GNU Radio Based Software-Defined FMCW Radar for Weather Surveillance Application

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Abstract—**In this paper, a GNU Radio based software-defined FMCW (Frequency Modulated – Continuous Wave) radar is studied for weather surveillance application. The FMCW radar that has been gaining popularity due to the use of solid state microwave amplifier to generate a signal source is proposed for the design since the current weather surveillance radar is usually using a pulse-radar type that needs high power in pulse generation and high cost in the deployment. In addition, by using software-defined radar, therefore the designed FMCW radar can be implemented and configured at a reduced cost and complexity. The FMCW radar prototype is implemented using both open sources of software and hardware. The software part of the radar is realized using GNU Radio, whilst the hardware part is implemented using USRP (Universal Software Radio Peripheral) N210. Based on the design specification, an FMCW radar prototype based on GNU Radio is then realized and examined. From the performance-test, the prototype that works at a center frequency of 2.1GHz with a bandwidth of 750kHz is able to perform range detection of targets after utilizing the FFT (Fast Fourier Transform) function using MATLAB. In addition, the discussion of system design of software defined FMCW radar and performance-test of its prototype are presented.**

Keywords-pulse radar, FMCW radar, GNU Radio, USRP N210, software defined radar.

I. INTRODUCTION

Between 1980 and 2000, weather radar networks have become the norm in North America, Europe, Japan and other developed countries. A weather-radar also knows as weather surveillance radar, is a type of pulse radar used to locate precipitation, calculate its motion, estimate its type such as rain, snow, hail, etc., and forecast its future position and intensity. The radar works by sending directional pulses of microwave radiation, on the order of a microsecond long, using a cavity magnetron or klystron tube connected by a waveguide to antenna. The wavelengths of 10–100mm are approximately ten times diameter of the droplets or ice particles, as the Rayleigh scattering occurs at these frequencies. This means that part of the energy of each pulse will bounce off these small particles, then back in the direction of the radar. Shorter wavelengths are useful for smaller particles; however the pulse signal is more quickly attenuated. Thus the 100mm radar (S-band) is preferred for the implementation but is more expensive than the 50mm radar (C-band) [1].

Since the pulse of pulse radar should be generated by use of magnetron or klystron that requires high power and high cost as well, therefore some radar scientists and engineers have proposed another type of radar namely FMCW (Frequency Modulated-Continuous Wave) radar that can be realized in low cost. Recently, this type of radar has been gaining popularity due to the fact that the radar uses of the emerging technologies of a solid state microwave transmitter to generate signals to be radiated and of very fast digital circuits, capable of generating and processing complex signal in real time [2]. Further, the FMCW radar system provides a convenient way to increase SNR, while reducing the required system power level and complexity [3]. As the signal source of FMCW radar is continuously modulated, the radar is continuously operating by transmitting a modest power [4]-[5]. The typical modulation of FMCW is linear in frequency.

In this paper, an FMCW radar system is investigated based on software-defined radio of GNU radio to be applied for weather surveillance application. The FMCW radar is implemented using both open sources of software and hardware. The software part of the radar is realized using GNU Radio, whilst the hardware part is implemented using USRP N210. A software-defined radio system is a radio communication system where components that have been typically implemented in hardware, e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc., are instead implemented by means of software on a personal computer or embedded computing devices [5]. Whilst a GNU Radio is a free software toolkit which is distributed under the terms of the GNU General Public License for learning about, building, and deploying software-defined radio systems. The GNU Radio project usually utilizes USRP which is a digital acquisition (DAQ) system facilitated with ADC and DAC converters, and support circuitry such as USB (Universal Serial Bus) interface. Prior to the realization, in the design process the specification of designed FMCW radar is determined such as the center frequency, chirp frequency, sampling rate, etc. From the specification design, the schematic diagram is drawn based on software-defined radio from GNU Radio. In the realization process, USRP N210 is applied for prototyping with 2 antennas as transmitter and receiver. Finally, the performance of FMCW radar prototype is examined experimentally to obtain its performance-test to be analyzed.

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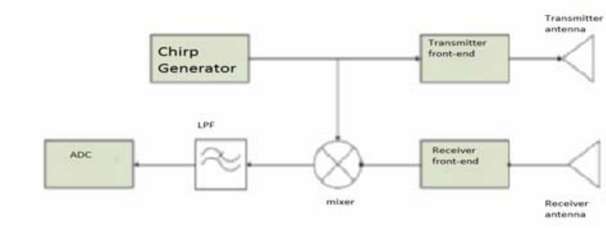

Figure 1. Block diagram of an FMCW radar system

II. SOFTWARE-DEFINED FMCW RADAR

A. Basic FMCW Principles

As shown in Fig. 1, the block diagram of a basic FMCW radar system consists of chip generator as signal source for the transmitter and for the mixer input of receiver as well. FMCW signals, commonly referred as chirp, have many different kinds of signal form. In this case, a linear type of frequency modulation is used. The FMCW waveform is a result of carrier signal that is frequency-modulated by a periodic linear signal *m*(*t*). A chirp signal can be written as follows,

$$f(t) = f_0 + f_t \tag{1}$$

where f_0 is initial frequency, f_t is chirp rate ($f_t = B/T$), and T is a duration of a chirp. The shape of FMCW signal in the time and frequency domain can be seen on Figs. 2 and 3 [6].

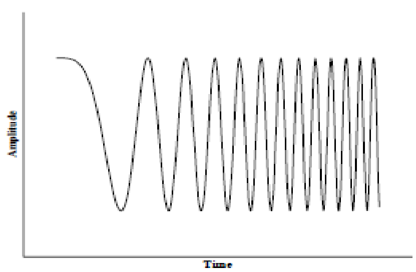

Figure 2. FMCW signal form in time domain

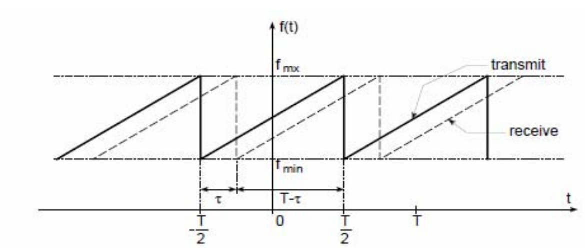

Figure 3. FMCW signal frequency as a function of time

The range resolution of an FMCW radar is given by the following equation,

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

where *ΔR*, *c*, and *B* are the radar range resolution, the speed of light in free space, and the bandwidth of used frequency, respectively.

An FMCW radar can determine the range of target from the difference in frequency between the transmitted and received signal (*Δf*) by considering a chirp signal that begins at $t = 0$ and ends at $t = T$. The signal from the transmitter hits a target at range of *r* and is then reflected back to the receiver in t_0 seconds in which the range of target is expressed in (3). By mixing the transmitted and received signals, a frequency difference of Δf is acquired, as illustrated on Fig. 4.

$$r = \frac{c\Delta f T}{2B} \tag{3}$$

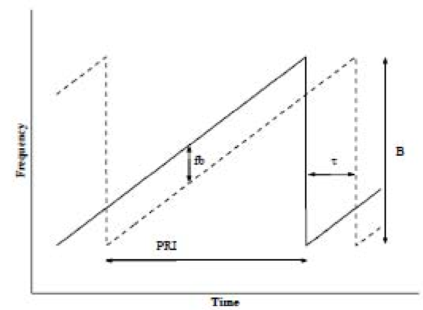

Figure 4. Frequency difference between transmitted and received signal

After mixing the transmitted and received signals and filtering the mixed signals using lowpass filter, the output signal, $x(t_k)$, is obtained. To get the range information about target, the output signal is then performed by use of Fourier transform as written in the following equation.

$$X_r(w,k) = \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t_k) e^{-j\omega t_k} \, dt_k \tag{4}$$

B. System Design

The architecture design of software-defined FMCW radar system is illustrated in Fig. 5. The prototype of the system is realized by use of GNU Radio and USRP N210.

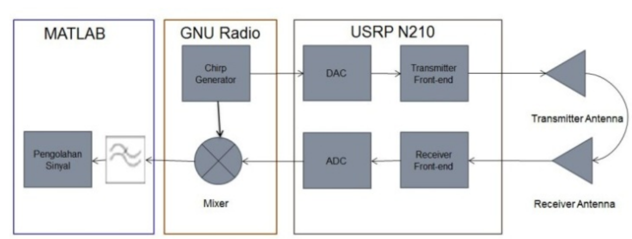

Figure 5. Architecture design of software-defined FMCW radar system

The GNU Radio is used to perform the modulation of FMCW signal and to mix the transmitted and received signal components to obtain beat signal. Hence, the MATLAB® is used to process the lowpass filtering and FFT (Fast Fourier Transform) to obtain the range component of the radar target. The design specification of the radar system is summarized in Table 1.

TABLE I. DESIGN SPECIFICATION OF SOFTWARE-DEFINED FMCW RADAR SYSTEM

Parameter	Dimension
Center frequency	2.1GHz
Chirp frequency (*f*)	0.75MHz
Chirp waveform	Sawtooth
Chirp period (*Ts*)	1ms
Sampling rate	6MS/s
Maximum unambiguous range	150km
Range resolution Doppler	400m
Maximum speed	±35.7m/s

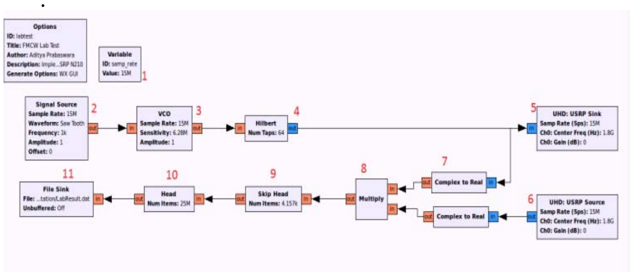

Figure 6. GNU Radio schematic design

In the GNU Radio, the designed schematic has the same components as an FMCW radar system as shown in Fig. 6. The components that are implemented using GNU Radio are chirp generator, transmitter, receiver, and mixer. The overall flow of the system is as follows; the signal source (2) is used to generate a sawtooth signal to be used to modulate a frequency carrier using VCO (3), resulting in a chirp signal. As the sent signal using USRP N210 needs to be in a complex form, the signal is transformed using a Hilbert transform block (4) and sent to the USRP N210 using a UHD sink block (5). The reflected signal is received by the USRP N210 and sent to GNU Radio using a UHD source block (6). The received complex signal is then reverted back into its real form using a complex to real block (7). Then, the transmitted and received signals are mixed together using a multiply block (8) and the result is then saved into a binary float file using block (9), (10), and (11). Low pass filtering and Fourier transform process are carried out by using MATLAB® in order to reduce the computational loading. In the implementation, the design system uses transmitter and receiver UWB antennas placed next to each other to accommodate wideband characteristic of the system. To simulate the delay caused by the reflection from a target at some certain range, a delay block is added in the GNU Radio schematic as shown in Fig. 7.

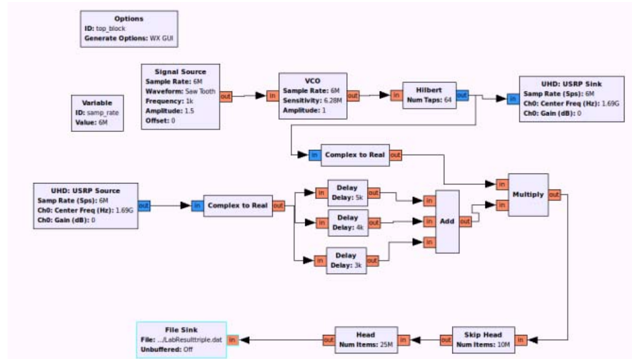

Figure 7. GNU Radio schematic with additional delay blocks

III. PROTOTYPE AND CHARACTERIZATION

In order to characterize the software-defined FMCW radar system, a prototype of the radar system is realized using USRP N210 as shown in Fig. 8. Hence, Fig. 9 shows 2 UWB antennas used for transmitting and receiving signals [7].

Figure 8. USRP N210 for software-defined FMCW radar system prototyping

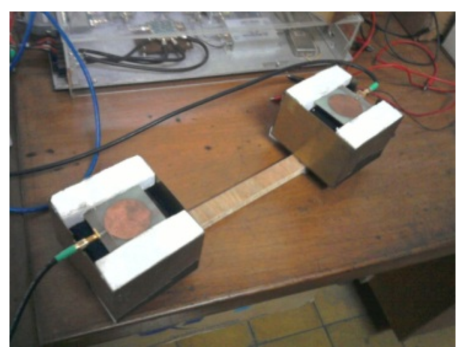

Figure 9. UWB antennas used as transmitter and receiver

From the characterization result, it can be seen that the software-defined FMCW radar is able to perform range detection using the frequency component of the beat signal. Figure 10 shows the beat signal for single target detection prior the Fourier transform performance, whilst Fig. 11 plots the output signal to obtain range information. It should be noted that for a single target the beat signal will have a single frequency corresponding to its reflectivity and range.

Furthermore, the characterization is also to range 3 different targets using delay blocks with different values. The beat signal for 3 different targets is depicted in Fig. 12, whilst the frequency spectrum of beat signal for 3 different targets is shown in Fig. 13. Theoretically, all 3 frequencies plotted in Fig. 13 should have equal amplitude; however the nonlinearity and skewing in FMCW radar system has caused the frequencies to be in unequal amplitude.

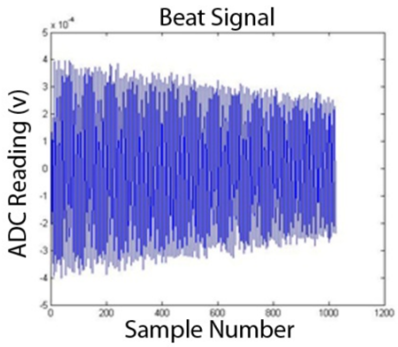

Figure 10. Beat signal for a single target

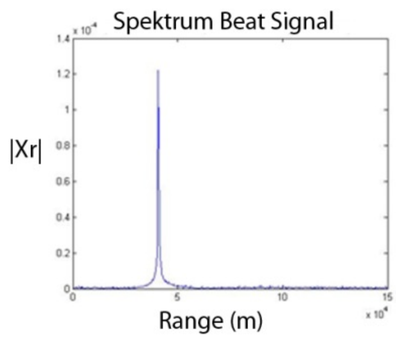

Figure 11. Frequency spectrum of beat signal for a single target

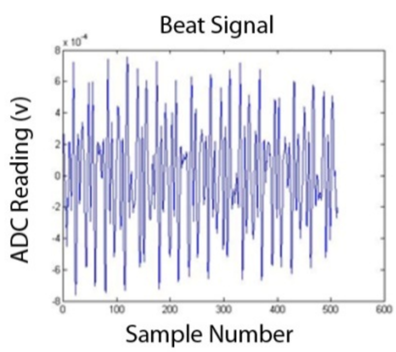

Figure 12. Beat signal for 3 different targets

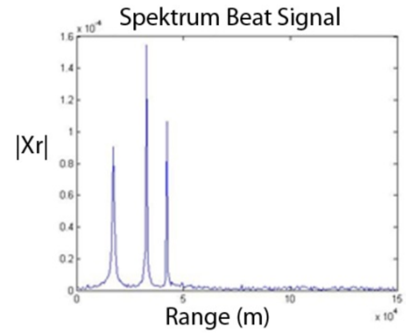

Figure 13. Frequency spectrum of beat signal for 3 different targets

IV. CONCLUSION

A software-defined FMCW radar has been investigated for weather surveillance application. The prototype of FMCW radar that has working frequency of 2.1GHz (S-band) with bandwidth of 750kHz has been implemented using open source of GNU Radio for the software part and USRP N210 for the hardware part. From the characterization result, it has been demonstrated that the prototype of software-defined FMCW radar system can perform range detections for 1 target and 3 different targets. Although the prototype is just characterized only for ranging detection for some target due to some limitations, however from the results it can be concluded that the prototype can be more developed for other purposes such as particles motion detection as well as position and intensity of some particles. This will be very useful to be applied, in particular for weather surveillance radar.

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