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Chattering Mitigation in Monopulse Radar Using HOSM

by

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TO MY PARENTS AND BELOVED FAMILY

CERTIFICATE OF APPROVAL

Chattering Mitigation in Monopulse Radar Using HOSM

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Abstract

Tracking radar uses pencil beam to track the true range and bearing of target. They are used in several applications like to supervise the specific air routes, military applications, radio astronomy etc. Monopulse tracking radars are under study since many past years. Monopulse tracking radars have the benefit over other radar systems using conical scanning method because they are not affected by the fluctuations in the strength of target echo. Monopulse radar detects the range and bearing of target by comparing the amplitudes of received beams. Monopulse tracking using IMM, Kalman and particle filter are some of the algorithms that have been proposed in the literature. Monopulse tracking in the robust framework has not been observed in the literature yet. In monopulse radar the error cannot be minimized past a certain value, instead it fluctuates within a certain limit. Thus beam of monopulse radar always has an oscillatory motion during target tracking. This oscillatory motion can be described by chattering phenomena. The ability of a monopulse radar to efficiently measure the target angle is greatly reduced by the chattering phenomena. This work focuses on removing the chattering phenomena using a model free Smooth Super Twisting Controller while estimating the true target trajectory. Smooth Super Twisting Algorithm is used for this purpose as it is independent of model parameters. Undesirable chattering in tracking target trajectory is shown to be suppressed up to a great extent.

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Abbreviations

AGC	Automatic Gain Control
ALLRT	Average Likelihood Ratio Test
CRLBs	Cramer-Rao Lower Bounds
EM	Electromagnetic
FSPL	Free Space Path Loss
HOSM	Higher Order Sliding Mode
IF	Intermediate Frequency
IMM	Interacting Multiple Model
SNR	Signal to Noise Ratio
SSTA	Smooth Super Twisting Algorithm

Symbols

c	Speed of Light
R	Maximum Range
Δt	Pulse Repetition Interval
P_r	Recieved Power
P_t	Transmitted Power
G_t	Transmiter Gain
G_r	Reciever Gain
σ	Radar Cross-Section
λ	Wavelength
θ	Azimuth Angle
ϕ	Elevation Angle
P_N	Noise power at the receivers input
K	Boltzmanns constant
T_o	$290^o K$
B	Noise bandwidth of the system
F	Noise factor
G	Target Gain

Chapter 1

Introduction

1.1 Radar-An Introduction

Radars, an acronym for Radio Detection and Ranging, are used for detecting targets in a volume of space using the properties of electromagnetic waves. They work by propagating a radio signal and then by applying different processing techniques on the reflections obtained after these signals strike different objects by using various algorithms [1]. These result in the revelation of various parameters of the target, such as its direction (bearing) relative to the receiver, the targets range, and its speed. Depending on the processing applied on the radar and the type on antenna, varying degrees of parameters can be obtained from a radar. Radars are used for air and terrestrial traffic control, for detection of motor vehicles, aircraft, ships, weather formations and missiles. Modern radar systems are related with machine learning and advanced digital signal processing and can extract useful information even when the noise is extremely high.

1.2 Historical Background

Radio Detection And Ranging (Radar) measures the returned energy of transmitted signal scattered from targets. Invention of radars refers us back to the

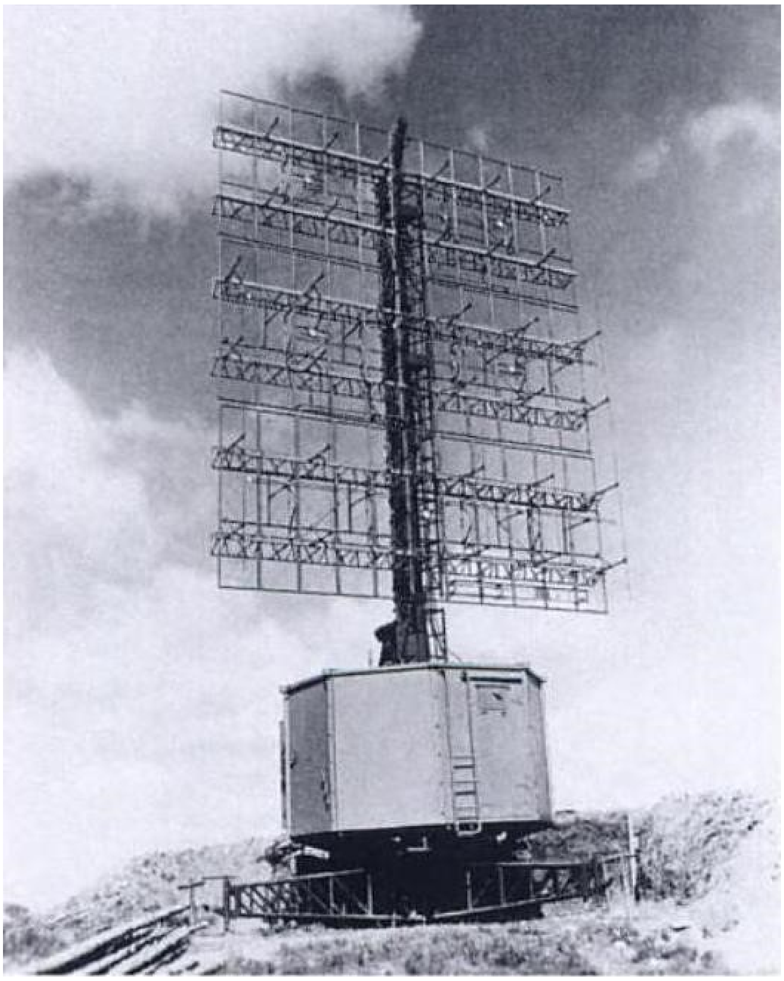

Figure 1.1: Freya-German WW2 radar

2nd World War when the British Ministry of War recognized the importance of wireless technology. Rapid development of radars started in this era helping the Britains Royal Air Force in detection of both aerial and sea borne targets. Performance and functionality of the radars improved throughout the 2nd World War enforcing enemies to build counter technology for radars such as jamming, chaff, decoys and stealth. Also, the requirements asked of the radar have increased, such as the number of targets that must be tracked, and the precision with which this task must be carried out. The result is highly sophisticated modern day radars, which remain a vital tool for both civil and defence applications. Early systems, at the beginning of the war, could simply provide angle and range estimates for detections made. Later, after the invention of the first Plan Position Indicator (PPI) displays, plot tables were used to enable skilled operators to maintain track on targets.

The 1960s saw the widespread development of phased arrays which allowed electronic (rather than mechanical) steering of the antenna beam. This technology, with the emergence of digital control, allowed the automatic operation and control of phased array radars, and the advent of the multi-function radar, in which the electronically scanned antenna is multiplexed between many different tasks.

Since then, both microwave and digital technology have advanced at an extremely rapid pace. New radars are emerging which are capable of adapting many aspects of their operation to the scenario and environment in which they are operating, under computer control. The flexibility provided by a software controlled phased array antenna supported by adaptive waveforms, signal processing and beamforming allows the modern multi-function radar to modify almost any aspect of its radar performance on a task to task basis. Such flexibility permeates all aspects of multi-function radar design and gives the potential to optimise performance and efficiency to meet weapon system design needs.

Whilst the concept of phased array multi function radars has been around for many years, the realisation of their full potential has been constrained by the availability of technology at realistic prices. It is only relatively recently that technology has progressed to a point where the software and processing power, and the antenna components have both become readily available to provide multi-function radars with the full flexibility that electronically adaptable phased arrays can offer.

1.3 Main Subsystems of Radar

Figure (1.2) represents the generic block diagram of a mono-static radar.

The main subsystems of Radar are classified as follow [2]:

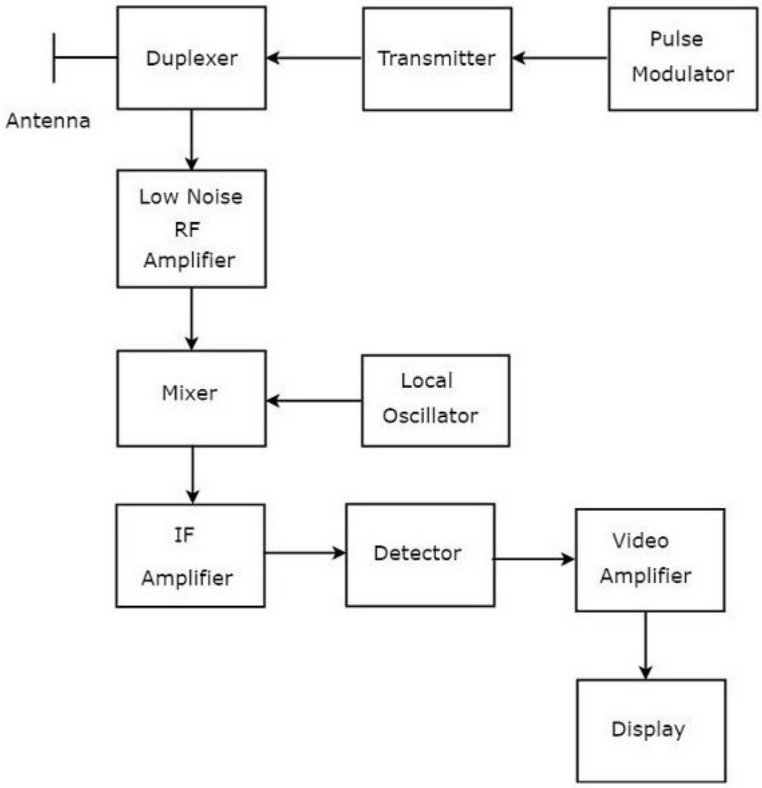

Figure 1.2: Generalized Block Diagram

1.3.1 Antenna

RF energy from the transmitter is radiated through antenna subsystem. Antenna subsystem radiates RF energy in a directional beam and collects the returning echoes. Received signals are then fed to the receiver with a minimum loss. Antenna subsystems include:

1. Waveguide
2. Transmission lines from the transmitter to radiating antenna
3. Transmission line and waveguide from the antenna to the receiver

Duplexer is often considered as a part of the antenna subsystem.

FIGURE 1.3: Raytheon Radar Antenna

1.3.2 Transmitter

The transmitter of radar generates high power electromagnetic pulses at specific time intervals. With use a of high power microwave oscillator like klystron, magnetron high power is achieved. Microwave solid state amplifier is also sometimes used to attain high power. The most important parameter of any radar transmitter is its power amplifier portion.

1.3.3 Duplexer

The duplexer alternately switches the antenna between the transmitter and receiver so that only one antenna needs to be used. This switching is necessary because the high-power pulses of the transmitter would destroy the receiver if energy could enter the receiver. Circulator is another device that is also used in radars in place of duplexer.

1.3.4 Receiver

Antenna system feeds weak signals from the target to the receiver. Receiver performs three main tasks on the received signal:

1. Amplification
2. Detection of the pulsed envelope
3. Sends it to the indicator

High frequency modulated signal is converted to low frequency signal by the receiver so that it can be easily amplified. Lower frequency is called IF (Intermediate Frequency). This type of receiver (converting high frequency to intermediate frequency) is called heterodyne receiver. The use of super heterodyne receiver guarantees stability and very high sensitivity in radar systems. Stability is confirmed by carefully designing the overall sensitivity, which is greatly increased by the use of multiple IF stages.

1.3.5 Signal Processor

The task of the signal processor is to process the reflected signal from target and interfering signals such that target echo signal power increases hence increasing signal to noise ratio (SNR). Target detection is also done in this system i.e. whether the target is present or not and also get the information about target's range and velocity.

1.3.6 Power Amplifier

Using RF power amplifiers, low power RF signal is converted into high power RF signal. RF power amplifiers drivers are the key element of radar transmitter. Designing goals are often, power output, high bandwidth, power efficiency, high gain, linearity, heat dissipation and input output impedance matching. The main portion of any radar transmitter is its power amplifier stage. To achieve the desired power which is normally in kilowatts, multiple RF power amplifiers are used in parallel topology. When multiple RF amplifiers are implemented in parallel topology, the use of high power divider/combiner becomes critical.

1.4 Classification of Radars

Depending upon the usage, antenna type and transmitted pulse, radars can be classified into different types as mentioned below:

1.4.1 Classification based on Functionality

One of the classification of the radars can be done based on their functionality as mentioned below:

1.4.1.1 2D Radar

These are used to detect target's range, bearing and speed. They typically use parabolic antenna. They are the oldest type of radar mostly used for detecting civil and military aircraft.

1.4.1.2 3D Radar

These radars perform all the functions of a 2D radar, but they provide additional height information. They are also used for aerial surveillance and use Phased-array antenna.

1.4.1.3 Synthetic Aperture Radar

These radars are used to get an image of the ground terrain. They can capture image irrespective of day/night and weather conditions.

1.4.1.4 Weather Radar

These radars are used to detect the weather conditions including wind speed and rain etc. They are also used to help aircraft for avoiding bad weathers.

1.4.1.5 Tracking Radar

Tracking is a process whereby the radar follows a position of one or more objects. Tracking radars ignore the content of space which is not occupied by the target. In tracking radars antenna beam axis should always be aligned with the selected target.

1.4.2 Classification based on Transmitted Pulse

Radars can also be classified on the basis of transmitted pulse:

1.4.2.1 Pulsed Radar

These radars use high-power pulsed signal for transmission Figure (1.4). They are mostly used in air surveillance application both in civil and military. They

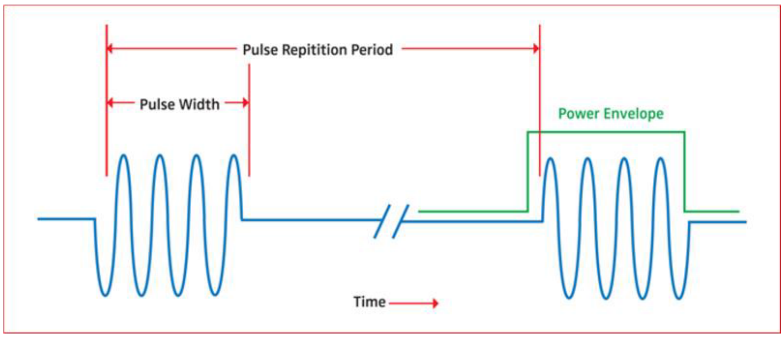

FIGURE 1.4: Pulsed Radar Waveform

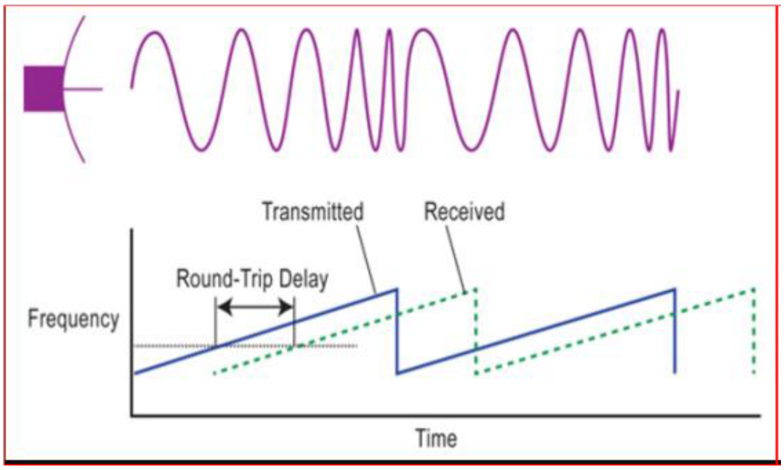

FIGURE 1.5: CW Radar Waveform

are complex and expensive to manufacture but they possess anti jamming and anti-interference features.

1.4.2.2 CW Radar

CW Radar use continuous wave signals Figure (1.5). They are simple and easy to manufacture and use much lower transmitted power than their pulsed counterparts. Their applications include proximity sensors, radio altimeters and low-distance ranging. They have the interference and jamming problems thus they are not generally used for military applications. Most common modern application of these radars are the self-driving cars that use CW radars for detecting vehicles in front.

1.4.3 Classification based on Antenna

Radars can also be classified based on the antenna type as mentioned below:

1.4.3.1 Mono-static

These radars use same antenna for transmission and reception Figure (1.6). They are easy to manufacture, deploy and use as compared to bi-static radars. Moreover, there are no synchronization issues with these radars.

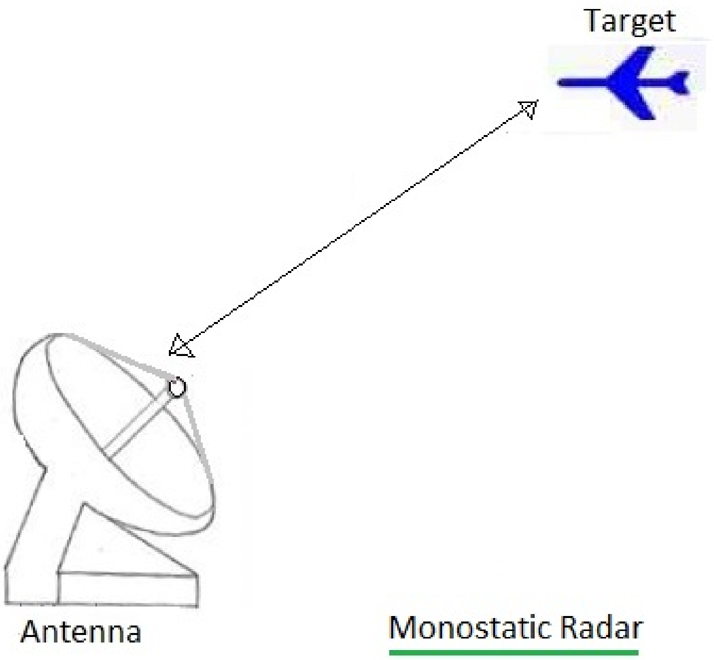

Figure 1.6: Monostatic Radar

1.4.3.2 Bistatic

These radars use different antenna for transmission and different antenna for reception as shown in Figure (1.7). These radars are generally difficult to deploy and use because of the tight synchronization requirements. However, they can detect stealth targets.

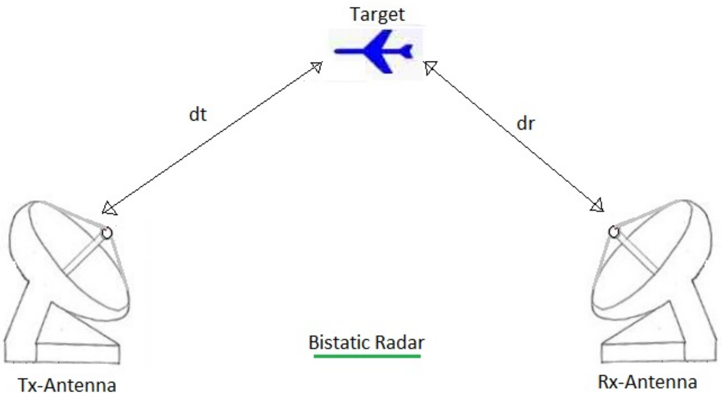

FIGURE 1.7: Biostatic Radar

Thesis Outline

This thesis is comprised of five chapters with details as follows

Chapter 02: This chapter introduces different types of tracking radar available and its basic operation. Literature survey conducted has also been made part of this chapter. The chapter summarizes with the gap analysis and problem statement of the research work.

Chapter 03: This chapter explains in details the basic modeling of Monopulse radar. The chapter also covers necessary knowledge required for operation and understanding of Monopulse radar. Basic introduction to model-free control is discussed in the later part of the chapter.

Chapter 04: PID and Sliding Mode Controller designed for the target tracking with Monopulse radar are explained in this chapter. The chapter also discusses in details the simulation results obtained using both controllers. Performance of the controllers in terms of target tracking is evaluated in the later part of the chapter.

Chapter 05: This chapters gives future direction and recommendations of the research work.

Chapter 2

Tracking Radar

2.1 Radar Tracking

Tracking is a process whereby the radar follows a position of one or more objects. Tracking radars ignore the content of space which is not occupied by the target. In tracking radars antenna beam axis should always be aligned with the selected target.

Tracking radar can be distinguished from the surveillance and Track-While-Scan radar by the fact that the beam of tracking radar follows the target motion. Such radars have a very high directional radiation pattern (i.e., narrow beam). For each coordinate a corrective signal is produced when the target deviates from the beam axis. The corrective signal is of the polarity/sign indicating the direction of deviation and is proportional to angular deviation of the target in the coordinate. The corrective signal is used to move the beam of the radar towards the target. Target can be located with much higher accuracy than the search radars or TWS radars. Unlike search radars which update the target position every few seconds lacking the information of target motion between scans, tracking radars monitor the target continuously such that the position of the target is known regardless of the motion of the target.

2.2 Tracking Principles

The main function of a tracking radar is to measure precise angle information and range of the target. The primary focus of this work is on the angle measurement. For this specific application only angle tracking is of importance. Tracking is achieved using both the radar hardware and the radar signal processing, which results in a closed-loop system. There are many kinds of tracking principles that can be roughly categorized in four classes as explained in the next section:

2.2.1 Single-Target Tracker (STT)

Single-Target Tracking gives continuous and precise information about a target's position, speed, and acceleration, which may all be consistently changing. To accomplish this, separate semi-independent tracking loops are normally settled for range, range- rate (Doppler) and angle.

2.2.2 Automatic Detection and Track (ADT)

Unlike Single-target tracking, in Automatic Detection and Track, rate of target observations is lower. This rate depends upon the time taken by the antenna to complete its rotation. The tracking of the target is done open loop and thus the antenna position is not determined by the data track.

2.2.3 Track While Scan (TWS)

TWS is the class of tracking that keeps track of a number of targets in the area of coverage. This is same as ADT and is considered as a subclass of the ADT.

2.2.4 Phased Array Radar Tracking

Phased array radars are the modern development of radars. Through the use of electronically steered phased array it has become possible to track many targets while keeping the data rate very high. Antenna beam can be rapidly switched through electronic beam steering to different target locations and thus, with proper time sharing between targets, the radar is able to maintain high data rate for each target.

2.3 Tracking Techniques

Commonly employed tracking techniques in radars are as follows:

1. Sequential lobing
2. Conical scan
3. Monopulse

2.3.1 Sequential Lobing

Sequential lobing is a tracking technique in which angle measurement is obtained using a single beam that interchange between two separate beam directions.

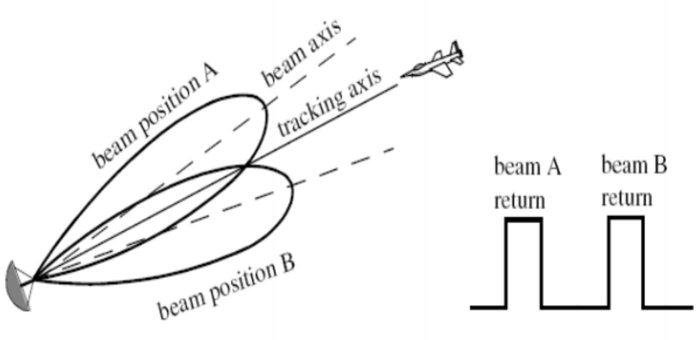

Figure 2.1: Sequential Lobbing

Figure (2.1) illustrates this concept. The beam is switched between position A and position B in order to align the target on the switching axis. If the target is not on axis of beam switching, voltage difference between the return signal of the two beam positions will give displacement of target from the switching axis.

2.3.2 Conical Scan

In conical scan radar systems antenna beam is slightly squinted from antenna axis. The antenna beam is rotated in a circular path around the axis. If target is not aligned to the axis of rotation than the amplitude of the target return signal varies with change in antenna beam position. Due to this change in amplitude the location of the target can be determined. This variation is because of the reason that different gains are pointed at the target while the beam was changing its position. If the target is aligned with the axis of rotation of antenna beam than the target return signals from different antenna positions will be same. Figure (2.2) illustrates conical scan tracking. With the target located at A, the conical scan will determine the phase difference between the axis between A and the rotation axis of the beam. This difference is then applied to the rotation axis.

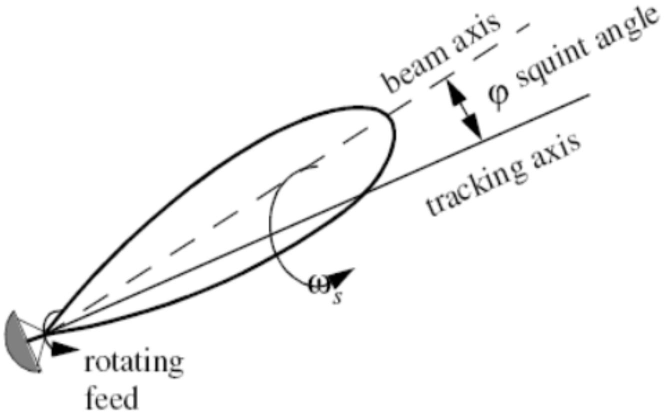

FIGURE 2.2: Conical scan

2.3.3 Monopulse Tracking

Monopulse radars are used for tracking the range and bearing of target. In monopulse radar, single pulse is used to determine the target location instead of using multiple pulses simultaneously. Monopulse radars offer improved resolution and angle measuring accuracy as compared to other typical radar systems. Simultaneous lobing technique is utilized in monopulse radar to estimate the bearing of target. In monopulse radars, information obtained from error signal is then used to align the antenna axis relative to the target position. Monopulse radars have an additional advantage that they are not affected due to variations in the target echo because the information is retrieved by comparing the several beams received simultaneously.

They are used in military applications in order to guide the weapons like missiles, fire guns and also in space vehicles. Monopulse tracking radars are also used to predict the future position of the selected target. They have benefit over the other conventional scanning radars because they use “Simultaneous Lobing” technique [3]. In earlier radars, “Sequential Lobing” technique was used for estimating the target angles.“Lobe Switching” and “Conical Scanning” techniques; both are included in “Sequential Lobing” technique. Such techniques were unsuccessful in the cases when fluctuations were observed in the strength of the target echo. Another problem encountered in the Conical Scanning was that due to mechanical vibrations it was difficult to align the beam axis with respect to target. Monopulse tracking radars use pencil beams for tracking and try to align the axis of the beam with respect to the chosen target. Due to very narrow beams they have highly directional patterns. An error signal is generated for both coordinates (azimuth and elevation) when the axis of beam is not aligned with the target. That error signal is then sent to servo to align the beam axis with respect to the target and the sign of error signal tells about the direction of the deviation of target.

The tracking radars extract information about the range of target by centering the range gate on the desired target. During tracking, the signals received only within that range gate are accepted and others are discarded. Error signal is generated when the echo pulse from the target is deviated from the center of the range gate. Doppler information regarding the target can also be derived in some radars using addition processing.

The monopulse has been categorized as the amplitude and phase-comparison Monopulse. In "Amplitude Comparison" monopulse, information about the target is determined by comparing the amplitudes of the beams received at different receivers. Phase Comparison monopulse extracts target information by measuring the relative phase of the received beams.

The common thing in all Monopulse is that the information is determined from the simultaneous receiving beams. Monopulse offers benefits over the other traditional angle tracking techniques but the cost and complexity also increases because several receivers are required. Succinct summaries about Monopulse are also proposed by Barton [4] and Rhodes [5].

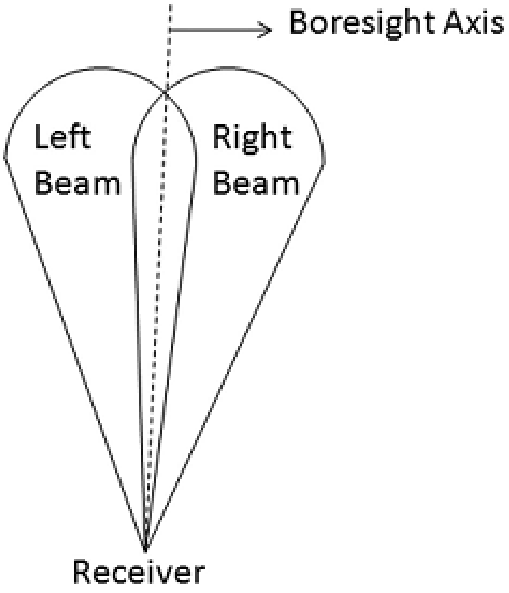

FIGURE 2.3: Overlapping Monopulse Beams

In monopulse radar, echo signal from target is received at four different receivers that are covering different areas. For the 3-D angle tracking i.e. in azimuth and elevation, four separate receivers are required. Strength of beams received at different receivers is analyzed and tracking errors are obtained. From the hardware

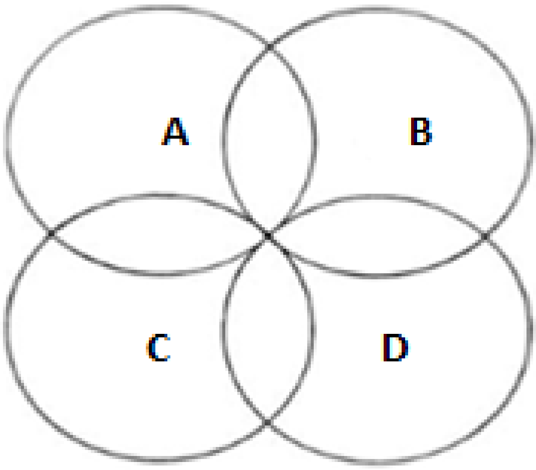

Figure 2.4: Recieving Beams

point of view, comparators are used to create the sum and difference signals by adding and subtracting the received beams. These signals obtained are then sent to servo to generate azimuth and elevation correction signal. Range information is obtained by measuring time difference between the transmission of pulse and reception of echo from the target. The receiving beams may be characterized as A, B, C and D beams and are shown in Figure (2.4). Equations for the difference and sum beams are given as follows:

$$\sum = (A + B + C + D) \tag{2.1}$$

$$\Delta_{az} = \frac{1}{2}[(A + C) - (B + D)] \tag{2.2}$$

$$\Delta_{el} = \frac{1}{2}[(A + B) - (C + D)] \tag{2.3}$$

$\sum$ is used to normalize Δ channel, the boresight deviation off the target θ can be obtained from the ratio.

$$\frac{\Delta}{\sum} = k\theta \tag{2.4}$$

Where, k is the slope of real part of the voltage $\frac{\Delta}{\sum}$ curve near $\theta = 0$ [6].

Monopulse processor then creates a difference to sum ratio that is then passed to a device called as “Product Detector”. AGC is used prior to this device in order to normalize the sum and difference beams. AGC will prevent the receiver from being saturated by adjusting the voltage of the incoming signals. It performs a fundamental job in the closed loop tracking system

2.4 Literature Review

Monopulse tracking radars are under research since numerous past years. During the study of monopulse radar it has been observed that the error cannot be minimized past a certain value, rather it fluctuates within a certain limit. Thus beam of monopulse radar always has an oscillatory motion during target tracking. This oscillatory motion can be described by chattering phenomena. The ability of a monopulse radar to efficiently measure the target angle is greatly reduced by the chattering phenomena.

In 1960, Kalman filter was introduced that played a vital role in such tracking radars for reduction of fluctuations in target measurement. In 1968, extended version of Kalman filter was introduced. Tracking radar also makes predictions regarding the future position of target using Kalman filters. They are used in many applications like to monitor the specific air routes and also in numerous military applications [7]. Literature has proposed Kalman filters for smoothing of the data to minimize the chattering effect.

In [8] the author uses frequency diversity plus amplitude weighting to minimize the error in angle measurement. A Nonlinear Gaussian Mixture Kalman Filter (NL-GMKF) is applied to track the target in glint environment for MMW monopulse. The simulation results proves that the target is effectively tracked in glint environment using the proposed methodology but with a disadvantage that the calculation is increased. In [9] the author reduce computational requirements, effects of nonlinearities and ill-conditioning in target tracking by designing decoupled kalman filters. The proposed method provides computational efficiency against covariance matrix factorization techniques. In [10] the tracking performance is enhanced by proposing a robust processing technique for KF to reduce glint noise. The performance of a KF in a basic angle tracking planar missile/target simulation is assessed by comparing the performance of the robust and non robust estimators on both Gaussian and a class of contaminated Gaussian target signatures.

In [11] for the combined estimation tracking of two closely space unresolved targets by using monopulse radar author proposes four algorithms. ML estimation with traditional KF is used as a first technique for resolving two targets and estimation of their position by joint-bin-processing of sum-difference channel. Two separate Kalman filters are used for tracking in the second algorithm using the Gibbs sampler as measurement extractor. The importance of using the Gibbs approach is that it provide an additional measurement-error covariance information. In the third algorithm kalman filter with Gibbs approach is used to jointly track the targets by using cross-covariance information between the targets. In the fourth technique integrated particle filter is used to track the target directly using sum-difference channel of the monopulse at matched filter output. out of the four techniques disused the particle filter approach gives promising results. [12] proposes a particle filter based Track Before Detect (PF-TBD) algorithm for high PRF monopulse Radar for the improvement and estimation performances un low SNR. Based on the target and measurement models PF-TBD algorithm with resample-move operation is developed. The results show that detection and estimation performance is improved by the proposed algorithm. In [13] an IMM filter combined with Kalman filter which assumes a low process noise, and a Kalman-Levy filter, which assumes a high process noise is proposed for tracking of maneuvering targets. The author compares the proposed algorithm results with a benchmark. improved results are obtained for tracking of maneuvering targets using the proposed technique.

In [14] John D. Glass proposed the IMM filter technique for the detection of maneuvering targets. Average Likelihood Ratio Test (ALLRT) was proposed for the detection that proved to be better than the other existing detectors for radar. Unbiased estimation for the DOA of target was done using Cramer-Rao Lower

Bounds (CRLBs) technique. [15] Uses kalman filter for tracking enhancement of target in presence of interference. The author minimzes mean squared error of the Line of Sight tracking angle in presence of interference. [16] utilizes Adaptive Interacting Multiple Model (AIMM) with extended Kalman filter for target tracking with monopulse radar. [17] Presents tracking with debiased consistent centered to accurately track the target. The author compares the method with mixed coordinate extended Kalman filtering and converted measurement approach. [18] proposed an IMM estimator with an adaptive policy for real time selection of sampling interval. The algorithm improves the tracking performance as compared to Kalman filter.

Going through the literature it has been observed that most of the research work is focused on model based technique that includes Kalman filtering, extended Kalman filtering, IMM and AIMM. The bottleneck in the model based arises due to the un-availability of precise process models. Even if suitable models exist, they may not be precise enough to accurately represent the process over the entire envelope of operation, for example in case of maneuvering targets. Therefore a model-free approach is proposed in this work for robust target tracking and to mitigate the fluctuations in the radar measurement.

2.5 Problem Statement

To design a Robust controller for monopulse radar to mitigate chattering.

Chapter 3

Implementation of Monopulse Radar

The modeling implemented in the simulation is explained in this chapter. It covers basic understanding of tracking radar and its operation. Figure (3.1) shows closed loop monopulse tracking implemented in the simulation. The main function of a radar is to measure the range of a target present in space using electromagnetic(EM) waves. This is generally accomplished by generating a pulsed signal of a specific frequency, which is transmitted by an antenna. Therefore, a radar will need a pulse signal generator, a transmitter, a transmitting-receiving rotating antenna, a receiver, a signal processor, and a display to show the detected targets and to indicate their positions.

3.1 Radar Range Equation

When the antenna is pointing in the direction of target, EM energy radiated from the antenna strikes the target and is reflected and scattered. The EM energy reflected back in the direction of the antenna may be captured and passed on to an adequately sensitive receiver.

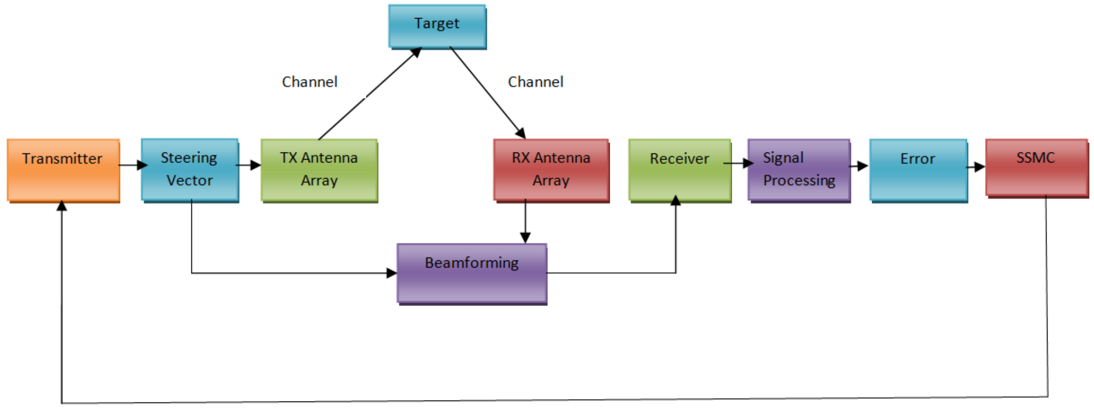

FIGURE 3.1: Closed loop Monopulse tracking using HOSM

After receiving the electromagnetic energy, radar measures the time Δt for EM pulse to cover distance R to the target and the distance covered by the pulse reflected back by the target in the direction of antenna is also R. So the total distance covered by the EM pulse is $2R$, round trip distance. In empty space EM energy travels at the speed of light $c = 3 \times 10^8 m/s$.

As distance is equal to the product of velocity and time, so this expression can be written as

$$2R = c\Delta t \tag{3.1}$$

$$R = \frac{c\Delta t}{2} \tag{3.2}$$

where c is speed of light, R is max range and Δt is Pulse Repetition Interval (PRI) of the radar.

Electromagnetic pulse travels back to antenna after reflected back from the target, power P_r appearing on the receiving antenna (for mono-static radar) is given by the equation below. From the equation, it is obvious that the reflected power from distant targets is going to be very small as it declines as the fourth power of the range.

$$P_r = \frac{P_t G_t G_r \sigma^2 \lambda}{(4\pi)^3 R^4} \tag{3.3}$$

where

P_r	Received Power
P_t	Transmit Power
G_t	Transmitter Gain
G_r	Receiver Gain
λ	Wavelength
σ	RCS
R	Range

3.2 Coordinate Transformation

If the target is located at point P and is denoted as (r, ϕ, θ) in polar coordinate system as shown in Figure (3.2) and the position of its coordinates in the rectangular coordinate system is (x, y, z), then the transformation relation between the

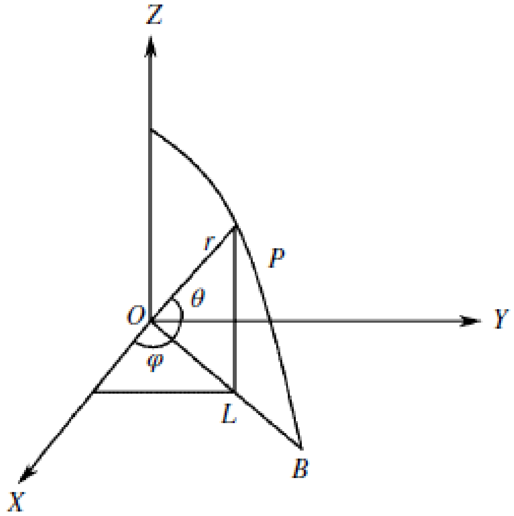

FIGURE 3.2: Space Polar Coordinate System

polar and the rectangular coordinate system of the antenna is

$$x = r\cos\phi\cos\theta \tag{3.4}$$

$$y = r\sin\phi\cos\theta \tag{3.5}$$

$$z = r\sin\theta \tag{3.6}$$

$$r = \sqrt{x^2 + y^2 + z^2} \tag{3.7}$$

$$\phi = \tan^{-1}\frac{y}{x} \tag{3.8}$$

$$\theta = tan^{-1}\frac{z}{r} \tag{3.9}$$

where r is range, θ is azimuth angle and ϕ is elevation angle.

3.3 Radar Waveform

Waveform that a radar transmits is represented as

$$x(t) = \alpha(t)\sin(\omega t + \theta(t)) \tag{3.10}$$

The term ω in sin function is the radar's carrier frequency and $\alpha(t)$ represents the amplitude modulation of the RF carrier. In pulsed radar $\alpha(t)$ is a rectangular function that turns the transmit pulse on and off. Phase or frequency modulation of the carrier is done using $\theta(t)$; it can be zero or nonzero. In the simulation rectangular pulse is used as transmit pulse.

Figure(3.3) represents the on time of the rectangular pulse modulated on the carrier where τ is the on time of rectangular pulse.

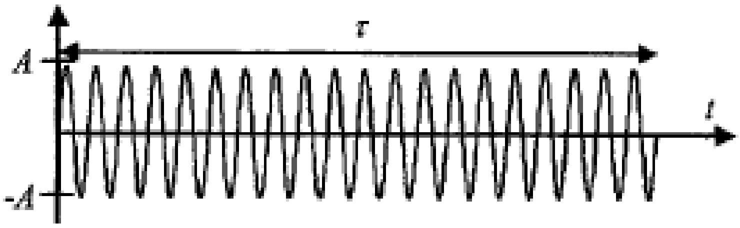

Figure 3.3: Modulated Pulse

3.4 Free Space Path Loss

The propagation of radar's RF signal through space is explained by using free space path loss model. It is one of the simplest model for the propagation of RF signal. When a radar transmits a signal, as this signal propagates it attenuates. This attenuation is proportional to the inverse of the square of the distance covered by the signal.

$$Signal = \frac{k}{d^2} \tag{3.11}$$

This loss can alse be represented in terms of frequency and wavelength

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{3.12}$$

$$FSPL = \left(\frac{4\pi df}{c}\right)^2 \tag{3.13}$$

3.5 Antennas

An antenna is that component of the radar which radiates power coming from transmitter into space or it collects power from the incoming reflected wave and transfer this power to a receiver.

Antenna provides coupling or impedance matching between the transmitter and space or between space and the receiver. A single antenna can be shared by one or more transmitters and one or more receivers. Monopulse is concerned primarily with reception. Some of the antenna terminology had its origin in transmission but by reciprocity it applies to reception as well.

Three main categories of antennas used in monopulse radar (as well as in other radars) are lenses, reflectors and arrays, and each category can be divided into various types. The principal distinction between monopulse antennas and similar antennas used for other purposes is the nature of their feeds.

In a monopulse radar antenna having multiple feeds, the sum and difference signals, or rather linear combinations of the feed outputs, are formed using certain passive microwave devices. Usually these are four-port devices with two input ports and two output ports, each output voltage being a different linear combination of the two input voltages. The same or similar devices are also used for other radar functions, such as power division or combining, but here we will concentrate on monopulse functions. There are several forms of these devices i.e. hybrid junctions and Magic-T junctions. In this work array antenna is used.

A simple method of obtaining monopulse operation is to split the array into symmetrical quadrants. The outputs of the elements in each quadrant are summed to produce four signals that are then combined to form a sum and two differences.

3.6 Receiver

In simulation while modeling receiver, only thermal noise is considered. This noise is generated in the radar itself in the first stage of receiver. To remove this noise matched filter is used. The bandwidth of the receiver is directly proportional to the power of thermal noise. Thermal noise power at the receiver's input is given as.

$$P_N = KBFT_o \tag{3.14}$$

Table 3.1: Radar Specification

Propagation Speed	$3 \times 10^8 m/sec$
Array Size	60×60
Element spacing	$0.015m$
Range Resolution	50 m
Pulse Width	$3.335 - 07sec$
Band Width	$2.9979e + 06Hz$
Wavelength	$0.03m$
Sampling frequency	$1.7987e + 07Hz$
Peak Power	$20000Watt$
Max Range	$50000m$
PRF	$2.9979e + 03Hz$
Transmitter Gain	$20dB$
Receiver Gain	$20dB$
Frequency	$1.0000e + 10Hz$
Receiver Noise figure	5
Target RCS	$4m^2$
Receiver Beam width	3.3851^o
Receiver Antenna Directive gain	$35.56dB$

Where

$P_N =$ Noise power at the receiver's input

$K =$ Boltzmann constant

$T_o =$ $290^o K$

$B =$ Noise bandwidth of the system

$F =$ Noise factor

3.7 Radar Specification

The radar specification used in the simulation work are tabulated in table (3.1).

3.8 Beamforming

Directional signal transmission and reception in radars is done using a technique known as beamforming i.e. beamforming allows radar to transmit and receive

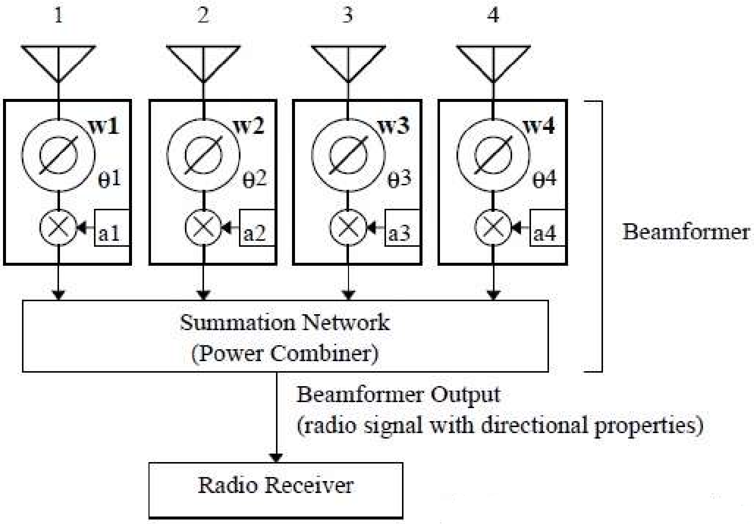

FIGURE 3.4: Analog Beamforming Receiver

signal from a particular direction. Using beamforming direction of the target is determined.

3.8.1 Analog Beam Forming

In analog beamforming gain/phase variation is done to analog signal at the transmitter. At the receiver end signal from different antennas is added up before analog to digital conversion in analog beamforming. The figure (3.4) represents analog beamforming receiver. In the figure complex weights are applied to the output of each antenna in the array and then all of the signals are summed together into one output. This gives required directional pattern from antenna array.

Therefore, we require only one DAC and one ADC when performing ABF. However, the phase shifters have to be implemented in the analog domain which perform the fixed phase shifting and cannot be used to perform varying phase shifts.

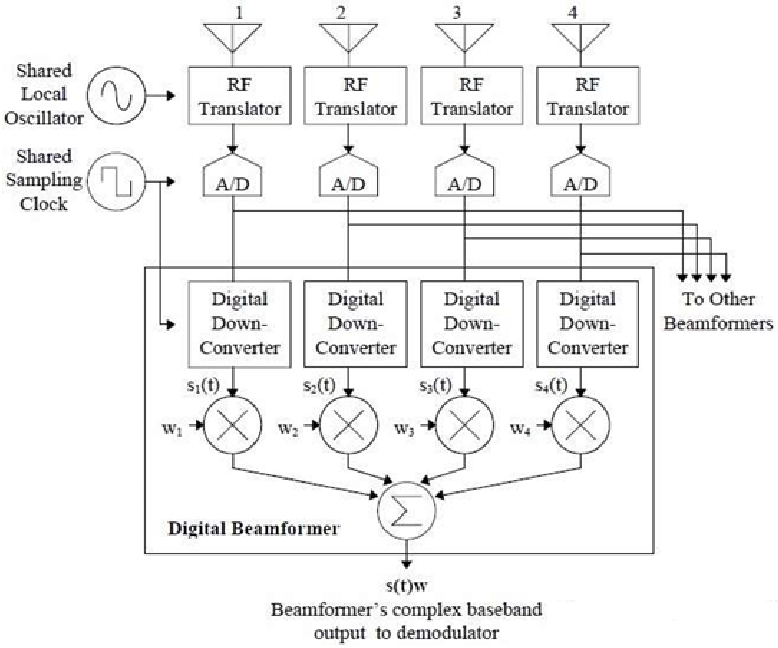

FIGURE 3.5: Digital Beamforming Receiver

3.8.2 Digital Beam Forming

If the amplitude scaling, adding and phase shifting is done digitally, we get digital beamforming. The digital implementation enables the provisioning for forming several simultaneous beams in various directions. Digital beamforming on the receiver end is used in many phased array radars and communication applications [5]. In a phased array radar, filtering is possible in both the doppler shift and angle of arrival. It is therefore, important to characterize the data in each range bin in terms of doppler and AOA. This can be used to get the location of the target in the Angle-Doppler Space. At the transmitter end in digital beamforming gain and phase variation is applied to the digital signal before the signal is converted from digital to analog. On the receiver side first the signal is converted from analog to digital domain and then digital down conversion takes place. After this step complex weights are applied and output from the different antennas is added . The figure (3.5) shows digital beamforming receiver.

Digital beam-forming includes analog to digital converters, RF translators, Digital down converters multiplication with complex weights and addition operation. The function of the RF translator is to convert RF frequency signal to a lower IF frequency. RF mixer is used for this purpose. Local oscillator signal is fed to the RF mixer in order to convert RF frequency signal to IF frequency signal. At the input and output of the mixer proper filters are used. So the process requires separate ADCs and DACs for each channel that is digitized and therefore, requires intense processing to be carried out on each channel. It can generate multiple beams from a single array and it can handle multiple data streams.

3.9 Matched Filter

The main function of matched filter is to maximize signal to noise ratio (SNR). For a given input signal x(t) consisting of target return signal and noise, the output of the matched filter is given by the result of the convolution.

$$y(t) = \int_{-\infty}^{\infty} x(s)h(t-s)ds \tag{3.15}$$

$$h(t) = ax^*(T_m - t) \tag{3.16}$$

so y(t) becomes,

$$y(t) = \int_{-\infty}^{\infty} x(s)x^*(s + T_m - t)ds \tag{3.17}$$

Equation (3.17) represents the cross-correlation of the target return signal with noise with the transmitted pulse. This shows that the matched filter implements a correlator. Thus in matched filter the transmitted pulse acts as a reference signal. Matched filter is also used for pulse compression in radars.

3.10 Target Definition

For a nonpolarized signal x, the signal y reflected from the target is given by the relation.

$$y = \sqrt{G}x \tag{3.18}$$

Where x is the signal propagating towards the target and G is the target gain factor

$$G = \frac{4\pi\sigma}{\lambda^2} \tag{3.19}$$

where,

σ is RCS of the target.

λ is the wavelength of the incoming signal. The target used in the simulation is non-fluctuating target and it is moving towards the radar.

3.11 Range-Tracking Loop

The main objective of the early radars has been automatic range tracking. In World War II the first range tracking unit was developed. The purpose of range unit is to follow target in range and provide continuous distance information. Suitable timing pulse provides range gating so that AGC circuits and angle tracking circuits only work on a small range or time interval. This is the time during which echo signal from the target which is being tracked appears on the receiver.

In a pulsed radar the echoes from the target which is being tracked arrive at a time equivalent to the target range. All other ranges contribute only clutter, noise or unwanted signal from other targets. Monopulse processor rejects unnecessary echoes and noise and to work only on echoes received from the desired target, a range tracking loop keeps a range gate (time gate) centered on the desired target. Width of the gate is the same as transmitted pulse. Only signals from the receiver output during the gate are passed on to the Monopulse processor. If there is AGC, it also responds only to outputs within the gate. The position of the gate provides measurement of target range. The range gating feature is not unique to Monopulse but is needed in all angle-tracking pulsed radars.

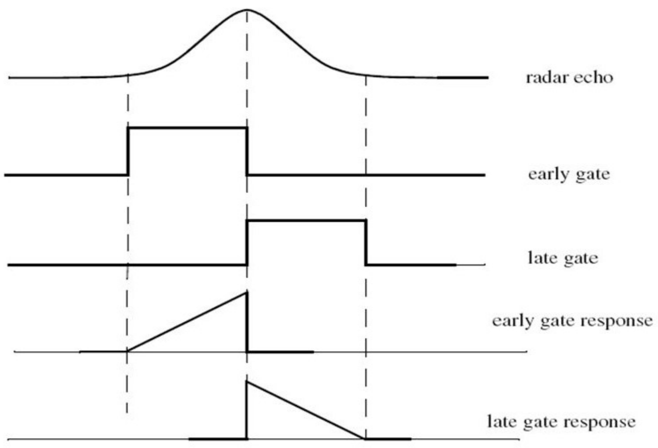

Figure 3.6: Early Late Gate

Like angle tracking, range tracking operation is also performed by close loop tracking. Error of the target echo pulse from the center of range gate is measured and then the gate is moved to minimize that error. There are many techniques to measure range tracking error. The commonly used technique is known as early-late gate.

3.11.1 Early-Late Gate

Early-Late gate is a technique used to improve range tracking in a radar while tracking a single target. Range gate or range bin is divided into two parts known as early gate and late gate. The main objective of this technique is to keep the target in the center of the range gate or to keep the echo signals voltage equally divided between early and late gate. A target can appear in the two gates at the same time, as shown in figure. In the above figure, the target is present in the middle of the range gate and hence its response is equally divided between the early and late gates. If more portion of target is present in early gate than in late gate then the voltage measured in early gate would be greater. This is termed as the range discriminant.

$$e = R_L - R_E \tag{3.20}$$

Thus if this error is minimized then range can be measured more precisely than implied by range resolution. The range-tracking loop measures the target's current range and keeps a range bin centered on the target's location (isolating the target signal for angle tracking and doppler tracking). The tracking error is defined as the difference between early and late gate samples i.e. $R_L - R_E$. The function of the range discriminant is to keep the range gate perfectly centered on the target. Range discriminant is formed by subtracting the amplitudes of the two range gates. Normalization is done by the difference with the sum of the range gates i.e. $R_L + R_E$.

$$\Delta R = \frac{R_L - R_E}{R_L + R_E} \tag{3.21}$$

Subsequently, the sampling times must be shifted to center the range gate on the targets echoes as a function of the difference between R_L and R_E. By using range discriminant and previous range gate command target's acceleration and range can be estimated.

3.12 AGC

A common standardization procedure in monopulse radar is to develop an AGC control voltage from the sum-channel output and use this to control the gains of all three receivers. While instantaneous AGC action is possible (using a time constant that is a fraction of the pulsewidth), but such a response leads to increased tracking error on fluctuating targets, so an AGC that averages at least several pulses is often used instead.

In the tracking radar, output of the range tracker or range gate is fed to AGC. The output of the range tracker is a gated signal with gate located at middle of the echo signal. As the range of the target and its cross-section changes, amplitude of the echo signal also changes.

The error detector of a coordinate tracker (range, angle or Doppler tracker) generally develops an error voltage that is proportional to both the coordinate error and amplitude of signal to the error detector. A tracking servo is designed to produce an error correction that is proportional to the error. The proportionality constant should be fixed at a specific design value, for it is a factor in a servo loop gain; it would be intolerable to have this factor vary with signals amplitude. The function of AGC is to provide a constant average signal level into the trackers. The AGC loop filter performs the averaging, over many received pulses. Usually, the AGC detector incorporates a boxcar circuit that stretches the detected target pulse to duration nearly equal to the PRI. Without stretching the average of the pulse samples would be proportional to the transmit duty factor. Stretching increase the average and consequently the AGC loop gain.

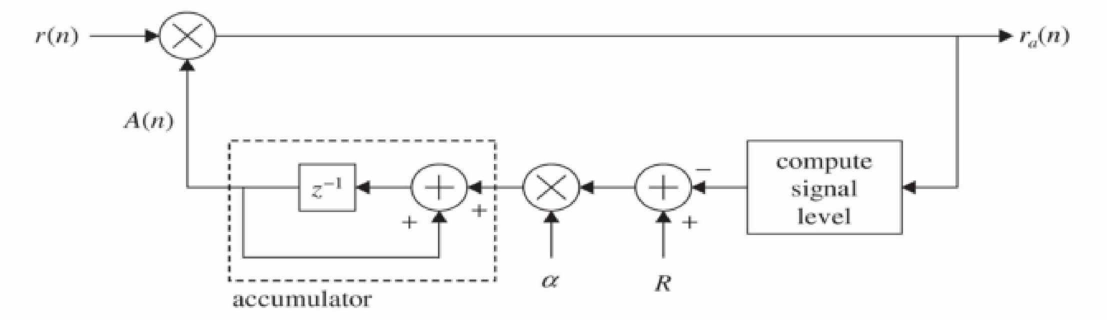

Figure 3.7: Block Diagram of Digital AGC

$$A[n+1] = A[n] + \alpha(R - |A[n]A_{in}[n]|) \tag{3.22}$$

$$A[n+1] = A[n](1 - \alpha A_{in}[n]) + \alpha R \tag{3.23}$$

where

α = Step Size

R = Reference Value

$A[n]$ = Gain

$A_{in}[n]$ = Amplitude of the input signal

3.13 Model Free Controllers

From the last decade many improvements have been done for the development of nonlinear control systems. It has been tried to achieve flexibility, robustness and to develop adaptive controllers to achieve the desirable performance.

In the existing control techniques, initial knowledge has been required about the dynamical system due to their non-linear behavior. The initial knowledge about the system dynamics is not known or may not be available. Due to the absence of prior knowledge model free controllers are being used because in such controllers the parameter modeling of a system is not a problem [19].

Model free controllers are very famous because they are very easy to implement. Desired performance for a dynamical system can be achieved using such controllers by the minute tuning of controller gains. Data is measured from the input as well as output of the system and high performance can be achieved using model free controllers [20].

Chapter 4

Controller Design and Simulation Results

This chapter covers PID and SMC controller design for single target tracking. The results are simulated using Matlab. Simulation results obtained using PID and SMC are compared in the later part of this chapter.

The following assumptions are considered during the simulation performed

1. Antenna Beamwidth: The target is assumed to be within the antenna beam. If the target is not within the antenna beam tracking will be lost.
2. Clutter: Clutter has not being considered in the simulation.
3. RCS Fluctuations: A constant RCS is assumed during the simulation.
4. Multipath: Multipath effect is ignored.

4.1 PID Control

PID controller is found in a wide range of applications for industrial process control. A PID controller calculates an error $e(t)$ which is the difference between desired reference value and measured output and applies a correction based on proportional, integral and derivative terms. Mathematically the PID controller can be expressed by

$$u(t) = k_p e(t) + \frac{k_i}{T} \int e(t) + k_D e\dot{(t)} \times T \tag{4.1}$$

where k_p,k_i and k_D are all non-negative coefficients for the proportional, integral and derivative terms respectively (sometimes denoted P, I and D).

The PID control was used to minimize the target error and achieve the desired tracking. For target tracking the objective is to minimize the azimuth (Δ_{az}) and elevation (Δ_{el}) error. Gains for the PID control were tuned on hit and trial basis. Results achieved are given below.

4.1.1 Azimuth Angle

Figure (4.1) shows azimuth angle of the detected target in degrees. Actual target is denoted by dashed red line while solid blue line represents the azimuth angle measured by the radar with a PID controller. The radar starts tracking the target from 18 degrees in azimuth (initial condition for azimuth angle). Actual target azimuth angle during the initial time is seen to be 17.25 degree. With an objective to track the azimuth angle by minimizing azimuth error, the radar starts tracking the target by moving its beam from 18 degrees towards the actual target position.

4.1.2 Azimuth Tracking Error

The azimuth angle tracking error is shown in figure (4.2). The simulation results show maximum tracking error of 0.2 degree in azimuth angle at the start of the simulation. This maximum tracking error is due to the initial gap between the actual target azimuth angle and initial target angle to the radar. PID tracks the azimuth angle with an average error of approx. 0.1 degree.

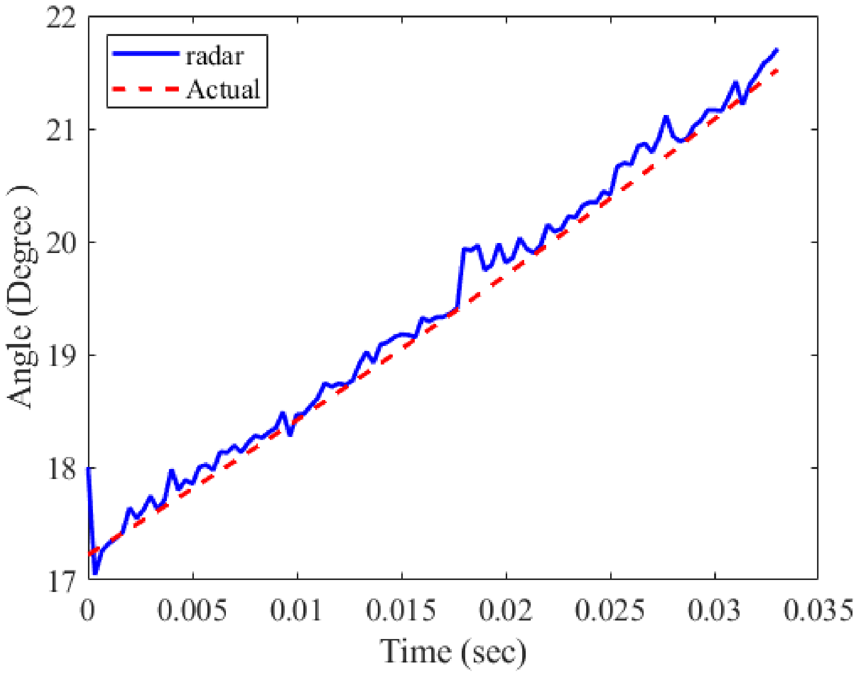

FIGURE 4.1: Azimuth Angle

4.1.3 Elevation Angle

The result for elevation angle of the detected target is shown in figure (4.3). Dashed red line shows the actual target elevation angle while the detected elevation angle is shown with solid blue line. The actual target was at 0.3 degree while the radar starts its initial scan from 2 degrees and moves towards the actual target elevation angle.

4.1.4 Elevation Tracking Error

The elevation angle tracking error is shown in figure (4.4). The simulation results show maximum tracking error of 0.5 degree in elevation angle at the start of the simulation. This maximum tracking error is due to the initial gap between the actual target elevation angle and initial target angle to the radar. PID tracks the elevation angle with an average error of approx. 0.1 degree.

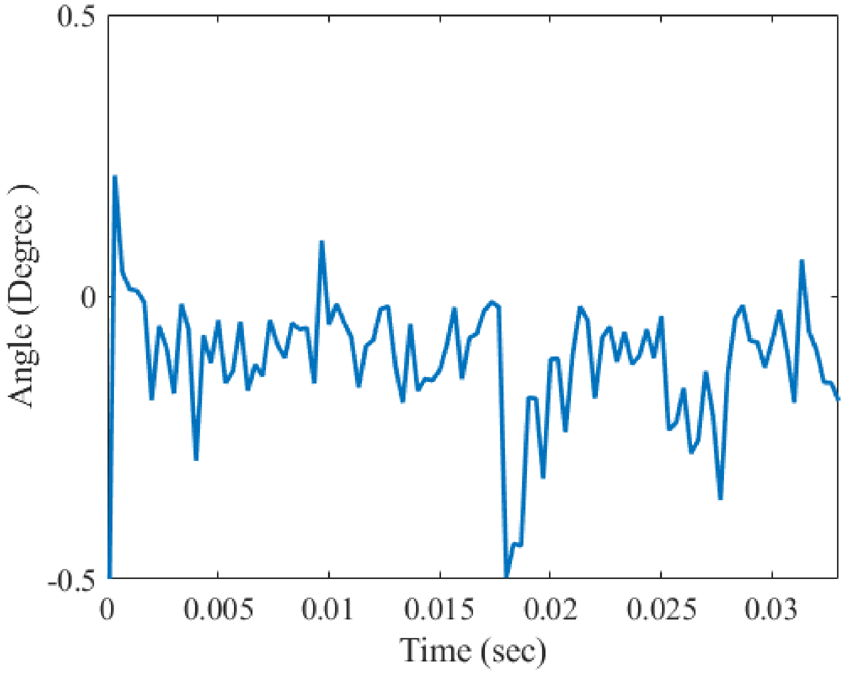

FIGURE 4.2: Azimuth Error

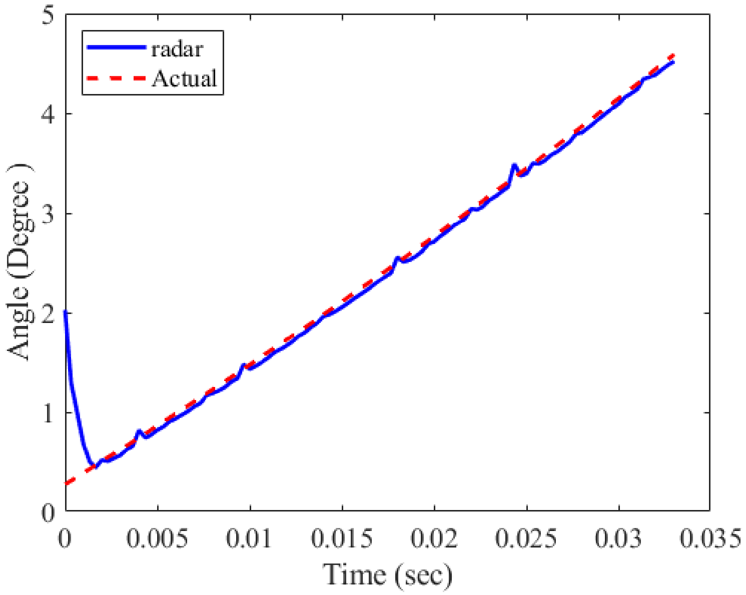

FIGURE 4.3: Elevation Angle

4.1.5 Target Range

The detected target range is shown in Figure (4.5).

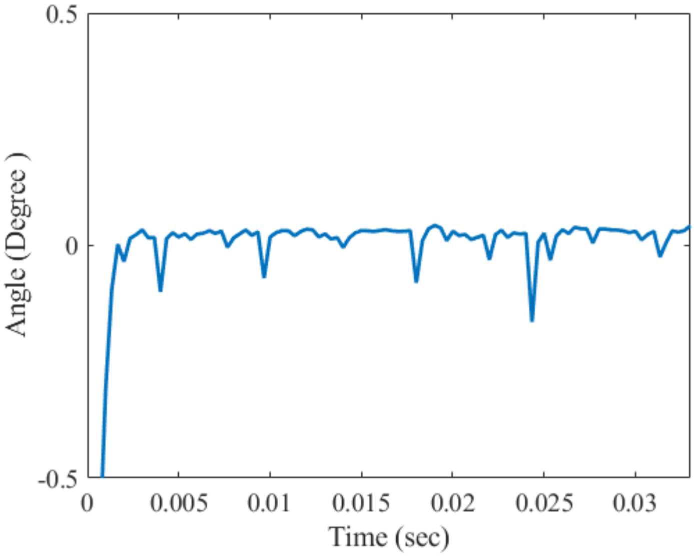

FIGURE 4.4: Elevation Error

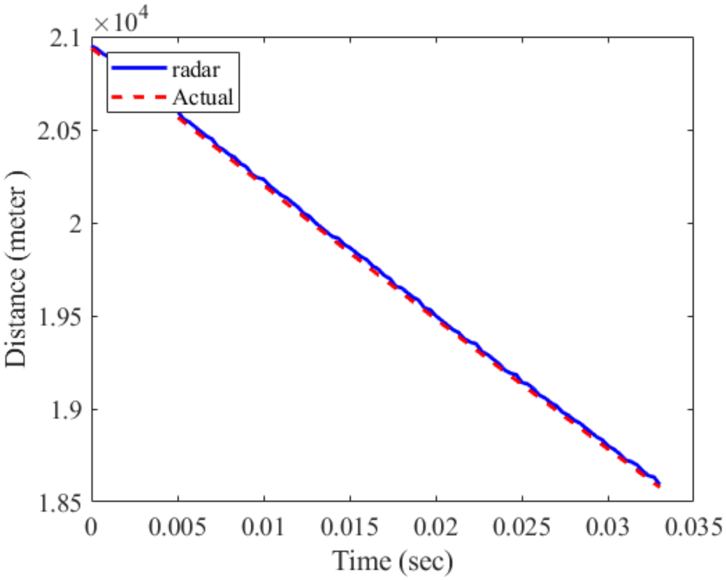

FIGURE 4.5: Target Range

4.2 Sliding Mode Control

One of the important robust control technique used in literature is Sliding Mode Control. SMC is a type of non-linear controller that can alter the dynamics of system by using control signal which is discontinuous and it allows the system to slide on a specific and predefined sliding surface. Infinite gain is used by SMC to force the dynamic system to slide along the sliding surface. The beauty of using SMC is its robustness property because the control process may just involve switching from one state to another state. Precision is not always there so SMC is insensitive to variations in parameters due to its robustness property. SMC is used with great care as compared to other non-linear control techniques. In SMC the controller used is of discontinuous type that's why the sliding phase is assumed to be achieved in finite time duration. The robustness property of Sliding Mode Controller (SMC) as compared to other non-linear controllers makes it the most suitable choice. It is the appropriate controller due to its decoupling nature and insensitivity to system parameters when system is in sliding phase [21].

The algorithm of Sliding Mode Control has been divided into two main phases: the first one is reaching phase and the other one is the sliding phase [22] [23].

- **Reaching Phase:** In the first phase, a discontinuous controller is being used to drive the dynamics of the system by starting from the initial conditions and reaching on a predefined surface also called as sliding surface, hyper plane or sliding manifold.
- **Sliding Phase:** The second phase is known as sliding phase where the system trajectories are forced to slide along the predefined hyper-plane in order to achieve the equilibrium point.

Good closed loop performance can be achieved using SMC because it is insensitive to parameter variations and shows the robustness against the matched disturbances. Uncertainties may appear due to imperfect modeling of the dynamical system that may create problems. Another eminent property is that during the sliding mode the system is in reduced order. The discontinuous controller used to achieve sliding phase has very large switching frequency that may be considered as infinite and this will ultimately result in a phenomenon known as chattering. Chattering are oscillations that are observed in the output of system and are harmful. There are many techniques for the suppression of chattering like boundary layer solution, observer based solution, regular form solution and disturbance rejection. This undesirable chattering in the system may cause damage to actuators and finally results in the failure of specific control system.

The relative degree and the requirements for the system model is another limitation on the use of First Order SMC. Conventional sliding mode control just act upon the first time derivative of system states but higher order sliding mode controller acts upon the higher time derivatives of system states and also ensure the fast time convergence of states and accuracy as well.

Higher Order Sliding Mode Control (HOSMC) technique has been discussed in the literature to cater with the problems being faced in Conventional Sliding Mode Control (SMC) [24] [25] and [26]. When the sliding order is increased, the chattering phenomenon decreases in the locality of sliding surface and the control effort is also assumed to become more continuous. The sliding order is increased in the Higher Order Sliding Mode (HOSM) which is upto rth degree. HOSM is simple to implement because it is independent of the model parameters that are under observation and offers robustness in case of disturbances and uncertainties. Another benefit offered by HOSM control is finite time convergence of sliding variables and their derivatives towards their equilibrium point.

Among the Higher Order Sliding Mode (HOSM), the Second Order Sliding Mode (SOSM) appears to be more attractive because it is very easy to implement.

4.3 Super Twisting Control

Super twisting sliding mode control is included in second order sliding mode control. In the super twisting algorithm, information about the derivatives of the sliding variable is not required so its implementation is easy as compared to real twisting algorithm. While implementing the HOSM, relative degree of system also plays a very important role. When the relative degree of system is observed to be ‘1’ then “Super Twisting” algorithm is used and for relative degree 2, Real Twisting algorithm is used. Super twisting controller can be implemented even if the mathematical model of the system is not available.

Super twisting is among the HOSM that involves finite time convergence of both the sliding variable and its derivative without using the knowledge of $\dot{\sigma}$. Chattering phenomena can also be reduced to great extent using Super Twisting Algorithm.

The control law for Super Twisting Algorithm can be written as [25].

$$u = \lambda |s|^p sign(s) + u_1) \tag{4.2}$$

$$\dot{u}_1 = -\alpha sign(s) \tag{4.3}$$

If the following conditions are fulfilled by the controller gain, then the finite time convergence is achieved by sliding variables. $\lambda, \alpha\sigma_o > 0$ and $0 < \rho \leq 0.5$.

Here control is continuous, because the chattering effects are smoothed out due to the power of sliding variable and integral in the second terms of (4.2) respectively. The drift term of the compensated system can be canceled out with the help of $\alpha \int sign(\sigma)dt$ after finite time. Graphically, the convergence of the algorithm can be shown in Figure (4.6) [25].

4.4 Smooth Super Twisting Control

Chattering effects are reduced to great extent by using Higher Order Sliding Mode (HOSM) but this algorithm appears to be sensitive regarding the fast dynamics that are not properly modeled. Using Higher Order Sliding Mode (HOSM) the chattering is observed may be later in the system. The Smooth Super Twisting Algorithm (SSTA) [27] is another version of Super Twisting Algorithm (STA) and is a sliding mode controller having the second order. Its structure appears to be general and very simple having the good robustness property and also show better performance. Control free from chattering is required for some systems that appear to be sensitive.

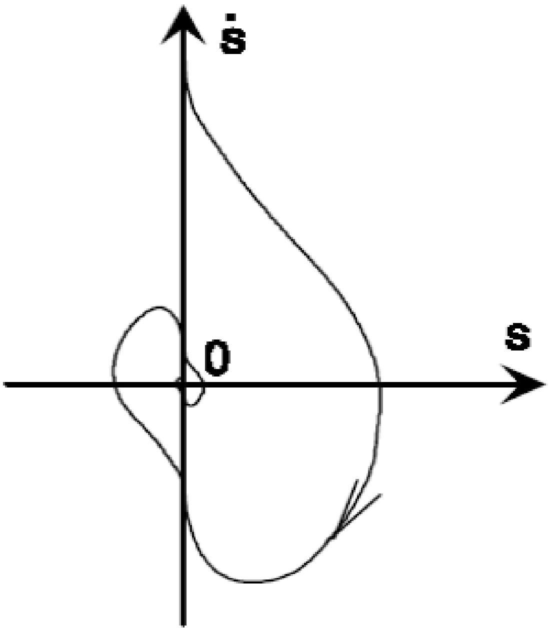

Figure 4.6: Super Twisting Algorithm Convergence

The Smooth Second Order Sliding Mode control is proposed by [27] is expressed below as:

$$u = \lambda|s|^{\frac{2}{3}} sign(s) + u_1 \tag{4.4}$$

$$\dot{u}_1 = -\alpha|s|^{\frac{1}{3}} sign(s) \tag{4.5}$$

where $\lambda, \alpha > 0$ and s is sliding surface.

In Smooth Super Twisting Control (SSTC) when the trajectories reach the sliding surface then the gain decreases and the control effort appears to be smooth. Due to this smoothness of control, accuracy is achieved without the existence of uncertainties and disturbances.

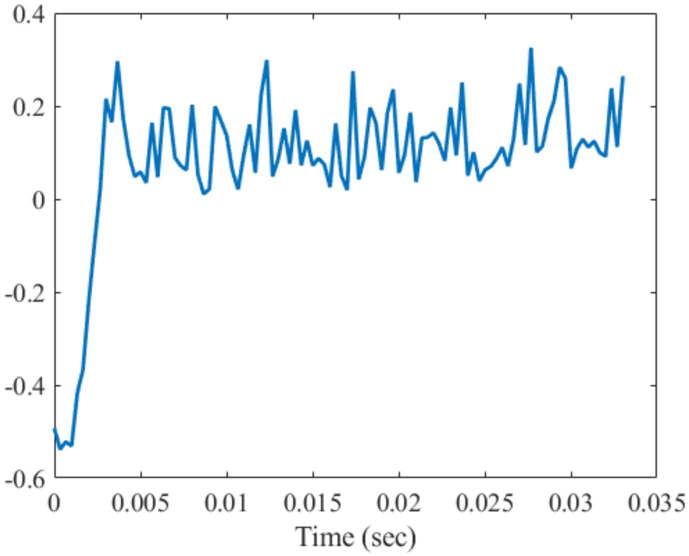

FIGURE 4.7: Azimuth Surface

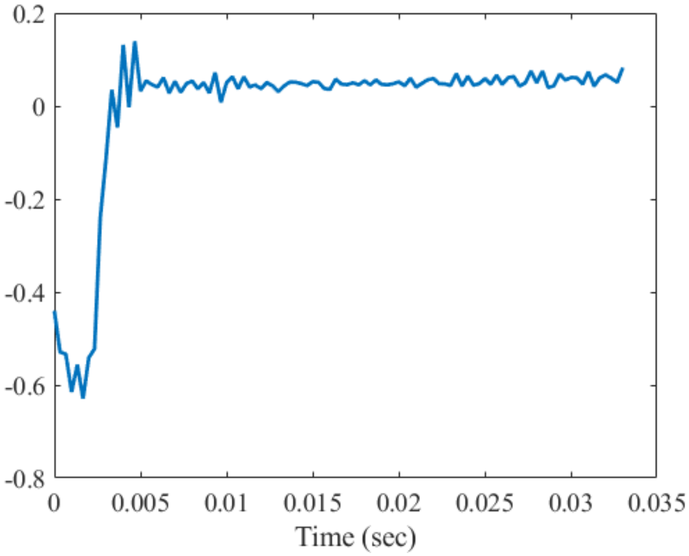

FIGURE 4.8: Elevation Surface

The sliding surface considered in this work is given by s which is the error signal related by the equation:

$$s = e = \frac{\Delta \cos \phi}{\sum} \tag{4.6}$$

where Δ is a difference channel, $\sum$ is a sum channel and ϕ is the phase difference between $\sum$ and Δ. Figure 4.7 and Figure 4.8 shows the azimuth and elevation surfaces respectively.

4.4.1 Azimuth Angle

Figure (4.9) shows azimuth angle of the detected target in degrees. Actual target is denoted by dashed red line while solid blue line represents the azimuth angle measured by the radar with SSTA. The radar starts tracking the target from 18 degrees in azimuth (initial condition for azimuth angle). Actual target azimuth angle during the initial time is seen to be 17.25 degree. With an objective to track the azimuth angle by minimizing azimuth error, the radar starts tracking the target by moving its beam from 18 degrees towards the actual target position.

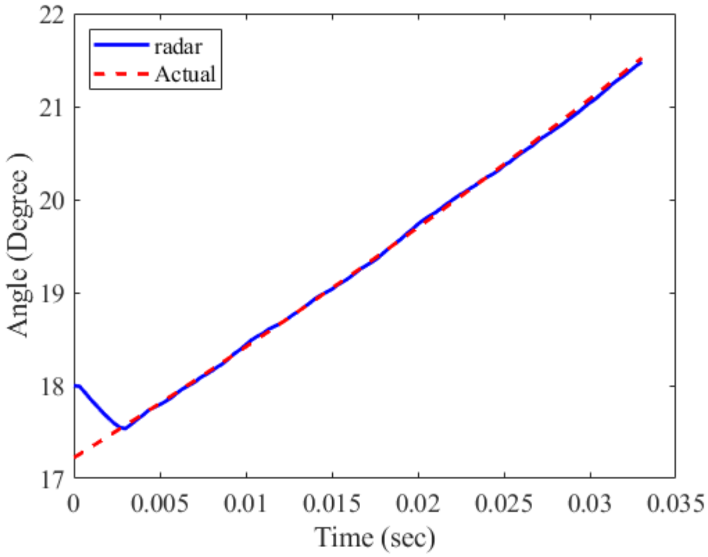

Figure 4.9: Azimuth Angle with SSTA

4.4.2 Azimuth Tracking Error

The azimuth angle tracking error is shown in figure (4.10). The simulation results show maximum tracking error of 0.05 degree in azimuth angle at the start of the simulation. It can be seen from the figure below that the tracking error in azimuth is reduced with SSTA. As stated above this maximum error is due to the initial gap between the actual target azimuth angle and initial target angle to the radar. SSTA has an average tracking error of 0.02 degree in azimuth.

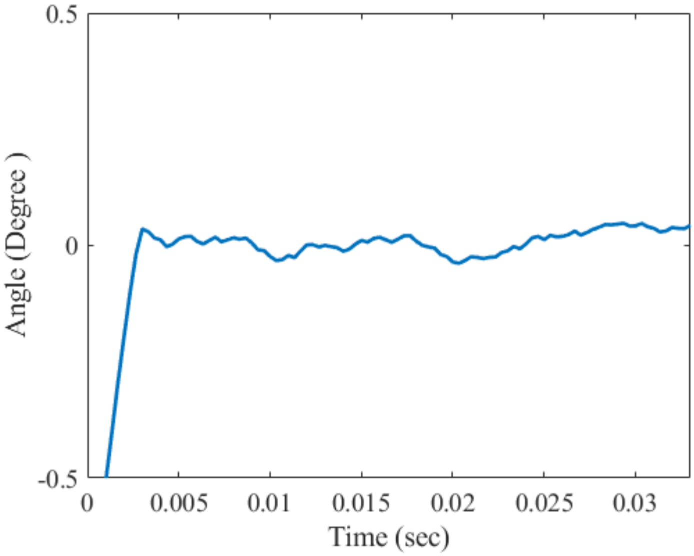

FIGURE 4.10: Azimuth Error with SSTA

4.4.3 Elevation Angle

The elevation angle of the detected target is shown in figure (4.11) with dashed red line showing the actual target elevation angle while the detected elevation angle is shown with solid blue line. The actual target was at 0.3 degree while the radar starts its initial scan from 2 degrees and moves towards the actual target elevation angle.

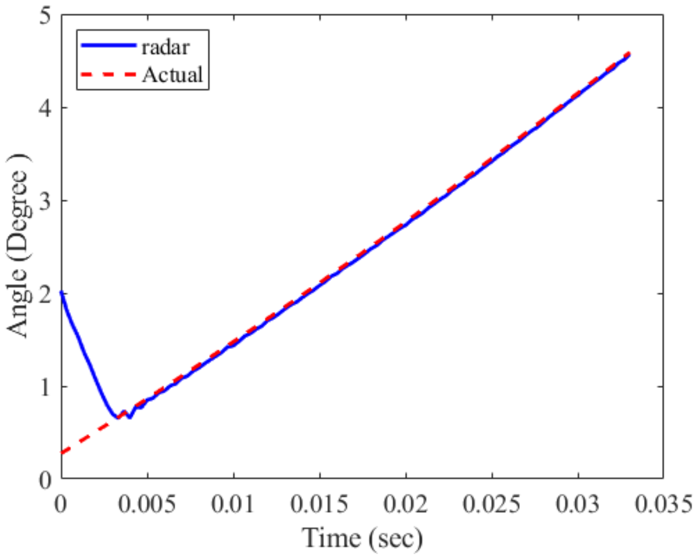

FIGURE 4.11: Elevation Angle at SSTA

4.4.4 Elevation Tracking Error

Elevation Error with SSTA is shown in figure (4.12). The simulation results show maximum error of 0.08 degree in elevation angle at the start of the simulation. The tracking error in elevation is reduced with SSTA as compared to PID. This maximum tracking error is due to the initial gap between the actual target elevation angle and initial target angle to the radar. SSTA tracks the elevation angle with an average error of approx. 0.02 degree

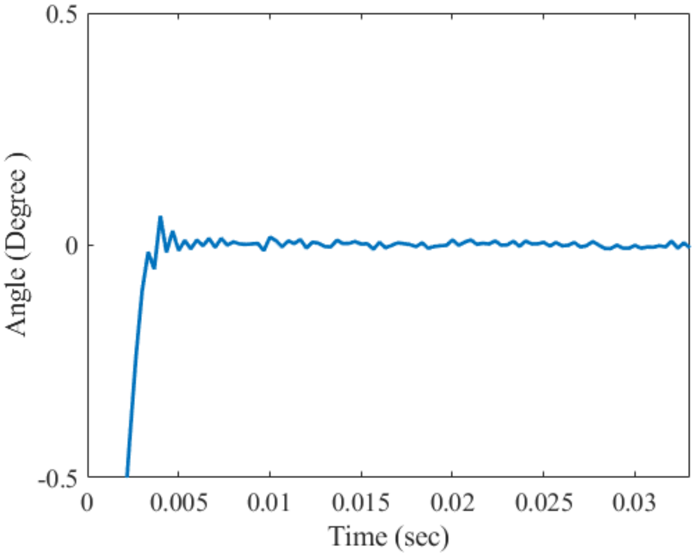

FIGURE 4.12: Elevation Error with SSTA

4.4.5 Target Range

The detected target range is given in figure (4.13).

4.5 Comparison between PID and SSTA Results

A graphical comparison between PID and SSTA results in terms of azimuth and elevation error is discussed in this section.

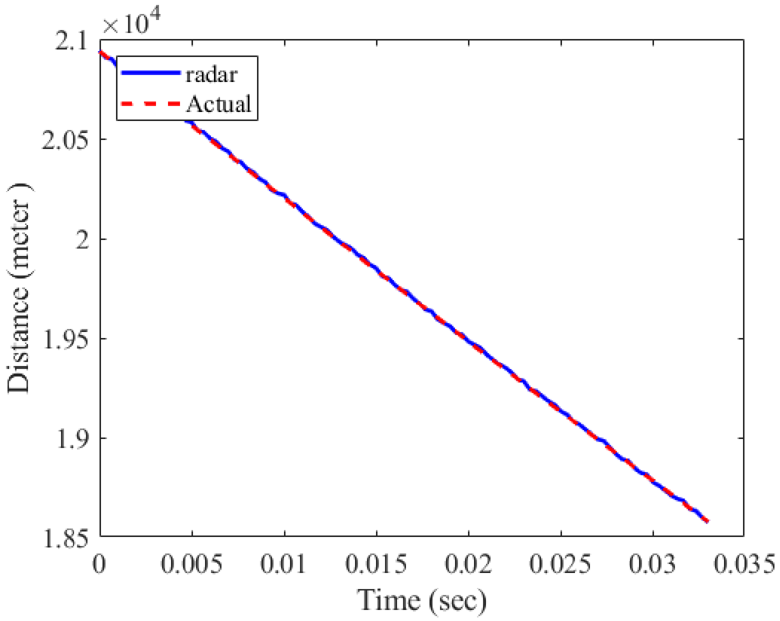

FIGURE 4.13: Target Range with SSTA

The results obtained with SSTA have decreased error in azimuth and elevation as compared to to conventional PID. Figure (4.14) shows Azimuth tracking error with PID and SSTA. Simulation results show that the tracking error is quite high and fluctuating with PID, while SSTA has smoothed the error with a reduce amplitude.

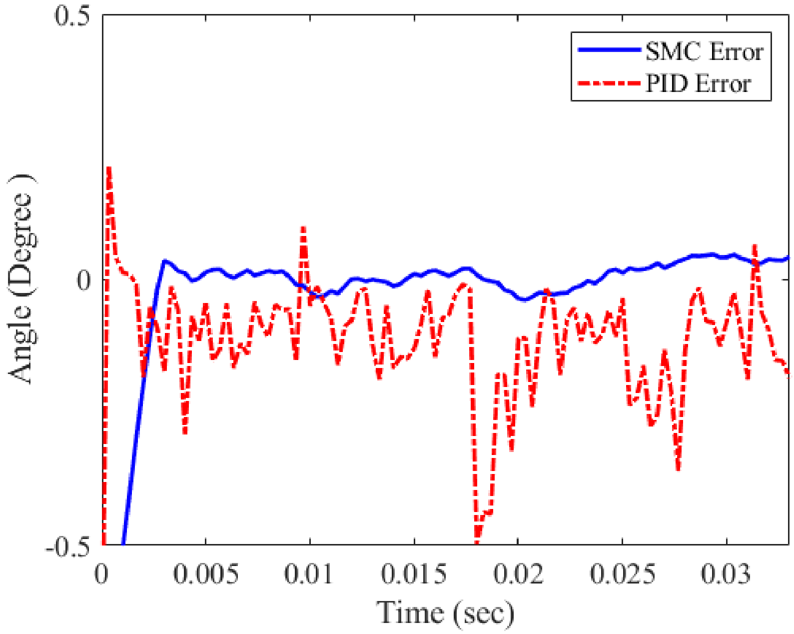

FIGURE 4.14: Azimuth Error Comparison

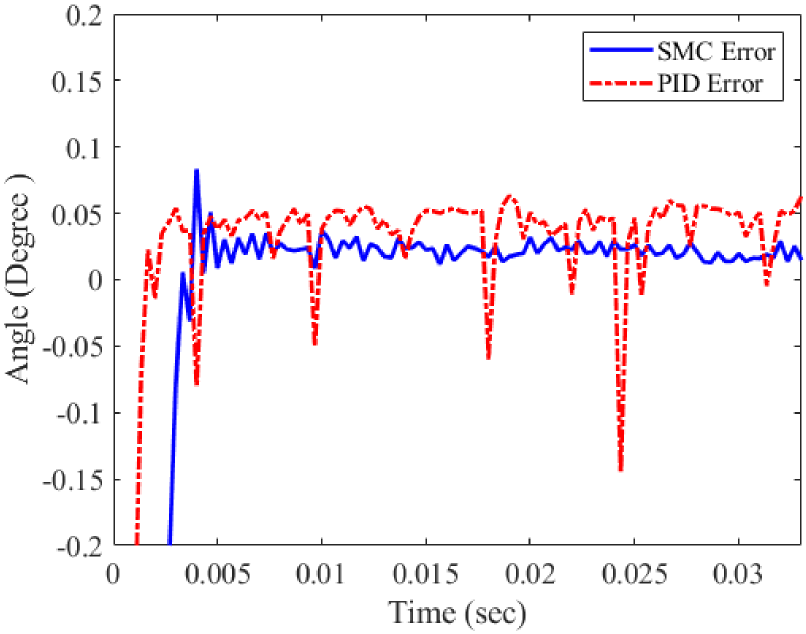

Figure 4.15: Elevation Error Comparison

Similarly Elevation tracking error is shown in Figure (4.15). It can be seen that the error with SSTA is minimized as compared with PID.

The simulation results show that SSTA gives a smooth output in terms of Azimuth and Elevation tracking errors as compared to a quite fluctuating response with PID control. Based on the results achieved it can be concluded that for a better target tracking Smooth Super Twisting Algorithm can be a good choice.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The thesis covers appropriate technique for the removal of chattering observed in the target trajectories measured by monopulse radar. Two controllers, PID and Smooth Super Twisting Control Algorithm (SSTA) were designed for the said objective.

PID not being the robust controller could not handle the chattering observed in the target detection. In order to achieve the desired objective a smooth second order model free robust controller known to be Smooth Super Twisting Control Algorithm is used. The undesirable chattering in the target tracking trajectories were suppressed by the designed controller. SSTA is easy to implement as compared to other Higher Order Sliding Mode (HOSM) controllers as it does not depend upon the derivative of sliding surface. Simulation results depict that the response of the system has become smooth and stability is also ensured. After the implementation of Super twisting algorithm, chattering is reduced to great extent and desired results are achieved. The results of simulations portray the efficiency and uniqueness of Higher Order Sliding Mode (HOSM) control. It was also shown that SSTA provided more accurate, disturbance free steady state tracking as compared to the PID.

5.2 Future Work

The work carried out in this research can be extended in multiple ways. The robustness of the controller can be further verified using a complex radar model. Different model free techniques like intelligent Proportional Derivative (iPID) and model free adaptive control can be applied and the results may be compared with the SMC to check the robustness and error reduction with these techniques. A comparison between the results will give us a suitable controller to mitigate the problem addressed in the research work.

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