Micro-Doppler Signature of Toroidal Propellers and Outdoor Drone Detection Trials Using Portable V-Band Radar

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ABSTRACT

This paper presents the outcomes of two different experimental runs using a 66 GHz (V-band) portable research radar. The first experiment consists of comparing micro-Doppler signatures from two different toroidal propellers with two and three loops, as well as, four different traditional propellers with two, three, four, and six blades. It was found that the toroidal propellers exhibit a lower micro-Doppler response than the traditional propellers used in this experiment, indicating that more sensitive detection is required to identify UAS equipped with toroidal propellers. The second experiment consists of using the V-band radar to detect the micro-Doppler signatures of small Unmanned Aerial Systems (UAS) undergoing various manoeuvres in an outdoor environment. The overall aim is to use signatures from the V-band radar signal to detect and differentiate between different UAS configurations as part of the constantly evolving Counter-UAS (CUAS) efforts.

1.0 INTRODUCTION

Usage of small Unmanned Aerial Systems (UAS) for both civilian and military applications have seen significant growths over the years. Sophisticated small UAS are readily available in the consumer market, and are capable of being manipulated for malicious intent. UAS can also have similar flight characteristics as birds making them difficult to differentiate in complex environments. Detecting such UAS is of importance to civilian and military establishments. 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 in order to deploy the appropriate counter-measures. Some commonly used methods to detect small UAS include: radar, acoustic, thermal, and optical. 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 have been used to detect and track moving targets such as the UAS by analysing Doppler shift. 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. However, the majority of these UAS use propellers to generate lift for flying. Therefore, additional features, such as the micro-Doppler signatures produced by these rotating propellers have been used to detect and differentiate various types of UAS [1]. Also designs of these propellers have remained unchanged since their introduction. Recently, the Massachusetts Institute of Technology (MIT) has designed and tested new toroidal propellers for small UAS applications [2],[3]. These new toroidal propellers are reported to have reduced acoustic noise and operate quieter than the traditional propellers paving the way for future UAS applications. Therefore, the objective of this paper is two-fold: first is to compare the micro-Doppler signatures of the novel toroidal propellers against the traditional propellers using a 66 GHz (V-band) portable radar and second is to examine if the V-band radar is capable of detecting small UAS in the outdoor environments.

The V-band (frequency range: 40-70 GHz, wavelength: 7.5-4 mm) [4] of the Electromagnetic (EM) spectrum is rarely used for commercial application as compared to the other bands, where many studies have been performed to detect UAS using the micro-Doppler signatures. For example: Beasley et. al., used multistatic X-band (8.5 GHz) and L-band (1.3 GHz) radars to characterise micro-Doppler signatures of DJI Matrice 600 and Phantom 4 UAS [5]. White et. al. used spectrograms produced using a L-Band radar to classify between birds and drones [6]; whereas, Rahman & Robertson used the micro-doppler signatures from K-band (24 GHz) and W-band (94 GHz) radars to detect and differentiate between different types of drones and birds [7]. Kolev et. al. used experimental K-band (24 GHz) radar setup and simulations to study micro-Doppler signatures of drone frame vibration and propellers rotation [8]. Tahmoush used a G-band radar to collect and analyse micro-Doppler signatures of a small helicopter [9]. Wit et. al. used X-band radar to differentiate between helicopter, and multicopters using micro-Doppler signatures [10]. The authors have also used micro-Doppler signatures using the V-band radar to differentiate between different types of drones such as helicopter, quadcopter, hexacopter, and octocopter in indoor and outdoor settings. [11]

In this paper, micro-Doppler signature from two different toroidal propellers with two and three loops, as well as, four different traditional propellers with two, three and four blades were compared. The blades were fabricated using a 3D printer, example of which is shown in Figure 1. As for the outdoor trials, drones undergoing different manoeuvres were recorded and analysed. The overall aim is to use these signatures to detect and differentiate between different UAS configurations as part of the constantly evolving CUAS efforts.

Figure 1: Example of 3D printed toroidal and traditional propeller blades.

2.0 EXPERIMENTAL SETUP

Two sets of experiments were conducted, one to compare the micro-Doppler signature of the toroidal blades, and another outdoor trials to simulate real world drone detection capability of the portable V-band radar.

2.1 V-Band Radar

The portable software-defined mmWave MMI-100 research radar used in this study is designed and manufactured by aiRadar, Inc. located in Vancouver, Canada. The radar employs frequency-modulated continuous wave (FMCW) waveforms with a centre frequency of 66 GHz (V-band) and a bandwidth of 4 GHz. The radar has three transmit (Tx) and three receive (Rx) 64-element arrays. The radar is capable of arbitrary operational modes including sector scanning real aperture radar (RAR), single pass interferometric synthetic aperture radar (InSAR), and generating digital surface models. The transmit bandwidth of up to 4 GHz provides images with less than 5 cm resolution. The vertical beamwidth is modified with tapering to produce a 37-degree beamwidth with sidelobe levels below -20 dB. It can scan 90° in azimuth with a two-way beam pattern exhibiting better than 0.9° angular resolution. This research radar is highly configurable using the compiled aiRPL language, with a C-like syntax, which makes it capable of adaptive pulse code modulation, multilevel looping, and modifying radar configurations on a PRI-to-PRI (pulse repetition interval) basis. For micro-Doppler analysis, the radar is configured to dwell on a single beam containing the target of interest, emitting short pulses at a high pulse repetition frequency (PRF) in order to sample the targets' Doppler spectrum.

2.2 Toroidal Blade Experimental Setup

In this setup, a drone from THIUS Canada Inc. [12]. was used in a single arm configuration to rotate one propeller at a time. The THIUS drone was secured in a tripod and was placed approximately 1.5 m above the ground and 5 m away from the radar. The radar itself was secured to a tripod and was placed approximately 1 m above the ground. The radar was first run in a scanning mode with 5 cm range resolution with the Moving Target Indication (MTI) overlay 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° azimuth from the centreline was used to transmit and record the radar signal for approximately 5 seconds. Data were collected for two cases: one while the propellers were spinning at a constant speed to simulate hovering and another at a varying speed to simulate manoeuvring. This experiment was conducted indoor in a laboratory environment and the setup of which is shown in Figure 2.

Figure 2: Experimental setup to collect data from the toroidal and conventional blades.

2.3 Outdoor Trial Setup

Outdoor trials were conducted at Area XO in Ottawa, Canada. For this trial the radar was secured to a stand and placed approximately 1.5 m above the ground to reduce any ground clutter. Team of students and researchers from Carleton University, Ottawa led by Prof. Jeremy Laliberte flew the drones manually and / or by using waypoints to perform different manoeuvres. Four different drones were used during the experiments, which were: DJI M30T, Mavic 2 Pro, Skydio 2, and DJI Mavic Mini Pro 3. Some of the simple manoeuvres 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. Setup for this experiment is shown in Figure 3.

Figure 3: Experimental setup for outdoor drone detection trials.

3.0 ANALYSIS AND RESULTS

The analysis consists of using micro-Doppler signatures to differentiate between toroidal and traditional propellers, as well as, to detect and identify different types of UAS undergoing different manoeuvres.

3.1 Toroidal and Traditional Propellers

Figure 4 shows the micro-Doppler spectrograms for each of the six propellers spinning at constant speeds. Although the toroidal propellers have a low overall response at high Doppler frequencies, brief flashes containing energy at Doppler frequencies between 7 kHz and 12 kHz are visible in the spectrograms for both the two-loop and three-loop toroidal propellers. This suggests that there are certain discrete angles at which the toroidal propellers produce a strong response from the outer segments of the loop. These likely occur at the points where the loops are joined together. This is especially the case for the three-loop propeller used in this study (see Figure 1), where the joints between the loops have sharp concave corner-like features which are likely to cause strong radar returns. It should be noted that a toroidal propeller specifically designed for the avoidance of radar detection would likely not have such features, and as such the micro-Doppler spectrum would have even less high frequency content.

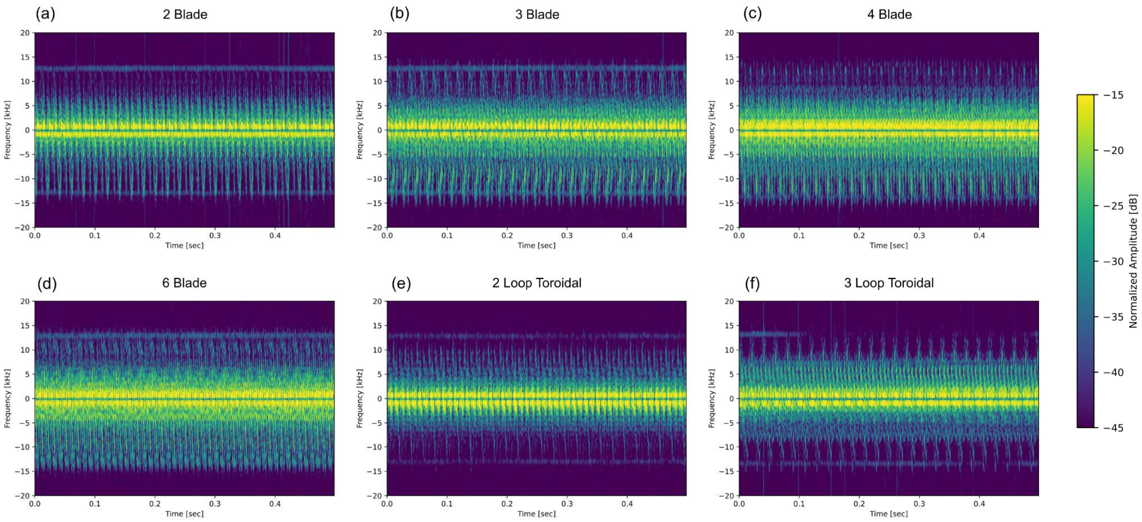

Figure 4: Micro-Doppler spectrograms of: (a) two blade, (b) three blade, (c) four blade, (d) six blade, (e) two loop toroidal, and (f) three loop toroidal, operating at a constant angular velocity. Spectrograms are computed using a window duration of 1.103 ms and a window overlap of 50%.

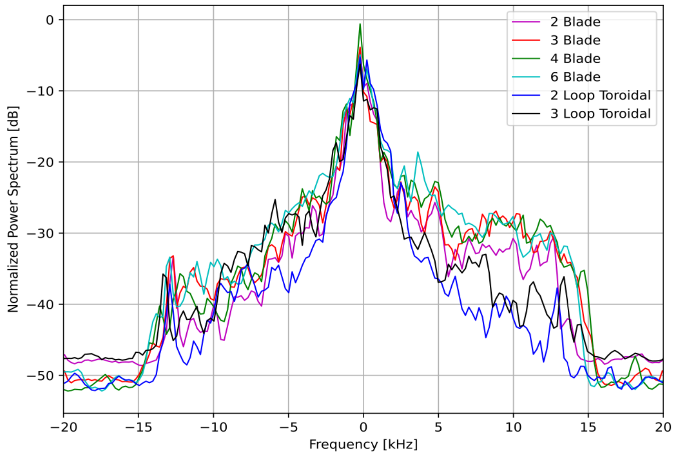

Figure 5: Power spectrum comparison for the six different propeller types.

Figure 5 shows the power spectrum of the response from each of the six propeller types operating at a constant angular velocity (which can be thought of as an average of the micro-Doppler spectrograms from Figure 4 along the time axis). As was shown in the micro-Doppler spectrograms, the micro-Doppler spectra of the two toroidal propellers are lower in amplitude than the micro-Doppler spectra of the propellers with the traditional blades, particularly at Doppler frequencies above 3 kHz. This indicates that the toroidal propellers have a lower monostatic Radar Cross-Section (RCS) than the traditional propellers, and that the returns from the traditional propellers have a higher contribution from regions near the blade tips.

Figure 6 shows the micro-Doppler spectra for the two toroidal propellers, as well as the two-blade and the three-blade conventional propellers rotating with variable angular velocity. As the velocity is increased, the spectrogram is both compressed in the temporal direction (the time between successive blade flashes decreases) and stretched in frequency. This change in the spectrogram characteristics can be used to detect the changing rotor velocities which occur when the UAS is manoeuvring.

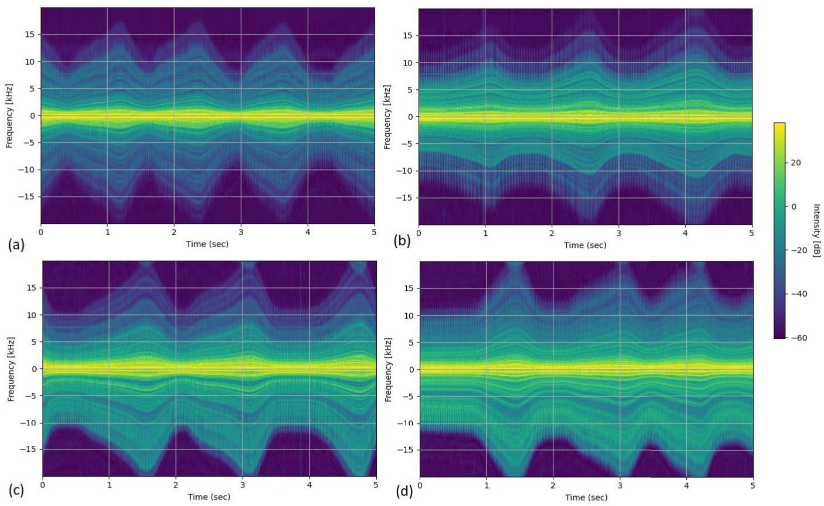

Figure 6: Micro-Doppler spectrograms of 4 propeller types operating at variable speeds. (a) two loop toroidal, (b) three loop toroidal, (c) two blade conventional, and (d) three blade conventional.

This study has focused on distinguishing toroidal propellers and traditional propellers based on variations of the monostatic RCS in the plane of the propeller's rotation. 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 to different features in the micro-Doppler spectrum. Further work is required to determine the properties of the toroidal propeller Doppler spectrum using bistatic measurements and at a variety of incidence angles.

3.2 Results from the Outdoor UAS Trials

It is to be noted that results from only a small subset of the outdoor trials are presented in this paper.

3.2.1 Comparison of Micro-Doppler Signatures of Various UAS

Figure 7 shows the micro-Doppler spectra observed from four different UAS platforms. Significant visual differences are observed between the different UAS spectra. In particular, the overall bandwidth of the micro-Doppler spectra, as well as, the density of the rotor modulation lines varies. The differences observed between the micro-Doppler spectra of the different UAS attests to the discriminative capability of the micro-Doppler spectrum. This encourages the further development of automated UAS classification techniques leveraging micro-Doppler analysis, for example fundamental pitch analysis and various machine learning-based classification techniques.

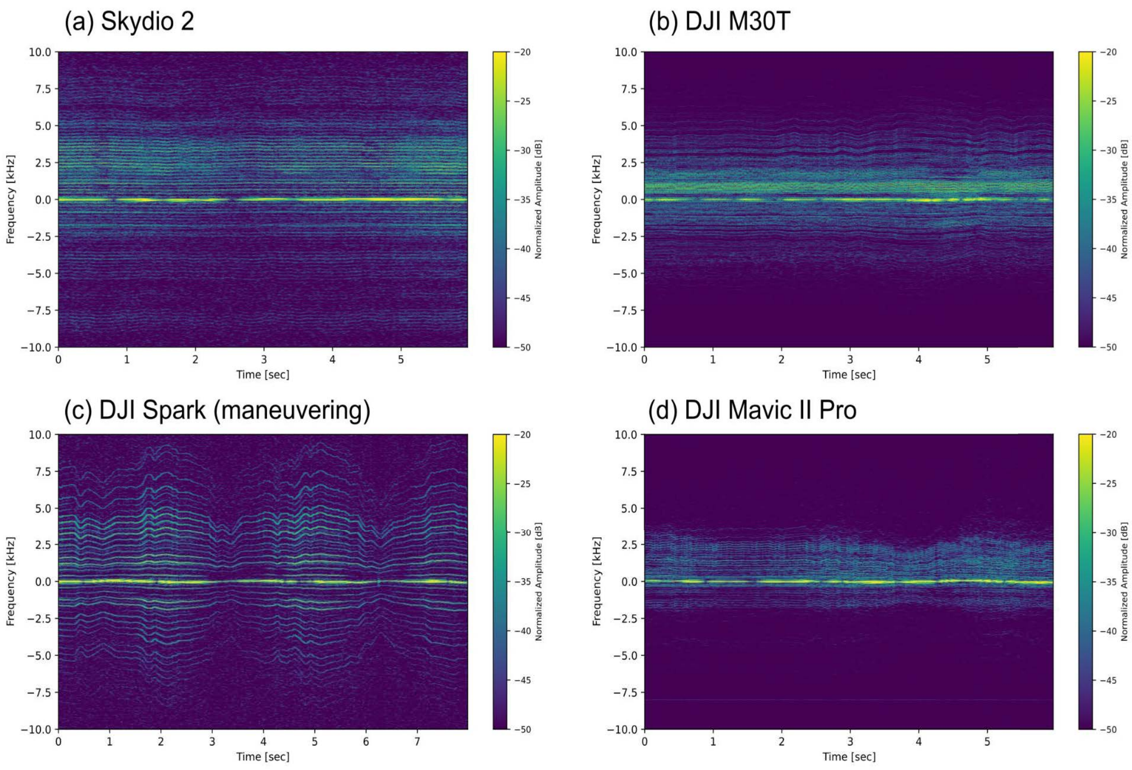

Figure 7: Micro-Doppler analysis of various UAS platforms in outdoor environments: (a) hovering Skydio 2 at 28 m range; (b) hovering DJI M30T at 30 m range; (c) DJI Spark manoeuvring up and down at 10m range; and (d) hovering DJI Mavic II Pro at 30 m range. All spectrograms are processed using a STFT window of 51.2 ms.

3.2.2 Detection and Analysis of UAS Payloads

The micro-Doppler analysis of a small drone (DJI Mavic 2 Pro) with a suspended payload is shown in Figure 8. The payload consists of two aluminum beverage cans which were tethered to the UAS and were dropped at time (T) = 3.5 s from the start of radar data acquisition. Since the UAS and the payload are spatially resolved (see Figure 8(c)), the micro-Doppler spectra of the two can be analyzed separately. Figure 8(b) shows the micro-Doppler spectrum of the UAS. A dip in the Doppler frequency of the UAS rotor modulation lines can be observed as the payload is dropped and the UAS reacts to the reduced load by slowing its propellers. Note that a range sidelobe of the payload response is also visible in the UAS spectrum. Figure 8(d) shows the micro-Doppler spectrum of the payload. The spinning of the payload can be observed before it was dropped. This demonstrates the potential of using micro-Doppler analysis to detect UAS carrying a payload and identify if / when, and approximately where the payload has been dropped.

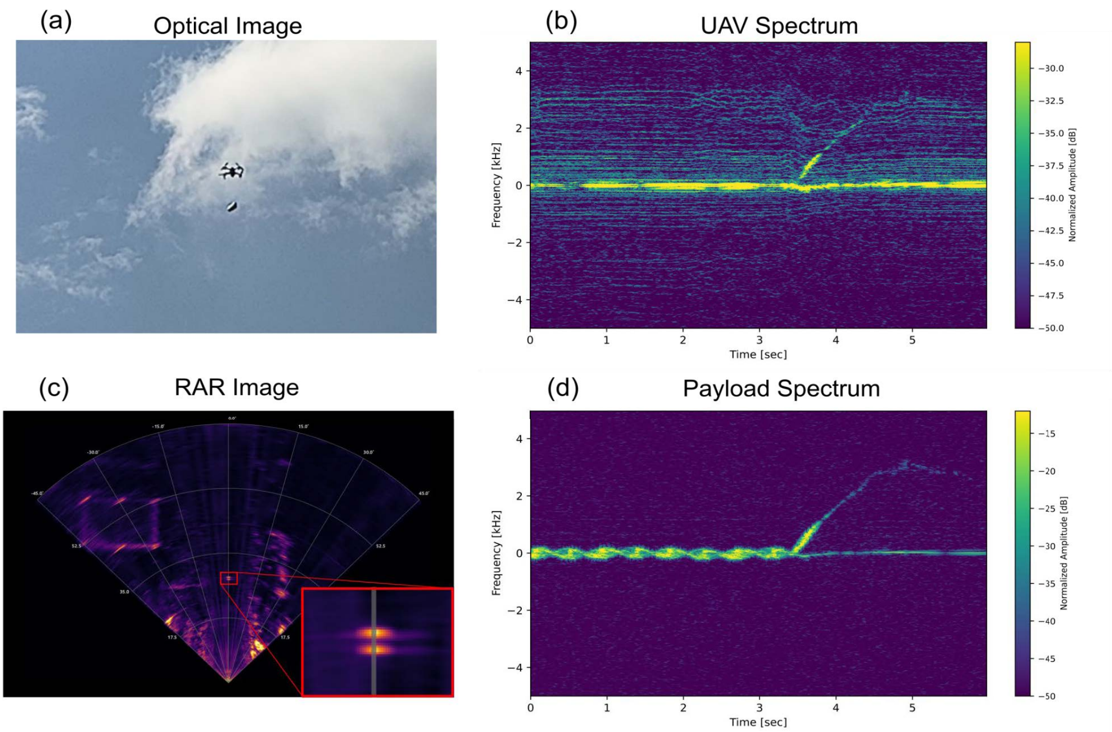

Figure 8: Micro-Doppler analysis of the UAS dropping a payload at 50 m range. (a) Optical image of the UAS (DJI Mavic 2 Pro) with suspended payload. (b) Micro-Doppler spectrogram of the UAS as the payload is dropped. (c) RAR image showing the UAS and the payload. (d) Micro-Doppler spectrogram showing the payload rotating before being dropped. Spectrograms are processed using a STFT window of 51.2 ms.

4.0 CONCLUSIONS

Design of the propellers used to generate lift to fly the majority of the small Unmanned Aerial Systems (UAS) have remained unchanged since their introduction. Recently, new toroidal propellers with reduced acoustic noise that can operate quieter than the traditional propellers were introduced by the Massachusetts Institute of Technology (MIT). This paper compared the micro-Doppler signatures of the novel toroidal propellers against the traditional propellers using a 66 GHz (V-band) portable research radar. It was found that the micro-Doppler spectra of the toroidal propellers were lower in amplitude than the traditional ones, particularly at the Doppler frequencies above 3 kHz. This indicates that in addition to being acoustically quieter, toroidal propellers can be more challenging to detect using micro-Doppler than the traditional propellers. In addition to the propeller comparison, the V-band radar was also used to detect UAS in an outdoor environment. 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. This work has focused on the analysis of UAS micro-Doppler signatures at short range and with high Signal to Noise Ratio (SNR). Further work is required to explore the discriminative ability of micro-Doppler at longer range and with less favorable SNR. Future work also includes processing all the data acquired during the outdoor trials.

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