Field study of a 24 GHz FMCW radar system suitable to detect small-sized RPAS under 5 kg MTOW

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ABSTRACT

This work evaluates a new lightweight frequency modulated continuous wave (FMCW) radar system for airborne environment sensing and detection of small remotely piloted aircraft systems (RPAS) with a maximum take-off weight (MTOW) under 5 kg during a field study. The survey is composed of three different ground- and air-bound outdoor experiments in combination with specific environmental conditions to assess the principle detection eligibility.

NOMENCLATURE

B	Bandwidth [MHz]
R	Range [m]
T	Ramp Time [s]
c_0	Speed of Light [299,792,458 $\frac{m}{s}$]
Δf_1	Frequency Offset [Hz]
ΔR	Range Resolution [m]
Δt_p	Specific Duration [s]
CAN	Controller Area Network
FFT	Fast Fourier Transformation
FluCo	Flight Control Computer
FMCW	Frequency Modulated Continuous Wave
MTOW	Maximum Take-Off Weight
RPAS	Remotely Piloted Aircraft Systems
SPI	Serial Peripheral Interface

1 INTRODUCTION

Self-reliant environmental sensing abilities on-board of unmanned aerial vehicles are of paramount importance to enable autonomous flight missions in unknown surroundings. As these sensing technologies have been miniaturized in combination with a lowered power consumption demand during the last few years, it is now possible to embed a variety of sensors into small RPAS. Today, a lot of the remote sensing techniques are based on electro-optical sensors. This sensor technology has the disadvantage of a high dependency onto weather as well as day and night conditions in combination with a necessary demand of power consuming analysis computer systems [1]. Altogether, this remote sensing technique needs a major amount of payload dimensions and weight in combination with a considerable power consumption, making it unwieldy for small RPAS under 5 kg with typically small fuselage dimensions.

In comparison, radar systems show a higher robustness against weather conditions as well as a higher detection range [2]. This practical study tries to evaluate and quantify the suitability of a low power FMCW miniature radar system with integrated measurement data evaluation to detect other airspace participants over different distances.

2 THE INVESTIGATED RADAR SYSTEM

2.1 Technical data

The 24 GHz radar system built by IMST [3] is a frequency modulated continuous wave radar system with small dimensions (length x width x height: 75 mm x 80 mm x 40 mm). It has a power consumption of 5 W and a weight of 164 g, including environmental shielding. The radar system is composed of three different modules:

- The antenna frontend module with one transmitting antenna and two receiving antennas (Tx2Rx-Design).
- An onboard signal processing unit, capable of slant range and bearing calculation in real-time.
- The hardware interface module with serial peripheral interface (SPI) and controller area network (CAN) bus connection possibilities.

The composition of the system is shown in Figure 1.

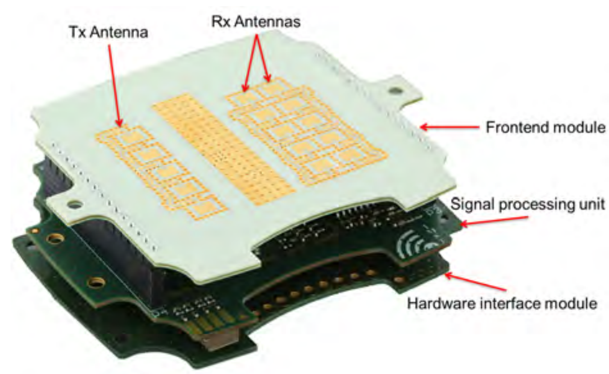

Fig. 1: Sandwich structure of the IMST 24 GHz radar system, own elaboration based on [4].

The radar system can be operated between 22.3 GHz and 24.8 GHz carrier frequency band in fourteen different

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bandwidth steps, ranging from 50 MHz to 2500 MHz. This ensures a minimal interference with the surrounding atmosphere, as the electromagnetic impulses are only slightly damped by the water molecules in the air at this carrier frequency band. The subsequent Figure 2 shows the influence of the earth atmosphere on the IMST 24 GHz radar system, the utilized frequency band is surrounded in red.

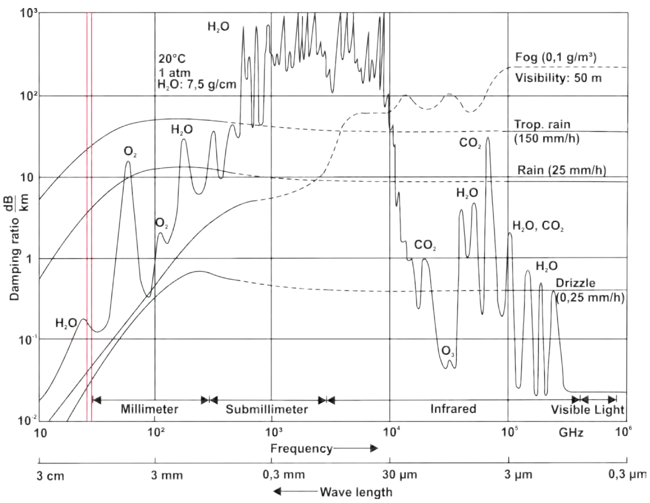

Fig. 2: Damping of electromagnetic waves through atmosphere and rain, own elaboration based on [2].

The maximum detection range in the sky on board of an airborne system is theoretical stated to 250 m, depending on the target dimensions, with a horizontal aperture angle of 70° and vertical aperture angle of 24°, as specified by the manufacturer. The angular resolution amounts to 1° per 5 m.

The radar systems offers four different signal processing modes during the FMCW operation. Depending on the chosen mode, the radar system performs a frequency analysis of the gathered radar data and sends the processed data to a connected host system.

The most suitable signal processing mode for aerial applications is the mode magnitude in combination with object angle. This mode returns to the host system the echo signal level in conjunction with the distance and relative angle of a detected object, transformed in polar coordinates relative to the radar system. An example of an object detected by the magnitude and object angle mode is given in Table 1. Within the

TIC [mm]	Mag1 [dB]	Mag2 [dB]	Mag3 [dB]	Mag4 [dB]	Angle1 [°]	Angle2 [°]
600.5	-8.74	-7.57	-8.71	-7.51	12.11	12.00

Tab. 1: Example of processed radar data.

Table 1, TIC represents a specific distance to the radar system in millimetres. Each antenna has two channels named I and Q, representing the real and imaginary part of each detected signal [2]. The columns Mag1 to Mag4 represent the detected signal strength of those four channels. The columns Angle1 and Angle2 represent the specific angle of the detected object to each antenna.

To determine if an object has been detected, a filter algorithm has to be implemented. At first, the algorithm has to check for coherent angle values. Within the next step, the correspondent I (channel 1 and 3) and Q (channel 2 and 4) couples have to be examined for coherence. The last step verifies, if the found signature has a sufficient signal to noise ratio. If this four boundary conditions are satisfied, it is likely that an object has been successfully detected.

By transforming this polar coordinates to the principal axes of the radar carrying aerial vehicle and further to the local geodetic coordinate system, the exact distance can be calculated.

Although, the measurement field of view is three-dimensional, the data analysis of the radar system has a two-dimensional data output. Every detected target has only values in x and y axis expressed through polar coordinates, but no value given in the z-axis. To achieve a real three dimensional detection, a second radar system has to be installed besides the first radar system in a 90° distortion. Also, both radar data signals have to be merged in order to get a three-dimensional perception of the surrounding environment.

2.2 *Operating principle of a FMCW radar system*

The function principle of the investigated radar system is based on the same uniform function as all other radar systems:

A radar system generates high powered electromagnetic impulses of short duration within a transmitter unit. These impulses are directional emitted by an antenna segment into the surrounding medium. If this impulses encounter an object, they will be reflected into different direction as an echo signal, depending on the grade of electric conductivity of the surface of the encountered object. These reflections are perceived by the antennas of the receiver unit embedded in the radar system. Depending on the intensity, amplitude, phase shift and duration between emitting and reflected signal the radar system is able to calculate the slant range, bearing and dimension of the reflecting object [2].

A frequency modulated continuous wave radar like the IMST 24 GHz radar system emits a consequently modulated electromagnetic impulse by changing its frequency during operation. This modulation types can be linear ramp modulations, frequency shift keying or Doppler. As the radar system will be mainly examined with linear ramp modulation, this modulation type will be described in detail by Figure 3. To facilitate the apprehension of FMCW based target detection, the constellation of emitted and received signal also marks a special case, as the radar system and the detected object move with the same velocity and in the same direction. In case the

detected object moves with a different velocity and direction, the received signal would be shifted in frequency known as Doppler shift [2].
The radar system emits a frequency modulated signal with a specific ramp time T and certain bandwidth B. It also receives an echo signal with an frequency offset Δf_1 after a specific duration Δt_p.

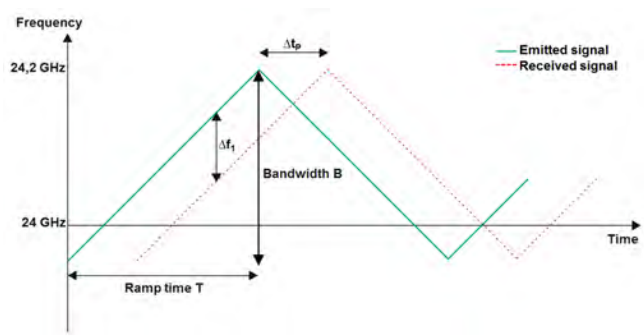

Fig. 3: Linear ramp modulation of a FMCW radar system, own elaboration.

From this signal courses characteristics, the radar system can calculate the slant range R of the detected object with the following three equations based on [2], where c_0 marks the speed of light. The distance calculation between radar and detected target can be formulated as:

$$R = \Delta t_p * \frac{c_0}{2} \tag{1}$$

The variable Δt_p can be expressed with the following equation:

$$\Delta t_p = \Delta f_1 * \frac{T}{B} \tag{2}$$

If Δt_p is substituted through Equation 2, this leads to the characteristic FMCW radar slant range Equation 3:

$$R = \Delta f_1 * \frac{T}{2B} * c_0 \tag{3}$$

The analysis of this equation shows that the variation of the ramp time T and bandwidth B directly inflicts the slant range. A shorter ramp time in combination with a wider range of bandwidth implies a higher frequency difference. This leads to a better detection behaviour and range resolution of the detected objects. The range resolution means hereby the minimum distance between two objects to be detected separately. The range resolution can be calculated through Equation 4, stated in [5]:

$$\Delta R = \frac{c_0}{2B} \tag{4}$$

Both equations emphasize also the main problem of a FMCW radar system, choosing the appropriate slant range in combination with a sufficient range resolution. As the system has physical limitations regarding bandwidth, ramp time and amount of discrete frequency sample points of the frequency offset Δf_1, a sufficient solution for each use case has to be determined by field studies. The possible slant ranges in combination with the equivalent range resolutions per bandwidth step of the FMCW radar system are given in Appendix A.

3 Experimental Setup

3.1 Radar system setup

The radar system is connected through a SPI bus to the flight control computer ”FluCo” which has been developed at the Institute of Flight System Dynamics. The FluCo serves both as flight control computer and logging tool for the radar system sensor data. This combined system is placed on the roof of the mobile mission command centre belonging to the Institute of Flight System Dynamics to reduce ground clutter signals to a minimum. The vehicle is shown in Fig 4.

Fig. 4: The mobile mission command centre.

3.2 RPAS serving as radar targets

Two RPAS, an octocopter and a quadcopter with different dimensions and weight, serve as radar detection targets. Both vehicles are mainly made of carbon fibre as it can be seen in Fig 5. This characteristic ensures the radar detectability, as carbon fibres have a good electric conductivity and will reflect an echo signal on their surface to the radar system [6].

Fig. 5: The utilized octo- and quadcopter radar targets.

The dimensions of the octocopter are 900 mm x 640 mm x 280 mm (length x width x height) with an MTOW of 5 kg. The dimensions of the smaller quadcopter are 400 mm x

400 mm x 120 mm (length x width x height) with an MTOW of 2.3 kg. Both copters have in addition the ability to transfer their current height data directly to the remote control in order to verify the measured radar data.

3.3 Test area

The test area is a model flight airfield located northwest of the city of Aachen between agricultural farm land. Due to this fact, the area itself is not obstructed by buildings which could interfere with the radar measurements. An overview is given in Figure 6. The airfield itself is surrounded in red, it has a length of 150 m and a width of 83 m, as shown in the Figure 6.

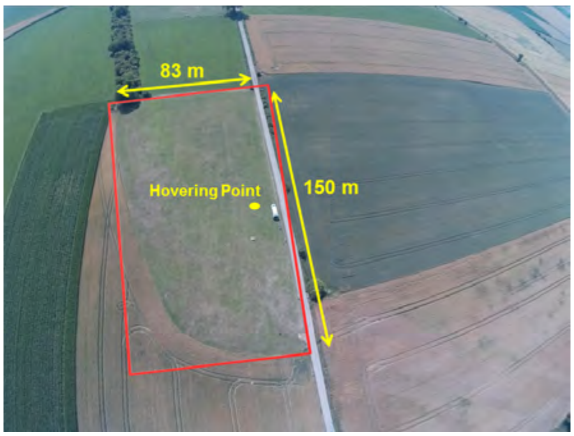

Fig. 6: Aerial view of the model flight airfield Orsbach.

4 Conducted Experiments

This section describes the test area as well as the methodology of the three conducted field tests.

4.1 Range test

This test sequence has the task to evaluate the maximum detection distance of the radar system. For this case, the octocopter radar target will be hovering in different heights above the airfield. The hovering point is shown in Figure 6. The sensor will be placed on the roof of the mobile ground control centre and perform radar measurements in several defined distances to the hovering target. The distances will be adjusted in different intervals, as the mobile mission control centre will be placed in different lateral distances to the hovering points. In addition, the bandwidth of the radar system will be altered in order to ensure range detectability.
The range test showed a good detectability within specific intervals. Primarily, the radar system took a measurement of the test airspace without any hovering RPAS in it. The detection range was set to 250 m with and chosen bandwidth of 250 MHz. The corresponding Fast Fourier Transformation (FFT) data is given in Figure 7:

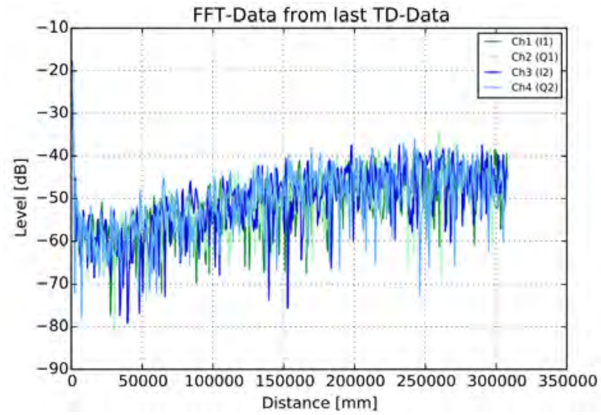

Fig. 7: Background identification of the test airspace with a radar bandwidth of 250 MHz.

Looking at the data, it is noticeable that the received radar signal strength is increasing after 50 m distance to the radar system. This behaviour is explained by a hard- and software integrated distance compensation to detect the same target within a specific distance interval. This exaggerated dual compensation gives further distanced measurement values an increased value, using a quadratic relation between signal and distance. This has no effect on the detection of targets itself, as this compensation handles distance and signal-level independent from each other. This compensation appears in every measurement, independent form the chosen bandwidth and ramp time.
The first measurement, the octocopter serving as a target could be clearly detected in about 41.7 m height above the radar system. The corresponding FFT data is given in Figure 8:

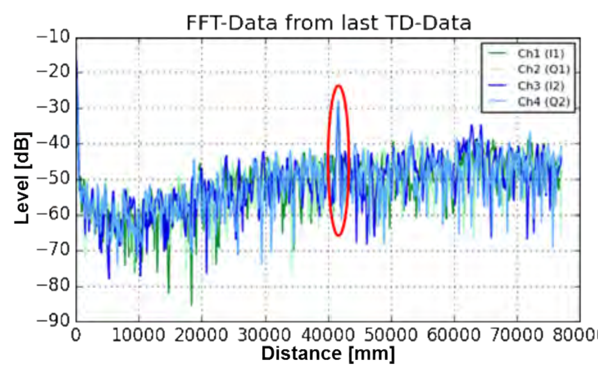

Fig. 8: Detection of the octocopter in 41.7 m vertical distance with a radar bandwidth of 1000 MHz.

The distance interval between 40 m and 50 m shows a strong peak of reflection with a measured signal strength of -28.23 dB around 41.7 m. This signal strength differs about 18 dB to the surrounding noise signals, making it hundred times stronger in signal strength. As the distance between mobile mission command centre and octocopter increases during the range test, the bandwidth of the radar system has to be altered from 1000 MHz to 250 MHz in order to ensure range detectability, as stated before. Figure 9 shows a measurement of the octocopter in a height of 66.8 m above the mobile mission control centre. The analysis of the data shows

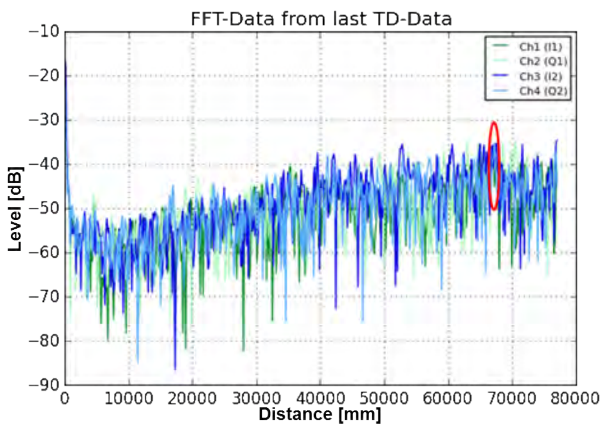

Fig. 9: Detection of the octocopter in 66.8 m height at 1000 MHz.

a strong decreased echo signal strength in comparison to the 41.7 m measurement. The coherent signal path marked in red still shows the actual position of the octocopter relative to the measurement point. The next measurement was performed in a distance of 106.2 m to the radar system. As the bandwidth decreased to 500 MHz, the range resolution increased to 0.31 m per frequency sample point. This implies, that the target octocopter is now represented by one or two frequency sample points. In the shown measurement in Figure 10, it is indeed one frequency sample point, as both antennas detected a singular coherent echo signal.

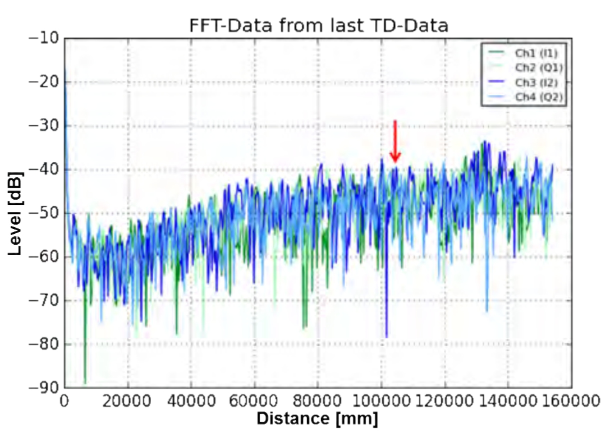

Fig. 10: Detection of the octocopter in 106.2 m distance at 500 MHz.

Above the slant range of 130 m, the detection of the octocopter gets more sensitive. To achieve this enhancement of range, the operator has to choose a bandwidth of 250 MHz for the radar system. Through this, the range resolution is vice versa increased to a value of 0.6 m per sample point. As a result, the octocopter will be only represented by only one frequency sample point. A measurement performed in 237.7 m distance between radar system and octocopter depicts the decreased range resolution in Figure 11.

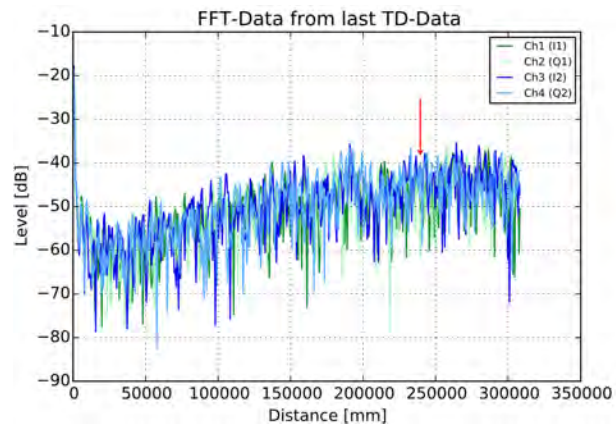

Fig. 11: Detection of the octocopter in 237.7 m distance with a radar bandwidth of 250 MHz.

Summarized, the range test showed a good and distinct radar detection with the greater octcopter radar target over a distance of 237.7 m. The target dimension consideration will show the the feasibility of detecting smaller targets than the octocopter RPAS.

4.2 Target dimension test

Considering the results of the range test investigation executed with the greater octocopter RPAS as a radar target, the maximum detection range of the smaller quadcopter should be shorter, as its dimensions are nearly one-eighth of the size of the octocopter. In order to compare the reflection strength of both radar targets, the quadcopter will be sequential hovering at the same positions as the octocopter. The radar system will perform the same radar measurements as in the range test procedure to obtain the maximum detection distance for the smaller RPAS.

The result of the radar measurement undertaken with 1000 MHz bandwidth is given in Figure 12.

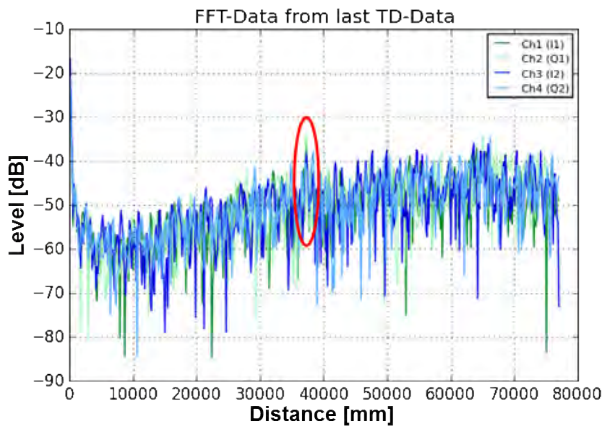

Fig. 12: Detection of the quadcopter in a vertical distance of 38 m with a bandwidth of 1000 MHz.

The Figure shows a clearly detection of the quadcopter in 38 m distance. The reflection level of the quadcopter with -38 dB is considerably weaker then the octocopter reflection level of -28 dB at nearly the same range. As the radar measurement with a bandwidth of 1000 MHz has a range resolution of 0.15 m, three sample points describe the radar reflection of the quadcopter. Considering this range resolution, it is clear that the radar system can only detect the quadcopter with a minimum bandwidth of 500 MHz, as this implies a range resolution of 0.3 m. A 500 MHz measurement has been performed in the Figure 13, where the quadcopter had a distance of 143 m to the radar system.

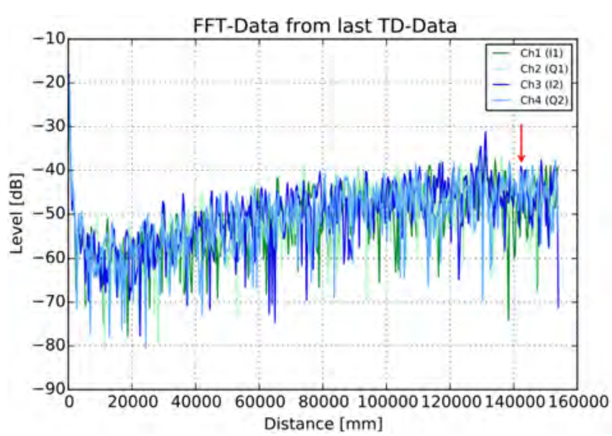

Fig. 13: Detection of the quadcopter in a distance of 143 m with a bandwidth of 500 MHz.

The radar reflection of the copter is only detected within one coherent sample point. This observation gives also a clear statement regarding the maximum detection range. The next possible lower bandwidth step of the radar system to enhance the slant range is 250 MHz, being in line with a range resolution of 0.6 m, making the quadcopter invisible to the system. This limits the maximum detection range of the quadcopter to 150 m with an operational bandwidth of 500 MHz of the radar system.

4.3 Weather dependency test

As stated before in Section 2, the main influence on the radar detection is the concentration of water molecules in the atmosphere. In order to determine the influence of rain and air humidity, the radar system will perform a measurement task under rigid weather conditions with the quadcopter target. The test has been performed on the 4th of August 2015, as the weather was rainy in Orsbach. The amount of rain at this day has been measured to 2.1 mm per hour. At first, a background scanning has been carried out with 250 MHz to determine the damping characteristic of the rain itself on the radar system. The measurement is shown in Figure 14:

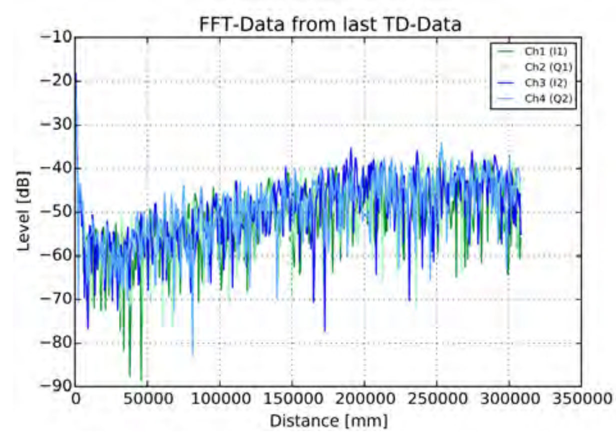

Fig. 14: Background identification of the test airspace under rainy conditions with a bandwidth of 250 MHz.

The background identification showed no noticeable difference in the received signal strength, compared to the measurement under dry conditions. In contrast to the other background measurement performed at a sunny day, a slightly higher noise has been observed during rainy conditions.

In addition to the background scan, a quadcopter measurement has been conducted to compare the received signal strength of the reflected radar signature, see Figure 15.

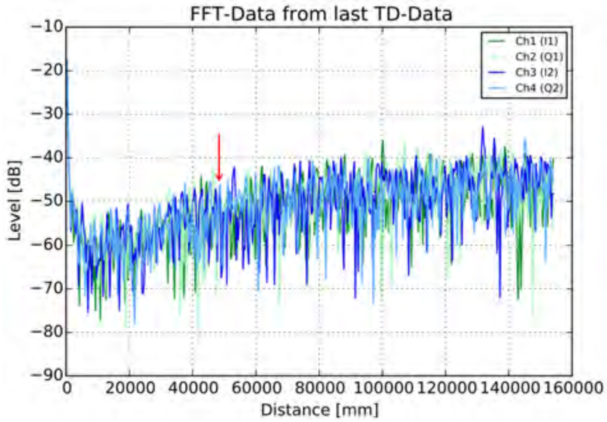

Fig. 15: Detection of the quadcopter under rainy conditions in a vertical distance of 49 m with a bandwidth of 500 MHz.

The detected signal strength had a value of -45 dB. In comparison to the measurement conducted at 40 m under dry conditions, the detected signal had a difference of 3 dB.

5 Conclusion

Different ground- and air-bound experiments have been realized to assess the principle detection eligibility of small RPAS under 5 kg MTOW through an IMST 24 GHz radar system. During this tests, the principle detection ability of different sized RPAS in combination with varying measurement distances has been proven and quantified.

It becomes apparent, that the configuration of the utilized radar system has to be adapted to the dimensions of the RPAS trying to detect. Due to the fact that a FMCW operated radar system has a high dependency between slant range and range resolution, as both characteristics are mainly regulated and limited through the chosen bandwidth in a contrary way, a reasonable trade-off has to be found. A RPAS with greater dimensions can be detected within greater distances, as its dimensions allow a smaller bandwidth coming with a wider detection range. Vice versa, a smaller sized RPAS can be detected with a higher bandwidth in a shorter distance. This has to be accounted for sense and avoid applications, for example by scanning the surrounding environment in different bandwidths during flight to ensure the detection of small RPAS.

Besides that, the further advantages of the system are its peripheral friendly connectivity to host control systems in combination with the on-board evaluation of the radar signals. This characteristics, together with the potential high detection range, acceptable weight and weather independence, make the radar system attractive for outdoor sense and avoid applications on smaller RPAS.

References

[1] Kimon P. Valavanis and George J. Vachtsevanos. *Handbook of Unmanned Aerial Vehicles*. Springer, Dordrecht, 2015.

[2] J. Detlefsen. *Radartechnik - Grundlagen, Bauelemente,Verfahren, Anwendungen*. Springer, Berlin, 1989.

[3] IMST GmbH. *24 GHz FMCW Radar Product Demonstrator, Installation and Short Manual*. IMST GmbH, Kamp-Lintfort, 2015.

[4] T. Klein W. Simon and O. Litschke. Small and light 24 GHz multi-channel radar. In *Antennas and Propagation Society International Symposium*, pages 987–988. IEEE, 2014.

[5] M. Jankiraman. *Design of Multi-Frequency CW Radars*. SciTech Publishing Inc., Raleigh, 2007.

[6] H. Schuermann. *Konstruieren mit Faser-Kunststoff-Verbunden*. Springer, Berlin, 2007.

Appendix A: IMST 24 GHz radar system characteristics

Bandwidth [MHz]	Slant range [m]	Range resolution [m]
2500	30.72	0.06
2200	35.08	0.068
2000	38.6	0.075
1800	42.9	0.083
1500	51.4	0.1
1200	64.3	0.125
1000	78	0.15
800	96	0.1875
500	155	0.3
250	307	0.6
230	333	0.65
125	617.4	1.2
75	1029	2
50	1543	3.01

Tab. 2: Possible bandwidth steps and equivalent slant ranges / range resolutions of the IMST 24 GHz radar system.