Low-cost SDR based FMCW radar for UAV localization

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***Abstract*—In this paper, we study a Software Defined Radio (SDR) based frequency-modulated continuous-wave (FMCW) radar which can be used as a low cost solution for the localization of unauthorized unmanned aerial vehicles (UAV's). The FMCW radar is evaluated through several simulations implemented in GNU Radio in order to verify its behaviour in the detection of stationary and moving targets as well as the effects of attenuation due to signal propagation and signal noise corruption. The software implemented on GNU Radio will be used as a basis for a future implementation using SDR platforms, namely URSP N210, BladeRF and LimeSDR, combined with high gain antennas and a high power amplifier in order to test the performance of the FMCW radar in real-life scenarios involving the detection of UAV targets.**

***Index Terms*—Software Defined Radio, Radar, Frequency modulation, beat frequency, Unmanned Aerial Vehicles**

I. Introduction

Currently, Unmanned Aerial Vehicles (UAV's) are used in various areas and for different purposes. Their applications range from defence, namely in conducting surveillance in military operations, to emergency response and disaster assessment, for example assessing damage and locating victims, among many others. [1] However, in recent years, the marketing of these devices has begun to emerge, many with very affordable prices, and it has become possible for anyone to own a drone, which is verified by the large growth in the number of UAV's for civil use. [2] This proliferation has been accompanied by an increase in the number of incidents with these devices, which have created several problems for the authorities. The use of these devices in restricted areas, including airports, is only one example of such dangers, as they disrupt air traffic and possibly endanger human lives. [3] This type of situation has led to solutions being sought all over the world to prevent these devices from circulating in certain areas. In some countries, for example, the rules on the use of drones have been changed and fines have been imposed on those who do not comply with them. [4] However, despite these new rules, there are still those who insist on using the devices in restricted areas, creating several problems. For this reason, some ways have been found to prevent drones from entering these restricted areas. One example was the use of eagles by the Dutch police, who were trained to capture UAV's. However, in addition to causing injury to the animal, this type of solution is too rudimentary and limited. [5] The ideal solution for restricting these objects should be based on radio signals, using jamming and/or spoofing techniques. However, before these restriction measures are carried out, it is extremely important to have efficient measures for locating and monitoring UAV's. One of the most appropriate measures for this task is the creation of a radar. A radar consists of the transmission of a signal in the microwave band. This signal on reaching the target is reflected. Part of this reflection, called echo, is received by the radar's receiving antenna and then sent to the receiver to obtain the direction and distance of the target. The distance is calculated using the following equation:

$$R = \frac{c\tau}{2}, \tag{1}$$

where τ represents the time delay between the transmitted and the received signal.

However, many of the existing radars are expensive and complex, which can make them unfeasible for many applications. The solution studied on this paper is simpler and less costly, since it will use Software Defined Radio (SDR). This type of solution has already been studied by other authors. [6] presents a Software defined FMCW Radar with GNU Radio and the USRP N210 for weather surveillance. The prototype of this system is realized by use of GNU Radio and USRP N210. GNU Radio is used to generate the FMCW waveform and to mix the transmitted and received signal components in order to obtain the beat signal. To perform low pass filtering and FFT, in order to obtain the range of the target, Matlab is used. To transmit and receive the reflected signals, USRP N210 is connected with the host computer and with two UWB antennas (one for the transmitted signal and the other for the

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received signal). On [7], a series of SDR hardware platforms are investigated and their performance is compared. Of the studied platforms it is concluded that both USRP N210 and the QM-RDKIT board can be used, since they have suitable operating frequency, bandwidth, sampling rate, uncomplicated programming task, and friendly software support. After this studied, two FMCW Radar systems are developed and they performance is compared. One of the systems used the QM-RDKIT Radar Demonstration kit. The other system used USRP N210 and GNU Radio for the software part of the FMCW radar. Taking into account the previously presented motivation, it is proposed with this work to study if an SDR based Frequency Modulation Continuous (FMCW) Radar with GNU Radio can be used for target detection through a set of simulations, in order to use that software together with USRP N210 for real time detection of UAV's. This paper is organized in the following way. Section II explains the concept of FMCW Radar. Section III concentrates on the simulations and their results. Section IV presents the conclusion and future work.

II. FMCW Radar

The FMCW radar is a type of continuous radar (CW) in which the carrier wave undergoes frequency modulation. This way, and unlike continuous radar, it is possible to measure, in addition to speed, the distance at which a target is located. Fig. 1 shows the block diagram of the FMCW Radar

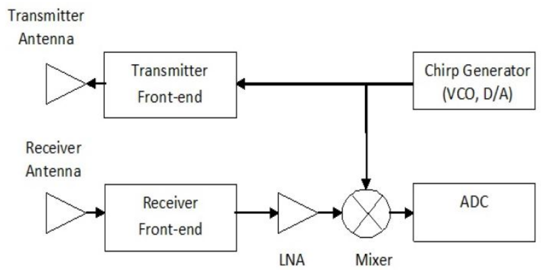

Fig. 1. Block Diagram of FMCW Radar [8]

A. FMCW Radar Principle

The FMCW radar transmits a continuous signal that is modulated by a periodic function. The chirp generator functions as a signal source in the transmitter and as a mixer in the receiver. The VCO in the chirp generator controls the frequency oscillation in order to frequency modulate the signal. The resulting signal is called the chirp signal [8]

$$x_t(t) = A_t \cos(2\pi(f_0 + \frac{B}{2T}t)t), \tag{2}$$

where A_t represents the amplitude of the transmit signal, f_0 the initial frequency, T the chirp period, and t the time inside a single sweep/chirp period.

The chirp signal is transmitted, reflected on a target, and received by the front end of the receiver

$$x_r(t) = A_r \cos[2\pi(f_0 + \frac{B}{2T}(t-\tau)](t-\tau), \tag{3}$$

where A_r represents the amplitude of the received signal and τ the time delay between the transmission and the reception of the signal.

The received signal is very weak, so it passes through a low-noise amplifier in order to amplify it at high gain and low noise. Fig. 2 shows the transmitted and the received signal.

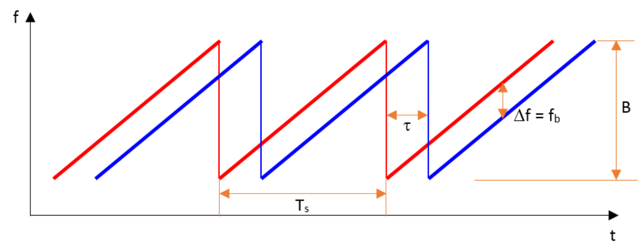

Fig. 2. FMCW Radar chirp signal [9]

After amplification, the signal is mixed with the reference signal

$$x_t(t) \cdot x_r(t) = A_t \cos(\Omega_t).A_r \cos(\Omega_r) \tag{4}$$

After the signal is mixed, two signals with the following frequencies appear

$$\begin{aligned} &\Omega_t + \Omega_r \\ &= 2\pi(2(f_c + \frac{B}{2T_c}t)t - \frac{B}{2T_c}\tau t \\ &-f_c\tau - \frac{B\tau}{2T_c}t + \frac{B\tau^2}{2T_c} \end{aligned} \tag{5}$$

$$\Omega_t - \Omega_r = 2\pi(\frac{B}{T_c}\tau t + f_c\tau - \frac{B\tau^2}{2T_c}) \tag{6}$$

The beat frequency is obtained through equation 6. To obtain that frequency, the mixed signal passes through a low pass filter in order to remove the higher frequency. This frequency is proportional to the distance from the target

$$f_b = \frac{B\tau}{T} \tag{7}$$

$$R = \frac{Tc}{2B}f_b \tag{8}$$

B. Range Resolution and Maximum Unambiguous Range

Range Resolution refers to the minimum distance between two objects that allows you to distinguish them as being different objects. [10]

$$\Delta R = \frac{c}{2B} \tag{9}$$

The maximum unambiguous range refers to the maximum range of a target. In practice, the maximum range is much lower than this limit due to power constraints. [11]

$$R_M = \frac{cT}{2} \tag{10}$$

C. Doppler Effect

When a target moves, the beat frequency will suffer a Doppler Frequency Shift.

$$f_d = \frac{2v}{\lambda} \tag{11}$$

,where v is the speed of the target and λ is the wavelength of the radar. One part of the beat frequency will increase and the other part will decrease. That means there will be two different beat frequencies. The summed part will be used to get the range of the target and the subtracted part the velocity of the target. For this reason, when the target is moving, triangular waveform should be used instead of sawtooh waveform for the transmitted signal. Fig. 3 shows the Doppler Shift Effect on the received signal, for the triangular waveform. [10]

$$f_{bu} = f_b - f_d \tag{12}$$

$$f_{bd} = f_b + f_d \tag{13}$$

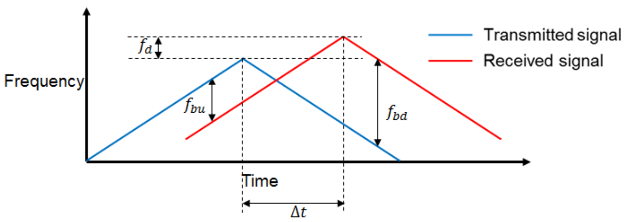

Fig. 3. Doppler Shift Effect on FMCW Radar [12]

III. Simulation

Before the implementation of the FMCW Radar with GNU Radio and the USRP N210, several simulations were made on GNU Radio in order to verify if the developed flow graph was capable of detecting targets.

A. Software Used

To develop the simulations, GNU Radio was used. GNU Radio is a software development tool that provides signal processing functions to implement SDR. The digital processing blocks are developed in C++ and the link between the various blocks is developed in Python. However, an integrated software environment, such as GNU Radio Companion, can be used to realize the applications through a graphical interface.The software developed on GNU Radio can be used without any SDR board in order to perform signal processing in a simulation environment, or in conjunction with a board, such as the USRP N210.

B. Simulation Parameters

1) Sample Rate Value: The sample rate value will influence the bandwidth and subsequently the range resolution. In this system the chosen value for the sample rate was 10 Msps, because even though a higher value would reduce the range resolution, it would require more more computational load.

2) Bandwidth Value: For the bandwidth, the value to be used must comply with the Nyquist theorem, so the maximum bandwidth of the signal is equal to 5 Mhz. The value of the bandwidth translates in a range resolution of 30 meters, which can be to high to distinguish targets, bit as said before, to achieve a bigger bandwidth, a bigger value for the sample rate was needed, and that would require a bigger computational load.

3) Waveform: For the static target simulations, the sawtooth waveform was used since it is simpler, but for the moving target simulations, the triangular waveform was then used.

The following table summarize the specifications for the FMCW Radar simulations.

TABLE I
FMCW Radar Simulation Parameters

Parameter	Value
Sample Rate	10MS/s
Waveform	Sawtooth
Chirp Period	1ms
Bandwidth	5MHz
Range Resolution	30m
Maximum Unambiguous Range	150km

The value of the bandwidth translates in a range resolution of 30 meters, which can be to high to distinguish targets. However, to achieve a bigger bandwidth, a bigger value for the sample rate was needed, and that would require a bigger computational load.

C. Simulation for one static target

The first simulation was made to test the behaviour of the flow graph in the detection of a single static target. The displayed flow graph has the following structure: the Signal Source block is responsible for producing a sawtooth signal. The Delay block introduces a delay in the transmitted signal in order to simulate the presence of a target and to simulate the signal received by the radar. The transmitted and received signals pass through the Multiply block that acts as a mixer of the signals in order to obtain the beat signal. By analyzing the FFT of the beat signal, the frequency difference between the transmitted and received signal is obtained. Fig.4 shows the flowgraph for a single static target.

For this simulation, a delay of 200 samples was used, which means that the delay is 20 microseconds, which corresponds to a range of 2998 meters, from equation 1. According to equation 7 the expected beat frequency is 100 kHz.

$$\tau = \frac{N_s}{f_s} = 20\mu s, \tag{14}$$

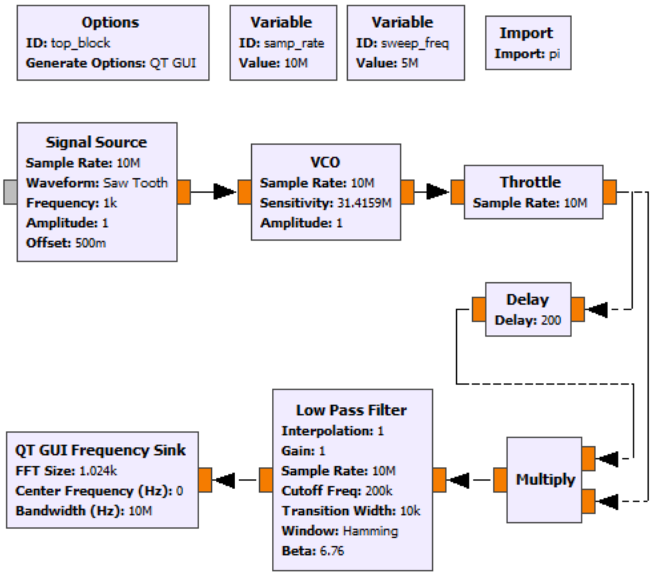

Fig. 4. Static target flowgraph

where N_s represents the number of samples, and f_s the sample rate.

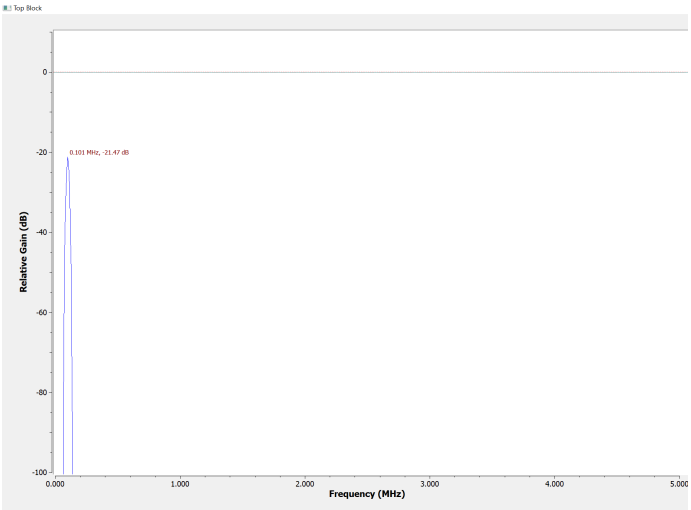

Fig. 5. Static target beat frequency

The observation of the graph shows that the beat frequency obtained with the simulation is in agreement with the theoretical value, which means this flowgraph can obtain the range of the target.

D. Simulation for three static targets

This simulation aimed to verify the behaviour of the flow graph when it has to detect more than one target. To simulate that, two more delay blocks were added to the previous flow graph, one of 400 samples and the other of 600 samples

For this simulation the expected values for beat frequency are 100, 200 and 300 kHz.

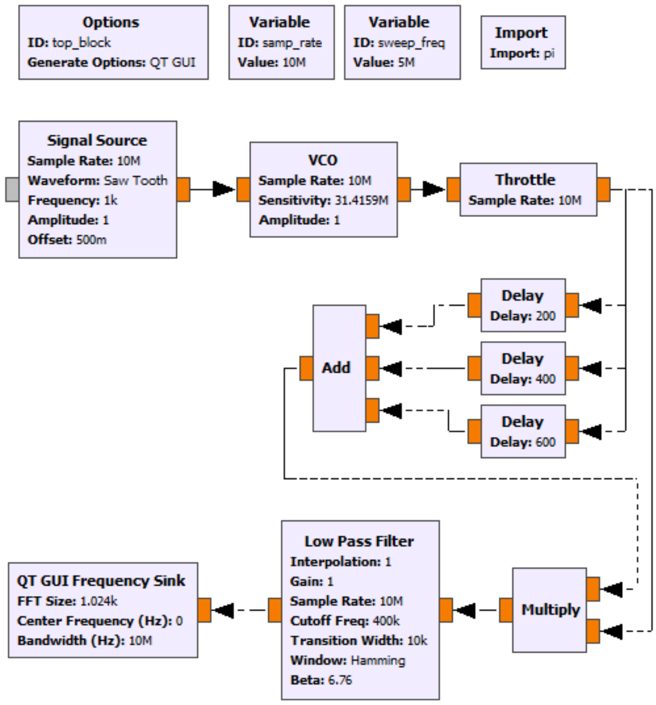

Fig. 6. Static target flowgraph for three targets

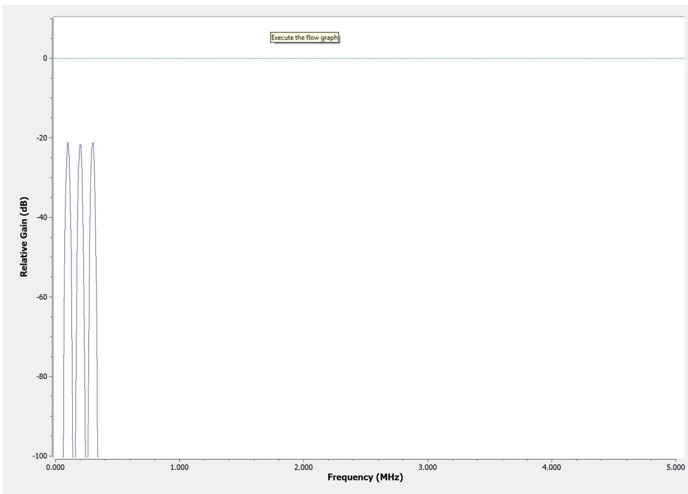

Fig. 7. Beat Frequency for three targets

Fig. 7 shows that this flowgraph is capable of detecting various targets as long as they have a separation bigger than the range resolution.

E. Simulation of a moving target

This simulation was made to verify if the flow graph was capable of detecting a slowly moving target. To achieve that the delay block has a variable value. That variation was made with a signal that varies the delay between a set of two values, and that value is being saved in a variable with the function probe block. The target was simulated to move at a speed of

15 m/s by varying the delay between 100 samples and 200 samples during approximately 100 seconds.

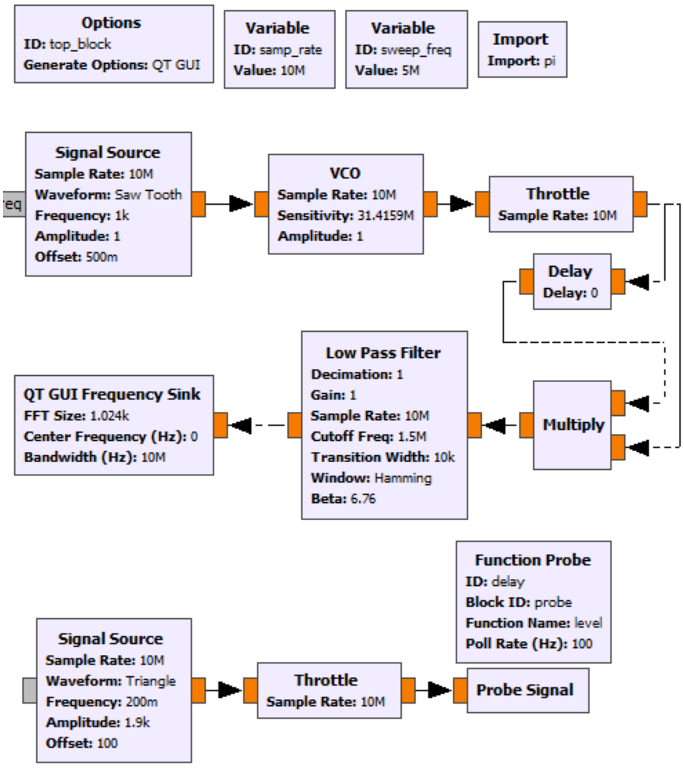

Fig. 8. Flow graph of a moving a target

The beat frequency changes between 50 kHz (for 100 samples) and 100 kHz (for 200 samples). For this flow graph the Doppler shift was not taken under consideration.

F. Doppler Shift Effect

For this simulation, a frequency offset (f_d) of 20kHz was added to the received signal in order to simulate a Doppler frequency from a moving target. For this simulation, a triangular waveform was used since it makes it easier to detect the two frequencies. Fig. 9 shows the designed flowgraph of this simulation.

Fig. 10 shows that two frequencies appear, instead of only the beat frequency. One of the frequencies is equal to $f_b - fd = 80kHz$ and the other is equal to $f_b + fd = 120kHz$.

G. Effect of Noise and Signal Propagation

When a signal is received in real time it suffers attenuation due to propagation through the channel and corruption effects due to noise, which can make if difficult to detect a target. This simulation aims to verify if those effects still make it possible for the developed flow graph to detect targets. The noise effect has the following equation:

$$N = \frac{-178 + 10\log(B) - 30}{10} \tag{15}$$

The attenuation is calculated with the following equation:

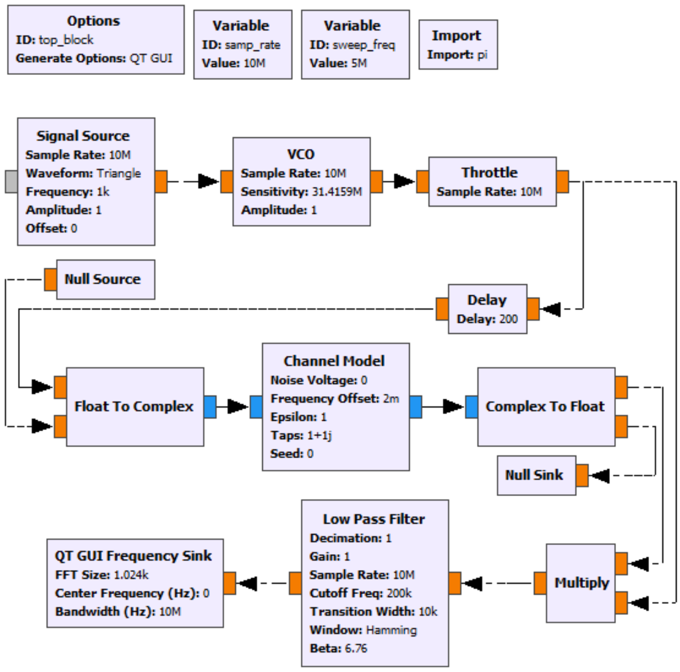

Fig. 9. Flow graph of the effect of Doppler frequency

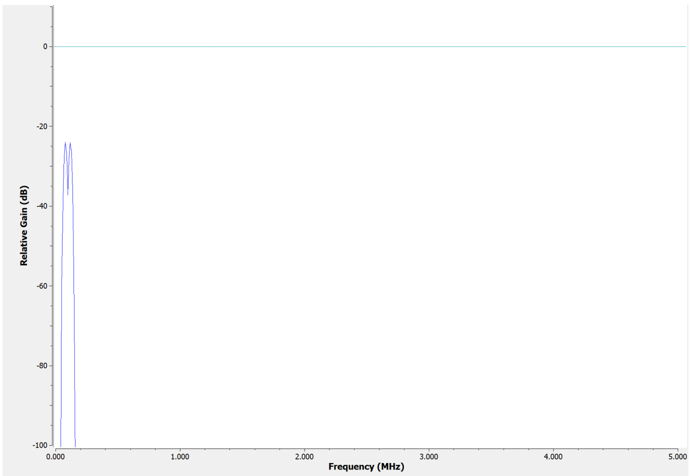

Fig. 10. Doppler Shift Effect

$$FSPL = \sqrt{\left(\frac{\lambda}{4\pi 2R}\right)^2}, \tag{16}$$

where R represents the range of the target and λ the wavelength of the radar. For this simulation it was used a range value for an object delayed 200 samples, which is about 2998m, from equation 8 and a bandwidth of 868 MHz. That gives a noise value with an amplitude of $8.9 \cdot 10^{-8}$ and an attenuation of $4.584 \cdot 10^{-6}$.

The observation of Fig. 12 shows that the signal noise increased, when compared to the simulation without these effects.

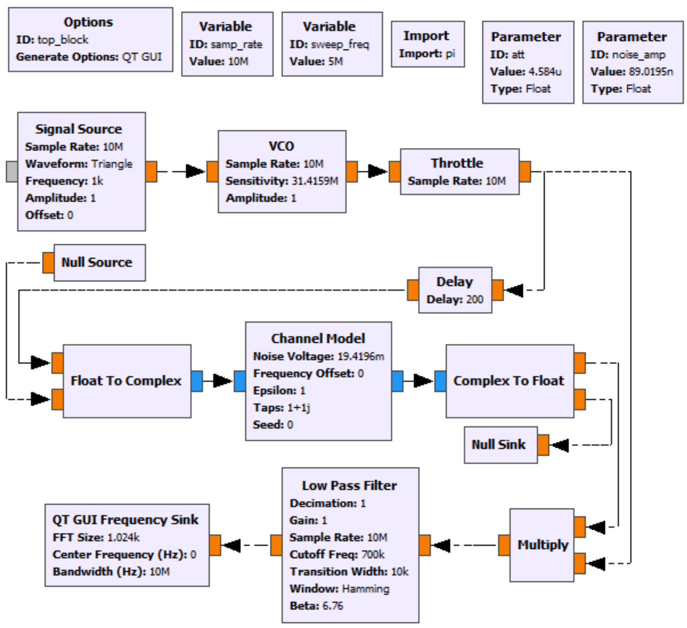

Fig. 11. Flow graph of static target with the effects of noise and attenuation

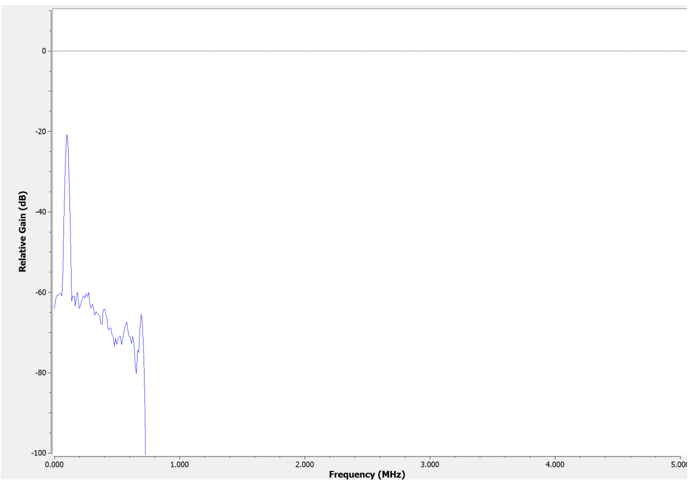

Fig. 12. Power vs Frequency with effects of noise attenuation

IV. Conclusions and Future Work

This work aimed to study a low cost SDR based FMCW Radar which can be used for real time detection of UAVs. A set of simulations implemented with GNU Radio made it possible to verify the initial capabilities and limitations of the SDR based FMCW radar. Future work consists on evaluating the developed software with different SDR hardware. In the future, other modulation waveforms will also be studied.

V. Acknowledgement

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