MS3
Microwave Sensing
Signals & Systems

#250

Simulation of Radar Micro-Doppler Patterns for Multi-Propeller Drones

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Outline

- **Introduction**
- **General Approach**
- **Single propeller characterization**
  – models and measurements
- **Multi-propeller drone simulations**
- **Conclusion**

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Introduction

- Drones are popular
  - Environmental monitoring, delivery, emergency services

Drone revealing fire damage to Notre Dame

- They pose threats
  - Collision hazards, privacy violation, illegal reconnaissance, smuggling, terrorism

www.theverge.com/2019/4/16/18410723/notre-dame-fire-dji-drones-tracking-stopped-thermal-cameras

Introduction

- Response to these threats
  - Detection, Tracking, Characterization, Classification
  - then – acting (interception / destruction / jamming)
- All these tasks can be done based on **radar micro-Doppler patterns**
  - Long range sensing, stable in most weather and light conditions, provides range and velocity information
- What do we need to know for about drones?
  - It is necessary to understand the relations between the observed micro-Doppler pattern, radar parameters and properties of specific drone's rotating parts:
  - Algorithms for aforementioned sensing tasks…

Objectives of the study

- To develop an approach that will give a possibility to study the relation between the micro-Doppler pattern, radar parameters
  - Operational frequency
  - Pulse Repetition Frequency (PRF)
  - Coherent Processing Interval (CPI)

  properties of specific drone's rotating parts:
  - number and length of blades in propeller,
  - number of propellers/rotors,
  - rotors rotation speed and synchronization

  and observed scene
  - Drone's motion (hovering or moving) and orientation

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State of the art

- Data collection methods in **previous researches**
  - Simulated data
  - Indoor measurements
  - Outdoor measurements
- Problems
  - Time consuming
  - Constant synchronization of propellers (hovering only)
  - Only for a particular drone (drones collection?)
  - Mostly studied for the short CPI, when the propeller's rotation period is much longer this CPI

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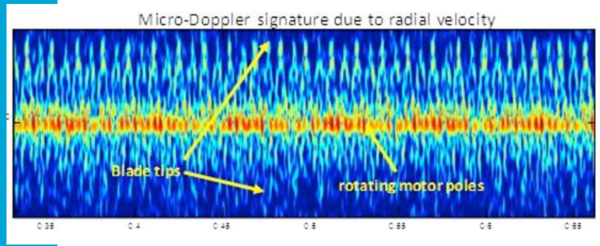
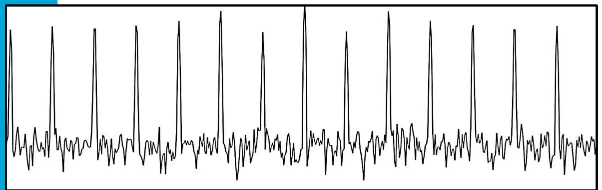
Short and Long Coherent Processing Intervals

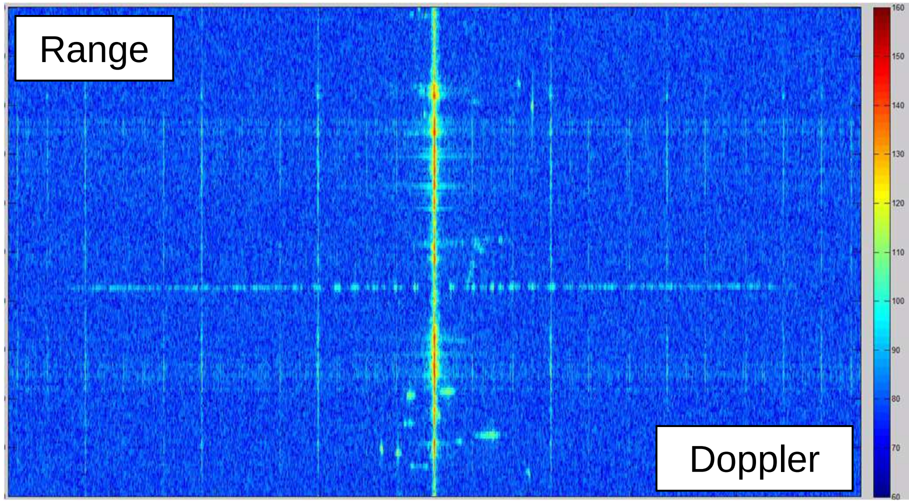
Short CPI << Rotation Period



Long CPI ~ Rotation Period



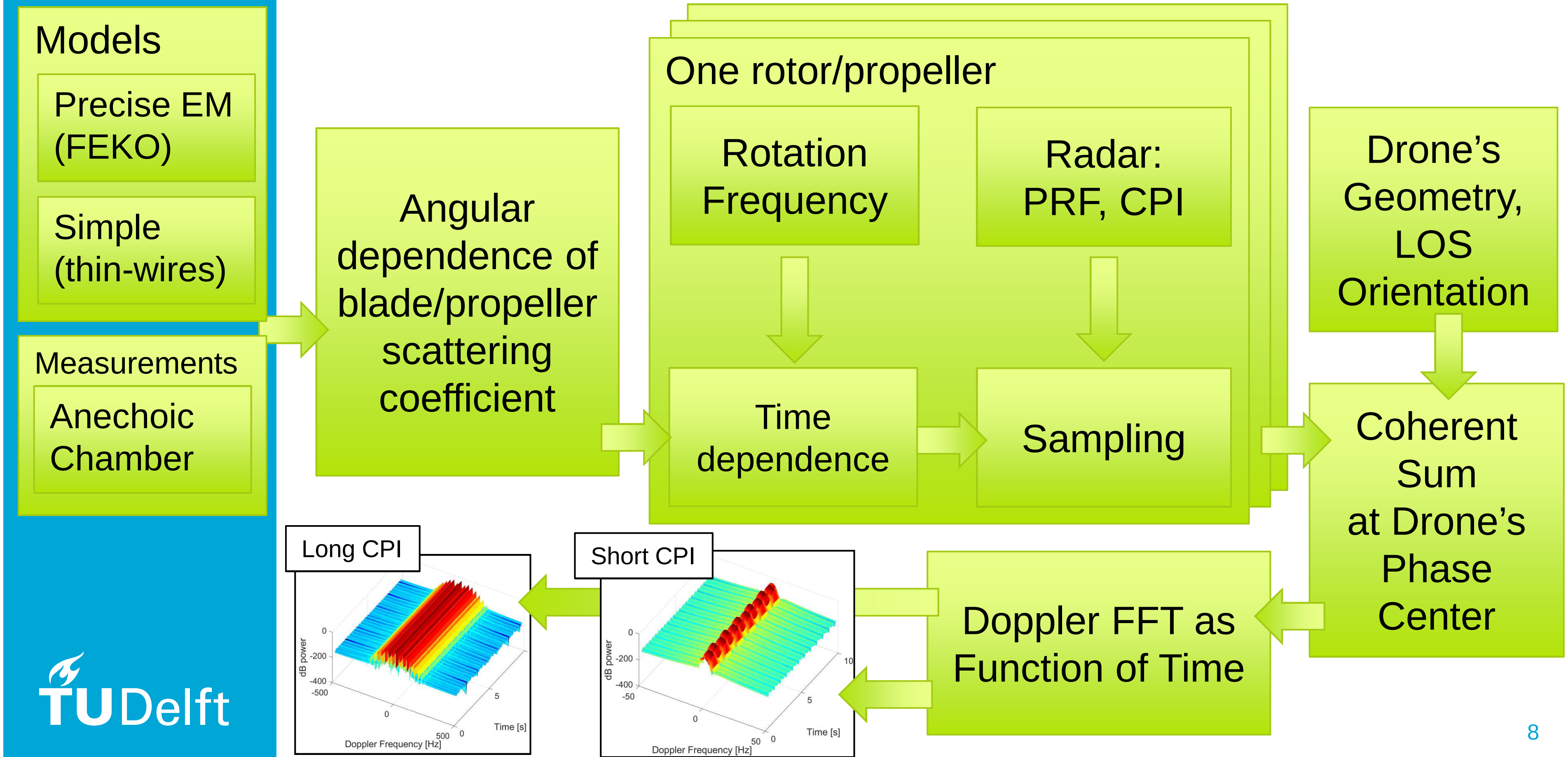
Line spectrum



DJI Matrix-600, PARSAX radar, HH polarisation,
Range 9 km, 3.315 GHz, PRI = 240us, B=16.8MHz,
PRF = 4.17 kHz, CPI = 0.98 s, SNR ~ 20 dB

Oleg A. Krasnov and Alexander G. Yarovoy "Radar Micro-Doppler of Wind Turbines: Simulation and Analysis Using Slowly Rotating Linear Wire Structures", International Journal of Microwave and Wireless Technologies, 7(3-4), 2015, pp 459-467

Our proposed simulation approach



Our proposed simulation approach

Models

Precise EM (FEKO)

Simple (thin-wires)

Measurements

Anechoic Chamber

- Study the importance of input data quality (the choice of model source) on final micro-Doppler pattern
- To adapt simple thin-wires model for drone geometry and to study:
  - Efficiency of simplified mathematical model
  - Flexibility of simulation results as function of drone's geometry, propellers number and synchronization in rotation frequencies and initial positions, radar settings (operational frequency, PRF, CPI)
  - New scenarios: low SNR => long CPI

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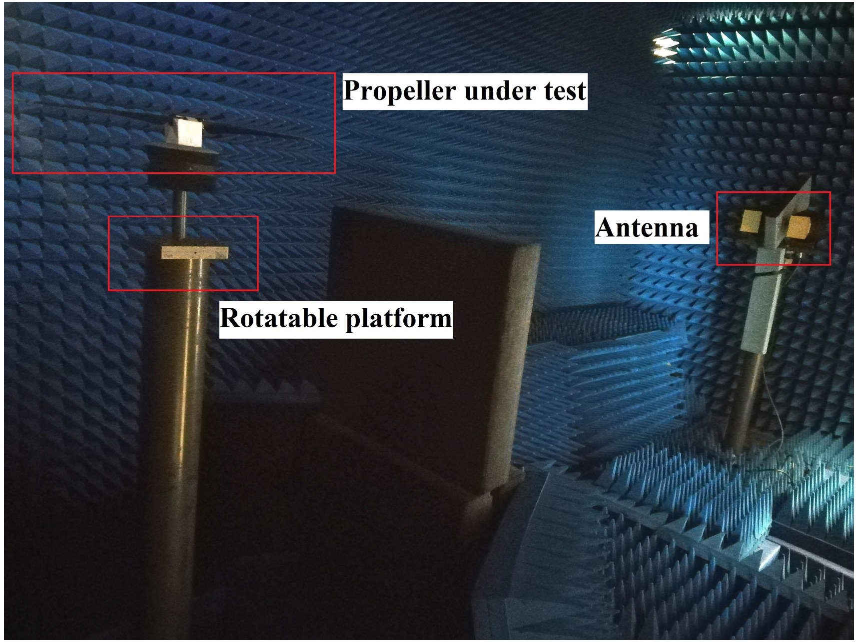
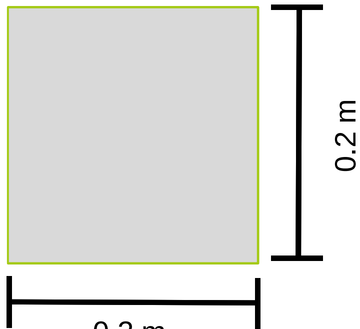
Radar signal scattering on single propeller

- Anechoic chamber measurements
  - HH polarization



Anechoic chamber setup

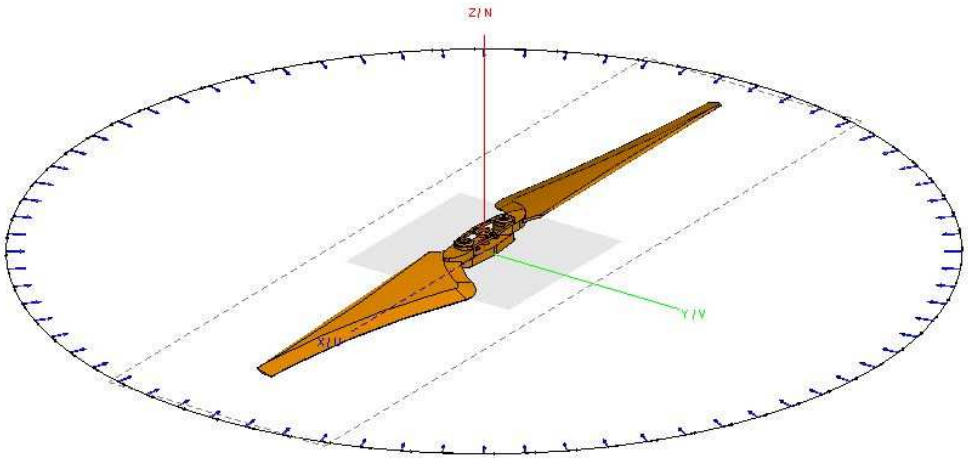
DJI R2170 Propeller under test



Aluminium plate has been used as a reference

Radar signal scattering on single propeller

- FEKO software simulations
  - Far field, plane wave, HH polarization
  - Carbon fiber material

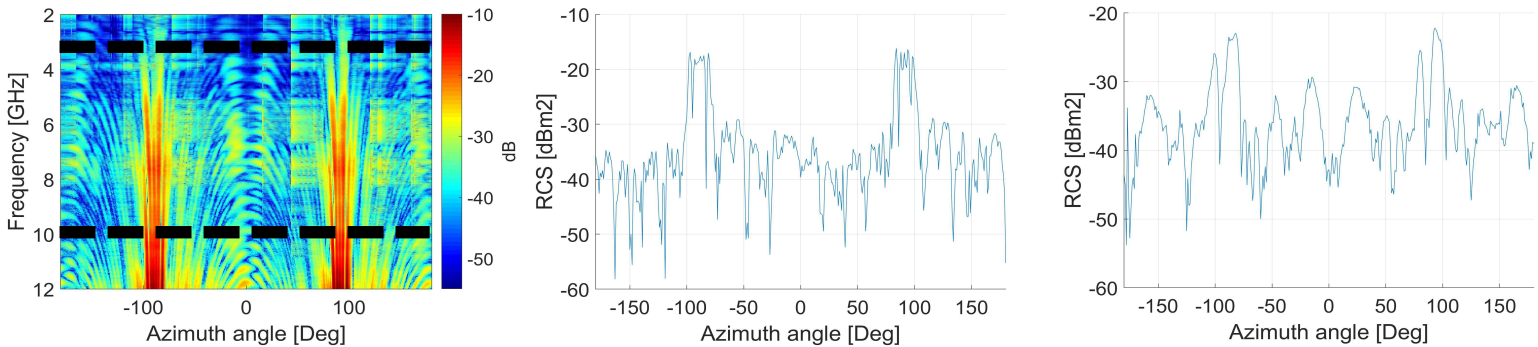


3D propeller model under simulation

Radar signal scattering on single propeller

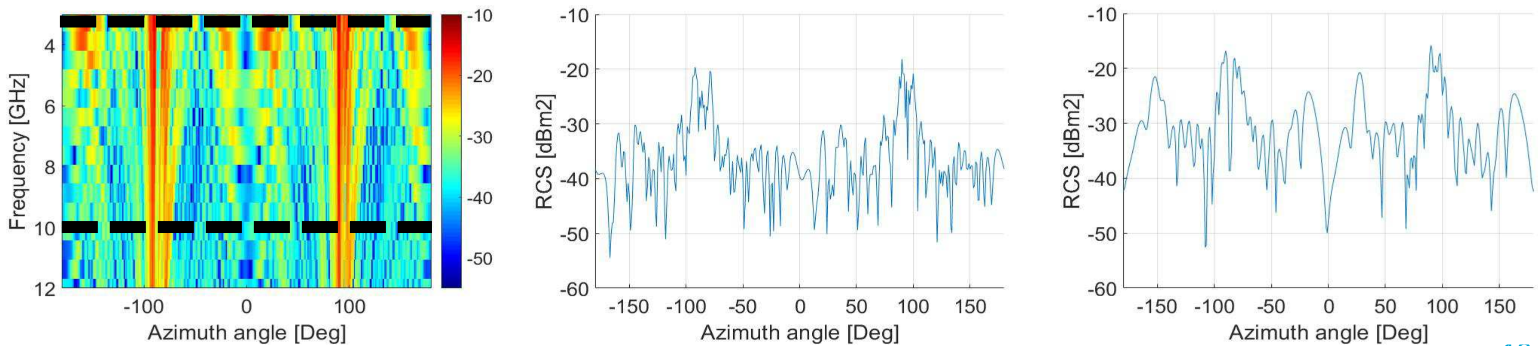
- RCS of single propeller – results from DUCAT and FEKO

DUCAT Anechoic Chamber



Propeller RCS | **Propeller RCS at 10 GHz** | **Propeller RCS at 3 GHz**

FEKO



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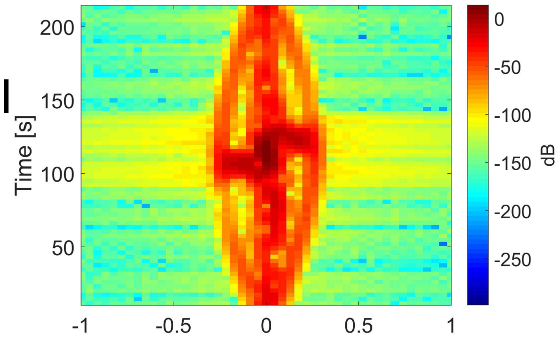
Radar signal scattering on single propeller

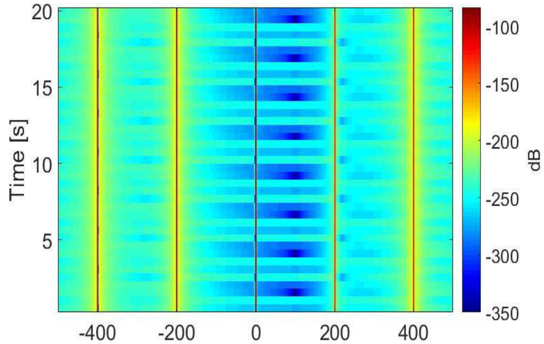
- Micro-Doppler pattern of a rotating propeller

Doppler processing of the rotating propeller scattering coefficient

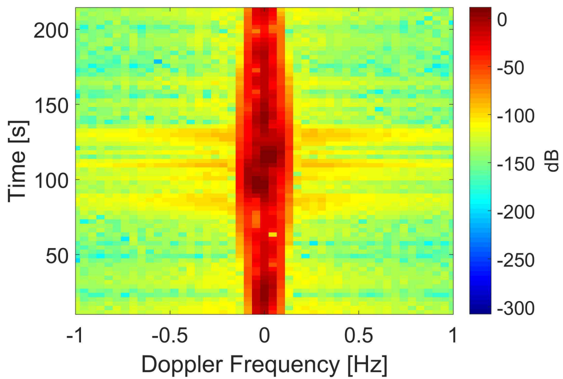
10 GHz, short CPI



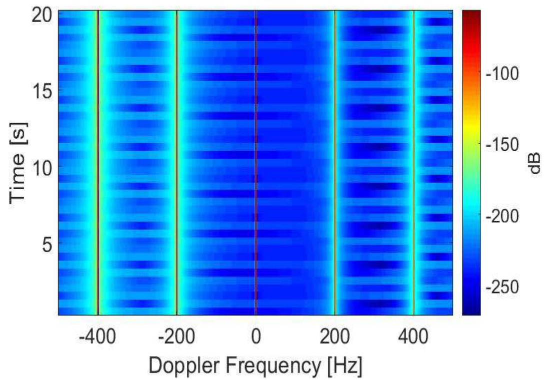
10 GHz, long CPI



3 GHz, short CPI



3 GHz, long CPI

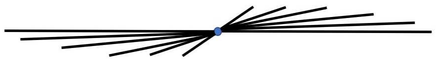


Radar signal scattering on single propeller

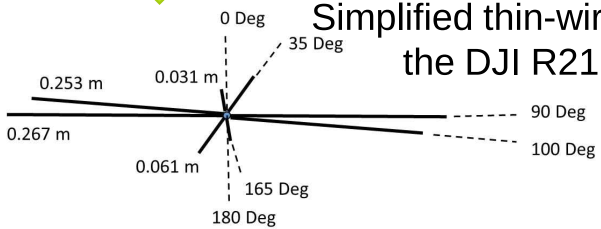
- Adaptation for drone’s propeller at thin-wire simplified EM model

Describe propeller’s geometry structure in horizontal plane

Propeller R2170



Thin-wire model of the propeller



Simplified thin-wire model for the DJI R2170 propeller

EM reflection from thin-wire model of propeller

$$E^{prop}(t, r_p, \theta_{b,w}, l_{b,w}) \sim \sum_{b=1}^{B} E_b^{blade}(t, r_p, \theta_{b,w}, l_{b,w})$$

$$= \sum_{b=1}^{B} \sum_{w=1}^{W} E_{b,w}^{wire}(t, r_p, \theta_{b,w}, l_{b,w})$$

$$= \sum_{b=1}^{B} \sum_{w=1}^{W} \int_0^{l_{b,w}} j\eta \frac{ke^{-jkr_p}}{4\pi r_p} \times E_{r_p}^{in}(t) \sin^2(\theta_{b,w} + \Omega t) \times e^{j2ky'_{b,w} cos(\theta_{b,w} + \Omega t)} dy'_{b,w}$$

Oleg A. Krasnov and Alexander G. Yarovoy "Radar Micro-Doppler of Wind Turbines: Simulation and Analysis Using Slowly Rotating Linear Wire Structures", International Journal of Microwave and Wireless Technologies, 7(3-4), 2015, pp 459-467

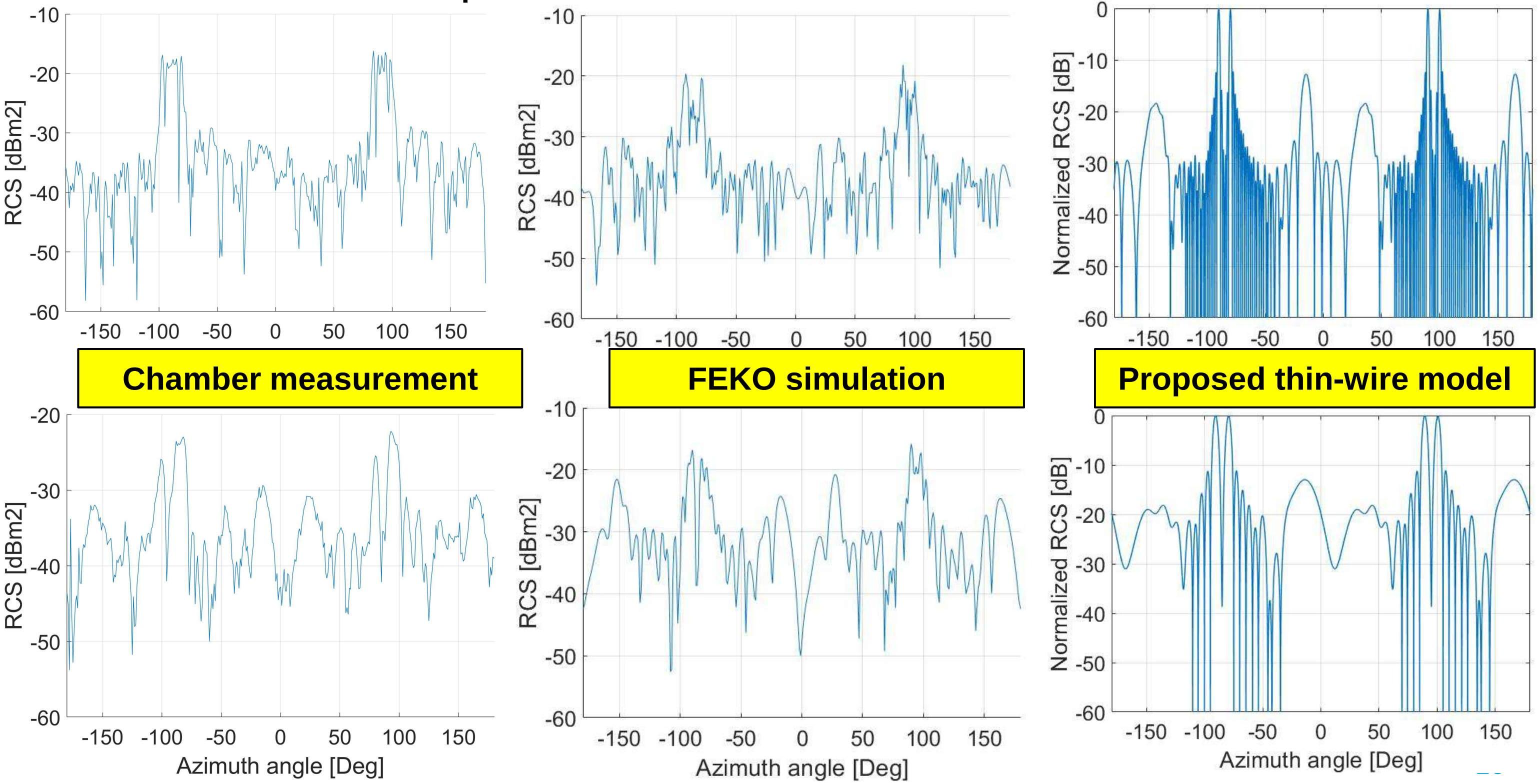
Radar signal scattering on single propeller

- RCS of a single propeller – from thin-wire model

Thin-wire model comparison with the measurements and FEKO sim

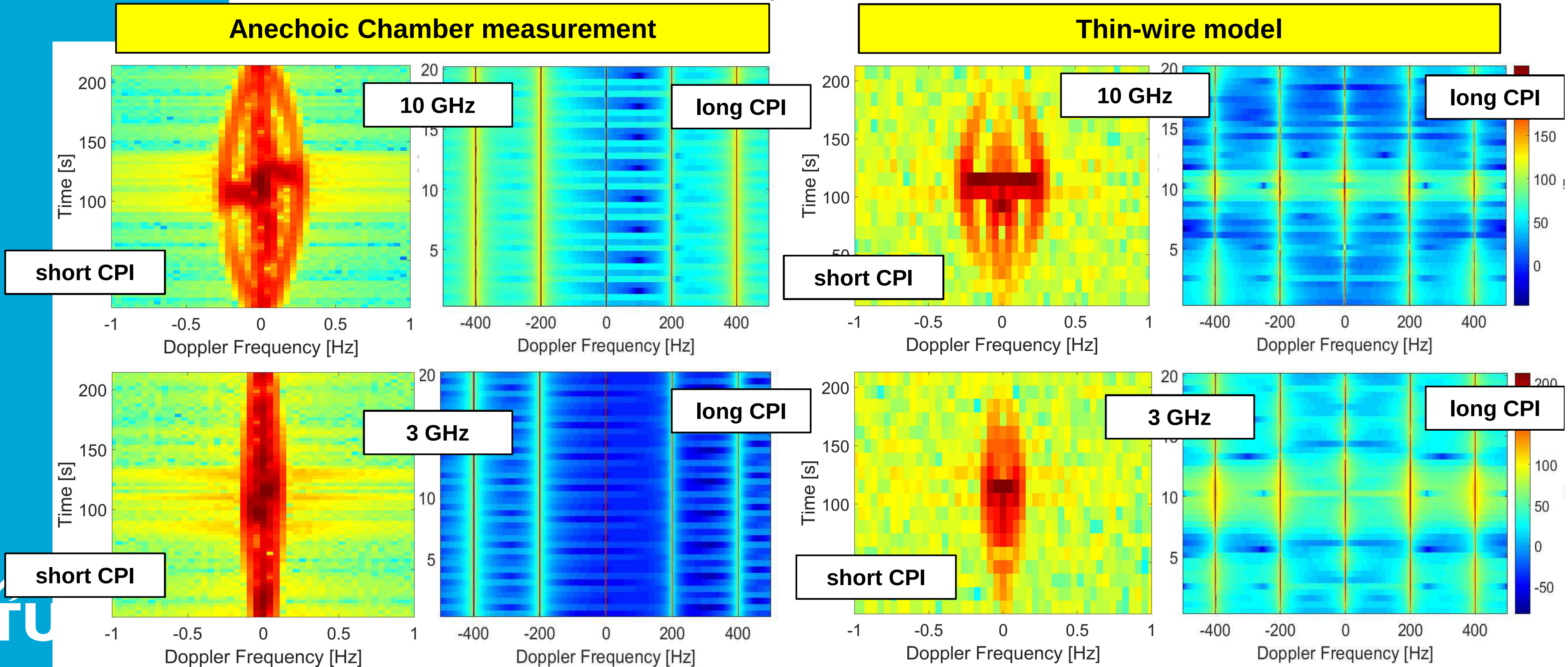
10 GHz

3 GHz



Radar signal scattering on single propeller

- micro-Doppler patterns of a single propeller
  - Thin-wire model comparison with the measurements



Radar signal scattering on single propeller

- Developed simplified representation of the propeller geometry as a bunch of thin wires with very low computational complexity of electromagnetic simulations
- The comparison with measurements in X-band and S-band show
  - in case of short CPI there are visible differences in micro-Doppler patterns – better to use for analysis pre-simulated or measured look-up tables
  - For the case of the long CPI only line spectrum frequency components are visible and their relative amplitudes are well reproduced by simple thin-wires model

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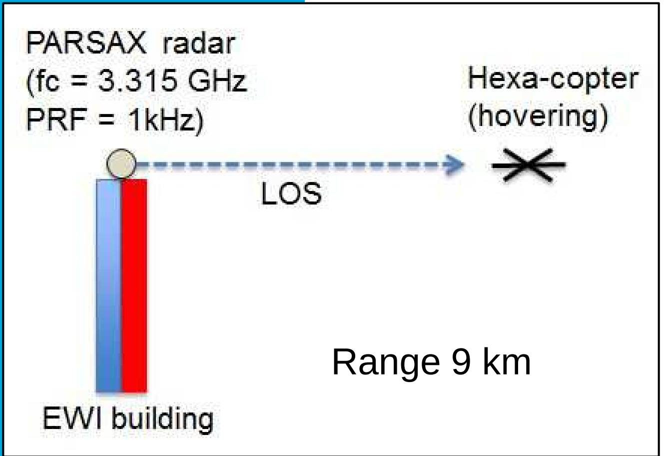
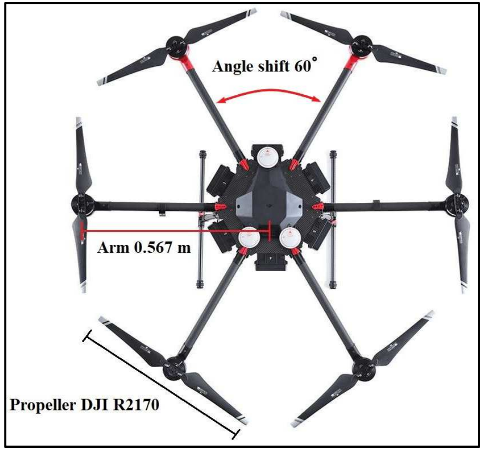
Radar signal scattering on multi-propeller drone

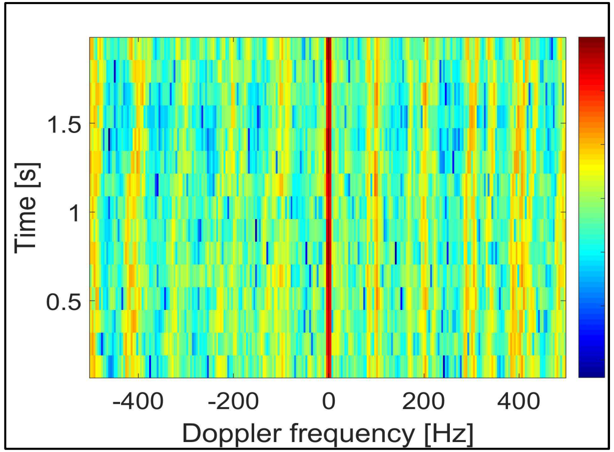
- m-D pattern of a multi-propeller drone
  - Open air measurements by the PARSAX radar



Real measurements



DJI Matrix 600
Hexa-copter under test



micro-Doppler pattern
of hexa-copter (long CPI)

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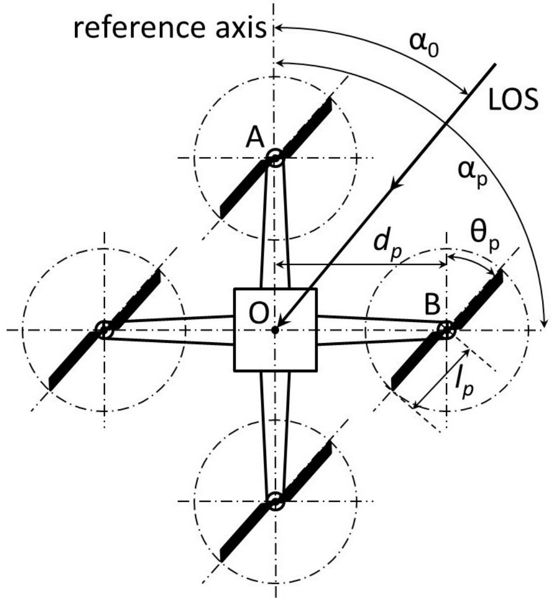
Radar signal scattering on multi-propeller drone

- Thin-wire model - describes the multi-propeller drone's geometry structure in horizontal plane via coherent summation of individual propellers, phase shifted to the drone's phase center:



Geometry of multi-propeller drone (quad-copter for example)

$$
\begin{aligned}
E^{drone}(t,r_0) &\sim \sum_{p=1}^{P} E_p^{prop}(t,r_p,\theta_{p,b,w},l_{p,b,w}) \\
&= \sum_{p=1}^{P}\sum_{b=1}^{B}\sum_{w=1}^{W} E_{p,b,w}^{wire}(t,r_p,\theta_{p,b,w},l_{p,b,w}) \\
&= \sum_{p=1}^{P}\sum_{b=1}^{B}\sum_{w=1}^{W} \int_0^{l_{p,b,w}} j\eta \frac{ke^{-jkr_p}}{4\pi r_p} \\
&\times E_{r_0}^{in}(t)\sin^2(\theta_{p,b,w}+\Omega_p t) \\
&\times e^{j2ky'_{p,b,w}\cos(\theta_{p,b,w}+\Omega_p t)}\, dy'_{p,b,w} \\
&= \sum_{p=1}^{P} j\eta \frac{ke^{-jkr_p}}{4\pi r_p} \cdot E^{propeller}
\end{aligned}
$$

where $r_p = r_0 - d_p \cdot \cos(\alpha_p - \alpha_0)$

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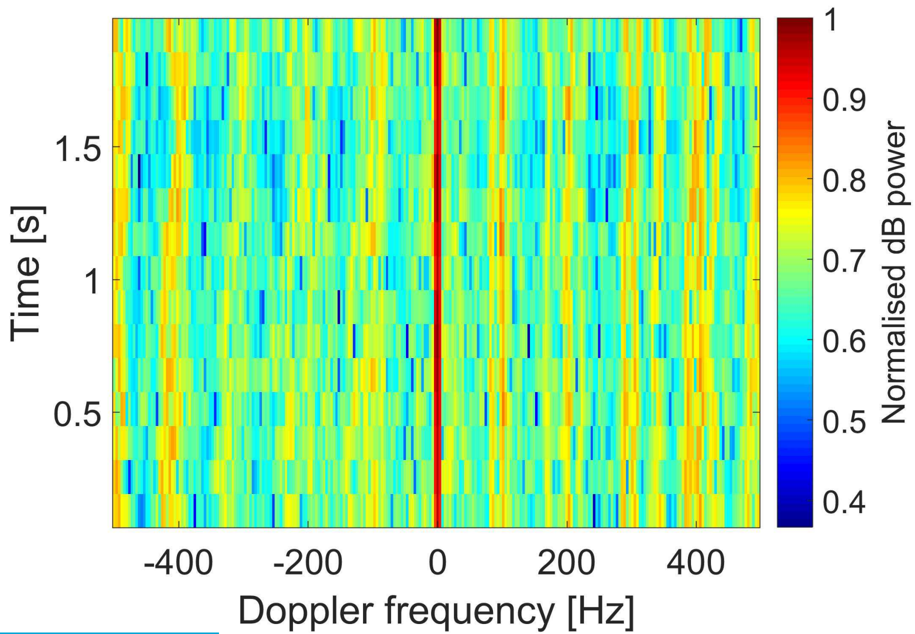
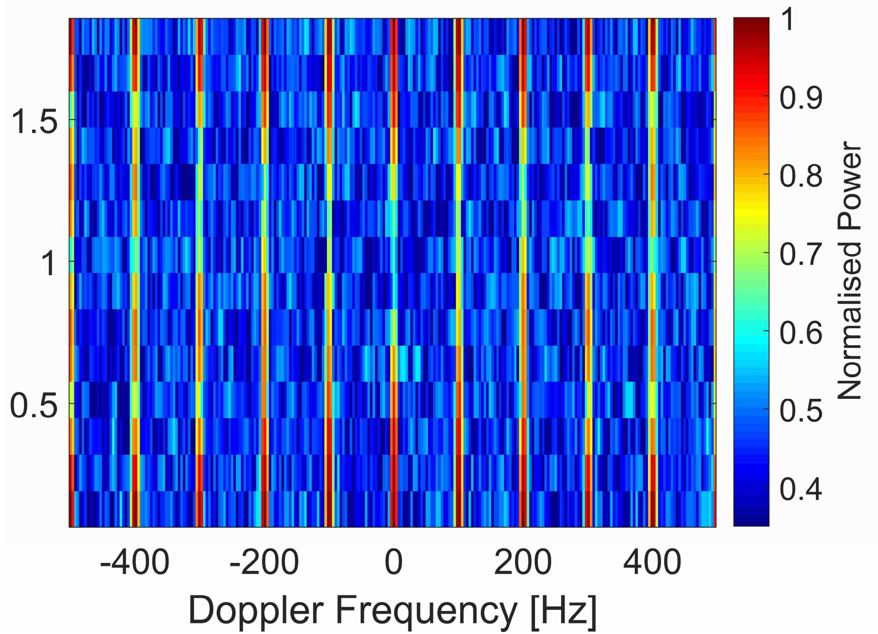
Radar signal scattering on multi-propeller drone

- The comparison of the M600 hexa-copter's micro-Doppler patterns measured with real radar and simulated with thin-wire model



PARSAX measurement



Thin-wire model

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Radar signal scattering on multi-propeller drone

- The proposed model of a multi-propeller drone gives a possibility
  - To synthesis and analyze micro-Doppler patterns of drones with different numbers and configurations of multiple propellers
  - To simulate and analyze the influence of observation angles and propeller synchronization on resulting micro-Doppler pattern
  - The simulation results show good agreement with experimental measurements in long distance (low SNR and, as result, requested long CPI) circumstances

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Conclusion

- Has been presented and illustrated a general approach for multi-propeller drones micro-Doppler patterns simulation based on modelled or experimentally measured angular dependencies of a single propeller scattering coefficients

- Low computational complexity simplified thin-wire model has been proposed to simulate multi-propeller drones micro-Doppler patterns as a function of radar parameters, drone's geometry and rotating propellers variables.

- Its validation by the comparison with real radar measurements at S-band shows good agreement in observed and simulated micro-Doppler patterns in case of radar observations with long CPI in terms of propeller rotation period.

- For more general cases can be used the proposed simulations approach that uses pre-defined (measured or precisely EM modelled) look-up tables of single propeller angular dependencies of scattering coefficient. It can be done for different polarizations and frequencies…

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Questions?

The usage of this model for the recognition of drones with different number of rotors will be illustrated within our presentation on the EuRAD-2019 conference in Paris