24GHz FMCW Radar, Basic Theory and Real-World Measurements

Michael Roberts

Slipstream Engineering Design Ltd

mroberts@slipstream-design.co.uk

Abstract –

As millimetrewave radar continues to be used more and more in our everyday lives, this paper reviews the principles behind Frequency Modulated Continuous Wave (FMCW) radar and associated 2D FFT doppler, range and angle processing. We take a look at how virtual antenna are formed by precise physical layout and additional processing. A 24GHz evaluation radar from Analog Devices is used to take measurements of various real-world targets with synchronised images to show the target scene.

1. Introduction

Although by no means a new concept, Frequency Modulated Continuous Wave (or FMCW) radars are becoming increasingly popular in automotive, marine and robotic applications. By employing a continuous wave output, FMCW radars have a number of benefits over the more traditional pulse based radars. Radar sensitivity is based on received energy, which is the product of power and time. Pulsed radars achieve good range resolution by using short pulses and as such, they must employ very high peak power levels in order to maintain an acceptable received energy level. High peak power levels and short pulses lend themselves well to magnetron sources, but with the bulky nature of magnetrons and the rise of solid state, a radar system that operates with lower power and increased illumination time, such as FMCW, is more suited to increased integration.

This paper does not claim to present any new information or novel techniques, rather the aim is to provide explanation of the principles behind a FMCW radar system and also present the results of some practical field trials with a 2 x TX and 4 x RX 24GHz phased array radar.

2. FMCW Basic Operation

At the heart of the FMCW radar is the chirped local oscillator (LO). This LO is frequency modulated or chirped over the described bandwidth. This chirp is sent to the transmit antenna and radiates towards the target. This signal will scatter back from the target and be received at time t later. The received signal is then mixed together (multiplied) with a sample of the local oscillator. Since the received signal is time delayed relative to the local oscillator, at any given point in time, there will be a frequency difference between the transmitted and received chirps because the local oscillator will have progressed in frequency by the time the return signal arrives back at the radar. This frequency difference generates a beat frequency or IF tone in the IF port of the mixer. The value of this frequency is proportional to the time delay to/from the target and hence the distance to the target knowing the speed of light. Figure 1 shows a diagram of the basic FMCW system.

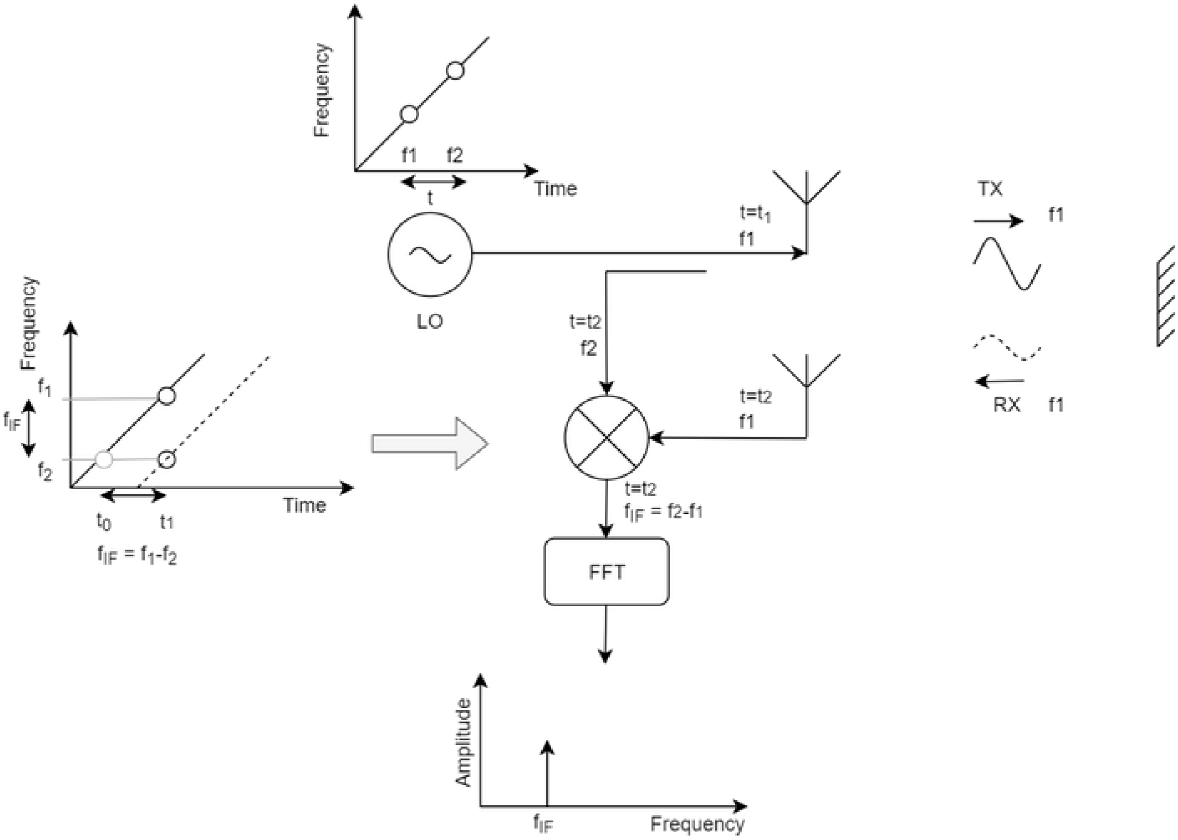


Figure 1: FMCW System Operation

3. FMCW Range

Range is simply defined as:

$$d = ct/2$$

where c = speed of light and t is the time taken for the return signal.

The IF frequency for a given range is a function of the chirp structure as shown in Figure 2, giving:

$$f_{IF} = \frac{2Sd}{c} = \frac{2Bd}{cTc}$$

Where S is the slope of the chirp which is equal to B/T_C where B is the chirp bandwidth and T_C is the chirp duration.

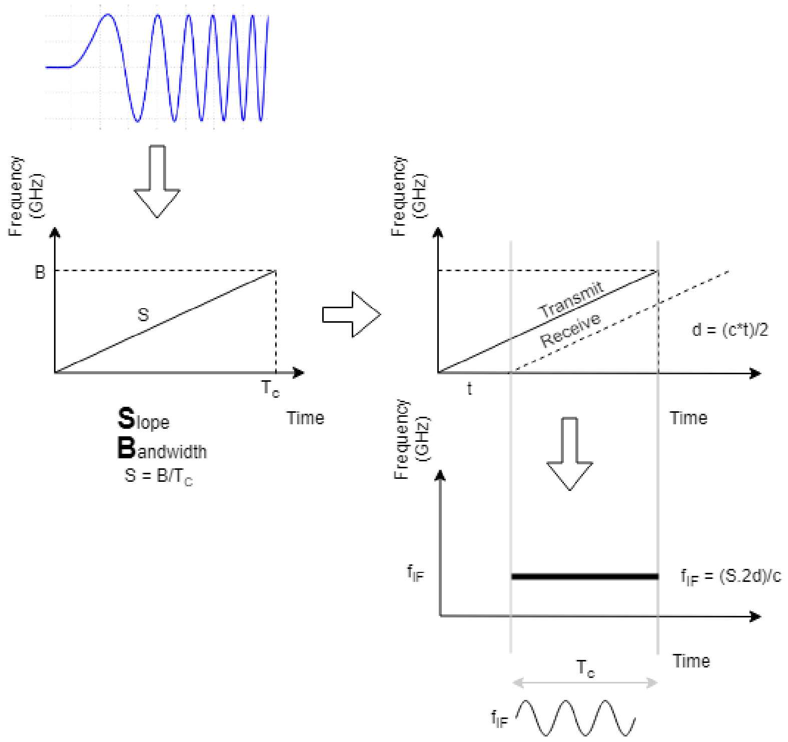


Figure 2: Chirp Structure and Definitions

4. FMCW Range Resolution

Range resolution is the ability for a radar to discern between two closely spaced objects. This can be understood in a pulsed radar by considering the fact that for a finite pulse duration, the returns from two closely spaced objects will overlap in time and it will be impossible to determine that there are two objects present. See Figure 3. It is clear that shortening the pulse duration will improve the ability to resolve two targets and hence improve range resolution.

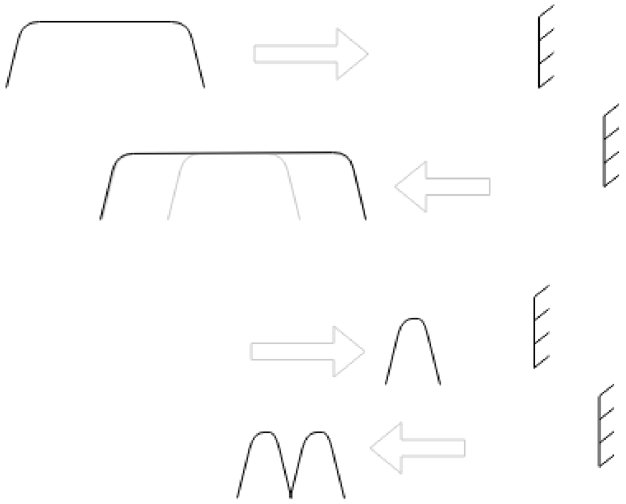
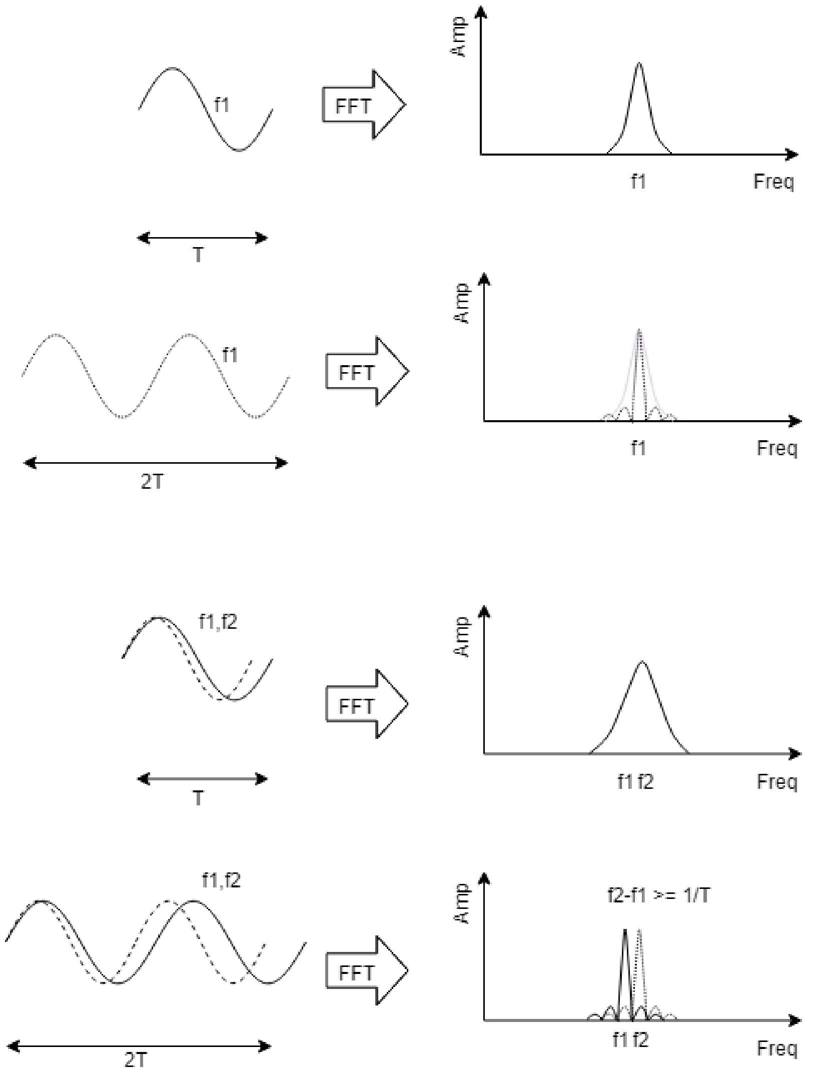


Figure 3: Range resolution explanation in pulsed radar

Since a target is represented as an individual frequency in FMCW, increasing range resolution means increasing resolution in the frequency domain, which means increasing the length of the IF capture in time, see Figure 4.



1) Increasing length of IF sample timeT increases frequency resolution and hence range resolution

2) To discern two frequencies minimum seperation must be greater than 1/T

Figure 4: FMCW Range Resolution

In order to discern two frequencies in the frequency domain it is necessary for the difference in frequency to be greater than 1/T where T is the duration of the time domain capture. For two objects separated by distance Δd, the separation of the two IF tones will be Δf. Since

$$\Delta f = \frac{2S\Delta d}{c} > \frac{1}{Tc}$$

Where T_c is the duration of the chirp and the corresponding IF capture on which the range FFT will be based (see Figure 2). Range resolution can be calculated as follows:

$$Since\ S = \frac{B}{Tc} \quad \rightarrow \quad \frac{2S\Delta d}{c} > \frac{1}{Tc} \quad \rightarrow \quad \frac{2B\Delta d}{cTc} > \frac{1}{Tc} \quad \rightarrow \quad \Delta d > \frac{c}{2B}$$

$$Range\ resolution\ d_{res} = \frac{c}{2B}$$

Range resolution therefore depends only on the bandwidth of the chirp. For a 24GHz radar operating in the ISM band of 24 to 24.25GHz, the range resolution is ~60cm. For a 77GHz radar operating with 1GHz bandwidth, range resolution is ~15cm.

5. FMCW Velocity Determination

Velocity can be extracted using up and down chirps, but the method proposed here is based on FFT methods which allows the simultaneous determination of velocity for multiple targets. The FFT method uses phase detection as the primary means of velocity determination. This method works by monitoring the way the phase changes between multiple chirps. Assuming a single target for simplicity, for each single chirp a single range FFT is produced. This produces a complex number (for each target) which represents the frequency and phase of the IF signal used to generate it. If multiple range FFT's (i.e. multiple chirps) are taken, then it is possible to track the phase and frequency progression of the IF over time. For the radar example shown in Figure 5, the target is moving at 4.3mph (1.9m/s). For successive chirps this relates to a frequency change of only 5Hz which is a long way below the range resolution of the radar.

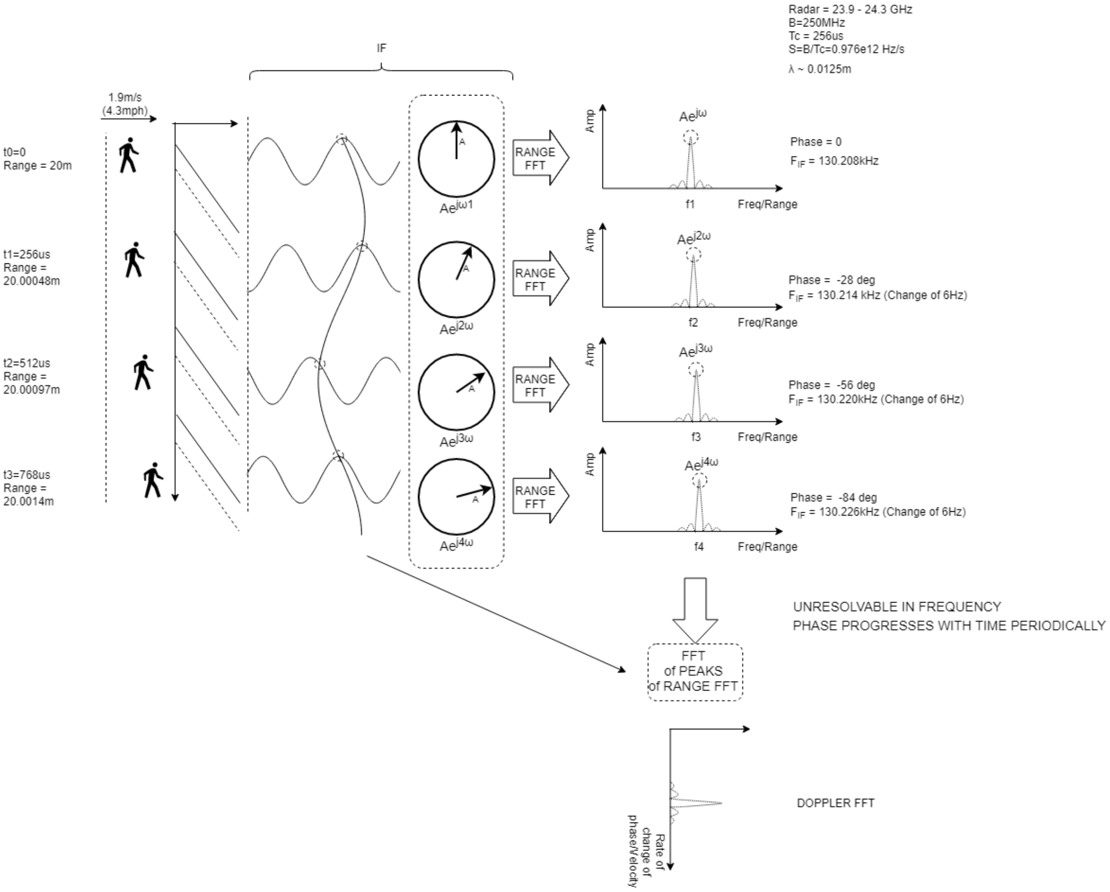


Figure 5: Velocity determination using Doppler FFT

This means it is not possible to discern the velocity of the target by tracking the change in frequency of the IF. However, the change in phase between successive chirps due to the changing position of the person is significant. At this relatively slow speed of 4.3mph speed (and chirp rate of 256us) the phase change is 28 degrees between chirps. For a constant velocity, the phase will increase or decrease by the same amount between chirps and the phase progression will be linear. Since an FFT takes a linear progression in a property and tells us the rate and phase of that property, therefore taking the FFT of the peaks of all the range FFTs in a frame of chirps will yield peaks corresponding to the different phase rates/velocities. This FFT is termed the Doppler FFT. Each peak in the Doppler FFT relates to a particular velocity. A key advantage of such an approach is that it allows simultaneous velocity monitoring of multiple targets, since the Doppler FFT is able to resolve multiple phase rate content that exists in the range FFTs.

There are limitations to the velocity measurement. Notably, if the velocity is too great, then it may generate a phase change between chirps of greater than 180°. For example, a positive phase change of 185° could have been generated by a negative phase change of -175°. This places a limit on the maximum velocity of:

$$v_{max} = \frac{\lambda}{4T_c}$$

where T_C is the chirp time and λ is the wavelength of the radar carrier frequency. For the radar shown in Figure 5, this equates to 12.2m/s or 27.2mph. It is possible to increase maximum observable velocity by reducing the chirp period T_c, since this reduces the time available for a phase change which means a target must travel faster for a given phase change.

In the same way that two frequencies must be separated by > 1/T to resolve in the frequency domain, two phase repetition rates ω_1 and ω_2 must be separated by > 2π/N where N is the number of range FFT results. This leads to a limit on the velocity resolution of:

$$v_{res} = \frac{\lambda}{2T_f}$$

Where T_f ($N.T_c$) is the frame time

6. FMCW Angle Estimation

Angle estimation requires the use of multiple antenna with a known separation. Antennas are normally separated at λ/2 since this gives the maximum unambiguous angle measurement and therefore largest field of view.

For the array arrangement shown in Figure 6, the phase at each antenna progresses in a linear manner due to the physical separation of the antenna. This is because the phase difference between each antenna is related to the angle of arrival of the received signal, with the angle being:

$$\theta = \sin^{-1}\left(\frac{\omega\lambda}{2\pi d}\right)$$

This behaviour is similar to the velocity determination as seen in the previous section. The linear progression of phase across the array means that an FFT of these phases will produce a peak which corresponds to a particular phase repetition interval, which in turn corresponds to a particular direction/angle. The advantage of this approach is that multiple signals from multiple angles can be resolved simultaneously. In a similar fashion to the velocity determination, the longer the sample length, the higher the resolution achieved. In the case of angle estimation, this relates to a larger number of antennae. With the angular resolution given by 2/N for λ/2 spacing between antenna and at 0-degree incidence.

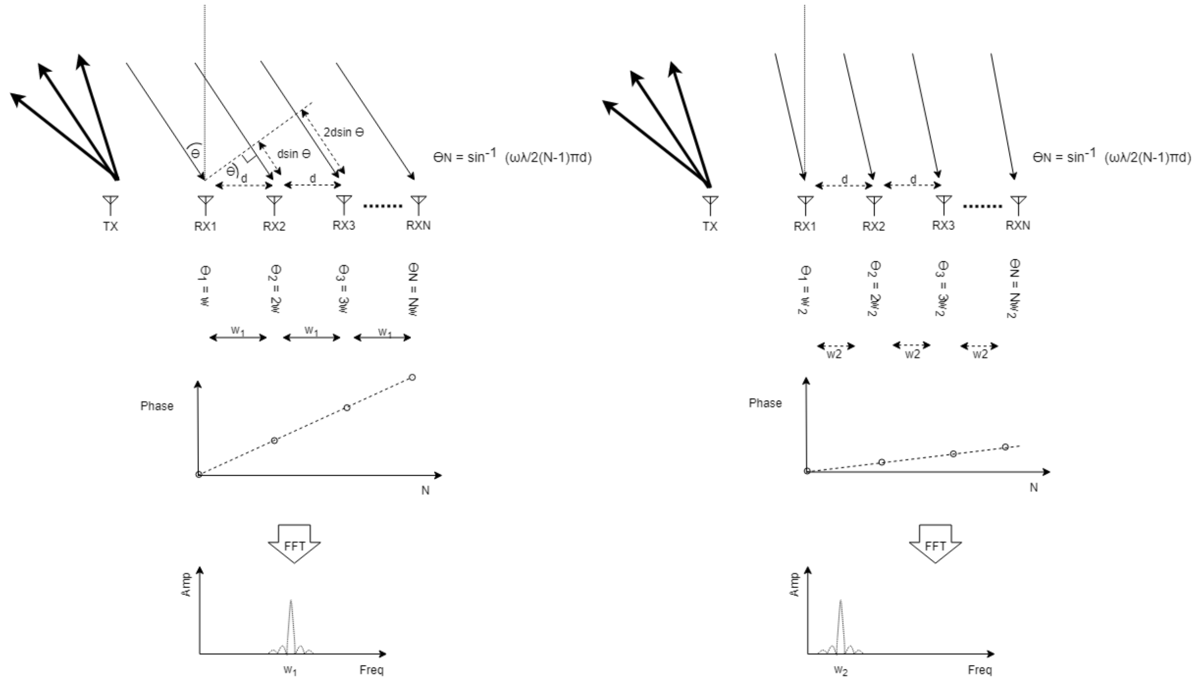


Figure 6: Angle estimation using multiple antenna

7. Virtual Antenna

As shown in the previous section, increasing the number of antenna leads to a direct increase in theoretical angular resolution (2/N). Of course, it is possible to keep adding antenna (see Figure 7), but this requires additional receivers and quickly becomes expensive. An alternative approach is to create a set of virtual antennae by adding an additional transmit antenna which is arranged to have an additional phase shift relative to the first transmit antenna. This is best understood by way of an example, see Figure 7 and Figure 8. In Figure 7, the extension of the phase progression required to increase resolution is achieved by adding more antennae – see dark circles. Relative to antenna RX1, these antennae (RX5,6,7,8) have a phase shift of 4w,5w,6w and 7w because of their physical separation from RX1. The aim of the virtual antenna approach is to match this phase progression up to 7w without adding physical antenna. This is achieved by adding an additional transmit antenna that effectively has a built-in phase shift of 4w relative to the other transmitter i.e. the signal leaving TX1 will effectively already have a 4w phase shift applied relative to TX2. This means that the signal arriving at antenna RX1 (in Figure 8) from TX1 will have a phase shift of 4w.

Likewise, the signal arriving at antenna RX2 from TX1 will have a phase shift of 5w. In this way, a phase progression that is identical to the 8-antenna approach is achieved.

The key to this approach is to be able to identify the antenna from which the received signal originated.

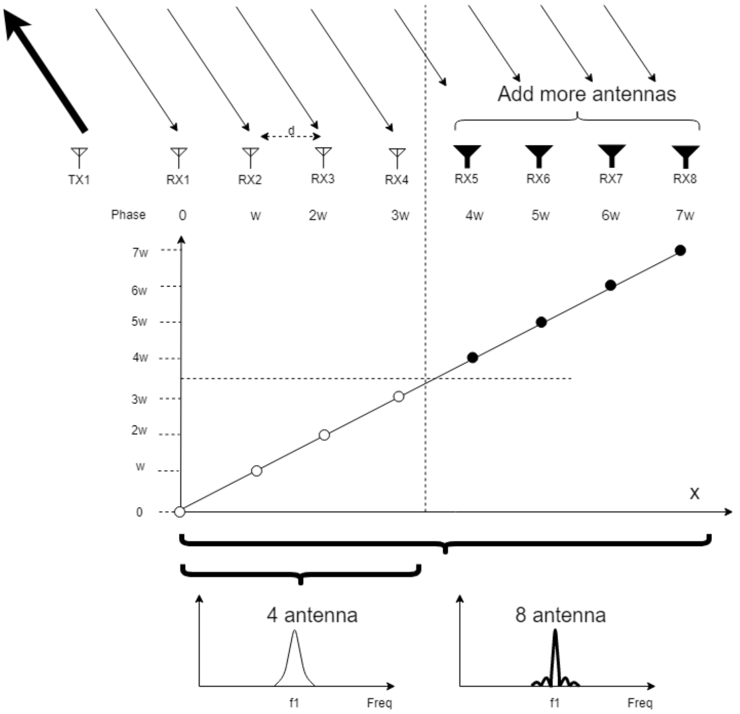


Figure 7: Resolution improvement by adding more antenna

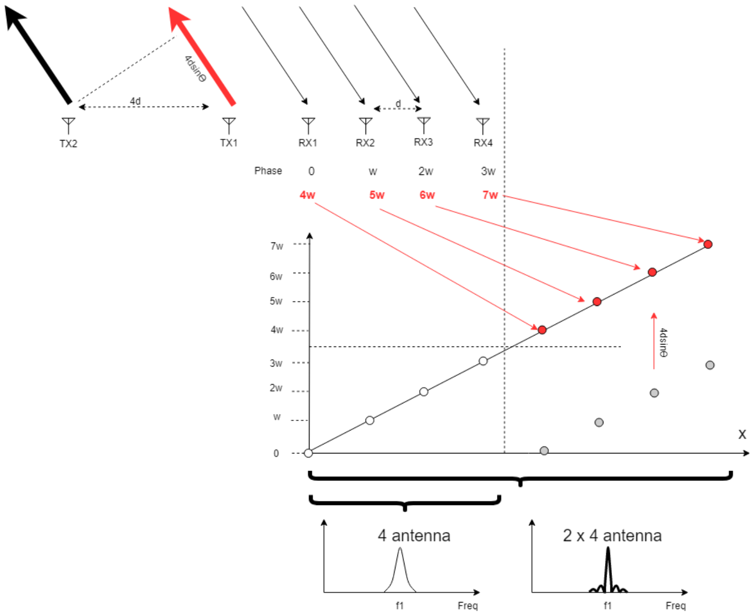


Figure 8: Virtual antenna concept

The simplest way of achieving this is to implement a TDD approach and switch off TX2 whilst TX1 is transmitting and vice versa. This way, all the receive signals associated with TX1 can be placed after those from TX2 in an array prior to applying the angle FFT, thus achieving the same effect as having 8 antennae, but with only 6 antennae. The total number of antennae synthesised is equal to NTx * NRx. Although this example is given for a 1-D array, this approach can also be implemented in 2D, see Fig 14 of [2]. The resolution enhancement for this virtual antenna/MIMO approach for the radar used in this paper can be seen in [3] (Figure 4.18 on page 56)

8. 24GHz Radar Measurements

The radar used to gather real world measurements is the DemoRad evaluation radar from Analog Devices. It uses a two transmit and four receive format with a fixed beam in the azimuth. Note the spacing of the transmit antenna is 4x that of the receive spacing as discussed above.

Figure 9: 24GHz 2 x 4 Radar Used for Measurements with Antenna Labelled

Parameters are shown below in Table 1. The primary way of visualising the output data is using a range Doppler map which displays the output of the velocity FFT (row wise bins) for each range bin (column wise bins) – see Figure 10.

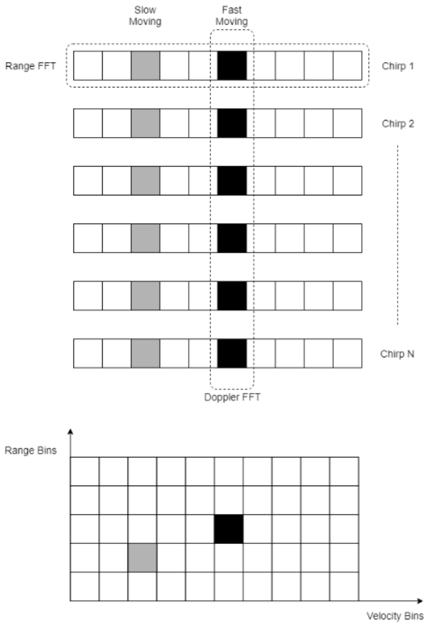
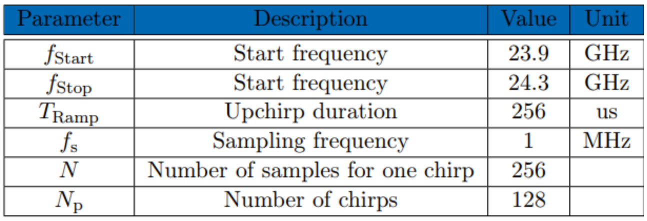


Figure 10: Range Doppler map structure

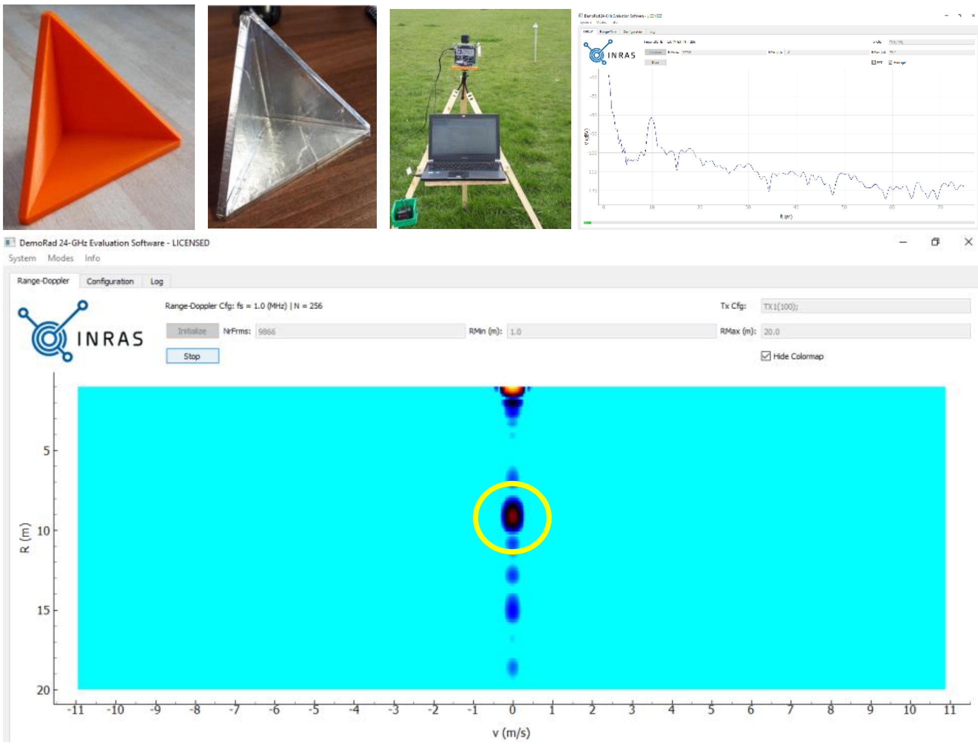


Parameter	Description	Value	Unit
f_{Start}	Start frequency	23.9	GHz
f_{Stop}	Start frequency	24.3	GHz
T_{Ramp}	Upchirp duration	256	us
f_{s}	Sampling frequency	1	MHz
N	Number of samples for one chirp	256	
N_{p}	Number of chirps	128	

Table 1: DemoRad Properties

Static Range Measurement with Corner Reflector

These measurements use a 3D printed corner reflector with a radar cross section area of 1m^2. The corner reflector is mounted on a plastic tube at around 10m range. Measurements are made on a downward sloping field in an attempt to minimise ground reflections. The output of the range Doppler map is shown in Figure 11. Figure 12 shows a person standing approximately 1m behind the corner reflector. These two targets are resolved in range. Since the chirp bandwidth of this radar is 400MHz, the expected range resolution is around 0.375m.



Range-Doppler Cfg: fs = 1.0 (MHz) | N = 256

NrFrms: 9866

RMin (m): 1.0

Tx Cfg: TX1(100);

RMax (m): 20.0

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Figure 11: RCA 1m2 static corner reflector at 10m

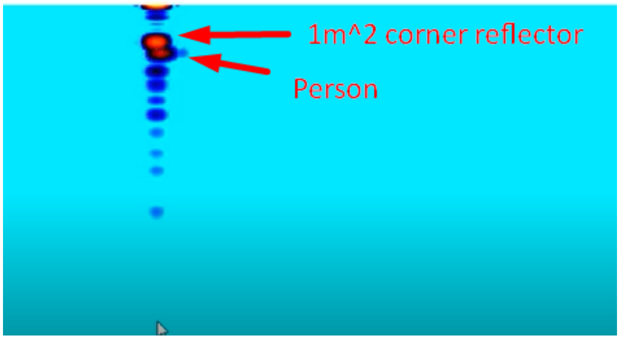
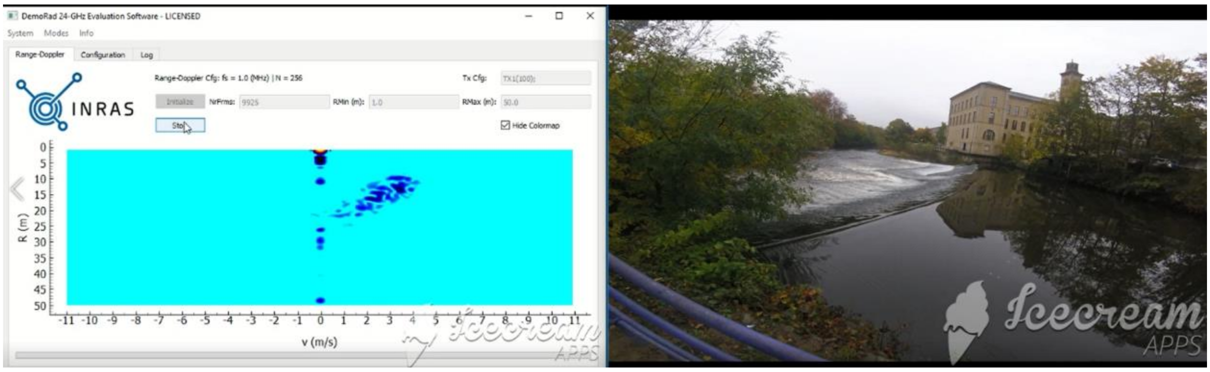


Figure 12: Corner reflector and person stood ~1m behind corner reflector showing range resolution

Range Doppler Measurements

Figure 13 shows a river weir. The constant flow of water creates a constant Doppler trace. The flow of the water can be clearly resolved by the radar. Such an approach has applications for non-contact water flow measurements.


DemoRad 24-GHz Evaluation Software - LICENSED

Range-Doppler Cfg: fs = 1.0 (MHz) | N = 256

Tx Cfg: TX1(100);

NrFrms: 9925

RMin (m): 1.0

RMax (m): 50.0

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Figure 13: Range Doppler measurement of river weir

Figure 14 shows a busy road junction with multiple static and moving targets. The static targets produce the strong vertical returns at v=0. This plot shows the ability for this type of radar to clearly resolve targets that are at similar ranges but with different velocities. The challenge of target tracking can be clearly seen in this image.


Range-Doppler Cfg: fs = 1.0 (MHz) | N = 256

Tx Cfg: TX1(100);

NrFrms: 9244

RMin (m): 1.0

RMax (m): 50.0

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Figure 14: Range Doppler measurement of busy road junction

9. Summary

An overview of the fundamentals of FMCW has been provided with a number of real-world radar examples given.

10. References

[1] Introduction to mmwave Sensing: FMCW Radars – Sandeep Rao, Texas Instruments

[2] The Post-War Development of Fighter Radar in Europe – A British Perspective, J.Roulston 2008

[3] Frequency – Modulated continuous – wave radar in automotive applications, E. Guerrero – Menendez 2018