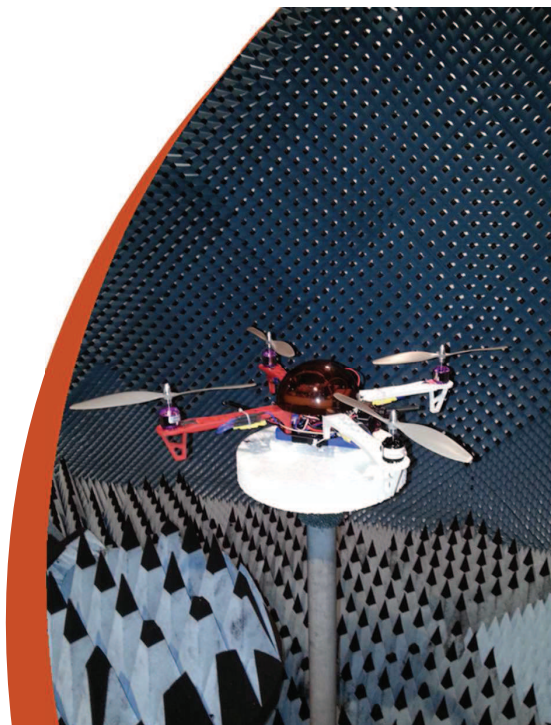


## Small UAVs and their buzz... How micro-Doppler makes the difference

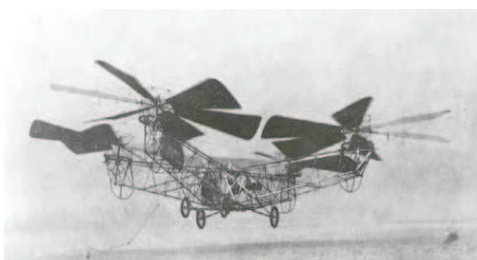
JACCO DE WIT, TNO  
RONNY HARMANNY, THALES NEDERLAND B.V.

For the slides containing the D-RACE logo, the following applies:  
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## The future is now!



de Bothezat helicopter, 1923 photo  
Source: Wikipedia

Easy to fly, low cost!

miniaturization

Sensors  
Processing  
Batteries  
Electromotors  
Communication  
Remote control  
Servos  
GPS



DJI Mavic 2 Enterprise  
Source: www.dji.com

## In this keynote

- Applications, regulations and developments
- Small UAVs as radar targets
- Radar detection and classification
- Radar recognition
- Conclusion

3

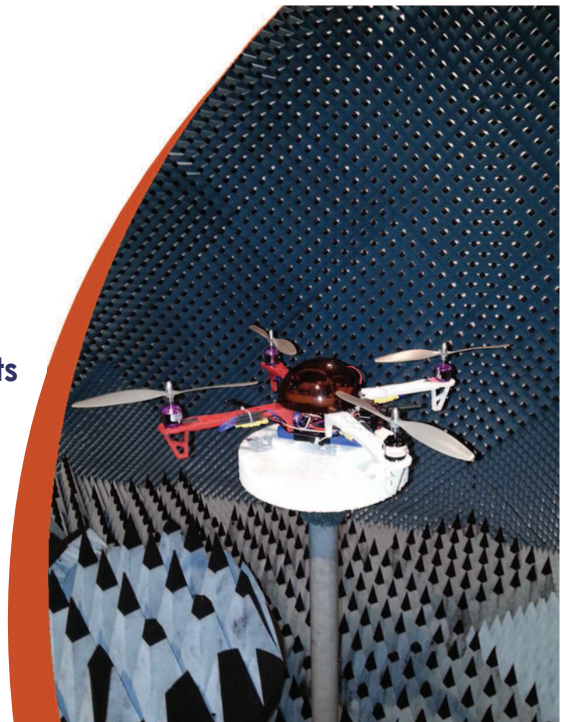
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## Applications, regulations and developments



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## Applications: fun!

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- hobby
- do-it-yourself mentality
- drone racing
- big events
- ...

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## Applications: commercial use

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- courier and delivery services
- industrial and crop monitoring
- TV and film recordings
- 3D terrain mapping
- internet and WiFi drones
- ...

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## Applications: government use

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- crowd monitoring
- crime fighting
- wild life protection
- first responders
- search and rescue
- disaster relief
- ...

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## Applications: military use

---

- reconnaissance
- forward observer
- weapon platform
- loitering munition
- swarms
- ...

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## Regulations

### Dutch legislation

- fly in daylight only, line-of-sight mandatory
- maximum altitude: 120 m
- do not fly above close-knit buildings
- do not fly above waterways and roads
- do not fly above crowds
- do not fly near airfields
- do not fly in No Fly Zones

### Professional use even more restricted!

### For privacy, separate laws apply!



Source: <https://kadaster.kadaster.nl/dronekaart/>  
(visited December 5<sup>th</sup>, 2018)

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## Regulations

### New European legislation (starting June 2019)

- maximum altitude 120 m
- built-in chip to avoid no-fly zones
- special permits for beyond line-of-sight flights
- main consequences for *professional* drone pilots

### Acknowledgement of potential benefits of drones

- room for innovation
- but more experience required



Source: [https://ec.europa.eu/transport/modes/air/aviation-strategy/innovation\\_en](https://ec.europa.eu/transport/modes/air/aviation-strategy/innovation_en)  
(visited December 5<sup>th</sup>, 2018)

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## Developments

### Flight principles

- Fixed wing
- Single main rotary wing (heli)
- Dual rotary wing (chinook)
- Multi rotary wing (multicopter)
- Blimp / balloon
- Kite
- Rockets
- Wing flapping
- Hybrids

### Sensors & comms

- GPS
- Inertial Measurement Unit
- Ultrasound altimeters
- Ground stabilization camera
- Object avoidance cameras
- Comms link

### Computational means

- CPUs/GPUs
- Memory

### Thrust and steer capability

- Jet engines
- Propellers/rotors
- Rocket engines
- Flaps/elevators/rudders/ailerons
- Electro motors/servos
- Batteries/fuel engines

### Software

- Embedded OS
- Flight control
- Image recognition
- Mission add-on control

### Mission add-ons

- HD camera (EO/IR)
- Laser pointer/range finder
- Radar
- Microphone
- Speaker
- Flash lights
- Bomb/IED
- Gun
- <add your favorite here>

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## Developments

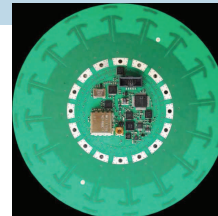
### Biggest game changers

- > improvement in battery life and weight
- > increase in computational power
- > miniaturised (sensor) technology
- > artificial Intelligence → autonomy, swarming
- > drone traffic control

### Big do-it-yourself community

- > 3D printing technology
- > open source design, sharing and improving of ideas

### Big future for small UAVs!



TNO's 32-channel omnidirectional UAV radar

Source: Matern Offen, Noud Maas et al., *Circular Micro-SAR for Mini-UAV*, Proc. EuRAD, September 26-28, 2018, Madrid, Spain, pp. 321-324.

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## Small UAVs as a threat

---

- (unintentional) abuse
- protests, creating chaos
- criminal acts
- ...

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## Small UAVs as a threat

---

- adversarial use
- creating chaos
- terrorism
- ...

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## Challenge for sensors

### Improved situational awareness

#### > single drone

- whereabouts (detection, tracking)
- type (classification)
- intent (objective and method)
- use of mission add-on deployment

#### > swarm

- intent (objective and method)
- finding the leader of the pack, if any
- detect and track individual drones
- use of mission add-on deployment

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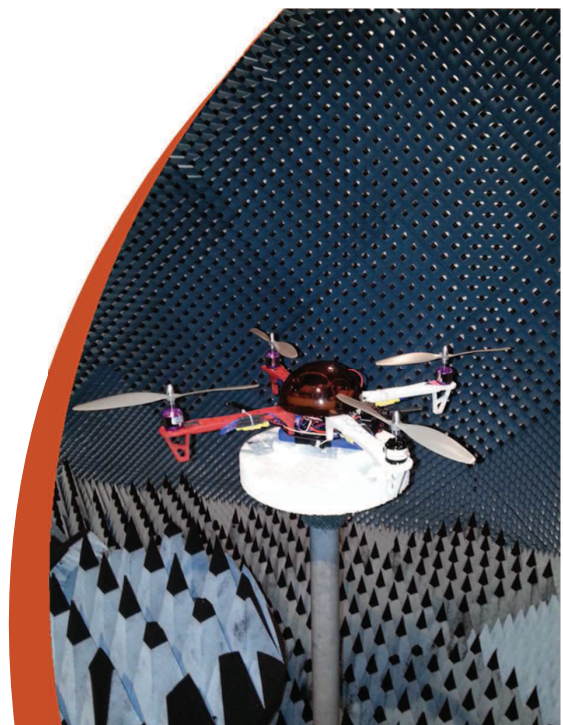
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### Small UAVs as radar targets



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## UAS military grouping

NATO UAS CLASSIFICATION						
Class	Category	Normal Employment	Normal Operating Altitude	Normal Mission Radius	Primary Supported Commander	Example Platform
Class III (> 600 kg)	Strike/Combat*	Strategic/National	Up to 65,000 ft	Unlimited (BLOS)	Theatre	Reaper
	HALE	Strategic/National	Up to 65,000 ft	Unlimited (BLOS)	Theatre	Global Hawk
	MALE	Operational/Theatre	Up to 45,000 ft MSL	Unlimited (BLOS)	JTF	Heron
Class II (150 kg - 600 kg)	Tactical	Tactical Formation	Up to 18,000 ft AGL	200 km (LOS)	Brigade	Hermes 450
Class I (< 150 kg)	Small (>15 kg)	Tactical Unit	Up to 5,000 ft AGL	50 km (LOS)	Battalion, Regiment	Scan Eagle
	Mini (<15 kg)	Tactical Subunit (manual or hand launch)	Up to 3,000 ft AGL	Up to 25 km (LOS)	Company, Platoon, Squad	Skylark Raven
	Micro ** (<66 J)	Tactical Subunit (manual or hand launch)	Up to 200 ft AGL	Up to 5 km (LOS)	Platoon, Squad	Black Widow

Source: Róbert Szabolcsi, *UAV Operator Training – Beyond Minimum Standards*, Int. Conf. Knowledge-Based Organisation KBO, June 9-11, 2018, Sibiu, Romania. Available online: <http://www.afahc.ro/ro/afases/2016/RP/SZABOLCSI.pdf> (visited December 9<sup>th</sup>, 2018)

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	Micro ** (<66 J)	Tactical Subunit (manual or hand launch)	Up to 200 ft AGL	Up to 5 km (LOS)	Platoon, Squad	Black Widow
	Nano (< 250 g)	Tactical Subunit (manual or hand launch)		Up to 2 km (data link)	Squad	Black Hornet

Source: Róbert Szabolcsi, *UAV Operator Training – Beyond Minimum Standards*, Int. Conf. Knowledge-Based Organisation KBO, June 9-11, 2018, Sibiu, Romania. Available online: <http://www.afahc.ro/ro/afases/2016/RP/SZABOLCSI.pdf> (visited December 9<sup>th</sup>, 2018)

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## Potential sensors

Sensors	Long range	Position accuracy	Identification	Multiple targets	Low visibility conditions	Night	Passive system	Price
Visual	++	++	++++	++	-	-	++++	++
Infrared	++	++	++++	++	- (except SWIR)	++++	++++	+
Acoustic	-	-	+++	++	++++	++++	++++	++++
Radar	++++	++++	++	++++	++++	++++	-	-
Electronic support measures	++++	++++	++	++++	++++	++++	++++	+
Human surveillance	+	+	++++	-	-	-	++++	++++

Source: Peter Wellig, Peter Speirs, et al., *Radar Systems and Challenges for C-UAV*, 19<sup>th</sup> International Radar Symposium IRS, June 20-22, 2018, Bonn, Germany.

## Small UAVs as radar targets

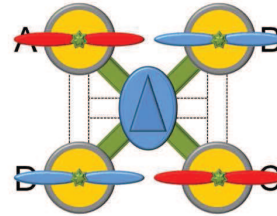
Challenges	Impact to radar
Small sizes (sUAVs) and non-metallic hulls	Small RCS values
Birds	False alarms or unwanted targets such as birds
Low flying, i.e. very low airspace	Results in ground clutter
Unconventional flight patterns, small velocities and hovering positions	Fast variations, small Doppler velocities
Terrain masking effects	Targets are not observable, no line of sight
Urban environment	High radar clutter
Active sensor	Electronic countermeasures, jamming
Long ranges and high performance UAVs	High power and AESA-based radars, military frequency bands, access difficult to no-military users.

Source: Peter Wellig, Peter Speirs et al., *Radar Systems and Challenges for C-UAV*, 19<sup>th</sup> International Radar Symposium IRS, June 20-22, 2018, Bonn, Germany.

## Small UAVs as radar targets

### Large variety of small UAVs

- > complex targets, many materials, many shapes
- > battery, electronic circuits, electromotors
- > plastic, carbon fibre, metals → rotor blades!
- > many different payloads
- > do-it-yourself



### Moving parts

- > Multicopters: four, six or eight rotors, different and varying rotation rates
- > helicopter: main rotor and smaller tail rotor, mechanically fixed
- > fixed wing aircraft: one or two propellers, sometimes one additional rotor (VTOL)

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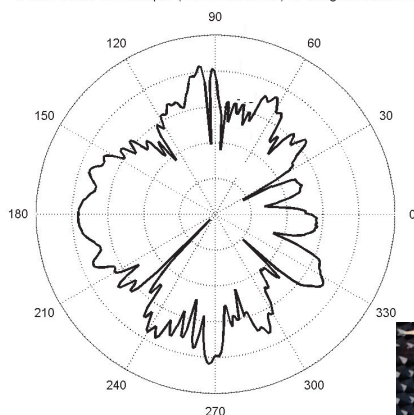
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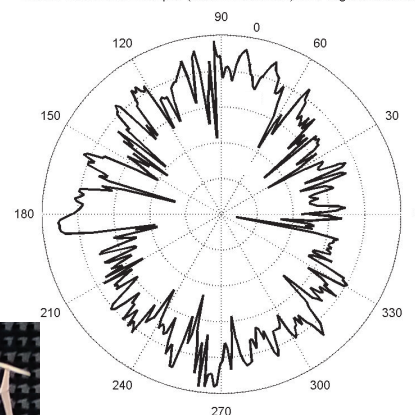
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## Small UAVs as radar targets: RCS

3 GHz RCS of the Helicopter (rotor inline with tail) for 0 degrees elevation



10 GHz RCS of the Helicopter (rotor inline with tail) for 0 degrees elevation



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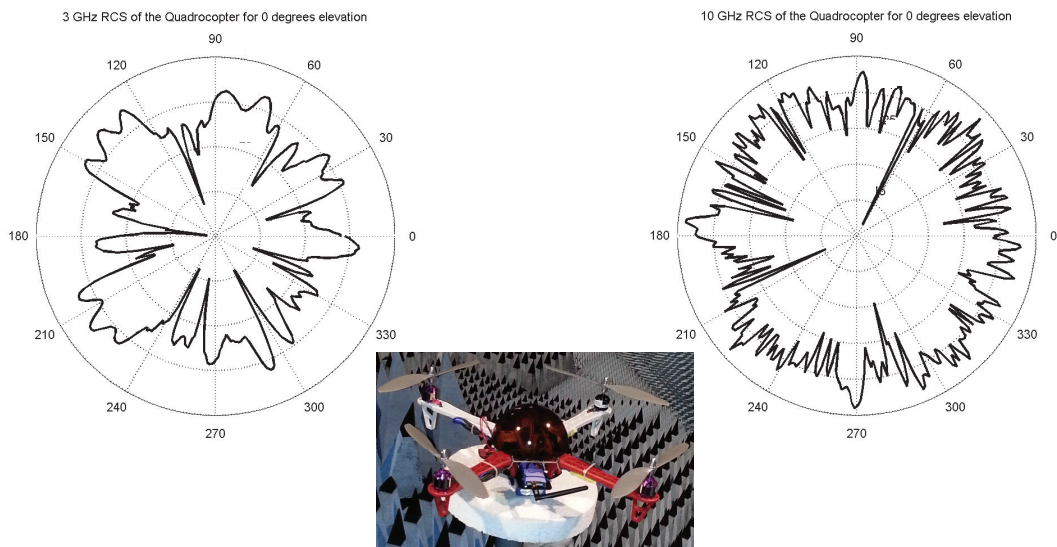
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## Small UAVs as radar targets: RCS



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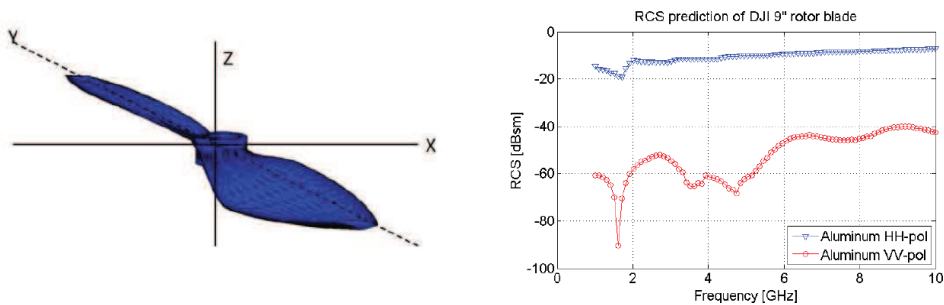
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## Small UAVs as radar targets: polarisation



Source: Matthew Ritchie, Francesco Fioranelli et al., *Micro-Drone RCS Analysis*, IEEE Radar Conf., October 27-30, 2015, Johannesburg, South Africa.

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## Radar detection and classification



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### In this Specialists' Meeting....

#### Low, Small and Slow

- Detection improvement in dynamic clutter conditions
  - Presentation of Marc
- Advanced denoising, and decluttering with known confusers
  - Presentation of Lorenzo
- Detection & classification, e.g. bird versus drone
  - Next slides
- Recognition
  - Concluding slides

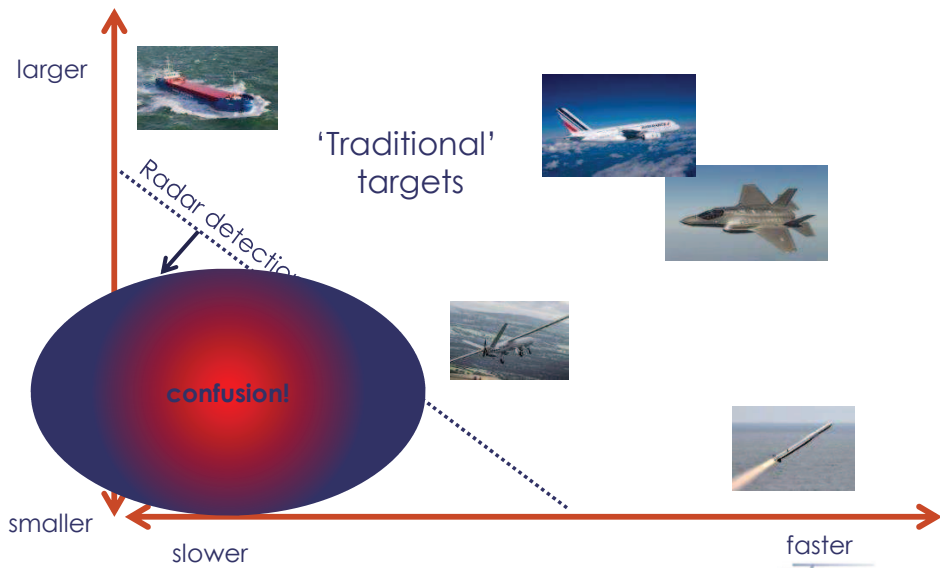
SP +  
Machine  
Learning

Machine  
Learning

SP

Machine  
Learning

## Detection and classification



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## D-RACE approach for classification

### Ideally: “instant classification” (combined detection and classification)

- > Quick response, especially at close range
  - So no lengthy track analysis, especially in bird rich environment
  - Track analysis can be done at medium to long range
- > Technologically limited impact on existing radar hardware
  - No full polarimetric radar front-ends
  - No ultra-wideband solutions



Micro-Doppler

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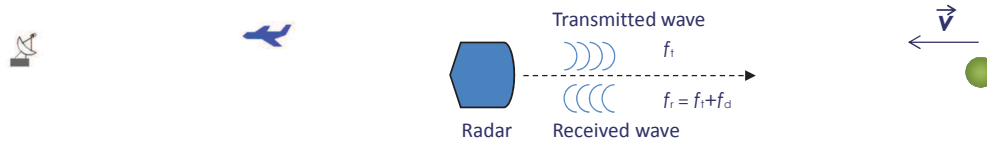
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# Micro-Doppler

## Doppler effect

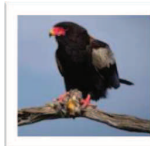
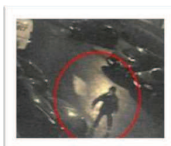
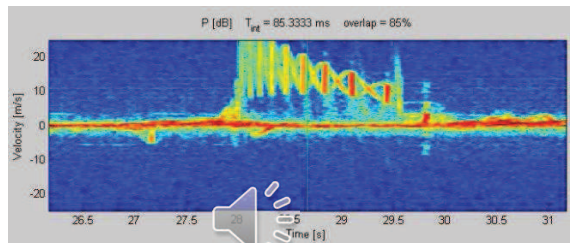
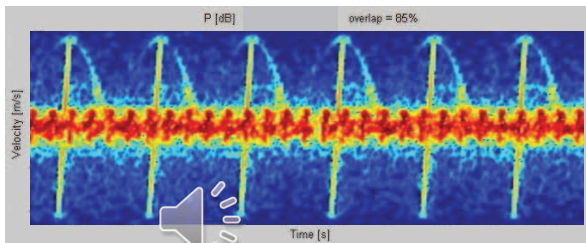
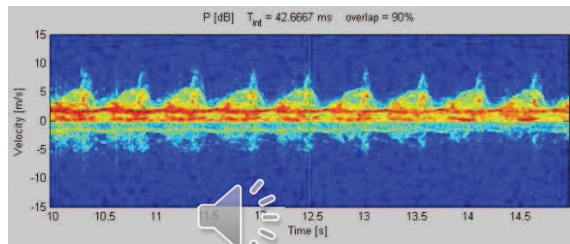
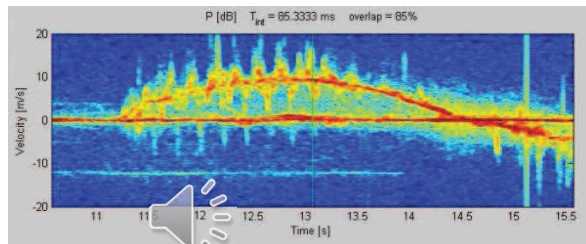
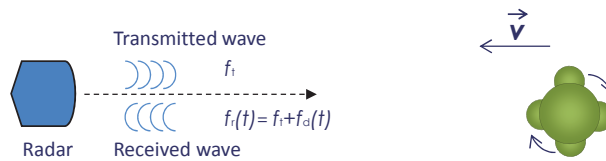


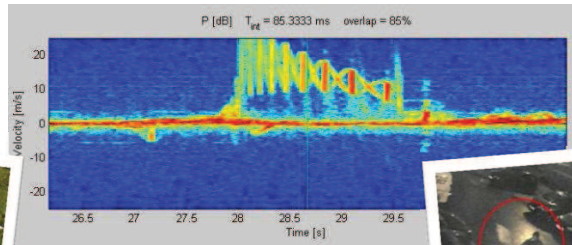
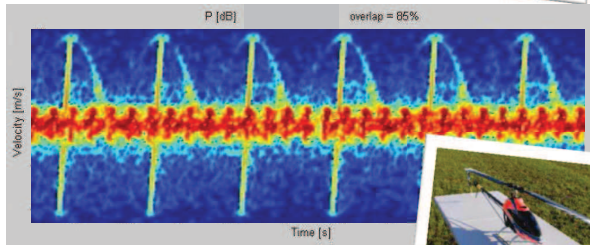
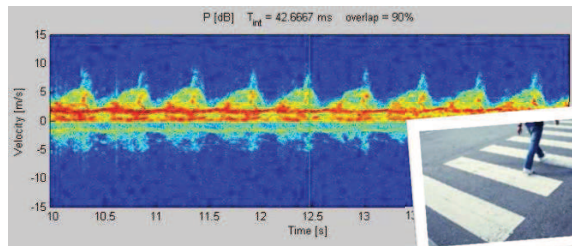
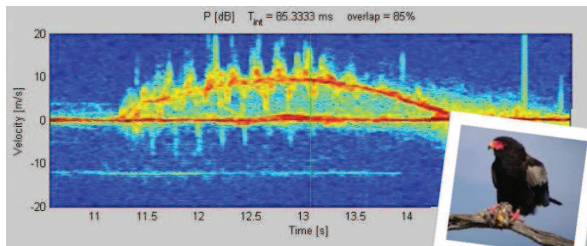
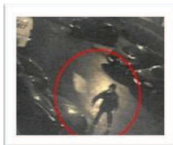
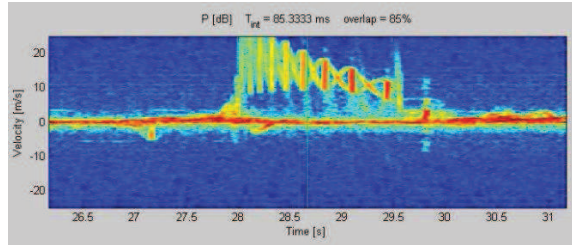
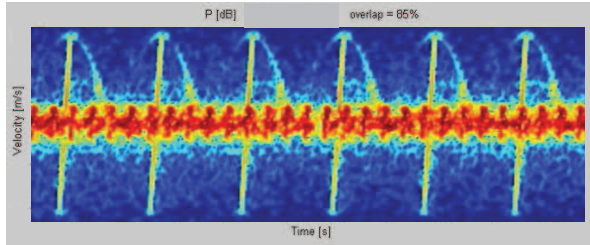
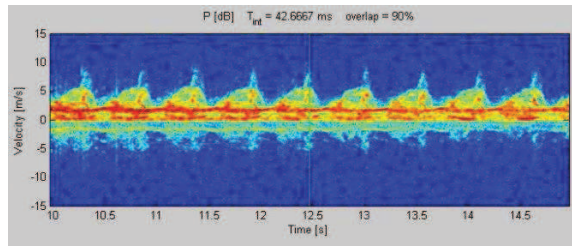
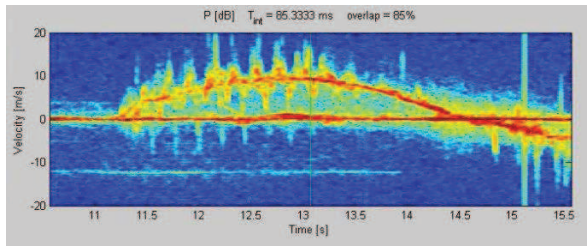
$$f_d = -\frac{2v_r}{\lambda}$$

$$\delta v = \frac{\lambda}{2T}$$

PRF/SRF

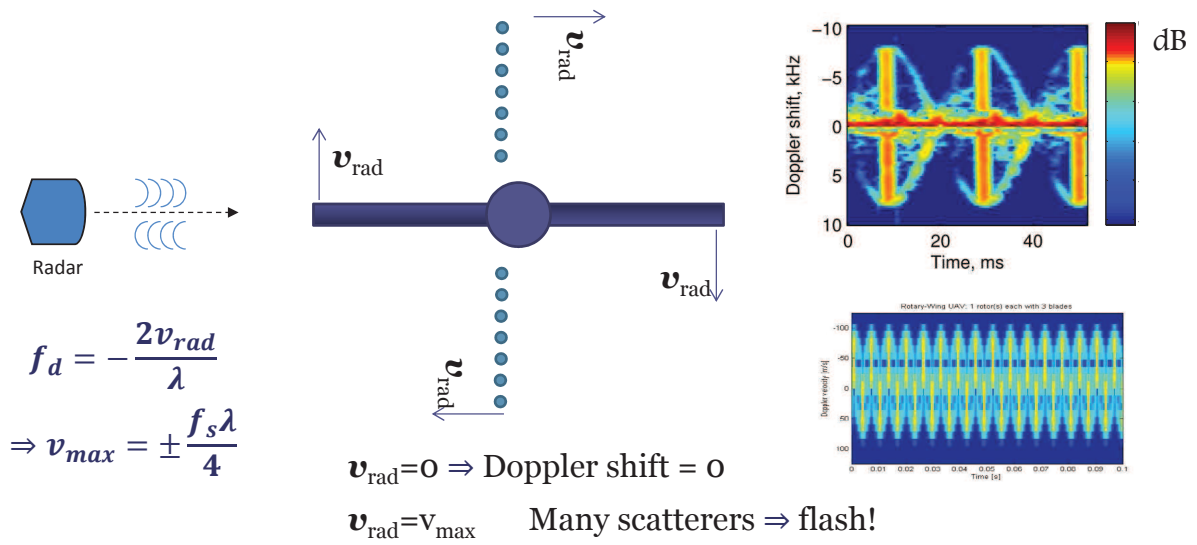
## micro-Doppler phenomenon







## Signature of a rotor



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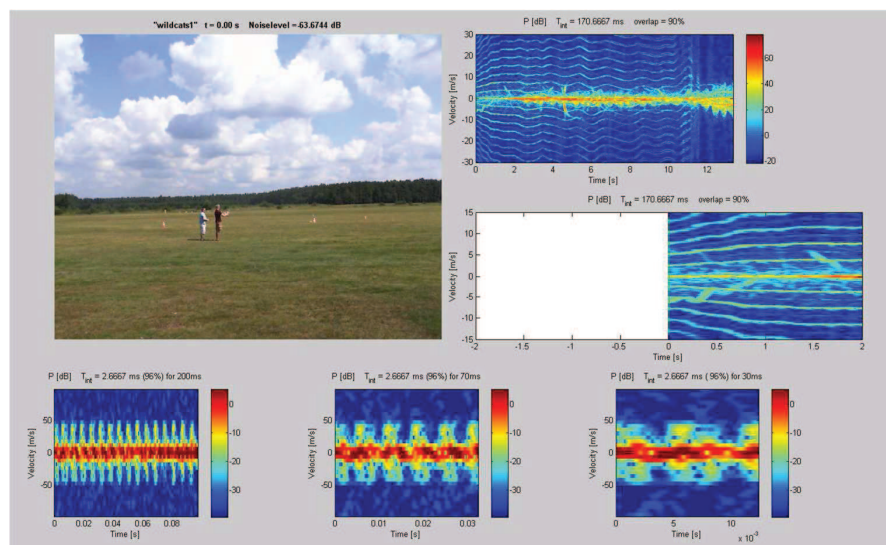
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## μDoppler signature of a rotor



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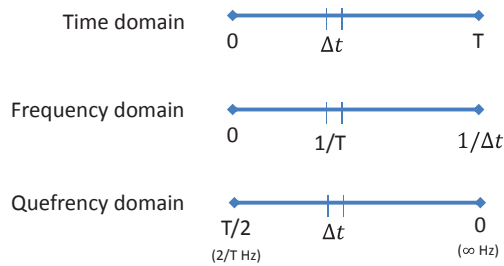
# Cepstral Analysis

This is not a typo!

## Cepstrum: exploit long integration interval

$$\Xi\{f(t)\} = |\mathcal{F}^{-1}\{\log(|\mathcal{F}\{f(t)\}|^2)\}|^2$$

	Spectrum	Cepstrum
Increase integration time	Better resolution	Lower frequency components
Increase sampling rate	Higher frequency components	Better resolution



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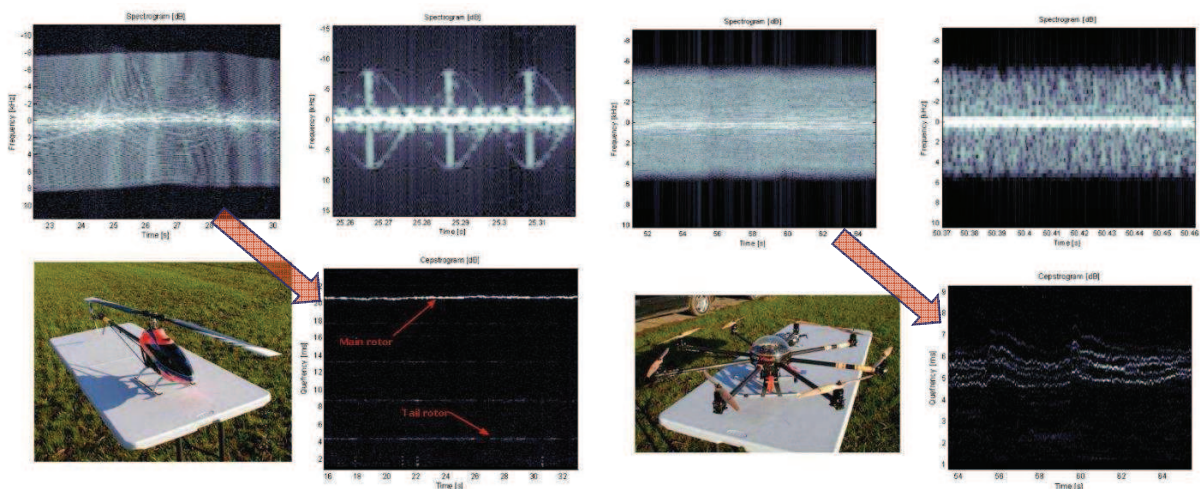
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# Cepstral Analysis



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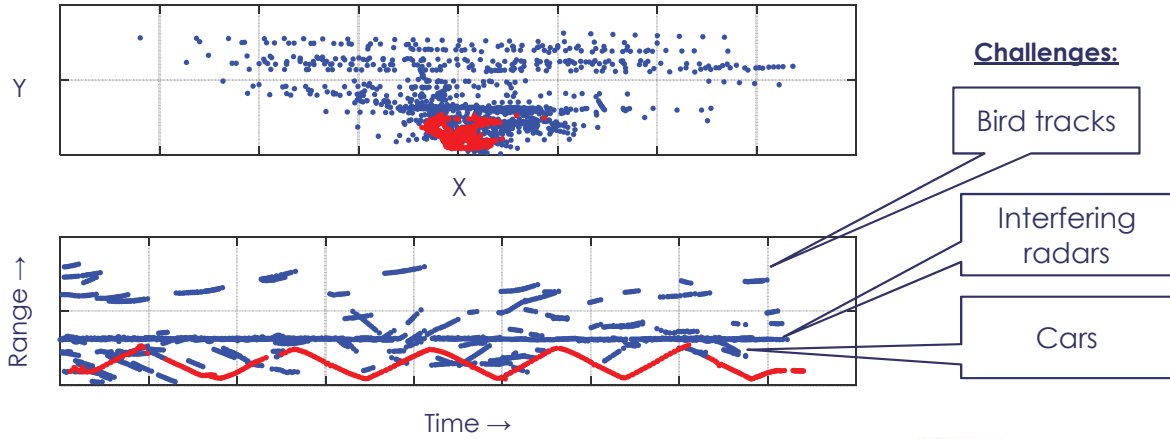
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## Classify-while-scan



### Classifier Results

➤ Track messages (red = mini-UAV classification)



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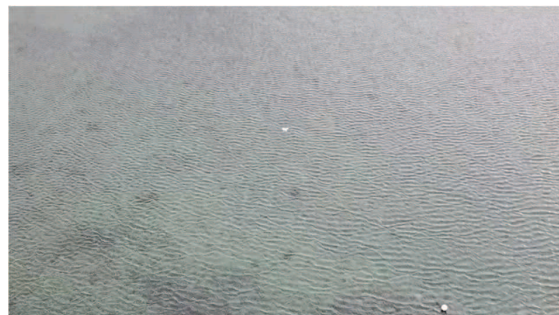
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## SQUIRE (TRL 8/9) Counter drone application with Kongsberg for NDMA



11 October 2017  
Trondheim (NO)



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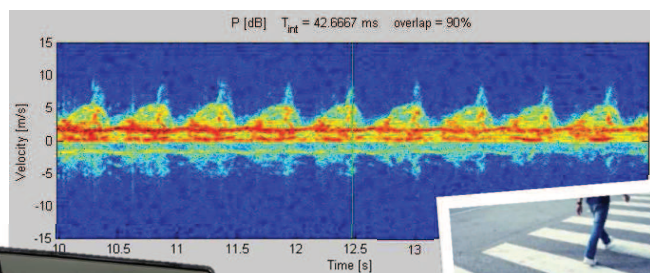
## Radar recognition



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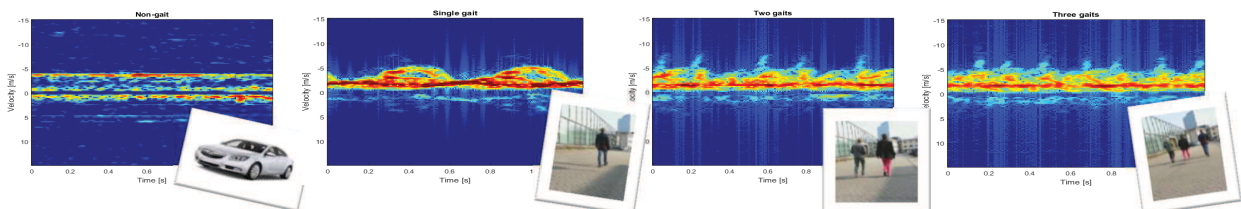
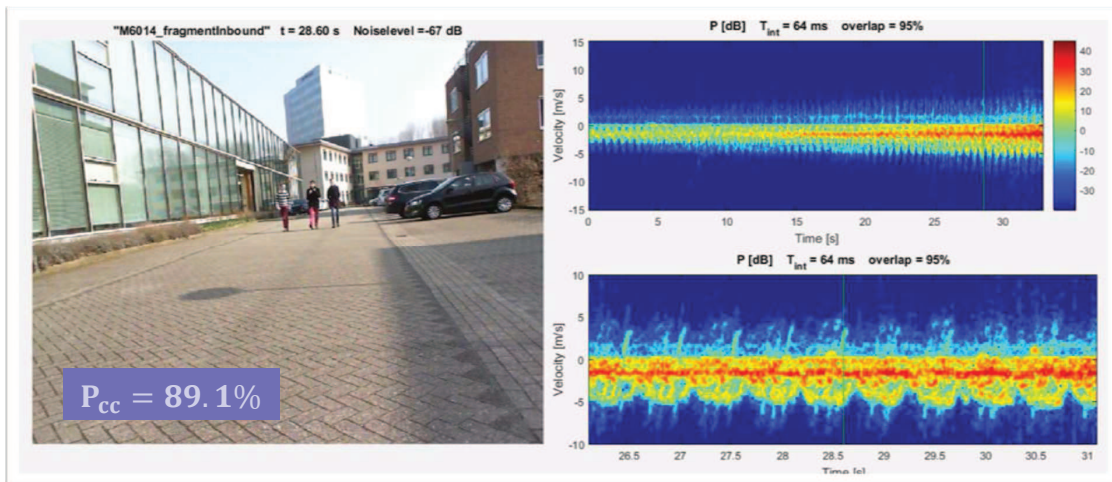
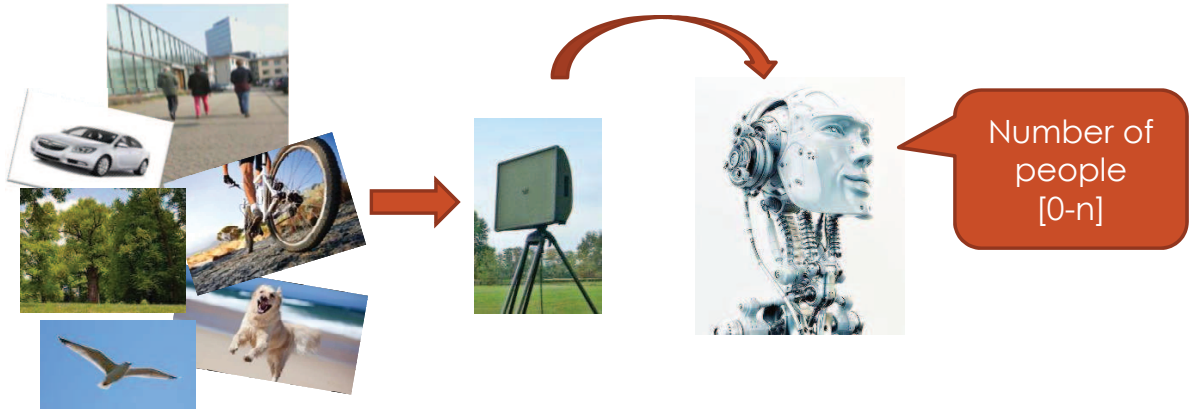
## Research question

How much information does  $\mu$ Doppler hide?

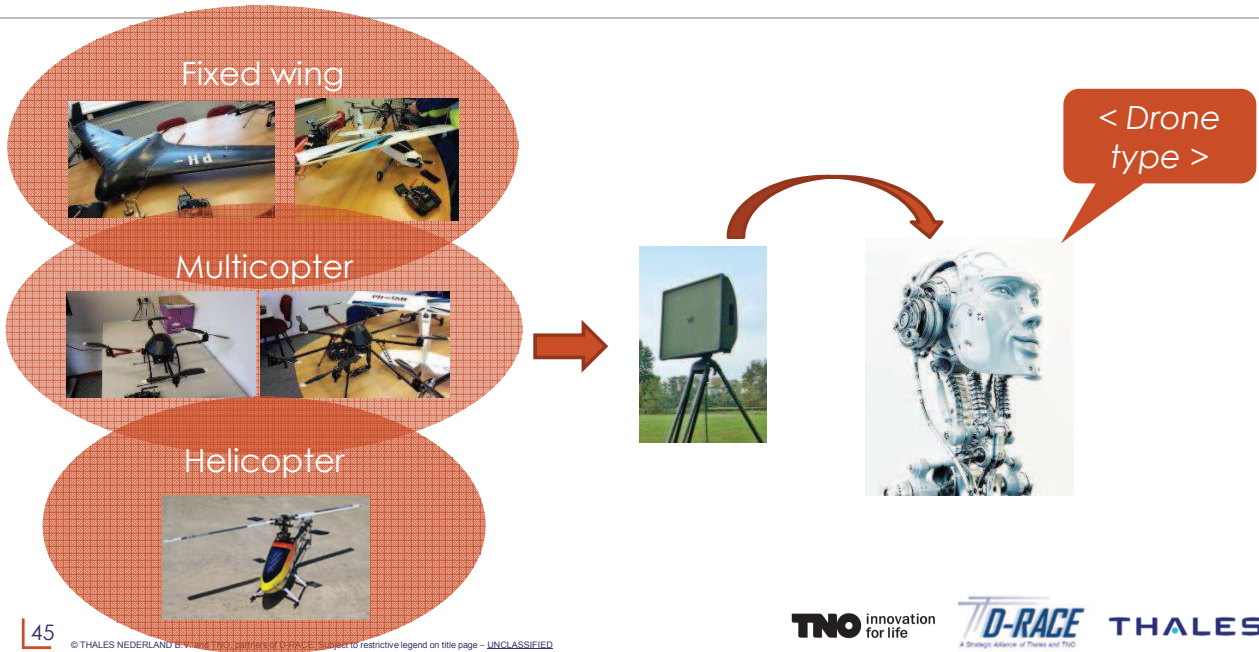




# Experiments: Human gait classification

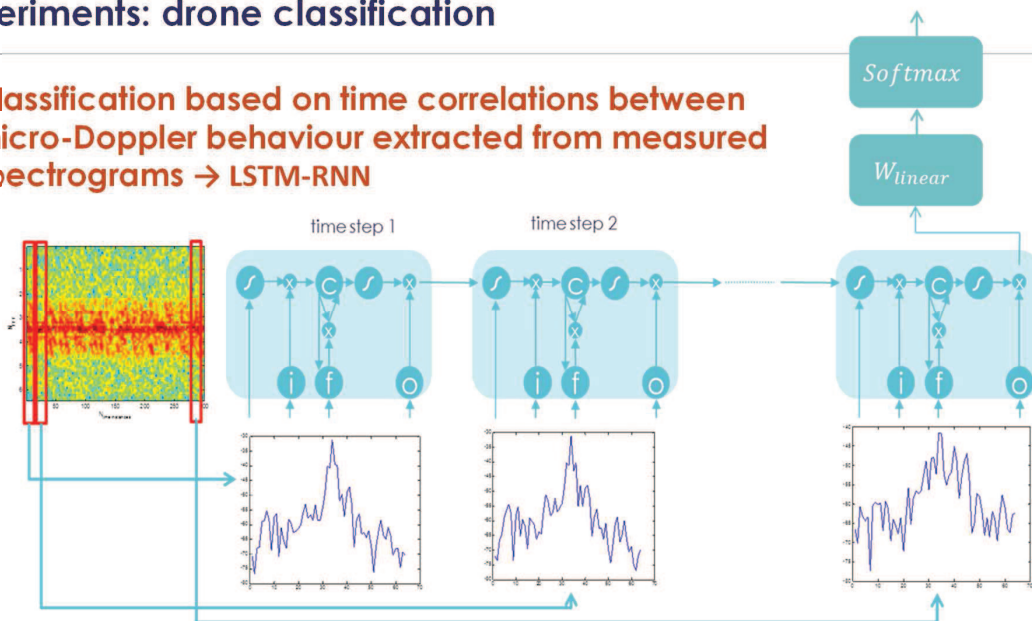


## Experiments: drone classification



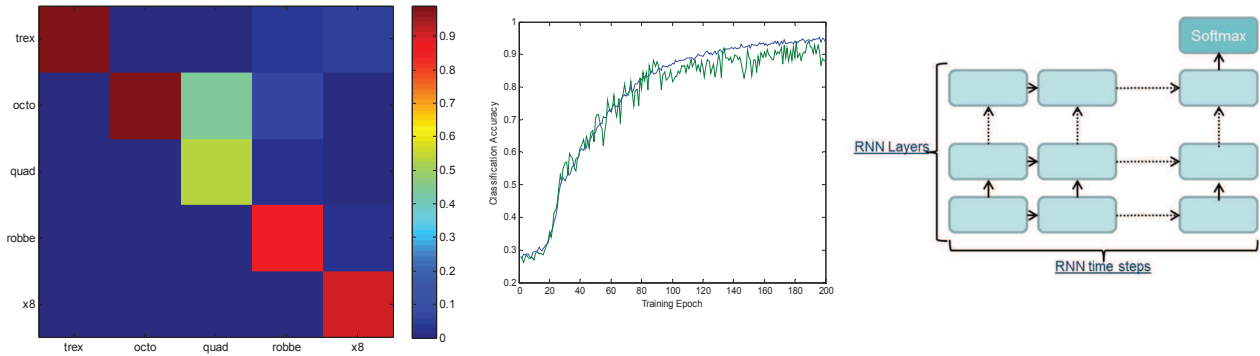
## Experiments: drone classification

Classification based on time correlations between micro-Doppler behaviour extracted from measured spectrograms → LSTM-RNN



## Experiments: drone classification

### Results



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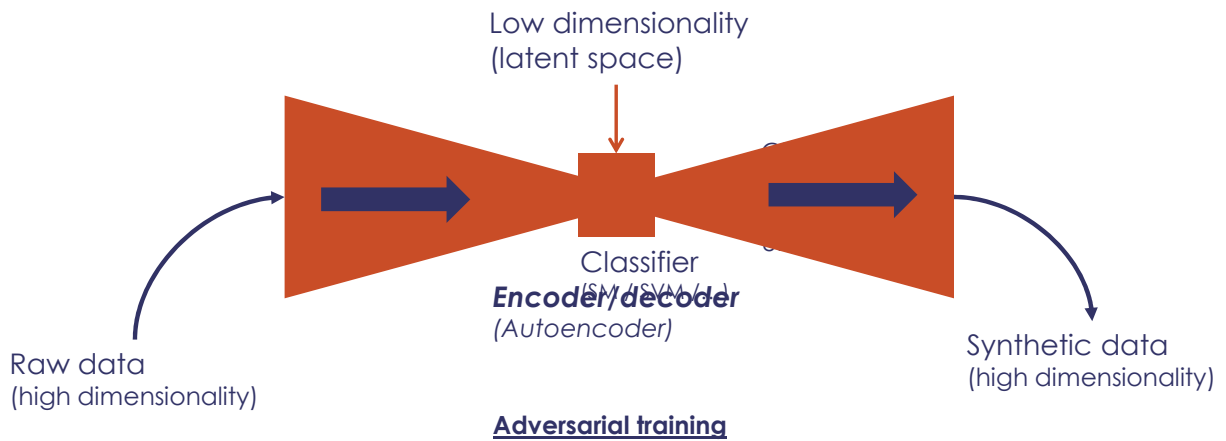
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## Deep Learning

### Deep Neural Network that ingests raw data, i.e. implicit feature extraction



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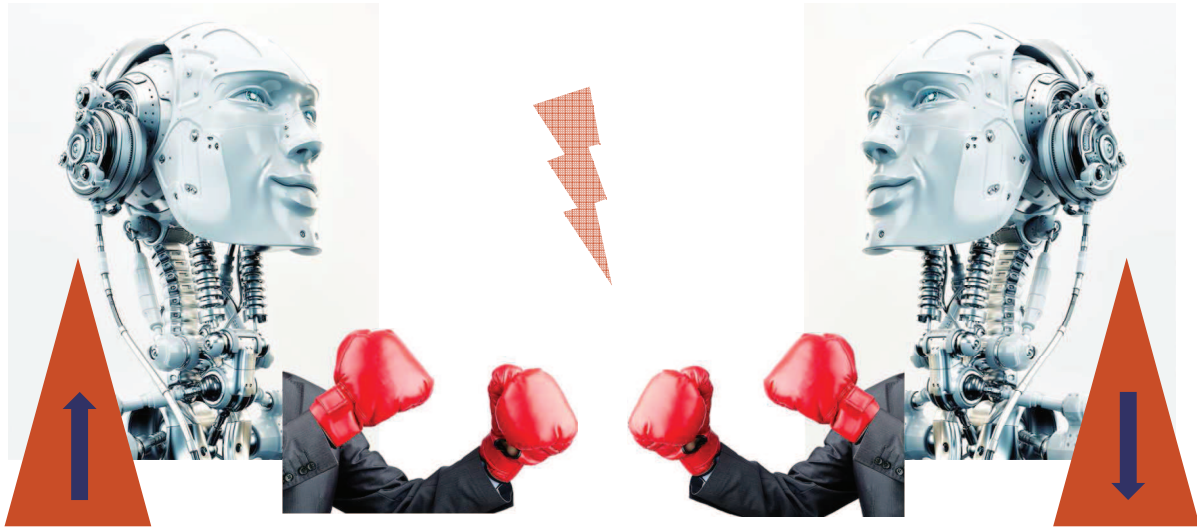
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## Adversarial Training



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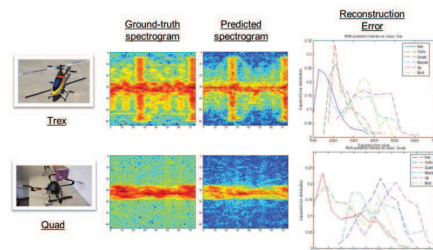
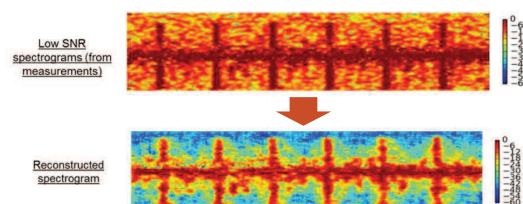
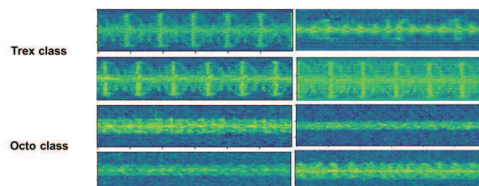
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## Encoder/Decoder architectures + adversarial training

### New possibilities

- > Data augmentation
- > Outlier detection
- > Decluttering / denoising
- > ...



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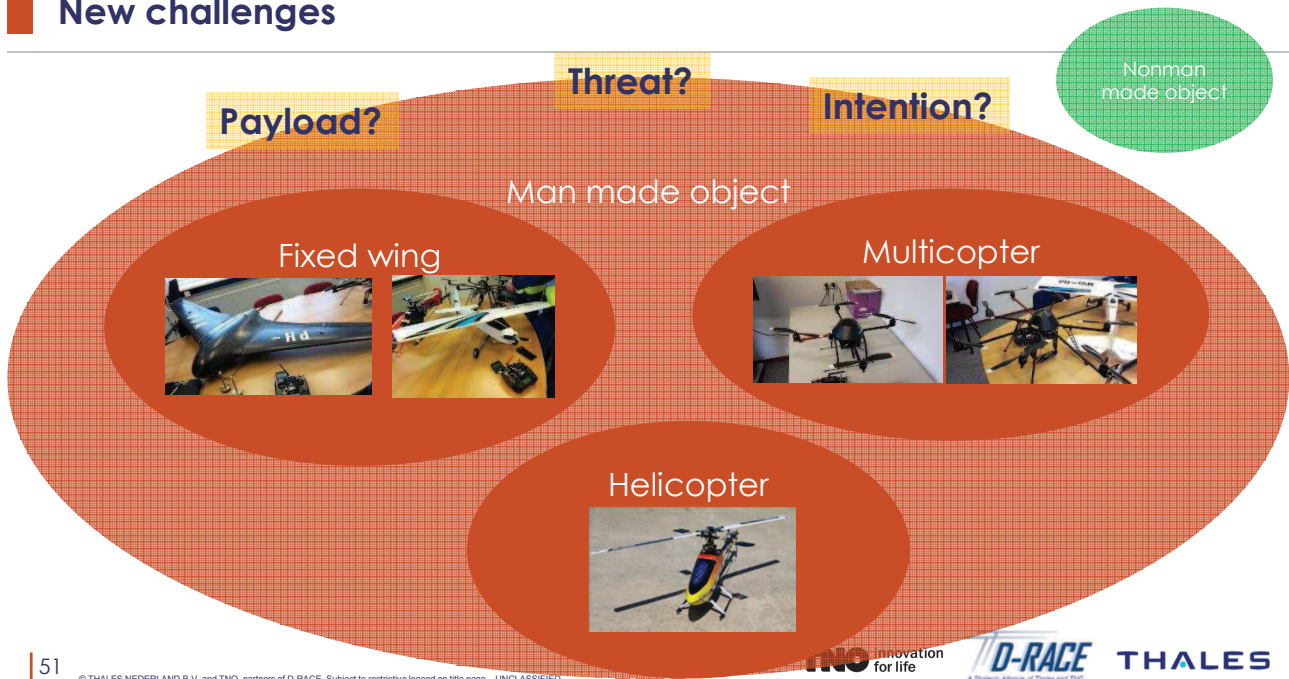
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## New challenges



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## Future challenges and opportunities

### Further assess the information content of $\mu$ Doppler

- Unsupervised Learning
- Different rotor shapes and configurations should appear differently in  $\mu$ Doppler

### Specialize DL algorithms for radar signals

- Current work focuses on audio, text, images and video



### Collect micro-Doppler from relevant targets

- Main military and most popular commercial s-UAVs

### Follow DL developments

- Hyperparameter tweaking → meta learning
- Black Box behavior → explainable AI
- Lack of training data → data augmentation



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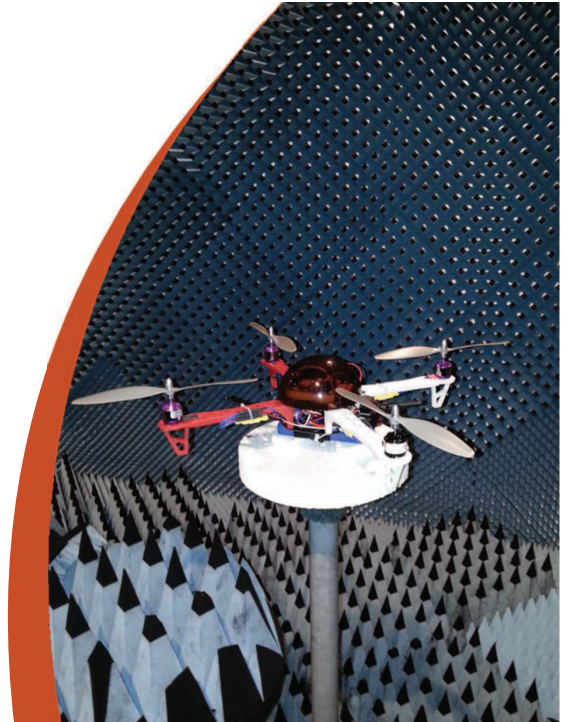
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## Conclusion



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## Conclusion

### Conclusions

- We can expect **massive growth in sUAV usage** combined with these important game changers
  - Updated legislation to allow commercial and governmental applications
  - Technology boost for better endurance and improved flight safety
  - Further application of AI for e.g. autonomy
- **Radar** can play an important role in drone traffic safety in civilian, governmental and military use
  - **Micro-Doppler** is one aspect that can be measured by radar that allows extraction of target details from its moving parts for e.g. classification
  - AI, and in particular **Deep Learning**, can be used to recognize subtle differences in micro-Doppler in challenging conditions. This can play a key role in drone safety, as well as many other radar applications.

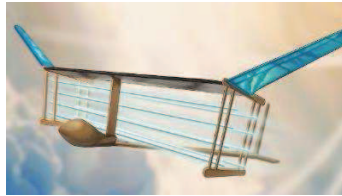
## Conclusion

That is how Micro-Doppler makes the difference!

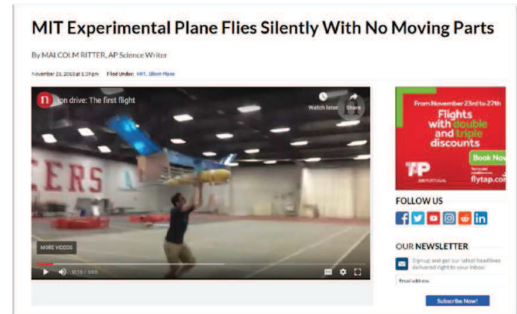
➤ Or does it ?



"Robird" drone Clear Flight Solutions



A new MIT plane is propelled via **ionic wind**. Batteries in the fuselage (tan compartment in front of plane) supply voltage to electrodes (blue/white horizontal lines) strung along the length of the plane, generating a wind of ions that propels the plane forward. (Image credit: Christine Y. He )



Thanks for your attention