Radar Signal Processing

Based on

Nonlinear Frequency Modulated Waveforms

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CERTIFICATE

I hereby declare that the work which is being presented in the dissertation entitled, **"RADAR SIGNAL PROCESSING BASED ON NON LINEAR FREQUENCY MODULATED WAVEFORMS"** by me in partial fulfillment of the requirement for the award of degree of M.E in Electronics and Communication Engineering submitted in the Electronics and Communication Engineering Department of Thapar University, Patiala is an authentic record of my own work carried out under the supervision of **Dr. Sanjay Kumar**, Assistant Professor, ECED.

The matter presented in this dissertation has not been submitted in any other University/Institute for the award of degree.

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ABSTRACT

The linear frequency modulated (LFM) signal is extensively worn in practical radar systems. A weighting function is required for LFM in order to reduce the side lobes, which considerably decreases the SNR. In an attempt to attain low autocorrelation side lobes without applying weighting function, a different kind of radar waveform is needed, that exhibits high SNR and high range resolution. A Non linear frequency modulated (NLFM) waveform is then investigated which have the ability to overcome all the corns of the linear frequency modulated (LFM) waveform.

The objective of this dissertation is to study and observe different performance parameters for the NLFM and LFM with the help of computer simulations. Moreover Radar ambiguity function (RAF) is also analyzed and used for studying various performance parameters of both NLFM and LFM waveforms. The comparative study of both the waveforms and their respective parameters is done.

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LIST OF ABBREVIATIONS

RADAR	Radio Detection and Ranging
LFM	Linear Frequency Modulation
NLFM	Non Linear Frequency Modulation
RAF	Radar Ambiguity Function
MF	Matched Filter
SNR	Signal to Noise Ratio
PSL	Peak Side Lobe
LOS	Line of Sight
EM	Electromagnetic
PRF	Pulse Repetition Frequency
CW	Continuous wave
PR	Pulsed Radar
IPP	Inter Pulse Period
PRI	Pulse Repetition Interval
TR	Trans receiver
PSD	Power Spectral Density
AWGN	Additive White Gaussian noise
SP	Signal Power
NP	Output Noise Power

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION:

The capability of human eye is that it recognizes the colour and improved particulars of an article lying at smaller distances, with no presence of any obstructing medium. The eye limits its capacity in detecting the objects at larger distances. Radio detection and ranging (RADAR) is known to be an electromagnetic system which is a substitutional move towards extending vision capability. Radar carries an image of collecting information about remote objects of targets by transmitting electromagnetic signal at them and analysing the arriving echoes. The echoes are applied to avail the information about the object like length, distance, colour, range and many more characteristics. Various directive antennas have been used by the radar systems to transmit electromagnetic energy into a exact volume in space to hunt far targets. Targets within a particular area will return portions of the echo back to the receiver. All the information related to the target such as height, distance, colour, range etc are then obtained from the radar echoes after being processed by the radar receiver [1].

Radar is an electromagnetic system for the recognition and localisation of objects. It operation is based on transmission of a specific kind of waveform, a pulse-modulated sine wave and confirms the behaviour of the echo signal. Radar is generally applicable to broaden **the potential of one's senses for observing the environment, in particular the wisdom of** visualization. The significance of radar is that it performs the functions which are really not performed by a human eye. Radar is not able to determine the colour or other characteristics of the objects to the degree perfection with which an eye can do. But radar is capable to perform in all the conditions in which the human eye is resistant to work like fog, haze, snow, darkness etc. Moreover, unlike human eye, radars have been able to compute the range or distance to the object. It is the most important feature of radar [1].

Radars are said to be of the following types known as space borne, ground based, airborne and ship radar systems. Radar system can also be categorised based on the type of description like antenna type, waveform utilized and frequency band. Another category which deals with the working of the radar consists of fire control, weather, horizon and terrain radars. Array antennas that are having some phase are used in phased array radars. Phased array antenna is an amalgamation of antennas formed from more than two prime radiators. Phased array antennas produce beams that are directive which are then steered electronically and mechanically. Radar was modified as a device which detects the coming aircrafts in the near boundary and also used for directing purposes of the weapons. Now a days, a well designed radar have the capability to not just measure the range, distance, and other features but also gather the other information as well. Besides radar, there is no technique at present which can measure the target range so accurately and precisely [2].

1.2 Principle of radar:

The basic principle of radar lies in measuring the distance of target range. A modern designed radar system gathers more information about the object than just the range, distance, and other features. Basically, a radar system is said to have a transmitter which sends electromagnetic waves in predestined areas and when electromagnetic waves comes in touch with the target they returned or reflected back in numerous directions. Materials that are having good conductivity like sea water, metals etc reflects the radar signals pretty well. The signal which are of prime importance are the ones which are reflected back towards the transmitter that make radar work. In the radar system operation doppler effect comes into picture when change in frequency of radio waves occur when the object is moving either towards or away from the transmitter [2].

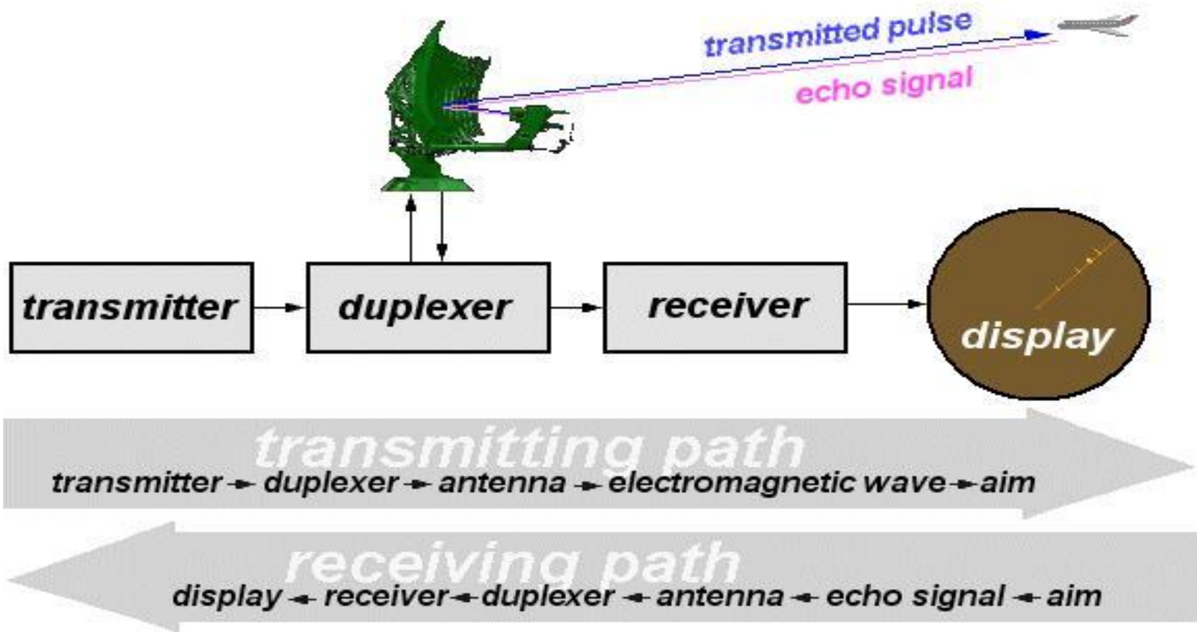

Figure 1.1 Block diagram of radar [1]

Transmitter: Transmitter usually contains a system that emits the electromagnetic waves of required energy and power. The signals generated are the short pulses.

Receiver: Receiver mainly deals with the number of signals that are reflected back. Only these signals are of prime importance. Receiver performs operation on these returned signals called echoes to gather the required information.

Antenna: In all the radar systems the only type of antenna that is used is the directional antenna. Same directional antenna can be used as transmitter and same antenna can be used as a transmitter. According to the type of process that is transmission or reception antenna will change its operation.

Duplexer or circulator: As we know that same directional antenna is applied in radar systems, therefore a device is required that can change the antenna function from being transmitter to a receiver and also permits energy flow. This device is called as duplexer or circulator in different radars

1.3 Radar equation: The power Pr returning to the receiving antenna is given by the equation [1].

where =transmitter Power $P = P G A \sigma F^4 / 4 \quad R \quad R$ (1)

= receiving antenna effective aperture of

F= pattern propagation factor

= transmitter to the target distance

= target to the receiver distance the same location, and the term

can be replaced by R^4, where R is range $R = R$

R R

$$P = P G A F^4 / 4 \quad R^4 \quad (2)$$

1.4 Radar Ranging Equation: The line extending from the radar system directly to the object is referred to as line of sight (LOS). The length of this line of sight is called range. The range R can be calculated from the elementary relation

Distance = velocity*time

Here, c = velocity of EM wave

T=time measured

Distance= 2R (forward distance +backward distance)

Therefore, the range equation is

R=0.5*C*T (3)

1.5 Range Resolution:

The range resolution is defined as the capability of the radar system to take apart two reflecting objects on a comparable bearing, but at different ranges from the antenna. The capability is dogged primarily by the pulse length in use. Range ambiguity is a technique used in radar to obtain range information for distances that exceed the distance between transmit pulses. Pulse Doppler radar is required with signal processing technique [1].

Distance > (C/2×PRF) (4)

where PRF is pulse repetition frequency

Range resolution for given radar can be considerably enhanced by using very short pulses

- Short pulses often reduces average transmitted power which can h**amper radar's** standard mode of operation.
- Generally it is advantageous to increase pulse width while concurrently maintaining range resolution because average transmitted power is directly proportional to received SNR.

1.6 Angular Resolution:

Angular resolution is the least difference in the separation of the angle at which two targets having same range can be distinguished. Antenna beam having -3dB angle determined the features of the angular resolution of radar.

1.7 Radar pulse:

A radar system transmits τ and receives a train of pulses. The inter pulse period (IPP) is T and the pulse width is .The Pulse Repetition Interval (PRI) is the second name of IPP. The inverse of the PRI is the PRF, which is denoted by Fr [2].

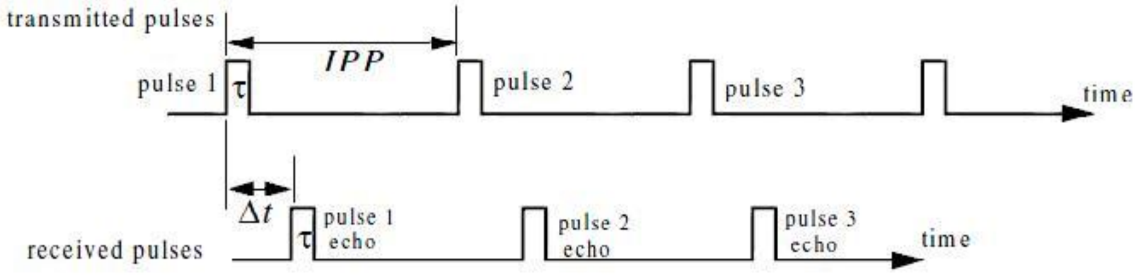

Figure 1.2 Pulse of radar [2]

Radar P radiates I (5)

energy only for seconds during each PRI and listens for target returns for the

F = = /T

rest of the PRI. The radar transmitting duty cycle (factor) is defined as the ratio T

τ

d d = τ/

The radar average transmitted power is $P_a = P\,D$ (6)

where **P** denotes the radar peak transmitted power.

1.8 Classification of Radar:

Radars are said to be of the following types known as space borne, ground based, airborne and ship radar systems. Radar system can also be categorised based on the type of description like antenna type, waveform utilized and frequency band. Another category which deals with the working of the radar consists of fire control, weather, horizon and terrain radars. Radars consists of two types which includes Continuous Wave (CW) or Pulsed Radars (PR). Most widely used type of radar is pulsed radar [1].

Continuous wave radar is a kind of radar system in which radio energy of stable frequency continuous wave is transmitted and then received from any reflecting objects. Continuous radar systems are used at both ends of the range spectrum.

- Continuous wave radars are much simpler to install and operate as the energy is not pulsed here.
- The overall bandwidth and transmitter power resolute the maximum distance in continuous wave radar. This bandwidth is determined by two factors: one is transmitting energy density and another is receiver filter size.

Pulsed radars (PR) is a radar system that uses the pulse-timing technique to determine the range target distance. It also determines the velocity of the object by using the doppler shift of the returned signal. It combines both the features of pulse radars and continuous wave radars, which were previously separate due to the complication of the electronics.

1.9 Radar Losses:

A SNR varies inversely with radar losses as it is given by the radar equation, a little increase in the losses of radar drops the SNR. Therefore, it decreases the probability of detection of losses since it is a function of the SNR. Radar losses are the single main aspect which can form a point of difference between a good radar design and a poor radar design. Radar losses include statistical losses and ohmic losses. [2].

Transmit and Receive losses:

Losses that occur on the transmitter side and the receiver side respectively and their input and output ports. Such kind of losses is also known as plumbing losses. Plumbing losses typically are of the order of 1 to 2 dBs.

Antenna Pattern loss and Scan loss:

From the radar equation maximum antenna gain is assumed. It can be achieved only when the **object is positioned along the antenna's bore sight axis. When a target is scanned by t**he radar, the antenna gain which is in the course of the object and having least maxima value as given by a radiation pattern. Antenna pattern loss is defined as SNR loss that came into picture on the object every time by not having highest antenna gain value. The amount of antenna pattern loss can be calculated mathematically [2].

When scan rate of the antenna is very fast then transmitting or receiving gain doesn't remain same. Moreover, additional scan loss can also be calculated and adjusted to beam shape loss. Scan loss is also calculated in a same manner.

Atmospheric loss:

Atmospheric losses consists of the hindrances caused by the rain, fog etc. The electromagnetic waves finds it difficult to penetrate through the layers having fog, water vapours and many more obstructing media of the atmosphere.

Collapsing Loss:

A drop in SNR occurs when the many incorporated reflected noise pulses are greater than the target returned pulses. It is known as collapsing loss. The collapsing loss factor is defined as

$$= n + m / n \quad (7)$$

where n is the pulse number having signal and noise

m is the pulse number having noise only.

Radars distinguish targets in doppler, range and azimuth. This type of above mentioned losses often result in the poor functioning of the radar system in detection of the target. These type of losses need to be corrected as soon as possible in the system.

Other losses:

These types of losses may include hardware losses may be due to equipment degradation or may be due to efficiency. Cross over losses also come under this category.

1.10 Radar frequency bands:

There is a particular range of frequencies under which radars operation is based. The radar frequency range was first elected by code letters for privacy during World War 2, they are still in regular use, even though the accurate frequency intervals to which they relate have undergone some redefinition [2].

It include within the UHF, SHF, and EHF radio frequency bands.

Table 1.1 Radar frequency band:

Frequency Band	Frequency Range (GHz)	Wavelength Range (cm)
L band	1-2	15-30
S band	2-4	7.5-15
C band	4-8	3.75-7.5
X band	8-12	2.5-3.75
Ku band	12-18	1.67-2.5
K band	18-27	1.11-1.67
Ka band	27-40	0.75-1.11
V band	40-75	0.4-0.75
W band	75-110	0.27-0.4

S, C, and X band radars are the ones largely used for rainfall measurements. K, Ka and W band radars are capable to perceive clouds, they are used for cloud observation though they are not able to go through far through precipitation.

1.11 Applications:

Various fields of application of radar are broadly classified as:

1. Military
2. Remote sensing
3. Air traffic control
4. Law enforcement and highway security
5. Aircraft safety and navigation
6. Ship safety
7. Miscellaneous applications

Military

- Radars find a very prominent use in the defense system and all the weapons used in the defense system.
- It is also used in controlling the weapon, tracking and detection of the target.

- It is often used in measuring the correctness of appointment of a weapon to an intercept.

Remote Sensing

- Radars are used in observing the conditions of the weather.
- It is also used in the observation of all the planets in the universe.
- All the work done can be made possible with the help of the radar systems.
- It is often used in the reporting of the T.V channels.

Air Traffic

- Radars are having a great role in managing air traffic.
- Aircraft taxing can also be controlled using radars.
- Pilot can communicate in the ground base using radars.

Law Enforcement and Highway Security

- Radars are used in maintaining speed limits by police.
- These are also used for the security purposes on the highway.
- It is also used in the enforcement of law.

Aircraft Safety and Navigation

- Radar systems are generally used to navigate through the sea.
- Airborne obstructions like wind and rain are also outlined by the radar systems.
- It is also used in the operation of the military aircrafts.
- It is used to avoid high terrain and obstruction collision.

Ship Safety

- Radar is found on the ships to navigate when the visibility is poor.
- It is also found on boats and ships to avoid collisions.
- It is also used to manage river traffic and used for surveillance purposes.

Space

- Radar systems are used by the various astronauts for clocking and landing purposes.
- It is used for exploring planets and other bodies in the universe.

- It has been used for tracking of the heavenly bodies, satellites and many space objects.
- It is also used for astronomy.

Miscellaneous Applications

- It is used for measuring distance.
- Animal life can also be studied with the help of radars.
- It is also used in medical science.

1.12 Pulse Compression:

Pulse compression is an essential process used in radar systems to improve the SNR and the range resolution irrespective of the transmit power. As a replacement, the pulse which is transmitted is enhanced or modulated by exact phase or frequency prototype. Pulse compression is a process which makes it possible for us to attain a standard transmission power of a comparatively extended signals mean while getting the range resolution equivalent to a short pulse [3].

Pulse compression is a technique largely applied in echography, sonar and radar to enhance the SNR and range resolution. It can be achieved by the correlation of the returned signal with the original signal after modulating the original signal.

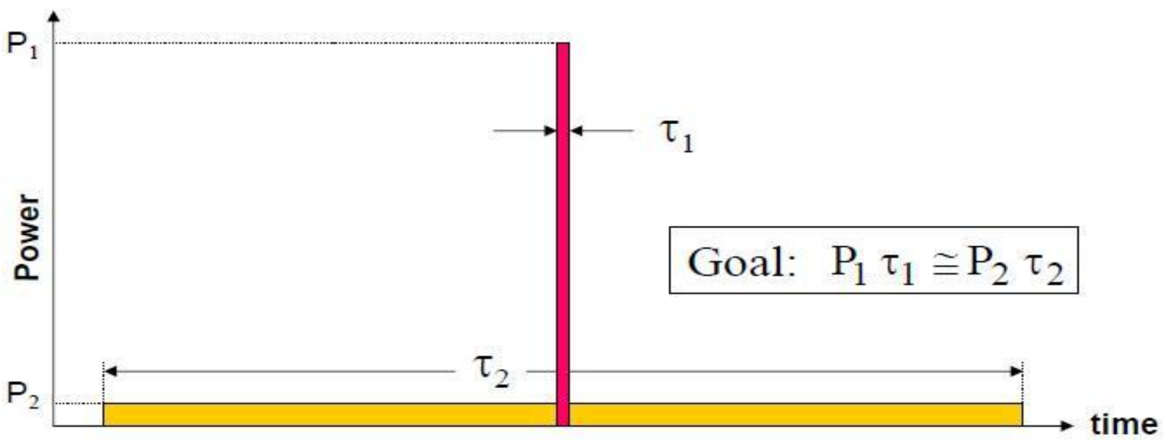

Figure 1.3 Pulse compression [2]

Long pulse is generated by using a short pulse. A short pulse is believed to be carrying a numerous frequency components which is having an exact phase relationship stuck among them. When the corresponding phases are altered by a phase-distorting filter, the components of frequency merge to fabricate an expanded or stretched pulse. The transmitted pulse comprises of the transmitted pulse. The processing of the returned echoes takes place in the receiver with the help of a compression filter. The frequency components having relative phases of a compression filters altered in a way so that a compressed or narrow pulse is produced again. The pulse compression fraction is the ratio of the breadth of the extended pulse to that of the compressed pulse. The pulse compression ratio which is equal to the product of the time extent and the spectral bandwidth of the transmitted signal. The selection of a pulse compression system is reliant upon the category of waveform selected and the technique of processing and generation. The most important factors influencing the collection of a exacting waveform are usually the radar requirements of range coverage, Doppler coverage, Doppler side lobe levels and range waveform flexibility, signal-to-noise ratio (SNR) and interference rejection [1].

Pulse compression can bring following changes in radar systems:

- Range resolution is increased
- SNR is increased

In this transmitted signal is phase or frequency modulated but not amplitude modulated, then the received signal need to be correlated with the transmitted signal. Since range resolution depends on the bandwidth of the received signal, bandwidth is inversely proportional to the range resolution. Therefore, short pulses are better for range resolution [1].

Pulse compression is a process which gives us a reduced transmitted power and still attain the desired range resolution. The cost of using pulse compression in radar systems include

- Complexity of transmitter and receiver.
- Must contend with time side lobes.

The primary factors influencing the assortment of a exacting waveform are typically the radar requirement of range, range coverage, doppler coverage and doppler side lobe level. Pulse compression can be attained by modulating the frequency or phase of the transmitted pulse throughout a longer pulse girth.

Following are the advantages of pulse compression:

- Pulse compression helps us to maintain the pulse repetition frequency.
- Pulse compression increases range resolution while maintaining detection capability.
- It increases the average transmitted power.
- It increases the signal to noise ratio.

The block diagram of a pulse compression radar system is shown in the following figure.

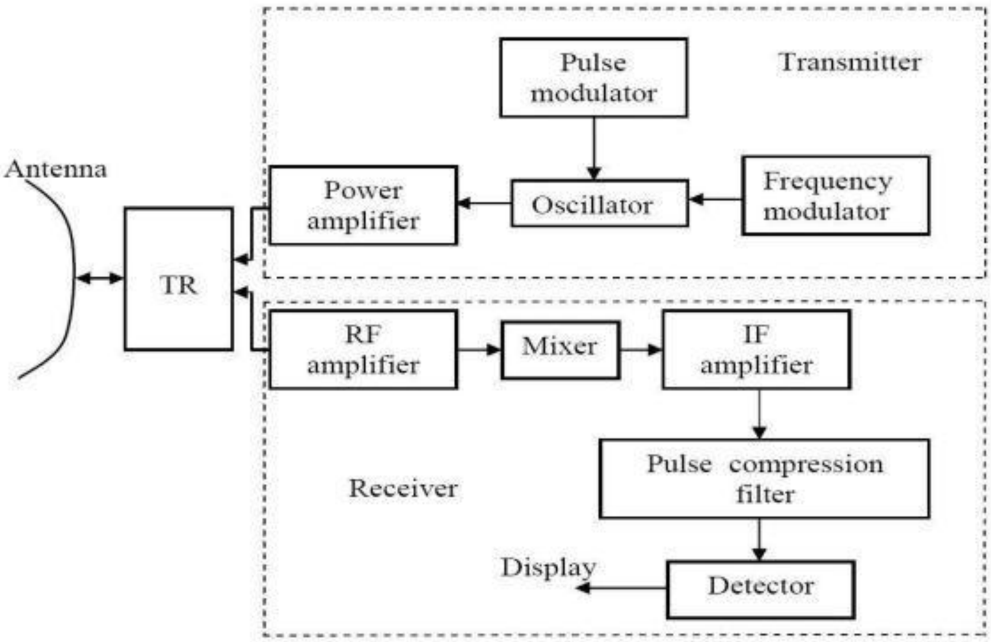

Figure 1.4 Pulse Compression Radar System [2]

To increase the bandwidth the transmitted pulse is either phase or frequency modulated. Trans receiver (TR) acts as a switching unit helps to use same antenna as transmitter and receiver. The pulse compression filter can be said to be a type of filter whose transmitter waveforms and response of frequency both are aligned. The filter forms a bond between the pulses that are transmitted and the pulses that are received. The pulses that are of matched filter use are the ones which are comparable to the returned pulses where as other arriving pulses are ignored [2].

Different kind of window function can be used for the purpose of pulse compression in case of LFM like hamming window, rectangular window etc. While in case of NLFM no weighting/window function is required, they have an inbuilt weighting function. This is one of the most important advantages of the NLFM.

1.13 Matched Filter:

Matched filter is a system in which a renowned signal or its pattern is correlated to a unfamiliar pattern so that it could identify the occurrence of the pattern in unfamiliar pulse. It is same as doing the convolution of the unfamiliar pattern and the conjugate of the original edition being reversed in time. The matched filter is the best possible linear filter used to maximize the SNR in existence of AWGN. Matched filters are mainly used in radars where a waveform which is previously known is transmitted and the returned pulses are examined so that it could find the familiar information of the departing waveform. Matched filter is basically a filter which is said to be linear in nature in which the value of the impulse response comes out in a way such that the filter output earns maximized SNR in presence of AWGN [1].

An input signal s(t) along with AWGN is feed as input to the matched filter which is shown in the following fig. Let be the power spectral density (PSD) of AWGN. It is necessary frequency response H(f) impulse response h(t) or that yields maximum SNR

to calculate the N/

at a predestined delay . Or we can say that, h(t) or H(f) is determined to maximize the given by

t

output SNR which is

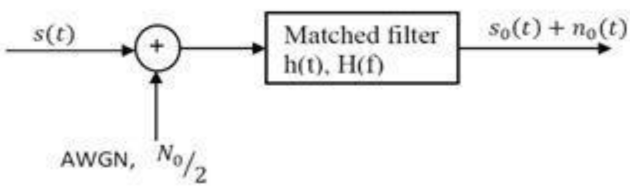

Figure 1.5 Matched Filter Model [1]

$SP/NP_o = |s_o t| / n_o t$ (8)

where SP is signal power

NP is output noise power

so t o is the value of the signal output so t at t = t

n t is the noise mean square value

t is calculated as

Suppose S(f) is said to be the Fourier transform of s(t), then s

s t = −∞∞ H f S f exp j ft df df

The value of s t at t = t is

s t = ∫∞ H f S f exp j ft

−∞

The mean square value n t of the noise is evaluated as n t = N / ∫∞ |H f | df

−∞

Rearranging the above equations we get

SP o = | −∞∞ H f S f∞exp j ft df |

NP N / −∞ |H f | df

Using Schwarz inequality the numerator can be written as

| ∫∞ H f S f exp j ft df | ∫∞ |H f | df ∫∞ |S f exp j ft | df

−∞ −∞ −∞

The above equation holds good if

H f = K [S f exp j ft]* = K S* f exp −j ft

where *K* is said to be an arbitrary constant and * stands for complex conjugate.

Therefore, P −∞∞| f |2 f (9)

NP o = N20 = E/N

where *E* is the finite time signal energy and defined as

$$E = {}_{-\infty}^{\infty} |S\ t|\ dt = {}_{-\infty}^{\infty} |S\ f|\ df \quad (10)$$

1.14 Matched filter response to LFM waveforms:

In case of LFM, the frequency is a linear function of time. The bandwidth of the matched filter is not dependent of the pulse width. The matched filter response of radar signals is approximately a sinc function. In case of LFM waveforms the side lobes of the matched filter output is around -13 dB and in case of NLFM waveforms the side lobes of the matched filter output is around -40 dB [1].

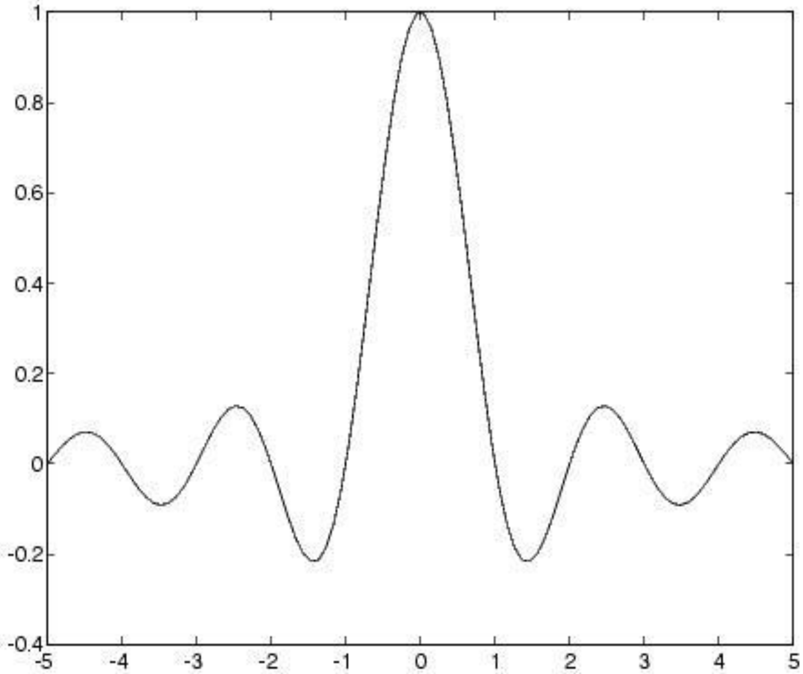

Figure 1.6 Sinc function [1]

The matched filtered response of a waveform is obtained by correlating the transmitted signal from the radar and the received one from the radar. Both the waveforms are correlated to obtain the matched filter response [1].

Chapter 2

Literature survey

Kelly *ET AL.* authors proposed and worked on the two alterations of the conservative radar theory of the matched filter and the ambiguity function. The first amendment is that to have the procedure applicable for targets having high velocity and another one is to embrace the belongings of speeding up. They worked on the form of data dispensation necessary for the quantity and the effects of stepping up on clutter problem [3].

Auslander *ET AL.* ambiguity function and cross ambiguity function both are explained to a level where the orthonormal basis function of a signal is linked to a rectangular pulse. The explaination of ambiguity function in terms of interconnected ambiguity function makes it easier when the calculations have to be made. The categorisation of ambiguity function ensuing from this extension is useful. It is proved about the ambiguity function that it is congested on the topology except for a case where the sum of two or more function is not an ambiguity function [4].

Soliman *ET AL.* In this paper a universal spread ambiguity function is explained thoroughly **and its association to woodward's ambiguity function, for various targets is urbanized. Spread** ambiguity function characteristics has been discussed in detail. The fact is proved that the ambiguity function properties does not get affected if we smoothen the ambiguity function using the dispersal function of the canal. Doubly spread targets in the signal design can be done by using the spread ambiguity function [5].

Levanon *ET AL.* authors made a association between linear FM and phase coded CW radars. The classical linear FM CW radar signal is compared with P3 and P4 phase code CW signals. The comparison covers the theoretical delay-doppler response, the spectrum and the performances in digital processors. The receivers produce a matrix of delay and doppler cells. The LFM signal requires additional weighting and even then does not approach the low range side lobes of P signals. The two signals exhibit almost identical performances which are similar to the performances of LFM in the matched receiver [6].

Mudukutore *ET AL.* In this paper pulse compression for weather radars is discussed. A imitation process is developed to precisely explain the waveform returning after hitting the object with coding involving pulse compression. The process is exclusive and gets better on the work done by having the effect of the object while the transmission of pulse time which holds genuine credits for long duration signals. The replication process is skilled developing various input range profiles of reflectivity, mean velocity, spectrum width, and SNR. Conclusions from the simulation are used to estimate the presentation of phase coded pulse compression in conjunction with matched and inverse compression filters. The assessment is dependent on relative examination of the integrated sidelobe level and Doppler sensitivity after the compression procedure. For comprehensive targets like precipitation systems, range sidelobe mask and corrupt observations of weak phenomena occurring near areas of strong echoes. Hence, sidelobe suppression is extremely important in precisely shaping the echo scattering region [7].

Wang *ET AL.* authors proposed a recognition method for LFM based on time frequency procedure. The designing of these planned detectors is usually dependent on the fact that the ambiguity function envelope amplitude or modulus square. The maximum over the chirp rates of the LFM signals is capitulated by the projected detectors. This diminishes the 2-D problem of the conventional Wigner-Ville distribution (WVD) based recognition or the Radon- Wigner transform (RWT) based recognizer to a 1-D problem and subsequently **diminishes the calculation load and keeps the feature of "built-in" fi**ltering. The outcome is an instrument for LFM detection, as well as the time-varying filtering and adaptive kernel design for multi component LFM signals [8].

Pei *ET AL.* In this paper, continuous Fractional Fourier Transform performs a range revolution of signal in the time frequency plane and it obtains a necessary tool for time changing signal analysis. In this paper a new discrete Fractional Fourier Transform is proposed. The new DFRFT will grant alike transform and rotational properties as those of continuous Fractional Fourier Transforms. furthermore, the association between FRFT and the planned DFRFT has been conventional in the same way as the conventional DFT to continuous Fourier transform [9].

Collins *ET AL.* In this paper authors used Non linear frequency modulated (NLFM) waveform as a solution to the problem of deprivation in the SNR in the process of range side lobe suppression. Range side lobe inhibition in pulse compression radar and sonar is traditionally carried out using the windowing function like blackman window, hamming window etc. Using. It is possible to reshape the energy spectrum of a signal using NLFM waveform, attaining low range side lobes, exclusive of the want for any amplitude windowing and hence maintaining highest efficiency. This paper tells that it is shown that a amalgamation of windowing functions along with NLFM is used to attain a settlement between doppler tolerance, side lobe suppression and shading loss [10].

Lesnik author proposed non linear frequency modulated signal design. The NLFM signal synthesis method in which limitations relating the signal spectrum width are taken into considerations. In this method the Zak transform application for the RAF calculations and the stationary phase method used for a definite integral approximate solution are applied. The problem formulation and general description of the NLFM signal synthesis method based on the Zak transform are presented [11].

Salemian ***ET AL.*** In this paper authors thoroughly discussed the radar pulse compression techniques. This paper aims at providing an preface to principle following the pulse compression radar. Pulse compression is a significant signal processing method applicable in radar systems to lower the highest power of a radar pulse by escalating the length of pulse, without sacrificing the range resolution linked with a shorter pulse [13].

Zhang ***ET AL.*** This paper deals with the characteristics of the (LFM) signal and applied the process of ambiguity function to examine the characteristics. In pulse compression system radar (LFM) signal with time bandwidth product which is quite high is widely worn. Hamming windowing the matched filter output response and reproduction the output signal through windowing, and analyses the pressure of weighting function to the matched filter output response and the distance resolution [14].

Wang ***ET AL.*** In this paper authors introduced an integrated cubic phase function (ICPF) for the inference and recognition of linear frequency modulated (LFM) signals. The ICPF extends the standard cubic phase function (CPF) to grip cases involving low signal to noise ratio (SNR) and multi-component LFM signals. Assessment with quite a few alive approaches is also incorporated, which shows that the ICPF serves as a good contender for LFM signal analysis [15].

Sharma author studied and analyzed multiple input multiple output (MIMO), MIMO radar performs by transmitting distinguishable waveforms from numerous transmitters and the consequential radar echoes are arriving by multiple receivers. And studied ambiguity function on the multiple input multiple output (MIMO) radars [16].

Cowell ***ET AL.*** In this paper division of linear frequency modulated (LFM) signals is being done by means of Fractional Fourier Transform (FRFT). Here, author explained how the application of the Fractional Fourier Transform (FRFT) is used to separate overlapping LFM time signals. A short preamble to FRFT and its procedure and calculations are offered. The planned signal parting method is explained by application to a simulated ultrasound signal [17].

Levanon author analyzed **the relation between periodic ambiguity function and Woodward's** ambiguity function. Ambiguity function is distinct for a finite signal processed by its matched filter. Periodic ambiguity function can grip periodic signals with infinite (or large) numeral of periods, and a processor that is matched to fewer periods [18].

Hindberg ***ET AL.*** In this paper a class of ambiguity function relative to a discrete time procedure is proposed. For this reason, the various important properties of the ambiguity function forming awareness of a particular process is imitative and the moments of the stationary signals in the processes are engrossed. Based on the various properties of the ambiguity function, a particular level is chosen and data ia tested on that level.[19].

Bokal ***ET AL.*** this paper produces a new technique to the description of radar ambiguity function. Using the conception of the copula a non parametric expansion of the wideband ambiguity function for random signals is recommended. This conception can be used for non parametric signal recognition and also for the radar signal investigation [20].

Geroleo ***ET AL.*** In this paper authors proposed a transform known as wigner ville transform which is in the sub optimal form and explained the constraints judgment of LFM waveform. They can be formed by using various LFM waveforms. The recognition and assessment question is used to take into report the various signals which are accessible in an surveillance period when the receiver is active [21].

Ruggiano ***ET AL.*** In this paper, the characteristics of the matched filter is imitated with the procedure which is implemented in the adaptive pulse compression. The examination of the presentation is completed for a multi-target situation where targets are closing as much as necessary for the side lobes of a target to get in the way with the main lobe of second target.

Therefore, both the output power statistics as well as the capabilities of the unmasking are applicable. The output peaks of the matched filter are aligned with the evaluated output peaks of the complex valued filter. In addition, the presentation of the procedure is adjudged for OFDM radar signals and mean while compared with LFM which aim at concurrent use of the radar waveform. Coded OFDM, like numerous other coded waveforms, attains intrinsic high range side lobes after matched filtering. Subsequently particular handing out at the receiver is obligatory that can hand out for side lobe suppression in order to keep away from target masking. on the other hand unmasking is not the only apprehension. It becomes essential to estimate the filtering scheme of side lobe suppression potential and in terms of output signal-to-noise ratio (SNR) [22].

Khalid ***ET AL.*** authors analyzed the ambiguity function and Wigner transform in time frequency domain. They offered an analogy of the ambiguity function and the Wigner distribution for waveforms on the sphere. Wigner distribution is illustrated for spectral or spatial localization of a signal in joint Spatial-spectral domain. The outcome **numeric's** offer **the first step in conniving more primitive transforms on the** sphere [23].

Thomas ***ET AL.*** authors generated a code set using a new scheme called piecewise Nonlinear Frequency Modulation (PNFM). The code set are having a good autocorrelation with minute peak side lobes and cross section. Generally a weighting function is applied it reduce the side lobes. In an attempt to achieving low autocorrelation side lobe level without the use of weighting function, PNFM signal has been observed. The new class code is believed to have high-quality ambiguity function with the capability to bear a practical range of Doppler shift. A matched filter with improvement is used in receiver in Doppler detection with good SNR [25].

Baylis ***ET AL.*** worked on the spectral compliance measurements of the radar signal. The spectral compliance is critically accessed by measuring a chirp signal. The sequence of frequency domain impulse functions is obtained by having fourier transform of a linear frequency modulated signal. The spectrum analyzer method the waveform with a finite-bandwidth intermediate-frequency (IF) filter, the bandwidth of this filter is critical to the power level and shape of the reported spectrum. Measurement results are presented that show the effects of resolution bandwidth and frequency sampling interval on the measured spectrum and its reported shape. The objective of the measurement is to align the shape of the measured spectrum with the true shape of the signal spectrum. This paper demonstrates an approach for choosing resolution bandwidth and frequency sampling interval settings using the example of a linear frequency-modulation (FM) chirp waveform [26].

ET AL. **Cao** authors proposed a method called wavelet based method that is effective for the side lobe suppression in radar signals. A different approach that re**lates to this paper's** proposed waveform is called the costas waveform for effective side lobe suppression. The waveform shows significant advantages over conventional linear frequency modulated (LFM) and Costas waveforms for effective side lobe suppression. Another benefit comes from the wavelet packets, each of which occupies a sub band in the frequency domain. Sub band adaptation of the waveform in both magnitude and phase becomes bendable, responding to varying target and environmental conditions. The latter facilitates the development of powerful cognitive radars [27].

Sinitsyn ***ET AL.*** authors explained the application of the wideband radar ambiguity function and its nonparametric variant in radar and navigation system is considered. The new non parametric variant of the ambiguity function, which is based on the copula notion, is discussed. The suggested function can be used for the signal synthesis and detection in different electronic systems for signals with an unknown spectrum and probability density function [28].

Tan ***ET AL.*** In this paper authors proposed a procedure to increase the performance of matched filtering for LFM signal as matched filtering for LFM signal is applied more and more widely and this is achieved by adding window. In this paper five typical window functions are selected to act on LFM signal so that impacts of different window functions on the performance of matched filtering for LFM can be discussed. For windows with adjustable parameters, the relation curves between the performance indexes of matched filtering and adjustable parameters are also given. As the adjustable parameters increase, the main lobe broadens and absorbs the sidelobe. So the impulse response width (IRW) of the output signal increases and the peak sidelobe rate (PSLR) decreases [29].

Chapter 3
Radar waveforms

3.1 Linear Frequency Modulated (LFM) waveform:

LFM waveform commonly known as linear chirps are the most commonly used waveform in radar systems as it can be easily generated, have good range resolution and more doppler tolerant than NLFM. A linear FM chirp has a linear time frequency description as its frequency varies linearly over the pulse duration of the signal. In case of LFM frequency increases or decreases linearly with time.

The complex exponential versions oft =theexp(jϕLFMchirpt) waveform is given as [2]

(11)

where is the instantaneousϕt phase= givenf+ktby the equation as below

The instantaneous frequencyf as=a linear/dϕ/dtfunction of time is expressed as [2] fi = f + kt

(12)

(13)

(14)

where k is the slope.

fo is the fundamental frequency.

Following figure shows the time-frequency characteristics of the signal. Fig 3.1 depicts the frequency versus time characteristics of a linear FM chirp.

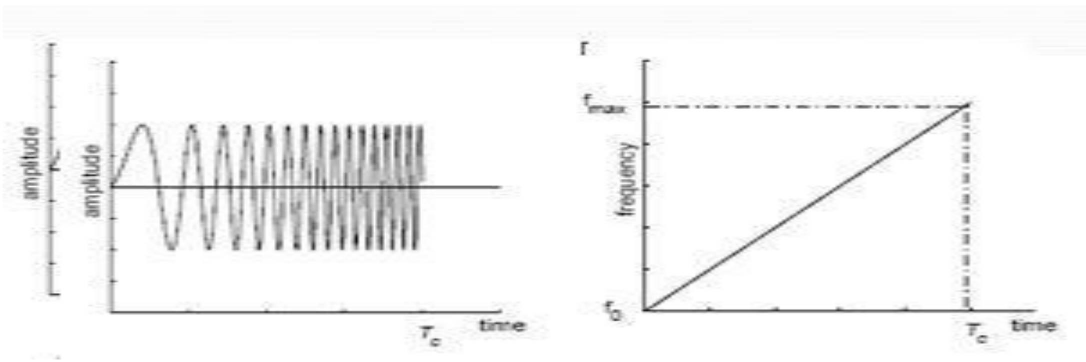

Figure 3.1 LFM waveform and its time frequency characteristics.

LFM signal is a type of waveform which is having a period which varies inversely with that of the bandwidth and pulse compression is a process that allows this to happen. The selection of compression of the given pulse is reliant on the decision of choosing a pulse and the technique involved in production and dispensation. The amount of compression is given and defined by the bandwidth of the signal. The LFM waveform exhibits higher bandwidth of the signals. The LFM signal is transformed over a band of frequencies. On the other hand, a LFM signal which is compressed in nature using pulse compression will be having the first side lobe at a level of – 13dB. In a case of LFM waveform, a windowing function is required in order to carry out the process of pulse compression. However, the output SNR clearly get reduced by 1 to 2 dB [1].

LFM is known to have many advantages like it is very easy to generate, very easy to install technically, has a very superior performance in pulse compression. The compressed pulse shape and SNR are fairly doppler tolerant means these waveforms can survive the doppler shifts. Despite the above advantages, LFM carries few limitations which cannot be ignored. A compressed LFM signal produces a first side lobe at a level of -13 dB to the peak of the main lobe at the receiver. But for this compression, the output SNR may get reduced typically by 1 to 2 dB. A single dB of SNR lost is equal to 25 % decrease in transmitter power [1]. Few more important corns of the LFM waveform are given below.

- Low signal to noise ratio (SNR).
- LFM always require a weighting function for pulse compression.
- Range resolution is not very good.

Due to this scientists concluded with use of a new waveform called non- linear frequency modulated (NLFM) waveform. NLFM waveform does not require any weighting function, they have inbuilt one. More over their range resolution in very good and their pulse shape is very much Doppler tolerant.

Non Linear Frequency Modulated (NLFM) waveform which overcomes the disadvantages of the Linear Frequency Modulated (LFM) Waveform is described in the next section. NLFM generation is costlier than the LFM generation still it is extensively used signal in radar systems.

3.2 Non Linear Frequency Modulated (NLFM) waveforms:

The non-linear frequency modulation (NLFM) waveform is yet another type of signal that is used by the radar system for its working. It is known that NLFM waveform provide better SNR than the LFM. Range resolution provided by the NLFM is quite better than LFM. **Moreover, the biggest advantage of NLFM over LFM is that it doesn't require any weighting** for pulse compression. NLFM is having superior detection rate features. In case of NLFM, it is observed that the time frequency characteristics are non-linear in nature [24].

The complex exponential of NLFM waveform is given by [24]

$$s\ t = \exp j\phi\ t \tag{15}$$

Here in this case, the instantaneous frequency **f** is given as [24] (16)

$$f = f + kt + \cos t$$

where f_0 is the fundamental frequency

t is the instantaneous time

k is the slope

The time-frequency characteristics of NLFM waveform is shown below:

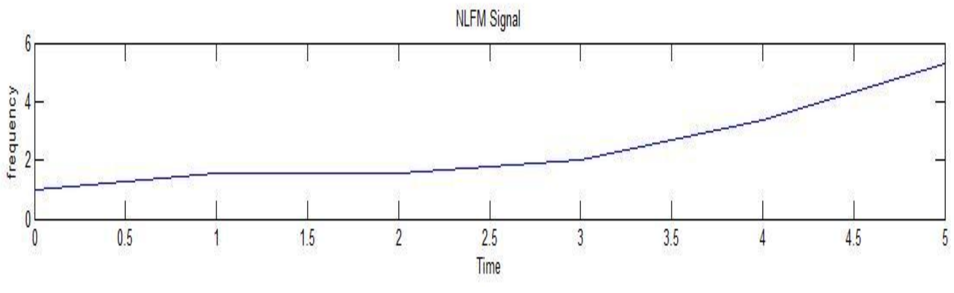

Figure 3.2 Time frequency characteristics of NLFM waveform

NLFM waveform is shown in the figure below:

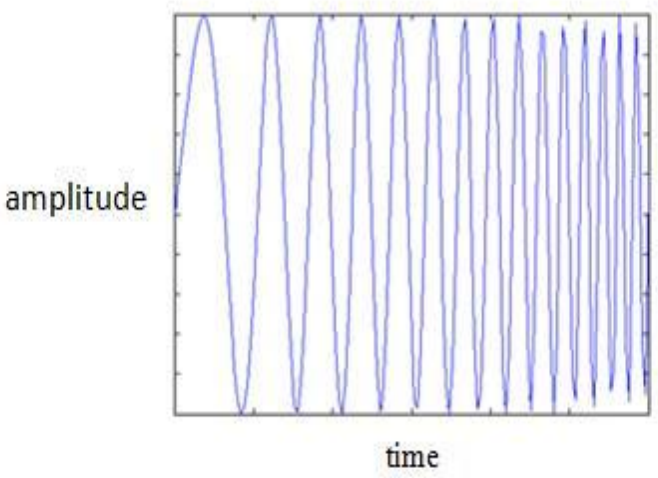

Figure 3.3 NLFM waveform

Non linear frequency modulation waveform does not require weighting function as they have an in built weighting function. NLFM is a waveform which cannot be easily generated. To understand the principle of generation of NLFM, one must understand the principle of stationary phase which is described in the next section.

3.3 Principle of Stationary Phase:

The method for evaluation of integrals of the type is given by stationary phase principle [24]

$$I = {}_{-\infty}^{\infty} F x e - \phi x \; dx \qquad (17)$$

where is function of x which is rapidly varying over most of the range of integration, *F(x)* gradually varying

is

The cancellation of sinusoids with rapidly varying phases is the basic idea of the stationary phase method. Rapidly varying phases means that the factor I is roughly zero above those regions of the integrand and the only significant non zero contribution to the integral occurs

in region of the integration where $d\phi/dx = 0$,

Points of stationary phase are labeled **x** and is defined by **ϕ** **x =**

It should be noted that F(x) = F(x_s)
Now expanding ϕ in a Taylor series near the point x and keeping only the first two non zero terms given by

$$\phi x = \phi x + / \phi'' x \ \ x - x$$

Substituting this in the integral

$$I = \sqrt{\ \ } \ /j\phi'' x \ \ F x \ e^{- \phi x} \tag{18}$$

NLFM waveforms offer many prominent advantages like:

- **It doesn't** require frequency or time weighting for range side lobe suppression.
- When a symmetrical FM modulation is used with time weighting to diminish the frequency side lobes, the non linear FM waveform will have a near ideal ambiguity function.
- It increases signal to noise ratio (SNR) to a great extent.

The major drawback of the NLFM waveforms is that it is doppler intolerant which means that with the use of NLFM as the transmitter pulse it is obligatory to use several filters at the receiver in order to detect the target return. This increases the complexity and cost for crafting such radar [12].

3.4 Comparison of LFM and NLFM waveforms:

Following few points describe the comparison between linear frequency modulated (LFM) waveforms and non-linear frequency modulated (NLFM) waveforms [2]:

- Linear FM or chirp waveform is easiest to generate while generation of NLFM is a complex procedure.
- In case of LFM the compressed pulse shape and SNR are fairly insensitive to doppler shifts but in case of NLFM we need to design receivers in such a way that they can behave as doppler tolerant.
- LFM applies pulse compression using different weighting functions but NLFM requires no time or frequency weighting for range side lobe suppression.

Chapter 4
Radar ambiguity function

4.1 Radar ambiguity function:

The foremost tool for analyzing radar signals is ambiguity function (AF). The ambiguity function is primarily used to gain an understanding of how a signal processor responds to a given returned signal. It defines the range and doppler resolution [2].

The ambiguity function of the waveform s(t) can be defined in terms of the cross-correlation of a Doppler-shifted version of the waveform, that is s(t)exp(j2 t) with the unshifted waveform [2].

$$x\ \tau, f\ = {}_{-\infty}^{\infty}[s\ t\ e \quad \pi fd\ ]\ [s_*\quad t - \tau\ ]dt \qquad f \tag{19}$$

where is the delay time

is the Doppler frequency shift

$$s\ t = \{ \quad ;\ \text{if} \quad t \quad t \quad ;\ \text{elsewhere}$$

As the function describes more about the waveform than just its ambiguity properties, hence the name ambiguity function is quite misleading.

Properties of radar ambiguity function:

1. Maximum at (0,0):

$$|x\ \tau, f \quad | \quad |x\ , \qquad | =$$

   This property tells that Ambiguity function is highest at the origin

2. Constant volume:

$$\infty \qquad \iint |x\ \tau, v\ |\ d\tau\ dv = \qquad -\infty$$

Property 2 states that the whole volume under the normalized ambiguity surface equals unity, and is not dependent of the signal waveform. The next two properties implies to the signals, normalized or not.

3. Symmetry with respect to origin: $|x(-\tau, -v)| = |x(\tau, v)|$

This property states that it is necessary to study two adjacent quadrants of the ambiguity function only. The remaining two can be derived from the property of symmetry.

4. Linear FM effect:

Let us consider a complex envelop u(t) has an ambiguity function $|x(\tau, v)|$

$$u(t) = |x(\tau, v)|$$

then after adding of linear frequency modulation (LFM), which is the quadratic-phase modulation implies that [27].

$$u(t) \exp j \quad kt = |x(\tau, v - k\tau)|$$

4.2 Proofs of the AF Properties:

Property 1: To prove this property, we apply the Schwarz inequality to the AF squared:

$$|x(\tau, v)| = |\int_{-\infty}^{\infty} u(t) u^*(t+\tau) \exp j \quad vt\, dt|$$

$$= \int_{-\infty}^{\infty} |u(t)| dt \quad \int_{-\infty}^{\infty} |u|^* \quad (t+\tau) \exp j\, vt\, dt$$

$$\int_{-\infty}^{\infty} |u(t)| dt \quad \int_{-\infty}^{\infty} u^* (t+\tau)\, dt = E.E = . =$$

Therefore, above equation will become

Now the $|x(\tau, v)|$

$$u(t) = [u^*(t+\tau) \exp(jvt)] = u(t+\tau) \exp(-j\, vt)$$

it happens when , v = 0

Thus, it is $\tau =$

$$|x(\tau, v)| \quad |x(,)| =$$

Property 2: After replacing v with –f, we rewrite the the ambiguity function:

$x\ \tau, -f\ = \int^{\infty}\ [u\ t\ u_{*}\ \ t + \tau\ ]\exp -j\ \ ft\ dt$

$-\infty$

which is recognized as the Fourier transform

of the function $x\ \tau, -f\ = F[\beta\ \tau, t\ ]$

$*$

Parseval's theorem says that the $\beta\ \tau, t = u\ t\ u\ \ t + \tau$

frequency domain: $\int \infty\ |\beta\ \tau, t\ |\ dt = \int \infty\ |x\ \tau, -f\ |\ df = \int \infty\ |x\ \tau, v\ |\ dv$

sides with respect to yields the volume v under the ambiguity function

Integrating both $-\infty$ τ $-\infty$ $-\infty$
squared.

∞ ∞

$\iint |\beta\ \tau, t\ |\ dt\, d\tau = \iint |x\ \tau, -f\ |\ df\, d\tau$

$-\infty$ $-\infty$

$=$ ∞

Now evaluate the integral on the left hand side $-\infty\ |x\ \tau, v\ |\ dv\, d\tau = v$

we have $t + \tau = t$

∞ . ∞ .

Jacobian is given by
where the $-\infty\ |u\ t\ u\ \ t + \tau\ |$ $dt\, d\tau =$ $-\infty\ |u\ t\ \ u\ t\ \ |\ |J\ t, t\ \ |dt\, dt$ $= v$

Using the above equations we get, ∞ $J\ t\ \ , t\ \ =$

$v = \iint |u\ t\ u_{*}\ t\ \ |\ |\ |dt\, dt$

$-\infty$

$=\ _{-\infty}^{\infty}\ |u\ t\ \ t\ \ dt\ \ -\infty^{\infty}\ |u_{*}\ t\ \ |\ dt\ = E.\ E = .\ \ =$

Property 3: To prove this property, we set $-\tau$ and $-v$ in the equation for $|x\ \tau, v\ \ |$:

$x\ -\tau, -v\ = \int^{\infty} u\ t\ u_{*}\ \ t - \tau\ \ \exp -j\ \ vt\ dt$

$-\infty$

and make one change of variable $t = t - \tau$, which yields

$$x(-\tau, -v) = \int_{-\infty}^{\infty} u(t+\tau) u^*(t) \exp[-j v(t + \tau)]dt$$

$$= \exp(-j v\tau) \int_{-\infty}^{\infty} u(t+\tau) u^*(t) \exp(-j vt) dt$$

The integral of a conjugate is $\exp(-j v\tau) \int_{-\infty}^{\infty} u(t+\tau) u(t) \exp(-j vt) dt$

linear operation. $x(-\tau, -v) = \exp(-j v\tau) [\int_{-\infty}^{\infty} u^*(t+\tau) u(t) \exp(j vt) dt]^*$

Taking the absolute value of the

$$|x(-\tau, -v)| = |x(\tau, v)|$$

Property 4: A new complex envelope is defined in which quadratic phase was added to the original envelope u (t):

The ambiguity function of $u(t) = u(t) \exp(j kt)$

$u(t)$

The new ambiguity function is $u(t) = |x(\tau, v)|$

$$x(\tau, v) = \int_{-\infty}^{\infty} u(t) u^*(t+\tau) \exp(j vt) dt$$

$$= \int_{-\infty}^{\infty} u(t) \exp(j kt) u^*(t+\tau) \exp[-j k(t+\tau)] \exp(j vt) dt$$

Now by taking the absolute

$$|x(\tau, v)| = |x(\tau, v - k\tau)|$$

4.3 Ambiguity function of LFM:

The linear frequency modulated (LFM) pulse which is widely used in radar systems attains good range resolution. The ambiguity function of the LFM is shown below:

The LFM pulse can be represen ed by: (20)

$$/kt$$

$$s t = s t \exp j \quad f_0 t +$$

$$= [s t \exp j kt \quad] \exp j$$

$$f t$$

where $S t \quad = \{ \; , \quad \text{if} \quad t \; t$

, elsewhere

where $\quad =$ pulse width

k = rate of frequency change in Hz/sec

The ambiguity function of LFM pulse can be written as

$$|x \tau, f \quad | = | \int_{-\infty}^{\infty} s t s * \quad t - \tau \exp \; j \quad f - k\tau \, t \, dt$$

$$= | \; - \frac{|\tau|}{s} \sin[t \; - \frac{|\tau|}{s} \quad f + k\tau]/ t \quad - \frac{|\tau|}{s} f \quad + k\tau \, | \quad \text{if} \; |\tau| \quad t ,$$

As we know that the ambiguity function of a ingle pulse given by

$$|x \tau, f \quad | = | \int_{-\infty}^{\infty} s t \quad s* \; t - \tau \exp j \; f t \, dt|$$

Comparing the above two equations, we conclude that they are identical, except that is

replaced by . Hence it is observed that the ambiguity function of the LFM pulse^f is a

shifted $f - k\tau$

graphically in the figure and it can be seen that the ambiguity function of the LFM waveform is just a rotated version of the ambiguity function of the single pulse.

4.4 Radar ambiguity functions for LFM signal:

The LFM complex envelope signal given by [1] s

$$t = \sqrt{\tau} \, \text{rect} \, \tau^{t} \, e^{j\pi u t}$$

(21)

where *u* is the doppler shift

For computing LFM complex envelope we take the following case:

When $0 \quad \tau \quad \tau'$

Therefore the integration limits becomes $-\frac{\tau'}{2}$ to $\frac{\tau'}{2}-\tau$

Now the ambiguity function is given by [8]

$-\infty$

$x\tau; f = \int^{\infty} s\,t\,s^{*}\ \ t+\tau\ e\ \pi fd\ \ dt$

Now by rearranging th above equations we get

$-\infty^{\infty}$

$x\tau, f \ = \ \text{rect}\ \ \text{rect}\ \tau^{+\tau'}\ e\ \pi\ \ 2\,e-\pi\ \ +\tau'\,2\,dt$

$\tau'\qquad\tau'$

And the above equation follows that

τ'

$x\tau, f \ = \ e-\pi\tau 2\ /\tau'\ \ -2\tau/-\tau\,e-\ \ \pi\ \ \tau-fd\ \ dt$

after applying integration steps we get the following equation

$x\tau; f \ = e-\pi\tau fd\ \ -\tau\tau'\ \sin(\ \tau'\ u\tau+f\ \ -\tau\tau')\ /\ \tau'\,u\tau+f\ \ -\tau/\tau',\ \ \ \tau\ \ \tau'$

Similarly, examination for the case when τ τ be able to be carried out where the

$-,$

τ

integration limits will become τ . Similar result can be obtained by by means

of the symmetry property of the - to / by $| = |x\tau, f\ |$

expression for $x\ \tau\ ;fd$

$\frac{|\tau|}{\tau'}$

$\pi\tau f_d$

and the LFM ambiguity function is

$$x\ \tau; f \quad = | \ - \frac{|\tau|}{\tau'} | \sin \quad \tau' \ u\tau + fd \quad - \frac{|\tau|}{\tau'} \ / \ \tau' \ \ u\tau + fd \quad - |\tau|/\tau' \tag{22}$$

Chapter 5

Results and Discussions

5.1 Results and Discussions:

Both linear frequency modulated (LFM) waveform and Non linear frequency modulated waveform (NLFM) is generated in MATLAB and their corresponding magnitude spectrum and matched filter response are also obtained in MATLAB.

For linear frequency modulated waveform:

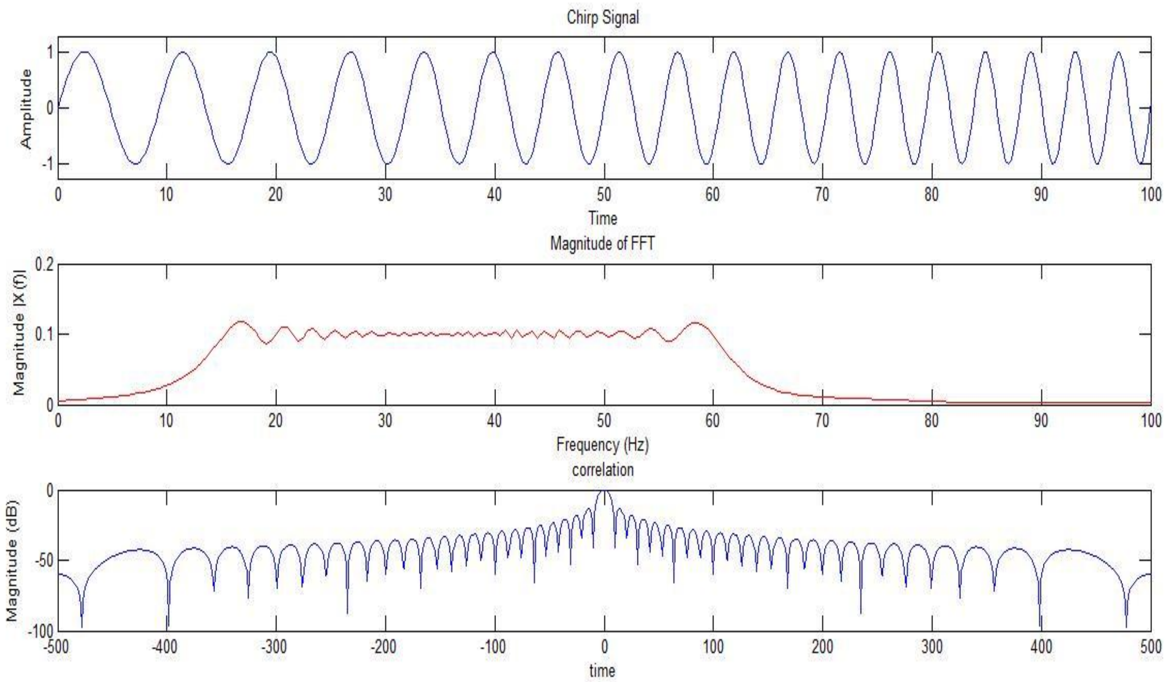

Figure 5.1 shows chirp signal, its magnitude spectrum and its matched filter response respectively.

Here in Fig. 5.1 chirp signal is generated and its corresponding magnitude spectrum is plotted. The matched filter response is the sinc function which is the autocorrelation function of the original signal. The side lobes of this matched filter response comes about -13dB.

For non linear frequency modulated waveforms:

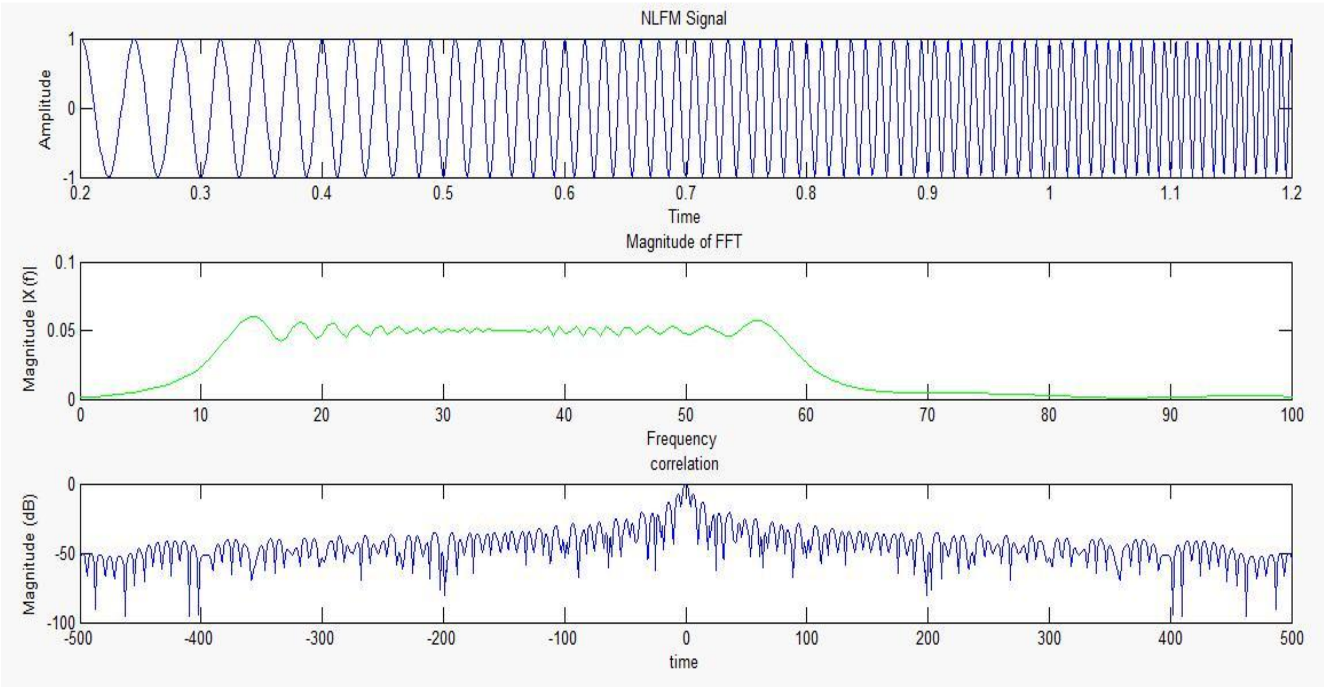

Figure 5.2 shows NLFM signal, its magnitude spectrum and its matched filter response respectively.

Here in Fig. 5.2 NLFM signal is generated and its corresponding magnitude spectrum is plotted. The matched filter response is the sinc function which is the autocorrelation function of the original signal. The side lobes of this matched filter response comes about -40dB.

Ambiguity plots:

Similarly ambiguity function plots for both the waveforms LFM and NLFM are also obtained in MATLAB. Contour plots which are the 3-D representation of the ambiguity plots are also obtained using MATLAB.

For linear frequency modulated waveforms:

Pulse Width 1 microsecond:

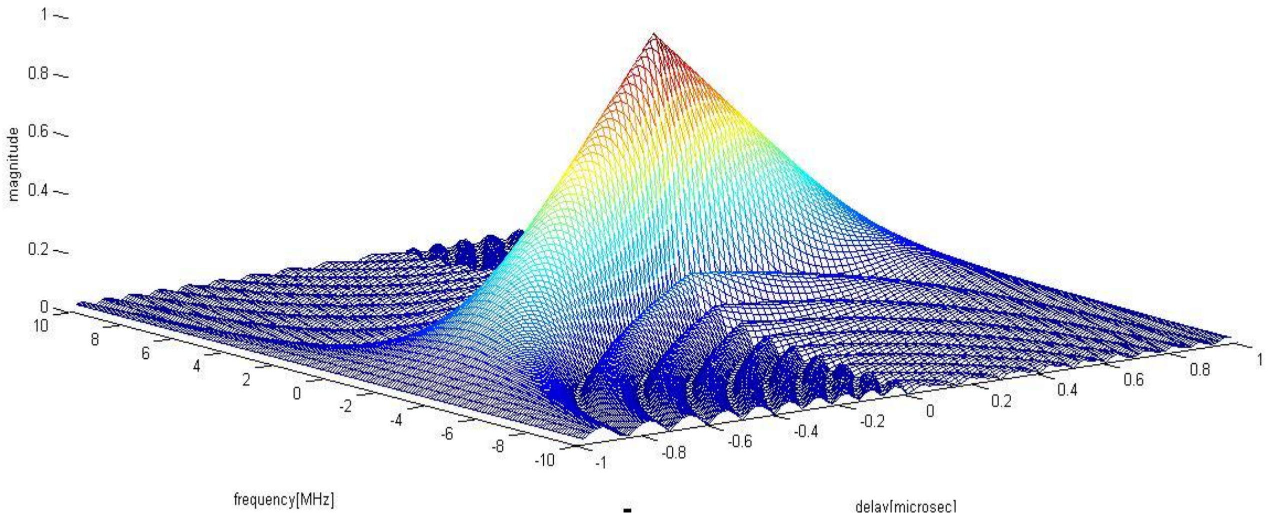

Figure 5.3 (a) Ambiguity plot of LFM

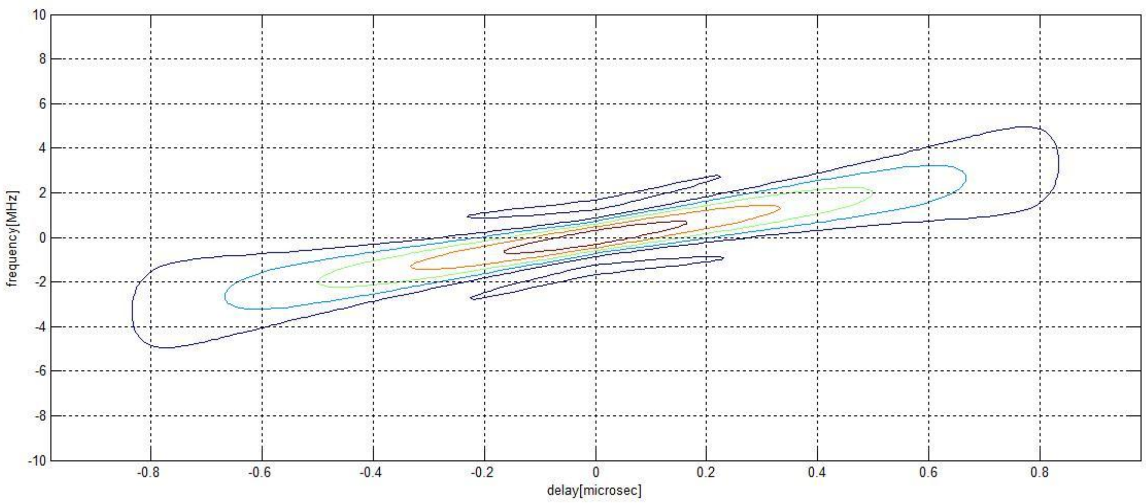

Figure 5.3(b) Contour plot of LFM

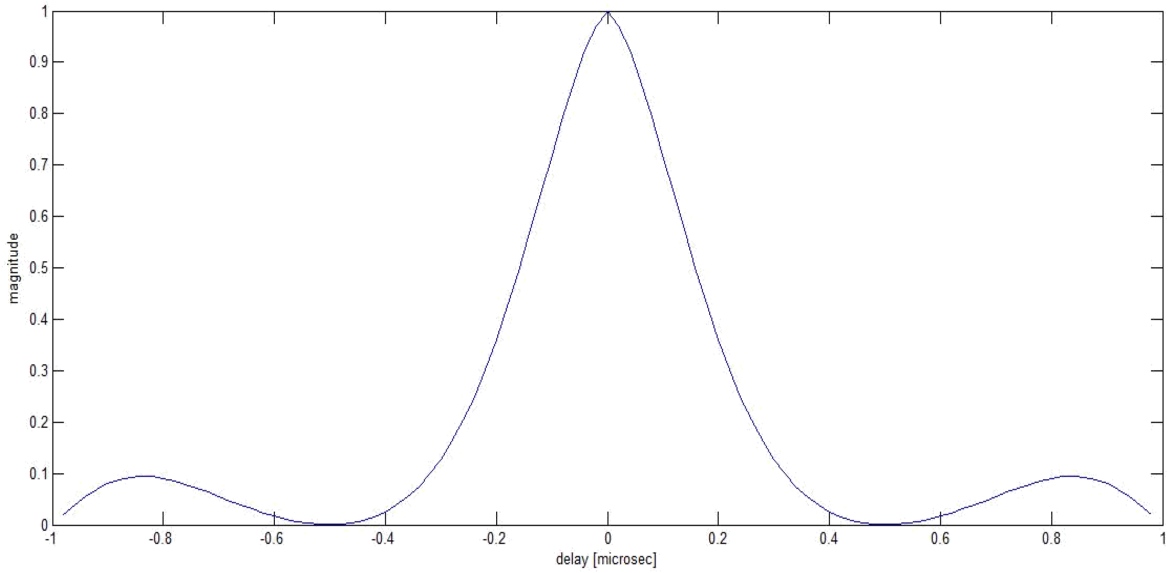

Figure 5.3(c) Doppler cut plot of LFM

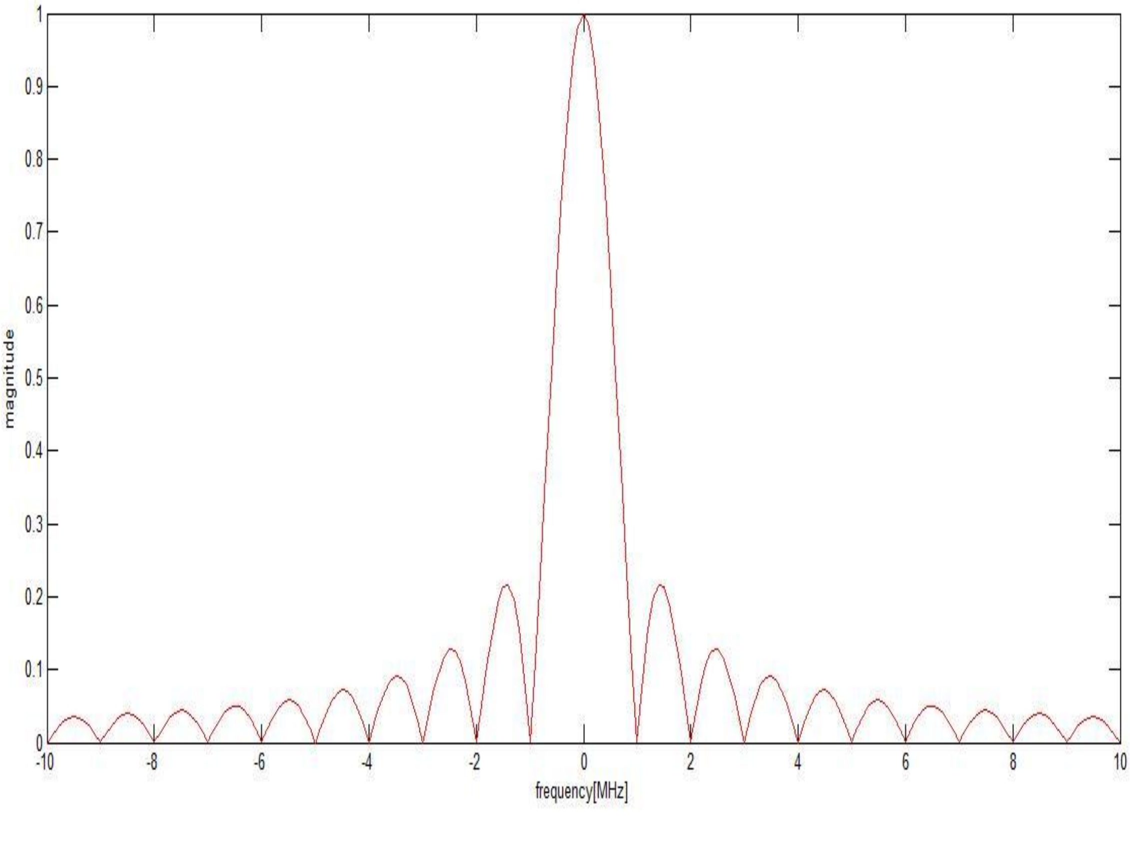

Figure5.3(d) Delay cut plot of LFM

For Pulse width 100 micro second:

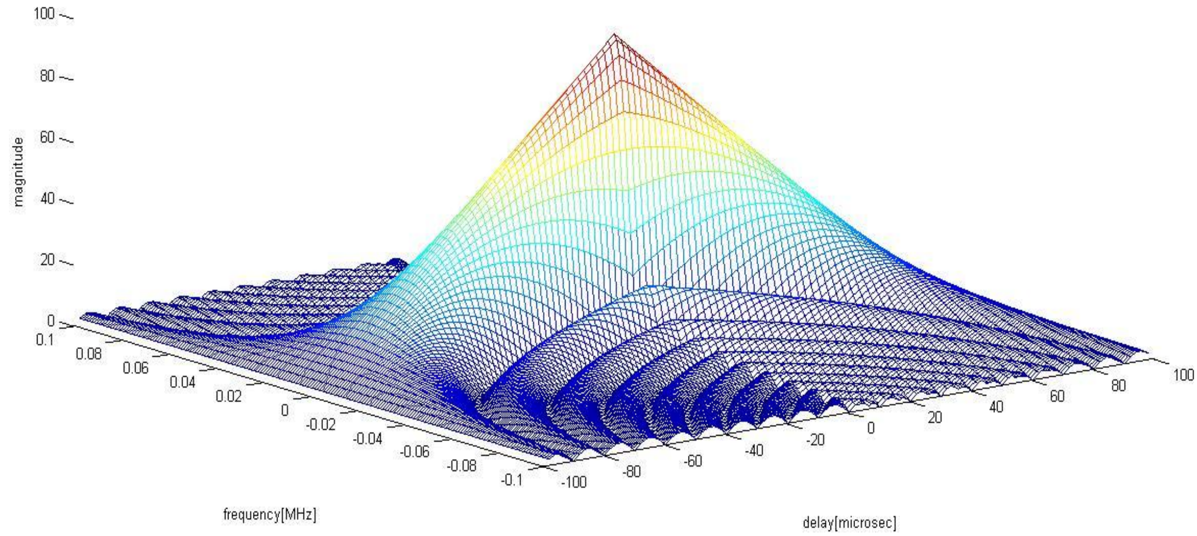

Figure 5.4 (a) Ambiguity plot of LFM

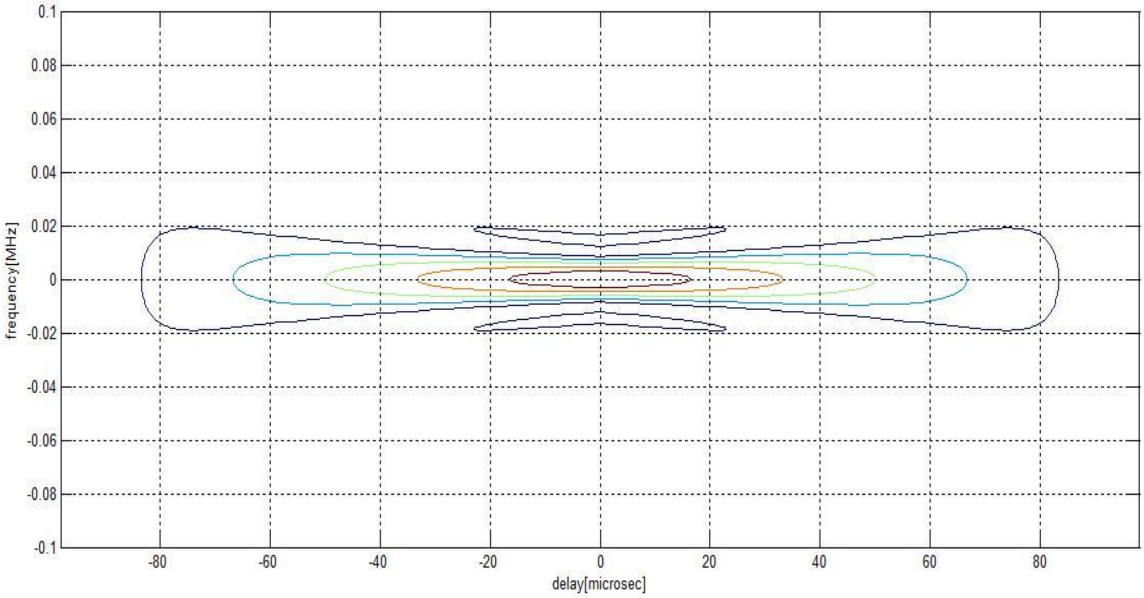

Figure 5.4(b) Contour plot of LFM

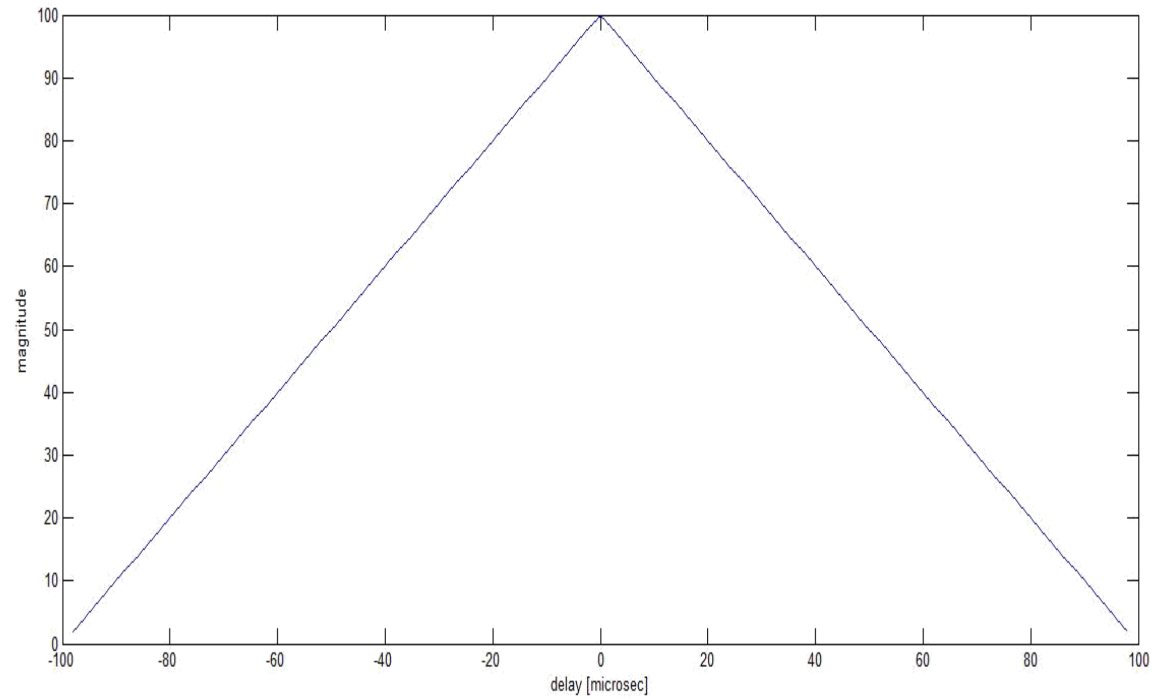

Figure 5.4(c) Doppler cut plot of LFM

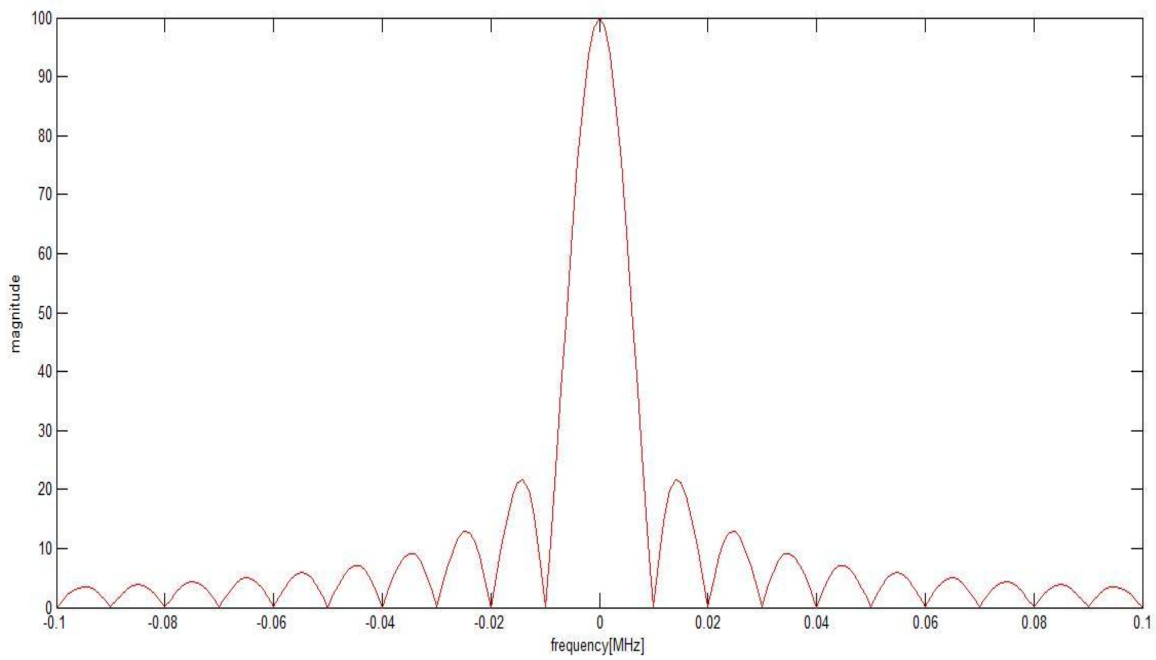

Figure 5.4(d) Delay cut plot of LFM

Pulse width of 1000 microsecond:

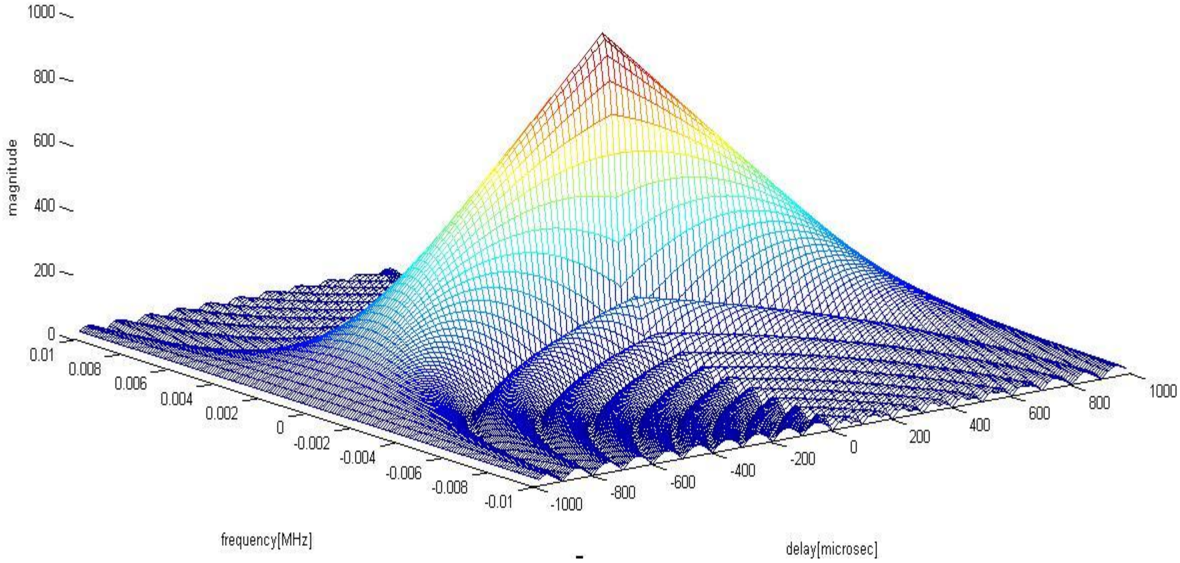

Figure 5.5(a) Ambiguity plot of LFM

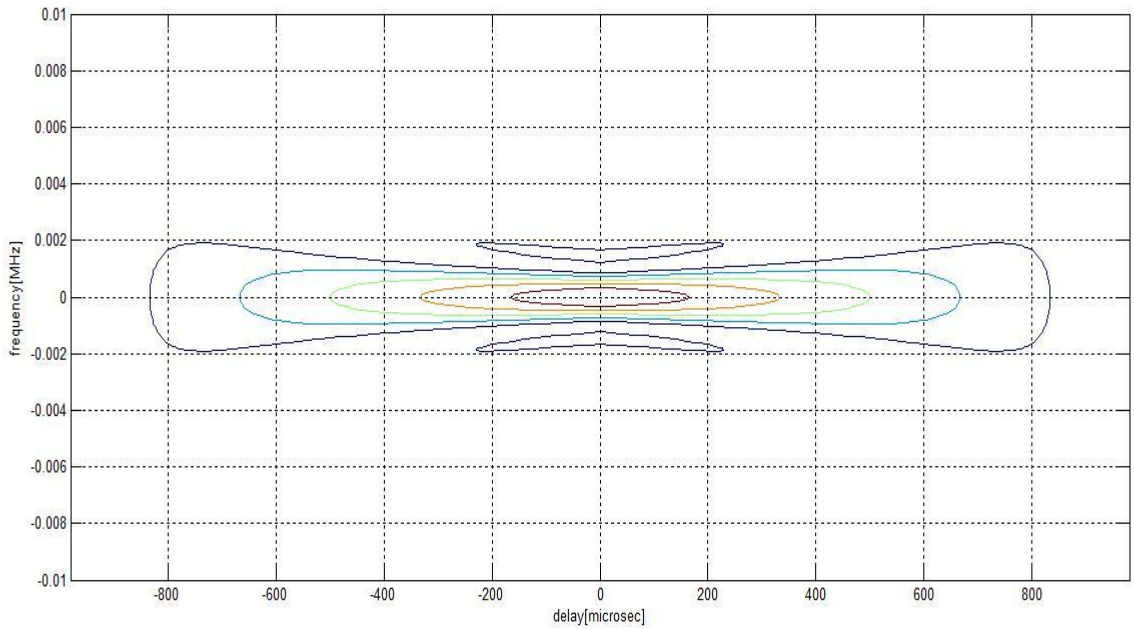

Figure 5.5(b) Contour plot of LFM

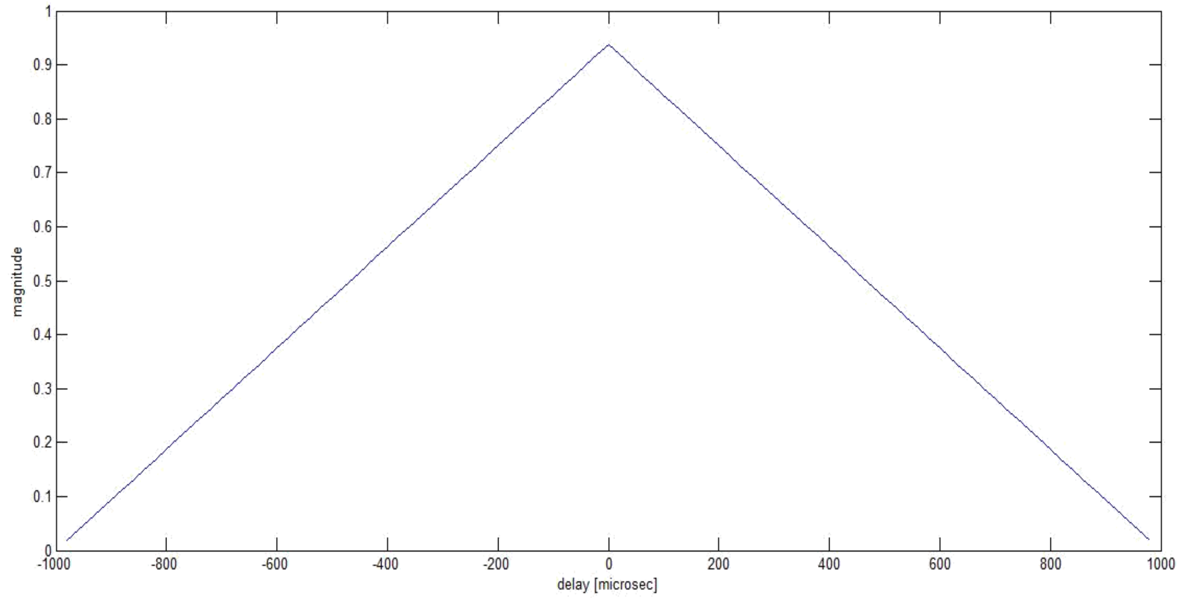

Figure 5.5(c) Doppler cut plot of LFM

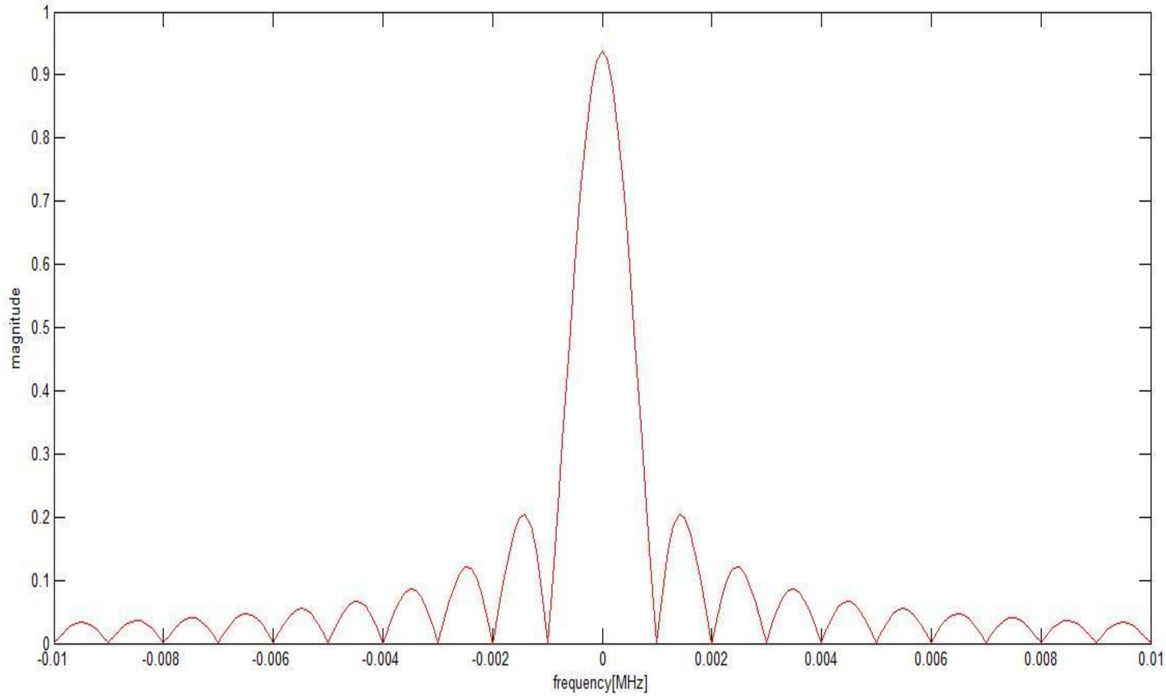

Figure 5.5(d) Delay cut plot of LFM

For non- linear frequency modulated waveforms:

Pulse width 1 micro second :

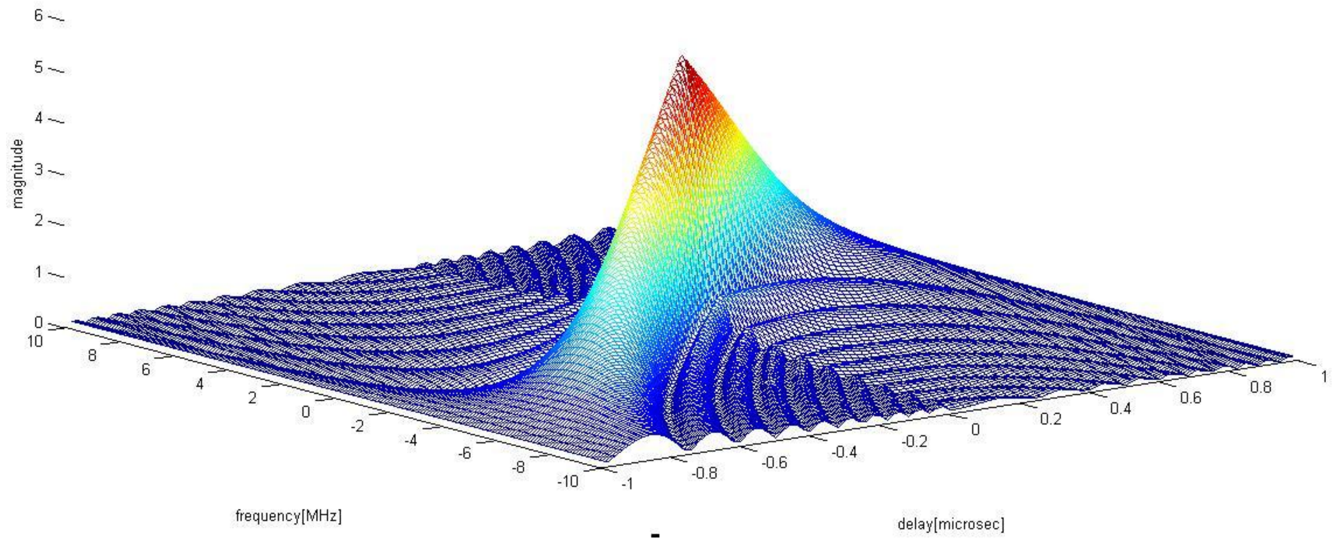

Figure 5.6(a) Ambiguity plot of NLFM

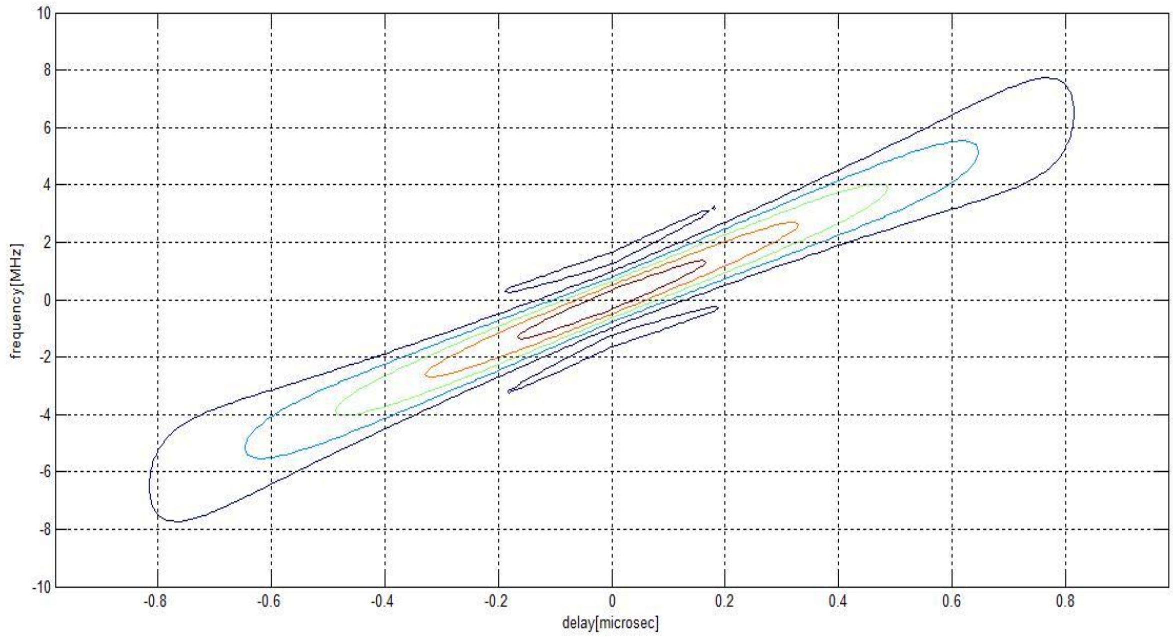

Figure 5.6(b) Contour plot of NLFM

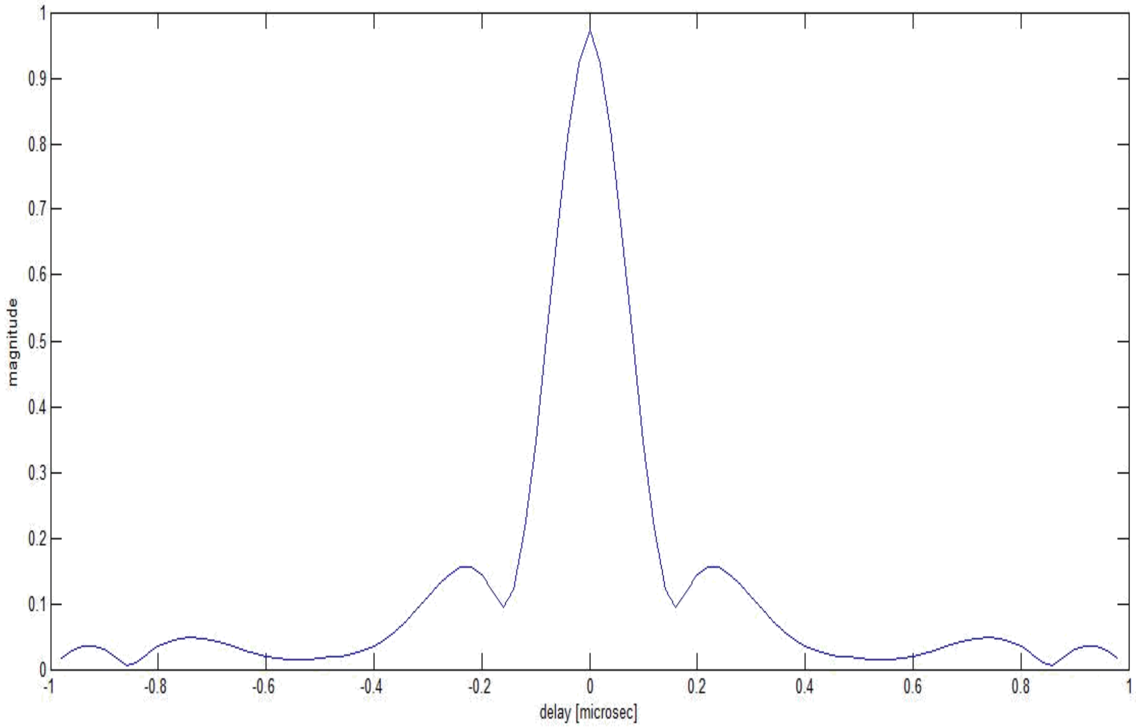

Figure 5.6(c) Doppler cut plot of NLFM

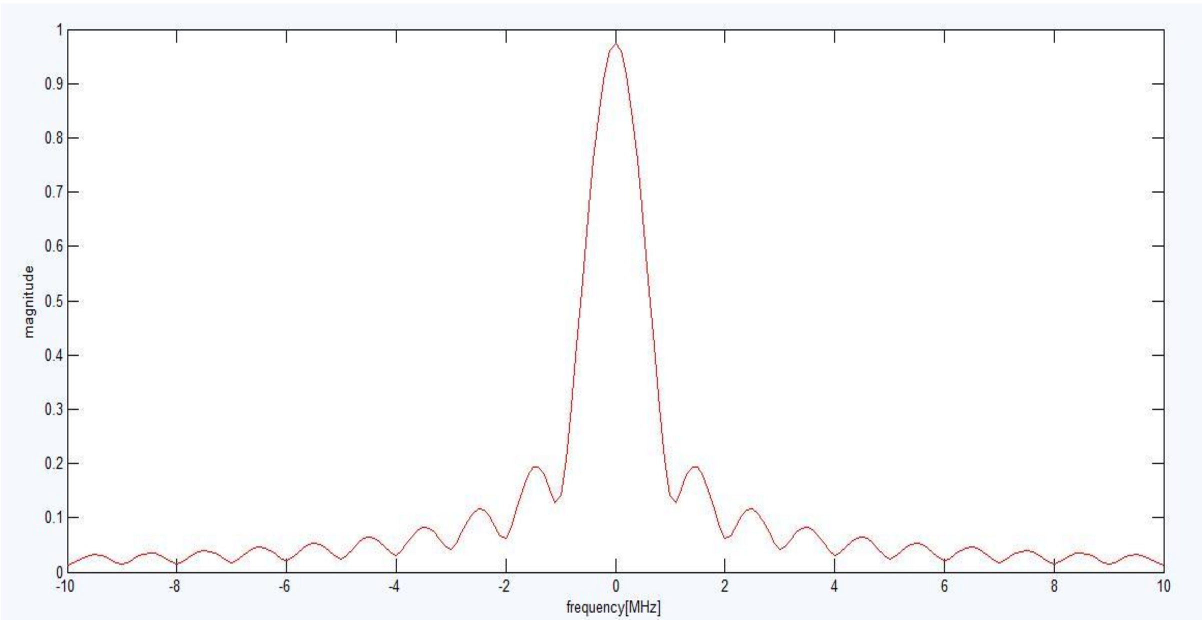

Figure 5.6(d) Delay cut plot of NLFM

For pulse width 100 microsecond:

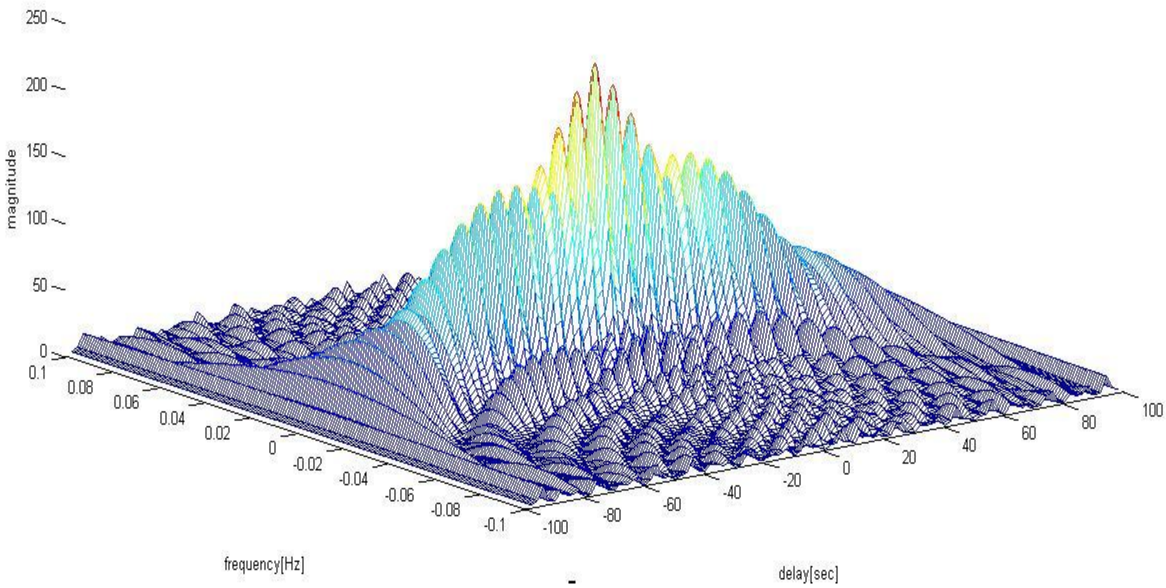

Figure 5.7(a) Ambiguity plot of NLFM

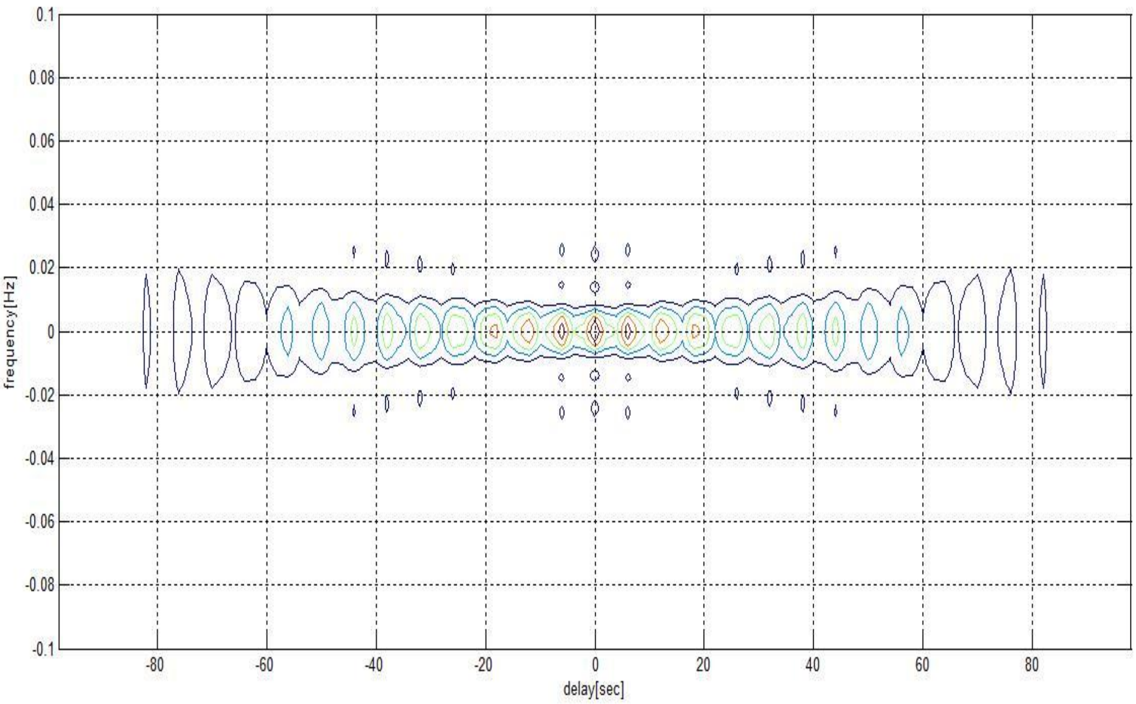

Figure 5.7(b) Contour plot of NLFM

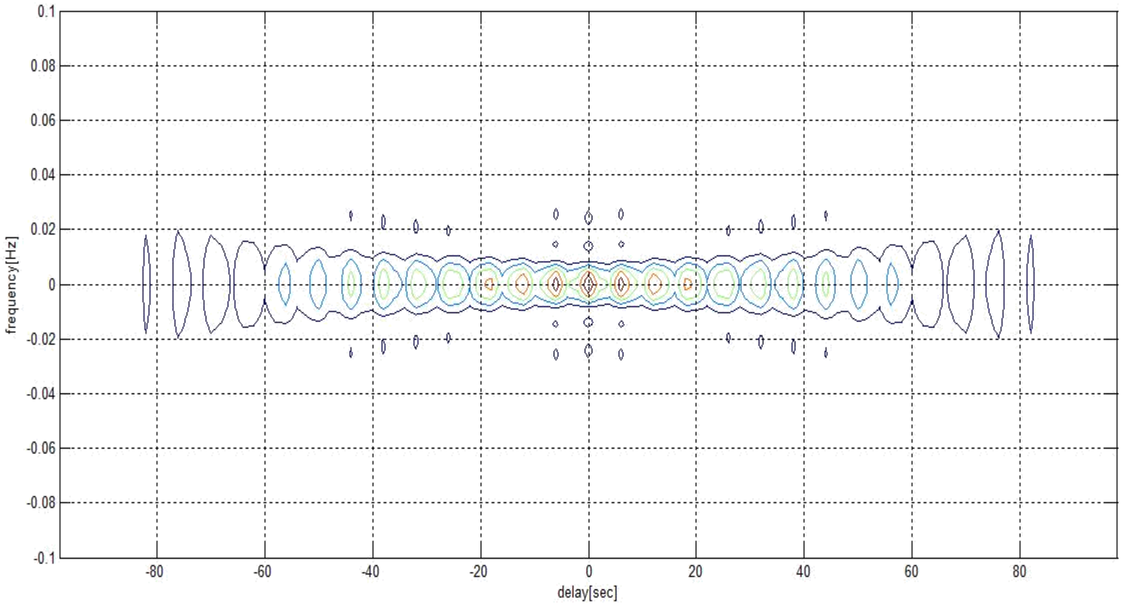

Figure 5.7(c) Doppler cut plot of NLFM

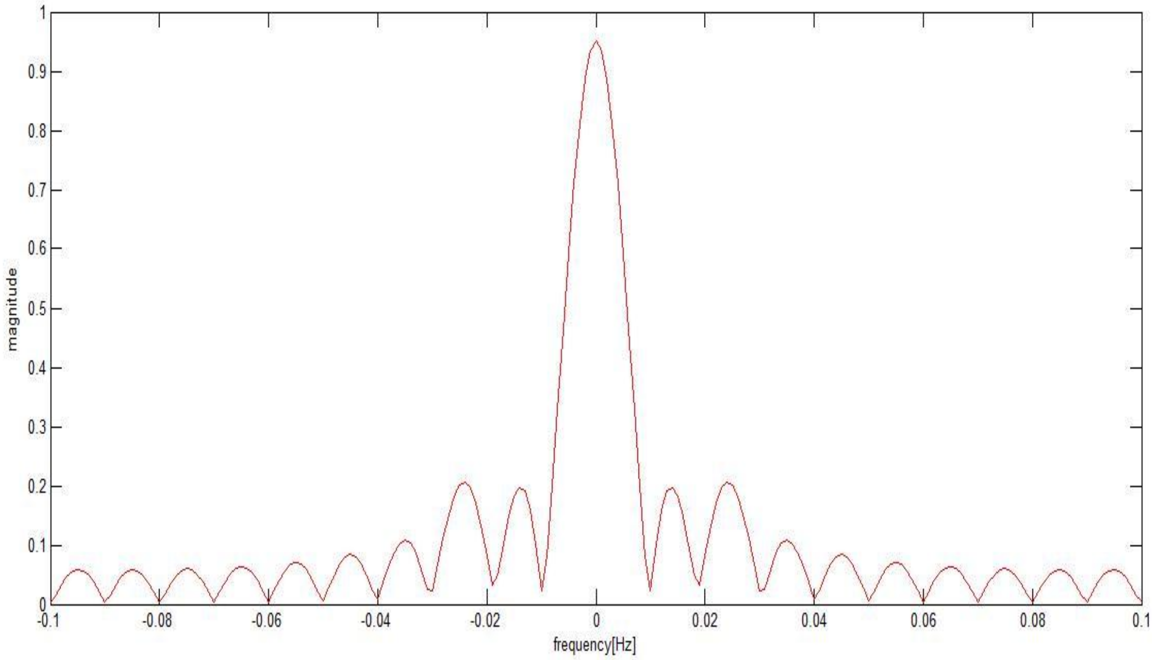

Figure 5.7(d) Delay cut plot of NLFM

For pulse width 1000 micro seconds:

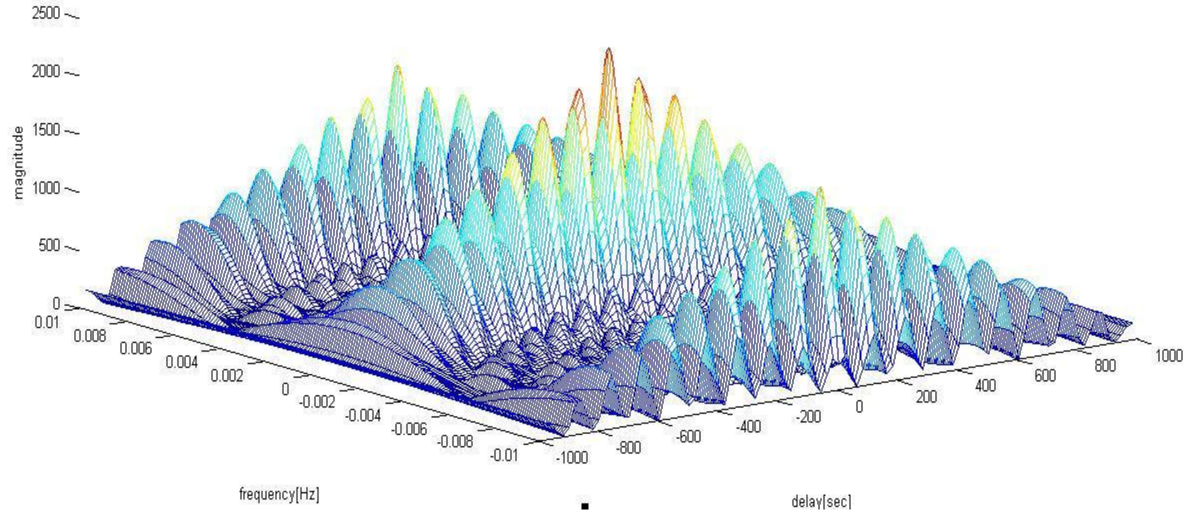

Figure 5.8(a) Ambiguity plot of NLFM

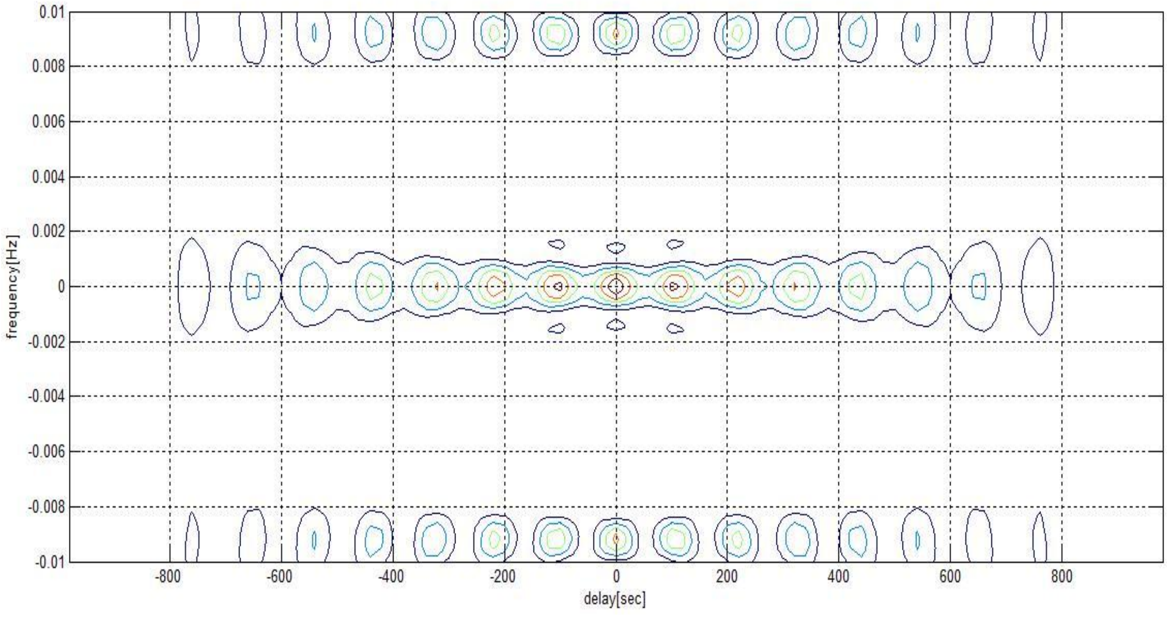

Figure 5.8(b) Contour plot of NLFM

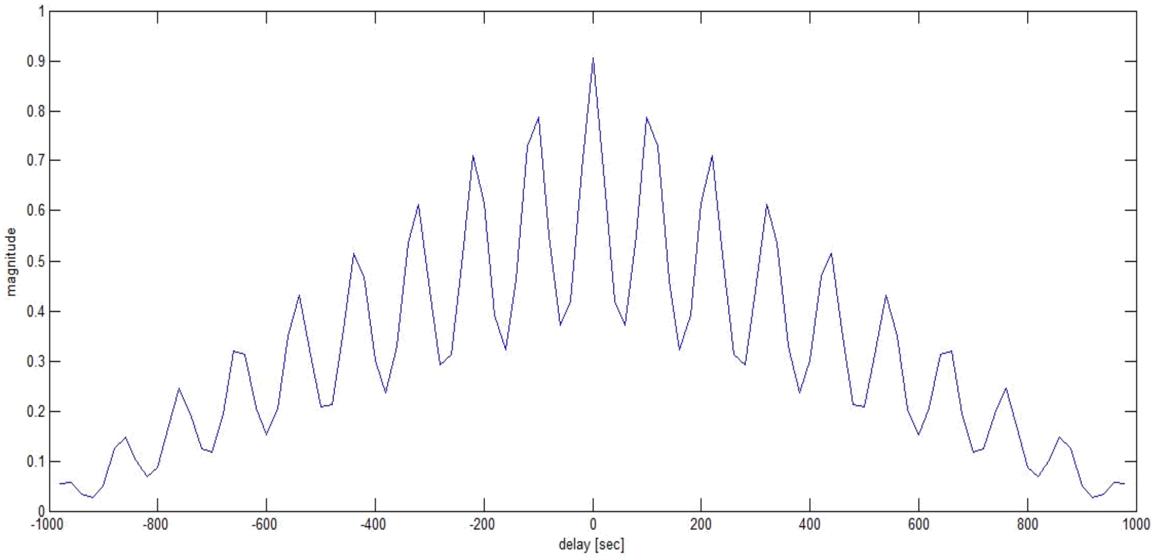

Figure 5.8(c) Doppler cut plot of NLFM

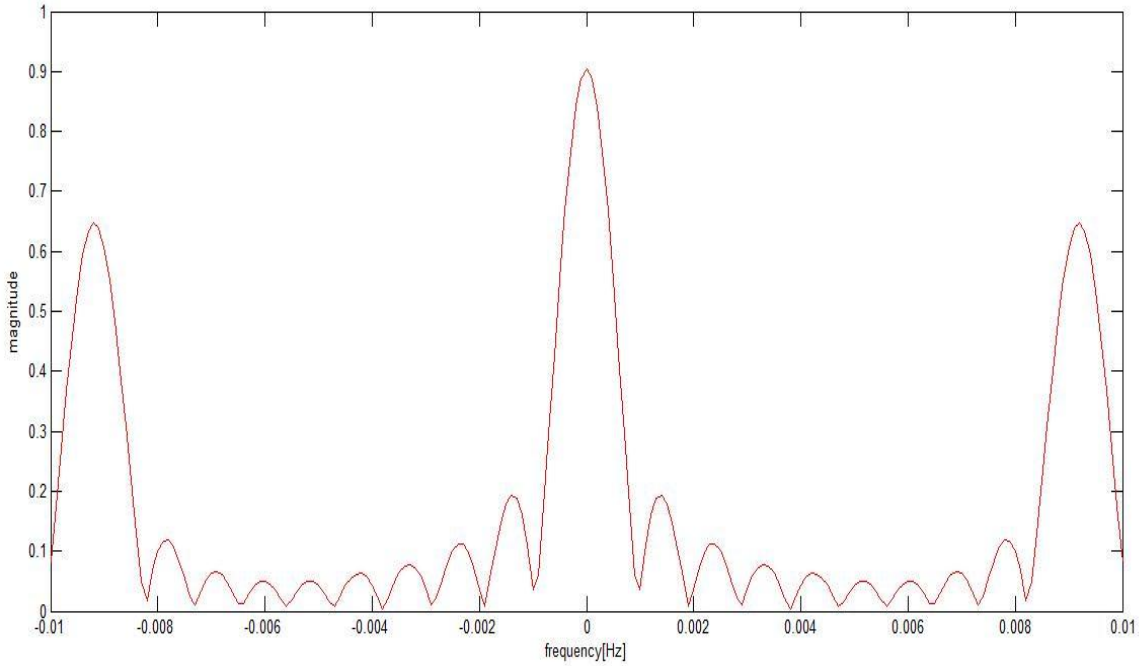

Figure 5.8(d) Delay cut plot of NLFM

The above shown plots are the ambiguity function plots for LFM and NLFM waveforms. Fig 5.3(a) shows the ambiguity plot, it is the plot showing the 3-D view of the ambiguity function. Fig 5.3(b) shows the contour plot of the ambiguity function for LFM, contour plot is the projection of the ambiguity function. By default, contour traces are assigned a colour from the rainbow colour. Red is having the minimum magnitude and violet is having maximum magnitude. Fig 5.3(c) shows the zero doppler cut of the ambiguity function plot which is obtained by putting f_d =0 in the ambiguity function. Doppler cut plot is of great importance as it tells about the range resolution of the waveform. Here in case of the LFM range resolution comes out to be 1/B which is equal to (1/0.5)= 2. Fig 5.3(d) shows the delay cut plot of the ambiguity function for LFM. Similarly we performed more iteration with pulse width of 100 microseconds and 1000 microsecond.

Correspondingly, Fig 5.6(a) shows the ambiguity function plot for the NLFM waveform, Fig 5.6(b) shows the projection of the ambiguity function which is known as the contour plot. Fig5.6(c) shows the zero doppler cut of the ambiguity function plot, it tells about the range resolution of the waveform and here in case of NLFM range resolution comes out to be (1/B)=(1/0.1)=10. Fig 5.6(d) shows the delay cut plot of the ambiguity function for NLFM. Similarly we performed more iteration with pulse width of 100 microseconds and 1000 microsecond.

5.2 Comparative analysis of LFM and NLFM waveforms:

There exist certain performance parameters that distinguish LFM and NLFM waveforms. They are mentioned as PSL, Range resolution, Doppler shift. Table 5.1 below shows different calculated values of these performance parameters via computer simulations.

Table 5.1 Main performance parameters of the LFM and NLFM waveforms:

Parameter	LFM	NLFM
PSL(peak side lobe)	-13dB	-40dB
Range resolution	2	10
Doppler shift	1 MHz	1.3 MHz

Chapter 6

Concluding Remarks and Future Scope

6.1 Concluding Remarks:

Following are the conclusions drawn from the work done in this dissertation.

- The detailed description of LFM and NLFM and their performance parameters is obtained. The main parameters embrace Peak Side Lobe (PSL), range resolution and doppler shift. It is observed that the magnitude spectrum of the LFM is purely flat from the centre and it is slightly curvy in case of NLFM. Moreover the matched filter response of both the waveforms LFM and NLFM is approximated by a sinc function, but the only difference lies in the side lobe suppression. In case of LFM, we have sinc function with -13dB side lobes and in case of NLFM; we have sinc function with -40 dB side lobes. It can be said that in case of pulse compression NLFM waveforms are more useful and appropriate than the LFM waveforms.

- Ambiguity function is one of the major tools for analysing and understanding radar signals. As ambiguity function is applied both on LFM and NLFM waveforms, it is observed that NLFM waveform gives better range resolution as compared to LFM. Here again NLFM comes out to be a better radar waveform than LFM.

- Doppler shift means that if two targets are at the same range, they need to have a difference of 1 MHz (LFM) and 1.3MHz (NLFM) in the doppler domain to be separated as found in the dissertation experimental results. In summary, NLFM came out to be a more practical, constructive and functional radar signal waveform. It has been an effective technique for side lobe suppression.

6.2 Future Scope:

During the course of this dissertation, several avenues for continuation of this study became evident. The topics which were considered worthwhile are summarized below:

- If the doppler intolerance of the NLFM is enhanced in a controlled manner, NLFM can be worn as the most used practical radar waveform in future.
- LFM still can be used effectively if its SNR can be maintained at a very good number.

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List of publications:

[1] Shruti Parwana, Dr. Sanjay Kumar, "Analysis of LFM and NLFM Waveforms and their **Performance Analysis" International Research Journal of Engineering and Technology** (IRJET).