Research Article

Enhanced Noise Tolerance Levels for Digital Receiver using Non-Linear Frequency Modulation

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Abstract: One of the critical issues concerning the industries of aerospace and Defence is the accuracy and precision levels of the possible range resolution. And equally important is the detection of the signal in the presence of noisy environments. Signal-to-Noise ratio is one such measure that ensures enhancement of target detection in tough environments. Besides this, high range resolution is also essential for the digital receiver to identify closely spaced multiple targets. The projected digital receiver design primarily highlights the possibility of pulse compression techniques combined with linear frequency modulation and non-linear frequency modulation waveforms for refining the range resolution of targets compared to their counterpsrts, the traditional waveforms. The range resolution and detection enhancement using the advanced signal processing techniques in the presence of noisy environments have been presented with evidence from the simulations accomplished in MATLAB. The ability of the pulse compression waveform to perform in the presence of noise has been tested. Further, this paper presents the minimum signal to noise ratio of the received echo signal for achieving the required range resolution with MATLAB simulations. The paper also includes further plan of work to make this design more robust as an adaptable receiver for industrial applications.

***Index Terms*—**Adaptable Receiver, Pulse compression, Noise Tolerance, Non-Linear Frequency Modulation, Range Resolution, Signal-to-Noise Ratio

I. INTRODUCTION

In addition to target detection with an acceptable range resolution which is a pressing factor in military and Defence industries, noise tolerance is another primary performance limiting factor for any radar receivers during the recent years i.e., detection of the target when its echo or return is masked or lost due to environment conditions. In the presence of the unwanted noisy environment, there is a high possible of false positives or false negatives at all as the incoming signal is completely distorted. False positives indicate the presence of target even when there is no target whereas false negative refer to the failure of identification of the targets. These conditions need to be addressed with utmost care to make sure a reconfigurable or an adaptable receiver a possibility.

The ability of the radar to resolve or identify the targets which are spaced very close to each other can ne termed as Range resolution. This attribute of the radar performance that primarily identifies the presence of two or more targets spaced close to each other is pulse width of the transmitted pulse. Many other factors affect the radar range resolution and they include target type, size and shape of the target. If the distance between the targets is than the pulse width of the transmitted waveform, then the targets can be distinguished easily. If not, the return echo from either of the targets will overlap with the signal of the other target, thereby resulting in false identification of two targets as a single target. The range resolution in the mathematical form can be expressed as

$$Range\ Resolution = \frac{c\tau}{2}$$

where τ is the pulse width of the radar waveform.

When a radar waveform is transmitted towards a target, much of the energy that is transmitted is lost due to the multiple obstacles or the presence of weather disturbances. Only a small proportion of the transmitted energy reaches the target and gets rebounded back towards the radar receiver. The rebounded signal also encounters the same level of distortion as that of the initially transmitted signal. Finally, the amount of signal energy received at the radar antenna will only be fraction of transmitted energy. Therefore, radars use long duration pulses to extend the range covered. But the transmitter pulse width cannot be increased forever in order to improve the radar's range without disturbing the other performance parameters of the radar. Larger pulse width delivers greater transmitter power which in turn enhances the Signal-to-Noise ratio of the receiver but has a negative effect on the ability of the receiver to distinguish the targets separated by a distance less than $\frac{c\tau}{2}$. To achieve fine range resolution the transmitted pulse width must be small but considerably reduces the transmitted power and thus SNR of the receiver and maximum range of the radar. Hence a trade-off is necessary between the resolution and the maximum range. This augments the requirement to select a pulse long enough to achieve respectable range and short enough to provide fine range resolution. With the use of pulse compression techniques, this can be made possible. Pulse compression helps us to incorporate the merits of both long duration and short duration pulses i.e., average transmitted power of a relatively long pulse and the range resolution achievable with a short pulse.

S. A. Taylor and J. L. MacArthur discussed some basic properties of the pulse compression, binary $0° - 180°$ phase modulation waveforms with the results obtained from hardware implementation in the article "Digital Pulse Compression Radar Receiver" [1]. They specifically stated that the ease in code generation and signal processing, the flexibility in compression ratio, signal integrity or uniqueness and reliability as some of the major advantages of digital pulse compression.

Another innovative pulse compression technique called Resolution Enhancement Compression (REC) Technique was proposed by Michael L. Oelze in order to improve the echo signal to noise ratio (eSNR) in the research "Bandwidth and Resolution Enhancement through Pulse Compression" [2]. The simulations have indicated enhancement in axial resolution and bandwidth. In addition, peak sidelobes were detected at -45 dB along with significant gain in the eSNR (9-16dB). This process of pulse compression was projected for applications in ultrasonic imaging requirements.

Fritz O'Hora, et.al., focused on Weather monitoring, a primary application of pulsed radars, in their paper "Improving weather radar observations using pulse compression techniques", proposing the use of non-linear frequency modulation (NLFM) pulse compression over the traditional uncompressed pulses [3]. Implementation of pulse compression with NLFM has been exhibited and has been strongly asserted for use in development of digital receivers for weather radars.

B. Damtie, et.al., compared the performance of matched, mismatched and adaptive pulse compression techniques at various levels of input SNR values in the paper "Comparison of the performance of different radar pulse compression techniques in an incoherent scatter radar measurement" [4]. In case of lower Signal to Noise Ratio values, the losses in mismatched filter were analyzed to be higher than the adaptive filter. However, all the three pulse compression techniques were found to have same performance in the case of high Signal to Noise Ratio values.

A new technique of amplitude weighting applied to the combination of incoming signal and its 1-bit shifted version has yielded a better peak side lobe ratio and integrated side lobe ratio than all other sidelobe reduction techniques while maintaining desirable SNR loss levels [5]. Vijay Ramya K. et.al., proposed this system in their research journal, "A New Pulse Compression Technique for Polyphase Codes in Radar Signals".

Mohammed Umar Shaik, et.al., presented Recurrent Neural Network (RNN), a new idea for pulse compression called in the paper "Pulse Compression techniques of Phase Coded Waveforms in Radar" as matched filtering the bi-phase coded radar signals create unwanted side lobes [6]. 13-bit and 35-bit barker codes were identified as input signal to RNN and results were compared with the Multi-Layer Perceptron (MLP) Network results. This provided confirmation that RNN converges faster than MLP in addition to yielding better signal to sidelobe ratio and would be preferable than algorithms like ACF (Auto Correlation Functions). However, the complexity of the receiver naturally increases with the addition of neural networks.

Chandan Singh D. Rawat, et.al., compared three important techniques in pulse compression i.e., Polyphase, Bi-phase and Linear Frequency Modulated Codes in their paper "High resolution low power Pulse Compression Techniques" [7]. The Polyphase Codes P3 and P4 which were derived from the LFM signals illustrate much better peak side lobe level of -31.7dB than LFM itself which is about -13.5dB. The low main lobe width makes them superior to other codes for Radar Pulse Compression.

Thin Thin Mar, et.al., in their research "Pulse Compression Method for Radar Signal Processing" addressed one of the key fundamental issues of a radar system, the capability to resolve two closely spaced targets located at long range [8,9,10]. Pulse compression with LFM pulse modulation was proposed in which the received signal is correlated with matched filter impulse response. The simulations prove that range and resolution can be enhanced with the compression of effective pulse width. Nevertheless, Linear Frequency Modulation generates large sidelobes which might hamper the detection of the smaller of the two targets close to each other at longer ranges[11,12,13].

Of all the techniques discussed, LFM has an inherent advantage of low complexity in the receivers and NLFM provides the advantage of sidelobe reduction without any additional windowing techniques. Also, the effect of noise on these chirp waveforms used for pulse compression and their tolerance levels have not been discussed in any other research work. Hence, this paper emphasizes on the noise tolerance levels of both the pulse compression waveforms such as Linear Frequency waveform and Non-Linear frequency waveform. The simulations will be performed with the help of MATLAB and analysis regarding the range resolution and Signal-to-Noise ratio and the noise tolerance will be presented in the final section.

II. MODIFIED PULSE COMPRESSION WAVEFORMS:

Traditional pulsed radar transmitters used narrow and high-voltage pulses as an input to magnetrons which generates and transmits microwaves. At the radar receiver, target echoes were observed and displayed on a CRT. The sweep of the CRT and the transmitted pulse were synchronized, making it possible to estimate the distance to a target. This is an unremitting process. The fraction of energy reflected in the direction of the receiving antenna from the target is directly dependent on the target size called the Radar Cross Section or the RCS [14,15,16].

Other parameters that effect the range of the radar such as transmitted power, gain of transmit/receive antenna, wavelength of the radar signal, Radar Cross Section (RCS) of the target and the minimum detectable signal are related by the expression below

$$Range = \left(\frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 S_{min}}\right)^{\frac{1}{4}}$$

The concept of pulse compression arises from the requirement of improving the range resolution of the radar receiver with a short duration pulse in addition to maintaining the range with a relatively longer pulse duration. It involves modulation of the transmitted pulse. The pulse is divided into sub pulses and each sub pulse is modulated with a different frequency. This makes it possible to overlap all the radar returns at the receiver and to compress it into a single short duration pulse. As the duration of the echo pulse is shortened, the process is called the Pulse compression. Thus, it is a method of increasing the width of transmitted pulse to improve the range of the radar, without degrading the range resolution.

Another aspect of pulse compression which is of interest is the improvement in Signal-to-Noise Ratio. For a conventional pulsed radar, the SNR is given as

$$SNR = \frac{P_T G_T G_R \lambda^2 \sigma \tau'}{(4\pi)^3 R^4 k T_{eff} F L}$$

Where $kT_{eff}FL$ is the noise power. k is the Boltzman's constant, T_{eff} is the effective temperature, F is the noise figure and L accounts for total radar losses. In the case of pulse compression, since the transmitted pulse can be viewed as a series of sub pulses with the duration of the required compressed pulse width τ_c, the SNR for a single subpulse is given by

$$SNR_{subpulse} = \frac{P_T G_T G_R \lambda^2 \sigma \tau_c}{(4\pi)^3 R^4 k T_{eff} F L}$$

As the number of sub pulses in the transmitted waveform increases the Signal-to-Noise ratio is improved drastically.

Pulse compression waveforms for radars which are designed with a specific intention such as to improve the Signal-to-Noise ratio and achieve fine range resolution of targets. This can be effectively accomplished by carrying out amplitude modulating or frequency modulating or phase modulating the pulse before transmission. Modifying the envelope of the pulse in accordance to an instantaneous signal is called intrapulse amplitude modulation which is used in cases where bandwidth of the waveform may have to be enhanced [12].

Phase Modulation or Phase coded waveforms consist of a number of chirps with intentionally varied phases between the sub pulses to obtain the intended main lobe width and sidelobe levels. There are many phase coded waveforms such Barker Codes, Frank Codes, Polyphase Codes P1, P2, P3, P4 etc. These codes generally rank below the Frequency modulated waveforms as far as the sidelobe attenuation is considered.

Frequency modulation is another technique of intrapulse modulation. Based on the instantaneous signal that is used to modulate the transmitting pulse, the intrapulse frequency modulation is subclassified into Linear Frequency Modulation and Non-Linear Frequency Modulation. The Linear Frequency Modulation is be used in cases where preserving the existing resolution is significant while reducing the required bandwidth. But Linear Frequency Modulation has some side effects such as Range sidelobes which in turn can be handled using windowing techniques. On the other hand, Non-Linear Frequency Modulation waveforms provide low side lobe levels when compared to LFM before the application of any windowing methods.

In addition, this paper also concentrates on the noise tolerance of these waveforms i.e., the performance of the receiver in terms of target identification for different levels of noise added to the received signal is also experimented. The instantaneous frequency used for the generation of the linear frequency modulated waveform during the research is specified in the equation below.

$$f_{LFM} = (f_0 + k * t) - - - - (1)$$

Here, f_{LFM} is a linear function of t and f_0 and k are constants. The frequency of the pulse for transmission is modulated according the variation of f_{LFM} in equation 1. The instantaneous frequency for the non-linear frequency modulated waveform is specified in the below equation.

$$f_{NLFM} = (f_0 + k * t + \cos(t)) - - - - (2)$$

Here, f_{NLFM} is a non-linear function of t i.e., t and f_0 and k are constants and hence the change in instantaneous frequency of the pulse is also non-linear as the cosine signal is non linear. In the subsequent sections, pulse compression technique is presented with both the Linear and Non-Linear Frequency Modulated waveforms which are generated by their respective instantaneous frequencies shown in Figure 1. The results generated for targets spaced at different ranges as well as the trade-offs adopted to improve the range resolution will be presented in the further sections.

III. SIMULATED RESULTS:

To perform pulse compression, the LFM and the NLFM chirp waveforms should be generated at the transmitter end.

The Pulse compression waveforms are generated in accordance to the instantaneous frequency variation in the Figure 1. The frequency changes are indicated for both LFM and NLFM waveforms are marked in the legend.

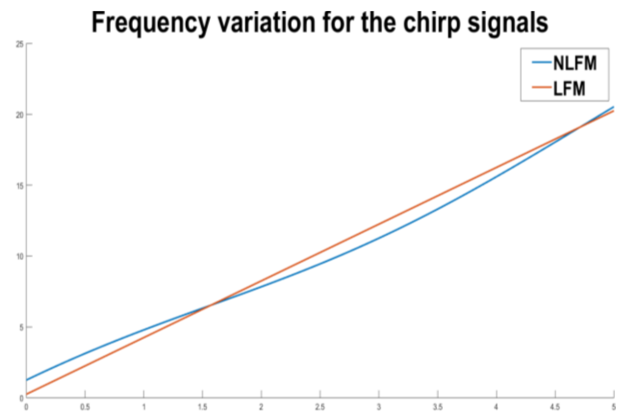

Figure 1: Instantaneous frequency for LFM and NLFM waveforms

The equation for generating the Linear Frequency Modulated waveform is shown below

$$Signal_{LFM} = sin(2\pi f_{LFM} t)$$

Non-Linear Frequency Modulated waveform is generated using the following equation

$$Signal_{NLFM} = sin(2\pi f_{NLFM} t)$$

The f_{LFM} and f_{NLFM} vary in accordance to the equations (1) and (2). LFM signal considered is a sine wave with linearly increasing frequency for a duration of $5\ \mu s$. The NLFM signal taken into consideration here is also a sine wave with frequency varying in a non-linear fashion as shown in Figure.4 for a duration of 5 µs. The waveforms of LFM and NLFM are indicated in the Figure 2.

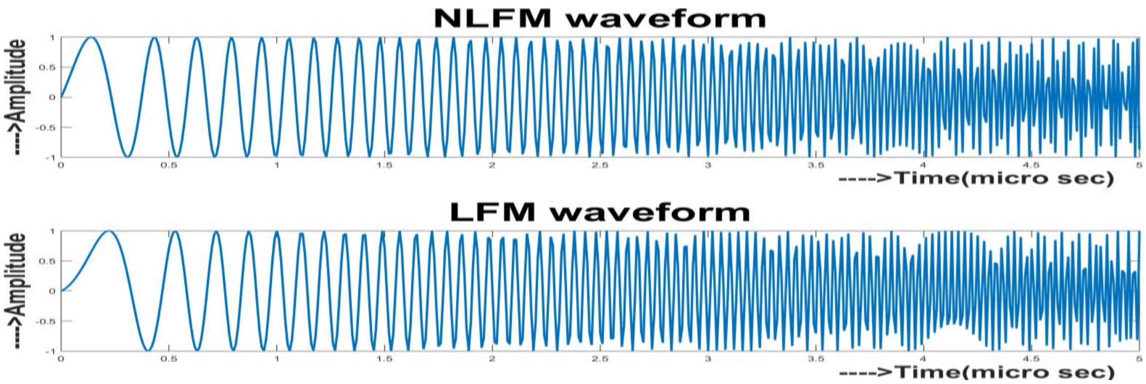

Figure 2: LFM and NLFM waveforms

Before performing the simulation in MATLAB, the targets are assumed to be located at 2000 m, 2200 m and 2200.3 m distance from the transmitter with radar cross section of $1m^2$. Sampling frequency is chosen at 800 MHz and it can be modified depending on the requirement. The simulations performed in MATLAB have also considered environmental conditions such as introduction of additive white gaussian noise.

At the receiver end, the echo signals from the individual scatterers are gathered and the same is shown in the below figure.4

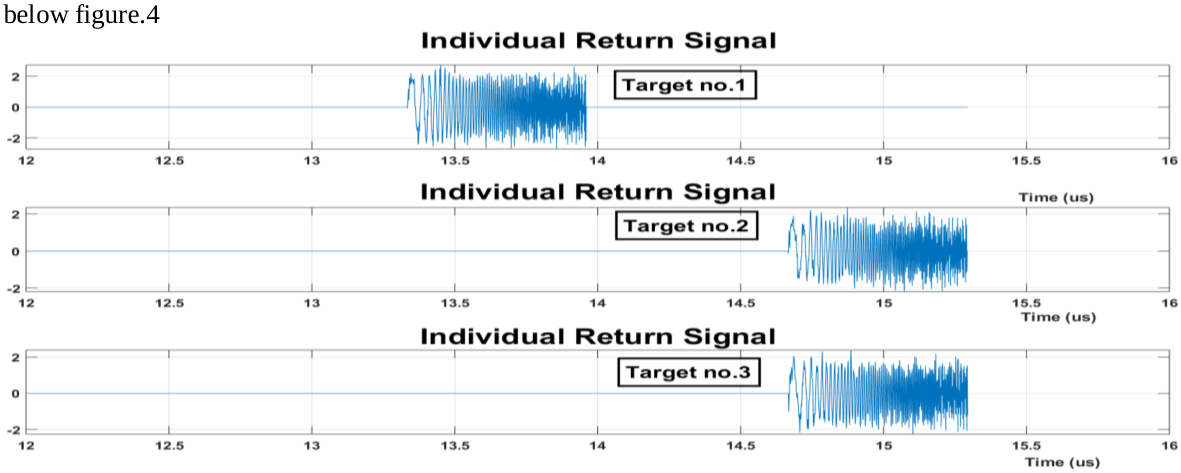

Figure 3: Individual return signals at the receiver

The composite signal is created by combining all of them. The composite signal is shown in the figure.4 below.

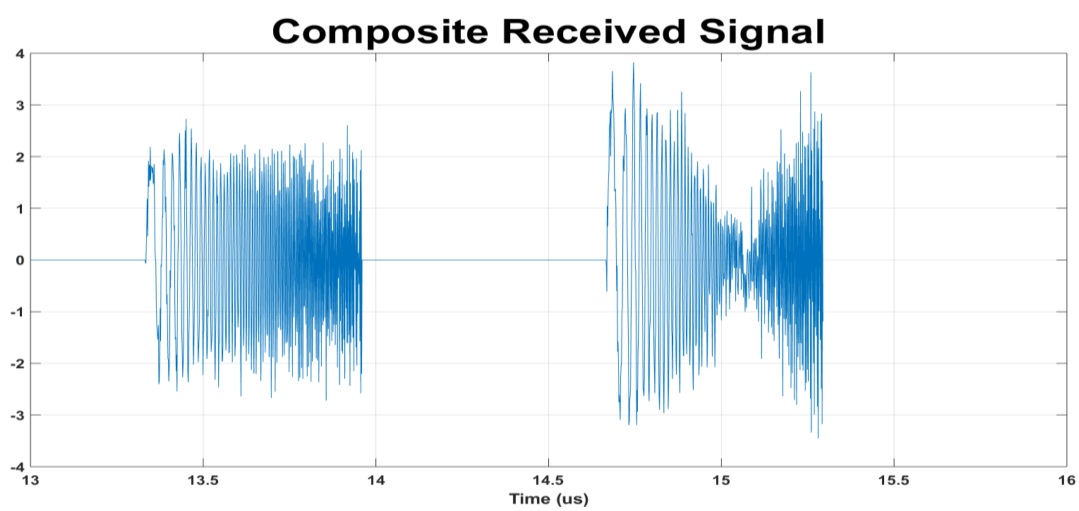

Figure 4: Received signal before matched filtering

Implementing pulse compression is similar to that of matched filter i.e., the received signal and exact replica of the transmitted signal are convolved to yield a narrow output pulse at the location of highest correlation [13]. Also, in order to reduce the side-lobes certain windowing techniques like Hanning window, Kaiser window and Taylor window are employed. Only NLFM technique is considered in this paper for target detection as it has an inherent advantage of very low side lobes over LFM. Hence this helps us to resolve closely spaced targets as they will not be overshadowed by the low sidelobes.

The waveforms after pulse compression are shown in the Figure 5 and Figure 6 respectively.

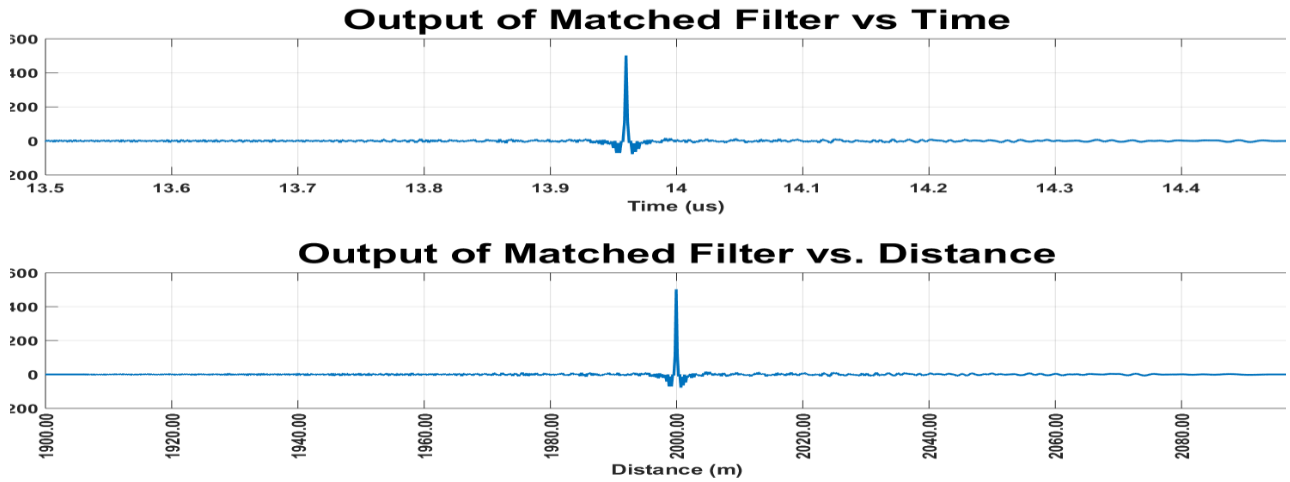

Figure 5: Pulse Compression with NLFM waveform (near target located at 2000m)

In Figure 5, the result of pulse compression near target at 2000m is displayed where it is clear that the echo signal has been clearly separated from the background noise introduced.

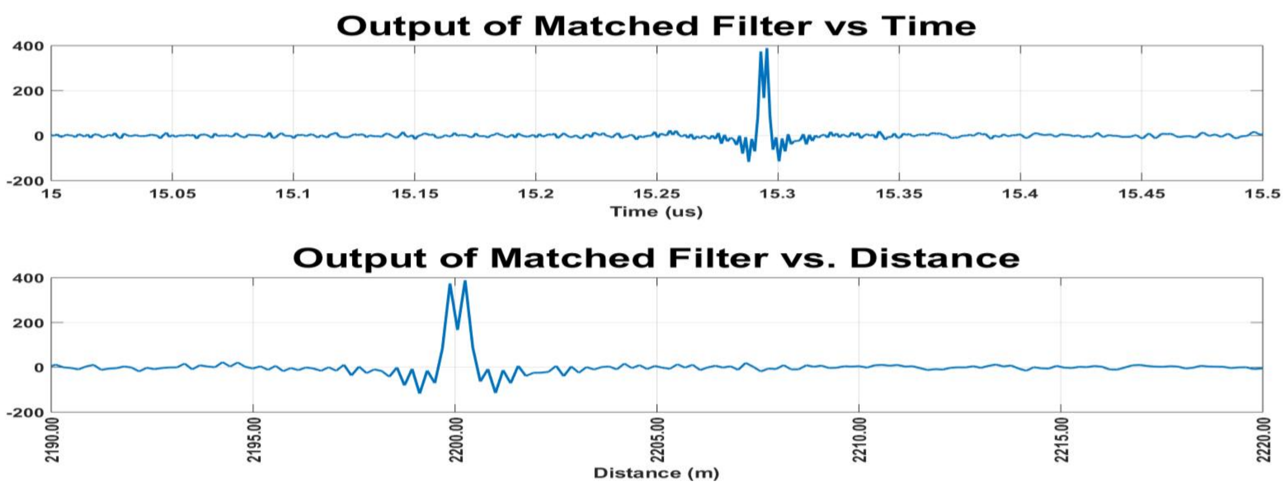

Figure 6: Pulse Compression with NLFM waveform (near targets located at 2200m, 2200.3m)

Figure 6 displays the pulse compression near the other two targets which are separated by 0.3m. The detections of the targets are based on a threshold value calculated using a MATLAB function for detection of SNR threshold for signal in white Gaussian noise. The threshold value was calculated to be -9.77dB. Therefore, if the received signal has the power greater than the threshold value after pulse compression, it is considered as detection. The output of pulse compression in dB scale is shown in the below figures.7 and figure.8

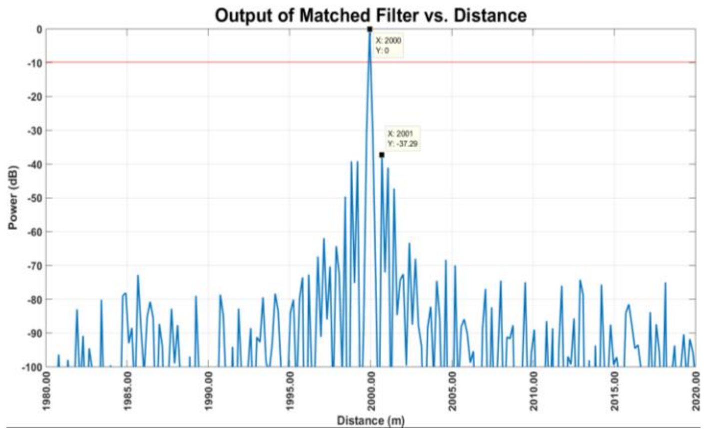

Figure 7: Detection of target located at 2000m

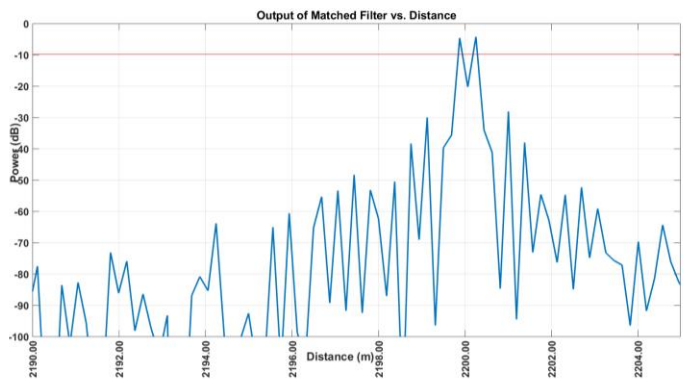

Figure .8 Power spectrum density

In addition to the above, the detections and the Peak Side Lobe Ratios were observed in case of different SNR values. These observations are recorded in Table 1.

Table 1: Comparison of LFM and NLFM PSLR's against SNR of the received signal

SNR (dB) of the received signal	Peak Side Lobe Ratio (dB)	
	LFM	NLFM
0	-27.98	-39.84
-3	-25.39	-37.29
-7	-23.1	-32.7
-8	-23.38	-30.04
-9	-21.87	-31.23
-10	-19.86	-30.26
-11	-20.85	-29.66
-12	-17.03	-22.92
-13	-9.507	-14.52

From the data recorded in Table 1, it is clear that Non linear frequency modulated waveforms provide better peak side lobe ratios compared to Linear frequency modulation waveforms due to very low side lobes advantage. Also, when the SNR of the received signal is 0dB i.e., when the signal power and noise power are equal, we are able to identify the 3 targets as shown in Figure 5 and Figure 6 as the SNR is enhanced with the implementation of matched filtering or pulse compression. In fact, when the noise power is greater than the signal power in the received echo, pulse compression with the proposed NLFM and LFM waveforms were able to identify all the targets. For SNR below -12dB, some missed detections and false positives were observed. Hence the noise tolerance levels have been enhanced for two different LFM and NLFM waveforms and demonstrated using MATLAB.

IV. FURTHER RESEARCH

Fine range resolution for military and other radar applications has been successfully achieved bearing in mind the trade-offs between range and SNR along with high-speed ADC's for fast RF sampling. Further research will include utilizing the Software Defined Radios for implementing the above demonstrated techniques for testing in the real-world to judge the validity of simulations. Using the SDR will also become one of the best and low-cost solutions available for processing the radar data in real time. Hence, the ultimate goal of an adaptable receiver for industrial applications is possible.

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