Simulation the Hybrid Combinations of 24GHz and 77GHz Automotive Radar

Yahya S. H. Khraisat

Electrical and Electronics Department

Al-Huson University College/ Al-Balqa' AppliedUniversity

P.O. Box 50, 21510, Al-Huson, Jordan

E-mail:yahya@huson.edu.jo

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Abstract

In this paper we used MATLAB simulation to simulate the hybrid combinations of short range automotive radar (SRR) operating at frequency 24 GHz and long range automotive radar (LRR) operating at frequency 77 GHz. We obtained the velocity, the range and the time of scanning target. The objective of this work is to get the advantage of both SRR and LRR covering short and long distance with high resolution from 1m to 200m range.

Keywords: Automotive radars, Short range radar, Long range radar and the hybrid combinations

1. Introduction

Radars are already on the market as the active safety system to protect the driver and minimize damage of all road vehicles. The radar sensor systems are one of important elements in automotive technology, because these are virtually unaffected by harsh environmental conditions such as weather and light. Radars are especially effective and presently on the market as the safety systems for high performance automotive applications (Herman Rohling, Marc-Michael, 2001)

In work (Yahya S. H. Khraisat, 2010), we simulated 24GHz Short Range Wide Band Automotive Radar. In this paper we simulated the hybrid combination of both SRR at 24 GHz and LRR at 77GHz by establishing six sensors added to the car according to figures 1 and 2.

2. Overview of FMCW

There may be different forms of the FMCW waveform. The one we consider in this section is linear FM where the fly back portion is also chirped. This waveform is conceptually a normalized linear periodic signal m (t) which is frequency modulated onto a carrier.

Figure 3 depicts the frequency deviation of the waveform under consideration. If $t_{fb} = \tau$ the resulting signal may be called “triangular” FMCW. If the ratio of t_{fb}/τ is small, or zero, the waveform might be called “saw-tooth”. M (t) is frequency modulated onto a carrier such that the maximum excursions about the carrier will be $\pm 0.5B_c$, as shown in figure 4. Thus the FMCW signal’s frequency varies linearly over a range of B_c centered on the carrier, chirping up in frequency in a time of τ, and chirping back down again in a time of t_{fb}. A critical consideration in this analysis is that the signal is constant envelope. Any amplitude weighting would affect the spectrum, and must be considered in a separate analysis.

To facilitate the analysis we break this signal down into the convolution of two waveforms as shown in the figure 5 a and b.

3. Mathematical Model

Using the properties of the Fourier analysis we know that the spectrum can be obtained by multiplying figure 5a and b. Since the spectrum of a series of delta functions in time separated by period T is a series of delta functions in frequency separated by 1/T, the resultant will be the Fourier Transform of Figure 6 as a function of line spectra spaced by $1/(\tau+t_{fb})$.

Fig. 5 consists of a forward and return chirp both spanning the same frequency range, but at different rates (Hz/s). We condense these into one figure where the forward chirp occurs between $-\tau$ and 0, and the return chirp occurs from 0 to t_{fb}.

The following is a general expression of the voltage versus time waveform x (t) for FM modulation, where m (λ) varies between ±1:

$$x(t) = A\cos\left[\omega_o t + \Delta\omega\int_{-\infty}^{t} m(\lambda)d\lambda\right] \tag{1}$$

Performing the integration of (1) for a positive chirp (using figure 6) gives the following:

$$x(t)' = A\cos\left[\omega_o t + \Delta\omega\left(\frac{t^2}{\tau} + t\right)\right] \tag{2}$$

Differentiating the argument of (2) with respect to time shows the instantaneous frequency

$$\omega_i = \omega_o + \Delta\omega\left(\frac{2t}{\tau} + 1\right) \quad \Rightarrow \quad F_i = F_o + \frac{\Delta\omega}{\pi}\left(\frac{t}{\tau} + \frac{1}{2}\right) \tag{3}$$

Applying $-\tau \le t \le 0$ to (3) shows that the frequency varies between $F_o - 0.5\Delta\omega/\pi$ and $F_o + 0.5\Delta\omega/\pi$. Since we want it to vary between $\pm 0.5B_c$, this means that $\Delta\omega = \pi B_c$. The final form for the positive chirp is the following:

$$x(t)_{FMCW+} = A\cos\left[2\pi F_o t + \pi B_c\left(\frac{t^2}{\tau} + t\right)\right] \tag{4}$$

Where $-\tau \le t < 0$

For the negative chirp it is:

$$x(t)_{FMCW-} = A\cos\left[2\pi F_o t + \pi B_c\left(\frac{-t^2}{t_{fb}} + t\right)\right] \tag{5}$$

Where $0 \le t < t_{fb.}$

3.1 Implementing Continuous Phase (CP) FMCW

The FMCW waveform is continuous frequency because of the chirped fly back. The waveform is continuous-phase (CP) across the high frequency chirp transition because of the way the equations are written; but there is not necessarily phase continuity across the lower end. Because it has been suggested that phase discontinuities will broaden the spectrum, this section derives adjustments to FMCW that will force phase continuity across the periodic waveform.

The derivation is straightforward and begins by setting the arguments of (4) and (5) equal to each other.

$$2\pi F_o t_1 + \pi B_c\left(\frac{t_1^{\ 2}}{\tau} + t_1\right) = 2\pi F_o t_2 + \pi B_c\left(\frac{-t_2^{\ 2}}{t_{fb}} + t_2\right) + 2\pi n + \phi \tag{6}$$

The $2\pi n$ term is added because adding any integer multiple of 2π does not change the value of a sine wave. The ϕ term is added for analyzing the non-continuous-phase (NCP) case to ensure that phase differences are the same across different waveform periods.

$$2\pi F_o t_1 - 2\pi F_o t_2 = \pi B_c\left(\frac{-t_2^{\ 2}}{t_{fb}} + t_2\right) - \pi B_c\left(\frac{t_1^{\ 2}}{\tau} + t_1\right) + 2\pi n + \phi \tag{7}$$

$$2\pi F_o\left(t_1-t_2\right)=\pi B_c\left(\frac{-t_2^{\ 2}}{t_{fb}}-\frac{t_1^{\ 2}}{\tau}+t_2-t_1\right)+2\pi n+\phi \tag{8}$$

$$2F_o\left(-\tau-t_{fb}\right)=B_c\left(\frac{-t_{fb}^{\ 2}}{t_{fb}}-\frac{\tau^2}{\tau}+t_{fb}+\tau\right)+2n+\frac{\phi}{\pi} \tag{9}$$

$$F_o\left(\tau+t_{fb}\right)=n-\frac{\phi}{2\pi} \quad\Rightarrow\quad F_o=\frac{n-\phi/2\pi}{\tau+t_{fb}} \quad\Rightarrow\quad \phi=2\pi\left[n-F_o\left(\tau+t_{fb}\right)\right] \tag{10}$$

Last equation shows that CP (corresponding to $\phi = 0$) is achieved simply by ensuring that the product of center frequency and waveform period is an integer. For computer analyses, setting F_o to 0 is the simplest way to achieve CP. For NCP, equation (10) allows one to fix the amount of phase discontinuity so we can compare resulting X dB bandwidths across a number of different waveform periods. This also allows one to research whether bandwidths change depending on the amount of phase discontinuity. One might guess that smaller phase discontinuities would lead to smaller bandwidths.

Figures 7 and 8 show a single period of an FMCW waveform as implemented by (4) and (5), where the center frequency is adjusted according to (10) to achieve NCP and CP, respectively.

3.2 Rectangular FM chirp

It may be helpful to note that the FMCW waveform is the same as a rectangular FM pulse whose duty cycle is set to 100%. Figure 7 shows a rectangular pulse centered at 10 MHz, which chirps up a total of 10 MHz in 1 µsec, and down again in 1 µsec, with a duty cycle of less than 100%. Figure 8 shows how FMCW is formed simply by raising the same signal to a 100% duty cycle. In the frequency domain the continuous function of the Fourier Transform of a single pulse is sampled with frequency elements spaced apart by the PRF, ensuring that one of them coincides with the fundamental frequency. Although the spectrum appearance varies with duty cycle, the envelope of rectangular FM pulse spectrum is independent of duty cycle unless the duty cycle is exactly equal to 100%. This is due to the effect of pulsing on the FM chirp, which convolves the spectrum with that of the pulse shape. This effect abruptly goes away when the signal is no longer pulsed and indicates that the FM pulse bandwidth formulas cannot converge (with increasing duty cycle) to those we choose for FMCW.

4. Simulation

77GHz and 24 GHz radars are already on the market as the active safety system to protect the driver and minimize damage of all road vehicles. The radar sensor systems are one of important elements in automotive technology, because these are virtually unaffected by harsh environmental conditions such as weather and light quality. The 77GHz FMCW radars are especially effective and presently on the market as the safety systems for high performance automotive applications (Herman Rohling, Marc-Michael, 2001), (Yahya S. H. Khraisat, 2010) and (Karl M. Strohm and others, 2005). In FMCW radar, a typical approach to extract range and velocity is to analyze the Fourier spectrum of the received beat signal. The Fourier spectrum is usually determined by digital method using the beat signal sampled by ADC (Analog Digital Converter).

4.1 Assumptions

The range beat frequency rf and Doppler frequency df can be obtained by signal processing, and then the distance and velocity of the target can be estimated. We simulated this algorithm using MATLAB. The detail properties of FMCW radar, such as the transmitted bandwidth, the carrier frequency, the chirp period, the PRI (Pulse Repetition Interval), and the modulation frequency, are shown in Table 1. The sampling frequency of ADC is 2 MHz because the maximum range is 200 m and the maximum beat frequency is 533 kHz.

4.2 Main Results:

In this paper we *used* the following equations to obtain range, Doppler shift, velocity and time of the scanning targets.

$$R=\frac{C\times\tau\times Fr}{2B} \tag{4.1.1}$$

$$v = \frac{C \times fd}{2fc} \tag{4.1.2}$$

$$fs = 2(fd \times Fr) \tag{4.1.3}$$

$$fd = 2 \times \frac{v}{\lambda} \cos\theta \tag{4.1.4}$$

$$\boldsymbol{\lambda} = \frac{c}{f} \tag{4.1.5}$$

Where

R is the range between the target and radar.

C is speed of light which is equal 3×10^8.

τ is chirp period (half of PRI) and it approximate 2 ms.

Fr is the range beat frequency.

v Speed of target.

fd is the Doppler shift.

fc the carrier frequency (24GHz & 77GHz)

λ is wave length.

4.3 Targets Detection

In this part we showed how targets are detected at the two types of radars. The first type is the Short Range Radar (24 GHZ), which can detect targets with range less than 30 meters. Targets at range more than 30m can't be detected by this radar. We need to use the second type; Long Rang Radar (77 GHz) which has range reaches to 200 meters. Targets more than 200 meter can't be detected by both types (SRR & LRR).

Figure 11 shows the GUI (graphical user interface). On this part we will fill the block to operate the results.

- T1 which function is already prepared on Mat Lab, used to generate oscillation frequency. Assumption equal 0.2 s as shown in Figure 12.

Rf 1 is 24 GHz

Rf2 is 77 GHz

- Ranges 1,2 and 3 are ranges of target needed to be detected
- We assumed Range1 less than 30 meters so it can be detected by 24 GHz and can't be detected by 77 GHz. As shown in Figure13 (R = 21 meter)
- Range 2 less than 200 meter so it can be detected by 77 GHz radar, as shown in figure 14.
- Range 3 more than 200 meters so it can't be detected by earthier 24 GHz or 77GHz.
- On Figure 14 we can note that at 21 meter the target detected as line not as peak value of power. This is because of the short range compared with 122, so we used tool on Matlab to zoom this line and show the results on figures 15 and 16.
- Also we will show the relationship between Doppler shift and (θ) depend on the velocity. The maximum velocity of car is 62 m/s, so using equation 4 and depending on the operating frequency (24 GHz or 77GHz).
- Using equation 5 we calculated wavelength (λ) for each frequency:.

For 24 GHz $\lambda = 0.0125m$

and

For 77 GHz $\lambda = 0.00389\ m$

4.4. Determining Range, Operating Frequency, Velocity and Time Scanning

In this part we simulated in Matlab to determine range, operating frequency, velocity of target and time of scanning target. We assumed that received samples are in the range between 15 samples and 534 samples by troubleshooting. Fig19 shows the input and output of this part. Number of samples and Doppler frequency are inputs. These equations are used to obtain the outputs.

$$fs = \frac{Ns}{T} \tag{4.4.1}$$

$$fs = 2(fd = fr) \tag{4.4.2}$$

$$R = \frac{C*T*fr}{2B} \tag{4.4.3}$$

$$v = \frac{C*fd}{2fc} \tag{4.4.4}$$

$$fd = \frac{2v}{\lambda}\cos\theta \tag{4.4.5}$$

Assumptions:

T=0.5 ms

C=3*10^8

B=200*10^6

Doppler frequency is calculated by using maximum velocity of car which is 62 meter per second. Using equation 5, set theta to zero to get the maximum Doppler frequency.

Doppler frequency for 24 GHz is in the range from 3 KHz to 10 KHz and for 77GHz Doppler frequency is in the range from 3 KHz to 31 KHz.

5. Conclusion

This paper proposed method to improve the range and velocity for both short and long range target for the FMCW automotive radar. For the target in the long and close distance, the range is extracted and the peak appears as a number of possible targets.

The second part dealed with the calculations for range and time to detect and retreat the signal. It can be summarized as:

- Enter number of sampling
- Compute range
- Provide the operating frequency using the following function

```
If R < 30
    F_C=24e9;
else if R > 30 && R <200
    F_C=77e9;
else
    F_C=0;
end
```

- Compute the time to detect target and retreat.

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Table 1. FMCW radar Parameters

Item	Nomenclature	Specification
Bandwidth	B	200MHz
Carrier frequency	f_c	76.5GHz
Chirp period	T	0.5ms
PRI	T_m	1ms
Modulation frequency	f_m	1kHz
ADC sampling rate	f_s	2MHz

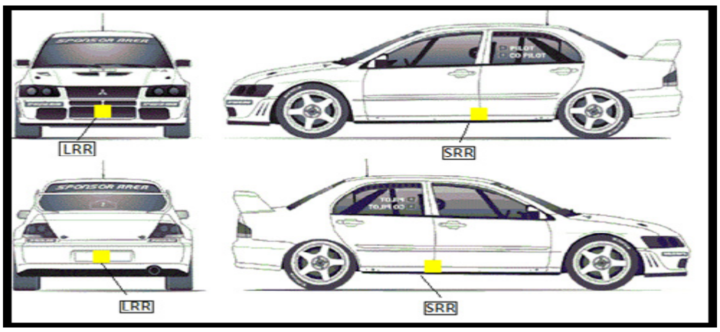

Figure 1. Short range and long range radar's location

Figure 2. Short range and long range radar's location

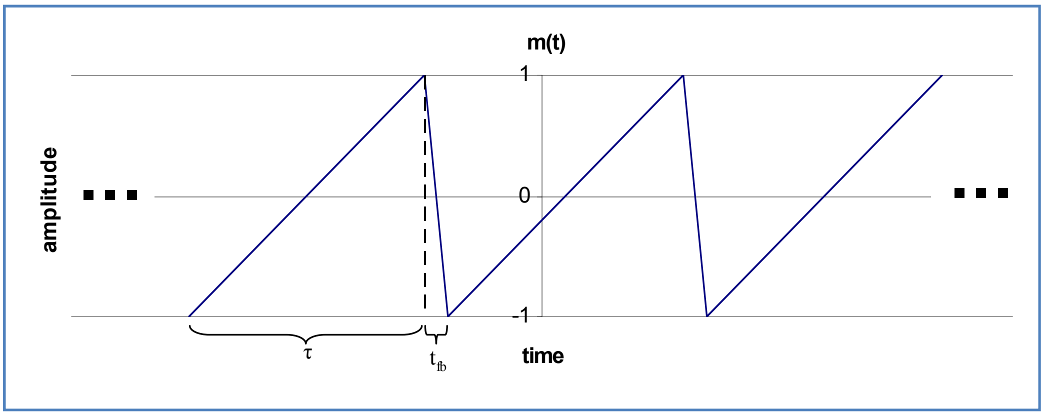

Figure 3. Saw-tooth waveform

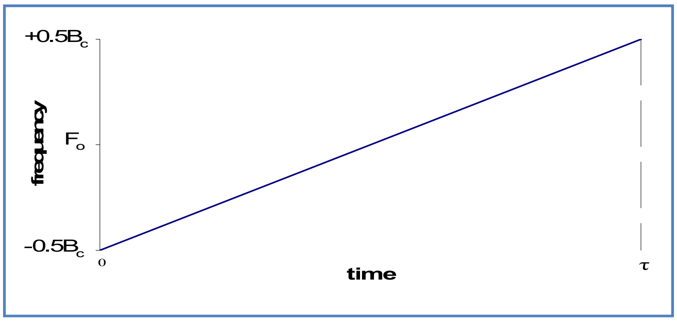

Figure 4. FMCW is a carrier whose frequency varies linearly between $F_o \pm 0.5B_c$ in time τ

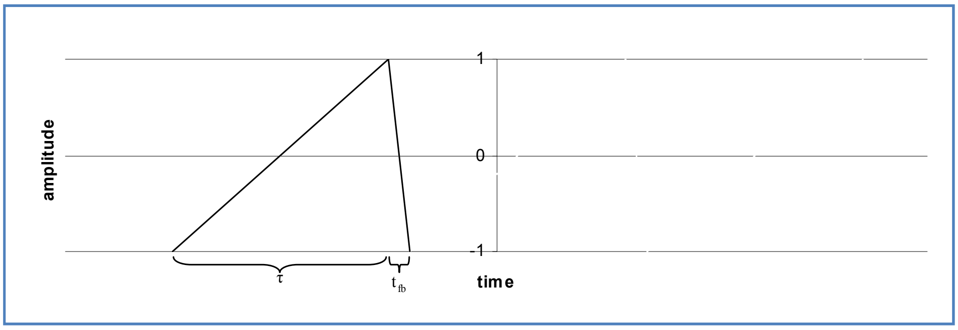

Figure 5. a. forward and return chirp

⊗(Convolved with)

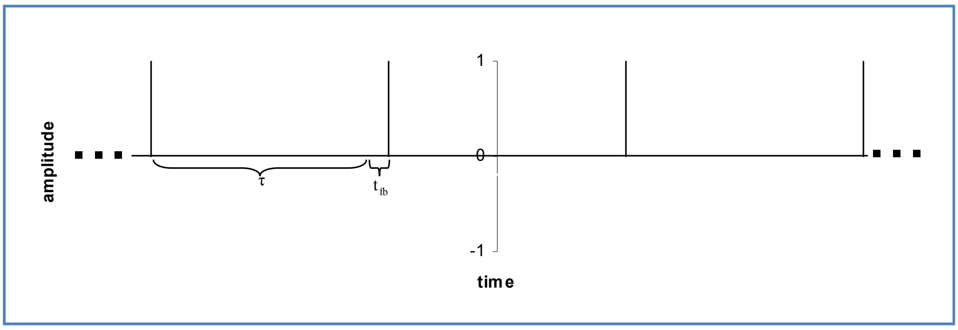

Figure 5. b a sequence of delta functions

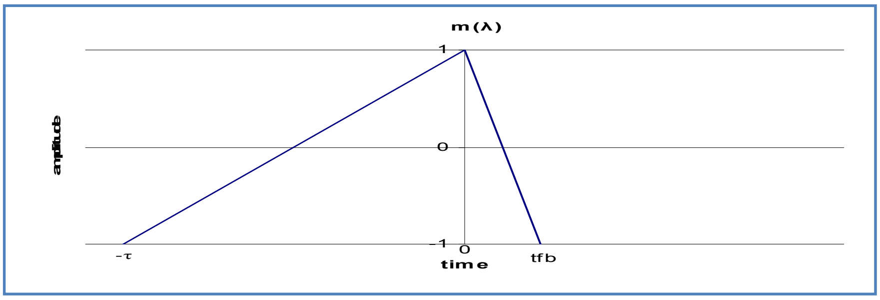

Figure 6. m (λ) truncated to an interval $-\tau \le \lambda \le t_{fb}$

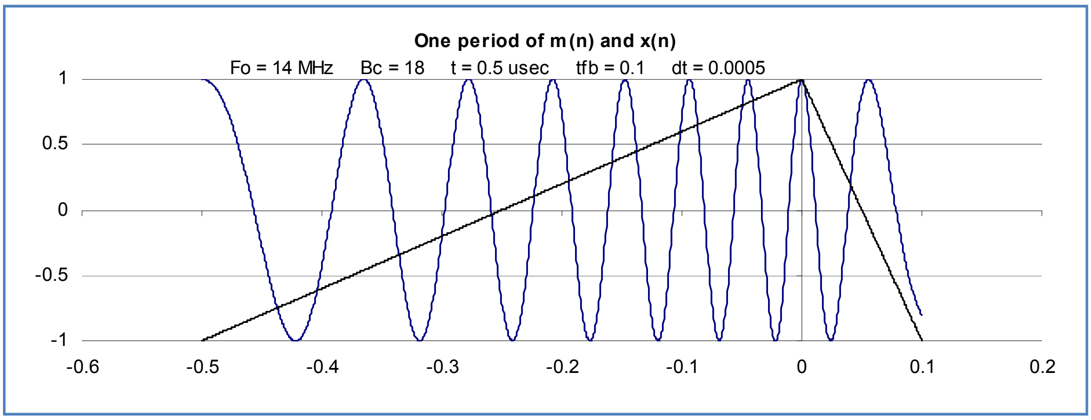

Figure 7. Example of phase discontinuity across periods

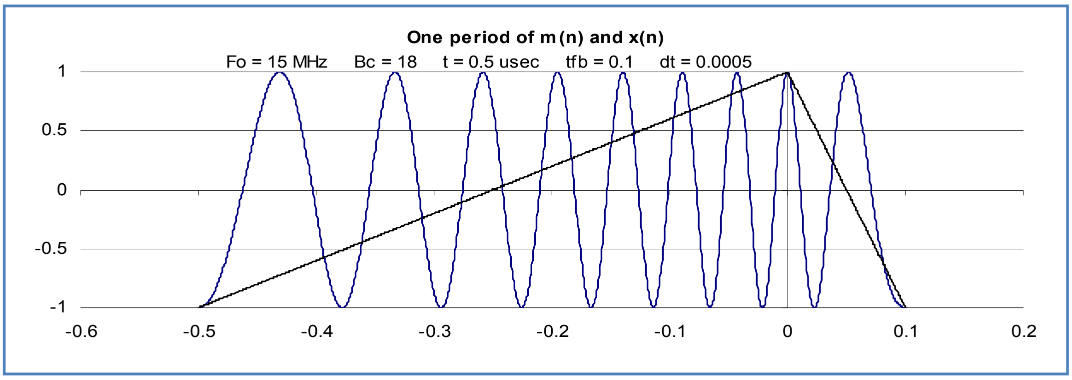

Figure 8. Fo adjusted according to (10) to achieve phase continuity

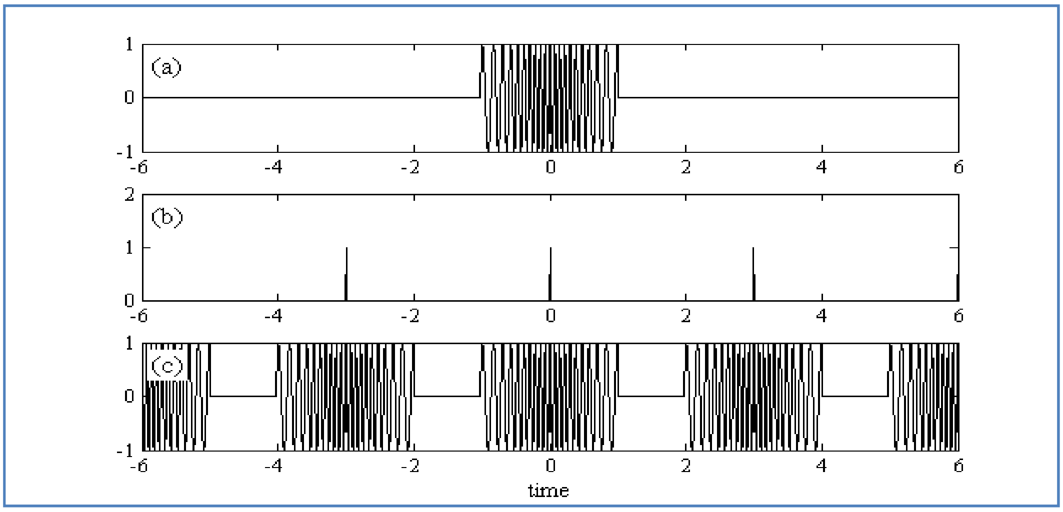

Figure 9. a forward and return chirp convolved with a sequence of delta functions

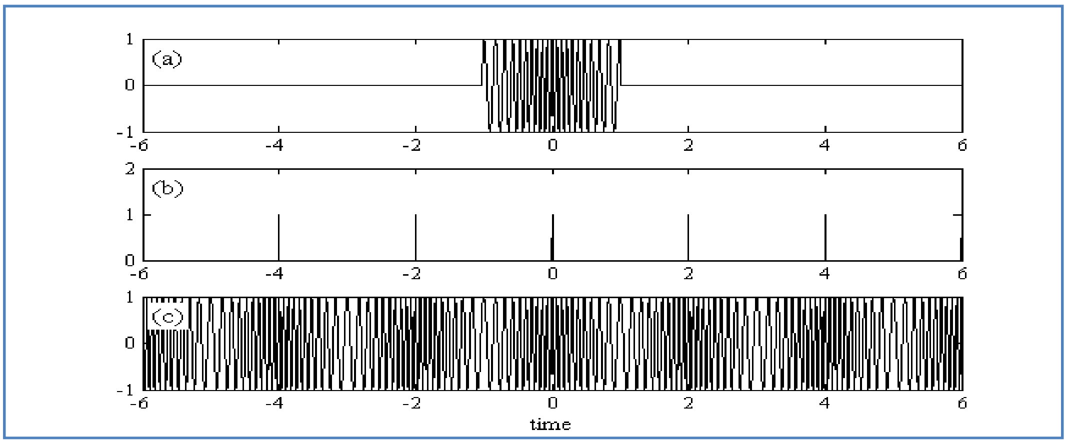

Figure 10. Delta function spacing matches width of forward and return chirp

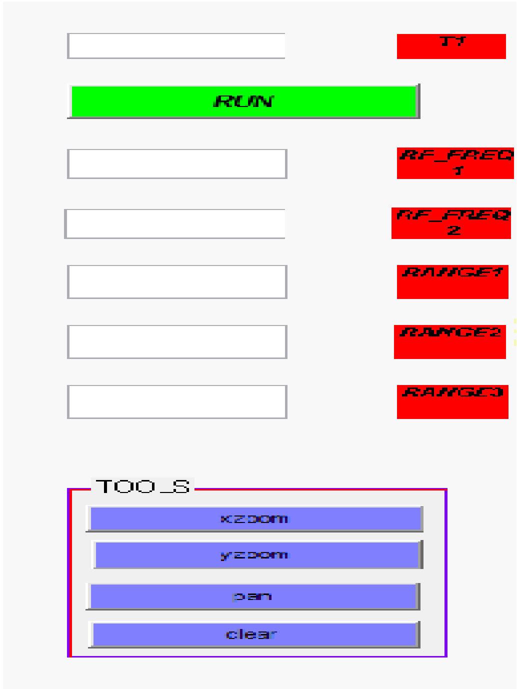

Figure 11. GUI

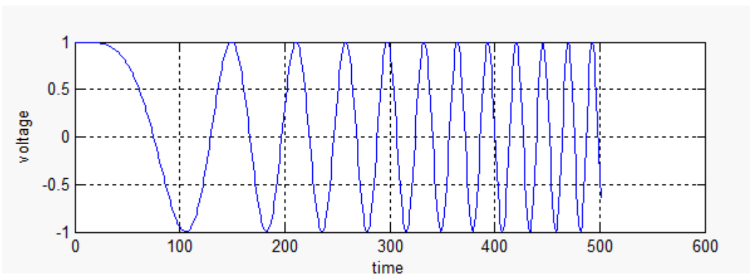

Figure 12. Oscillation frequency

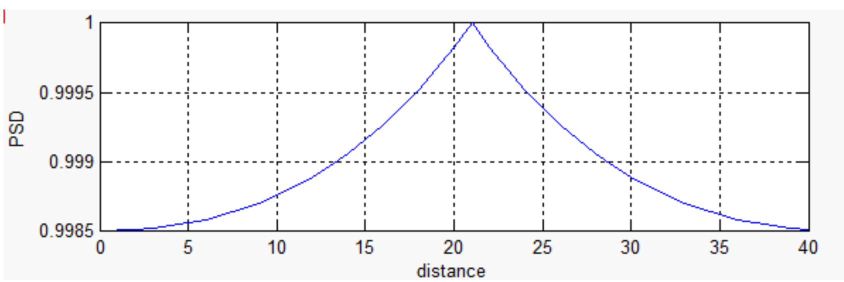

Figure 13. Short Range Radar; target on 21 meter are detected by 24 GHZ

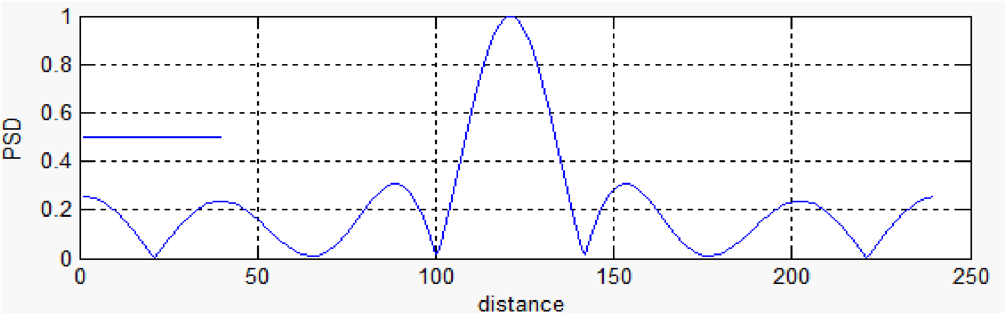

Figure 14. Long Range Radar; targets on 21& 122 meters are detected by 77GHz

Figure 15. Tools help to show SRR detection

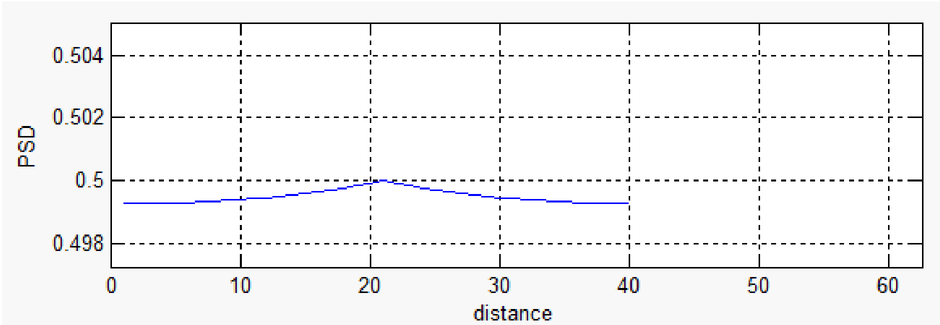

Figure 16. target on 21 meter is detected by 77 GHz. after zooming

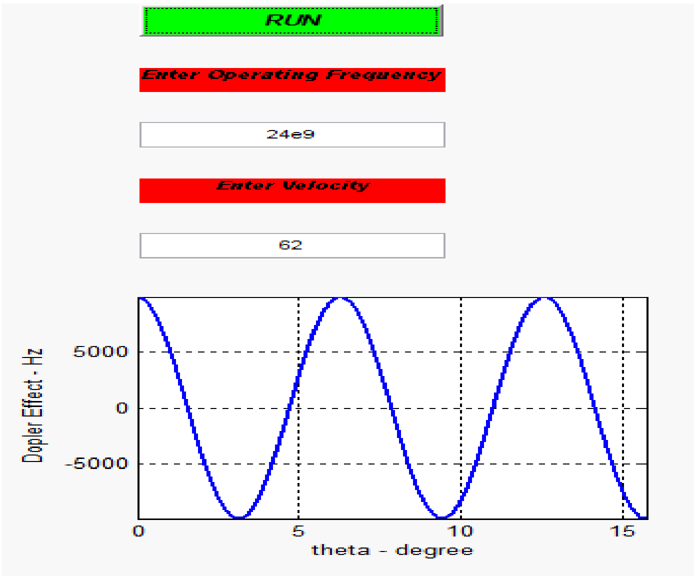

Figure 17. Maximum Doppler effect at 24 GHz

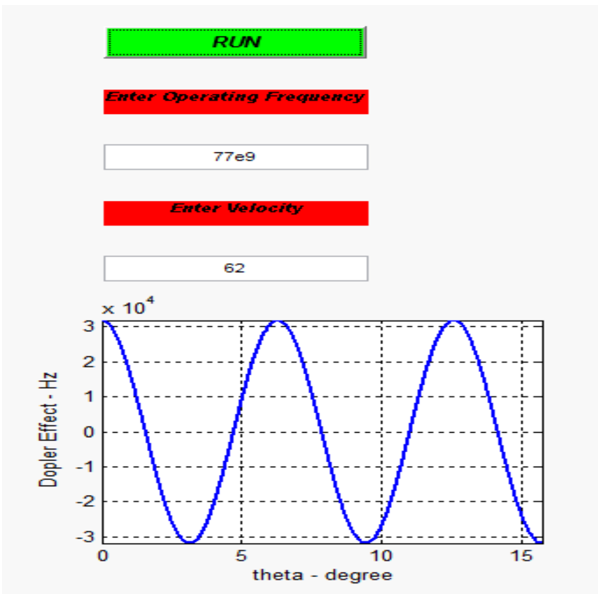

Figure 18. Maximum Doppler effect at 77GHz

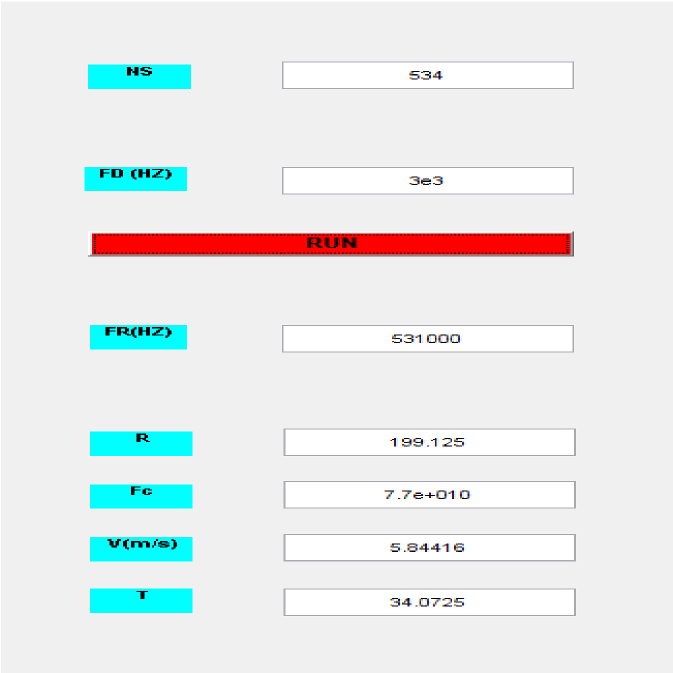

Figure 19. Inputs and outputs shows at GUI