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WakeNet3-Europe



A RADAR SIMULATOR FOR MONITORING WAKE TURBULENCE IN RAINY WEATHER

Zhongxun Liu

National University of Defense Technology, China

University of Toulouse, ISAE, France

Southampton, UK

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國防科學技術大學

NATIONAL UNIVERSITY OF DEFENSE TECHNOLOGY



Outline

Introduction

- Wake vortex hazards
- Wake vortex monitoring sensors

Methodology

- Raindrops & Wake Vortex Interaction
- Raindrops & EM waves Interaction

Results

- Trajectory of raindrops within wake vortex
- Radar signature of raindrops in still air
- Radar signature of raindrops within wake vortex

Conclusions

- What has been achieved
- Future Research Needs
- Acknowledgements
- References

Introduction

- Wake vortex hazards
- Wake vortex monitoring sensors

Wake vortex hazards



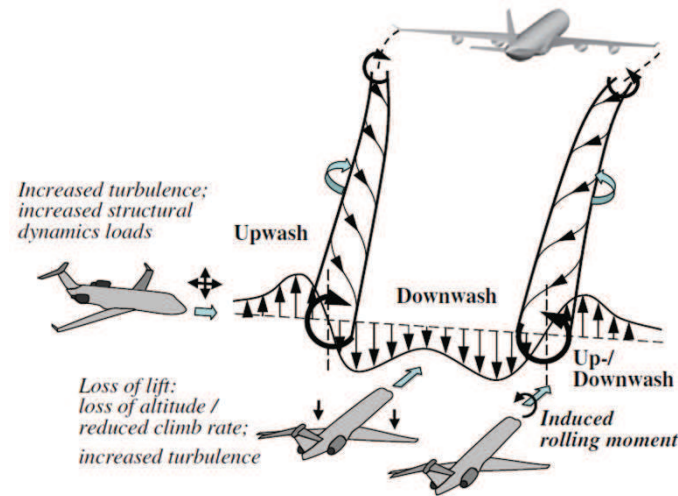
Boeing 777 Wake Turbulence

Long lifetime:

several minutes

Large strength:

potential hazards

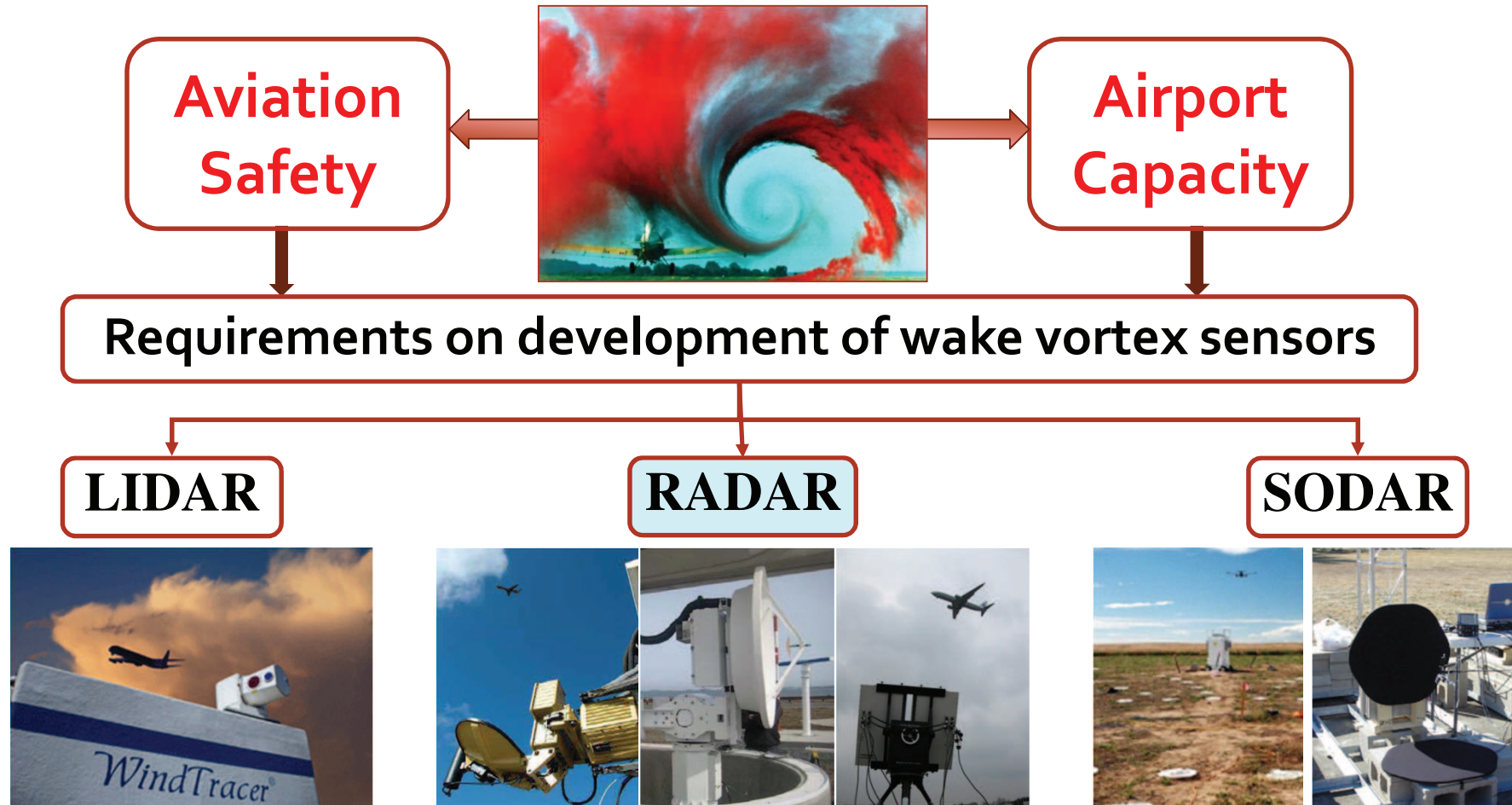


Wake Vortex Encounters

EU project: SESAR (2006-2020)

	by 2020	Long term
CAPACITY	+73%	× 3
SAFETY	× 3	× 10

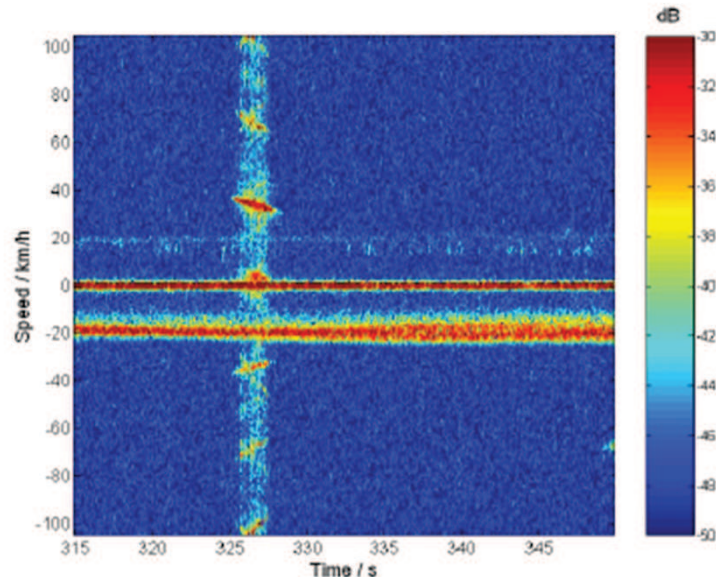
Wake vortex monitoring sensors



RADAR can detect wake vortex in foggy or rainy weather

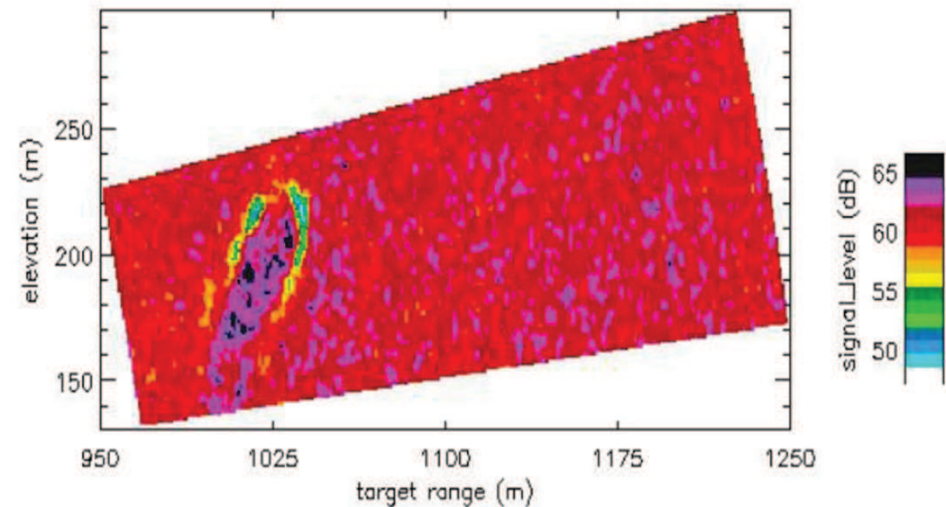
Wake vortex monitoring sensors

X-band Radar **F. Barbaresco 2006**



Wake Vortex Doppler Radar Signature in staring mode (with Rain)

W-Band Radar **T. A. Seliga 2009**



RHI Relative Power Profile (Reduced and enhanced concentration of raindrops)

How to theoretically understand the current phenomenon?

How to technically develop new wake vortex radar sensors?

Therefore, the development of a radar simulator for wake vortex monitoring in rainy weather is of great necessity!

Introduction

Wake vortex monitoring sensors

The development of a radar simulator

✓ Objectives:

- ❑ To estimate the RCS and Doppler spectrum of raindrops within wake vortex
- ❑ To evaluate the radar detectability of wake vortex in rainy weather and provide technical guidance for the development of new wake vortex radar sensors

✓ Functions

- ❑ to define the synthetic environment based on the parameters of raindrops, wake vortex and radar configurations;
- ❑ to generate the time series samples of the I and Q signals based on the synthetic meteorological environment and the update of the position and velocity of the raindrops;
- ❑ to estimate the RCS and Doppler spectrum of the raindrops based on the simulated radar echo by signal processing methods.

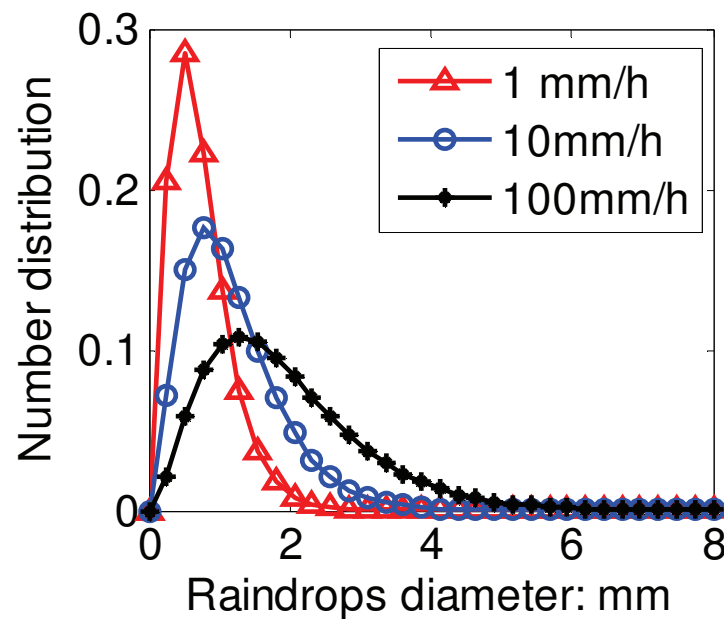
Methodology

- Raindrops & Wake Vortex Interaction
- Raindrops & EM Waves Interaction

|| Raindrops & Wake Vortex Interaction

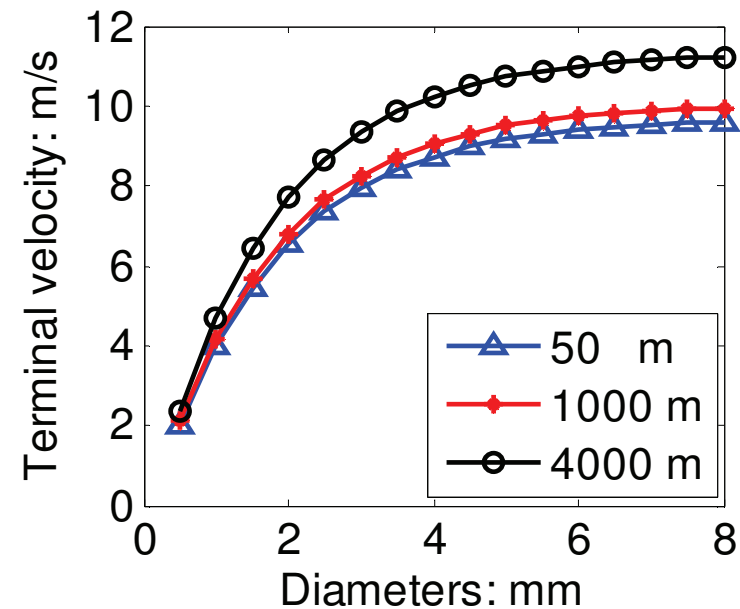
✓ Raindrop size distribution

- The relationship between Raindrop size distribution and Rain rate
- The number of raindrops as a function of diameters



✓ Terminal fall velocity in still air

- Terminal fall velocity as a function of diameters for raindrops at different altitude levels

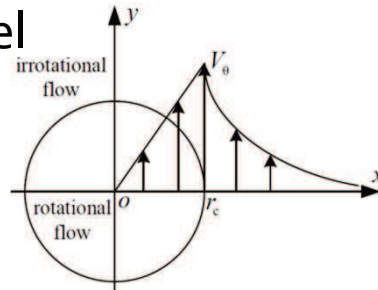


Raindrops & Wake Vortex Interaction

✓ Wake vortex velocity model

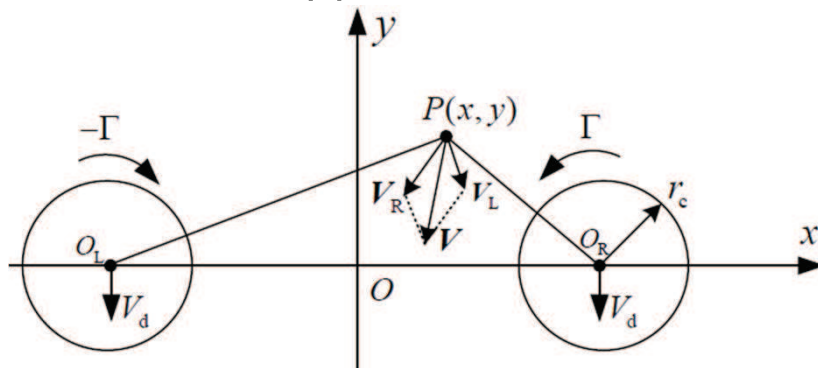
- Rankine vortex model
- Tangential velocity

$$V_{\theta}(r) = \frac{\Gamma_0}{2\pi r} \begin{cases} r^2/r_c^2 & \text{if } r < r_c \\ 1 & \text{if } r \geq r_c \end{cases}$$

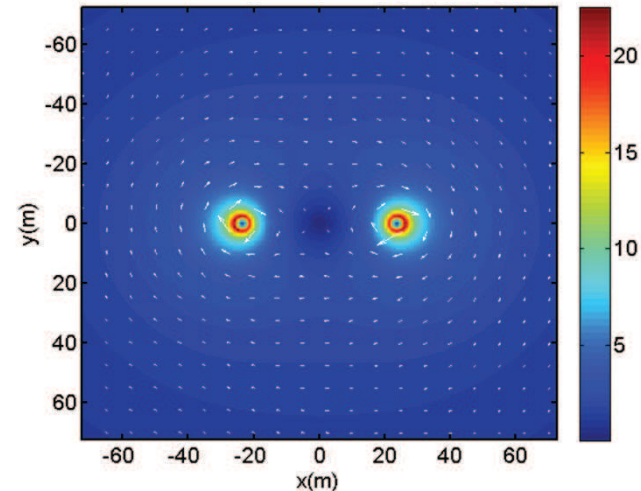


r : radius, r_c : vortex core radius, Γ_0 : circulation

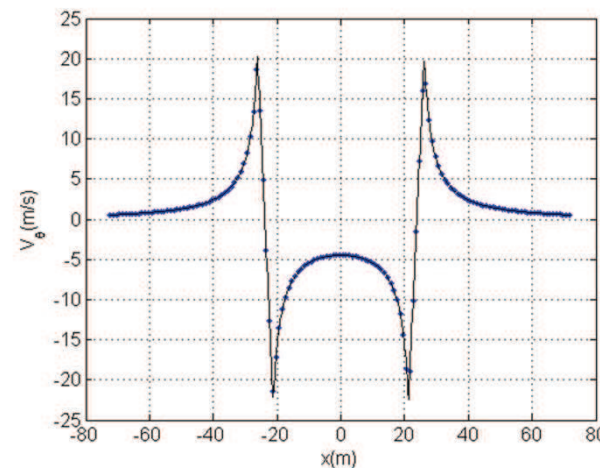
- Superimposing two independent vortices with opposite circulation



Methodology



2D wake vortex velocity distribution of A340



Velocity distribution along a horizontal line

|| Raindrops & Wake Vortex Interaction

✓ The motion equation of raindrops within wake vortex

Main assumptions:

1. the raindrops have a spherical shape
2. the interaction between raindrops (collision or coalescence) is negligible
3. the wake vortex is in stable phase

The motion of a raindrop within wake vortex is governed by its **gravity** and the **fluid drag force** on it

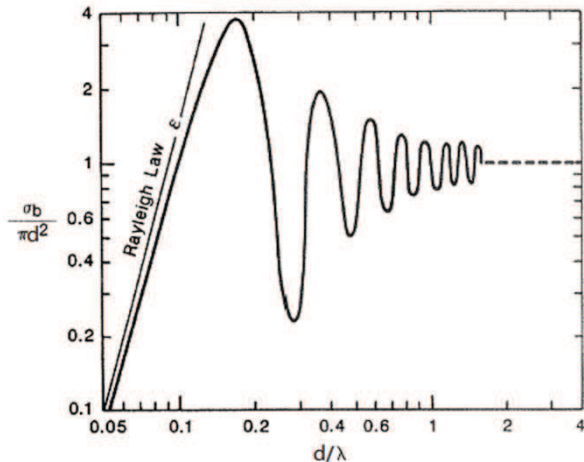
$$\mathbf{a}(t) = \frac{\mathbf{F}_{\text{drag}}(t)}{m_p} + \mathbf{g} \quad \mathbf{F}_{\text{drag}}(t) = \frac{g}{V_T} \delta \mathbf{v} \left[\frac{|\delta \mathbf{v}|}{V_T} \right]^{\eta_d - 1}, \quad \delta \mathbf{v} = \mathbf{u}(\mathbf{x}_p, t) - \mathbf{v}_p(t)$$

The drag force depends on **the velocity difference** between raindrops and wake vortex.

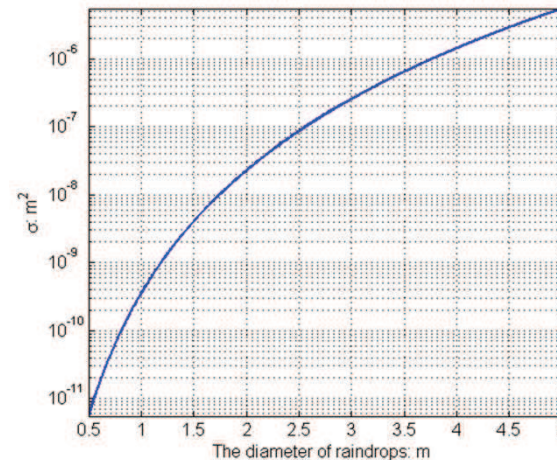
The **trajectory** of a raindrop within wake vortex can be obtained by solving the motion equation.

|| Raindrops & EM Waves Interaction

✓ Microwave properties of raindrops



Radar Cross Section (RCS) of a Metallic Sphere



RCS function of diameters for a raindrop

For an X-band radar, the backscattering cross section of a raindrop can be well described by Rayleigh approximation

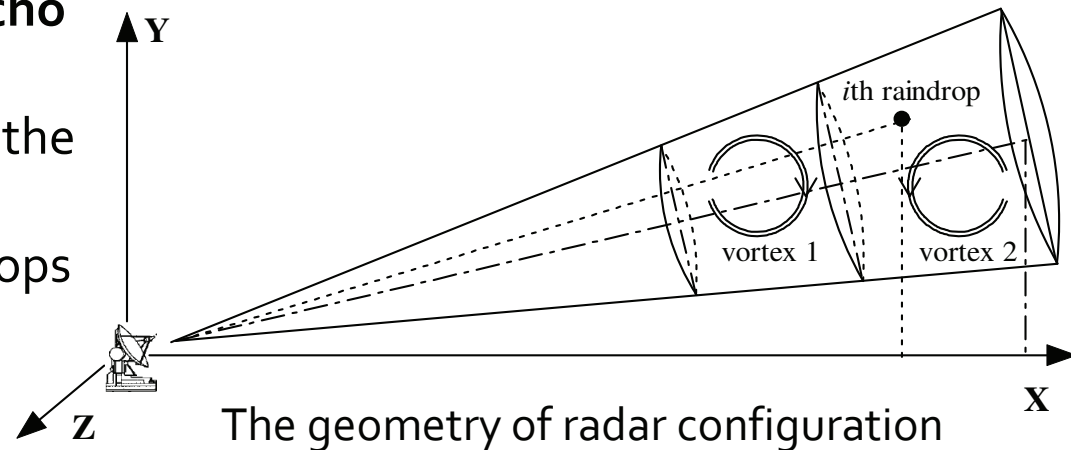
$$\sigma = \frac{\pi^5}{\lambda^4} |K|^2 D^6 \quad K = \frac{m^2 - 1}{m^2 + 2}$$

m is the complex refractive index of the raindrops

|| Raindrops & EM Waves Interaction

✓ Radar echo model, RCS and Doppler spectrum estimation

- **Properties of the received echo**
 - Volume scattering
 - Received signal = Sum of the backscattered baseband signals from all the raindrops in the radar cell



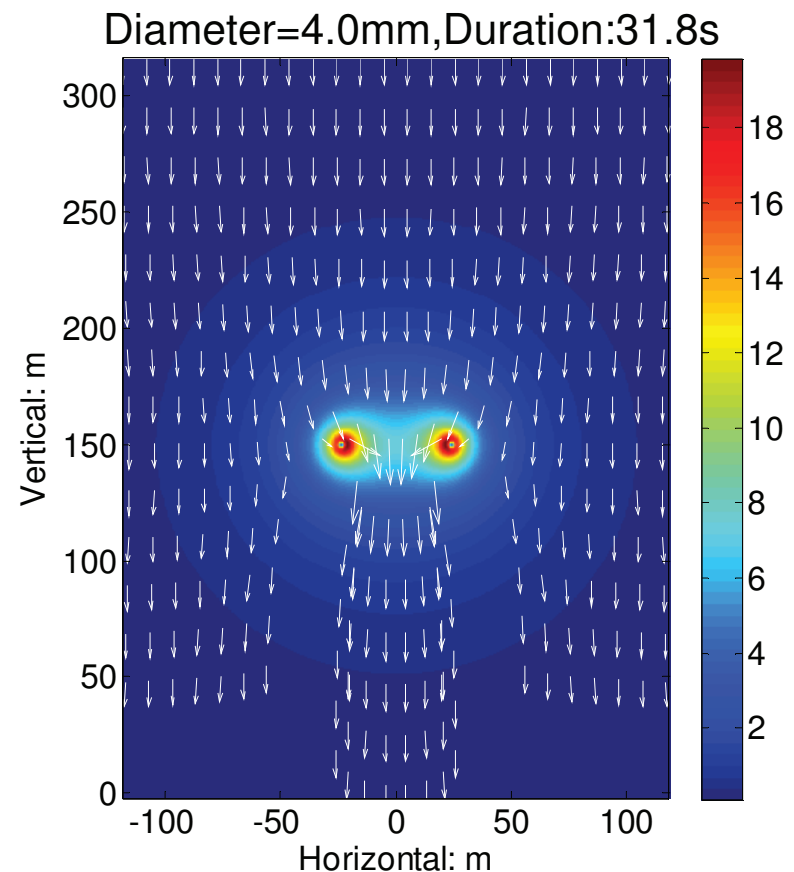
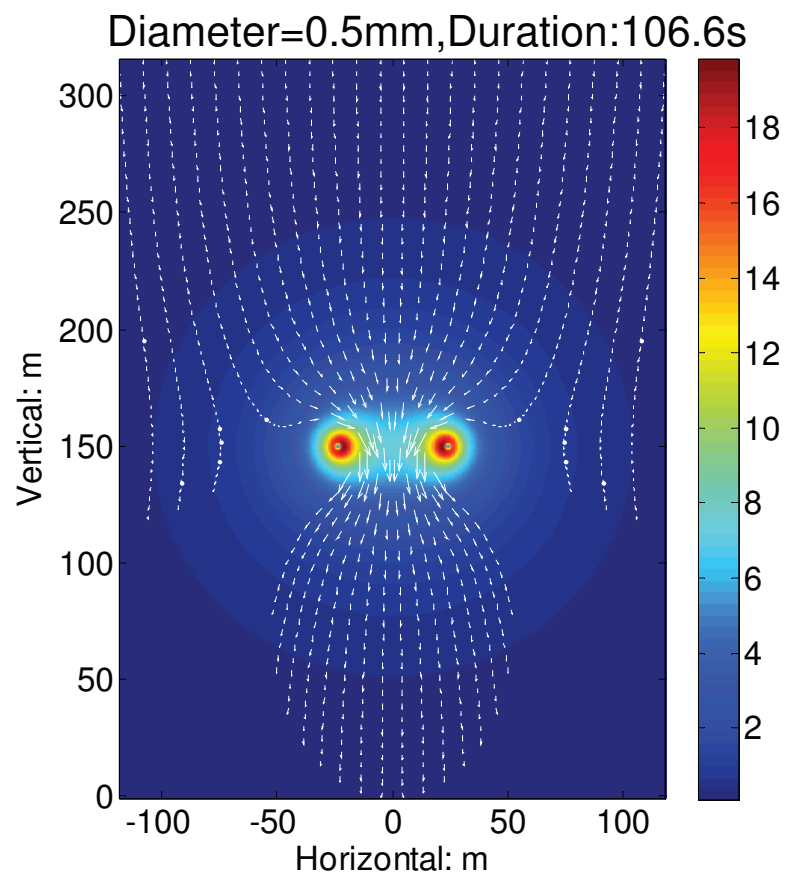
- **Simulation procedure**
 - Input the parameters of radar, raindrops, and aircraft wake turbulence
 - Generate the initial raindrops within wake vortices
 - For each time step
 - Computation of radar equation (Signal amplitude, noise)
 - Computation of I & Q radar signals (Signal phase)
 - Update of the position and velocity of raindrops within wake vortices
 - Estimation the RCS and Doppler Spectrum of raindrops

Results

- Trajectory of raindrops within wake vortex
- Radar signature of raindrops in still air
- Radar signature of raindrops within wake vortex

Trajectory of raindrops within wake vortex

The motion equation of raindrops are solved by using the 4th order 4-variables Runge-Kutta method. The trajectory of raindrops with smaller diameter seems to be more largely changed by vortex flow.



Results

Radar signature of raindrops in still air

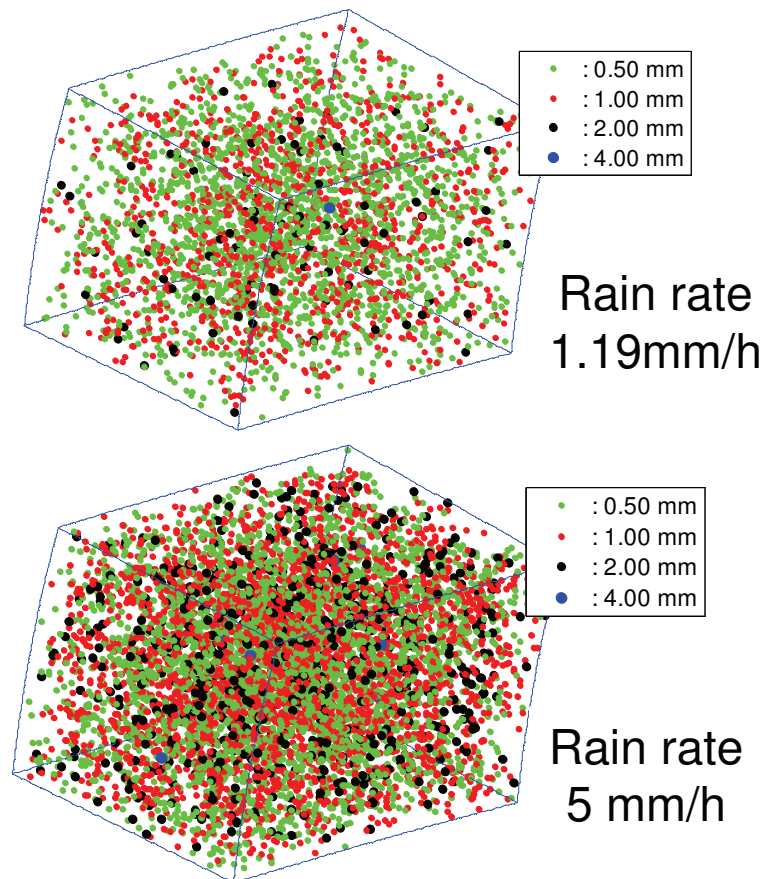
The simulator is capable of generating time series radar echo for raindrops in still air. The RCS and Doppler spectrum within a radar cell can be estimated for different ranges and rain rates.

The parameters of the raindrops

Rain rate	1.19mm/h, 5mm/h
Temperature of the water	10°C
Minimum diameter of the raindrops	0.5mm
Maximum diameter of the raindrops	4.0mm
Total number of diameter classes	100

Input parameters of the radar simulator

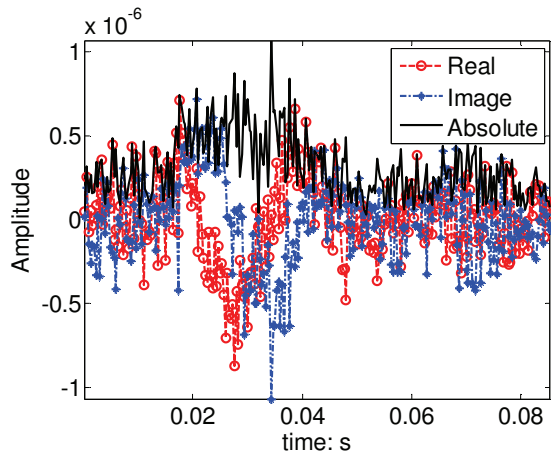
Radar frequency	10 GHz
Transmitted peak power	20 W
Noise figure	2 dB
System Loss	3 dB
Antenna gain	30 dB
Beam width	2.8° × 4°
Azimuth angle	0°
Elevation angle	5°, 90°
Distance of radar bin	1 km, 5 km
Pulse width	0.2 μs
Pulses Repetition Frequency	3 kHz
Number of pulses	256



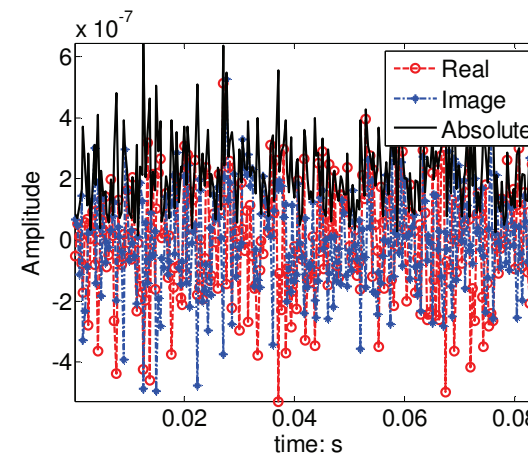
Results

Radar signature of raindrops in still air

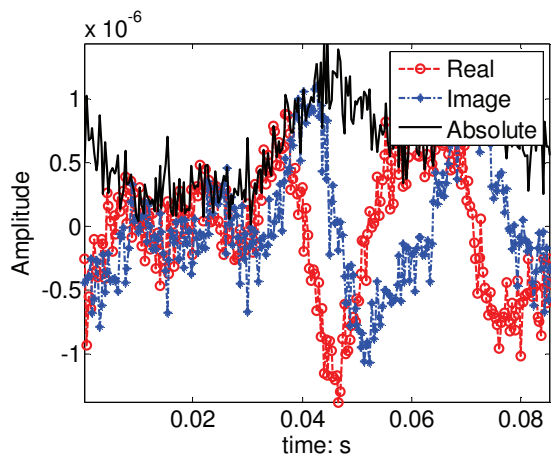
✓ Simulated radar echo induced by the raindrops in a radar cell



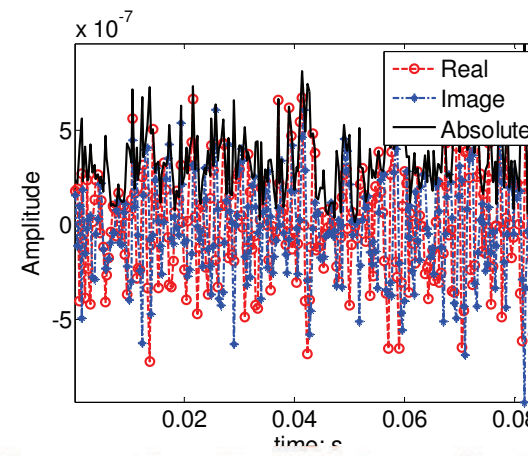
(a) $r_o=1\text{km}$, $R=1.19\text{mm/h}$, $\theta_0=5^\circ$



(b) $r_o=5\text{km}$, $R=1.19\text{mm/h}$, $\theta_0=5^\circ$



(c) $r_o=1\text{km}$, $R=5.0\text{mm/h}$, $\theta_0=5^\circ$

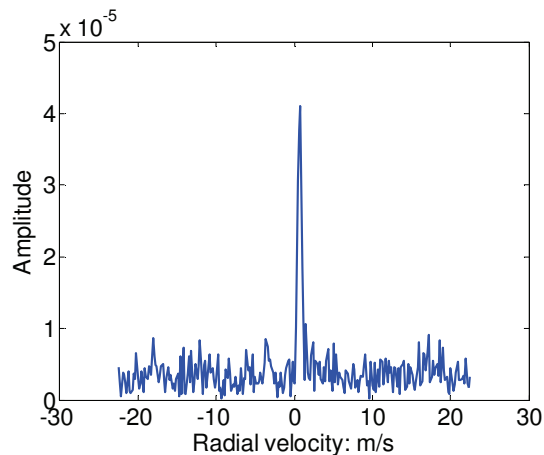


(d) $r_o=1\text{km}$, $R=1.19\text{mm/h}$, $\theta_0=90^\circ$

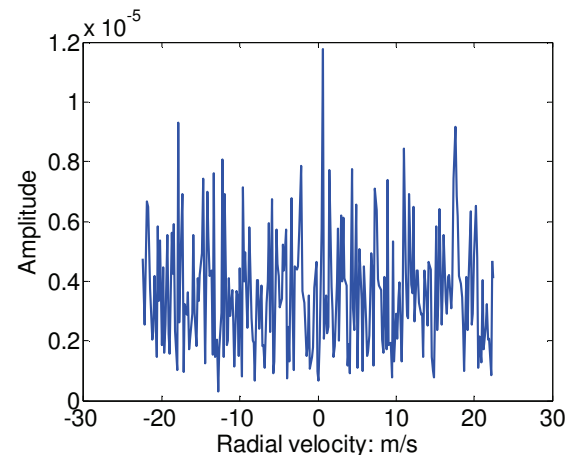
Results

Radarsignature of raindrops in still air

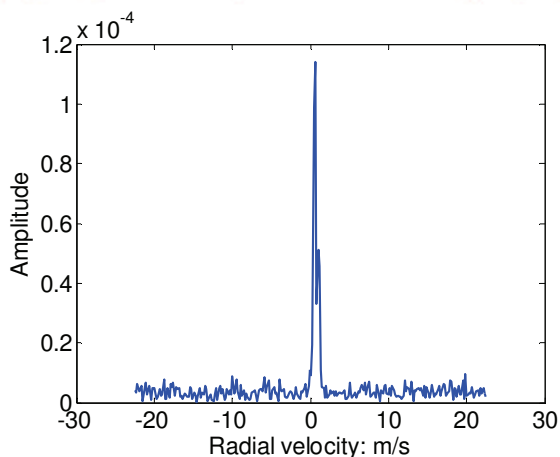
✓ Doppler velocity distribution of the raindrops in a radar cell



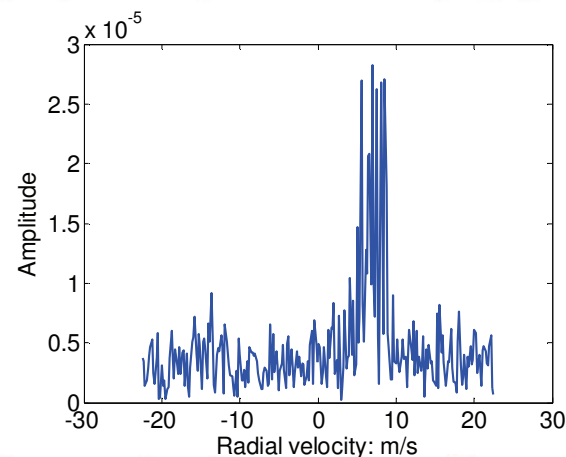
(a) $r_o=1\text{km}$, $R=1.19\text{mm/h}$, $\theta_0=5^\circ$



(b) $r_o=5\text{km}$, $R=1.19\text{mm/h}$, $\theta_0=5^\circ$



(c) $r_o=1\text{km}$, $R=5.0\text{mm/h}$, $\theta_0=5^\circ$



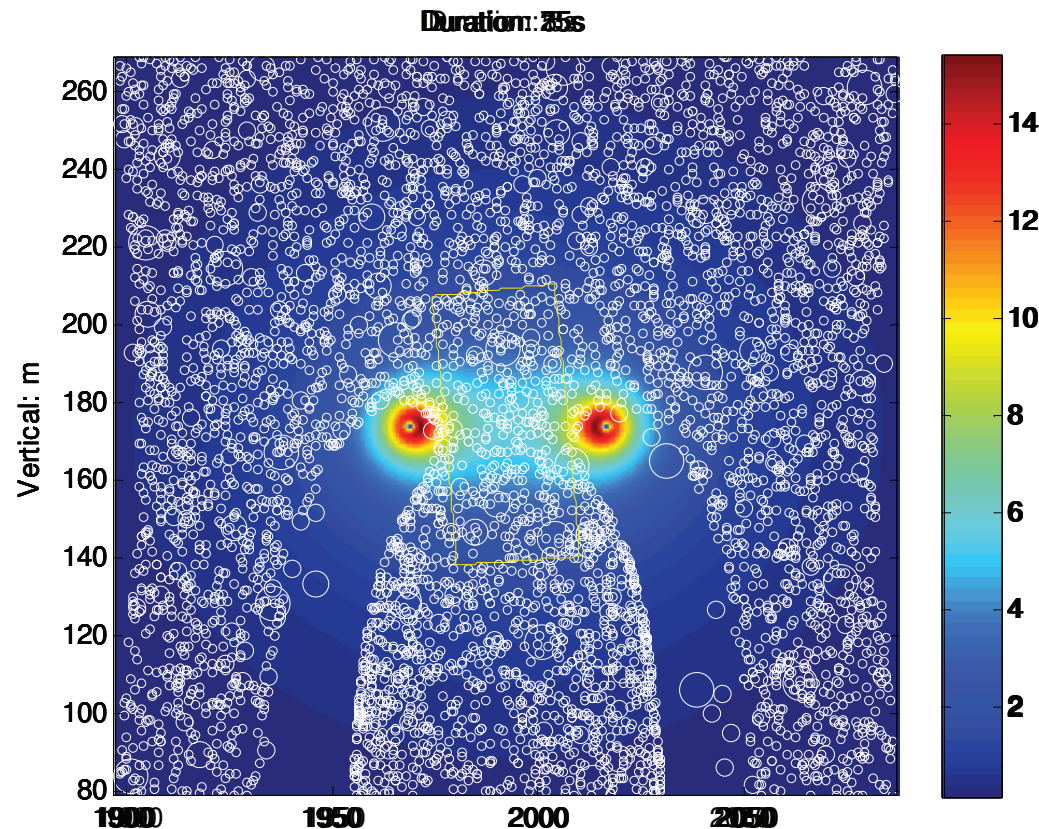
(d) $r_o=1\text{km}$, $R=1.19\text{mm/h}$, $\theta_0=90^\circ$

Results

Radarsignature of raindrops within wake vortex

✓ Generation of the initial raindrops

- Raindrops randomly settled at the top of the wake vortex box
- Update the positions and velocities until the smallest raindrops reach the bottom



Results

Radar signature of raindrops within wake vortex

✓ Generation of the initial raindrops

Enhanced concentration: between the two vortices

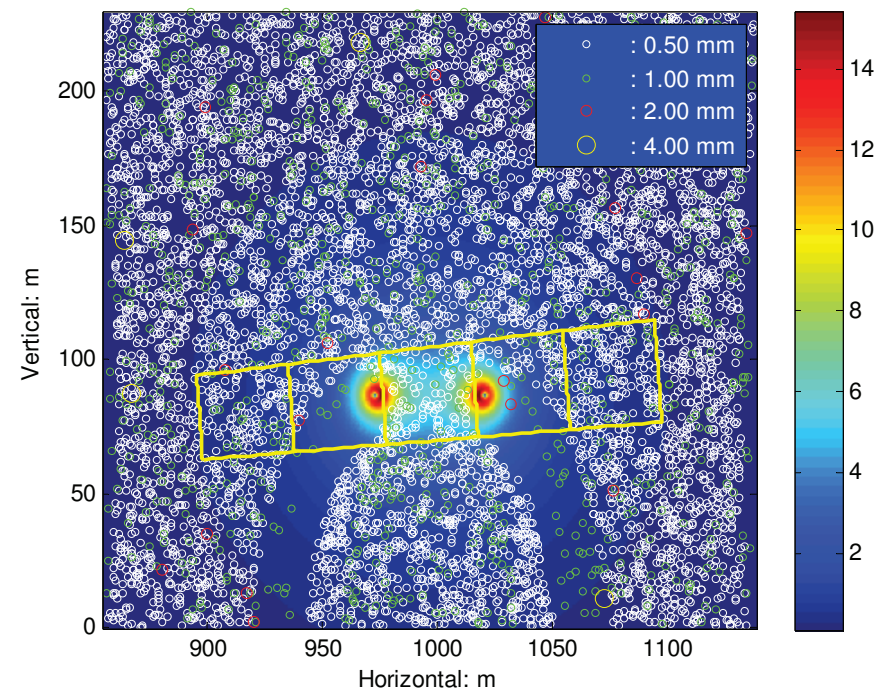
Reduced concentration: in columns below the two vortices

Similarity with the **W-Band Radar** observation by T. A. Seliga

Input parameters of the simulator

Radar frequency	10 GHz
Transmitted peak power	20 W
Noise figure	2 dB
System Loss	3 dB
Antenna gain	30 dB
Beam width	$2.8^\circ \times 4^\circ$
Azimuth angle	0°
Elevation angle	$3^\circ, 4^\circ, 5^\circ, 6^\circ$ or 7°
Distance of wake vortex	500 m
Number of radar bins	5, 6
Pulse width	$0.2 \mu\text{s}$
Pules Repetition Frequency	3348 Hz
Number of pulses	256
Maximum landing weight	259000kg
Landing velocity	290 km/h
The wingspan	60.30 m

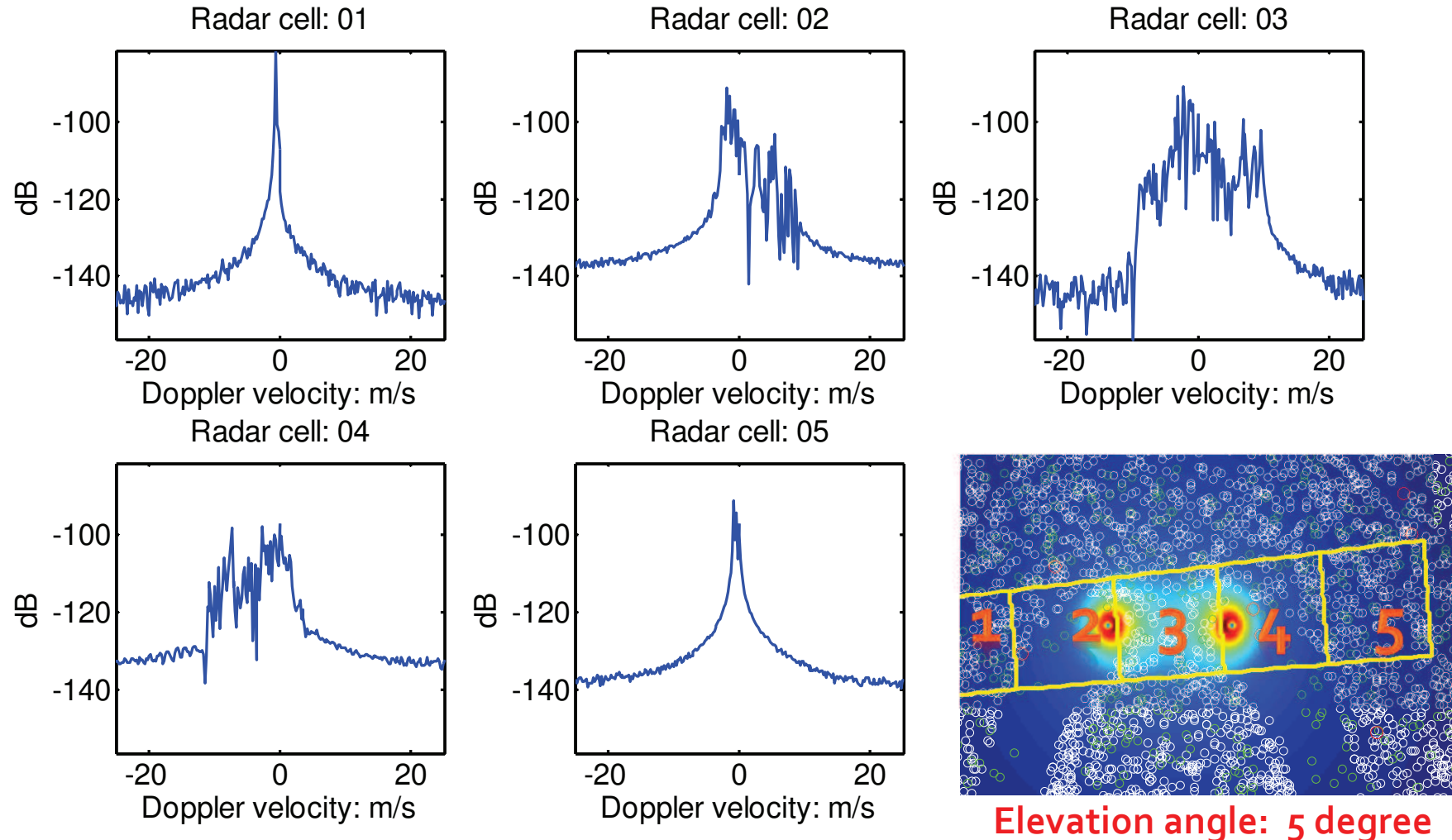
Geometry of radar cells, raindrops and vortex



Results

Radar signature of raindrops within wake vortex

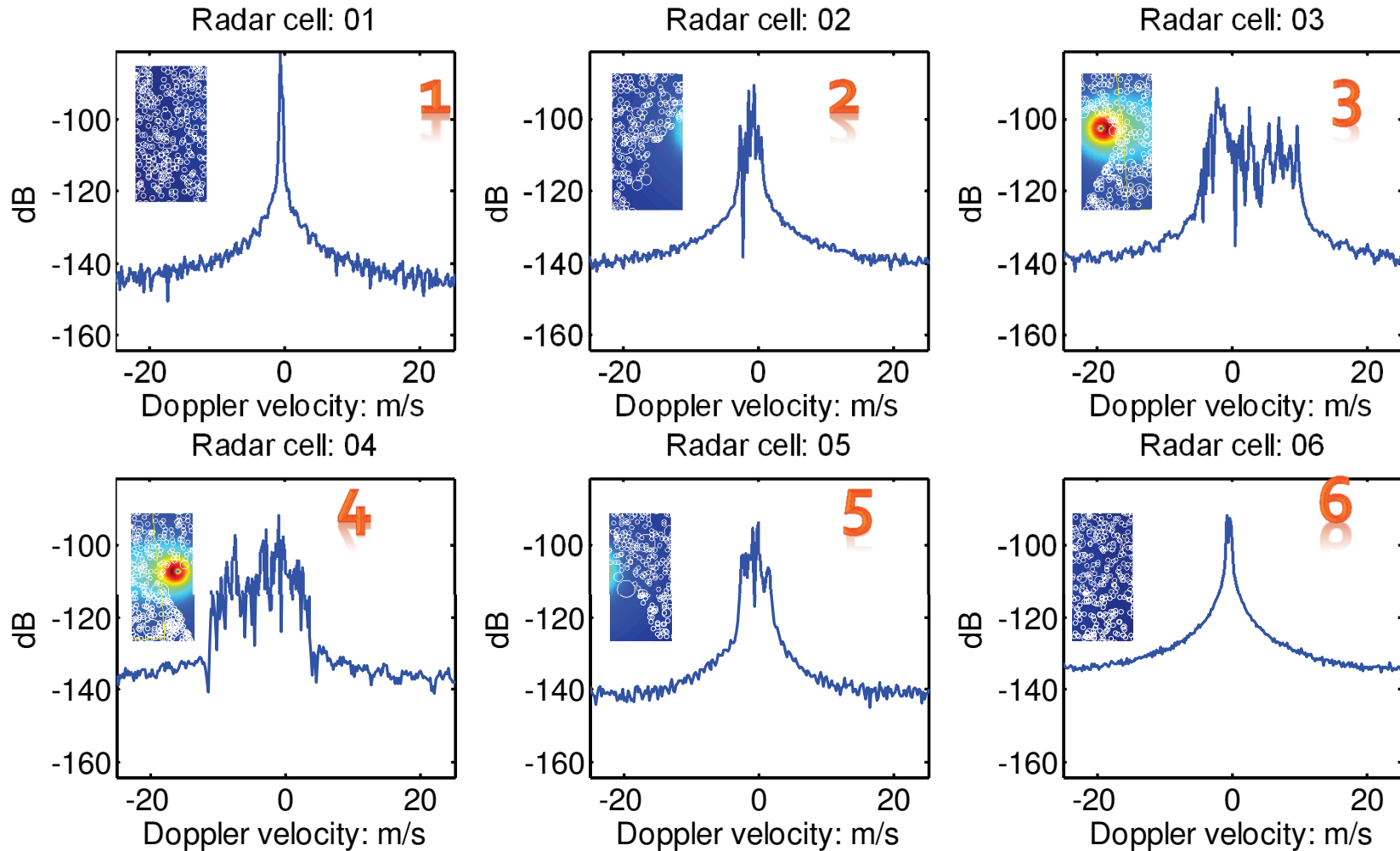
✓ Doppler spectrum of the raindrops within wake vortex



Results

Radar signature of raindrops within wake vortex

✓ Doppler spectrum of the raindrops within wake vortex



Simulation

Conclusions

- What has been achieved
- Future Research Needs
- Acknowledgements
- References

|| What has been achieved

A simulator has been developed for radar monitoring wake vortex in rainy conditions. It relies on:

1. a methodology to compute the trajectory of raindrops within WV;
2. the computation of the radar signal from the raindrops within wake vortices or in still air;
3. the implementation of Doppler spectrum estimation methods for the simulated signal.

Main results obtained from the simulator:

1. The phenomenon of enhanced and reduced concentration of raindrops within wake vortex is found by numerical simulation
2. The preliminary results on the Doppler spectrum of the raindrops in wake vortex region are proved to be able to provide information for identifying wake vortex from the ambient atmosphere.

Future Research Needs

The current work should be lately improved by

1. taking the wind and turbulence effect into account on the raindrops' motion, in order to increase the realism of the Doppler spectrum of raindrops not disturbed by wake vortex;
2. exploitation of the simulator (modifying carrier frequency, range, beam width, range resolution, Doppler resolution, geometry , etc.) for designing a radar dedicated to wake vortex detection in rainy conditions;
3. extending the medium effect analysis to non rainy conditions, i.e. clear air refractive index reflectivity backscattering through Bragg mechanism.
4. validating the simulator with real data from radar trials

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Thank you for your attention !

Questions ?