RADAR PULSE COMPRESSION

INTRODUCTION

A pulse compression radar system emits a long pulse with a pulse width of T and a peak power of P_t. This pulse is coded using frequency or phase modulation to achieve a bandwidth B, which is significantly larger than that of an un-coded pulse of the same duration. The width of the transmitted pulse is selected to achieve the single-pulse transmit energy ($E_{t1} = P_t T$), necessary for detecting a target. The received echo is processed using a pulse compression filter, resulting in a narrow compressed pulse response with a main lobe width of approximately 1/B, independent of the transmitted pulse's duration.

As shown in Figure 1.1, a basic pulse compression radar system's block diagram, the coded pulse is initially generated at a low power level in the waveform generator. It is then amplified to the required peak transmit power using a power amplifier transmitter. The received signal is mixed to an intermediate frequency (IF) and amplified by the IF amplifier. The signal is subsequently processed using a pulse compression filter, which includes a matched filter to achieve the maximum signal-to-noise ratio (SNR). If necessary for reducing time side lobes, a weighting filter follows the matched filter. The pulse compression filter's output is applied to an envelope detector, amplified by the video amplifier, and displayed to an operator.

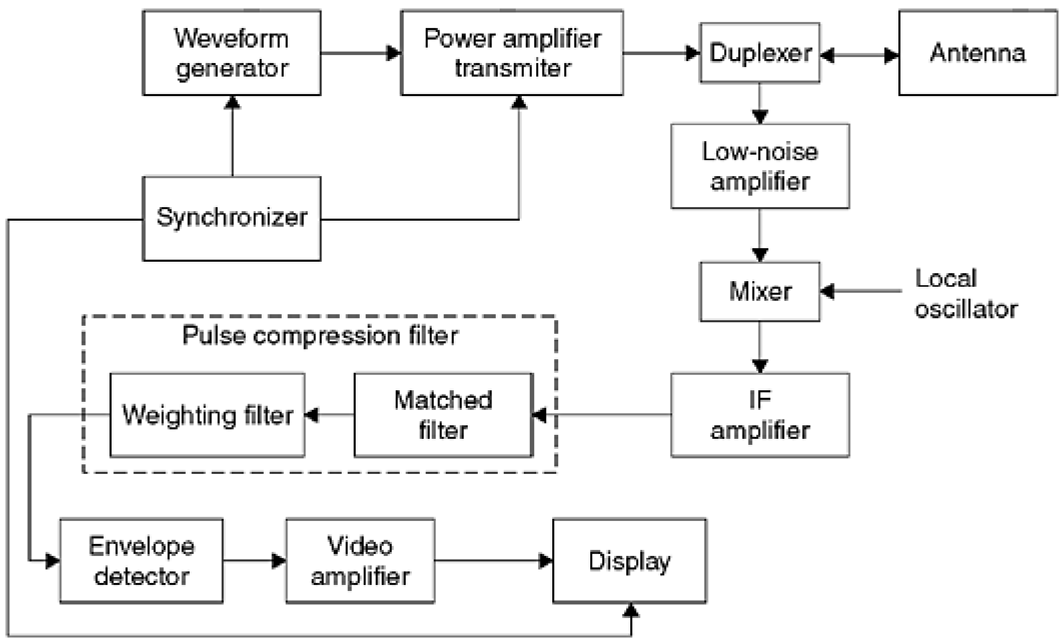

Figure 1.1 Block Diagram of Basic Pulse Compression Radar

The pulse compression ratio is defined as the ratio of the transmit pulse width to the compressed pulse main lobe width. This ratio is approximately T/ (1/B) or TB, where TB represents the waveform's time-bandwidth product. Typically, the pulse compression ratio and time-bandwidth product are significantly larger than one.

Pulse compression boosts radar performance by extending detection range without losing resolution, similar to narrow, un-coded pulse radars. It raises transmitted energy without going over peak power limits, increasing average power without altering PRF, maintaining unambiguous range, and decreasing susceptibility to interference. However, compressed pulse main lobes often have side lobes, which can hide targets detectable with narrower pulses. While some waveforms achieve acceptable side lobe levels with matched filters alone, linear frequency modulation typically needs extra weighting filtering, though this lowers the signal-to-noise ratio compared to using just matched filtering.

LITERATURE SURVEY

Pulse compression serves as a fundamental technology in contemporary radars, providing the desirable blend of high range resolution and substantial average power. Here are some of key development areas in pulse compression research:

- This research explores the development of automotive radars using CMOS technology for short-range applications in the K-band frequency range. It discusses the use of Ultra-wideband (UWB) radar technology for efficient spectrum utilization and the importance of code assignment for interference resilience and high-range resolution. The study also reports on a K-band UWB transmitter with an integrated pulse generator capable of a reconfigurable coding scheme.
- This review discusses pulse compression signals' importance in tracking radars, focusing on binary phase-coded signals like Barker codes and linear maximal length sequences. It explores the use of complementary sequences, linear frequency modulated signals, polyphase codes, and signals with simultaneous amplitude and phase modulation.
- The study by Arya V J and Subha V delves into the use of Pulse Compression Technique (PCT) in radar systems. PCT, which transforms a short pulse into a longer one and includes modulation, aids in maintaining range resolution while lowering peak power. The research also examines the role of Matched Filter systems in implementing Pulse Compression Radars with a goal to optimize the signal-to-noise ratio (SNR) of the received signal. Furthermore, it investigates the application of Linear Frequency Modulation in radar systems.

METHODOLOGY

Pulse compression involves modulating the transmitted pulse with a specific code or waveform, like linear frequency modulation (chirp).The receiver then applies a matched filter or correlator to compress the pulse in time and boost its peak power. This filter or correlator is designed to closely match the transmitted waveform, maximizing output when the received signal matches the expected signal. The following outline the characteristics of linear and nonlinear frequency modulation waveforms, phase-coded waveforms, and time-frequency coded waveforms.

1. **Linear Frequency Modulation :**
   A linear frequency modulated waveform is given as,

   $$x(t) = cos\left(\pi \frac{\beta}{\tau} t^2\right),\ \ 0 \le t \le \tau \qquad \text{Equation 1}$$

   The complex equation is

   $$x(t) = e^{i\pi\beta t^2} = e^{i\theta(t)},\ \ 0 \le t \le \tau \qquad \text{Equation 2}$$

The instantaneous frequency in hertz of this waveform is the time derivative of the phase function.

$$F_i = \frac{1}{2\pi}\frac{d\theta(t)}{dx} = \frac{\beta}{\tau}t\ \ hertz \qquad \text{Equation 3}$$

The function, assumes $\beta > 0$. Fi(t) linearly sweeps across a total bandwidth of β Hz during the τ-second pulse duration. The below figure illustrates the waveform x(t) for $\beta\tau = 50$. This waveform is commonly referred to as a Linear Frequency Modulation (LFM) waveform or chirp waveform, drawing an analogy to the sound of an acoustic sinusoid with a linearly changing frequency. When β is positive, the pulse is an upchirp; if β is negative, it is a downchirp. The Bandwidth-Time (BT) product of the LFM pulse is simply $\beta\tau$. For the LFM pulse to qualify as a pulse compression waveform, $\beta\tau$ should be greater than 1.

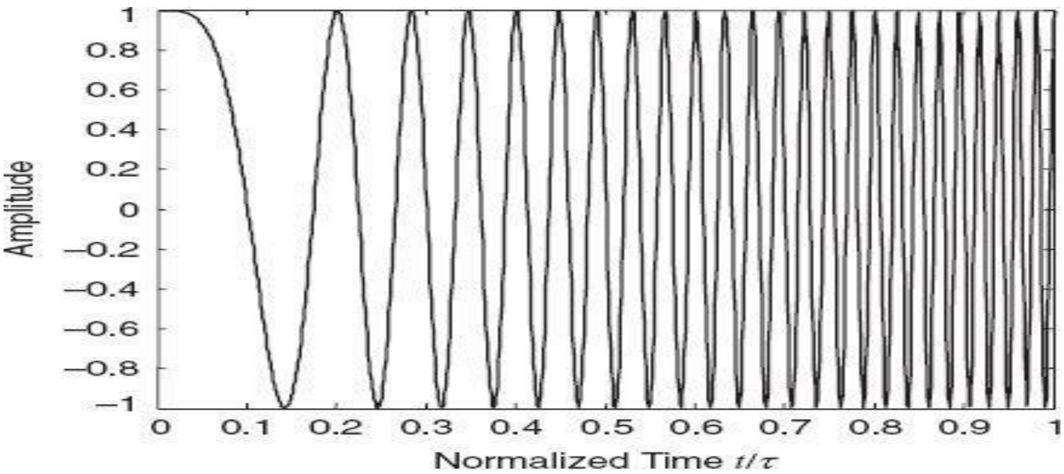

Figure 2 Real-valued LFM upchirp waveform, BT product βτ = 50.

The Linear Frequency Modulation (LFM) waveform offers precise control over pulse energy and range resolution by adjusting its duration and swept bandwidth, respectively. Utilizing matched filters enables pulse compression, where the filter output represents the autocorrelation function of the transmitted waveform rather than replicating it directly. By designing a waveform with extended duration and a focused autocorrelation, both range resolution and energy can be optimized simultaneously. Achieving this involves modulating a lengthy pulse to spread its bandwidth beyond the typical limit. The autocorrelation spectrum, being the squared magnitude of the waveform spectrum, concentrates most of its energy in a main lobe of approximately 1/β seconds duration when the spectrum is spread over β Hz. Linear FM pulses exemplify this concept, but phase-coded waveforms offer additional instances of this strategy.

The LFM waveform exhibits range-doppler coupling which causes the peak of the compressedpulse to shift in time by an amount proportional to the doppler frequency. The peak occurs earlier in time at t = −f T/B for apositive LFM slope, compared to peak response for a stationary target. The peak of the ambiguity function is shifted to τ = f T/B for a positive LFM slope.

With this pulse compression method, the transmission pulse is frequency modulated linearly. This has the advantage that the circuit can still be kept relatively simple. However, the linear frequency modulation has the disadvantage that interference can be generated relatively easily by so-called “sweepers”. In the following circuit example, the principle is illustrated using five frequencies present in the transmission pulse.

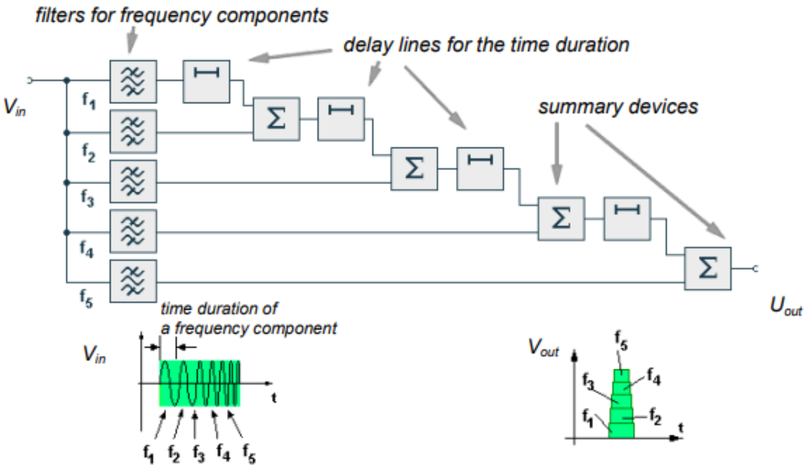

Figure 3 Pulse Compression Filter

The transmission pulse is divided into several time intervals with an assumed constant frequency. Special filters for exactly the frequency in the respective time interval result in one output signal each, which is added to an output pulse in a cascade of delay lines and adding stages.

One notable application of pulse compression with a linear FM waveform is found in the AN/FPS–117 air-defense radar. Despite its high circuit complexity, advancements in chip integration technology have made it entirely manageable.

Filters for linear FM pulse compression radars typically fall into two categories:

- Processor-Controlled Data Processing: After analog-to-digital conversion, the echo pulse is initially distributed across numerous memory cells. The processor is then responsible for detecting the exact memory pattern, especially when multiple echo signals are superimposed in this memory area.
- Analog SAW-Filters (Surface Acoustic Wave Devices): Alternatively, some systems utilize analog SAW-filters for pulse compression. These devices offer efficient signal processing capabilities for radar applications.

SAW Filter

SAW filters compress frequency-modulated echo signals in an analogous manner, operating on the piezoelectric principle. A broadband transducer is vapor-deposited onto a piezoelectric crystal, converting electrical oscillations into mechanical vibrations within the crystal. However, these mechanical vibrations propagate much slower than electrical signals along a line, resulting in relatively high delay times, typically in the range of microseconds.

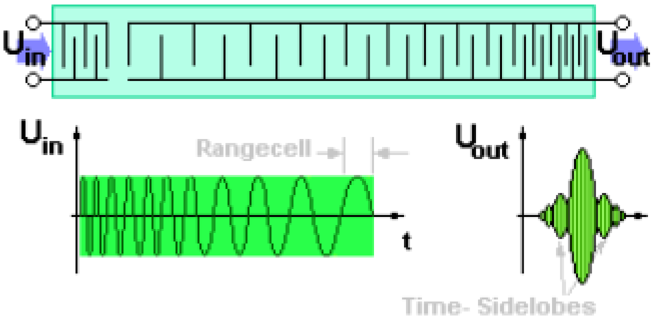

Figure 4 SAW Filter with linearly decreasing finger spacing

On the same crystal, a series of frequency-dependent transducers are deposited, converting mechanical oscillations back into electrical signals. The spacing of these transducers from the feeding system varies, causing different frequency components of the input signal to experience different time delays. This ensures that all frequency components of the input signal are shifted within the same range cell. This structure is primarily utilized in linear frequency modulation. The spacing between the "fingers" on the crystal determines the resonant frequency. The first frequency in the pulse (on the left side) requires the longest delay. Consequently, the vapor-deposited fingers on the piezoelectric crystal, tuned precisely to this frequency, are positioned at the opposite end of the feeding system.

2. Phase-Coded Waveform.

Phase-coded waveforms divide a pulse into subpulses, each lasting $\delta = T/N$ where T is the pulse width and N is the number of subpulses. These waveforms are distinguished by phase modulation applied to each subpulse. Binary Phase Codes involve two phases, known as binary or biphase coding. They maintain a constant magnitude with phase values of either 0° or 180°. The binary code comprises a sequence of 0s and 1s or +1s and −1s.

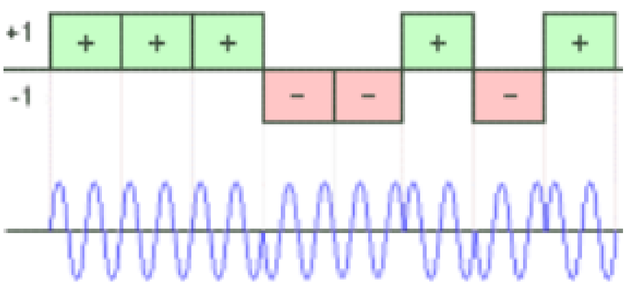

Figure 5 Phase Coded

The signal switches between 0° and 180° based on the phase code sequence, often causing discontinuities at phase-reversal points due to the frequency not aligning with the subpulse width. This leads to increased spectrum sidelobe levels but doesn't affect time sidelobes. Compressed pulse, acquired via matched-filter processing upon reception, typically has a width at the half-amplitude point equivalent to the subpulse width. Hence, range resolution directly relates to the duration of one code element, corresponding to one subpulse. The time-bandwidth product and pulse compression ratio are linked to the number of subpulses in the waveform, essentially the code's element count.

Optimal Binary Codes are sequences designed to minimize the peak sidelobe of their aperiodic autocorrelation function for a given length. In pulse compression radars, codes with low sidelobes or zero-doppler response are preferred. However, responses from moving targets differ, potentially increasing time sidelobes. Using a matched filter solely based on zero-doppler response may degrade as doppler shift increases. Employing a bank of matched filters covering expected doppler shifts can mitigate this, though older radar systems often don't due to computational limits. Modern radar systems, with enhanced computational capacity, find this approach more feasible.

Barker Codes, a special class of binary codes, have peak time sidelobe levels equal to $-20\log(N)$, where N is the code length. They exhibit minimum energy in the sidelobe region, uniformly distributed. Barker codes are the only uniform phase codes achieving this level. Known binary Barker codes are listed in table with lengths of 2, 3, 4, 5, 7, 11, and 13.

Length	Code
2	11, 10
3	110
4	1101, 1110
5	11101
7	1110010
11	11100010010
13	1111100110101.00

Figure 7 Binary Codes

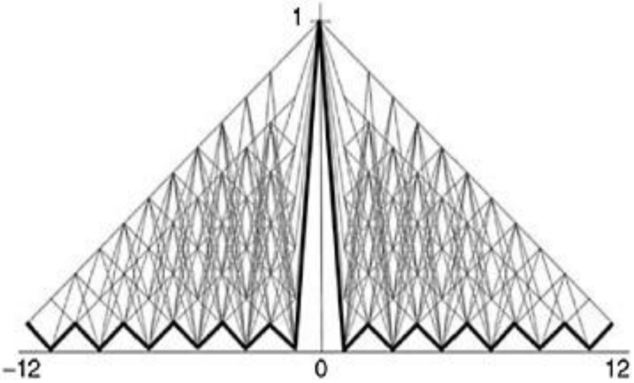

Figure 6 Barker Code of 13bit Code sequence

A pulse compression radar using Barker codes is limited to a maximum time-bandwidth product of 13. The autocorrelation function of a length 13 Barker code for zero doppler shift, overlaid with all possible autocorrelation functions of 13-bit binary sequences, demonstrates that Barker codes offer the lowest time sidelobe levels among possible codes.

MATLAB Implementation :

Rectangular Chirp : The pulse lasts for 1 second, with a frequency of 10 Hz (denoted as f0), and it is sampled at a rate of 1 kHz (denoted as fs).
Received Signal : This signal represents distant target seperated by 2sec and starting at 5sec based off the original signal with added gaussian white noise with SNR of 15dB.

```
fs = 1e3;
tmax = 15;
tt = 0:1/fs:tmax-1/fs;
f0 = 10;
T = 1;
t = 0:1/fs:T-1/fs;
pls = cos(2*pi*f0*t);
```

Figure 9 Transmit signal

```
t0 = 5;
dt = 2*T;
lgs = t0:dt:tmax;
att = 1.1;
ref = 0.2;
rpls = pulstran(tt,[lgs;ref*att.^-(lgs-t0)]',pls,fs);
SNR = 15;
r = randn(size(tt))*std(pls)/db2mag(SNR);
rplsnoise = r+rpls;
```

Figure 8 Receive Signal

Another receive signal is generated to compare with multiple target close these two signals are cross corelated with the transmitted signal and plot output of Matched filter.

```
[m,lg] = xcorr(rplsnoise,pls);
m = m(lg>=0);
tm = lg(lg>=0)/fs;
plot(tt,rplsnoise,t,pls,tt,rpls)
```

Figure 10 Cross Correlation

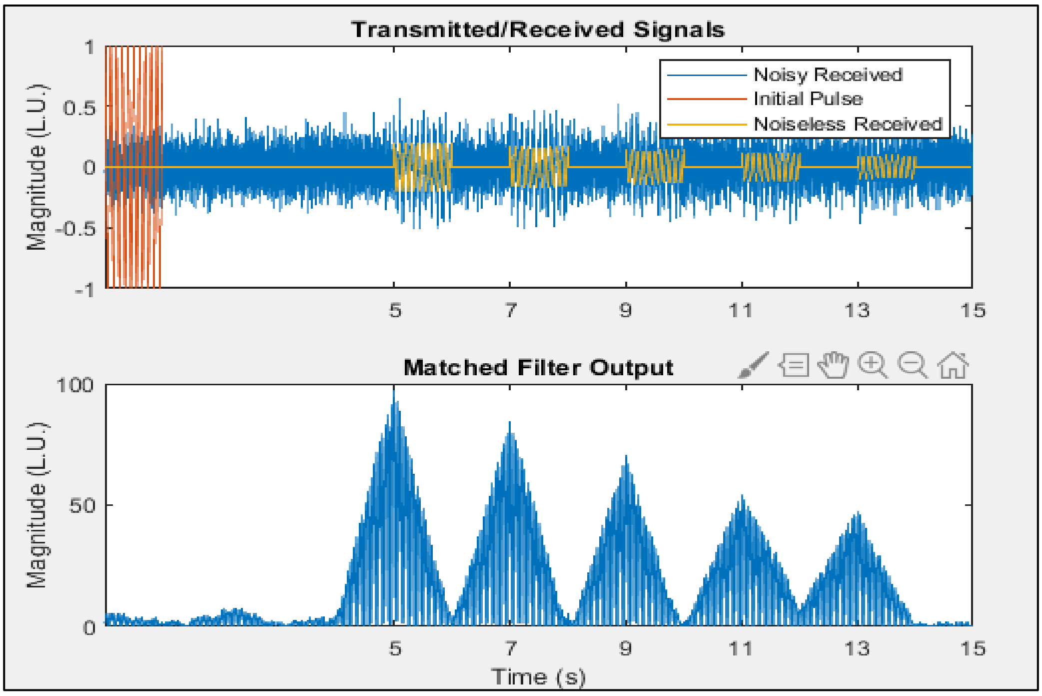

Figure 12 Cross Correlation with dt = 2sec

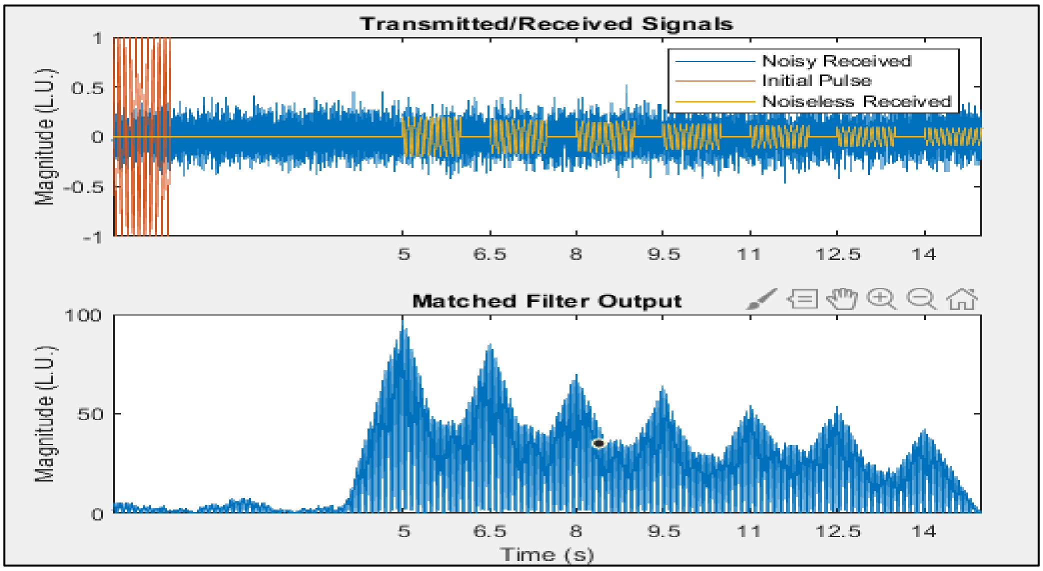

Figure 11 Cross Correlation with dt = 1.5sec

- The echoes from multiple target is been detected through cross correlation for the rectangular chirp signal the target identify from transmitted signal was observable for consideration of significant distance between multiple target detection
- When dealing with echoes from multiple targets, it becomes feasible to approximate the targets' positions because the echoes are sufficiently spread apart. However, when targets are closer together, their responses blend, making it challenging to discern individual targets.

Linear Frequency Modulation: Using a complex chirp starting from 0 Hz and linearly increasing to 10 Hz, real-world radar systems often employ these signals to enhance range resolution due to their larger and narrower matched filter response. Note that all plots must use the real part of the waveform as both the chirp and matched filter possess imaginary components.

```
pls = chirp(t,0,T,f0,'quadratic');
rpls = pulstran(tt,[lgs;ref*att.^-(lgs-t0)]',pls,fs);
r = randn(size(tt))*std(pls)/db2mag(SNR);
rplsnoise = r + rpls;
[m,lg] = xcorr(rplsnoise,pls);
m = m(lg>=0);
tm = lg(lg>=0)/fs;
```

Figure 14 Linear Frequency Modulation

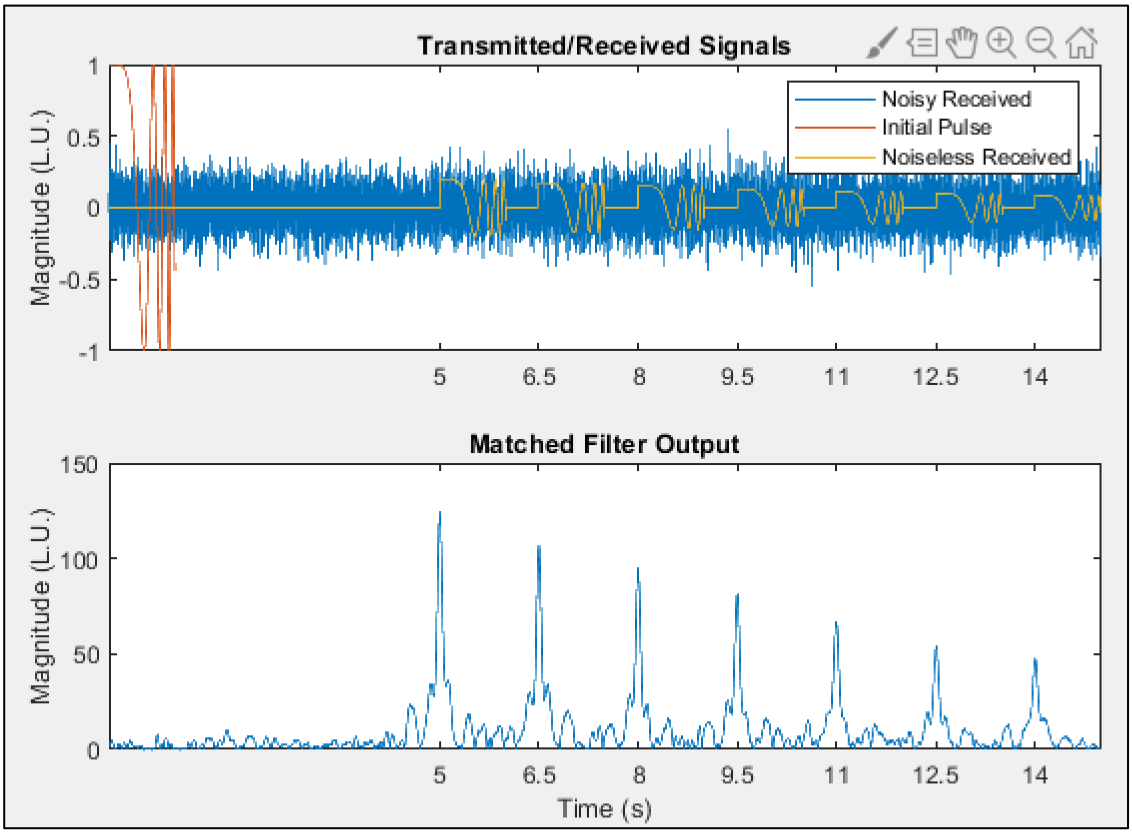

Figure 13 LFM Signal

- Cross-correlation using a linear FM chirp offers significantly finer resolution for target noise, even when the target echoes are closely spaced. Additionally, compared to the rectangular chirp, the side lobes of the echoes are substantially reduced, enhancing the accuracy of target detection.
- The use of Linear Frequency Modulated signal improved the range resolution and able to detect closely spaced target much better.

Phase Coded Waveform: Generated and visualize two-pulse phase-coded waveforms employing the Zadoff-Chu code. With a sample rate of 1 MHz, chip width of 5 microseconds, and 16 chips per pulse, we'll adjust the pulse repetition frequency (PRF). The first call will set PRF to 10 kHz using the PRF index, the second to 25 kHz, and the third back to 10 kHz. Then, plot the phase-coded waveforms.

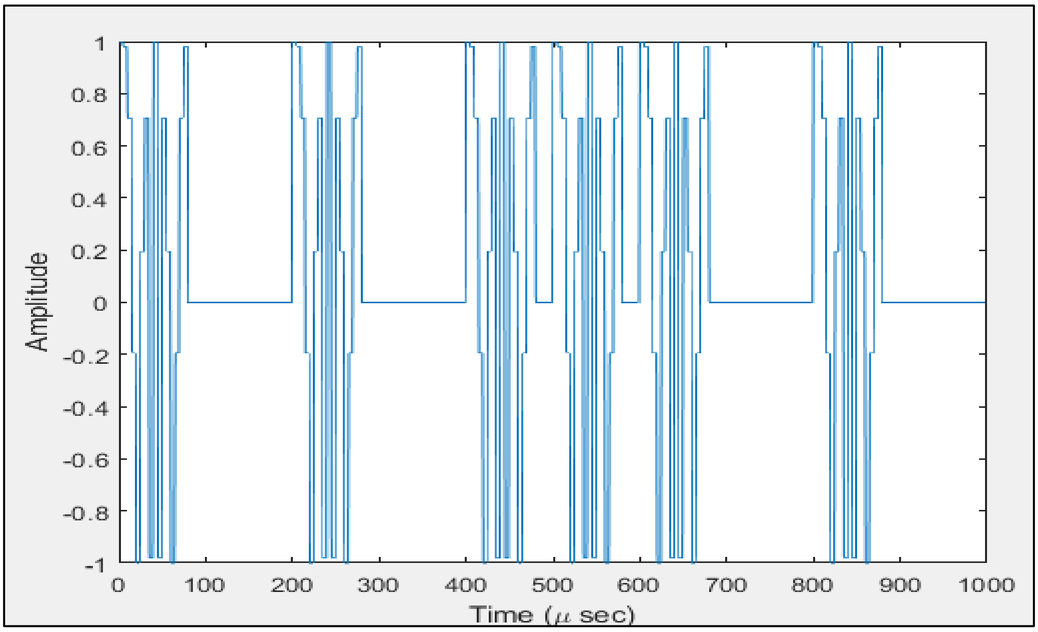

Figure 16 Phase Coded Waveform

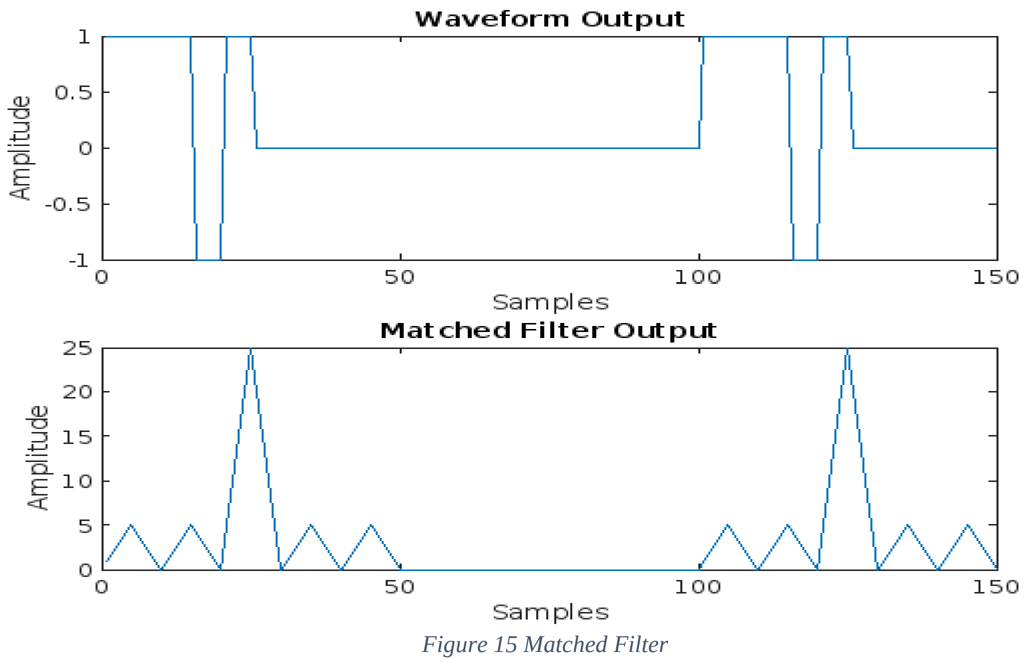

Figure 15 Matched Filter

CONCLUSION

In modern radar systems, pulse compression has become indispensable, offering highly efficient means of achieving better range resolution without the need for high-power transmitters and receivers. Phase-coded signals with minimal autocorrelation side lobes are commonly employed in radar and telecommunication applications. Contemporary radars and jammers leverage advanced digital technology, enabling dynamic adjustment of radar parameters from pulse to pulse and coherent pulse integration.

REFERANCES

1) *K. -W. Tan, A. -H. Lo, T. -S. Chu and S. S. H. Hsu, "A K-Band Reconfigurable Pulse-Compression Automotive Radar Transmitter in 90-nm CMOS," in* IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 4, pp. 1380-1387,*

2) *Arya, V. & Subha, V.. (2017). Pulse compression using linear frequency modulation technique. 921-926. 10.1109/ICICICT1.2017.8342688.*

3) *Kiran Patel., Usha Neelakantan.,Shalini Gangele, J.G Vacchani, N.M. Desai "Linear Frequency Modulation Waveform Synthesis" . IEEE Int'l.Conf, Electrical, Electronics and Computer Science,2012*

4) *Vijay Ramya K, A. K. Sahoo, G. Panda, "A New Pulse Compression Technique for Polyphase Codes in Radar Signals", International Symposium on Devices MEMS, Intelligent Systems & Communication (ISDMISC) 2011 Proceedings published by International Journal of Computer Applications (IJCA), Vol. 2, Issue 4, pp.15-17, 2011.*

5) *Anuja D. Sarate, Chandan Singh D. Rawat, , "High Resolution Low Power Radar Pulse Compression Techniques", International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE), Vol. 3, Issue 4, April 2014.*

6) *Hemsagar Patel, Shivangi Diwan. Development of Pulse Radar Detection Technique using Neural Network. Research J. Science and Tech 5(3): July- Sept., 2013 page 331-334.*