Radar Recognition of Multi-Propeller Drones using Micro-Doppler Line Spectra

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EuRAD, October 2019, Paris, France

Outline

- Introduction
- Simulation model for drone micro-Doppler spectrum
- Drone micro-Doppler features analysis and selection
- Application of features to simulated data
- Conclusion

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

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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…

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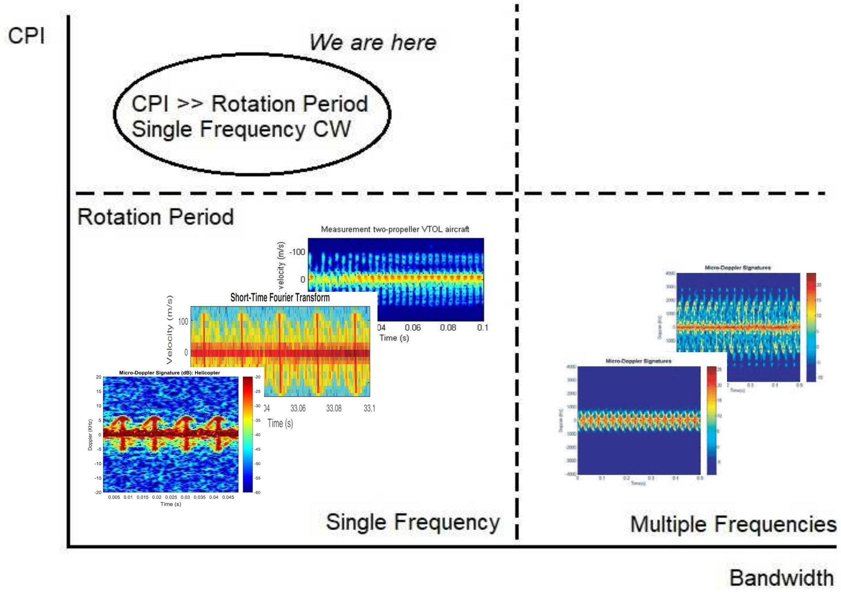
Objectives of the study

To study the drone's micro-Doppler pattern that are observed by a radar and to select the features that are most informative/useful for drone's type identification/recognition

- Use previously developed and presented general approach for drone's simulation and simplified EM model of scattered on drone signal

- Concentrate on the case of long Coherent Processing Interval (CPI)



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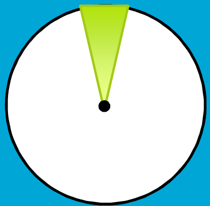
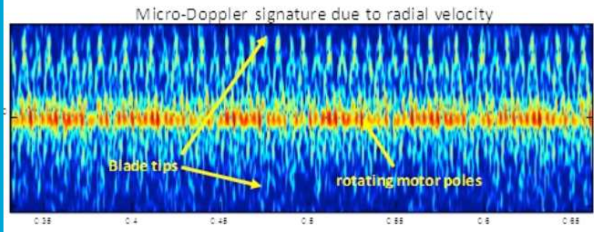
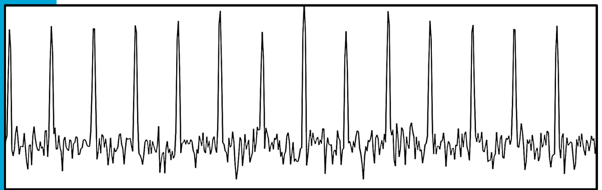
Short and Long Coherent Processing Intervals

Short CPI << Rotation Period

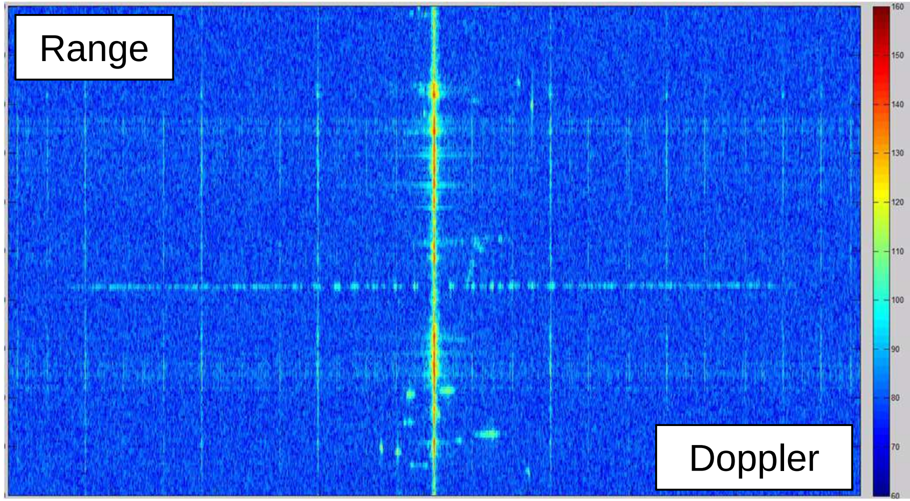




Long CPI ~ Rotation Period



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

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Our proposed simulation approach

Models
- Precise EM (FEKO)
- Simple (thin-wires)

Measurements
- Anechoic Chamber

Angular dependence of blade/propeller scattering coefficient

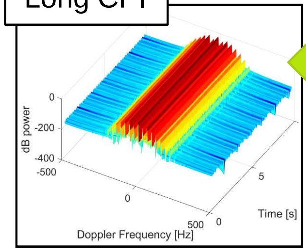
One rotor/propeller
- Rotation Frequency → Time dependence
- Radar: PRF, CPI → Sampling
- Time dependence → Sampling

Drone's Geometry, LOS Orientation

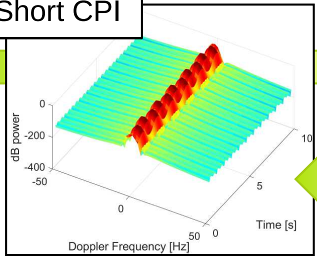
Coherent Sum at Drone's Phase Center

Doppler FFT as Function of Time

Long CPI

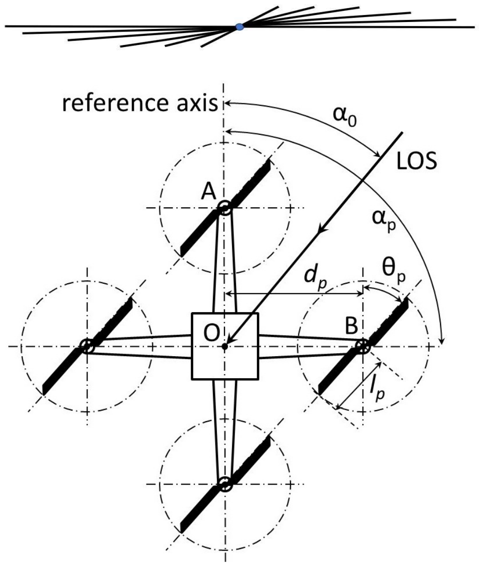


Short CPI



Simulation model for drone micro-Doppler spectrum

- Simulation model of drone's EM reflection (HH)



Thin-wire model of multi-propeller drone and each single propeller

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

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

* Synthesis and synchronisation of propellers

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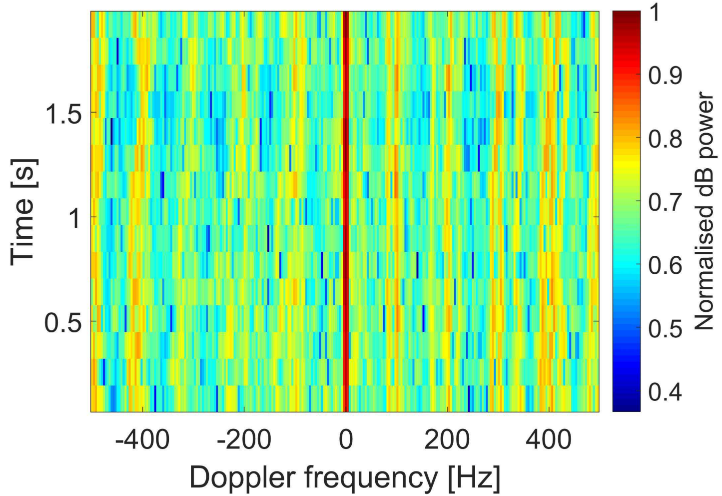
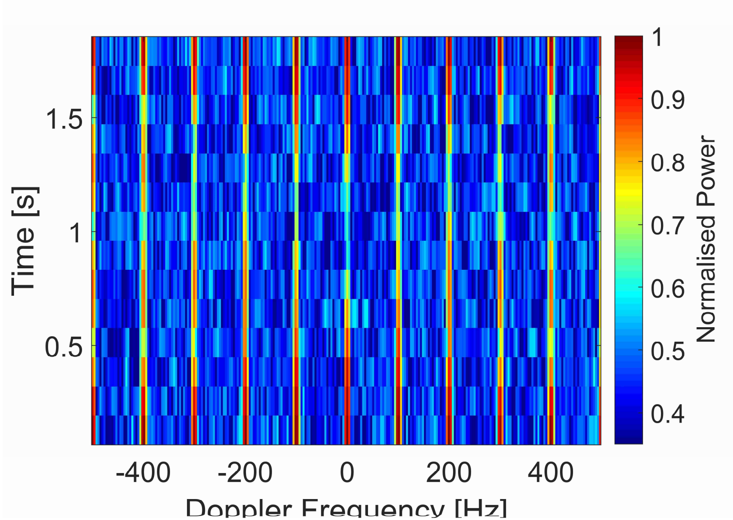
Simulation model for drone micro-Doppler spectrum

- Drone micro-Doppler pattern from simulation model
  - Doppler processing to EM reflection signal
  - Linear pattern in long CPI circumstance: S-band, DJI M600 drone, radar CPI much longer than propeller rotation period



Micro-Doppler pattern of hexa-copter (PARSAX radar measurement)



Micro-Doppler pattern of hexa-copter (Thin-wire model simulation)

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Simulation model for drone micro-Doppler spectrum

- Thin-wire model proposed for the simulation of drone micro-Doppler spectrum
  - Validated in S-band
  - Taking radar setup parameters and drone's properties as input variables
  - Generating line spectral micro-Doppler pattern within long CPI circumstance

Yefeng Cai, Oleg Krasnov, Alexander Yarovoy "Simulation of Radar Micro-Doppler Patterns for Multi-Propeller Drones" – RADAR-2019, Toulon, France

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Drone micro-Doppler features analysis

- Simulation model rewritten in Bessel functions

$$E^{drone}[n] \sim \sum_{p=1}^{P}\sum_{b=1}^{B}\sum_{w=1}^{W} s_{p,b,w}^{wire}[n]$$

Sums over wires, blades, propellers

$$= \sum_{p=1}^{P}\sum_{b=1}^{B}\sum_{w=1}^{W} \frac{\eta e^{-j\frac{2\pi}{\lambda}r_p}}{8\pi r_p} \cdot \frac{\sin^2(\theta_{p,b,w}+\Omega_p t_s n)}{\cos(\theta_{p,b,w}+\Omega_p t_s n)} \cdot \left(\sum_{q=-\infty}^{\infty} e^{j\frac{\pi q}{2}} J_q(2\frac{2\pi}{\lambda} l_{p,b,w}) e^{j(\theta_{p,b,w}+\Omega_p t_s n)q} - 1 \right)$$

Drone geometry (extra phase, extra amplitude)

Propeller rotation period (extra amplitude)

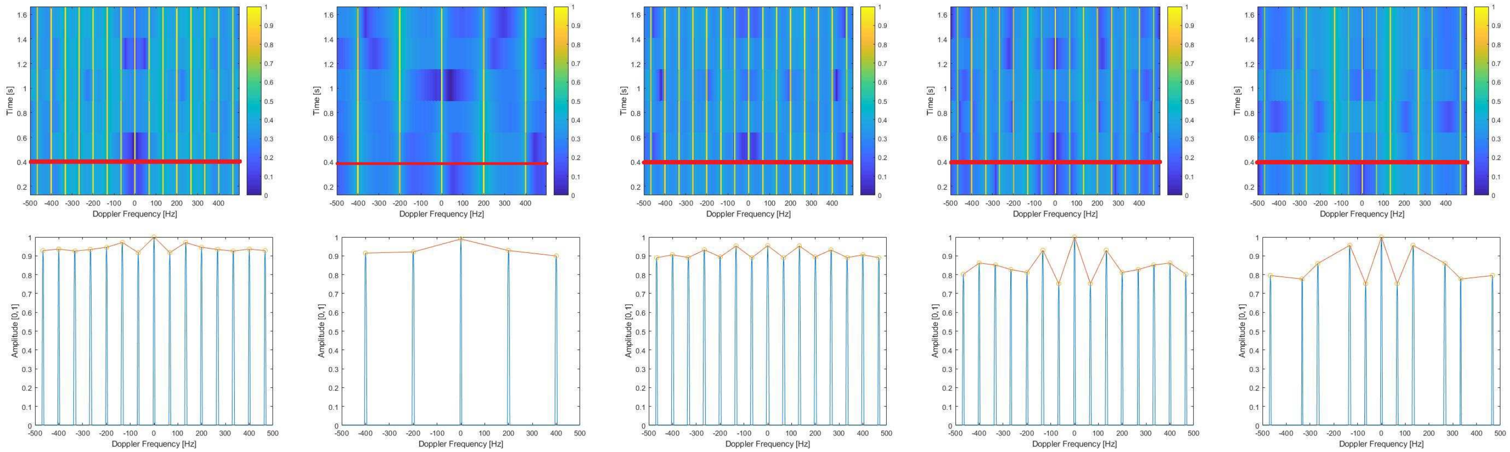
Bessel functions (amplitude)

Harmonic components (frequency)

- Influence factors: PRF, carrier frequency, drone's geometry, propeller's radius and rotation period
- Influence on the micro-Doppler spectrum: **Amplitude** and **frequency gap** of harmonic components

Micro-Doppler pattern vs Drone's Properties

- Influence of drones' properties on spectral lines' amplitudes, locations, the total bandwidth of non-folded Doppler spectra



(a)
2 blades
Short blades
4 propellers
No angle shift

(b)
3 blades
Short blades
4 propellers
No angle shift

(c)
2 blades
Long blades
4 propellers
No angle shift

(d)
2 blades
Short blades
4 propellers
Random shift of initial angles

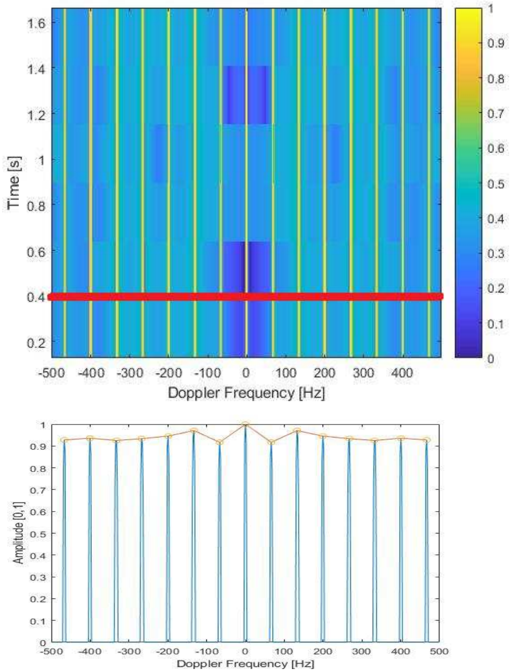
(e)
2 blades
Short blades
6 propellers
No angle shift

Micro-Doppler patterns of drones and their cuts at some time moment

Micro-Doppler pattern vs Propellers Velocities

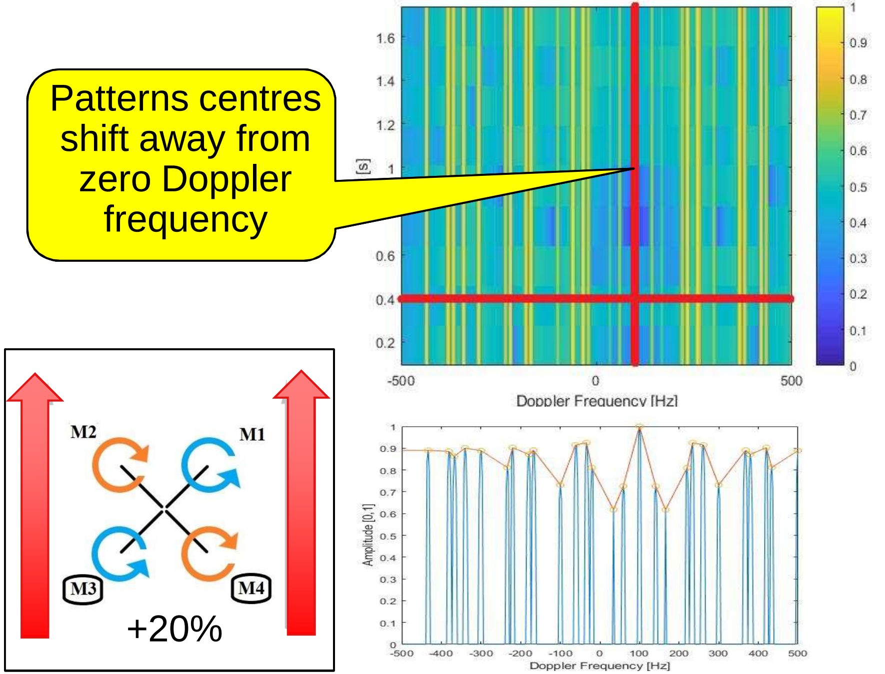
Hovering

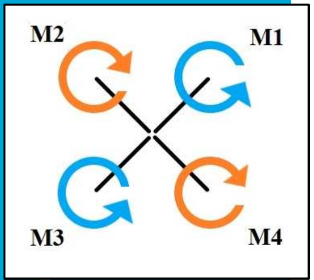
(propellers rotation is synchronous)



Maneuvering

(propellers rotate with different velocities)





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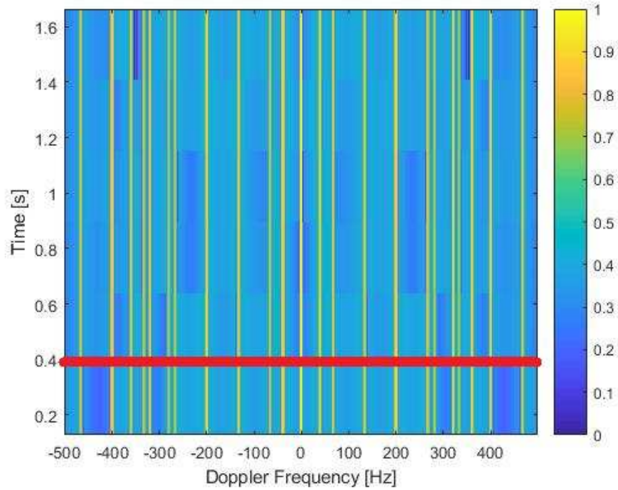
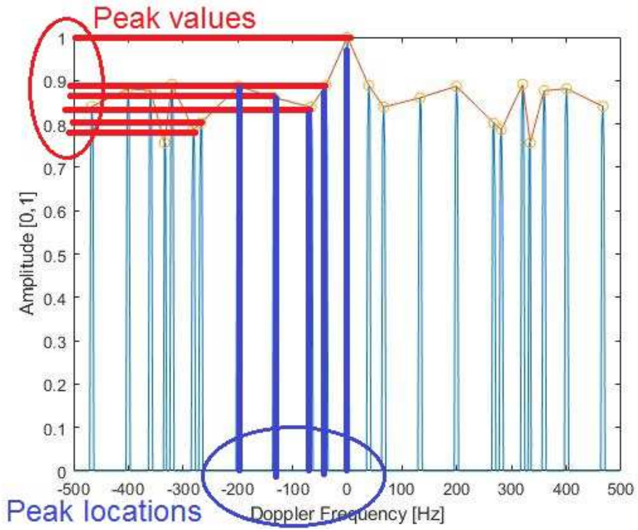
Micro-Doppler patterns of drones and their cuts at some time moment

Features for drones recognitions



An example of micro-Doppler pattern



Characteristics of line spectrum

Location = [0,0,1,0,0,…] [1 x N_{CPI}] vector, "1" if a peak appears

Amplitudes = [0.84,0.89,0.88,…,1,…] [1 x N_{peaks}] vector, peak values

Mean (Amplitudes), Standard Deviation (Amplitudes), Entropy (Amplitudes)

Features = [Location, Mean, Standard Deviation, Entropy]

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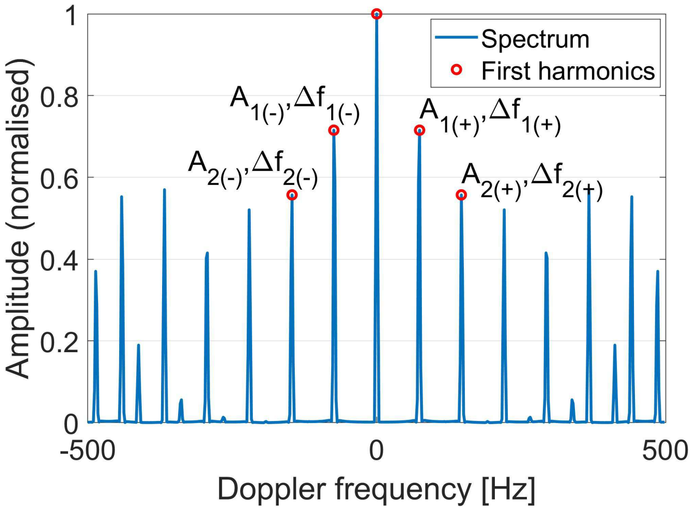
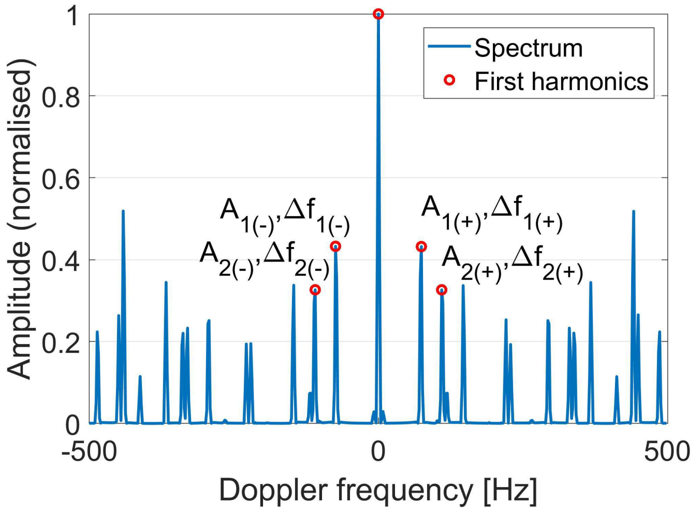
Drone micro-Doppler features selection

- Features that characterize the micro-Doppler spectrum
  - **Amplitudes** and **frequencies** of harmonic components
  - Only first 4 harmonic components shown in this example



Micro-Doppler spectrum of hovering quad-copter



Micro-Doppler spectrum of maneuvering quad-copter

* 2 amplitude modulation,

** Non-uniform frequency gap

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Drone micro-Doppler features selection

- Features selection for drone micro-Doppler spectrum in long CPI circumstance
  - Influential factors:
    - radar setup parameters
    - drone properties
  - Proposed features to characterize the spectrum:
    - Set of linear harmonics’ amplitudes
    - Set of frequency gaps between them
    - Sub-sets
    - Their statistical moments

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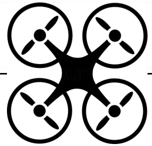
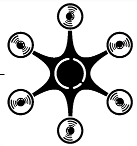
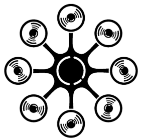
Application of features to simulated data

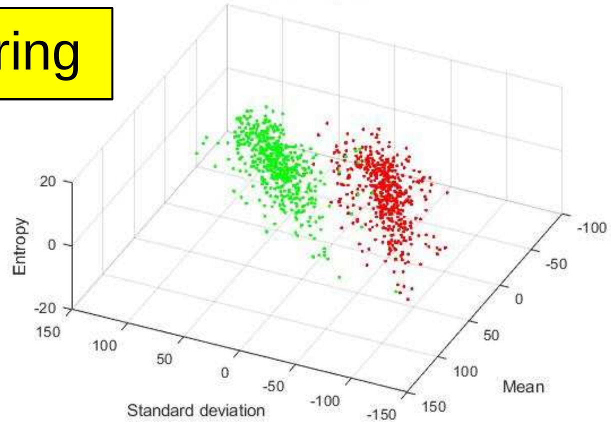
- Simulation data sets
  - Drones: Quad-, hexa-, octo-copter
  - Flight motion modes: Hovering, maneuvering

Combination of Input Variables	Drones & Flight Attitudes	Blade Length l [m]	Arm Length d_p [m]	Propeller Angular Velocity Ω [rpm]
	quadcopter hover	0.114	0.175	$2200 * [1, -1, 1, -1]$
	quadcopter cross range			$2200 * [1, -v_{asyn}, v_{asyn}, -1]$ $v_{asyn} = 1.5$
	hexacopter hover	0.267	0.567	$1800 * [1, -1, 1, -1]$
	hexacopter cross range			$1800 * [1, -v_{asyn}, v_{asyn}, -1]$ $v_{asyn} = 1.5$
	octocopter hover	0.267	0.567	$1500 * [1, -1, 1, -1]$
	octocopter cross range			$1500 * [1, -v_{asyn}, v_{asyn}, -1]$ $v_{asyn} = 1.5$

Two classes recognition

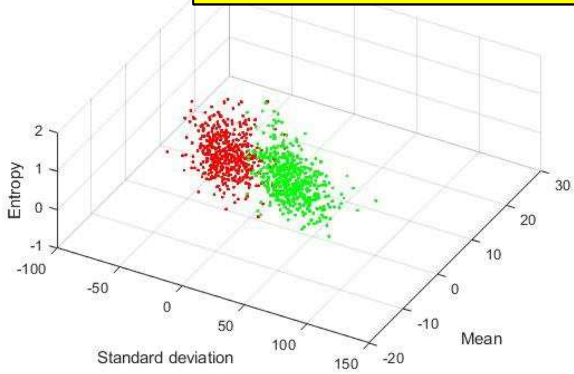
3D – only amplitudes' features

Hovering



Decision \ Truth	4-copter 464 obs.	6-copter 520 obs.
4-copter	462 observations (99.57%)	6 observations (1.15%)
6-copter	2 observations (0.43%)	514 observations (98.85%)

Maneuvering



Decision \ Truth	4-copter 488 obs.	6-copter 486 obs.
4-copter	454 observations (93.03%)	33 observations (6.79%)
6-copter	34 observations (6.97 %)	453 observations (93.2%)

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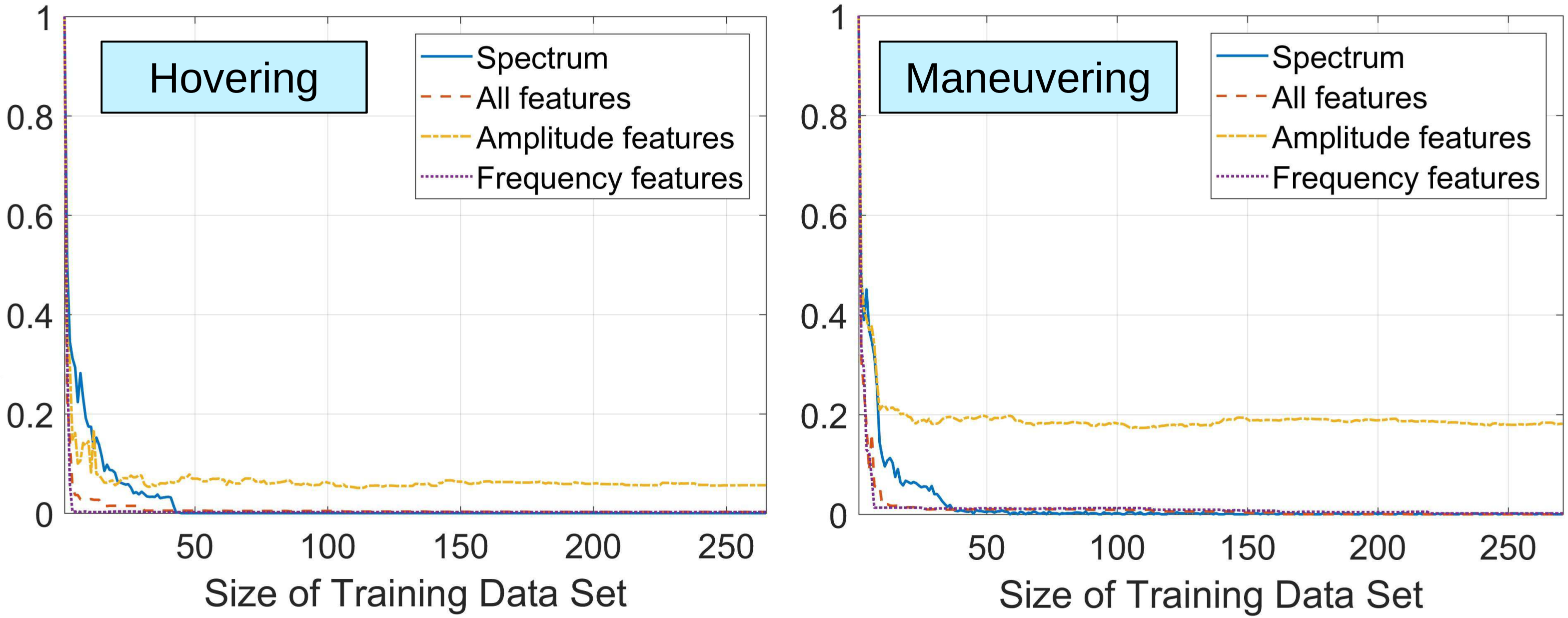
Application of features to simulated data

- Classification results on simulated m-D data
  - SVM classifier, 5-fold cross validation
  - Amplitude and frequency gap of first 4 harmonic components

Probability of classification error



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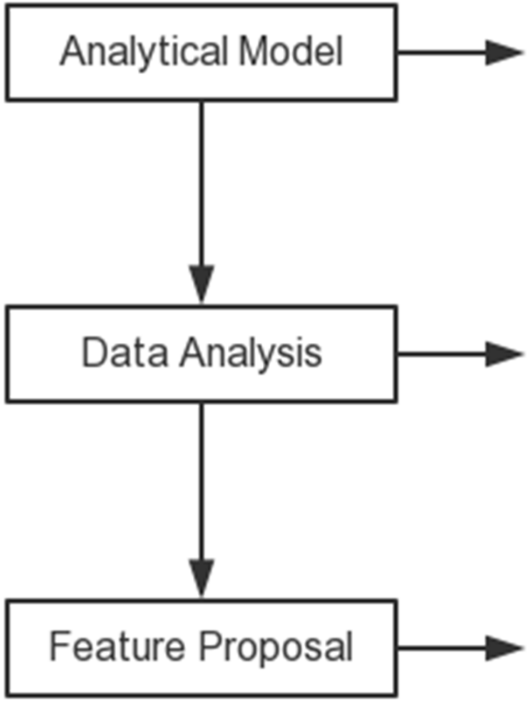
Conclusion



- The simple model efficiently generates micro-Doppler patterns for any selected propeller, drone and radar setup parameters
- The parameters of micro-Doppler pattern are strongly influenced with propeller, drone and radar setup parameters
- The measured during long CPI line spectral micro-Doppler patterns of different drones are precisely characterized with set (and sub-sets) of peaks' amplitudes and frequencies

Questions?