Internship Report

Modeling and Simulation of Direction Finding Algorithm for Electronic Warfare

PRAVEEN KUMAR N
1PE15EC106

ABSTRACT

In Electronic Warfare (EW) Systems,Estimation of Angle of Arrival (AoA) of threat radar signal is an important operational functionality.In a dense radar threat scenario, Multiple radar signals of various types, which are operating over multiple frequency range and impinging from all over the sphere pose threat for survivability of host Aircraft.The scenario poses challenges in all the three domains,Viz.Time, frequency and spatial.In this Internship project Amplitude comparision method for AoA estimation is Explored.various practical considerations,implementation aspects and simulation studies has been undertaken from a practical perspective.

Contents

List of Figures

Matlab Codes

Chapter 1

About the Oraganization

1.1 History and Background of DRDO

Figure 1.1: DRDO Logo

- DRDO (Defence Research and Development Organization) was formed in 1958 from the amalgamation of the then already functioning Technical Development Establishment (TDEs) of the Indian Army and the Directorate of Technical Development and Production (DTDP) with the Defence Science

Organisation (DSO). DRDO was then a small organisation with 10 establishments or laboratories. Over the years, it has grown multi-directionally in terms of the variety of subject disciplines, number of laboratories, achievements and stature.

- Today, DRDO is a network of more than 50 laboratories which are deeply engaged in developing defence technologies covering various disciplines, like aeronautics, armaments, electronics, combat vehicles, engineering systems, instrumentation, missiles, advanced computing and simulation, special materials, naval systems, life sciences, training, information systems and agriculture.

- Presently, the Organisation is backed by over 5000 scientists and about 25,000 other scientific, technical and supporting personnel. Several major projects for the development of missiles, armaments, light combat aircrafts, radars, electronic warfare systems etc are on hand and significant achievements have already been made in several such technologies.

1.2 DARE

Figure 1.2: DARE Logo

1.2.1 History and Background

- Defence Avionics Research Establishment (DARE) initially started as a Project Laboratory - Advanced Systems Integration and Evaluation Organisation (ASIEO), which was established in 1986 at Bangalore to pursue the goal of enhancing the operational capabilities of Indian Air Force through modern technologies.
- The erstwhile ASIEO was headed by Dr KG Narayanan, Distinguished Scientist since its inception. It became a full fledged self accounting organisation wef 01st June 2001 and was renamed as DARE (Defence Avionics Research Establishment). DARE and was formally taken over by Sri RP Ramalingam, Distinguished Scientist wef 18th January 2002.
- Over the last decade, DARE has made rapid progress in the areas of Airborne Electronic Warfare, Airborne Processors and Testing & Evaluation of Electronic Warfare (EW) systems. It has implemented concepts in concurrent engineering in partnership with the Industry in order to achieve shorter design to induction time frames and seamless transfer of technology.

1.2.2 Areas of Work

- DARE has two major wings the **Electronic Warfare** (EW) wing and the **Mission Avionics Wing** (MAW).
  1. The EW wing concentrates on design and development of Radar Warners, and EW suites for various aircrafts to enhance their survivability and mission accomplishment. These systems are under manufacture at Bharat Electronics.
  2. The MAW has pioneered indigenous development in the area of Mission Avionics. The mission computer for fighter aircraft have been developed and delivered in quantities.

1.2.3 Vision and Mission

- **Vision :** Spearhead Research and Development in the field of Airborne Electronic Warfare and Mission Avionics to achieve self-reliance in these critical technology areas.
- **Mission :** To conduct Research and Development in avionics technologies in order to equip Indian Armed Forces with Mission-effective aeronautical systems enhanced by
  1. Current and Futuristic airborne EW systems
  2. State of art Mission Avionics

Chapter 2

Introduction to Radar systems

2.1 Radar basic Principle of Operation

The word “RADAR” is an acronym for RAdio Detection And Ranging.Radar is an electromagnetic system for the detection and location of reflecting objects such as aircraft,ships,spacecraft,vehicles,people,and the natural environment.Its operation can be summarized as follows:

- The radar radiates electromagnetic energy from an antenna to propogate in space.
- Some of the radiated energy is intercepted by a reflecting object,usually called *target* located at distance from the radar.
- The energy intercepted by target is reradiated in many directions.
- Some of the reradiated (echo) energy is returned to and received by the radar antenna.
- After amplification by a receiver and with the aid of proper signal processing, a decision is made at the output of the receiver as to whether or not a target echo signal is present.At the time,the target location and possibly other information about the target is acquired.

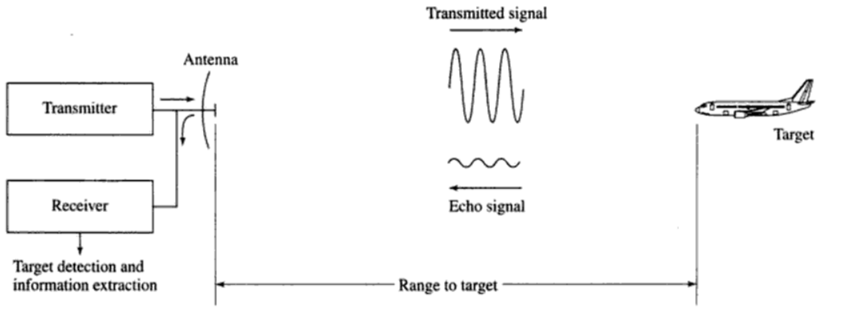


Figure 2.1: Basic Principle of Radar.

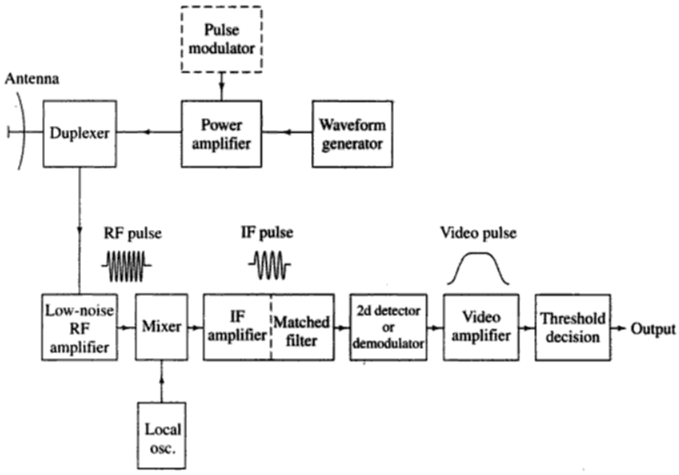


Figure 2.2: Simple block diagram of a radar employing a power amplifier transmitter and a superheterodyne receiver

2.2 Radar System Characteristics

In order for a radar system to determine range, azimuth, elevation, or velocity data, it must transmit and receive electromagnetic radiation. This electromagnetic radiation is referred to as radio frequency (RF) radiation. RF transmissions have specific characteristics that determine the capabilities and limitations of a radar system to provide these target discriminants, based on an analysis of the characteristics of the target return.

2.2.1 Doppler effect

The "Doppler effect" takes advantage of the fact that the frequency of RF waves will be changed or shifted when reflected from a target moving relative to the radar. The shifted frequency of the returning RF wave depends on the movement of the aircraft in relation to the radar. Let f_o be the transmitted frequency of the radar, and f_t be the frequency of the reflected RF wave from the target.

- For a stationary target, the frequency of the reflected signal will equal the frequency of the transmitted signal.

Figure 2.3: Zero Doppler Effect : Stationary Target

- For a target moving toward the radar, the frequency of the reflected signal will be higher than the transmitted signal.

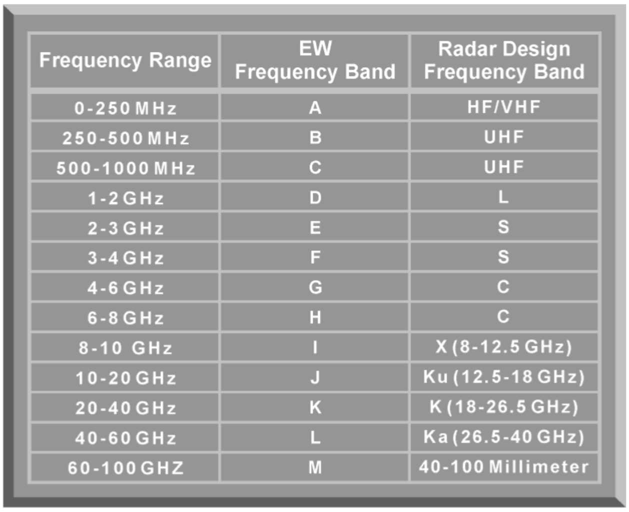
Figure 2.4: Doppler Effect : Closing Target

- The reflected frequency for a target moving away from the radar will be lower than the transmitted frequency.

Figure 2.5: Doppler Effect : Opening Target

2.2.2 Standard Radar frequencies

- There are no fundamental bounds on radar frequency. Any device that detects and locates a target by radiating electromagnetic energy and utilizes the echo scattered from a target can be classed as a radar, no matter what its frequency.
- Radars have been operated at frequencies from a few megahertz to the ultraviolet region of the spectrum. The basic principles are the same at any frequency, but the practical implementation is widely different. In practice, most radars operate at microwave frequencies, but there are notable exceptions.



Frequency Range	EW Frequency Band	Radar Design Frequency Band
0-250 MHz	A	HF/VHF
250-500 MHz	B	UHF
500-1000 MHz	C	UHF
1-2 GHz	D	L
2-3 GHz	E	S
3-4 GHz	F	S
4-6 GHz	G	C
6-8 GHz	H	C
8-10 GHz	I	X (8-12.5 GHz)
10-20 GHz	J	Ku (12.5-18 GHz)
20-40 GHz	K	K (18-26.5 GHz)
40-60 GHz	L	Ka (26.5-40 GHz)
60-100 GHZ	M	40-100 Millimeter

Figure 2.6: Radar Frequency Band Designations

2.2.3 Radar Transmitter Characteristics

Every radar produces a radio frequency (RF) signal with specific characteristics that differentiate it from all other signals and define its capabilities and limitations. Pulse width (pulse duration), pulse recurrence time (pulse repetition interval), pulse repetition frequency, and power are all radar signal characteristics determined by the radar transmitter. Listening time, rest time, and recovery time are radar receiver characteristics. An understanding of the terms used to describe these characteristics is critical to understanding radar operation.

Pulse Width and Pulse Recurrence Time

- **Pulse Width**: sometimes called pulse duration (PD), is the time that the transmitter is sending out RF energy. PW is measured in microseconds.
- **Pulse recurrence time**:is also known as pulse repetition time. PRT is the time required for a complete transmission cycle. This is the time from the beginning of one pulse of RF energy to the beginning of the next. PRT is measured in microseconds.

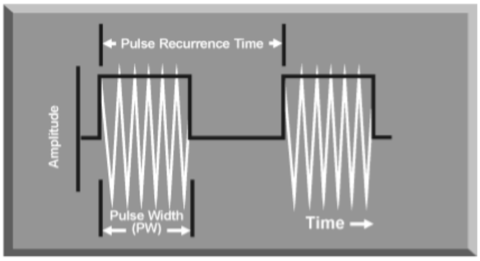


Figure 2.7: Typical Radar Pulse

Peak and Average Power

- The power output of a radar is normally expressed in terms of peak power or average power . Peak power is the amplitude, or power, of an individual radar pulse. It is simply the power, measured in watts or megawatts, that is radiated when the transmitter is on.
- The power a radar transmits is normally used to determine the maximum detection range of that radar. However, it is the energy in a radar pulse that determines maximum radar detection range.

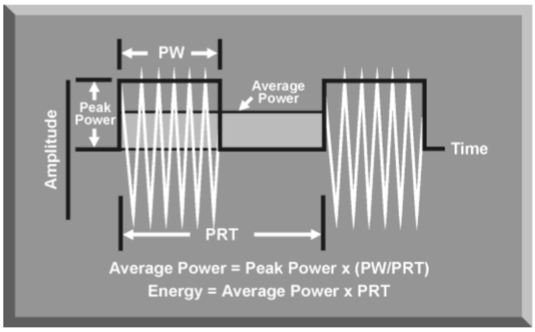


Figure 2.8: Peak Power and Average Power

2.2.4 Radar Receiver Characteristics

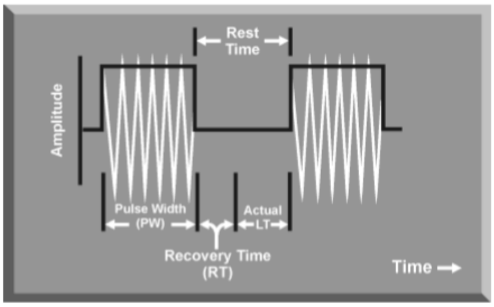


Figure 2.9: Radar Receiver Characteristics

- **Rest time**: is the time between the end of one transmitted pulse and the beginning of the next. It represents the total time that the radar is not transmitting.
- **Recovery time (RT)**: is the time immediately following transmission time during which the receiver is unable to process returning radar energy. RT is determined by the amount of isolation between the transmitter and receiver and the efficiency of the duplexer.
- **Listening time (LT)**: is the time the receiver can process target returns. Listening time is measured from the end of the recovery time to the beginning of the next pulse, or PRT minus (PW + RT).

2.3 Radar Equations

2.3.1 Target Range

- A basic pulse radar system consists of four fundamental elements: the transmitter, the receiver, the antenna, and the synchronizer, or master timer.
- The transmitter, through the antenna, sends out a pulse of RF energy at a designated frequency. The presence of a target is revealed when the RF energy bounces off the target, returns to the radar antenna, and goes into the receiver. The master timer measures the time between the transmission of a pulse and the arrival of a target echo.
- RF energy travels at the speed of light (c) which is 3 x 10^8 meters per second.Thus the time for the signal to Travel to a target at Range R and return back is $\frac{2R}{c}$.The Range to a target is then

$$R = \frac{cT_R}{2}$$

2.3.2 Maximum Unambiguous Range

- A limitation on radar detection range is the concept of a second time around echo. A second time around echo occurs when a target echo associated with a particular radar pulse arrives at the antenna after another radar pulse has been transmitted. The radar master timer always assumes the target echo is associated with the last pulse transmitted.
- Such an echo would appear to be at a closer range than actual and its range measurement could be misleading if it were not known to be a second time around echo.
- The range beyond which targets appear as second tie around echoes is the *maximum unambiguous range*,R_{un}.

$$R_{un} = \frac{cT_p}{2} = \frac{c}{2f_p}$$

where,T_p=pulse repetition period and f_p=pulse repetition frequency.

2.3.3 Doppler frequency and Radial velocity

- The radial velocity of the radar target can be measured by the Doppler effect, which means that the wavelength, or equivalently the frequency, of the returned wave is changed when reflected at a target moving radially relative the radar.
- For example, the wavelength will become shorter, and the frequency higher, when the target is approaching the radar. The relation between the Doppler frequency f_d, which is the frequency deviation for the received wave from the transmitted wave, and the radial velocity is

$$f_d = \frac{2v_r}{\lambda}$$

  where v_r is the relative radial velocity between radar and target, with positive sign when they are approaching each other, and λ is the radar wavelength.

2.3.4 Basic Radar Equation

- The basic radar equation relates the range of a radar system to the characteristics of the transmitter, receiver, antenna, and the target.
- Power density is the power of a radio wave per unit of area normal to the direction of propagation. The power density generated by a practical antenna can be expressed as

$$Power\,Density\,from\,Antenna = \frac{P_T G}{4\pi r^2} \tag{2.1}$$

- As the radar beam propagates through space, it arrives at a target at some range (R) from the antenna. As the radar beam travels through space, the wavefront of the beam expands to a very large cross-sectional area, especially in relation to the target dimensions. The power density of the radar beam, across this wide area, at the target,is

$$Power\,Density\,at\,Target = \frac{P_T G}{4\pi R^2}$$

– Since the cross-sectional area of the radar beam is so large, only a small portion of the total power in the beam can be reflected toward the antenna. The measure of the amount of incident power intercepted by the target and reradiated back in the direction of the antenna depends on the radar cross section (RCS) of the target.

$$Power\,Density\,at\,Antenna = \frac{P_T G}{4\pi R^2} * \frac{\sigma}{4\pi R^2}$$

– As the target echo reaches the antenna, part of the echo is captured by the antenna based on the effective aperture (Ae).This is the actual signal power received by the radar system.

$$Signal\,Power\,Density = \frac{P_T G \sigma A_e}{(4\pi)^2 R^4}$$

This is one form of the basic radar equation and is the signal strength of a radar return from a specific target at range (R) from the radar. Here P_T= transmitted power, G= antenna gain, A_e=antenna aperture area, σ= RCS, R= Range of target.

– The maximum radar range (RMAX) occurs when the signal power density received just equals the minimum detectable signal (SMIN) for the receiver.

2.4 Information Available from Radar Echo

The usual radar provides the location of a target in range and angle. The rate of change of target location can also be measured from the change in range and angle with time, from which the track can be established. In many radar applications a detection is not said to occur until its track has been established.

- **Range**:
  The ability to determine range by measuring the time for the radar signal to propagate to the target and back is probably the distinguishing and most important characteristic of conventional radar. No other sensor can measure range to the accuracy possible with radar, at such long ranges, and under adverse weather conditions.
- **Radial Velocity**:
  From successive measurements of range the rate of change of range, or radial velocity, can be obtained. The doppler frequency shift of the echo signal from a moving target also provides a measure of radial velocity. However, the doppler frequency measurement in many pulse radars is highly ambiguous, thus reducing its utility as a direct measurement of radial velocity.
  Any measurement of velocity, whether by the rate of change of range or by the doppler frequency shift, requires time. The longer the time of observation, the more accurate can be the measurement of velocity.
- **Angular Direction**:
  The direction of a target is determined by sensing the angle at which the returning wavefront arrives at the radar. This is usually accomplished with a directive antenna, i.e., one with a narrow radiation pattern. The direction in which the antenna points when the received signal is a maximum indicates the direction of the target.
- **Size and Shape** :
  If the radar has sufficient resolution, it can provide a measurement of the target's extent, or size. Since many targets of interest have dimensions of several tens of meters, resolution must be several meters or less. The size of a target is seldom of interest in itself, but its shape and its size are important for recognizing one type of target from another.

2.4.1 Target Discriminants

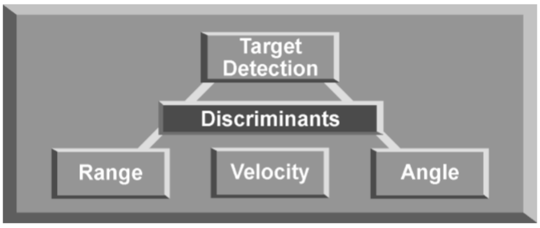


Figure 2.10: Radar Target Discriminants

Radar systems must use target discriminants to isolate the desired target return from the clutter. These target discriminants include range, velocity, and angle.

- **Range** is the first target discriminant. The time an RF wave takes to go to, and return from, a target allows measurement of the range to that target. We know that RF energy travels at the speed of light, or "c". Target range can be determined by using the basic radar range equation.
- **Target angle discrimination** is another critical capability of radar systems. In order for a radar system to detect a target, the antenna must be pointed at the target during the transmission and reception of RF energy. The ability of a radar system to accurately determine angle is a function of the horizontal beamwidth of the antenna. If the radar sweep is referenced to true North, the angle of a radar return can be measured relative to true North.

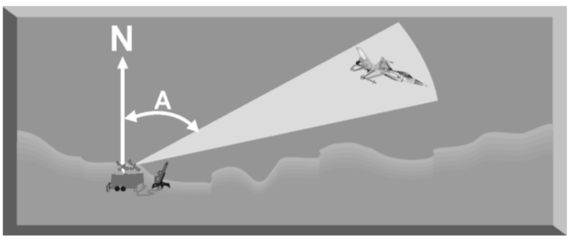


Figure 2.11: Angle Discrimination

– **Velocity discrimination** is a specific capability of CW and pulse Doppler radar systems. The transmitters of CW radars send out continuous RF at a specific frequency .The reflected signal frequency is changed, or shifted, by a specific amount by a moving target. This frequency shift, called the Doppler effect, allows the measurement of the velocity of that target relative to the radar. The receiver measures this frequency difference which equates to a specific radial velocity. Pulse Doppler radars can measure the Doppler effect while still obtaining the range.

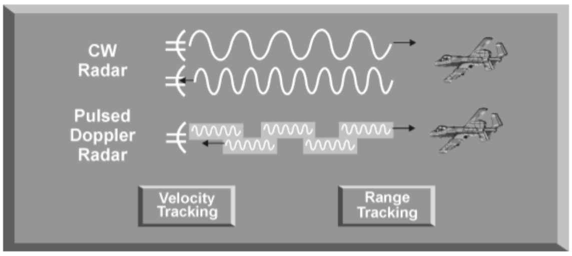


Figure 2.12: Velocity Discrimination

2.5 Advantages and Drawbacks of Radar

2.5.1 Advantages

The widespread military and civilian application of radar is based on its inherent advantages over the human eye.

- Radar can “see” farther than the human eye and more accurately assess the range or distance of an object.
- Radar works well in all-weather conditions and is relatively immune to smoke, haze, and clouds.
- What’s more, radar works 24 hours a day because it can transmit its own energy and does not have to rely on sunshine or ambient radiation.

Radar sensors have several advantages compared to electro-optical (EO) sensors, such as video and IR(infra-red)cameras. Here some advantages are listed. Radar:

- Can operate at day and night and in all weather. A radar can be much less affected by the weather than EO sensors.
- Can operate in dusty, dirty, hot, foggy and wet environments
- Can measure radial velocity very accurately.
- Can measure distance (range) directly. Can measure short distances (down to millimeters for industrial measurement radar) or long distances (up to 4000 km for skywave OTH [Over-The-Horizon] radar or even longer for space radar).
- Is less vulnerable to combating in military and security applications, thanks to the long-range capability.
- Can be installed concealed behind a covering surface and Is less affected by human clothing choices and is human privacy preserving in security applications.

2.5.2 Drawbacks

Radar systems also have some drawbacks.

- Radar can be interfered by several objects and mediums in the air.
- Large objects that are close to the Transmitter can saturate the Receiver.
- radio signals can be combined with other radio signals from other frequency.if not properly directed,the signals can be interrupted by other signals and alter the information being transmitted.
- Delivers output which looks different than what the human eye is accustomed to. This can be an impediment to humans.

There are some disadvantages of radar when compared to the human eye.

- First, radar does not have the resolution that the human eye has. While radar can detect the presence of an airplane, the human eye can discern, in great detail, the shape, size, color, and even markings. This can be a serious limitation if positive identification is required prior to engagement.
- Second, the human eye is not bothered by undesirable reflections, called clutter, the way radar sometimes is. Although metal is the best reflector of radio frequency (RF) energy, nearly any material will reflect some RF energy. Mountains, trees, buildings, rain, birds, and chaff all reflect RF energy.

2.6 Radar applications

Radar has very diverse utility with many applications within civil, scientific, security and military areas. Some examples are:

- Surveillance of air, sea and ground traffic.
- Anti-collision warning for aircraft and ships
- Navigation of ships.
- Automobile radar: driving aid and collision prevention and mitigation.
- Speed limit enforcement in road traffic.
- Weather radar.
- Distance (range) measurements, e.g. levels in tanks, altitude of aircraft, and industrial length measurements .
- Security surveillance within short distances.
- Remote sensing from aircraft or satellite from long distances to collect information about the earth surface for agriculture, forestry, environmental protection, humanitarian, scientific, military and other uses. Also remote sensing of other planets or moons like the Magellan mission to Venus .
- Military uses fighter aircraft radars, missile radar seekers, fire control radars, etc.

Chapter 3

Modeling and Simulation of DF Algorithm

3.1 Introduction

- With the development of radar technology and the complication of target background, more and more information which is not range but also angle need be known to target in order to track and orientate accurately.
- radio direction finders (DF) are used for finding the angle of arrival of the received signal over the whole (360^o) direction. This facility makes these systems important in military and civilian applications.
- To simplify the amplitude comparison analysis, signal levels which are fed from receiving antennas are compared with the expected signal levels in a specific Direction.
- This method makes the system simple in analysis and implementation and gives a good accuracy and resolution over a wide range of frequencies.The proposed system operates over a wide band of frequencies and covers the whole (360^o).

3.2 Modeling of DF Algorithm

- Here entire 360^o is divided into four regions, each covering 90^o .Angle of Arrival estimation in each region require signal levels from two antennas present in that region.Different regions with Antennas present in it and Range covered by that region is given below(Figure 3.1).

- Total of Four Antennas are present in the Antenna Assembly, Each antenna has 180^o coverage.Thier Boresight positions relative to aircraft north is specified below(Figure 3.2).

```
% Region 1 ---> Antennas 4 and 1  (315-0-45 degree)
% Region 2 ---> Antennas 1 and 2  (45-90-135 degree)
% Region 3 ---> Antennas 2 and 3  (135-180-225 degree)
% Region 4 ---> Antennas 3 and 4  (225-270-315 degree)
```

Figure 3.1: Different regions with Their Ranges

Receiver	Boresight Direction (in deg)
Forward Left (FL)	45
Forward Right (FR)	135
Aft Left (AL)	225
Aft Right (AR)	315

Figure 3.2: Antenna boresights relative aircraft north

- Here Antenna gain pattern is Assumed to be gaussian and All four Antennas are assumed to be identical.Gain pattern of Antenna Assembly system is given by:

- Here DF system consists of lookup tables including the Known values of the gain for each antenna at their associated angles over 360^o direction.

- There is an received radar signal simulator which generates the radar signal received by an Antenna in given direction(AoA) with specified characteristics

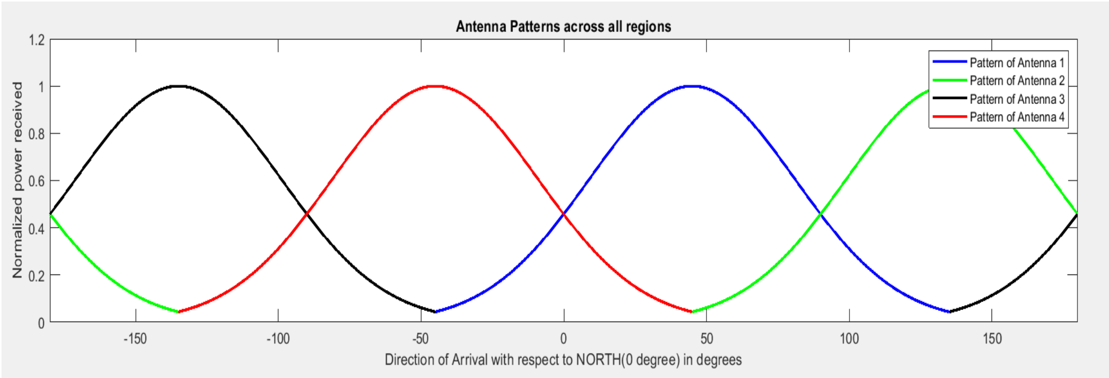


Figure 3.3: Gain pattern of Antenna assembly

derived from received radar signal(like frequency,pulse width(PW),pulse repetition frequency(PRF) etc), Amplitude corresponding to gain of Receiving Antenna for given AoA and add noise According to Channel characteristics(Signal to Noise ratio) and

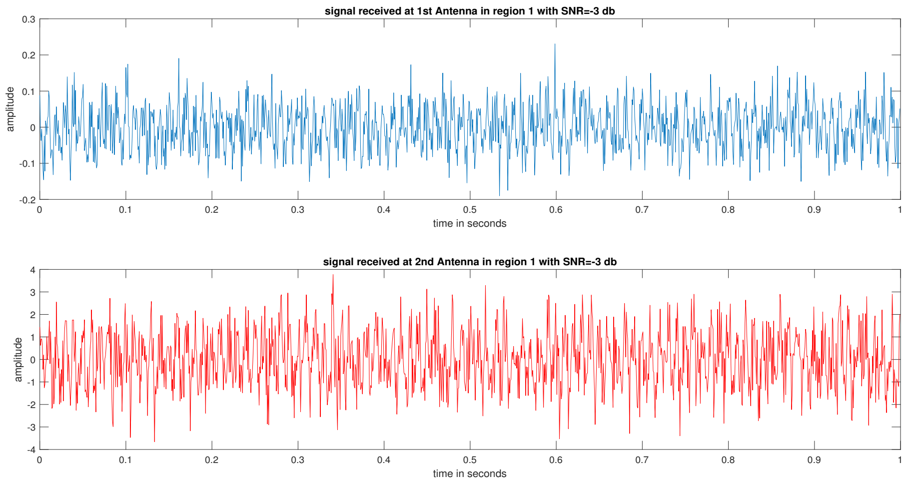


Figure 3.4: Received Radar Signal in presence of AWG noise

- AWGN channel with different SNR is simulated in matlab using *awgn* function.

3.3 Working and Simulation of DF algorithm

- For Simulating the DF Algorithm two functions were created

  1. one which simulates Radar signals received by different Antennas in given direction(AoA), with specified signal and add noise to this signal According to given channel characteristics.

     $$S_i = G_i(\theta_i)sin(2\pi f_c t) + n_i$$

     Signal received at Antenna i in the direction(AoA)=θ_i along with AWG noise(n_i) such that signal to noise Ratio= SNR given.Here $G_i(\theta_i)$ is the gain of Antenna i corresponding to angle=θ_i.

  2. another one which takes signals Received by two Antennas in a region,extract Amplitude information from them and compares the extracted amplitudes with the ones in the lookup table.Finally it finds Angle corresponding to which Error in Extracted and actual Amplitudes is small for both the Antennas in that region.

- Finally one Main function was created to call this functions which requires parameters like frequency(f_c) of radar signal, PW, PRF, SNR, sampling frequency(f_s).It also scatters Estimated AoA and Actual AoA for each iteration.

3.4 Simulation Results and Analysis

- DF algorithm was coded in Matlab and To check the performance of the Algorithm in the presence of AWG noise,Radar signals with different SNR values and with different AoA were generated and were fed to the Algorithm.

- For every SNR value,the Algorithm was iterated 1000 times. In each iteration,The difference between Actual AoA and Estimated AoA (Error) was calculated.

- For statistical Analysis of the result obtained *Mean absolute error*,*Mean Error* and *Standard Deviation* of the Error was calculated for every SNR value.
- similarly For every SNR value (i.e, for Every 1000 iterations) Maximum +ve & -ve Deviation was computed and plotted against SNR values.

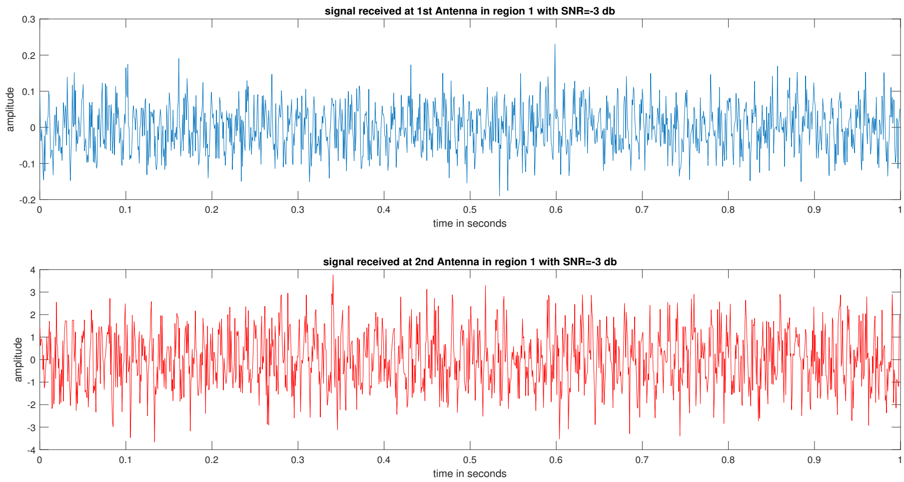


Figure 3.5: Received Radar Signal in presence of AWG noise

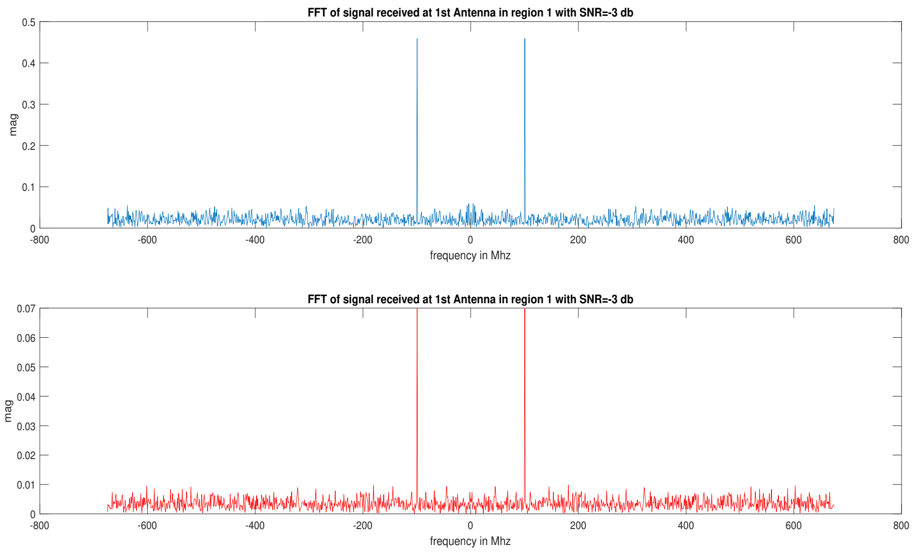


Figure 3.6: FFT of Received Radar Signal in presence of AWG noise

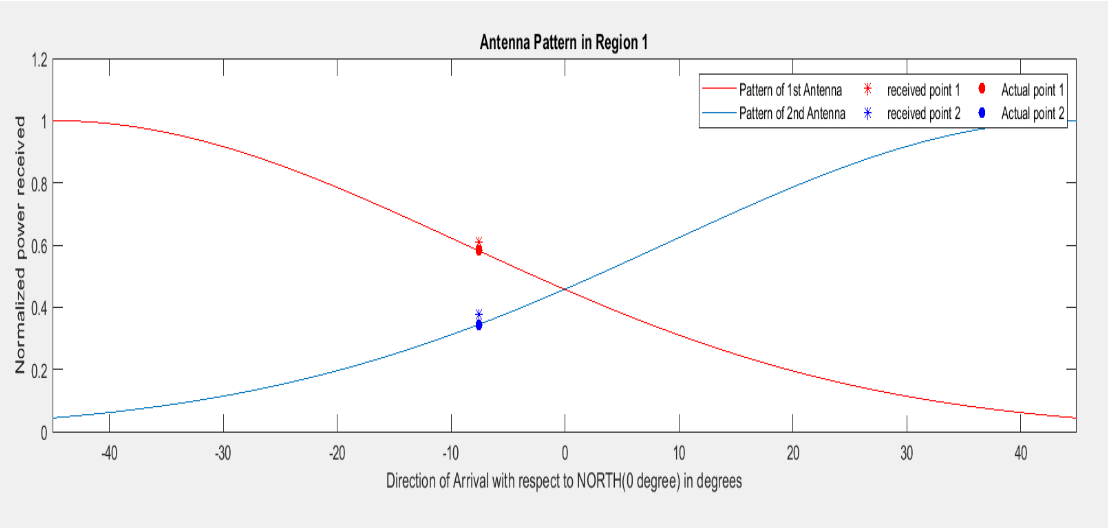


Figure 3.7: Antenna patterns in a Region

- Algorithm was tested for different values of SNR (i.e, -15 db to 15 db in steps of 3db).Scatter plots of Estimated AoA & Actual AoA and plots of Error for different SNR values is Shown in the figures Below

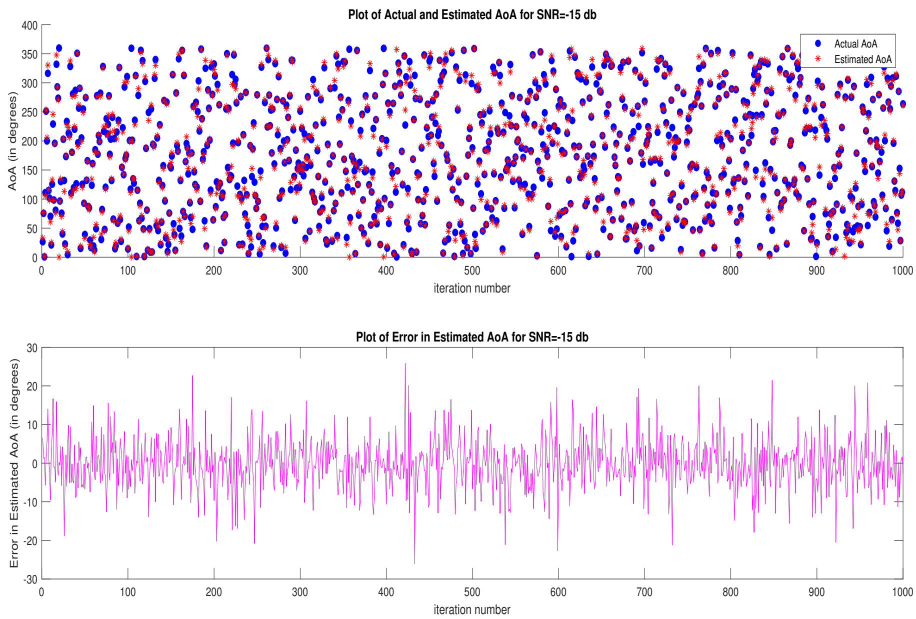


Figure 3.8: Scatter plot of Estimated & Actual AoA and corresponding Error

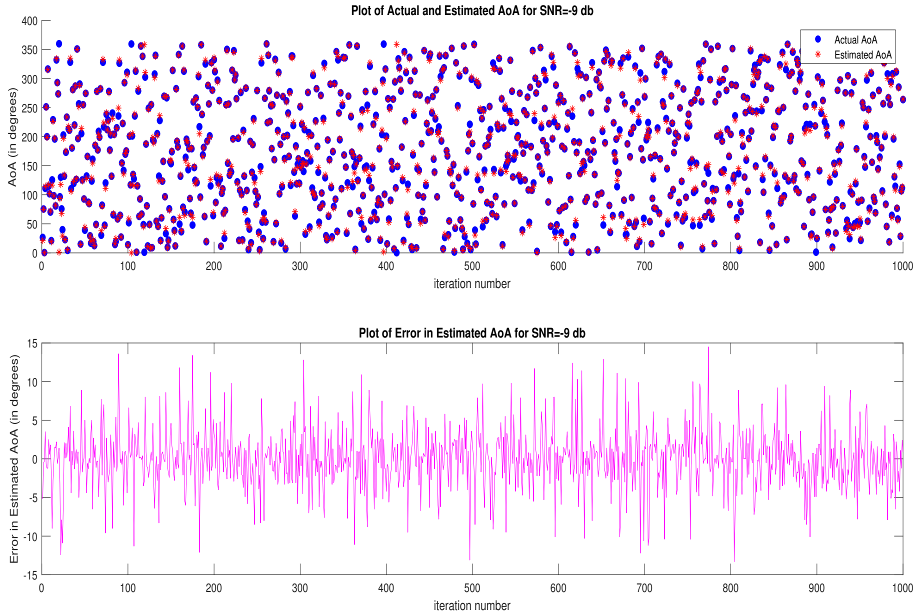


Figure 3.9: Scatter plot of Estimated & Actual AoA and corresponding Error

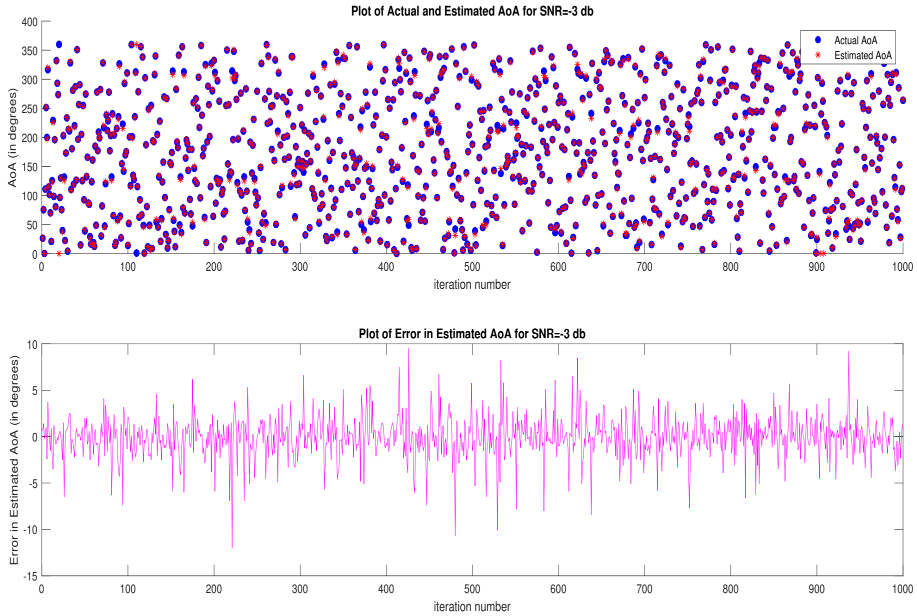


Figure 3.10: Scatter plot of Estimated & Actual AoA and corresponding Error

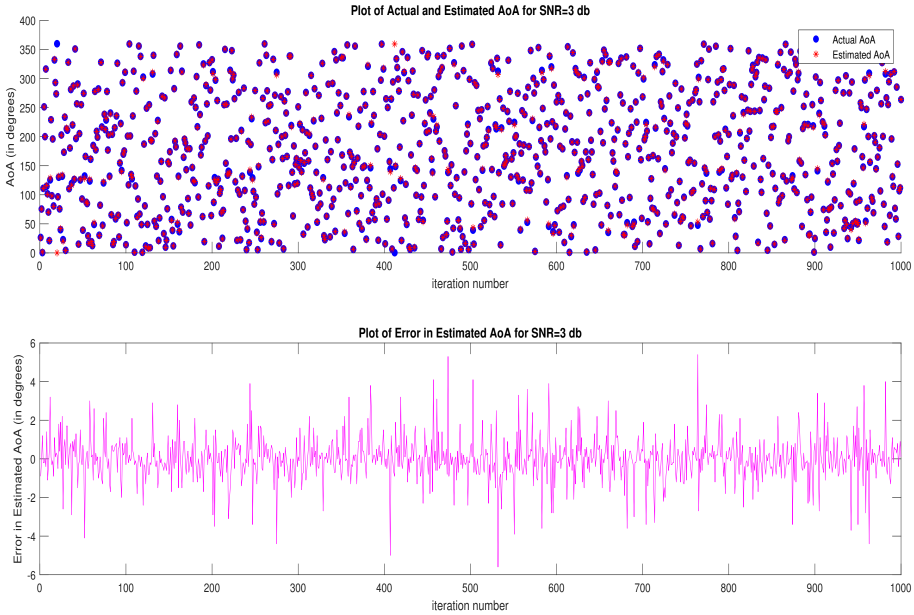


Figure 3.11: Scatter plot of Estimated & Actual AoA and corresponding Error

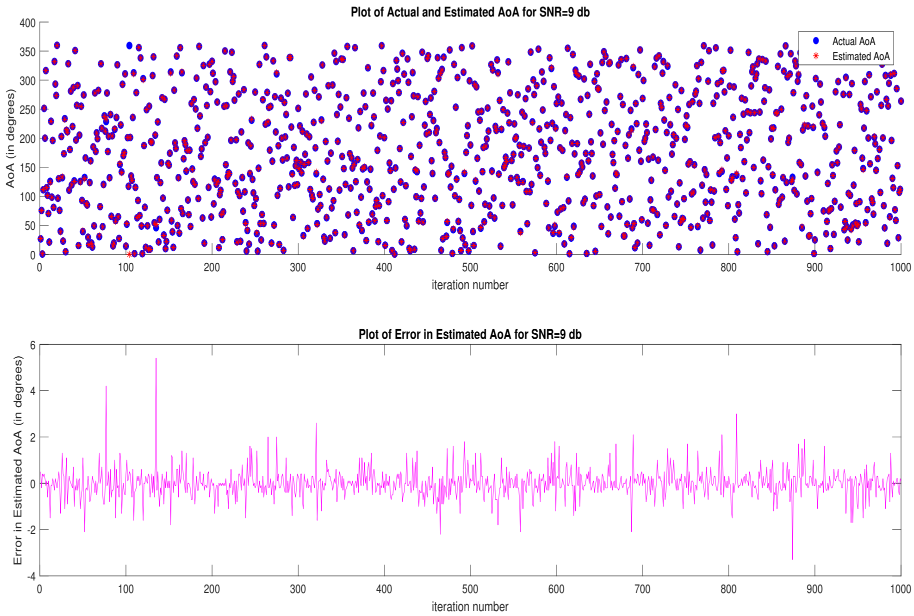


Figure 3.12: Scatter plot of Estimated & Actual AoA and corresponding Error

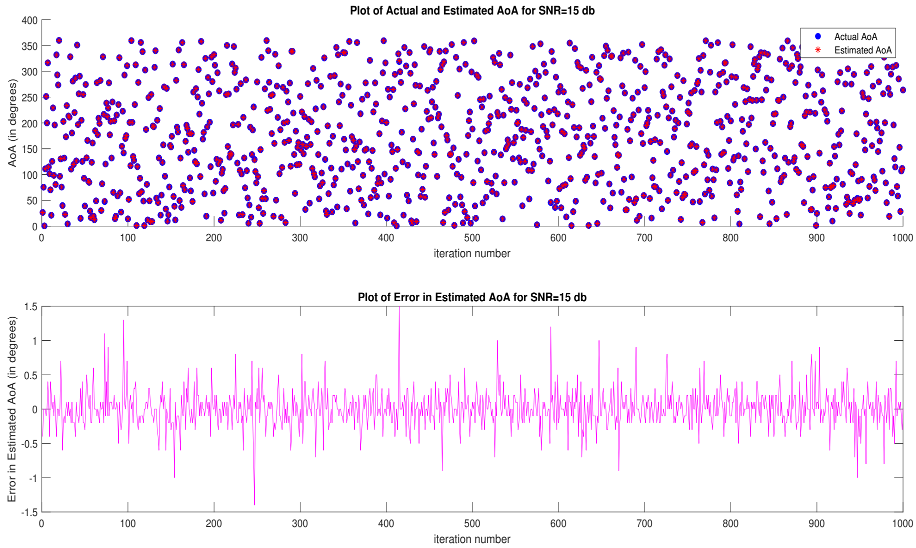


Figure 3.13: Scatter plot of Estimated & Actual AoA and corresponding Error

- Statistical Analysis of the Result obtained is carrried out.Below are the plots of various Statistical paramaters(i.e, *Mean Absolute Error*,*Max +ve & -ve Deviation*,*Mean Error* and *Standard Deviation*)for different values of SNR.

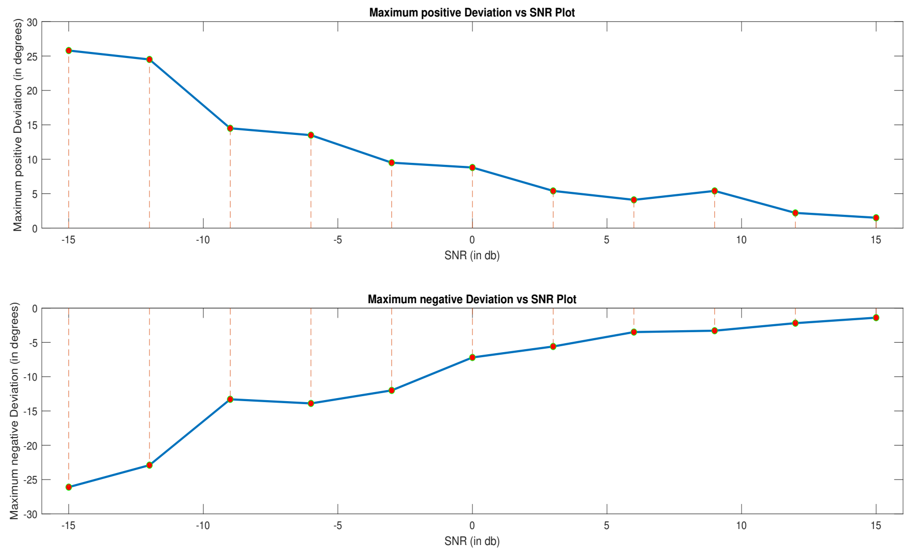


Figure 3.14: Maximum positive and negative Deviation in Estimated AoA *vs* SNR

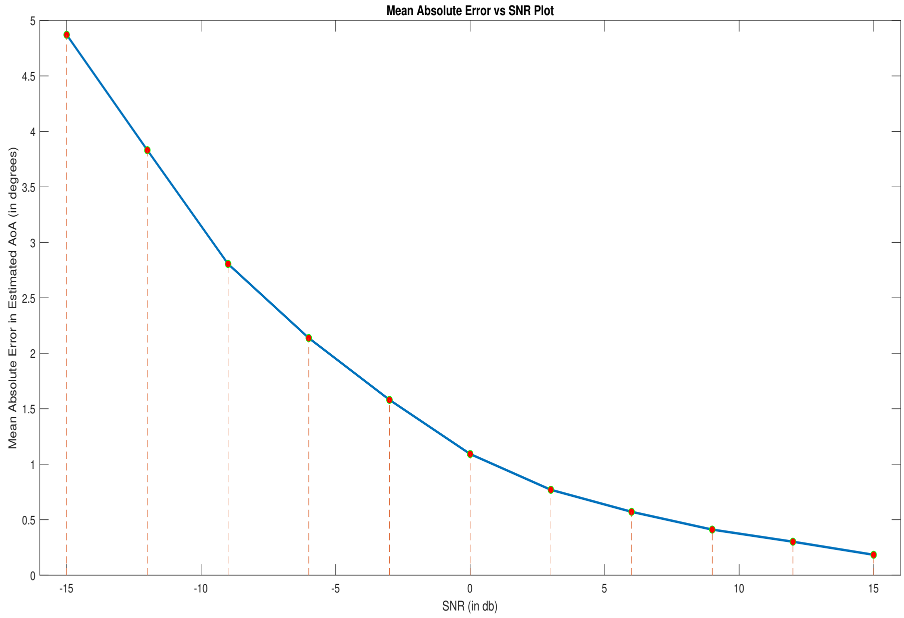


Figure 3.15: Mean Absolute Error *vs* SNR

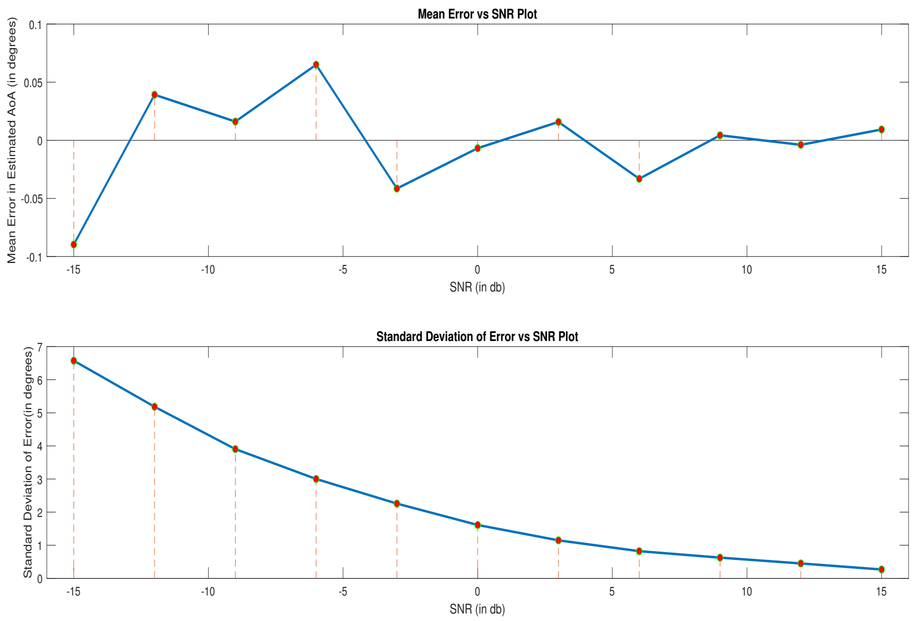


Figure 3.16: Mean Error and Standard Deviation *vs* SNR

3.5 Conclusion

- The purpose of this project is to better understand the process of AOA calculation and to estimate the Error in AoA estimation due to external AWG noise.

- The amplitude comparison system consists of a circular array of four equally spaced antennas with reference direction taken as due north.

- The antenna that receives the maximum pulse amplitude is determined; then the pulse amplitude received from the antenna, which is adjacent to this antenna, is determined. These two pulse amplitudes are taken into consideration and used in the DF algorithm.

- AWG noise has been introduced to the system to simulate external noises and performance of the Algorithm was recorded. from the observed plot we can see that Mean Absolute error and standard Deviation of the Error decreases as we increase SNR.

Chapter 4

Appendix

4.1 Matlab Codes

Matlab Codes 4.1: Main program

```
%------------ program to Test AoA Estimation function -------------------

clear all;
clc;
close all;
 %--------------------------- Inputs -------------------------------------
 global Niter i k snr res T;
 Niter=1000;               % number of iterations
 res=0.1;                 % resolution of antennas (in degrees)
 AoAa=randi([0,359],1,Niter)+randi([0 9/(10*res)],1,Niter)*res;
 % known Angle of Arrival of received signal
 % received signal characteristics in presence of awgn noise
 fc=100;                  % carier frequency of radar signal (Mhz)
 fs=1350;                 % sampling rate at which signal is sampled(Msps)
 T=1;                     % time for which signal is received
 snr=-15:3:15;  % signal to noise ratio
 ME=zeros(1,length(snr));   % Mean error of estimated AoA
 MAE=zeros(1,length(snr));  % Mean Absolute error of estimated AoA
```

```
MaxE=zeros(1,length(snr)); % Maximum Absolute error of estimated AoA
MinE=zeros(1,length(snr)); % Minimum Absolute error of estimated AoA
Stdv=zeros(1,length(snr)); % Standard Deviation of the error
for k=1:length(snr)
  AoAe=zeros(1,Niter);
  Error=zeros(1,Niter);
  for i=1:Niter
    %------- detecting region in which radar signal is received ----------
    regm=[((AoAa(i)≥315 && AoAa(i)<360) ||( AoAa(i)≥0 && AoAa(i)<45))...
    ,(AoAa(i)≥45 && AoAa(i)<135),(AoAa(i)≥135 && AoAa(i)<225)...
    ,(AoAa(i)≥225 && AoAa(i)<315)];
    reg=find(regm==1);

      %-------- function to generate signals received by two antennas-----
      %--- with given signal and channel characteristics and known AoA ---
      [SRl,SRr]=radar_doAgen(fc,fs,AoAa(i),snr(k),reg);

      %-------- function to calculate AoA given received signal ----------
      %--------- by the Antennas in the presence of Awgn noise  ----------
      AoAe(i) =radar_doA(reg,SRl,SRr); % Estimated AoA

      %------------- calculation of Error in Estimated AoA ---------------

      Error(i)=(AoAe(i)-AoAa(i));
      % Error in Estimated AoA with respect to Actual AoA

      if (AoAa(i)≥0 && AoAa(i)<45 && AoAe(i)<360 && AoAe(i)≥315)
          Error(i)=Error(i)-360;
      elseif (AoAa(i)<360 && AoAa(i)≥315 && AoAe(i)≥0 && AoAe(i)<45)
          Error(i)=mod(Error(i)+360,360);
      end
  end

%------------------ Intermediate Results and Plots -----------------------

figure('Name',...
sprintf('Analysis of AoA Estimation function for SNR=%d db',snr(k)));

subplot(211);
```

```
scatter((1:Niter),AoAa,40,'filled','MarkerFaceColor','b');hold on;
scatter((1:Niter),AoAe,34,'*','red');
title(sprintf('Plot of Actual and Estimated AoA for SNR=%d db',snr(k)));
ylabel('AoA (in degrees)');xlabel('iteration number');
legend('Actual AoA','Estimated AoA');

subplot(212);
plot(Error,'m');
title(sprintf('Plot of Error in Estimated AoA for SNR=%d db',snr(k)));
ylabel('Error in Estimated AoA (in degrees)');xlabel('iteration number');

%-------------- Statistical Analysis of the Result -----------------------
ME(k)=sum(Error)/Niter;
MAE(k)=sum(abs(Error))/Niter;
MaxE(k)=max(Error);
MinE(k)=min(Error);
Stdv(k)=std(Error,1);
end

%---------------------- Results and Plots --------------------------------

figure('Name','Analysis of AoA Estimation function');

plot(snr,MAE,'LineWidth',2);
hold on; stem(snr,MAE,'filled','--','MarkerFacecolor','red',...
'MarkerEdgecolor','green');
title('Mean Absolute Error vs SNR Plot');
xlabel('SNR (in db)');xlim([snr(1)-1 snr(end)+1]);
ylabel('Mean Absolute Error in Estimated AoA (in degrees)');

figure('Name','Analysis of AoA Estimation function');

subplot(211);
plot(snr,MaxE,'LineWidth',2);hold on;
stem(snr,MaxE,'filled','--','MarkerFacecolor','red',...
'MarkerEdgecolor','green');
title('Maximum positive Deviation vs SNR Plot');
xlabel('SNR (in db)');xlim([snr(1)-1 snr(end)+1]);
ylabel('Maximum positive Deviation (in degrees)');
```

```
subplot(212);
plot(snr,MinE,'LineWidth',2);hold on;
stem(snr,MinE,'filled','--','MarkerFacecolor','red',...
'MarkerEdgecolor','green');
title('Maximum negative Deviation vs SNR Plot');
xlabel('SNR (in db)');xlim([snr(1)-1 snr(end)+1]);
ylabel('Maximum negative Deviation (in degrees)');

figure('Name','Analysis of AoA Estimation function');
subplot(211)
plot(snr,ME,'LineWidth',2);hold on;
stem(snr,ME,'filled','--','MarkerFacecolor','red',...
'MarkerEdgecolor','green');
title('Mean Error vs SNR Plot');
xlabel('SNR (in db)');xlim([snr(1)-1 snr(end)+1]);
ylabel('Mean Error in Estimated AoA (in degrees)');
subplot(212)
plot(snr,Stdv,'LineWidth',2);hold on;
stem(snr,Stdv,'filled','--','MarkerFacecolor','red',...
'MarkerEdgecolor','green');
title('Standard Deviation of Error vs SNR Plot');
xlabel('SNR (in db)');xlim([snr(1)-1 snr(end)+1]);
ylabel('Standard Deviation of Error(in degrees)');
```

Matlab Codes 4.2: Received signal Generation function

```
%------ detection(generation) of received signal in presence of AWGN ------

function [SRl,SRr]=radar_doAgen(fc,fs,aoaA,SNR,reg)

global Niter XSRl XSRr i k snr res T;

N=180/res;        % number of samples in gaussian window
%(each antenna has resolution of 0.1 degree)
w1=gausswin(N);  % plot of antenna 1 placed at 45  degree
```

```
                 %----> Range(315 to 135 degree)
w2=gausswin(N);  % plot of antenna 2 placed at 135 degree
                 %----> Range(45 to 225 degree)
w3=gausswin(N);  % plot of antenna 3 placed at 225 degree
                 %----> Range(135 to 315 degree)
w4=gausswin(N);  % plot of antenna 4 placed at 315 degree
                 %----> Range(225 to 45 degree)

% for detection of doA(in degrees) in Region 1
%( using signal received by antennas A4 and A1)
i41=[315:res:360-res,0:res:45-res]';
w41=[i41,w4((N/2)+1:N),w1(1:N/2)];
% for detection of doA(in degrees) in Region 2
%( using signal received by antennas A1 and A2)
i12=(45:res:135-res)'; % index vector for Region 2
w12=[i12,w1((N/2)+1:N),w2(1:N/2)];
% for detection of doA(in degrees) in Region 3
%( using signal received by antennas A2 and A3)
i23=(135:res:225-res)';
w23=[i23,w2((N/2)+1:N),w3(1:N/2)];
% for detection of doA(in degrees) in Region 4
%( using signal received by antennas A3 and A4)
i34=(225:res:315-res)';
w34=[i34,w3((N/2)+1:N),w4(1:N/2)];
  w={w41,w12,w23,w34};
  ind=find(abs(aoaA-w{reg}(:,1))<0.000000001);
  ALa=w{reg}(ind,2);
  ARa=w{reg}(ind,3);
  t=0:1/fs:T-1/fs;
  %signal generated(received) for T seconds
  SRl=awgn(ALa*cos(2*pi*fc*t),SNR,'measured');
  % signal received at 1st Antenna
  SRr=awgn(ARa*cos(2*pi*fc*t),SNR,'measured');
  % signal received at 2nd Antenna
  %Adding wgn with specified noise power and load impedance
  %SRl=ALa*cos(2*pi*fc*t)+wgn(1,length(t),noise power,50);
  %SRr=ARa*cos(2*pi*fc*t)+wgn(1,length(t),noise power,50);
   if(k==length(snr) && i==Niter)
    %------- plotting of signals received at 1st and 2nd Antennas ---------
```

```
    figure('Name','Received Signals','NumberTitle','off');

    subplot(211);
    plot(t,SRl);xlabel('time in seconds');ylabel('amplitude');
    title(sprintf(...
    'signal received at 1st Antenna in region %d with SNR=%d db',reg,SNR));

    subplot(212);
    plot(t,SRr,'r');xlabel('time in seconds');ylabel('amplitude');
    title(sprintf(...
    'signal received at 2nd Antenna in region %d with SNR=%d db',reg,SNR));

    %----- plotting FFTs of signals received at 1st and 2nd Antennas ------

    tf=-(1-1/length(XSRl))/2:1/length(XSRl):(1-1/length(XSRl))/2;
    figure('Name','FFT of Received Signals','NumberTitle','off');

    subplot(211);
    plot(tf*fs,XSRl);xlabel('frequency in Mhz');ylabel('mag');
    title(sprintf(...
   'FFT of signal received at 1st Antenna in region %d with SNR=%d db',...
    reg,SNR));

    subplot(212);
    plot(tf*fs,XSRr,'r');xlabel('frequency in Mhz');ylabel('mag');
    title(sprintf(...
    'FFT of signal received at 1st Antenna in region %d with SNR=%d db',...
    reg,SNR));
  end
end
```

Matlab Codes 4.3: AoA Estimation function

```
%-- Function for detection of Direction of Arrival (DOA)of Radar signal ---
% Here entire 360 degrees is divided into 4 Regions (each of 90 degrees)
 % all regions share two Antennas
 % Region 1 ---> Antennas 4 and 1  (315-0-45 degree)
```

```
 % Region 2 ---> Antennas 1 and 2  (45-90-135 degree)
 % Region 3 ---> Antennas 2 and 3  (135-180-225 degree)
 % Region 4 ---> Antennas 3 and 4  (225-270-315 degree)

function [DoA] =radar_doA(reg,SRl,SRr)

global Niter XSRl XSRr i k snr res ;

N=180/res;        % number of samples in gaussian window
%(each antenna has resolution of 0.1 degree)
w1=gausswin(N);  % plot of antenna 1 placed at 45  degree
                  %----> Range(315 to 135 degree)
w2=gausswin(N);  % plot of antenna 2 placed at 135 degree
                 % ----> Range(45 to 225 degree)
w3=gausswin(N);  % plot of antenna 3 placed at 225 degree
                 %----> Range(135 to 315 degree)
w4=gausswin(N);  % plot of antenna 4 placed at 315 degree
                 %----> Range(225 to 45 degree)

% for detection of doA(in degrees) in Region 1
%( using signal received by antennas A4 and A1)
i41=[315:res:360-res,0:res:45-res]';
w41=[i41,w4((N/2)+1:N),w1(1:N/2)];
% for detection of doA(in degrees) in Region 2
%( using signal received by antennas A1 and A2)
i12=(45:res:135-res)'; % index vector for Region 2
w12=[i12,w1((N/2)+1:N),w2(1:N/2)];
% for detection of doA(in degrees) in Region 3
%( using signal received by antennas A2 and A3)
i23=(135:res:225-res)';
w23=[i23,w2((N/2)+1:N),w3(1:N/2)];
% for detection of doA(in degrees) in Region 4
%( using signal received by antennas A3 and A4)
i34=(225:res:315-res)';
w34=[i34,w3((N/2)+1:N),w4(1:N/2)];
w={w41,w12,w23,w34};

%---------- Extraction of Amplitude info from received signals ------------
```

```
 XSRl=abs(fftshift(fft(SRl,length(SRl))))/length(SRl);
 % Two sided spectrum(FFT) of signal received by 1st Antenna
 XSRr=abs(fftshift(fft(SRr,length(SRr))))/length(SRr);
 % Two sided spectrum(FFT) of signal received by 1st Antenna
 ALn=2*max(XSRl);
 % amplitude of received signal in presence of awgn noise at 1st antenna
 ARn=2*max(XSRr);
 % amplitude of received signal in presence of awgn noise at 2nd antenna

%------------------------ Error calculation ---------------------------------

Er=zeros(1,N/2);
for j=1:N/2
    Er(j)=sqrt((ALn-w{reg}(j,2))^2 + (ARn-w{reg}(j,3))^2);
    % caculating eucleidean distance
end
[¬,j]=min(Er);  % selecting the index with least eucleidean distance
DoA=w{reg}(j,1);% direction of Arrival of radar signal (in degrees)
if reg≠1
    ind=w{reg}(:,1);
    AoA=DoA;
else
    ind=[i41(1:N/4)-360;i41(N/4+1:N/2)];
    AoA=DoA-(DoA<360 && DoA>180)*360;
end

%------------ Plotting Antenna patterns in different Regions -------------
 if(k==length(snr) && i==Niter)
  figure('Name','Antenna patterns','NumberTitle','off');

  subplot(211);

 wl=w{reg}(:,2);
 wr=w{reg}(:,3);
 plot(ind,wl,'r');hold on;plot(ind,wr);hold on;
 scatter(AoA,w{reg}(j,2),'filled','blue');
 scatter(AoA,w{reg}(j,3),'filled','red');
 scatter(AoA,ALn,32,'*','red');
 scatter(AoA,ARn,32,'*','blue');
```

```
  xlabel('Direction of Arrival with respect to NORTH(0 degree) in degrees');
  xlim([ind(1) ind(end)]);
  ylabel('Normalized power received');
  title(sprintf('Antenna Pattern in Region %d',reg)); ylim([0 1.2]);
  lgd=legend('Pattern of 1st Antenna','Pattern of 2nd Antenna',...
  'received point 1','received point 2','Actual point 1','Actual point 2');
  lgd.NumColumns=3;

   subplot(212);

  p=zeros(1,6);
  p(1)=plot((-45:res:135-res),w1(1:N),'b',...
  'LineWidth',2,'DisplayName','Pattern of Antenna 1'); hold on;
  p(2)=plot((-180:res:-135),w2((N-N/4):N),'g',...
  'LineWidth',2,'DisplayName','Pattern of Antenna 2');hold on;
  p(3)=plot((-180:res:-45),w3(N/4:N),'k',...
  'LineWidth',2,'DisplayName','Pattern of Antenna 3');hold on;
  p(4)=plot((-135:res:45-res),w4(1:N),'r',...
  'LineWidth',2,'DisplayName','Pattern of Antenna 4'); hold on;
  p(5)=plot((45:res:180-res),w2(1:N-N/4),'g',...
  'LineWidth',2);hold on;
  p(6)=plot((135:res:180-res),w3(1:N/4),'k','LineWidth',2);
  xlabel('Direction of Arrival with respect to NORTH(0 degree) in degrees');
  xlim([-180 180]);ylabel('Normalized power received');
  title('Antenna Patterns across all regions');ylim([0 1.2]);
  legend(p(1:4));
 end
end
```

References

[1] *Introduction to Radar Systems*. Tata McGraw Hill, 2001.

[2] D. Adamy. *EW 101: A First Course in Electronic Warfare*. Artech House radar library. Artech House, 2001.

[3] Merrill Ivan Skolnik. *Radar Handbook*. Electronic engineering series. McGraw-Hill, 1990.