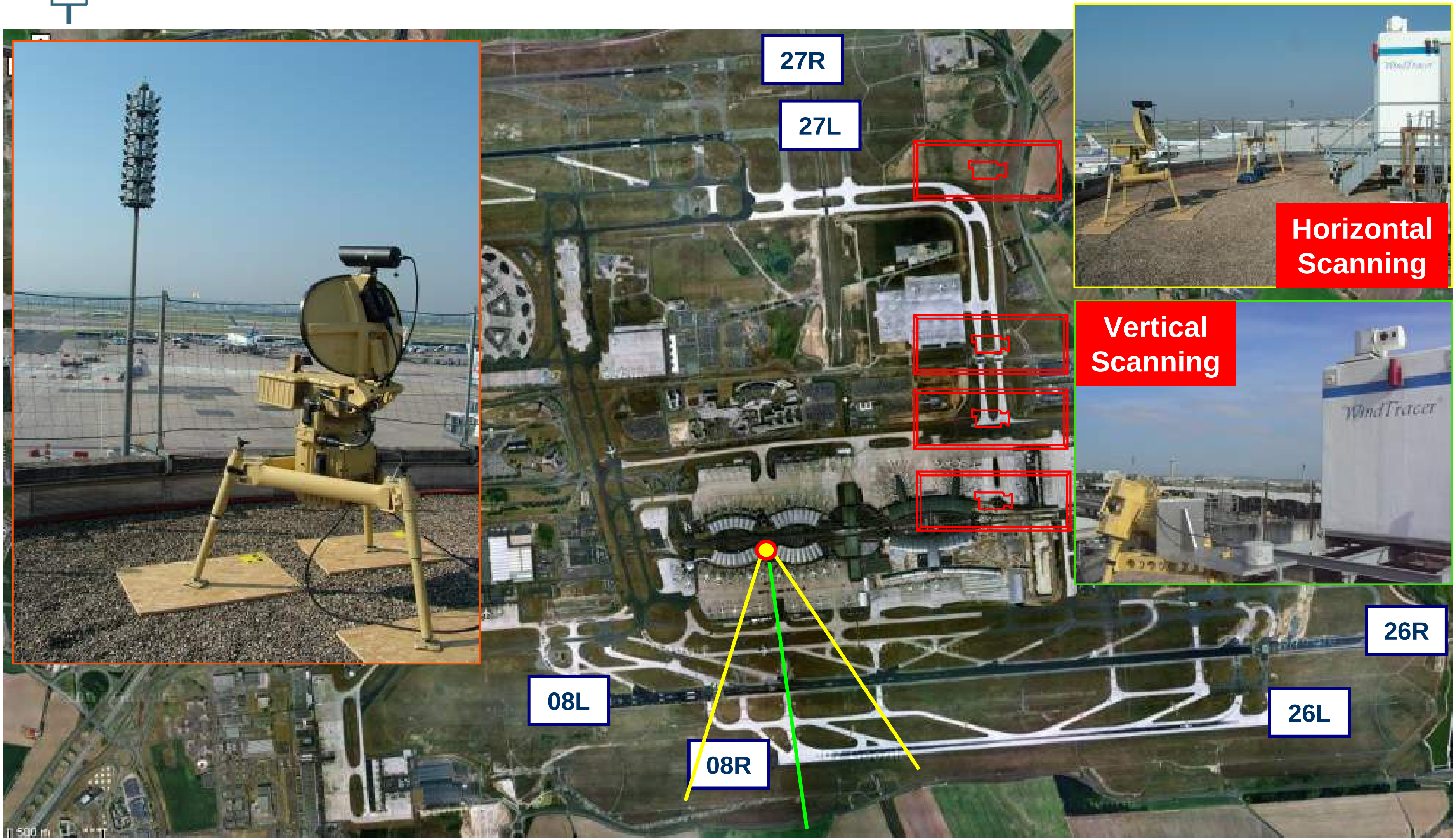
# Wake Vortex Monitoring based on HR Doppler

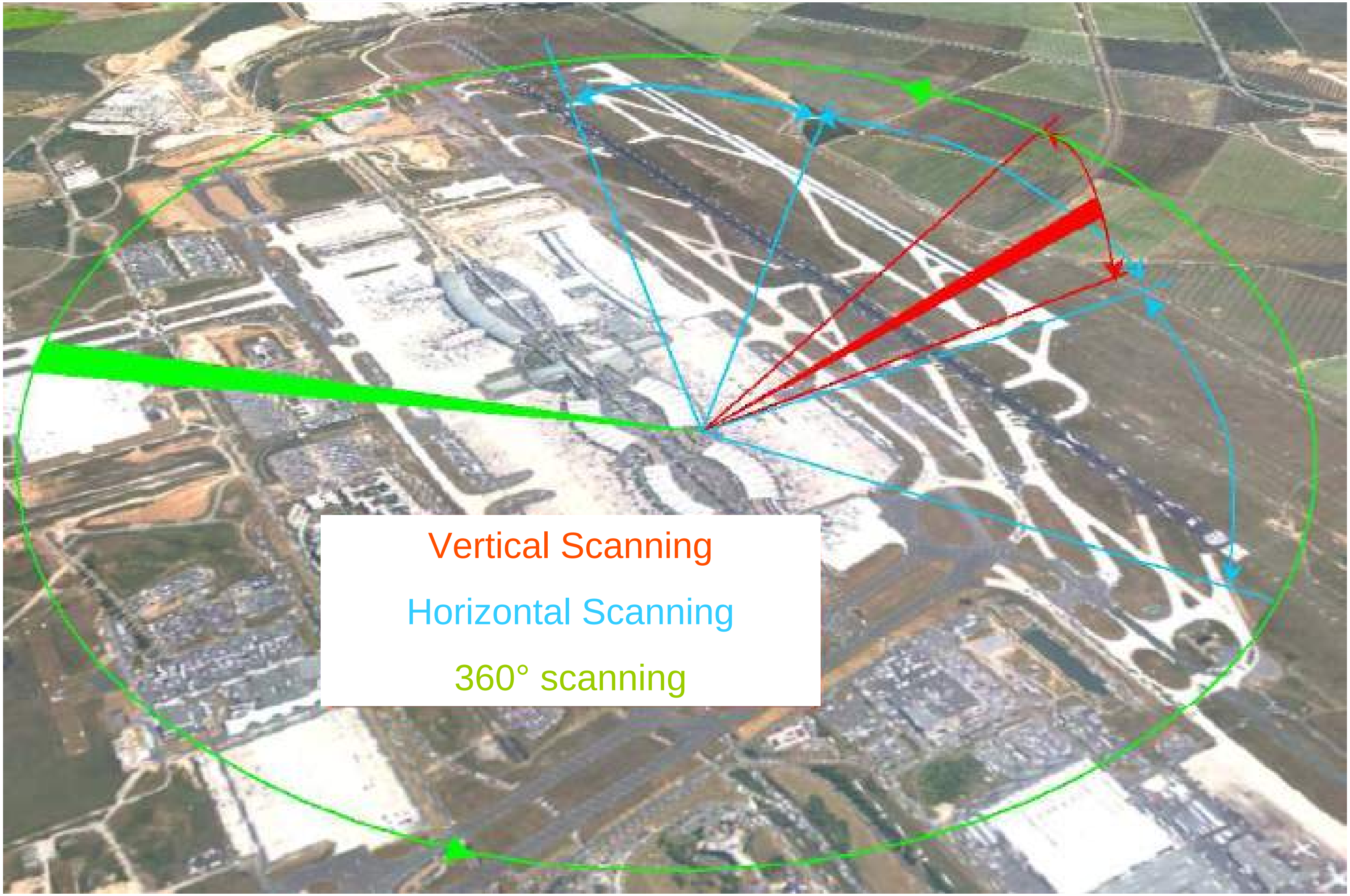



Vertical Scanning From Limours Tesbed Tower (Orly ILS Interception : 1500 m) Highly Turbulent Atmosphere !!

**Color = Doppler Entropy E = - log det(R) (R : covariance matrice)**

# CDG Airport 2008 (runway monitoring : departure/arrival)





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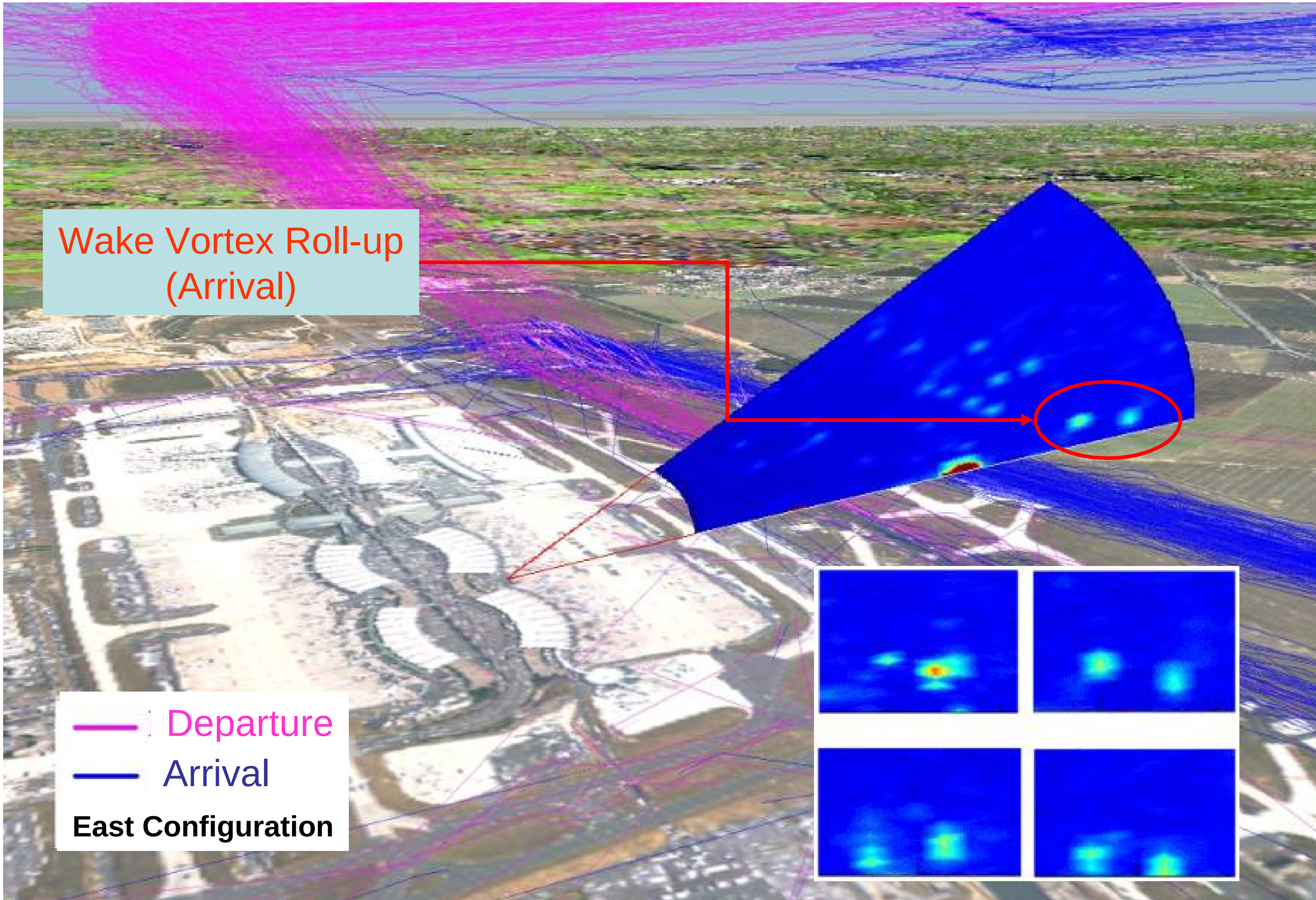
# Vertical Scanning: Monitoring of Arrival (2nd runway)



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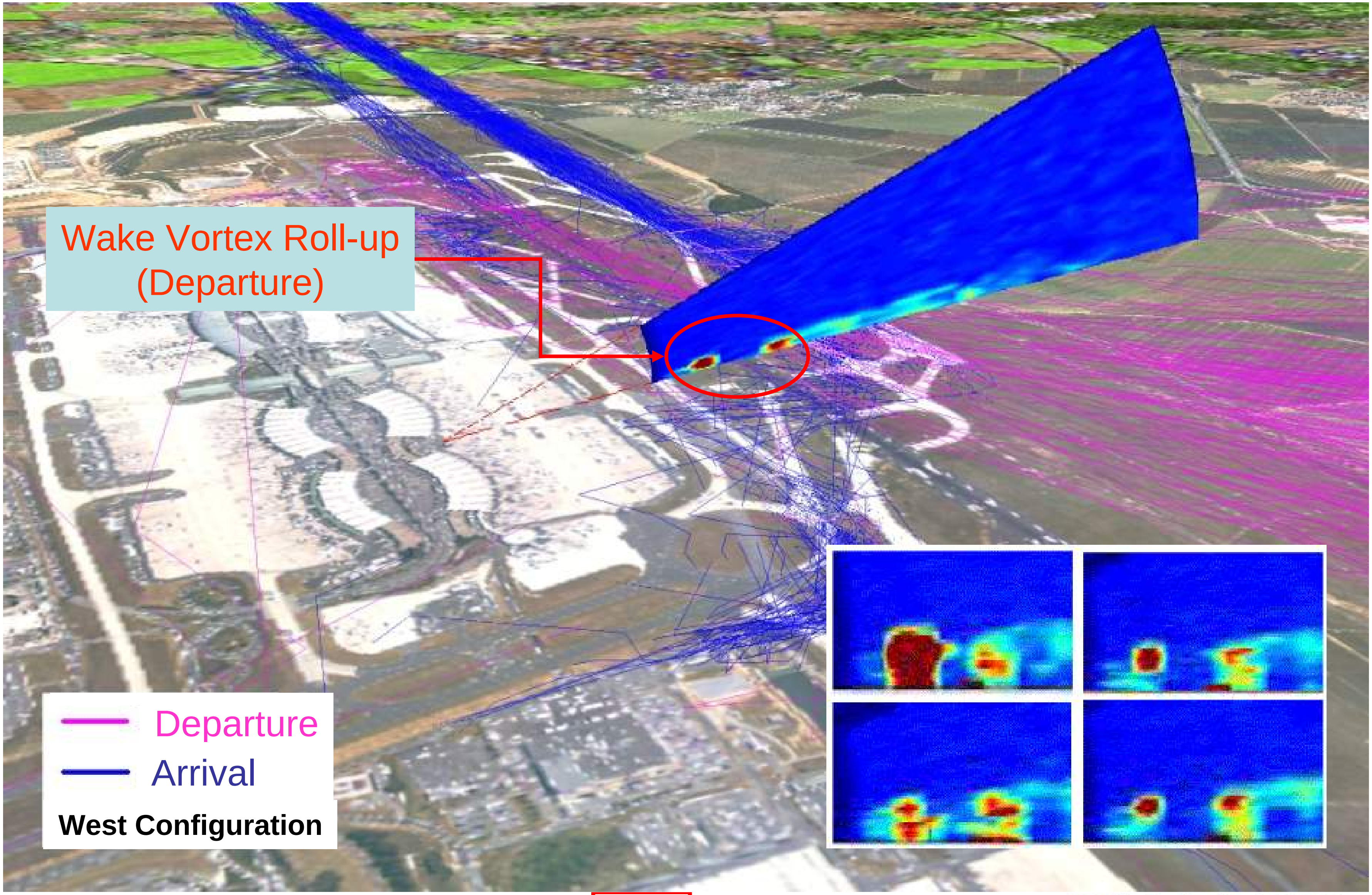
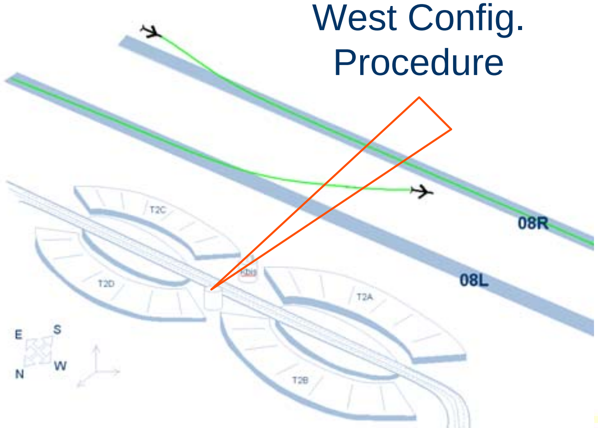
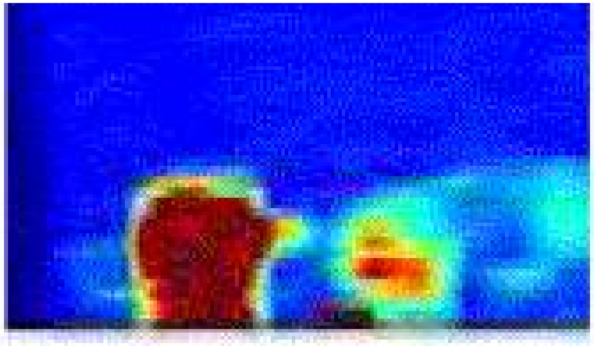
# Vertical Scan: Monitoring of Departure (1rst runway)

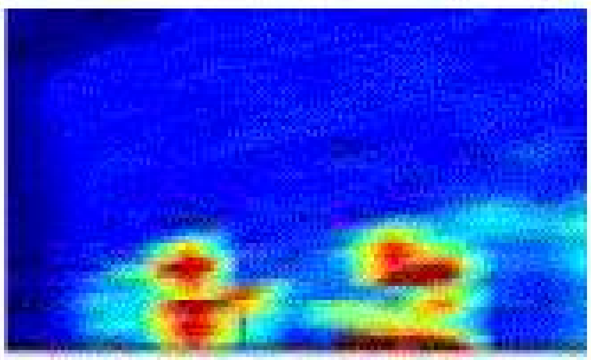


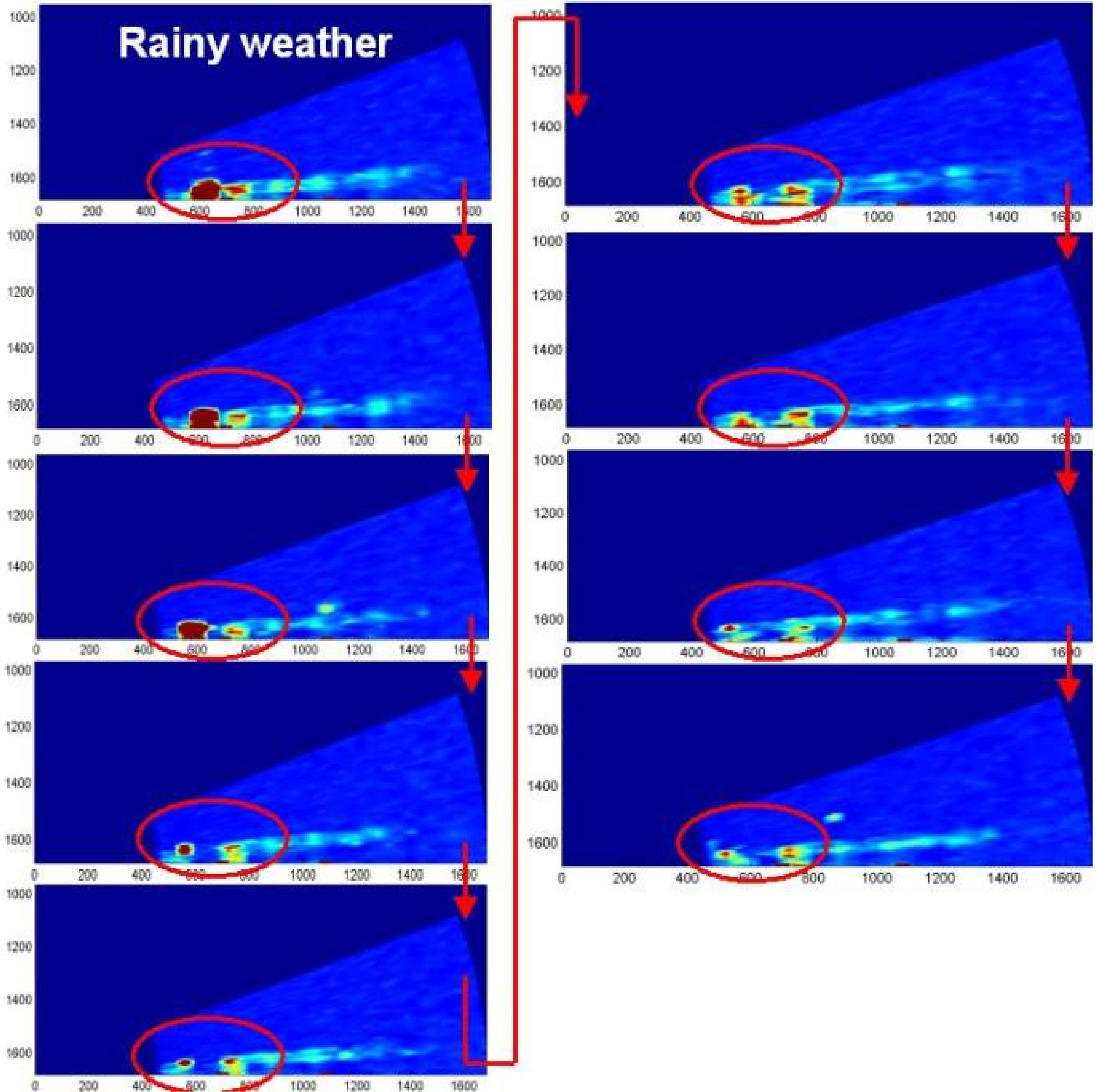
# From scan to scan : Departure

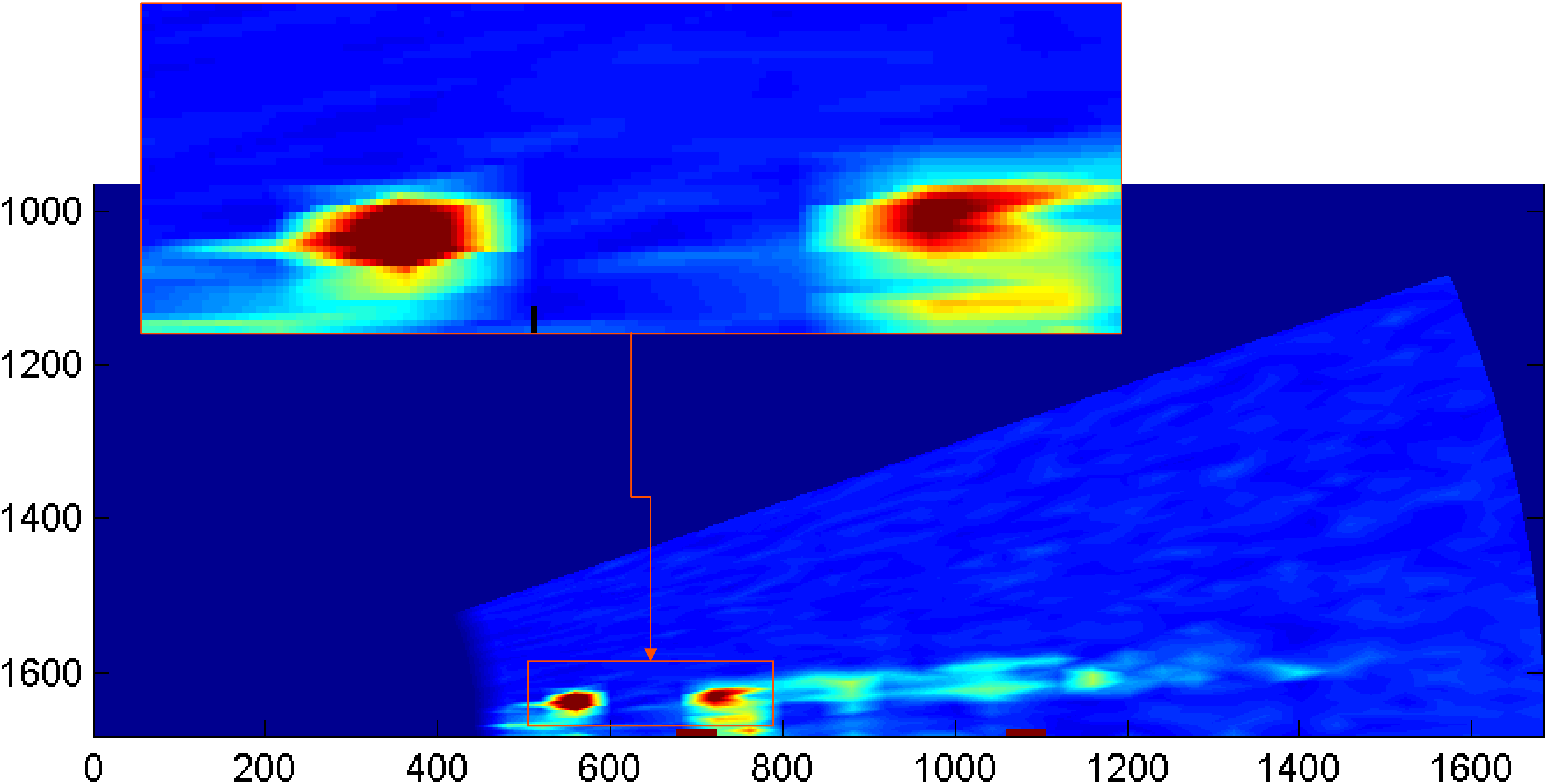
West Config.
Procedure








1000
1200
1400
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200
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1000
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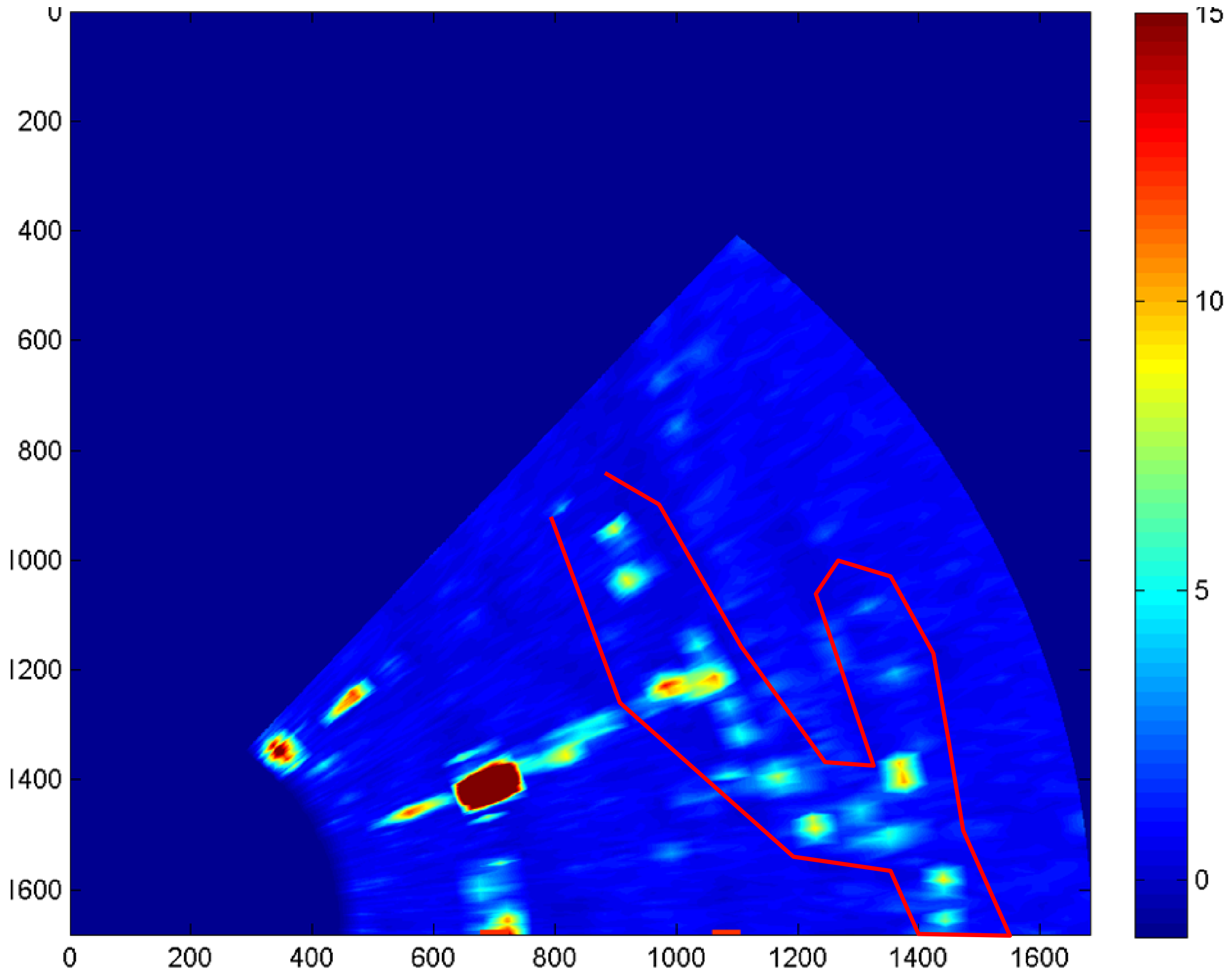
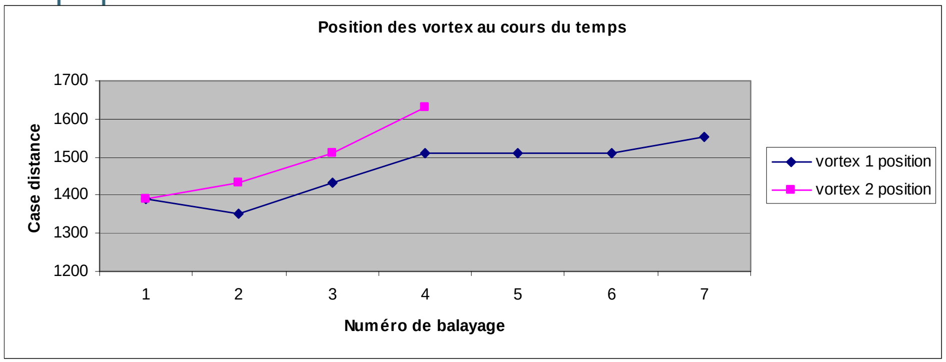
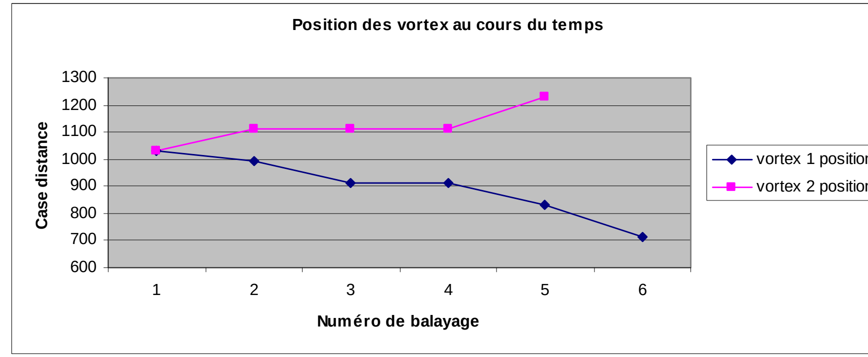
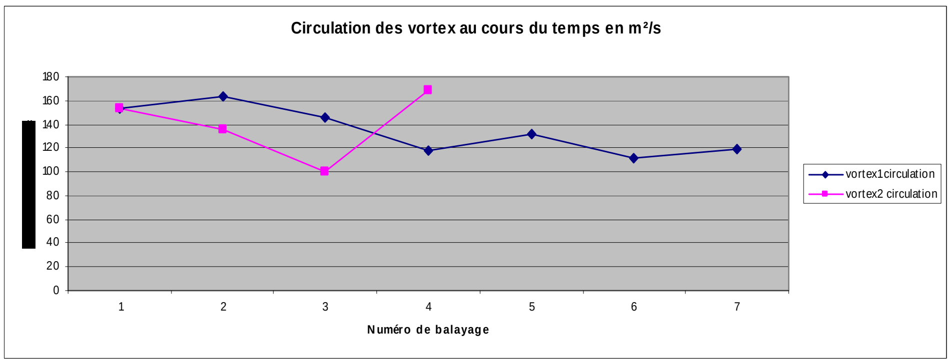
1600

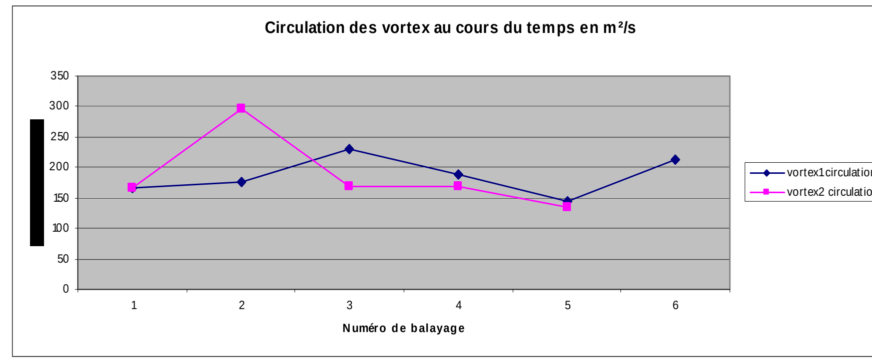

0
200
400
600
800
1000
1200
1400
1600
0
200
400
600
800
1000
1200
1400
1600
15
10
5
0

# Wake Vortex Position & Circulation (strength in $m^2/s$) along runway



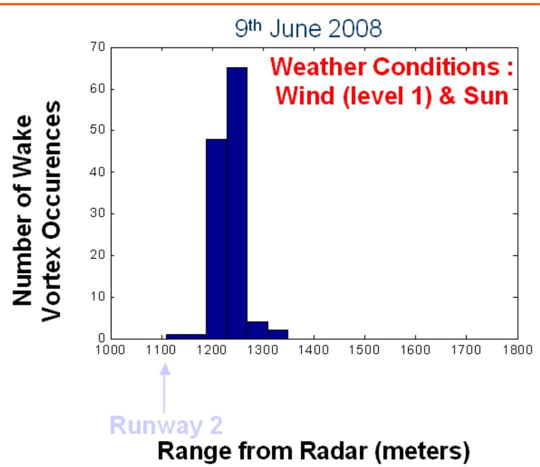



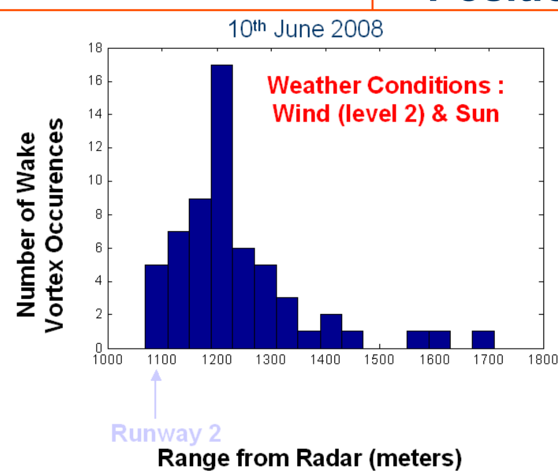

**5 s per scan (35 s)**
**Position at 1500 m**

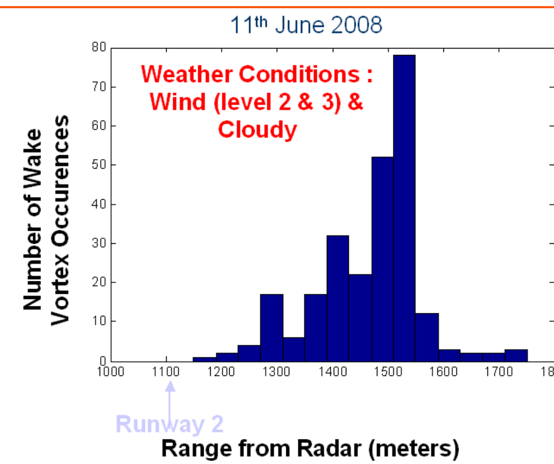
**With Cross-Wind**

**5 s per scan (30 s)**
**Position at 1000 m**

**Without Cross-Wind**

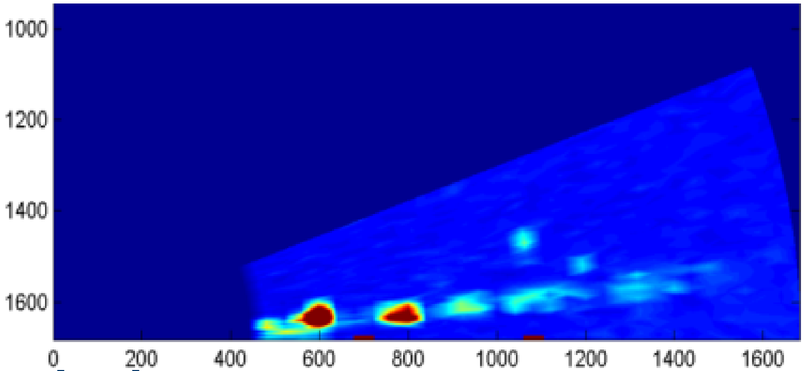


# Paris ORLY AIRPORT Campaign has proved that X-band Radar can :

- Detect Wake Vortex (RCS of 0.01 $m^2$ on medium aircraft) :
  - In all weather conditions (wet & dry at short range < 2 Km)
  - In Staring & Scanning Mode
  - In real Time / Update Rate of 11 s on 60° scan sector
- Localize Wake Vortex
  - in range/azimuth
  - With resolution : 40 m x 1°




- Characterize Wake Vortex
  - Geometry (Spiral)
  - Age (Young, mature, old, decaying)
  - Strength : Circulation ($m^2/s$)
- Characterize ambient air (in Rain Conditions)
  - Wind (based on Doppler & post-processing)
  - Ambient Air Turbulence (EDR & TKE)



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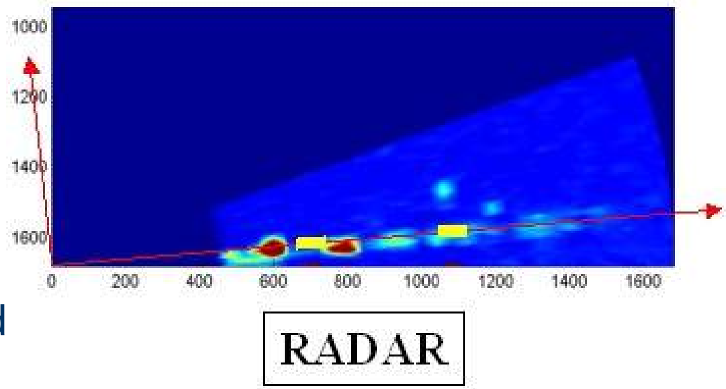
- **Wake Vortex Monitoring in All Weather Conditions (light to heavy rain, fog, turbulent atmosphere,…)**
  - **Operational Use to track Wake Vortex (transport, decay, rebound) in extreme weather conditions :**
    - **Wind burst (wind under Cb, turbulent atmosphere, wind shear…)**
    - **No Wind (foggy weather,…)**
  - **Non Operational Use for « Safety Case » by Data Collection :**
    - **Risks Assessment according to extreme wind conditions and not only on mean wind conditions (extreme values statistics)**
    - **Need for Wake Vortex Data in exhaustive cases of airport climatology (good/bad weather)**

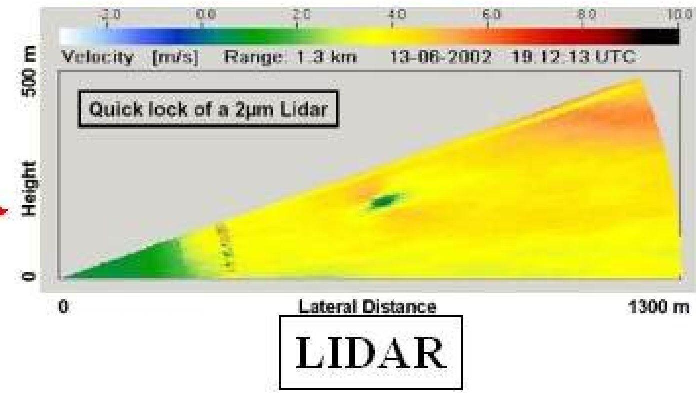
- **Fast Monitoring of very large volume (radar scanning) with high update rate (e.g. : 8°/s with mechanical scanning of BOR-A radar and faster with Electronic scanning)**

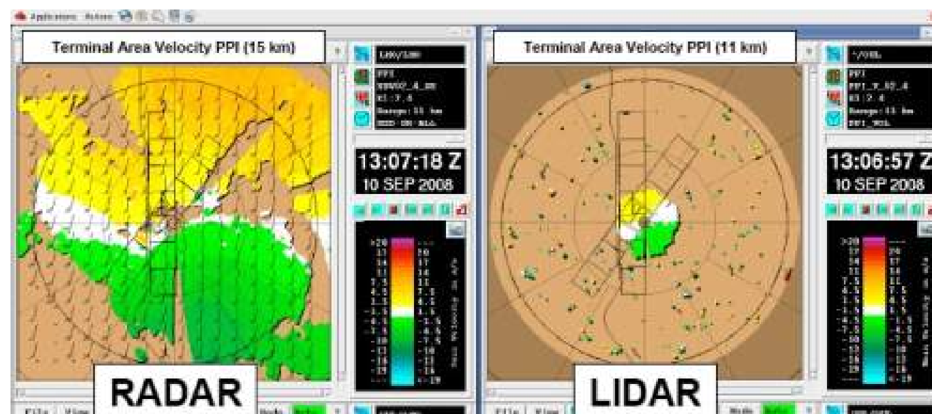
- **Highly sensitivity of Radar : monitoring of Wake Vortex for « medium » (high % of A320) aircrafts and not only « heavy / super heavy » (requested for traffic mix of « very light jets »)**

- Radar & Lidar are complementary sensors in all weather operations
  - THALES has proved by derisking campaign (Paris CDG-2008) that X-band Radar & Lidar are complementary for Wake Vortex Monitoring :


d
X-band &



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# WAKE-VORTEX & WIND SENSORS BENCHMARK

Air Systems Division

- **THALES will supervise benchmarking of :**
  - **Wake Vortex Monitoring Sensors**


M-Scan & E-scan
X-band Radars


2 µm Lidar

  - **Wind Monitoring Sensors**


Polar X-band
Radar


1.5 µm Lidar
Wind Profiler


UHF Radar
Wind Profiler

Ultrasonic
Anemometers

  - **Others**

Sodar

**In All Weather Conditions**



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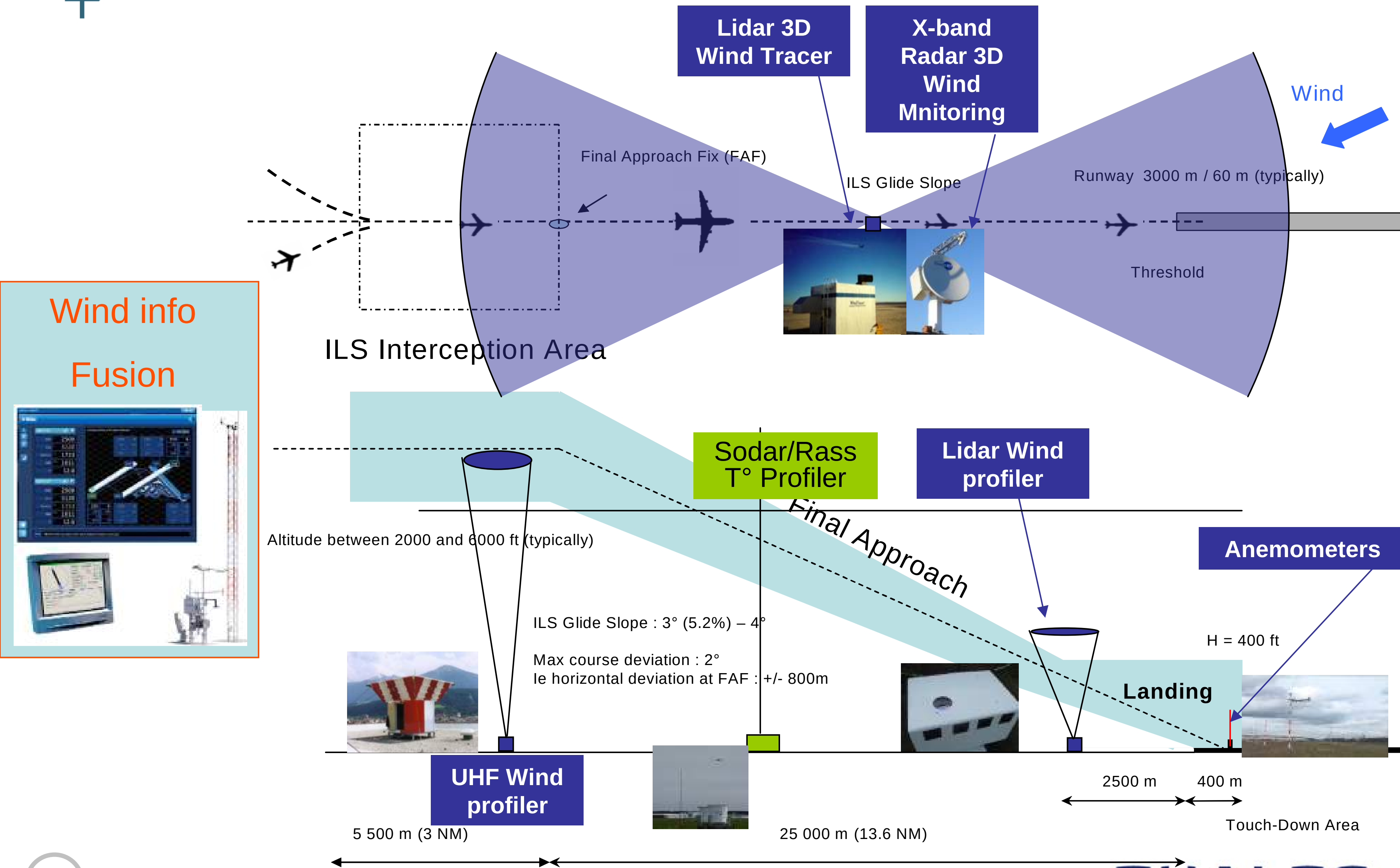
# One Instance of Weather Sensors Deployment



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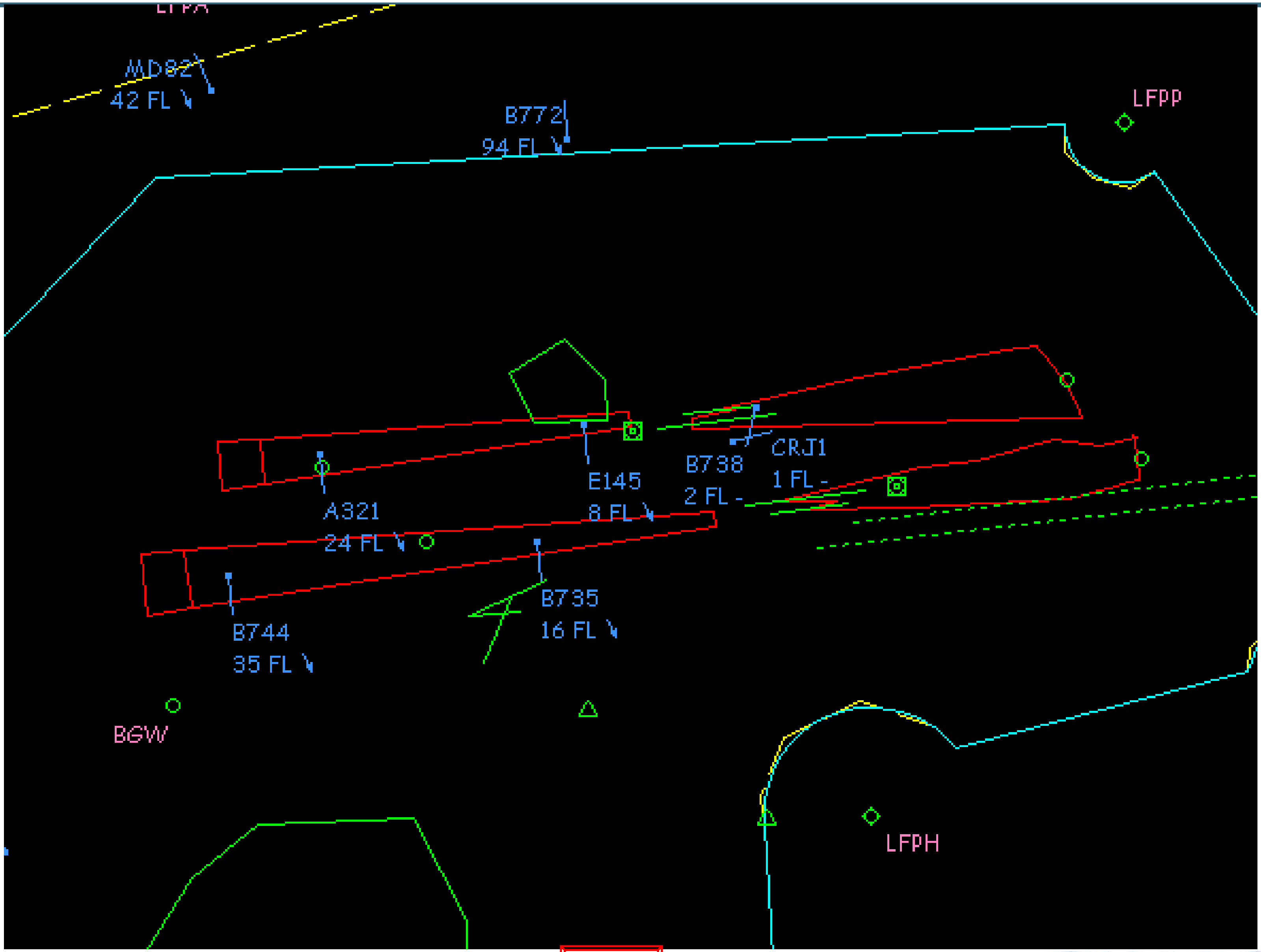
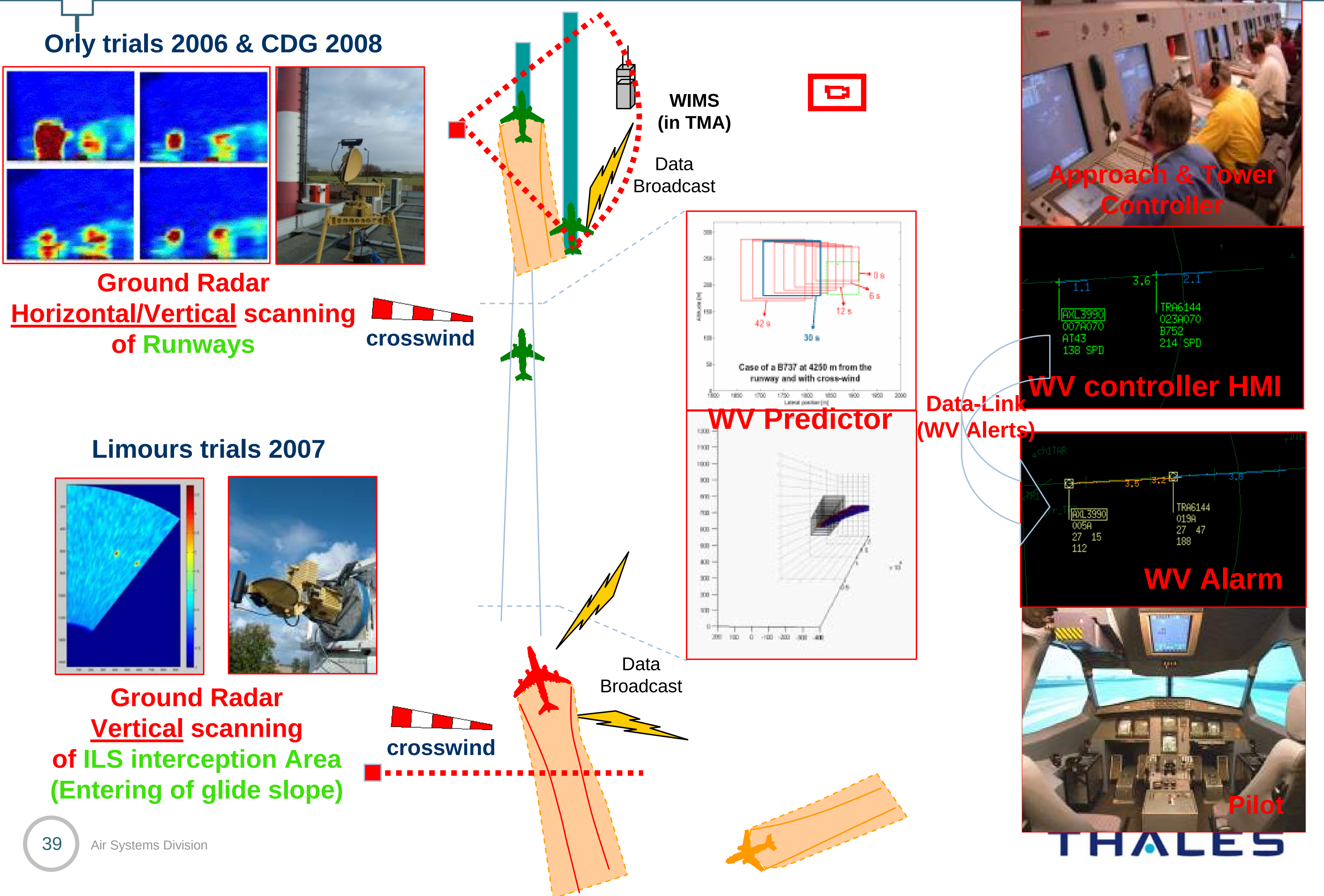
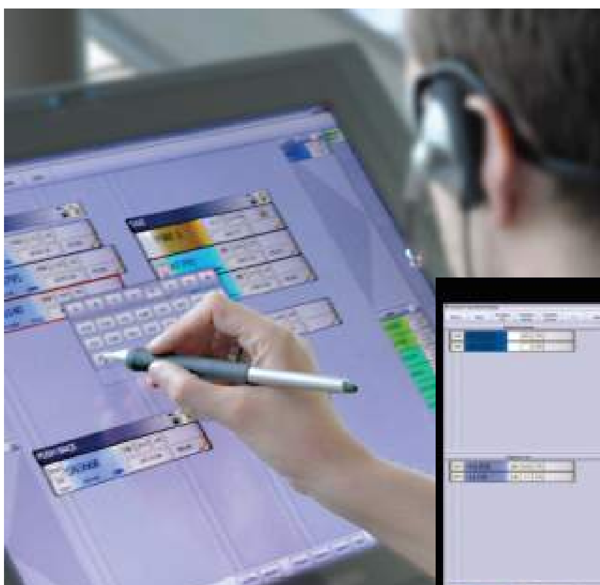

MD82
42 FL
B772
94 FL
LFPP
CRJ1
1 FL -
B738
2 FL -
E145
8 FL
A321
24 FL
B735
16 FL
B744
35 FL
BGW
LFPH

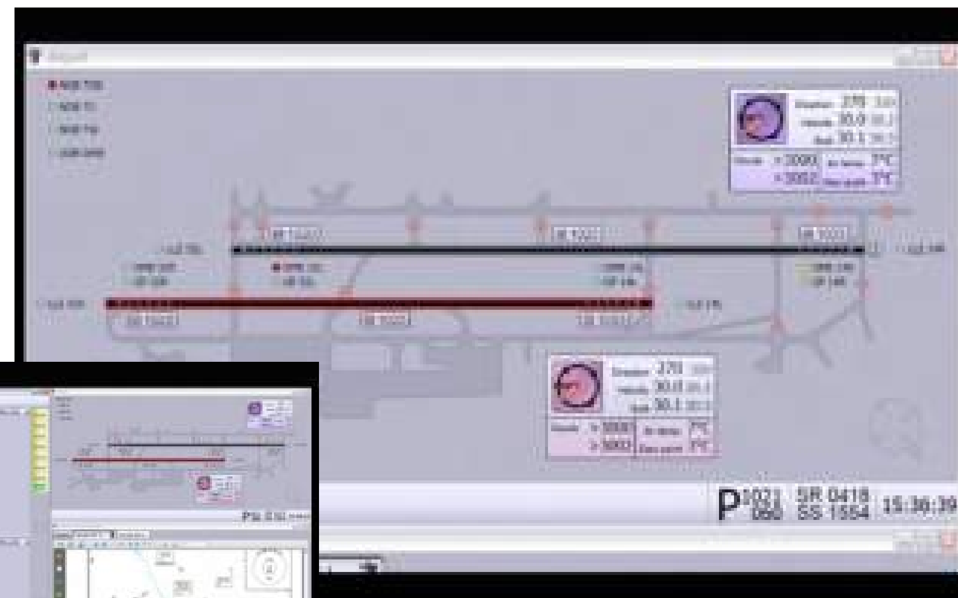
# Approach/Departure : Ground wake detection, tracking & alert



# Wake Vortex Alerts in THALES EUROCAT-T

- WVAS enables Air Traffic Control to:
  - Separate all aircraft down to radar separation minima without jeopardizing flight safety
  - Increase the airports/runways capacity
  - Address Arrivals and/or Departures
- WVAS will ingest Wake Vortex Monitoring Sensors data for Safety Net





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- Jean-Marc Receveau
- Daniel Duong
- Gilbert Herbulot

**DSNA Radar Team**

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- Alfred Harter
- Jean Jezequel

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- Guillaume Auquier


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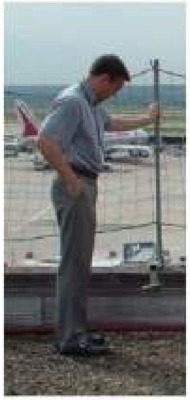

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