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# Micro-Doppler signature of toroidal propellers and outdoor drone detection trials using portable V-band radar

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# Background

Usage of small Unmanned Aerial Systems (UAS) have witnessed significant growths.

Sophisticated small UAS are capable of being manipulated for malicious intent.

Due to the diversity of shapes, sizes and advanced capabilities of the UAS, it is important to not only detect the UAS but also to identify the type and possibly the intent.

UAS can also have similar flight characteristics as birds making them difficult to differentiate in complex environments.

# Background

**Some commonly used methods to detect small UAS include: radar, acoustic, thermal, optical, etc.**

**Radars are at the forefront of counter-UAS (CUAS) efforts to detect UAS as they are operable in all-weather / lighting conditions and have been proven systems for air traffic controls for decades.**

**Radars can detect and track moving targets such as the UAS by analyzing Doppler shift.**

# Doppler / micro-Doppler

Doppler shift (change in frequency between the transmitted and received signal) occurs when an object moves relative to the radar.

The Doppler shift method provides velocity of the bulk target body, making it difficult to discriminate between UAS and other moving objects such as birds.

Other moving parts such as propellers – induce further frequency shifts, referred to as micro-Doppler, which can be exploited to detect and differentiate various types of UAS.

# Objective

**Recently, the Massachusetts Institute of Technology (MIT) has designed and tested new toroidal propellers for UAS applications. These new toroidal propellers are reported to have reduced acoustic noise and operate quieter than the conventional propellers paving the way for future UAS applications.**

**The objective of this paper is two-fold:**

1. Compare the micro-Doppler signatures of the new toroidal propellers against the conventional propellers using V-band (66 GHz) radar.

2. Examine if the V-band radar is capable of detecting small UAS in the outdoor environments.

# V-band portable radar

Software-defined MMI-100 series research radar.

Designed and manufactured by aiRadar Inc. in Vancouver, Canada.

Uses frequency-modulated continuous wave (FMCW) waveforms with a centre frequency of 66 GHz and a bandwidth of 4 GHz providing less than 5 cm resolution.

37 degrees vertical beamwidth and can scan 90 degrees in azimuth.

Configurable with C-like syntax to scan or stare at the target.

# TOROIDAL PROPELLERS

# Toroidal / conventional propellers

# Experimental setup

**UAS from THIUS Canada Inc. was used in a single arm configuration and was placed approx. 1.5 m above the ground and 5 m away from the radar, which was approx. 1 m above the ground.**

**The radar was first run in a scanning mode with 5 cm range resolution to align the drone at its boresight.**

**Once the drone was aligned, the radar was switched to a staring mode, where only a single central beam with a ±1.5° was used to transmit and record the radar signal for approximately 5 seconds.**

**Data were collected for two cases:**

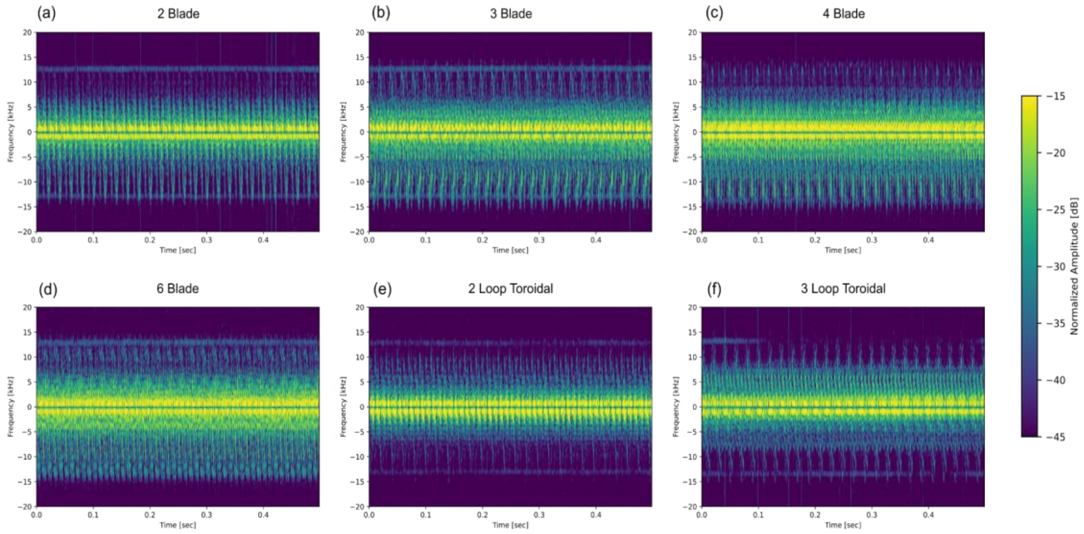
- Propellers spinning at a constant speed to simulate hovering; and
- Propellers spinning at varying speed to simulate maneuvering.

# Analysis and results – constant speed

**Blade flashes can be seen in the spectrogram for all propeller types.**

**Toroidal propellers seems to have low overall response.**

**At certain frequencies the three loop toroidal propellers seems to produce a strong response as compared to the two loop.**

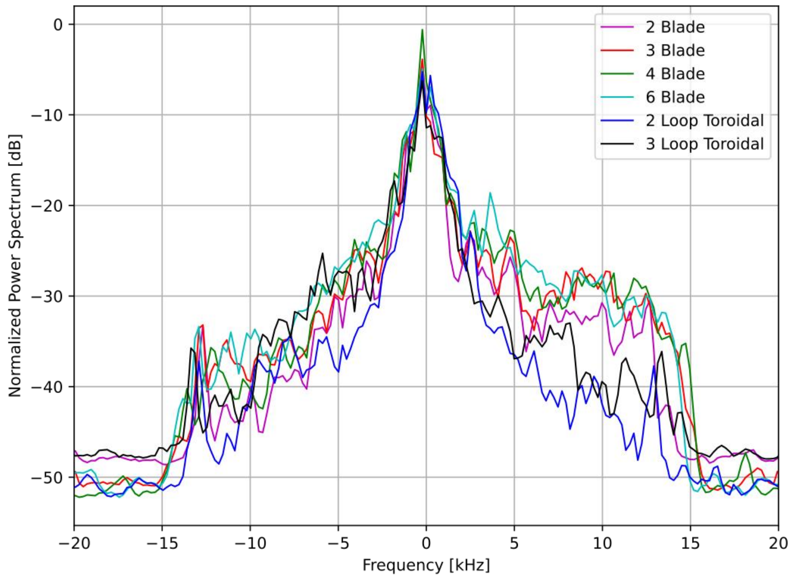



Micro-doppler spectrogram at constant propeller speed

# Analysis and results – constant speed

**Power spectrum shows that the micro-Doppler signatures for the toroidal propellers are lower in amplitude than the conventional propellers.**

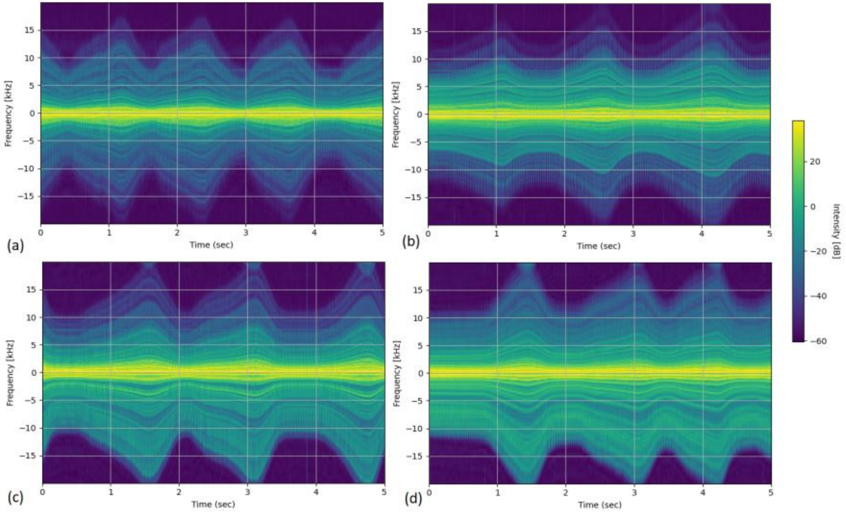
**Suggests that conventional propellers have higher contribution from the blade tips as compared to the toroidal propellers.**



# Analysis and results – variable speed

As the velocity is increased the spectrogram is compressed in time and increases in frequency.

Stronger (higher intensity) response from the conventional propellers as compared to the toroidal propellers.




(a) Two loop toroidal, (b) three loop toroidal, (c) two blade conventional, and (d) three blade conventional

# OUTDOOR TRIALS

# UAS used for outdoor trials

Mavic Mini Pro 3

Mavic 2 Pro

Skydio 2

DJI M30T

Image references:
Mavic Mini Pro 3: https://store.dji.com/ca/product/dji-mini-3-pro?vid=113991&set_region=CA&gad=1&gclid=Cj0KCQjw06-oBhC6ARIsAGuzdw06ypfniy-0c-Zyw0QpvLG1vOXD4Jg20_Z5kdhR-8ydvIGBcMwlE4MaAmf5EALw_wcB
Mavic 2 Pro: https://aerialtech.com/products/mavic-2-pro
Skydio 2: https://www.theverge.com/2019/12/11/21009994/skydio-2-review-self-flying-autonomous-drone-camera-crash-proof-price
DJI M30T: https://droneshopcanada.ca/products/dji-matrice-30t

# Experimental setup

## Outdoor trials were conducted at Area XO in Ottawa, Canada

## Some of the simple maneuvers include:

- Hovering, climbing / descending, flying the drone to-and-from and side-to-side from the radar, etc.

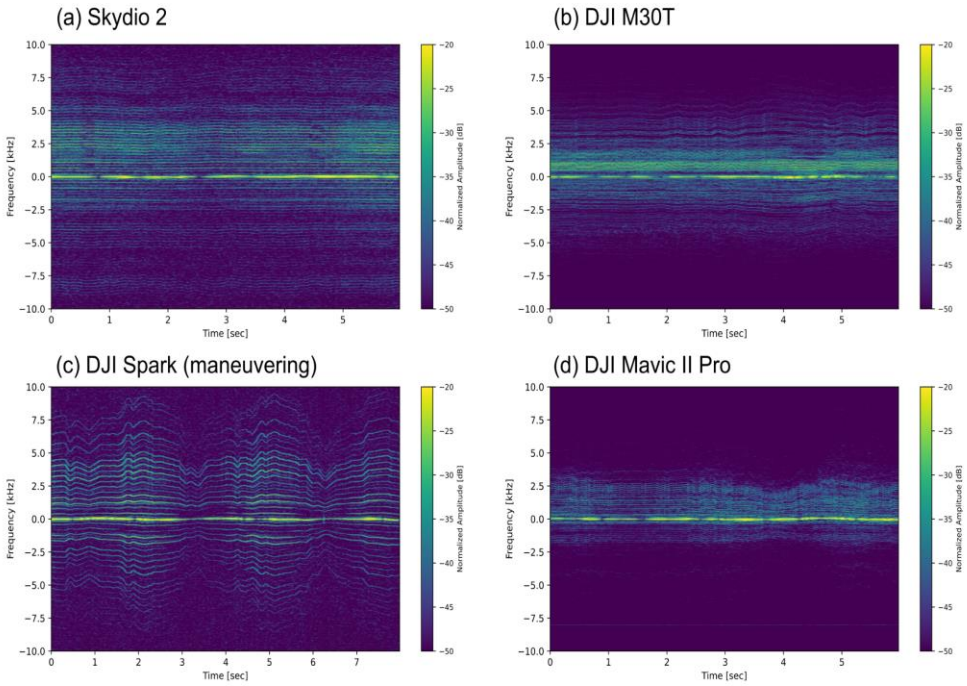
## The more sophisticated ones include:

- Multiple drones coming in and out the sight of the radar, flying over natural / man made clutters, using confusers such as flying the drone in front / behind a moving car, dropping payloads, etc.

# Analysis and results

**Micro-doppler spectra of four different drones, where visual differences can be observed in terms of rotor modulation lines.**

**These features can be exploited for UAS classification using machine learning techniques.**



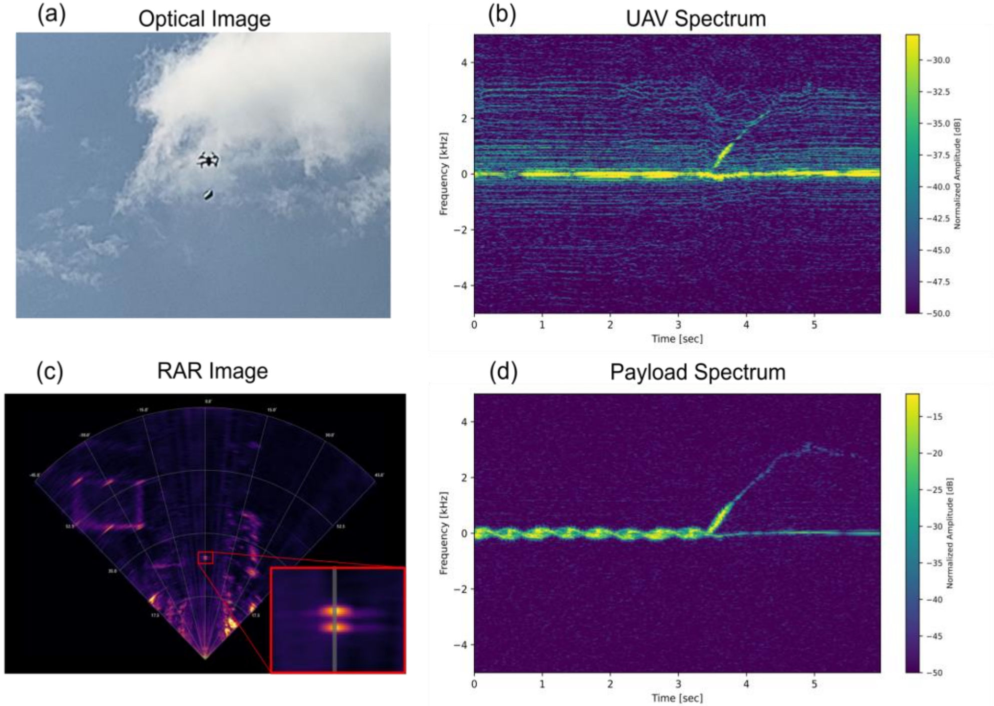

(a) Hovering at 28 m, (b) Hovering at 30 m,
(c) maneuvering (up and down) at 10 m, and (d) hovering at 30 m

# Analysis and results

**Payload drop by DJI Mavic 2 at 50 m**

**UAS and the payload can be spatially resolved, therefore, micro-Doppler of the UAV and the payload can be analyzed separately.**

**This demonstrates the possibility of using micro-doppler analysis to detect a payload drop.**




DJI Mavic 2 Pro carrying and dropping a payload at 50 m

# Summary / Conclusions

**Micro-doppler analysis was used to find any differences between the new toroidal propellers and the conventional propellers using the V-band radar.**

- The micro-Doppler spectra of the toroidal propellers were lower in amplitude than the conventional ones.
- Indicates that in addition to being acoustically quieter, optimally designed toroidal propellers can be more challenging to detect using micro-Doppler.
- However, in a more realistic scenario the radar beam is likely to impinge on the underside of the propeller, leading to a different viewing geometry and possibly different features in the micro-Doppler spectrum.

# Summary / Conclusions

**Results from the drone detection trials showed the possibility of using micro-Doppler analysis for detecting and differentiating different UAS types, as well as detecting a payload drop.**

- Micro-Doppler analysis revealed significant visual differences in the spectra observed from various UAS platforms.
- In some cases, the radar was able to clearly detect and identify the UAS using micro-Doppler signatures, such as: in the case of UAS carrying / dropping a payload.
- However, this work has focused on the analysis of UAS micro-Doppler signatures at short range and with high Signal to Noise Ratio (SNR).

# Future Work

**Further work include:**

- exploring the discriminative ability of micro-Doppler at longer range and with less favourable SNR;
- processing all the data acquired during the outdoor trials; and
- using machine learning techniques for detection and classification of UAS.

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# THANK YOU

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