# Radar signatures of drones equipped with liquid spray payloads


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***Abstract*— The widespread availability of cheap and robust commercial drones has increased the likelihood of these being used for malicious purposes. In some cases they may be equipped with threat payloads. This study reports on the distinctive radar signatures of drones spraying liquid, analogous to a drone delivering chemical weapons, for example. A commercially available crop spraying drone has been used as the basis for liquid droplet radar backscatter modelling and for experimental data acquisition. The spray nozzle droplet parameters were used to model the radar cross section (RCS) and the signal-to-noise ratio (SNR) of the liquid droplets at X-, K- and W-bands, using the Rayleigh approximation. Additionally, experimental data have been obtained simultaneously with 24 GHz and 94 GHz radars. The processed results show that they are in very good agreement with the model. It is clearly demonstrated that at W-band (94 GHz), the liquid spray produces strong micro-Doppler signatures observed from the range-Doppler plots whereas no such detection was possible at K-band (24 GHz). The experimental results validate the hypothesis that millimeter-wave radar offers superior sensitivity than lower frequency bands to reflections from liquid spray droplets of <<0.5 mm size. Hence, a millimeter-wave radar system can potentially be used for classifying a drone with a liquid spray payload.**



***Keywords—Drone, liquid spray, payload, millimeter-wave, FMCW radar***


## I. INTRODUCTION

Recent advancements in the area of commercial drone technology has generated significant security concerns along with the socio-economic benefits. Modification of drones is relatively easy, enabling lots of hobbyists to customize them. Carrying hazardous payloads with drones to disrupt safety is increasingly becoming an important security issue [1]. One of the major potential threats is the dispensing of chemical/biological weapons with drones [2].

Techniques for drone detection using radar have been explored quite extensively in recent years, primarily based on the micro-Doppler signatures imparted by the drone propeller blades [3]–[6]. However, in terms of signatures of drones with payloads, the number of reports is quite scarce. In [7], the difference in the micro-Doppler signatures of drones with and without payload has been reported, which may be used to identify a drone carrying a heavy payload. According to our knowledge, there is no literature available considering the radar signatures of drones delivering liquid spray. The aim of this study is to investigate and report on this topic.

The first section of the paper covers the modelling of scattering from very small liquid particles. We used the manufacturer's specification for a commercially available crop spray drone [8] to obtain the diameter size of the droplets from which we modelled the radar backscatter values. The second section provides a description of the experimental trials. We collected in-flight radar data of the drone spraying water downwards from the attached nozzles. The radar data was simultaneously collected with 24 GHz and 94 GHz radars, for direct comparison. The reason for using high frequency radar systems is because it is anticipated that such small liquid droplets will be quite transparent to lower frequency radar signals, as predicted by the model. Both radars operated coherently in Frequency Modulated Continuous Wave (FMCW) mode yielding range and Doppler information, as our aim was to quantify the return signal strength versus range. The last section depicts the results obtained from the signal processing and provides comparative analysis between the measured data and the theoretical values.

## II. LIQUID SPRAY RADAR BACKSCATTER MODELLING

The crop spray drone procured was a Joyance JT5L-404. The pesticide tank can contain 5 liters of liquid which can be sprayed from the four attached high-pressure nozzles, each located below a propeller, as seen in Fig. 1. According to the specification provided by the manufacturer, the droplet diameter size is 100-200 μm [9]. For modelling, the three frequency ranges we have considered are 10, 24 and 94 GHz. Our main interest lies in the latter two frequencies, as it is well understood that an X-band system will not be able to detect such small liquid drops. Still, due to the abundance of X-band radar clutter measurement data in the literature, the backscatter parameters at this frequency are also calculated for comparison.

Considering the maximum droplet size (200 μm) and assuming spherical shapes, the ratio of the sphere's circumference to the wavelength $2\pi a/\lambda$ ($a$ is the circumference and $\lambda$ is the wavelength) becomes 0.19 at 94 GHz and 0.05 at 24 GHz. In both cases, $2\pi a/\lambda \ll 1$, so the droplet sizes are quite small compared to the wavelengths, which makes the Rayleigh approximation appropriate for the volume reflectivity calculation [10]. At first, the radar reflectivity factor, Z, for an ensemble of particles of diameter

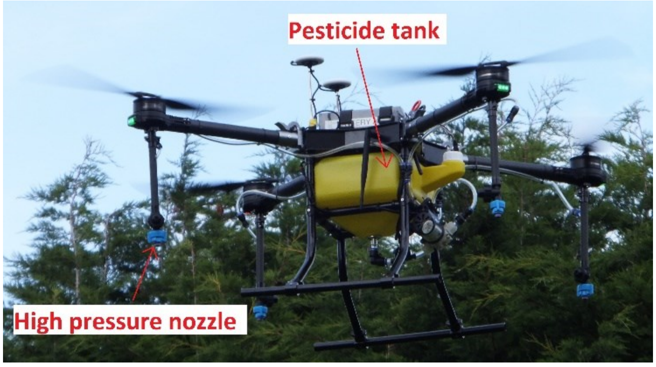


Figure 1: Joyance JT5L-404 crop spray drone.

$D$ can be written as [10],

$$Z = \sum D^6 \, N \, dD \tag{1}$$

where $N$ is the number of particles in the size interval $D$ to $D+dD$. The volume backscatter coefficient, $\eta$, can be calculated as follows [10],

$$\eta = \frac{\pi^5 f^4}{c^4} |K|^2 Z \tag{2}$$

where $f$ and $c$ are the operating frequency and the speed of light respectively, $|K|$ is the refractive index factor equal to $(m^2-1 / m^2+2)$, $m$ being the complex refractive index of the water drops. Here, $m = \sqrt{\varepsilon}$ and $\varepsilon$ is the dielectric constant. This value is calculated for 20°C using the Debye model [11]. Values obtained for $|K|^2$ at 10, 24 and 94 GHz are 0.92, 0.88 and 0.68 respectively.

Here, $Z$ is calculated by summing over different values of D ranging from 100-200 µm with $dD$ being 10 µm. $N$ is obtained from the total volume of atomised liquid divided by the average droplet volume [12]. For our crop spraying drone with a 5 liter tank we define the average droplet diameter to be 150 µm (assuming a uniform distribution) and obtain the following value for radar reflectivity factor (which is independent of frequency): Z = 0.6614 $mm^6/m^3$ and dBZ = 10*log(Z) = -1.8 dBZ. From this the volume backscatter coefficient $\eta$ is calculated to be 1.77e-10 $m^2/m^3$, 7.3e-09 $m^2/m^3$ and 1.3e-06 $m^2/m^3$ at 10, 24 and 94 GHz respectively. This validates the assumption that a 94 GHz radar will be better than lower frequencies for liquid spray backscatter signature detection as the backscatter coefficient is significantly higher at this frequency compared to X-band and K-band.

In meteorological radar one calculates the RCS as the product of the volume backscatter coefficient and the range cell volume. This approach is not appropriate in this case as the liquid spray underneath the drone will have a fairly limited volume and will not necessarily fill the beam at all ranges. Hence, we have calculated the fraction of the range cell occupied by the spray volume as a function range as follows.

The volume of the radar range cell is calculated assuming it has the shape of a frustum (truncated cone) with the volume $V = (\pi/4)\,(R\theta)\,(R\varphi)\,(c/2B)$. Here, θ and φ are the azimuth and elevation one-way 3dB beam widths respectively, R is the range and B is the signal bandwidth. We make the simple assumption that the volume of the spray emanating from the 4 nozzles on the drone forms a vertical cylinder of fixed diameter and height. We assume the horizontal diameter of the spray volume matches that of the spray width which is 1.2 m. We consider that the spray volume is uniform over a vertical height of 5 m, below which the spray has dispersed. This is the recommended operating height when delivering a consistent amount of crop spray. The range bin width is defined to be 25 cm (B = 600 MHz), which relates to the 94 GHz radar parameters from the experimental trial.

For the 94 GHz radar (T-220) used for data collection [13] θ = 0.9° and φ = 3°. An upper limit has been put on the arc length $R\theta$ (1.2 m) while calculating the volume V. In terms of elevation axis, the assumed 5 m vertical extent of the spray volume places an upper limit on how much of the elevation axis is filled as range increases and this has been

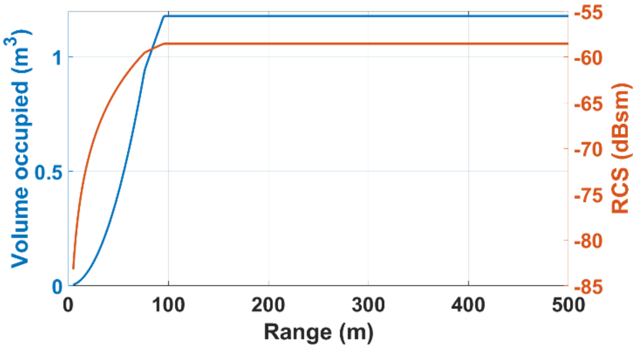


Figure 2: Volume occupied by liquid spray within each range cell and associated RCS at 94 GHz

used during the calculation of $R\varphi$. It should be noted that $\theta$ and $\varphi$ are in radians while calculating the arc lengths. We can thus calculate the volume within the radar beam occupied by spray as a function of range and this is shown in Fig. 2. It can be seen that at short ranges (below ~100 m) the spray fills the radar range cell as the beam size is smaller than the spray extent but at greater ranges the spray volume remains constant and is smaller than the range cell. For a given volume backscatter coefficient, $\eta$, the target radar cross section, $\sigma = \eta V$, is also plotted in Fig. 2. It can be seen that at ranges in excess of ~100 m, the RCS value of the liquid spray is around -58 dBsm. This is expected to be approximately 40 dB lower than the return signal strength from the drone itself [14]. Using the volumetric values, the SNR can be calculated according to the radar parameters. In section IV, the theoretical SNR plots obtained by using the corresponding parameters of the 94 GHz and 24 GHz radars are shown, along with the measured SNR.

## III. Experimental Setup

Data were collected principally using the 94 GHz T-220 radar with the drone either hovering or flying radially whilst spraying water over ranges of 20 to 60 m. Range bins of 25 cm were used. High resolution was selected to observe the signal return in finer details and to ensure that the micro-Doppler return from the liquid spray is well separated from the drone micro-Doppler. The radar antenna is circular polarized (CP) with a gain of 40.5 dBi. The transmit power is


Figure 3: In-flight Joyance JT5L-404 spraying water during experimental trial.

Table 1: FMCW Doppler parameters for liquid spray measurements.

| *Parameter* | *Value* | *Units* |
|---|---|---|
| 94 GHz Doppler parameters | | |
| FMCW Coherent Processing Interval (CPI) | 128 / 10.3 | chirps / ms |
| FMCW Doppler resolution | 97.0 / 0.155 | Hz / $ms^{-1}$ |
| 24 GHz Doppler parameters | | |
| FMCW Coherent Processing Interval (CPI) | 128 / 30.1 | chirps / ms |
| FMCW Doppler resolution | 33.2 / 0.208 | Hz / $ms^{-1}$ |

18 dBm. Data were also collected at 24 GHz with 1 m range bins. The radar used for this frequency [15] cannot operate at such high bandwidth as the T-220, hence the coarser resolution. The radar antenna is linear polarized with a gain of 24.5 dBi, where θ = 11.2° and φ =11.2°. Horizontal-horizontal (HH) polarization setting was used during the experimental trial. The transmit power is 24 dBm. Both the radars were well calibrated to enable absolute RCS measurement.

Acquiring the Doppler signature of the liquid spray was the main goal as it is better for both visual observation and target classification. Table 1 provides the relevant Doppler processing values used for this experimental trial.

## IV. EXPERIMENTAL RESULTS

Example 94 GHz FMCW range-Doppler plots for the liquid spray delivered by the JT5L-404 drone are shown in Fig. 4. The drone was flying at 20-40 m range with an altitude of ~4-6 m (aspect angle ~$12^0$ with respect to the ground). In Fig. 4 (top), the drone was hovering at ~35 m range and no liquid spray was being delivered. The micro-Doppler signature of the propeller blades is clearly visible. In Fig. 4 (middle and bottom), the drone was delivering liquid spray whilst flying very slowly (~1-2 $ms^{-1}$). In Fig. 4 (middle), the antenna was bore sighted at the drone and shows the spray can be difficult to separate from the micro-Doppler of the propellers unless it occupies different range bins. In this example the spray is about 35 dB below the bulk RCS of the drone. In Fig. 4 (bottom), the antenna was bore sighted slightly downwards at the spray to suppress the return from the drone and its propellers. The return from the liquid spray is much more evident and in this example extends over a few metres in range and has velocities up to -8 $ms^{-1}$, likely induced by wind.

A relative comparison of the radar detectability of liquid spray was performed by acquiring data simultaneously with the 94 GHz T-220 radar and the 24 GHz radar as the drone was flown radially away whilst spraying. Range-Doppler profiles were calculated for each coherent processing interval and animated to make range-Doppler movies which clearly show how the radar signals evolve during the flight. One example simultaneous pair of range-Doppler plots of the drone spraying water, captured when the drone was at a range of 32 m and flying at +4 $ms^{-1}$, is shown in Fig. 5 for 94 GHz (top) and 24 GHz (bottom) respectively. It is immediately evident that the liquid spray is clearly detected by the 94 GHz radar (appearing at negative velocities due to being wind-blown) but is below the noise floor of the 24 GHz radar. Note the range resolution of the 24 GHz radar was 1 m.

The crop spraying drone has a tank capacity of 5 liters which allows it to dispense spray continuous for up to 2 minutes during which time the spray is detectable by the 94 GHz radar. As see in Fig. 5 (top) the spray reflects most strongly close to where it is delivered by the spray nozzles on the drone. Once the spraying stops, the cloud of droplets disperses over several seconds depending on the wind.

The evolution of the liquid spray backscatter at 94 GHz as a function of range has been derived from the range-Doppler movie corresponding to Fig. 5 (top) as the drone flew radially from 20 to 50 m. For each range-Doppler frame, the average received signal in each range bin is calculated over the velocity range -0.5 to -5.0 $ms^{-1}$ with contributions from zero-Doppler and the band of propeller micro-Doppler excluded. The resulting set of range profiles shows the average backscatter from the liquid spray as it moves outwards in range. Examples of these range profiles corresponding to the drone positions of 30, 40 and 50 m are shown in Fig. 6 (top) along with a maximum hold curve which shows the envelope of all these range profiles along the complete flight path. There is a clear downward trend in received power as a function of range.

To compare these measured results with theory, the radar model described in section II was used to calculate the SNR as a function of range for the T-220 and 24 GHz radars using radar hardware parameters pertaining to each system. The results are shown in Fig. 6 (top) along with the measured SNR derived from the maximum hold trace in Fig. 6 (bottom),

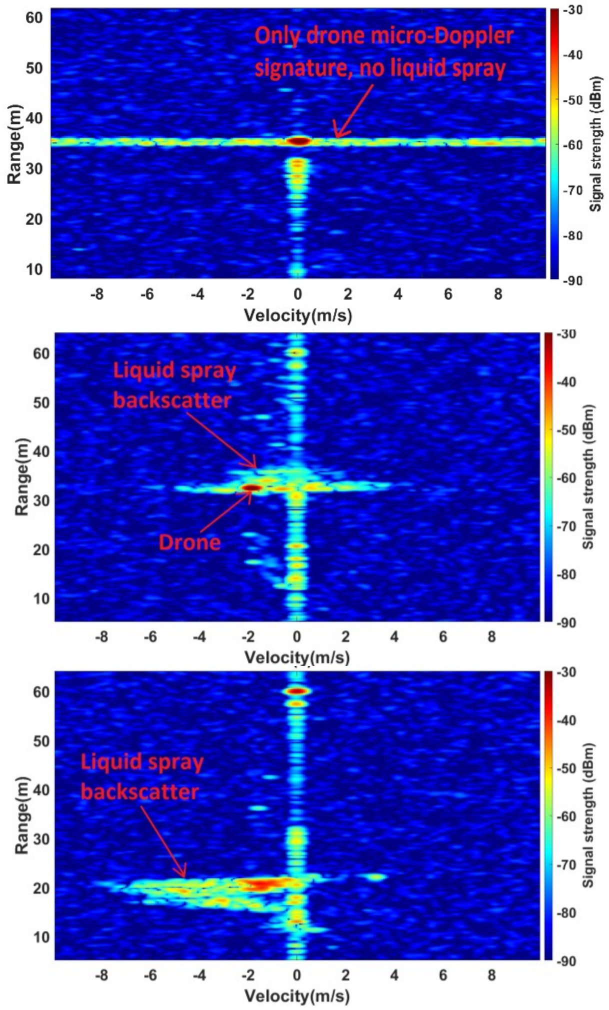


Figure 4: 94 GHz range-Doppler plots of crop spraying drone without liquid spray (top), when bore sighted at the drone (middle) and bore sighted at the spray below the drone (bottom).

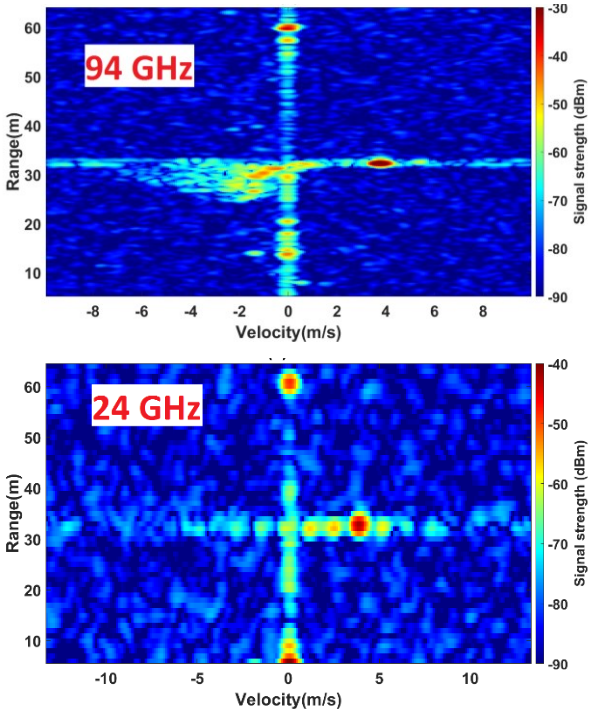


Figure 5: Simultaneous range-Doppler plots of crop spraying drone at 32 m range flying at +4 $ms^{-1}$ measured at 94 GHz (top) and 24 GHz (bottom). The micro-Doppler spread from the propellers is evident in both. The signal from the liquid spray is clearly evident at 94 GHz (at negative velocities) but is below the noise floor at 24 GHz.

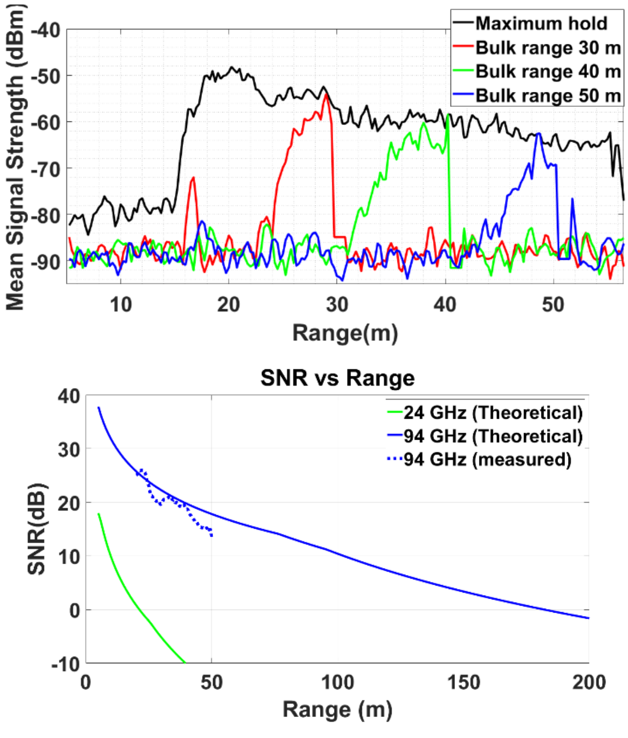


Figure 6: Liquid spray mean signal strength versus range at 94 GHz (top) showing range profiles at 30, 40 and 50 m and the maximum hold envelope for all ranges along the flight path, plus SNR versus range (bottom) showing theoretical curves for the 94 GHz and 24 GHz radars and the measured data at 94 GHz. No spray was measured at 24 GHz.

assuming a noise floor of -80 dBm, which is the average noise floor value from the maximum hold trace. The results in Fig. 6 (top) confirm that (i) liquid spray is undetectable using the 24 GHz radar (SNR < 0 dB) for all but the shortest ranges and (ii) liquid spray is well detected by the 94 GHz T-220 radar with detection possible up to 100 to 150 m with good agreement between experiment and modelling. It is also observed from the theoretical SNR at 94 GHz in Fig. 6 (bottom) that around 100 m range, the $1/R^2$ behaviour typical of beam filling meteorological radar targets changes to the $1/R^4$ behaviour of finite sized targets which are smaller than the range cell (sub-beamwidth).

## V. Conclusion

This work aimed to perform a comprehensive study of the radar signature characteristics of small water droplets sprayed from a drone, mimicking a chemical weapon attack, for example. Considering the current developments in the drone market and the diverse range of applications exploiting drones, the work can be considered quite timely due to the lack of literature available on this threat scenario. The results confirm our hypothesis that the short wavelength of millimetre-wave radar is optimum for detecting liquid spray dispensed from a drone and that a simple Rayleigh scattering model can be used to predict detection as a function of range and radar parameters. The micro-Doppler signature of the liquid spray can be masked by that of the propellers if they occupy the same range bin and depends on the antenna pointing so finer range resolution is advantageous.

The signature from small spherical droplets is expected to be fairly insensitive to polarization whereas the micro-Doppler from drone propellers tends to be greater in HH polarization. A comparison of HH and VV polarizations could enhance the contrast between the drone micro-Doppler and the liquid spray. Once a drone is detected based on its micro-Doppler, the presence of liquid spray can be ascertained by analysis of the surrounding range-Doppler space. If the diffuse signature of the liquid spray is detectable in range-Doppler bins adjacent to the drone then the two can be associated.

This work has confirmed the basic radar signature of liquid spray in a relatively controlled experiment. Applying this information in a wide area surveillance application will be challenging due to the weak signal. Our results predict the spray could be detected to ~150 m with a 94 GHz radar with specifications similar to T-220. Our verification that a simple Mie scattering model is appropriate will allow predictions for radar systems with different specifications. Detecting liquid spray at ~150 m may be relatively short range but the classification range for many drone detection radars is not much greater. Low frequency radars have greater detection and classification ranges but would not be able to detect the very low RCS spray. Whilst we used an existing radar at 94 GHz, which is an established radar band, 77 GHz may be a viable alternative frequency for which low cost chipsets are available. A full system could incorporate a long range, lower frequency search radar with a narrow beam millimeter wave radar for classification and detection of liquid spray.

In the future, the goal would be to use the millimeter wave range-Doppler information to train a classification model for automatic threat detection of liquid spray threat payloads.

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