Study of wake vortex roll up spiral geometry based on real conditions airport Doppler Radar Trials
During 90’s different Radar trials have been made in US for wake vortex monitoring in clear Air with positive results for different bands.

**USA:**
- During 90’s different Radar trials have been made in US for wake vortex monitoring in clear Air with positive results for different bands.

**EUROPE:**
- UK, GEC-MARCONI (1992) : detection at Range $R = 2.8$ Km with an S-band Radar (3 GHz) (DX04 Radar Campaign)
- France, CNRS/CRPE (1992): detection at Range $R = 0.5$ Km with an UHF-band Radar (961 MHz) (PROUST Radar campaign)
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:

  \[
  (n-1) \times 10^6 = 77.6 \left( \frac{P}{T} \right) + 64.8 \left( \frac{P}{T} \right) + 3.776 \times 10^4 \left( \frac{P}{T^2} \right)
  \]

  \[
  \text{with } n : \text{refractive index of humid air for frequencies below 20 GHz}
  \]

  \[
  P_a : \text{the partial pressure (mb) of dry air} \quad P_v : \text{the partial pressure (mb) of water vapour}
  \]

  \[
  T : \text{the temperature (K)}, \quad T_v = 288K
  \]

- **Adiabatic transport** of atmospheric fluid within a descending oval surrounding a vortex pair:

  \[
  (V(z) - \bar{V}(z)) \times 10^6 = -\bar{V}(z) \frac{N^2}{g} \Delta z \left[ 223 + \frac{\text{RH}(z)P_{sat}(T_v)}{P(z)} \left( 76.7 + 3.49 \times 10^4 \frac{T(z)}{P(z)} \right) \right]
  \]

  \[
  \text{with } N : \text{Brünt-Väisälä Frequency (stratification parameter)}
  \]

  \[
  \text{at Sea Level : } N = 0.014s^{-1} \text{ (in Summer) } N = 0.02s^{-1}-0.03s^{-1} \text{ (in Winter)}
  \]

  \[
  \Delta z : \text{Descend Altitude, and } P = P_a + P_v
  \]

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.
Operating Modes (Staring/Scanning 45°) & Weather

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

**Scanning Mode (8°/s on 45°)**

### No Rain
- Minimum Temperature: 8 °
- Maximum Temperature: 14 °
- Rain Rate: 0 mm
- Wind Speed: 22 km/h
- Wind Direction: South

### Rain
- Minimum Temperature: 9 °
- Maximum Temperature: 12 °
- Rain Rate: 1.19 mm
- Wind Speed: 20 km/h
- Wind Direction: South-East
Horizontal Monitoring of Wake Vortex (runways)
Wake Vortex Detection in Clear Air at 7 Km

Recording conditions:
- 29th November '06
- scanning mode
- scan angle 45°
- scan rate 8°/s
- long transmit pulse
- distance up to 7 km
- without rain
DOPPLER RADAR SIGNATURE OF WAKE VORTEX IN STARING MODE

All Wake Vortices (600 m from Radar) of Medium Aircrafts (Airbus A320,…) have been detected in wet and dry weather conditions.

RCS of Medium Aircraft Wake Vortex: 0.01 m²

S/N ≈ 15 dB (Range = 600 m)
WAKE VORTEX PROFILING: WAKE VORTEX AGE

Positive Time/Doppler slopes

Zero Time/Doppler slopes

Low speed Negative Time/Doppler slopes

Decaying WV

Young WV

Mature WV

Old WV

Negative Time/Doppler slopes

Thales Air Systems
Speed Variance of Rain can measure EDR & TKE (air turbulence)

\[ r = ae^{b\theta} \Rightarrow \frac{dr}{d\theta} = br \Rightarrow b = \frac{1}{2\pi} \log \left( 1 + \frac{\delta_r V}{V} \right) \]
WAKE VORTEX CIRCULATION (WV strength)

Doppler Spectrum on 256 Pulses

Spectrum Module

\[ S(V_i) = \frac{\Gamma^2}{8\pi V_i^3} \]

V\text{max} is related to r\text{c}

\[ V_{\text{max}} = \frac{\Gamma}{2\pi r\text{c}} \]

Doppler Spectrum Behaviour
Compliant with Theory

S(\nu) is decreasing like \(1/(\nu)^3\)
Wake Vortex Circulation Computation

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

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

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


Comparison of Observed and Calculated Vortex Strengths
Limours Radar Trials: September 2007

Vertical Monitoring of Wake Vortex (ILS Interception)

Scan 1
Scan 2
Scan 3

Detection by HR Doppler Entropy

Thales Air Systems
Wake Vortex Time Evolution: HR Doppler Entropy

Thales Air Systems
Paris ORLY AIRPORT Campaign has proved that X-band Thales BOR-A550 Radar can:

- Detect Wake Vortex (RCS of 0.01 m² on medium aircraft)
  - In all weather conditions (wet & dry at short range < 2 Km)
  - In Staring & Scanning Mode
  - In real Time
- Localize Wake Vortex
  - in range/angle
- Characterize Wake Vortex
  - Geometry (Spiral)
  - Age (Young, mature, old, decaying)
  - Strength: Circulation (m²/s)
- Characterize ambient air (in Rain Conditions)
  - Wind (based on Doppler & post-processing)
  - Ambient Air Turbulence (EDR & TKE)

Medium Aircraft
Wake Vortex RCS
0.01 m²
(e.g. : Airbus A320)

Thales Air Systems

EUROCONTROL LIDAR

Thales Radar

Horizontal scanning

Vertical scanning

New tripod for Vertical scanning

Real-Time HMI (C/GTK)

Vortices may rise (vortex bounce) under windshear conditions

½ Wingspan

31L 31R
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Thales Air Systems

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& member of SESAR

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Boeing B747-8

Airbus A380