2015 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS) November 9-12, 2015

Stationary and Moving Targets Detection on FMCW Radar Using GNU Radio-Based Software Defined Radio

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***Abstract*—This paper discusses the implementation of GNU radio-based software defined radio (SDR) for designing a frequency modulated continuous wave (FMCW) radar to detect stationary and moving targets. The use of SDR system in which its components are implemented by means of software is to reduce cost and complexity in the design and implementation. Whilst the signal processing of FMCW radar is carried out using Matlab® with triangular linear frequency modulation (LFM) waveform to obtain the target distance and the target relative speed for stationary and moving target, respectively. From the result, it is shown that the radar is successfully implemented using GNU radio-based SDR with the capability in distance target detection of 14.79km for a moving target away from the radar with the relative speed of 50m/s.**

***Keywords*—FMCW radar; GNU radio; moving target; software defined radio; stationary target.**

I. Introduction

Recently one technology that is being developed in the world of radio communication is software defined radio (SDR) which has simpler architecture than conventional radio systems as most of the modulation process is carried out by using software [1]. The technology provides some advantages such as flexibility in operation, lower in cost, faster and easier in of the design process as well as in the realization [1]– [2]. Since the radar technology is principally derived from the radio technology, therefore the SDR technology has highly potential to be implemented and operated as a radar. One of open source software and open hardware that is widely used in realizing devices based on the SDR technology is GNU radio and universal software radio peripheral (USRP) [3].

One type of radar that can be implemented using the SDR is a frequency-modulated continuous-wave (FMCW) radar. In general, the FMCW radar uses linear frequency modulation (LFM) waveform and emits waves in the entire range of its periodic time [4]– [6]. This is different with common pulse radar that sends pulses of short pulses in a periodic time range. Hence, the FMCW radar does not require a large transmit power to obtain sufficient value of signal-to-noise ratio for target detection [7]– [8]. From the hardware point of view, the FMCW radar can be realized using solid state amplifier which is compact in size and lower in cost compared to the magnetron usually used in pulse radar [9]– [10]. In addition to the advantages already mentioned above, there are some drawbacks of FMCW radar. One of them is the maximum distance ambiguity resolution of some target which is basically limited by the value of bandwidth used in the processing technique. Therefore, to overcome this issue, some technique of signal processing is proposed to get beat frequency in the FMCW radar system by performing a Fourier transform to obtain the distance information of the target.

In this paper, the FMCW radar is designed to be applied for the detection of statinoary and moving targets. The radar is implemented based on GNU radio which is known as an open source SDR project. The SDR system is a radio communication system where components such as mixers, filters, amplifiers, modulators/demodulators, detectors, etc., are implemented by means of software on a personal computer or an embedded computing device. In the implementation, a triangular LFM waveform is used for the radar signal processing which is carried out using Matlab® to obtain the target range and the target speed for statinoary and moving target, respectively. The design specification of FMCW radar such as carrier frequency, bandwidth, chirp period, sampling rate, range resolution, and target speed is determined prior the simulation process. From the design specification, the schematic diagram of FMCW radar is then drawn and implemented based on SDR of GNU Radio.

II. Brief Overview of FMCW Radar Based on SDR

A. Basic Principles of FMCW Radar

The block diagram of basic FMCW radar system is illustrated in Fig. 1. It consists of chirp generator as signal source for the transmitter as well as for mixer input at the receiver. The signal of FMCW radar is commonly defined as a chirp that can be from many different kinds of signal waveform type. Typically it uses LFM waveforms since the

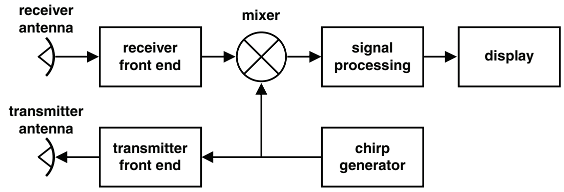

Fig. 1. Block diagram of basic FMCW radar system

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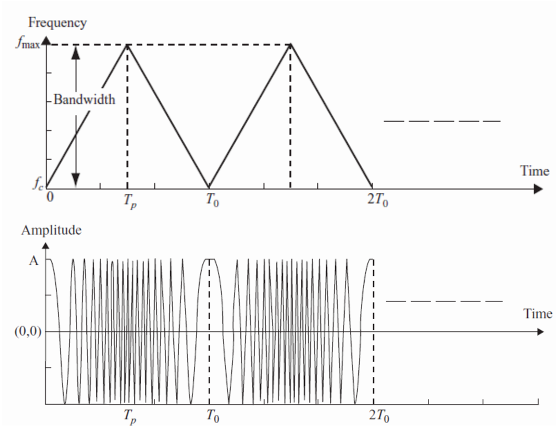

Fig. 2. Triangular LFM waveform for FMCW radar; time domain (top); frequency domain (bottom)

FMCW radar is one of continuous wave radar types. Fig. 2 shows a triangular LFM waveform that will be employed in the design [11]. The signal of FMCW radar is transmitted by a transmitter antenna into some targets, then the reflected signal from some targets is received by a receiver antenna to be mixed with the transmitted signal for further processing and showing in the display. The mixing process is carried out by the mixer which produces summation and subtraction frequency of 2 signals. The frequency difference between 2 signals is called as a beat signal which is proportional to the distance between the radar to the target.

The transmitted signal or chirp with the amplitude of chirp of A_t and the lowest frequency of f_0 can be expressed in (1).

$$S_t = A_t \cos\left(2\pi f_0 t + \pi\mu t^2\right) \tag{1}$$

where μ is the rate of frequency change or chirp rate as given in (2) where the bandwidth (B) represents the difference of highest and lowest frequencies, while the sweep time (T_p) is a chirp period and becomes T_0 for triangular LFM waveform.

$$\mu = \frac{B}{T_p} \tag{2}$$

When the FMCW radar radiates waves into a medium and the radiated waves are mashing the target, some of radiated waves is reflected back to the radar by the target. The reflected wave or signal in time domain can be expressed in (3) with A_r denotes the amplitude of reflected signal.

$$S_r = A_r \cos\left(2\pi f_0 (t-\tau) + \pi\mu(t-\tau)^2\right) \tag{3}$$

It shows that the reflected signal has similar characteristics as the transmitted signal with additional delay time of τ which is given by (4).

$$\tau = \Delta t = \frac{2R}{c} \tag{4}$$

where R and c denote the distance between the radar to the target and the speed of light in free space, respectively.

Furthermore, as the beat signal produced by the mixer consists of summation and subtraction frequency, a low pass filter is added to eliminate the summation frequency of 2 signals. Hence, the beat signal with amplitude of A_b after filtering process can be written in (5).

$$S_b = A_b \cos\left(2\pi f_0 \tau + 2\pi\mu\tau t - \pi\mu t^2\right) \tag{5}$$

Meanwhile the beat frequency (f_b) can be obtained by deriving the phase of beat signal as expressed in (6).

$$f_b = \frac{1}{2\pi}\frac{d\left(2\pi f_0 \tau + 2\pi\mu\tau t - \pi\mu t^2\right)}{dt} = \mu\tau \tag{6}$$

The range of R, i.e. distance between the radar to the target, can be obtained from the beat frequency by substituting μ in (2) and τ in (4) into (6) as expressed in (7).

$$R = \frac{T_p c}{2B} f_b \tag{7}$$

Then by using FFT to transform the beat signal in time domain to frequency domain, the peak of beat frequency spectrum can be obtained to be easily translated into the distance between the radar to the target.

B. *FMCW Radar Signal Processing*

In FMCW radar signal processing, when there is no doppler shift in the transmitted signal or stationary target, the beat frequency measures the target range, so $f_b = f_r$. If the slope of frequency change in the transmitted signal is f', then the beat frequency can be given in (8). The result of beat frequency when using triangular LFM waveform for stationary target is shown in Fig. 3 [11].

$$f_b = f'\Delta t = f'\frac{2R}{c} \tag{8}$$

Usually the modulation frequency which is chosen has $f_m = 1/2t_0$, hence the rate of frequency change (f') with a peak frequency deviation of Δf can be expressed in (9).

$$f' = \frac{f\Delta t}{t_0} = 2f_m\Delta f \tag{9}$$

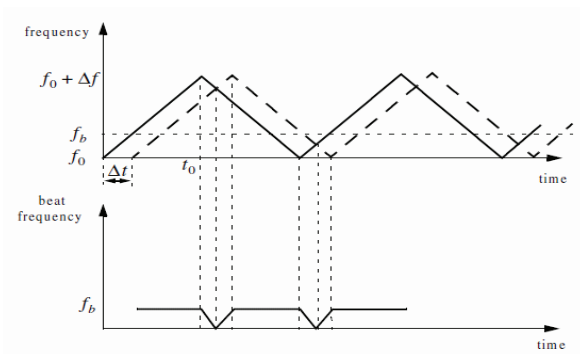

Fig. 3. Triangular LFM waveform and beat frequency for stationary target

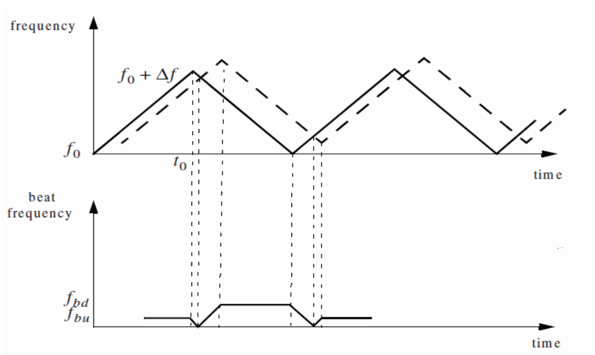

Fig. 4. Triangular LFM waveform and beat frequency for moving target

So that the beat frequency is generated as given in (10).

$$f_b = f' \Delta t = \frac{4Rf_m \Delta f}{c} = \frac{4Rf_m B}{c} \quad (10)$$

Moreover, if the target moves, there will be superimposed to the doppler frequency shift and the beat frequency should be considered in the demodulation. The doppler frequency will effect the sweep of beat frequency up or down. Fig. 4 shows the beat frequency when using triangular LFM waveform for moving target [11]. The distance and relative velocity for moving target can be estimated using the doppler frequency in FMCW radar in which the relative speed (ν_r) is calculated based on the doppler frequency (f_d) as given in (11).

$$f_d = \pm \frac{2\nu_r}{\lambda} = \pm \frac{2\nu_r f_0}{c} \quad (11)$$

III. Design and Simulation

A. FMCW Radar System Design

Fig. 5 illustrates the block diagram of FMCW radar system design which is simulated using SDR based on GNU radio. In the system design, GNU radio which can be run in a variety of computer-based Linux Operating System and operated on baseband or IF frequency range is applied to generate FMCW chirp signal, send and receive data, and perform mixing process between the transmitted signal and the received signal from receiver antenna. Meanwhile, the design specification of FMCW radar system is summarized in Table I.

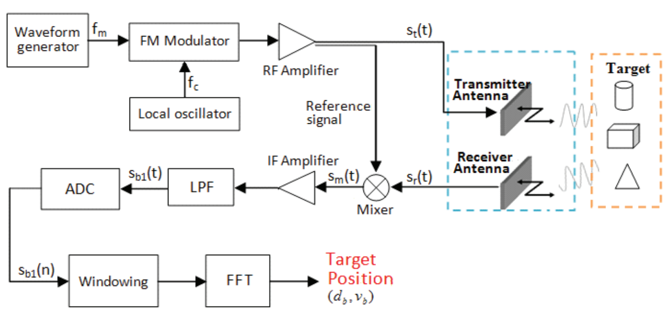

Fig. 5. Block diagram of FMCW radar system design simulated using SDR based on GNU radio

TABLE I. Design Specification of FMCW Radar System

Parameter	Specification
Carrier frequency (f_c)	1.5MHz
Bandwidth (B)	750kHz
Chirp waveform	Triangular
Chirp period (T_p)	1ms
Chirp number (N)	5
Modulation frequency (f_m)	500Hz
Modulation period (T_m)	2ms
Sampling rate of ADC (f_{sam})	6MHz
Range resolution (ΔR)	200ms
Maximum speed (ν)	50m/s

B. FMCW Radar Simulation Using GNU Radio-based SDR

The simulation scheme of FMCW radar system using GNU radio-based SDR is shown in Fig. 6. Some parameters of block used for the simulation scheme are given in Table II. There are 2 blocks of voltage controlled oscillator (VCO), the first VCO is connected to the block of Signal Source to produce FM signal, while the second one is connected to the block of Constant Source to generate sinusoidal source as carrier frequency. The output of first VCO block is chirp signal on the baseband frequency which linearly increases or decreases from 0Hz to 750kHz for 2ms modulation period. The triangular LFM signal triggers the first VCO to produce chirp signal with bandwidth of 750kHz.

On the output of modulation, there is a block that serves to delay a few samples of input signal. The output of Delay block is then multiplied with the carrier signal to implement the demodulation process. To obtain beat frequency, the output of demodulation is multiplied by the chirp signal at baseband frequency and followed by filtering process using a block of Low Pass Filter to get low order component frequency. The signal processing is carried out using Matlab® to obtain the distance of target.

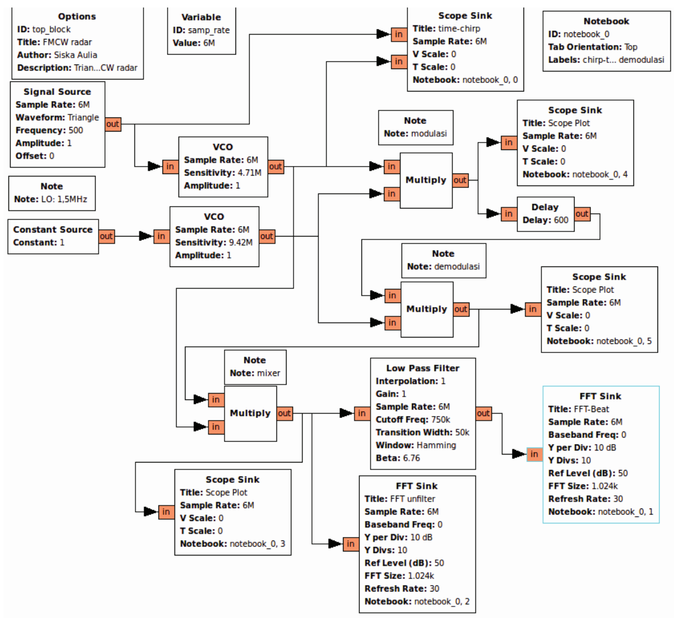

Fig. 6. Simulation scheme of FMCW radar using SDR based on GNU radio

TABLE II. PARAMETERS OF BLOCK ON GNU RADIO SIMULATION

Block	Parameter	Specification
Signal Source	Sample rate Waveform Frequency Amplitude	6MHz Triangular 500Hz 1V
Constant Source	Constant	1
First VCO	Sample rate Sensitivity Amplitude	6MHz 4.71MHz 1V
Second VCO	Sample rate Sensitivity Amplitude	6MHz 9.42MHz 1V
Delay	Constant	600
Low Pass Filter	Sample rate Cut-off Frequency Windowing	6MHz 750kHz Hamming

IV. RESULTS AND DISCUSSION

A. Single Stationary Target Distance

Figs. 7 and 8 plot the spectrum frequency of beat signal and the target distance for a single stationary target, respectively. It clearly shows from Fig. 8 that the distance of stationary target is 25km. From (7) the distance of target could be calculated theoretically with the calculation parameters shown in Table I. Moreover, the distance resolution (ΔR) of proposed FMCW radar system for single stationary target can be determined using (12). Based on parameters tabulated in Table I, the distance resolution is 200m.

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

B. Multi Stationary Targets Distance

In the simulation to detect multi stationary targets, the simulation data from GNU radio is processed by Matlab® and filtered using a low pass digital FIR filter to determine relationship between the distance and the target reflectivity. The Fourier transform is performed to transform the signal from discrete time domain to discrete frequency domain. From the result of transformation, the distance of multi stationary targets can be determined from the reflectivity.

Figs. 9 and 10 depict the spectrum frequency of beat signal and the target distance for 3 stationary targets, respectively. It shows that the spectrum frequency of beat signal for 3 stationary targets equals to the value of beat frequency for each stationary target. The value of beat frequency for 3 stationary targets equals to the one when beat frequency is modeled only for a single stationary target. Therefore, the distance of each stationary target can be distinguished.

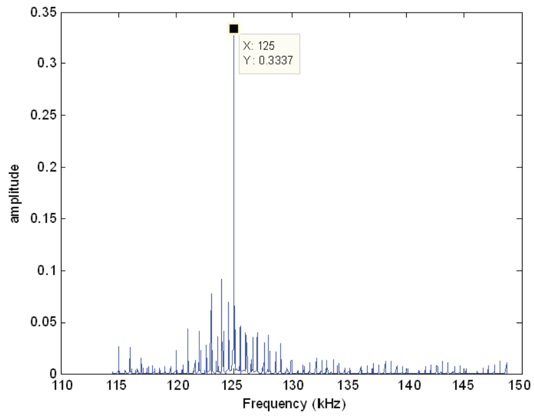

Fig. 7. Spectrum frequency of beat signal for single stationary target

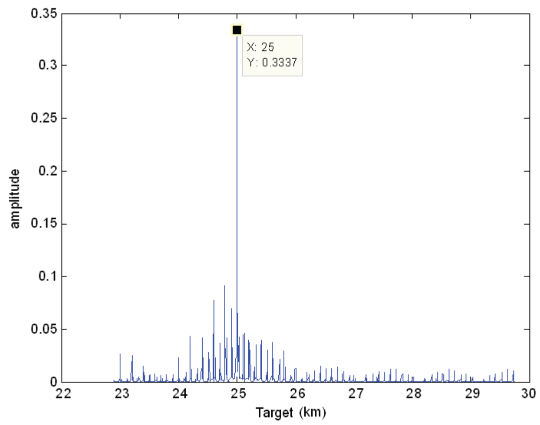

Fig. 8. Target distance for a single stationary target

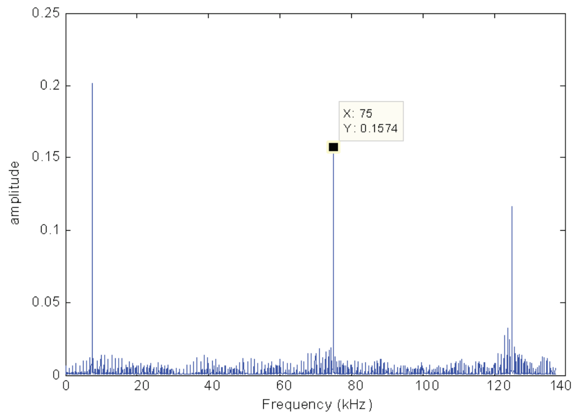

Fig. 9. Spectrum frequency of beat signal for 3 stationary targets

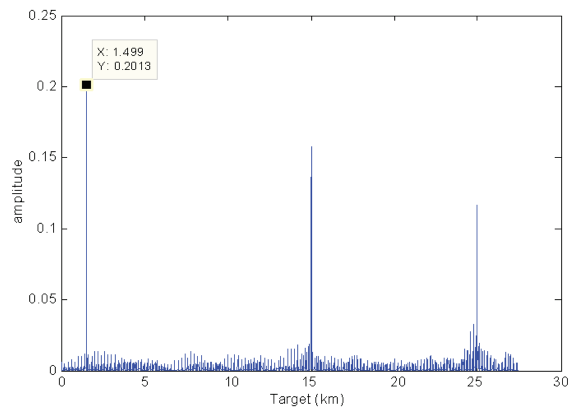

Fig. 10. Target distance for 3 stationary targets

C. Moving Target Distance and Relative Speed

There are 2 simulations performed for detection moving target; the first is simulation for moving target closer to the radar and the second is simulation for moving target away from the radar. To detect some moving targets, the simulations are carried out using triangular LFM waveforms. Figs. 11–13 plot the triangular LFM waveform, the spectrum frequency of beat signal and the target distance for detection of moving target closer to the radar, respectively. Meanwhile for moving target away from the radar, the triangular LFM waveform, the spectrum frequency of beat signal and the target distance are depicted in Figs. 14–16, respectively.

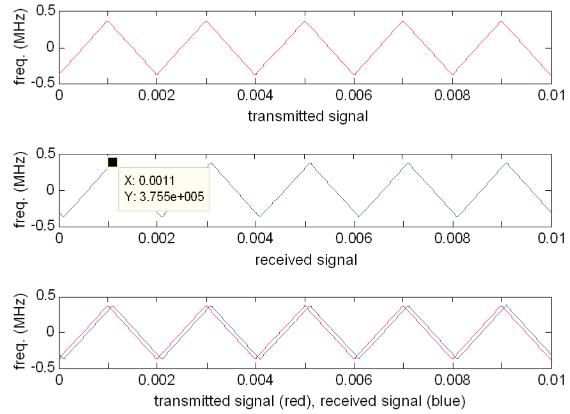

Fig. 11. Triangular LFM for detection of moving target closer to radar

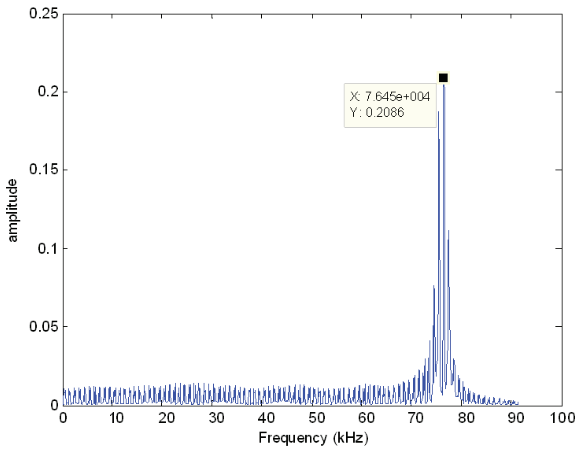

Fig. 12. Spectrum frequency for moving target closer to radar

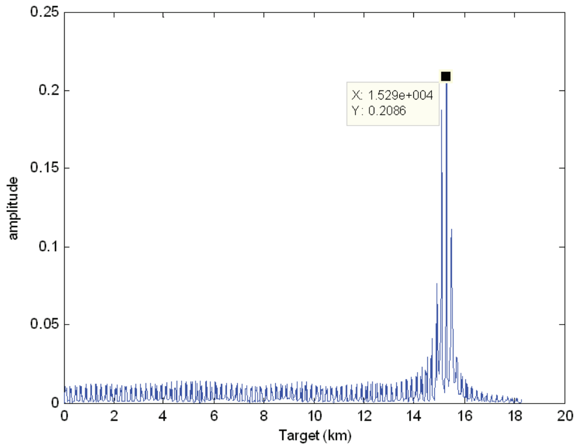

Fig. 13. Target distance for moving target closer to radar

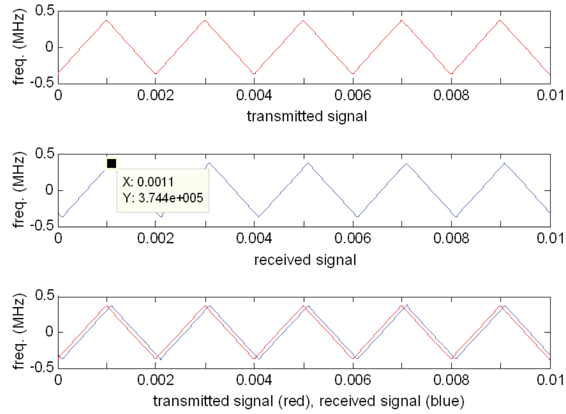

Fig. 14. Triangular LFM for detection of moving target away from radar

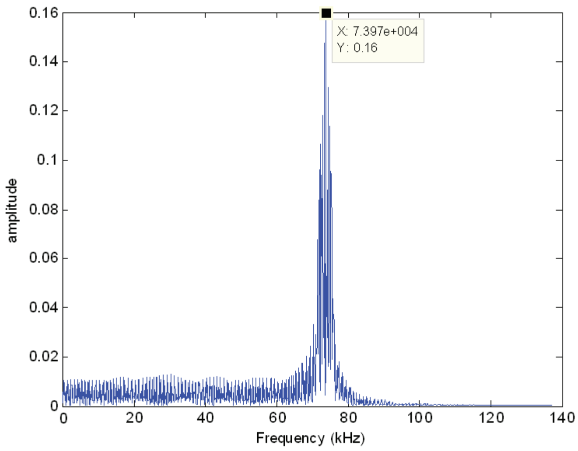

Fig. 15. Spectrum frequency for moving target away from radar

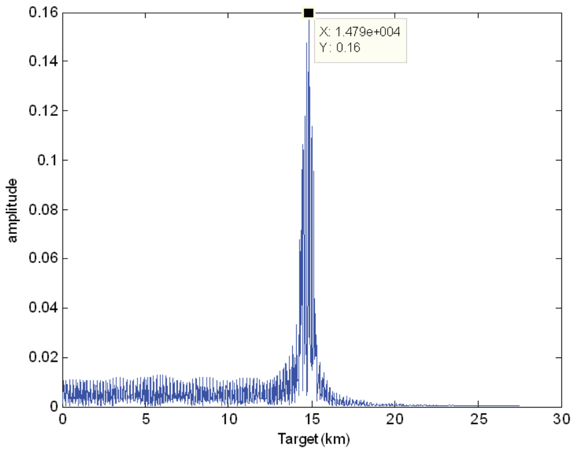

Fig. 16. Target distance for moving target away from radar

From Fig. 11, it shows that the frequency of transmitted signal (red curve) is up to 375kHz with a chirp period of 0.001s, while the frequency of received signal (blue curve) is up to 375.5kHz with a chirp period of 0.0011s. There is a time shift between the transmitted signal and the received signal around 0.1ms denotes the existence of target so that the received signal is delayed for 0.1ms. There is also a change of frequency sweep of 500Hz between the transmitted signal and the received signal indicating a change in Doppler frequency due to the moving target closer to the radar. Whereas from Fig. 13, the distance of moving target closer to the radar is detected at 15.29km.

Furthermore, from the triangular LFM waveform of detection for moving target away from the radar shown in Fig. 14, the frequency of transmitted signal (red curve) is up to 375kHz with a chirp period of 0.001s, while the frequency of received signal (blue curve) is up to 374.4kHz with a chirp period of 0.0011s. This opposites with the previous one where the frequency of received signal is higher than the transmitted signal. A time shift between the transmitted signal and the received signal around 0.1ms representing the existence of target so that the received signal is delayed for 0.1ms. While a change of frequency sweep is 600Hz indicating a change in Doppler frequency due to the moving target away from the radar. The target that moves away from the radar is expressed by the decrease of frequency of received signal, so that the target distance is 14.79km. Based on (11), the relative speed of moving target can be calculated and is 50 m/s.

V. Conclusion

The implementation of GNU radio-based SDR for designing an FMCW radar has been demonstrated to detect stationary and moving targets. It has been shown that the realized FMCW radar with Matlab® for signal processing was successfully applied to gain information of single and multiple stationary targets distance obtained from spectrum frequency of beat signal. Whilst for moving target detection, the FMCW radar has shown the capability to detect the distance of target using beat frequency shift and to calculate the relative speed of moving target closer to– and away from the radar based on Doppler frequency shift.

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