Radar Monitoring of Wake Turbulence in Rainy Weather: Modelling and Simulation

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February 29th, 2012    DFS Headquarters in Langen, Germany
1. Introduction
2. Modeling of the raindrops’ motion
3. Modeling of the radar signature
4. A wake vortex radar simulator
5. Conclusion
1. Introduction

- Candidate sensors for monitoring wake turbulence
- Comparison between different sensors
- Raindrops as wake turbulence “sensors”
Candidate sensors for monitoring wake turbulence

- **LIDAR**
  - the atmospheric aerosols in clear air (Mie formula)

- **SODAR**
  - the temperature (or density) fluctuations

- **RADAR**
  - the refractive index fluctuations
    -- rain/fog droplets (Rayleigh or Mie)
Comparison between different sensors

The most mature wake vortex sensor: LIDAR
✓ Detection and location
✓ Circulation estimation

However, in foggy, cloudy or rainy weather, it cannot work effectively.

The main operational advantages of RADAR:
✓ Good weather adaptability;
✓ Long detection range;
✓ Low economic cost;
✓ High spatial coverage;

Radar & Lidar are complementary sensors in all weather operations. (F. Barbaresco, 2011)
Raindrops as wake turbulence “sensors”

In clear air, Radar reflectivity of wake turbulence is very low:

- Air density
- Water vapor
- Total

Wake vortex RCS-Frequency Characteristics (Jianbing LI, 2010)
Raindrops as wake turbulence “sensors”

In rainy weather, raindrops are strong scatterers:
- F. Barbaresco, 2006: X band Radar
- T. A. Seliga, 2009: W band Radar

In our analysis, the raindrops’ contribution to Radar reflectivity is assumed to be much larger than wake turbulence.

- How the raindrops move in wake turbulence?
- How the raindrops reflect radar signal?
- How to evaluate the radar signatures of raindrops in wake turbulence?
2. Modeling of the raindrops’ motion

- Main assumptions
- Parametrization of raindrops and wake turbulence
- Motion of raindrops in wake turbulence
2. Modeling of the raindrops’ motion

- Main assumptions

Raindrops:
- the shape is spherical and not deformable
- the collision or coalescence between raindrops is negligible
- the effect of raindrops on wake turbulence field is neglected
- no significant evaporation or condensation of the raindrops

A. B. Kostinski and R. A. Shaw, 2009

Brian Lim, 2006
2. Modeling of the raindrops’ motion

Main assumptions

Wake turbulence:
- the background atmosphere is still air
- the wake vortex velocity field is steady (in stable phase)
- the descending velocity of wake vortex is neglected
- the drag coefficient for raindrops is constant

Ginevsky and Zhelannikov 2009
2. Modeling of the raindrops’ motion

- **Parametrization of raindrops and wake turbulence**

  **Raindrops’ properties in still air**
  - Modified gamma size distribution
  - the equilibrium between the inertial force (gravity) and the dragging force
  - Input: Rain rate, diameter classification, altitude, temperature
  - Output: Number density of raindrops, terminal fall velocity in still air

![Raindrop size distribution](image1.png)

![Terminal fall velocity in still air](image2.png)
2. Modeling of the raindrops’ motion

- Parametrization of raindrops and wake turbulence

Wake turbulence velocity field

- Single vortex model
  Hallock-Burnham model or Rankine vortex model
- Two counter-rotating vortices
  Superimposing two independent vortices with opposite circulation (Li et al. 2011)

- Input parameters
  - Aircraft landing weight: 259000 kg
  - Landing speed: 290 km/h
  - Wingspan: 60.30 m

- Output:
  - 2D velocity field

![Diagram of wake turbulence velocity field with parameters and output result.](image-url)
2. Modeling of the raindrops’ motion

- Motion of raindrops in wake turbulence

  The motion of a raindrop is governed by:
  - its gravity
  - the fluid drag force
  - its diameter
  - its initial horizontal location

The trajectory and velocity of a raindrop depends on:
- its diameter
- its initial horizontal location

Diameter=0.5mm

Diameter=1.0mm

Diameter=4.0mm
3. Modeling of the radar signature

- Raindrop’s Radar cross section
- Radar signal time series
- Doppler spectral analysis
3. Modeling of the radar signature

- Computation model of Raindrop’s Radar Cross Section

Radio radio-electric size

- Raindrop Diameter
- EM Wavelength

\[ \alpha = \pi \frac{D}{\lambda} \]

- Rayleigh Approximation
  - S, C, X bands

- Mie Formulas
  - Ka, W bands

<table>
<thead>
<tr>
<th>Diameter of raindrops: mm</th>
<th>10 GHz</th>
<th>94 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^{-16}</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10^{-14}</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10^{-12}</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10^{-10}</td>
<td></td>
</tr>
</tbody>
</table>
3. Modeling of the radar signature

- Radar signal time series

Radar pulse resolution volume:
- antenna beam width
- radial resolution

Volume scattering:

\[ S_r(n) = \sum_{k=1}^{N_r} s_k(n) + n_s \]
3. Modeling of the radar signature

- Radar signal time series

The procedure of generating radar signal time series:

- Raindrops parameters
- Wake vortex parameters

  Raindrops's motion equation

  Update the dynamic positions and velocities of raindrops

  Radar transmitter
  Radar parameters configuration
  Radar receiver

  Noise

  Radar I & Q time series
3. Modeling of the radar signature

- **Doppler spectral analysis**

  Doppler spectrum:
  - ✔ Power-weighted distribution of raindrops’ radial velocities
  
  ✔ Spectrum width

  **Methods:**
  - ✔ Fast Fourier Transform based spectrum estimation
  - ✔ High resolution spectral estimation (Parametrical methods)
4. A wake vortex radar simulator

- Description of the simulator
- X band Radar Simulation
- W band Radar Simulation
4. A wake vortex radar simulator

➢ Description of the simulator

1) Input the parameters of radar, raindrops, and wake vortices

2) Generate the initial raindrops within wake vortices

3) Compute the radar signal time series for each radar cell

4) Estimate the radar Doppler spectrum of raindrops
4. A wake vortex radar simulator

X band radar simulation

Geometry of radar cells, raindrops and wake vortex

The parameters of the raindrops

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain rate</td>
<td>1.19mm/h, 5mm/h</td>
</tr>
<tr>
<td>Temperature of the water</td>
<td>10°C</td>
</tr>
<tr>
<td>Minimum diameter of the raindrops</td>
<td>0.5mm</td>
</tr>
<tr>
<td>Maximum diameter of the raindrops</td>
<td>4.0mm</td>
</tr>
<tr>
<td>Total number of diameter classes</td>
<td>100</td>
</tr>
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</table>

Input parameters of the simulator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar frequency</td>
<td>10 GHz</td>
</tr>
<tr>
<td>Transmitted peak power</td>
<td>20 W</td>
</tr>
<tr>
<td>Noise figure</td>
<td>2 dB</td>
</tr>
<tr>
<td>System Loss</td>
<td>3 dB</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>30 dB</td>
</tr>
<tr>
<td>Beam width</td>
<td>2.8° × 4°</td>
</tr>
<tr>
<td>Azimuth angle</td>
<td>0°</td>
</tr>
<tr>
<td>Elevation angle</td>
<td>3°, 4°, 5°, 6° or 7°</td>
</tr>
<tr>
<td>Distance of wake vortex</td>
<td>500 m</td>
</tr>
<tr>
<td>Number of radar bins</td>
<td>5, 6</td>
</tr>
<tr>
<td>Pulse width</td>
<td>0.2 μs</td>
</tr>
<tr>
<td>Pules Repetition Frequency</td>
<td>3348 Hz</td>
</tr>
<tr>
<td>Number of pulses</td>
<td>256</td>
</tr>
<tr>
<td>Maximum landing weight</td>
<td>259000kg</td>
</tr>
<tr>
<td>Landing velocity</td>
<td>290 km/h</td>
</tr>
<tr>
<td>The wingspan</td>
<td>60.30 m</td>
</tr>
</tbody>
</table>
4. A wake vortex radar simulator

- X band radar simulation

Doppler spectrum of the raindrops within wake vortex

Radar cell: 01

Radar cell: 02

Radar cell: 03

Radar cell: 04

Radar cell: 05

\( \rho_r = 40m \)
4. A wake vortex radar simulator

- X band radar simulation

Doppler spectrum for different elevation angles

\[ \rho_r = 40\text{m} \]

Radar cell: 02

Radar cell: 03

Radar cell: 04

WakeNet3-Europe 4th major workshop “Wake Turbulence in Current Operations and Beyond”
4. A wake vortex radar simulator

- X band radar simulation

Doppler spectrum for 100m radial resolution

\[ \rho_r = 100m \]
4. A wake vortex radar simulator

- W band radar simulation

Radar is working in vertical scanning mode

W Band Radar Parameters (T. A. Seliga, 2009)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of Operation</td>
<td>94.0-94.25 GHz</td>
</tr>
<tr>
<td>Peak Transmit Power</td>
<td>100 mW</td>
</tr>
<tr>
<td>Waveform Type</td>
<td>Linear FM chirp</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Pulse Repetition Frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Pulse Duration (min- max)</td>
<td>1-10 µs</td>
</tr>
<tr>
<td>Antenna Diameter &amp; Type</td>
<td>48” Cassegrain</td>
</tr>
<tr>
<td>Antenna Beamwidth</td>
<td>0.18°</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>58 dB</td>
</tr>
<tr>
<td>Front-end Noise Figure</td>
<td>12 dB</td>
</tr>
</tbody>
</table>
4. A wake vortex radar simulator

- **W band radar simulation**

**Average received power and Doppler velocity field**

```
<table>
<thead>
<tr>
<th>Range (m)</th>
<th>Elevation (m)</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>850-1150</td>
<td>100</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>150-200</td>
<td>150</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>200-250</td>
<td>200</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Range (m)</th>
<th>Elevation (m)</th>
<th>-8</th>
<th>-6</th>
<th>-4</th>
<th>-2</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>850-1150</td>
<td>100</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>150-200</td>
<td>150</td>
<td>-2</td>
<td>-4</td>
<td>-6</td>
<td>-8</td>
<td>-10</td>
</tr>
<tr>
<td>200-250</td>
<td>200</td>
<td>-4</td>
<td>-6</td>
<td>-8</td>
<td>-10</td>
<td>-12</td>
</tr>
</tbody>
</table>
```

Rain rate 2.0mm/h, Range Resolution: 2 m

*W-Band Radar Measurements (T. A. Seliga 2009)*
A methodology to simulate the radar signature of wake vortices in rainy weather has been presented.

The particular shape of the Doppler spectrum of the raindrops within wake vortices can provide potential information for identifying wake vortex hazard in air traffic control.

The current work will be improved by:

- Comparing the Radar Doppler signature of raindrops in the presence of wake vortices, cross wind and atmospheric turbulence
- Validation of Radar signature simulator with real data from field tests
- Exploitation of the Radar signature simulator for the other parameter configurations
- Extraction of wake vortex parameters from the radar signature of raindrops
Thank you for your attention!