W Band High Range Resolution Altimeter Developments in ARRALIS

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ABSTRACT

The range resolution capability of the aircraft altimeter is one of the key parameters during the precise height measurements. During the landing of the rotary-wing aircraft, it is vital to detect the obstacles such as power cables, especially in poor visibility conditions like snow (White-out) and dust clouds (Brown-out) to assist a safe landing.

For lower height measurements, Frequency Modulated Continuous Wave (FMCW) radars are used to achieve a better resolution with the aid of higher bandwidth. However, this comes with two challenges: (1) the design complexity of the Radio Frequency Integrated Circuit (RFIC) (2) the high rate of atmospheric attenuation caused by the gases and aerosols.

Using the frequencies in the neighbourhood of 94 GHz for the transmission significantly reduces the atmospheric attenuation and provides an atmospheric transparency window.

In this paper, the W Band FMCW altimeter radar developed by ARRALIS is described. ARRALIS comes with the solution of both integrated circuits and modules used in a transmitter/receiver chain designed for the W Band. This provides a complete FMCW radar system working in the frequency range of 92-96 GHz with the aid of commercial off the shelf analog to digital converters and Digital Signal Processing (DSP) evaluation boards. Thus, by achieving a 4 GHz bandwidth at the centre of 94 GHz, a theoretical range resolution of 3.75 cm is achieved, which is then degraded by the windowing function factor during converting the signal into the frequency domain. The FMCW radar system uses a triangular waveform by default, which then can be converted to other waveforms as well.

Keywords: FMCW RADAR, W Band, Altimeter, High Range Resolution

1. INTRODUCTION

Radars are being used in various applications including defence, medicine, automotive, etc. for different purposes. Different specifications and requirements of the applications bring the change of three main parameters (frequency, waveform, and power) for each type of radar. The operating frequency of the radars begins from MHz range up to more than 100 GHz. As the frequency increases up to approximately 70 GHz, the atmospheric attenuation increases as well [1]. Also, higher frequencies contribute the path loss more because of lower wavelengths. This brings the requirement of more output power. The previous measurement results show that the atmospheric attenuation starts to decrease above 70 GHz and reaches a minimum between 92-96 GHz[1]. This frequency interval of W Band is regarded as a transparency window and ARRALIS developed an FMCW radar for taking the advantage of low atmospheric loss transmission. Using the whole frequency band provides a high range resolution, which will be given in detail in the following sections. The underlying theoretical principles of the radar, its implementation and measurement results are given as well. The proof-of-concept product has the range measurement capability and works in progress will add some sophisticated features as described later.

2. THEORY AND BACKGROUND

The basic idea behind an FMCW radar is to illuminate the target environment with a frequency-modulated chirp signal and then calculate the frequency shift after receiving the echo signal. Although commonly used chirp signals are in the waveform of a sawtooth or a triangle, depending on the application it may be sinusoidal or any other type of waveform as well.

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When the transmitted signal is reflected from a target, the received signal is now at a different frequency to the transmitted signal due to the time delay between transmit and receive signals. By mixing the received signal with the transmitted signal, a 'beat' frequency signal results which is proportional to the time delay between transmit and receive signals and therefore to the target range.

The FM chirp signal used in the radar has a triangular waveform.

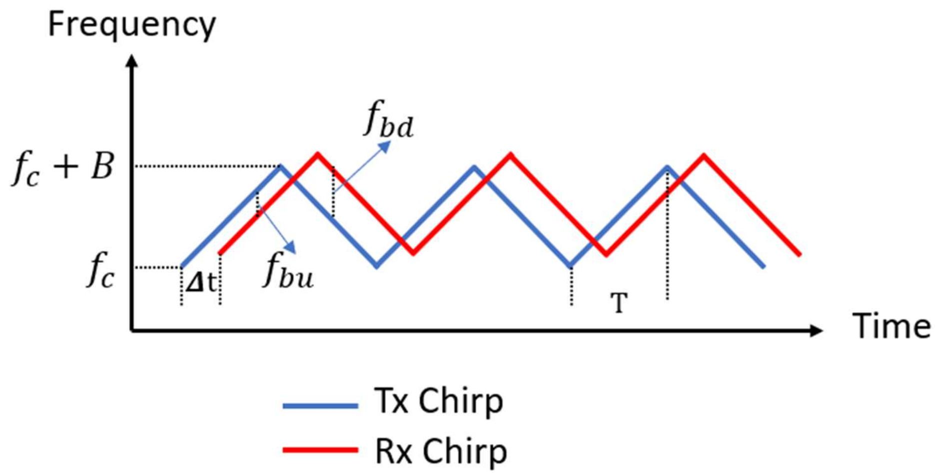


Figure 1. FMCW Triangular Waveform

Figure 1 illustrates the transmitted and received signal of a radar working by a triangular waveform frequency modulated (FM) chirp for a moving target. Here f_c denotes the starting frequency of the chirp, B is the bandwidth, Δt is the delay between the received and transmitted signals, f_{bu} is the beat frequency when the ramp is up and f_{bd} is the beat frequency when the ramp is down. The time delay is calculated by using the formula:

$$\Delta t = \frac{2R}{c} \tag{1}$$

Here, R and c denote the range and the speed of light, respectively. Also, we know that:

$$\frac{\Delta t}{T} = \frac{f_b}{B} \tag{2}$$

where T is the half period of the triangular waveform, f_b, is the beat frequency when the target is stationary. By using the equations (1) and (2), the beat frequency is calculated as:

$$f_b = \frac{2BR}{cT} \tag{3}$$

It is known that the Doppler frequency is

$$f_d = \frac{2Vf_c}{c} \tag{4}$$

where V is the radial velocity of the target. Then f_{bu} can be calculated by subtracting the Doppler frequency shift from the beat frequency when the target is stationary.

$$f_{bu} = f_b - f_d = \frac{2BR}{cT} - \frac{2Vf_c}{c} \tag{5}$$

and f_{bd} can be calculated by adding the Doppler frequency shift to the beat frequency when the target is stationary

$$f_{bd} = f_b + f_d = \frac{2BR}{cT} + \frac{2Vf_c}{c} \tag{6}$$

By using the beat frequencies for up and down ramp in equation (5) and (6), f_b and f_d frequencies can be calculated:

$$f_b = \frac{f_{bd}+f_{bu}}{2} \tag{7}$$

$$f_d = \frac{f_{bd}-f_{bu}}{2} \tag{8}$$

So, by using the equation (3), (4), (7) and (8) the range and the velocity of a moving target can be calculated for a triangular waveform.

Equation (3) gives us the range formula:

$$R = \frac{cTf_b}{2B} \tag{9}$$

By using equation (3), the frequency resolution can be given as:

$$\Delta f_b = \frac{2B}{cT}\Delta R \tag{10}$$

The frequency resolution is also equal to:

$$\Delta f_b = \frac{1}{T} \tag{11}$$

where 1/T is the frequency resolution of a Fast Fourier Transform (FFT) signal and T is the observation period, and here the sweep time for the up ramp. By equating the equation (10) and equation (11), the range resolution can be simplified as:

$$\Delta R = \frac{c}{2B} \tag{12}$$

Thus, we have obtained all equations to calculate the range, range resolution and velocity of a moving target.

Equation (12) shows that the range resolution can be improved by increasing the sweep bandwidth. The radar has 4 GHz bandwidth from 92GHz to 96GHz, thereby giving excellent target range resolution due to the wide operating bandwidth available at this frequency. The theoretical target range resolution with 4 GHz operating bandwidth is equal to 3.75 cm according to equation (12).

After applying Hamming windowing at the DSP section, range resolution increases to:

3.75 cm x 1.81 (factor for Hamming) = 6.79 cm.

3. HARDWARE IMPLEMENTATION

There are two versions of the RADAR; a one-channel version developed for altimeter applications and a three-channel version for 3D scanning imagery. For the altimeter applications, the extracted parameters are the target return strength (an indication of radar cross-section), range and velocity of the target. For the 3D scanning version, the target extracted parameters are the return strength, range, velocity, azimuth angle and elevation angle of the target.

A generic hardware was designed to support both versions. The hardware consists of an antenna/phase comparator network block to drive the FM chirp signal and collect the echo signal, an RF block to generate the chirp signal and extract the baseband beat frequency signal, a DSP block to process the baseband signal and extract the radar parameters.

The RF block diagram of the radar can be seen in Figure 2.

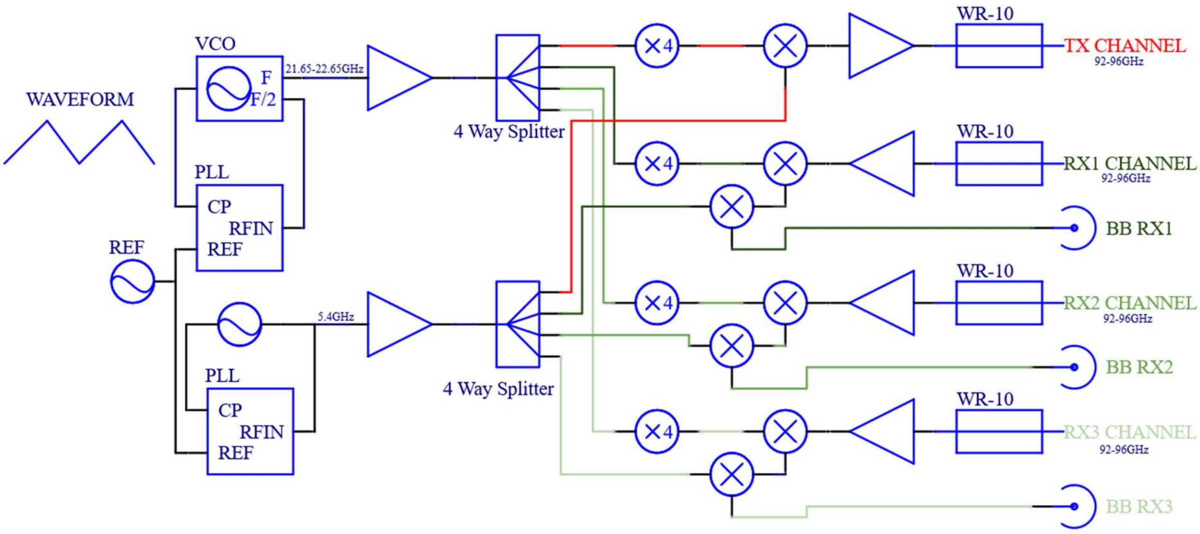


Figure 2. Block Diagram of the RF Section

The core of the RF hardware is an FM waveform generating synthesizer locked to half of the Voltage Controlled Oscillator (VCO) frequency. The waveform for the FM modulation can be either triangular or sawtooth. The number of the cycles applied, and waveform ramp rates are all programmable hence this brings us to change the chirp parameters for several types of applications. The 21.65-22.65 GHz locked VCO output is then split into four; one is used for the transmitter (TX) channel and the rest for receiver (RX) channels. The 21.65-22.65 GHz FM signal for TX is then multiplied by four (86.6-90.6 GHz) and drives the Local Oscillator (LO) port of the mixer. The Gallium Arsenide (GaAs) mixers and GaAs Pseudomorphic High-Electron-Mobility-Transistor (pHEMT) amplifiers used in the W Band are developed by ARRALIS. A 5.4 GHz fixed frequency continuous wave signal generated by another synthesizer is applied to the Intermediate Frequency (IF) port of the mixer, thus an FM chirp signal operating from 92-96 GHz drives the TX antenna and illuminates the targets in the environment. The echo signals coming from the targets to the RX antennas are converted to the IF signals by the same 86.6-90.6 GHz chirp signals applied to the LO port of the receiver mixers. After multiplying the IF signals by 5.4 GHz fixed frequency signals, the baseband beat frequencies carrying the range, velocity, and Direction of Arrival (DOA) information of the target are extracted.

The DSP block starts with a three-channel Analog to Digital Converter (ADC) to sample the analog beat frequency signals and converting them into digital domain (Figure 3). Then the channels are down-sampled in the decimation block to reduce the number of the samples hence the sampling frequency. A windowing function is applied to the received signal, because the frequency spectrum of a truncated sine wave output by a FMCW radar for a single target has the characteristic ‘sin x/x’ shape predicted by Fourier theory. The range side lobes in this case are only 13.3 dB lower than the main lobe, which is not satisfactory as it can result in the occlusion of small nearby targets as well as introducing clutter from the adjacent lobes into the main lobe. To counter these undesirable effects, a window function is applied to the sampled IF signal prior to FFT frequency estimation. For most FMCW applications, the Hamming window is used as it provides a good balance between sidelobe levels (-42.2 dB), beam width (1.32 bins), and loss in Signal to Noise Ratio (SNR) compared to a matched filter (1.34 dB)[2]. Then the time-domain digital signals are converted to the frequency domain signals by FFT. A squelch function is added for a user set threshold and Constant False Alarm Rate (CFAR) algorithm is used to eliminate the background noises and detect the peaks. After that, the range and velocity information of the target is extracted for the altimeter configuration and additionally azimuth and elevation DOAs for the 3D scanning configuration. All DSP functions are implemented in a Field Programmable Gate Array (FPGA) evaluation board and data acquisition is done through the USB port on the device.

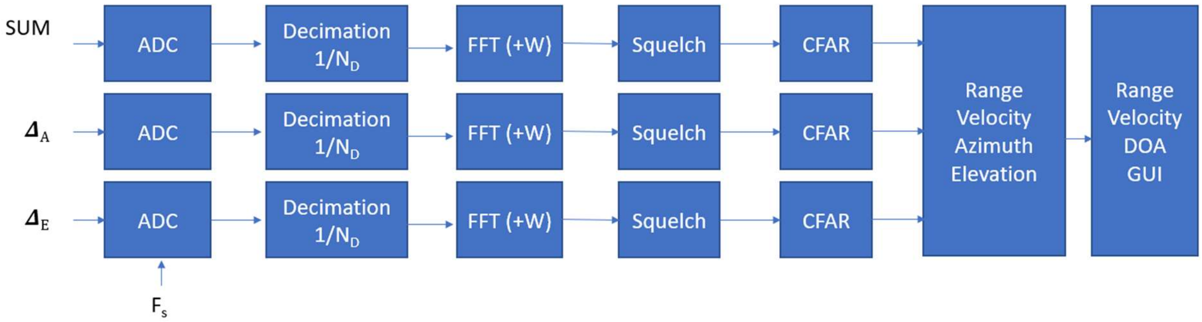


Figure 3. Block Diagram and Data Flow of the DSP Blocks

In altimeter configuration, only the first receiving channel (SUM) is used. The 3D scanning configuration uses all three channels.

As can be seen in Figure 4, in the altimeter configuration of the hardware, the TX and one of the RX channels are used.

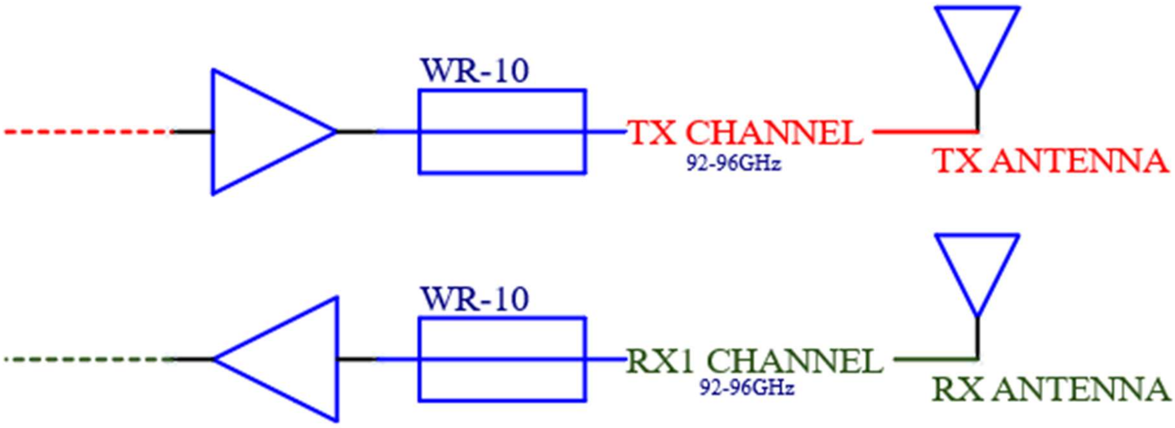


Figure 4. Altimeter Configuration

Standard gain horns antennas are used to transmit and receive the signals. The types of interfaces to the antennas are WR-10 waveguides with UG-387/U type flanges.

Figure 5 shows the 3D Scanning mode antenna/phase comparator network.

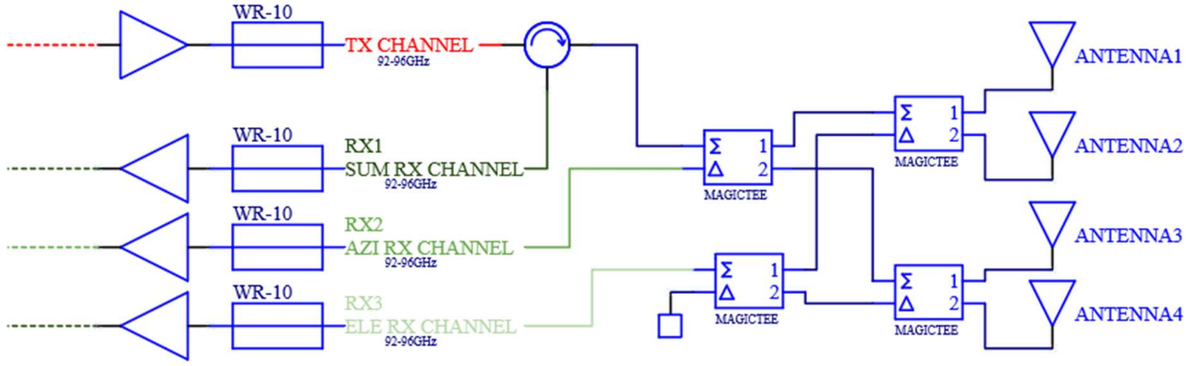


Figure 5. 3D Scanning Mode Configuration

The network uses four horn antennas and four magic tees to obtain the azimuth and elevation phase differences based on the amplitude comparison monopulse method. The WR-10 waveguides are used for interconnections, unused ports are terminated, and multiple isolators/circulators are used for proper isolation of the transmitter and the receiver.

The designed equipment can be shown in Figure 6. It is a prototype for the altimeter configuration, consuming 19 Watts of power. The 3D configuration and the velocity measurement algorithm has not been implemented yet. The output power of the transmitter is 15dBm.

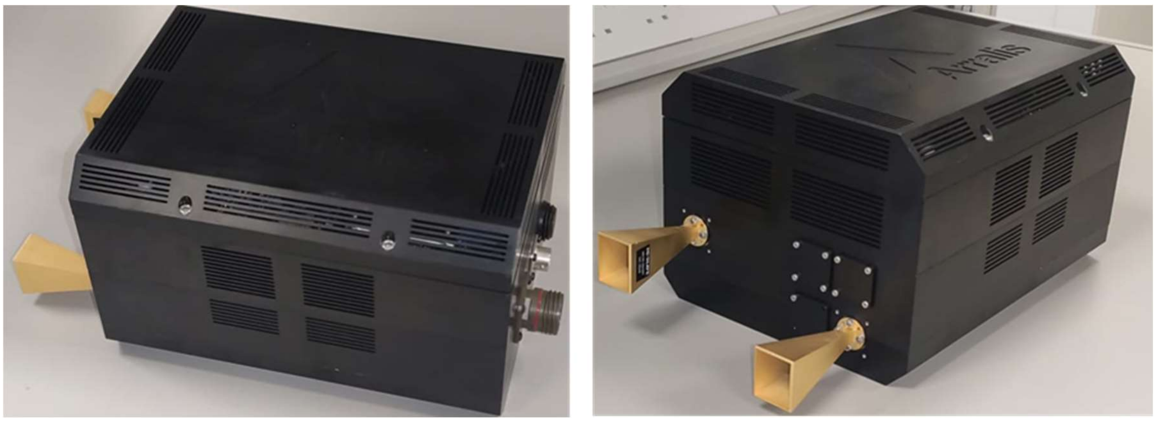


Figure 6. ARRALIS W-FMCW-9296 RADAR

4. TEST AND MEASUREMENT

Several tests were performed to measure the performance of the W Band RADAR (altimeter configuration). The waveform applied was a triangular signal with 4GHz/1 millisecond up and down ramp rates.

To determine the minimum range capability of the radar a 400 mm X 400 mm X 1 mm mild steel sheet, boxed with cardboard was set as the target. The target was approached to the radar until losing the echo signal below the phase noise of the carrier (Figure 7).

Figure 7. Minimum Range Measurement Setup

As can be seen in Figure 8, the target echo signal was lost for a range close to the transmitter, and the minimum range capability for the prototype was measured as 1.3 meters.

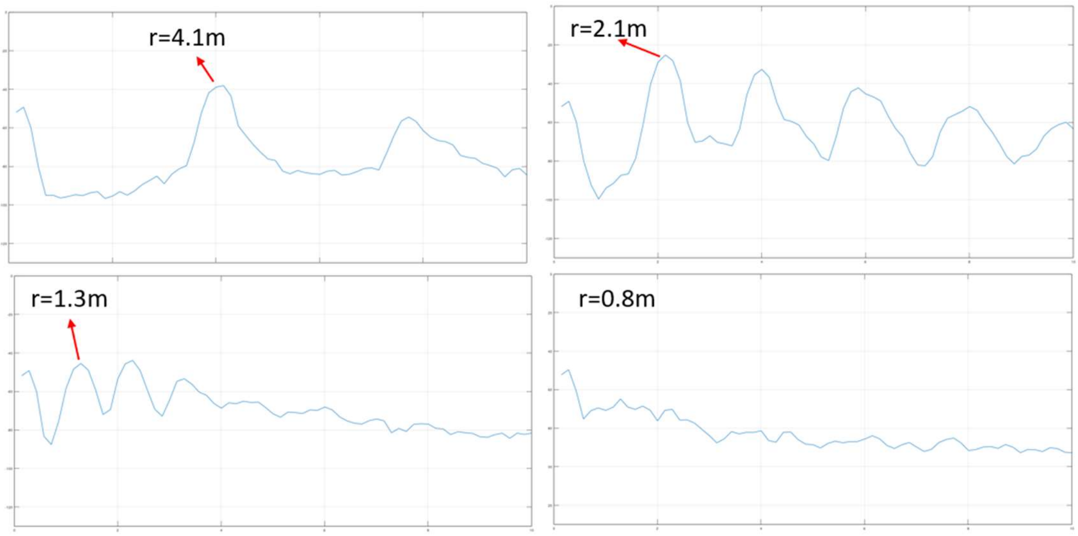


Figure 8. Minimum Range Measurement Spectral Range Plot

To determine the maximum range capability of the radar a human body at a 103-meter distance was set as the target. This was the maximum line-of-sight distance we have at the test site.

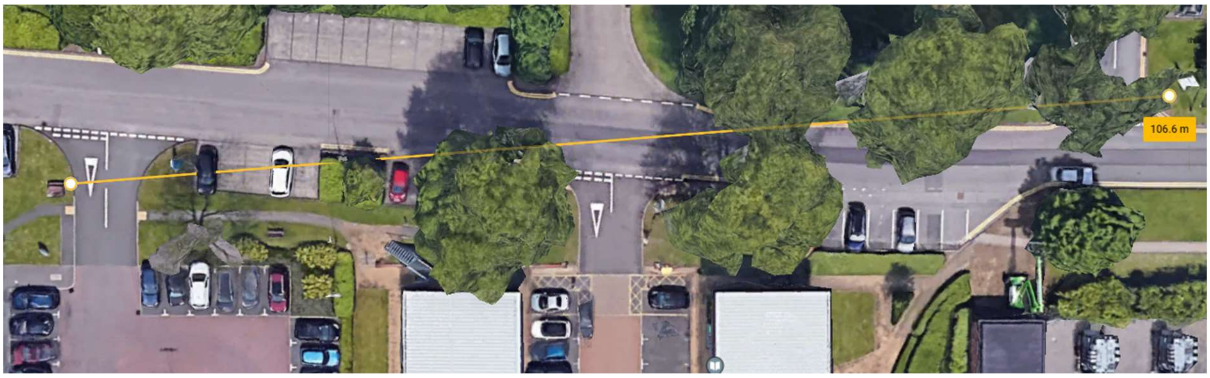


Figure 9. Maximum Range Measurement Test Site (Image from Google Earth)

Figure 9 shows the test side for the maximum range measurements. The point at the left-hand side shows the position of the radar, while the point at the right-hand side shows the position of the target.

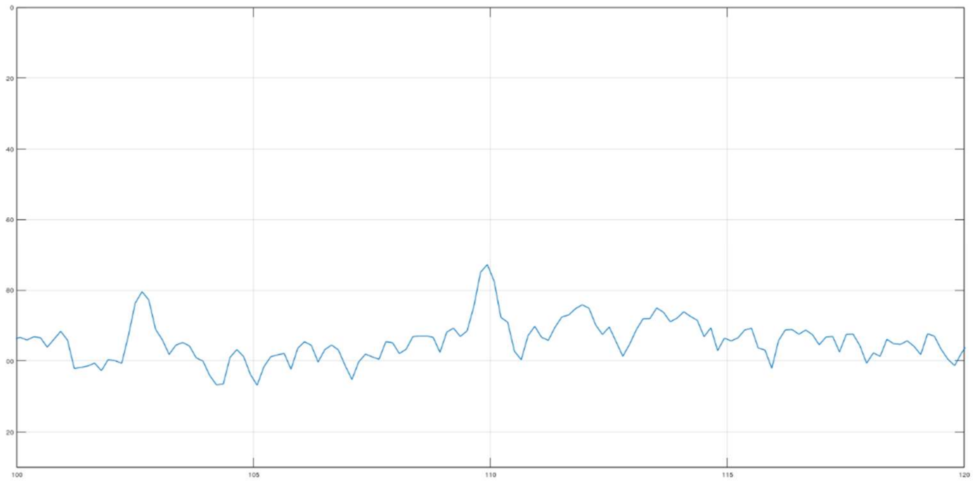


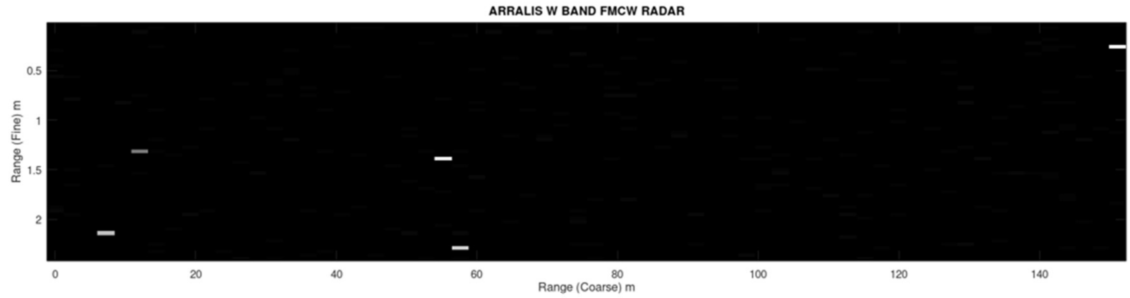
Figure 10. Maximum Range Measurement Spectral Range Plot, Target: Human Body (The left peak)

The maximum amplitude of the return signal was -78dBm (Figure 10) and the SNR is 22 dB. Under the assumption that 10 dB SNR is adequate for observing the target, the maximum range for a human body is calculated as follows:

R_{max} = 103m x 10(22-10)/40 = 205m

Based on the measurement results executed 76-81 GHz[3], The RCS of a human body is thought as approximately -8 dBms.

As can be seen in Figure (11), the range information of the targets is given in a Range Graphical User Interface (GUI) which has the 'coarse range' as x-axis and 'fine range' as y-axis. The 1D range information is provided in two axes instead of one axis because of the substantial number (4192) of the samples which makes the targets invisible on a classical display.



TARGET	RANGE (m)	STRENGTH (dBm)
1	153.2728	-54.4774
2	56.2125	-59.3728
3	57.7115	-64.9661
4	7.495	-69.011
5	13.1163	-84.5935

Figure 11. RADAR Two Axes 1D Range Plot

The radar and the GUI developed were tested for the moving targets (Figure 12) as well.

Figure 12. Two Axes 1D Range Plot for a Moving Target

The movement of the target was easily seen in the Two Axes 1-dimensional range display.

5. CONCLUSION AND WORKS IN PROGRESS

A high-resolution W Band FMCW radar has been developed by ARRALIS. A three-channel millimetre wave to baseband conversion hardware was designed. Here, the integrated circuits used in W Band has been designed by ARRALIS as well. By using a DSP evaluation board, a full chain radar has been implemented. A GUI was implemented to present the range information of the targets in the environment. The implemented hardware was tested under different scenarios and the measurement results were verified by the theoretically expected values.

As stated before, the range measurement capability has been implemented until now. The works for adding new features to the radar are in progress. The output power of the transmitter will be increased to achieve longer ranges. The pulse modulation capability will be added; thus, the device will have modulation in pulse feature to support more areas in the surveillance, security, medical and industrial applications. 3D scanning image feature will be implemented after completing the amplitude comparison monopulse circuitry soon. A gimbal will be added for scanning and increasing the field of the view to ±60° DOA. The proof-of-concept design will be converted to a lightweight, compact, and ruggedized device meeting the MIL-STD-810, MIL-STD-461 and MIL-BUS-1553 standards.

REFERENCES

[1] Sanders-Reed, J. N., "Applications and challenges for MMW and THz sensors", Proceedings Volume 9467, Micro- and Nanotechnology Sensors, Systems, and Applications VII; 94672E (2015)

[2] Brooker, G., [Introduction to Sensors for Ranging and Imaging], IET - Institution of Engineering and Technology, (2009)

[3] Fortuny Guasch, J., Chareau, J. M., "Radar Cross Section Measurements of Pedestrian Dummies and Humans in the 24/77 GHz Frequency Bands", JRC Scientific and Policy Reports, 2013