**PRELIMINARY STUDIES ON MONOPULSE SEEKER OPERATION**

INDUSTRIAL TRAINING REPORT

for the course

18ECP105L-IndustrialTraining- II


***Submitted by***

YOGESH KIMARI

(RA2111004010270)


**Semester – VI**

**Academic Year: 2023–24**

*In partial fulfilment for the award of the degree*

*Of*

BACHELOR OF TECHNOLOGY

in

ELECTRONICS AND COMMUNICATION ENGINEERING

of

FACULTY OF ENGINEERING AND TECHNOLOGY

SRM INSTITUTE OF SCIENCE & TECHNOLOGY

Deemed to be University u/s 3 of UGC Act, 1956

S.R.M. Nagar, Kattankulathur, Chengalpattu District

## SRM INSTITUTE OF SCIENCE AND TECHNOLOGY

(Under Section 3 of UGC Act, 1956)

### BONAFIDE CERTIFICATE

Certified that this report titled " **PRELIMINARY STUDIES ON MONOPULSE SEEKER OPERATION** " is the bonafide work of " **YOGESH KIMARI (RA2111004010270)**", who carried out the industrial training. Certified further, that to thebest of my knowledge, the work reported herein does not form any other project report or dissertation based on which a degree or award was conferred on an earlier occasion on this or any other candidate.

| | |
|---|---|
| Signature | Signature |
| Yogesh Kimari | Dr.Senthil Kumaran R |
| ECE III Year | Industrial Training Coordinator |
| Dept. of Electronics and | Dept. of Electronics and |
| Communication Engineering | Communication Engineering |

Department of ECE * SRM IST * Kattankulathur-603 203

# ACKNOWLEDGMENT

I extend my sincere gratitude for the invaluable experience and learning opportunities provided to me during my internship at the **Defence Research and Development Organization (DRDO)**. My heartfelt appreciation goes to **Dr. Sreena P.V**., my mentor, and supervisor, for her unwavering support and patient guidance throughout my tenure at DRDO. Under her mentorship, I have not only acquired invaluable knowledge about seekers but have also gained profound insights into various aspects of professional and personal development. Dr. Sreena P.V.'s guidance has been more than just technical; she has generously shared invaluable life lessons that have significantly enriched my learning experience. I am profoundly grateful for the depth of understanding and wisdom she has imparted to me, making my internship at DRDO an incredibly transformative and enriching journey.

I would also like to express my gratitude to my colleagues and fellow interns for fostering a collaborative and supportive environment.

I extend my thanks to the administrative and support staff, as well as the security personnel, for their diligence in creating a conducive and secure workspace.

A special acknowledgement to **Dr. Manoj Kumar Buragohain** and **Dr. Hemant Kumar** for bestowing upon me the invaluable opportunity to serve as an intern at the esteemed Defence Research and Development Organization (DRDO).

I am indebted to S.R.M Institute of Science and Technology for facilitating this invaluable experience. This internship has profoundly influenced my professional journey, and I sincerely thank everyone at DRDO for their kindness and guidance.

I would like to express my special thanks of gratitude to my course coordinator **Dr. Senthil Kumaran R** for their able guidance and support in encouraging me to do this training.

Last but not least, I record my sincere thanks to my parents for their continuous support and motivation.

**YOGESH KIMARI**

**'III' YEAR ECE DEPT.**

**'D' SECTION**

# Abstract

This report offers an introductory investigation into the fundamental aspects of monopulse seeker operation, emphasizing its foundational principles. The study focuses on the fundamental relationship between radar technology and seekers, with an exploration of seekers' significance in enhancing guidance and control mechanisms. Beginning with a simplified derivation of the radar range equation, the report establishes a basic understanding of radar principles.

The subsequent sections provide insights into the specific inputs contributed by seekers to guidance and control systems. This basic study aims to unravel the essential roles seekers play in enhancing the overall functionality and accuracy of radar-guided systems.

A central theme of the study is the examination of monopulse technology, a straightforward yet sophisticated radar technique commonly utilized in seekers. The report introduces the basic concepts of simulating sum and difference patterns and monopulse ratio, defined as the ratio of the difference pattern to the sum pattern, using both Python and MATLAB to enhance interpretation.

In summary, this report constitutes a very basic study on monopulse seeker operation, covering rudimentary radar principles, seeker contributions to guidance control, and basic simulation techniques. The straightforward analysis using Python and MATLAB lays the groundwork for introductory explorations into the realm of radar-guided systems.

# Table of Contents

# List of Figures

# List of Tables

दूरभाष/Telephone:040-24188039/8062
फैक्स/Fax :040-24344457/2488062
ई-मेल /E-mail: hrdg.asl@gov.in

भारत सरकार, रक्षा मंत्रालय
Government of India, Ministry of Defence
रक्षा अनुसंधान एवं विकास संगठन
Defence Research & Development Organisation
उन्नत प्रणाली प्रयोगशाला
ADVANCED SYSTEMS LABORATORY
डॉ. ए.पी.जे. अब्दुल कलाम प्रक्षेपास्त्र समष्टि
Dr. A.P.J. Abdul Kalam Missile Complex
कंचनबाग डाकघर, हैदराबाद - 500 058
PO Kanchanbagh, Hyderabad - 500 058

# CERTIFICATE

This is to certify that **Mr. Yogesh Kimari** (Roll No. RA2111004010270), III Year, B.Tech (ECE) from **S.R.M. Institute of Science and Technology, Kattankulathur Campus, Tamil Nadu** has successfully completed Internship on **"Preliminary Studies on Monopulse Seeker Operation"** at Advanced System Laboratory, DRDO, Hyderabad under the guidance of **Dr. Sreena P.V. Sc 'E'** from 11th December 2023 to 2nd January 2024.

This Certificate is issued by this Laboratory after completion of Internship as a part of their Educational Curriculum. No stipend / Salary is entitled by the candidate during the course of the Internship. The Certificate cannot be submitted as a documentary proof for claiming the Internship duration as service experience for any of their future employment / recruitment.

His performance and conduct during the period was good.

**(HEMANT KUMAR)**
**SCIENTIST 'E'**
**HRDG/ ASL**
**FOR DIRECTOR, ASL**

प्रधान, एच.आर.डी.जी. / Head, HRDG
उन्नत प्रणाली प्रयोगशाला / Advanced Systems Laboratory
रक्षा मंत्रालय, डी.आर.डी.ओ. / Ministry of Defence, DRDO
कंचनबाग, हैदराबाद / Kanchanbagh, Hyderabad-500 058

**(Dr. SREENA P.V.)**
**SCIENTIST 'E'**
**SSE / ASL**
**EXTERNAL GUIDE**

डॉ. पी.वी. श्रीना / Dr. P.V. SREENA
वैज्ञानिक / Scientist 'E'
रक्षा मंत्रालय, डी.आर.डी.ओ. / Ministry of Defence, DRDO
ए एस एल., हैदराबाद- 500 058 / ASL, Hyderabad- 500 058

# Chapter 1

# BRIEF INSIGHT INTO RADAR OPERATIONS

Radar, an acronym for **Radio Detection and Ranging**, is a technology that uses radio waves for various applications, including surveillance, navigation, and target tracking. To guarantee the clear accomplishment of countering potential airborne threats, anti-aircraft missile systems play a crucial role. At the core of these defence systems lie radars, encompassing both ground-based and airborne variants, strategically employed in anti-aircraft missile systems. A radar system, fundamentally an electrical apparatus, operates by transmitting radio frequency electromagnetic waves toward a designated region and subsequently receiving and detecting the reflected electromagnetic waves from objects within that region. The transmitted signal traverses through the atmosphere, reaching the target, where the EM wave induces electrical currents on metallic surfaces. These induced currents, in turn, re-radiate the EM wave into the environment[3].

Figure 1.1 illustrates the intricate process of radar signal transmission, encompassing propagation through the atmosphere, reflection from the target, and reception of the reflected signals. The radar system typically comprises a transmitter, antenna, receiver, and signal processor. The range to a target, $R$, is determined based on the round-trip time, $\Delta t$, of the EM waves, with

$$R = \frac{c\Delta t}{2},$$

where $c$ is the speed of light ($3 \times 10^8\ m/s$). This formula calculates the distance to the target based on the time it takes for the EM waves to travel to the target and back[3].

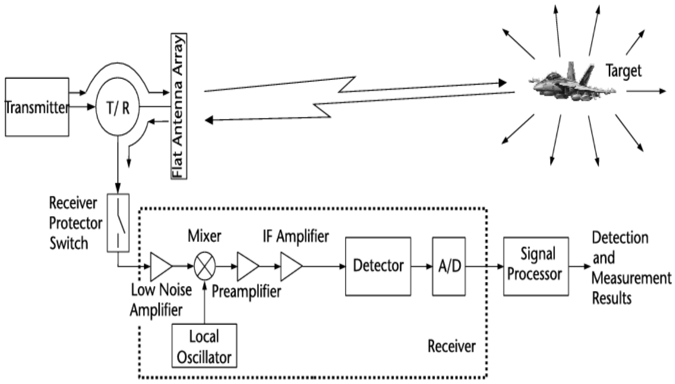



Figure 1.1: Radar Signal Transmission[3]

## 1.1 BASIC RADAR MEASUREMENTS:

Radar systems employ a combination of basic measurements to track targets in three-dimensional space. These fundamental radar measurements include azimuth, elevation, and range. By integrating these three coordinates—azimuth, elevation, and range—radar systems enable comprehensive and accurate tracking of targets, forming a crucial foundation for various applications such as air traffic control, military surveillance, and weather monitoring[5].

**Azimuthal Measurement:** Azimuth, represented by $\theta$, is a radar measurement representing the horizontal angle between the radar antenna's pointing direction and the target. This measurement provides essential information about the target's location in the horizontal plane. By determining the azimuth, radar systems establish the lateral position of the target, contributing to comprehensive tracking capabilities[5].

**Elevation Measurement:** In radar terminology, elevation, represented by $\phi$, pertains to the vertical angle between the radar antenna and the target. This measurement plays a vital role in indicating the target's position in the vertical plane. By analyzing elevation data, radar systems gain insights into the height or altitude of the target above the radar antenna, enabling a more complete three-dimensional understanding of the target's location[5].

**Range Measurement:** Range, represented by R, is the radial distance from the radar antenna to the target. It offers valuable information about the target's location along the line of sight. The range measurement is fundamental for assessing the distance between the radar system and the target, contributing to accurate target localization. By combining azimuthal, elevation, and range measurements, radar systems achieve a holistic representation of the target's spatial coordinates as shown in Figure 1.2[5].

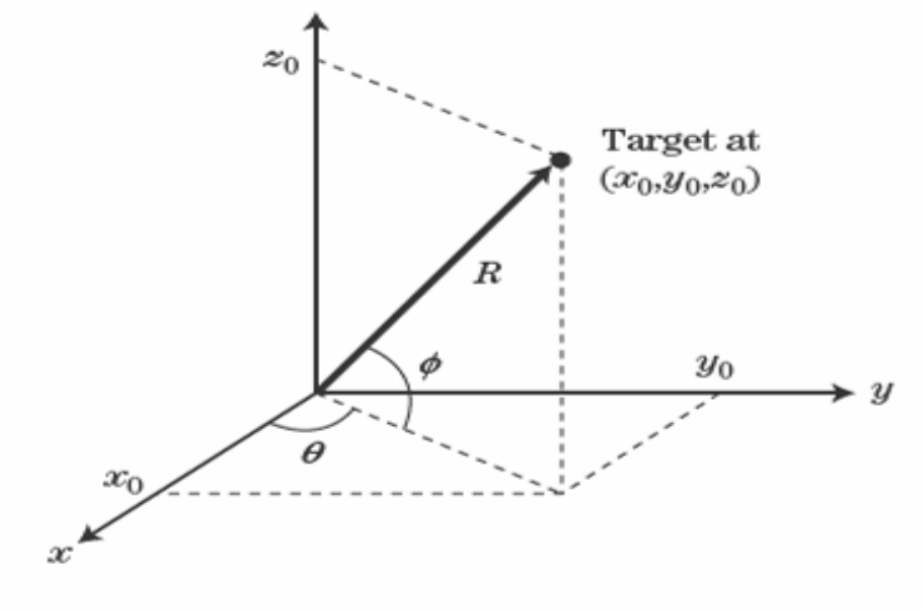



Figure 1.2: Target Special Coordinates[5]

## 1.2 BASIC RADAR FUNCTIONS:

1. Search/detect
2. Track
3. Image.

This report will primarily concentrate on the search/detect, and tracking functions, laying the groundwork for a better grasp of seeker modelling, which constitutes the principal objective of this report.

**SEARCH/DETECT:** Radars have to search in a given space volume and detect targets without a priori information regarding the target's presence or position. It explores a specific space by positioning its antenna in different ways to cover the entire volume of interest. There are two main ways it conducts this exploration: parallel survey and sequential survey[3].

**Parallel survey:** in a parallel survey by radar, the radar divides the area it's observing into smaller sections or slices, and it scans all these sections simultaneously. Each section is covered simultaneously, ensuring comprehensive coverage without missing any part of the sky. Consider an instance where the radar is tasked with surveying a 90-degree angular span in the sky. This entire angle is subdivided into segments of 10 degrees, further partitioned into finer divisions of 1-degree increments. Each of these 1-degree segments serves as the granularity or resolution of the radar system in its ability to detect and discern objects within the surveyed space[3].
**Sequential survey:** This method involves the radar systematically scanning the space in a step-by-step manner. It focuses on one specific area at a time, covering different angles and ranges separately. Instead of looking at all angles simultaneously, it moves its attention sequentially from one area to another. It focuses on one specific area or angle at a time, scans it thoroughly, and then moves on to the next area until it covers the entire region it needs to observe. Imagine the radar starts by looking at a 0-10 degree angle and scans all ranges within that angle. Then, it moves to the next section, say 10-20 degrees, and repeats the process until it covers the entire 90-degree angle[3].
Within each section of the sky, the radar sends out bursts of pulses (like short radio waves) and waits for them to bounce back. By analysing these returning signals, it decides if there's an aeroplane or another object. This decision depends on a certain power threshold—like how strong the returning signal needs to be to count as a detection. The time it takes to cover the space, i.e. time taken for a survey, depends on the number of pulses sent in each burst and the time interval between these pulses. The radar sends bursts of radio waves and listens for their reflections.

$$T_{\text{sur}} = \tau_b = n \times T_b$$

$T_{\text{sur}}$ represents the total time the radar spends scanning or searching a particular area of the sky. The total time the radar scans a specific area is equal to the time taken to receive one burst of reflected pulses. $\tau_b$ stands for the time it takes for the radar to receive a burst of reflected pulses. $n$ is the number of pulses sent in a burst. This number is determined based on how sensitive the radar needs to be to detect a potential target. The appropriate 'n' value involves trade-offs between sensitivity, resolution, false alarms, energy consumption, and the specific requirements of the radar system in detecting and classifying targets efficiently and accurately. $T_b$ denotes the time interval between each pulse within a burst[3].

**TRACK:** After the detection of a potential threat, the target states are measured as a function of time. The target states usually are positioned in the range, azimuthal, elevation angle and radial component of velocity. In radar tracking systems, Kalman filters are often integrated into the tracking algorithms to continuously update the estimate of the target's state, considering both predictions from the dynamic model and measurements from the radar. It plays a crucial role in improving the accuracy of target tracking systems under unwanted situations[3].

Tracking involves continuous measurement of the coordinates of a moving target to determine its trajectory. The radar antenna always points directly at the target to get the best signal quality. If the target moves away from the centre of the radar's view, it creates an error signal. By amplifying the error signal, the radar ensures that even small deviations from the target are detected and corrected promptly, maintaining accurate tracking. This amplified error signal is used to adjust the radar's antenna so that it stays locked onto the target[3].

The azimuth and elevation angles define the three-dimensional position of the target in space relative to the radar. The tracking angle is crucial in radar systems, especially in tracking radars used for military purposes. The radar continuously adjusts its tracking angle to keep the target within its beam, ensuring accurate monitoring and tracking. The radar system uses feedback mechanisms, such as error signals and servo motors, to maintain the correct tracking angle and stay locked onto the target despite any movements. This constant adjustment allows the radar to follow the target as it moves through the airspace[3].

# Chapter 2

# RADAR RANGE EQUATION

In Chapter 1, we introduced the primary functions of radar systems: searching and detecting targets, tracking detected targets, and, in some cases, generating an image of the target. These functions rely on the strength of the signal received from the target and are affected by interfering signals. When thermal noise in the receiver serves as the interference, the ratio of the target signal to noise power is known as the **signal-to-noise ratio (SNR)**. In the presence of clutter interference, the ratio is termed the **signal-to-clutter ratio (SCR)**. The overall ratio of the target signal to the total interfering signal is referred to as the **signal-to-interference ratio (SIR)**.

If the combined signal and noise at any given spatial position exceed the interference by a sufficient margin, then a detection is made, and a target is deemed to be at that position. In this sense, detection is a process by which, for every possible target position, the signal (plus noise) is compared with some threshold level to determine if the signal is large enough to be deemed a target of interest. The threshold level is set somewhat above the interference signal level. The probability that a target will be detected depends on the probability that its signal will exceed the threshold level[5].

## 2.1 Power Density at a Distance *R*

The radar transmitter's total peak power, denoted as $P_t$, is applied to the antenna system. If the antenna possessed an isotropic or omnidirectional radiation pattern, the power density $Q_i$ (in watts per square meter) at a distance $R$ (in meters) from the radiating antenna would be the total power divided by the surface area of a sphere with a radius $R$. The antenna gain ($G$), representing the directivity reduced by the losses the signal encounters during its travel from the input port to the point where it is "launched" into the atmosphere, is a crucial factor. Given $G_t$, the increased power density due to the use of a directional antenna is expressed as:[5]

$$Q_i = \frac{P_t \cdot G_t}{4\pi R}$$

## 2.2 Received Power From a Target

The incident radar signal induces time-varying currents on the target, transforming it into a source of radio waves. A portion of these waves propagates back to the radar, resembling a reflection of the illuminating signal. The reflected power from the target back toward the radar, denoted as $P_{\text{refl}}$, is determined by the incident power density and a factor called the radar cross section ($\sigma$) of the target, measured in square meters ($\text{m}^2$). The radar cross-section is influenced by various factors, including the physical size, shape, and material composition of the target's outer surface. The expression for the reflected power, whose derivation has been studied and is based on principles outlined in "Principles of Modern Radar" by Mark A. Richards, James A. Scheer, and William A. Holm. , ($P_{\text{refl}}$) from the target is given by:[5]

$$P_{\text{refl}} = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 \cdot R^4}$$

Here,

- $P_t$ is the peak transmitted power in watts.
- $G_t$ is the gain of the transmit antenna.
- $G_r$ is the gain of the receive antenna.
- $\lambda$ is the carrier wavelength in meters.
- $\sigma$ is the mean radar cross-section of the target in square meters.
- $R$ is the range from the radar to the target in meters.

When radar waves encounter an object, a portion of them rebounds. The Radar Cross Section (RCS) serves as a metric for the strength of this rebound. A higher RCS indicates a more pronounced reflection of radar energy, making the object easier to detect. Conversely, a smaller RCS signifies a diminished reflection, making the object more challenging to detect. The calculation of RCS involves comparing the power of the scattered waves in a specific direction to the power of the incident (incoming) waves:[5]

$$\sigma = \lim_{r \to \infty} 4\pi r^2 \frac{|E^{\text{scat}}|^2}{|E^{\text{inc}}|^2}$$

Here, $E_{\text{scat}}$ represents the scattered field, and $E_{\text{inc}}$ is the field incident at the target. RCS is expressed in units of area, specifically the effective cross-sectional area of the target. It is important to note that the RCS of a test object is an inherent property of the object itself.

The target RCS is normally a fluctuating value, so the mean value is usually used to represent the RCS. The radar equation therefore predicts a mean, or average, value of received power and, when noise is taken into consideration, SNR[5].

## 2.3 Receiver Thermal Noise

Random noise in the environment, primarily from solar effects, enters the antenna from various sources including cosmic (galactic) noise and solar noise. Cosmic noise is significant below 1 GHz but diminishes above that frequency, while solar noise, particularly influential due to the sun's proximity, is mitigated by antenna sidelobe gain unless the main beam points directly at the sun. Ground noise, entering through antenna sidelobes, is also a factor, though at a lower level than solar noise.

In addition to antenna-induced noise, thermally agitated random electron motion in receiver circuits generates noise, competing with the target signal. Successful target detection requires the target signal to exceed the noise signal, dependent on the statistical characteristics of the target.

Thermal noise power, termed "white" noise, is uniformly distributed across radar frequencies. Only noise within the receiver bandwidth ($B$) affects radar performance. The power ($P_n$) of thermal noise in the radar receiver is given by

$$P_n = kTSB = kT_0FB,$$

where $k$ is Boltzmann's constant (1.38 × 10^23 watt-sec/K), $T_0$ is the standard temperature (290 K), $T_s$ is the system noise temperature ($T_s = T_0F$), $B$ is the instantaneous receiver bandwidth in Hz, and $F$ is the noise figure of the receiver subsystem (unitless)[5].

The signal-to-noise ratio (SNR) is calculated by dividing the received target signal power ($P_r$) by the noise power ($P_n$). For a discrete target, this ratio is expressed as:

$$\text{SNR} = \frac{P_tG_tG_r\lambda^2\sigma}{(4\pi)^3R^4kT_0FB}$$

Ultimately, radar performance is determined by the signal-to-interference ratio (SIR), which can be influenced by interference sources such as receiver or jamming noise, clutter, and other electromagnetic interference. If the power from receiver thermal noise

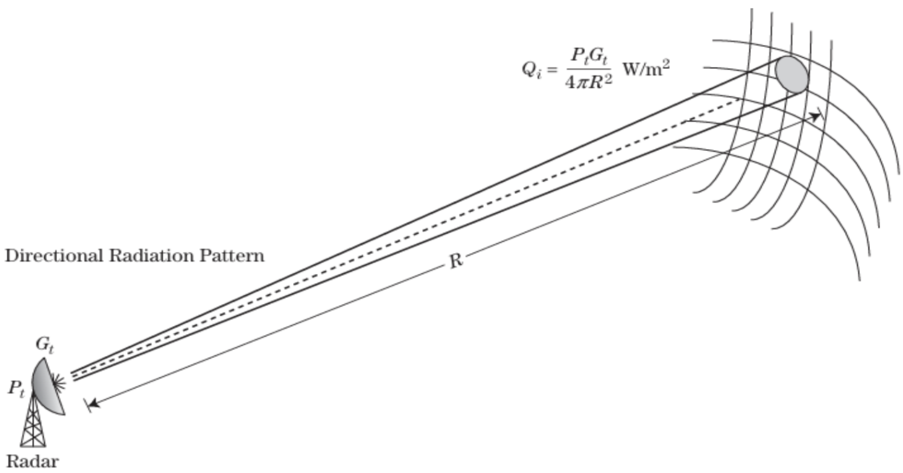



Figure 2.1: Power Density at a distance R[5]

is denoted as $N$, clutter as $C$, and jamming noise as $J$, then the SIR is given by:

$$\text{SIR} = \frac{S}{N + C + J}$$

A more appropriate form of the Radar Range Equation (RRE) when $n_p$ pulses are coherently combined is expressed as:

$$\text{SNR}_c(N) = \frac{P_t G_t G_r \lambda^2 \sigma n_p}{(4\pi)^3 R^4 k T_0 F B}$$

The dB form of the Radar Range Equation (RRE) can be expressed as:[5]

$$\begin{aligned}\text{SNR}_c[\text{dB}] = {} & 10\log_{10}(P_t) + G_t[\text{dB}] + G_r[\text{dB}] + 20\log_{10}(\lambda) + \sigma[\text{dBsm}] \\ & + 10\log_{10}(n_p) - 33 - 40\log_{10}(R) \\ & - (-204)[\text{dBW/Hz}] - F[\text{dB}] - 10\log_{10}(B)[\text{dBHz}] - L_s[\text{dB}]\end{aligned}$$

## 2.4 Summary of losses

Up to this point, the radar equation has been presented in an idealized form, neglecting any losses. However, the actual received signal power is typically lower than predicted when the effects of signal loss are taken into account. Factors such as atmospheric absorption, resistive losses in components, and nonideal signal processing conditions contribute to suboptimal Signal-to-Noise Ratio (SNR) performance.

The comprehensive system loss term, denoted as $L_s$, is expressed as the product of individual losses:

$$L_s = L_t L_a L_r L_{sp}$$

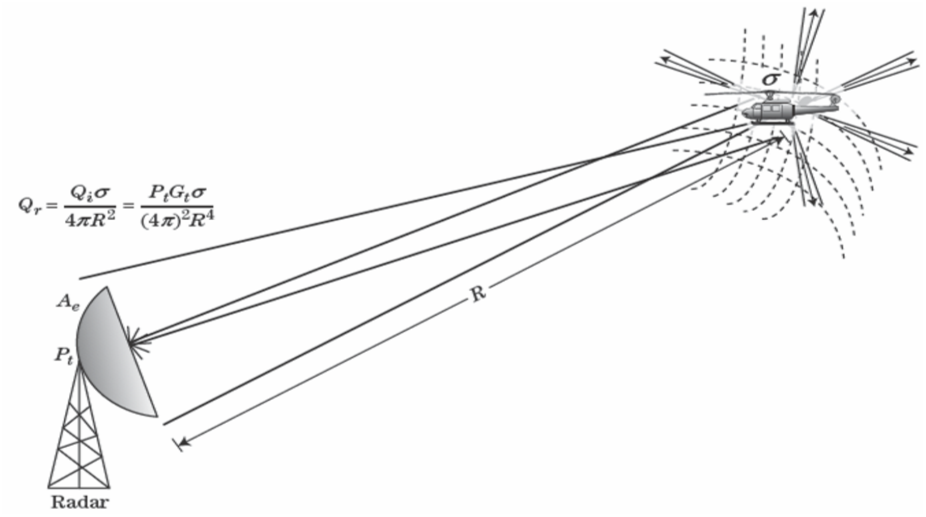



Figure 2.2: Received Power From a Target[5]

Here, $L_s$ represents the system loss, $L_t$ is the transmit loss, $L_a$ is the atmospheric loss, $L_r$ is the receiver loss, and $L_{sp}$ is the signal processing loss. Considering these losses, the Radar Range Equation (RRE) is modified to:

$$\text{SNR} = \frac{P_t G_t G_r \lambda^2 \sigma n_p}{(4\pi)^3 R^4 k T_0 F B L_s}$$

This modification accounts for the impact of various losses on the overall radar performance[5].

## 2.5 Search and Track form of RRE

The analysis of a system designed to scan a specified solid angular volume, Ω. within a given search frame time, $T_{fs}$, is often facilitated by employing the search form of the radar equation.

$$\text{SNR} = \frac{P_{avg} \cdot A_e \cdot \sigma \cdot T_{fs}}{4\pi k T_o F L_s R^4 \Omega}$$

The power-aperture formulation of the Radar Range Equation (RRE) provides a convenient method for organizing the essential radar parameters (Pavg, Ae, Ls, and F) when aiming to detect a target with a specific radar cross-section (RCS) at a given range R within a defined solid angular volume over the period Tfs.

$$\frac{P_{\text{avgAe}}}{L_s T_o F} \geq \frac{\text{SNR}_{\text{min}} 4\pi k R^4 \Omega}{\sigma T_f}$$

Similar to the search form of the radar equation, the examination of a system engineered to track multiple targets with specific precision is articulated using the power-aperture cubed, or equivalently, the power-aperture-gain format of the radar range equation. This variant is also referred to as the track form of the RRE[5].

$$\frac{P_{\mathrm{avgAe}}G}{L_s F} = \frac{\mathrm{SNR} \cdot (4\pi)^2 R^4 k T_0 \mathrm{PRF}}{\sigma}$$

# Chapter 3

# SEEKERS

Seeker technology plays a pivotal role in modern guided missile systems, providing the means for missiles to accurately locate and home in on their targets. Evolving from radar principles, seekers are sophisticated devices integrated into missiles, allowing them to actively track, identify, and pursue designated targets with precision.

**"Homing"** of seekers refers to the ability of a guided missile to actively navigate and adjust its trajectory to home in on a specific target. Seekers are integral components of guided missile systems, and their primary purpose is to guide the missile toward the intended objective with precision. The homing process aims to bring the missile into proximity to the target, ensuring a precise impact. The seeker's ability to measure the angle, velocity, and range of a target is complemented by its continuous tracking functionality.

Employing a **monopulse tracker**, the seeker ensures a persistent lock on the target, allowing it to compute the rate of change of the line-of-sight to the target concerning the missile. This information is essential for the missile's onboard computer **(OBC)** to calculate precise guidance commands necessary for successful homing[2].

The RF seeker, functioning as a sensor, possesses the capability to provide precise guidance signals. However, the sight-line rate from the RF seeker exhibits time-varying noise statistics with a high magnitude. As a result, a basic digital filter proves insufficient for effectively filtering out the noisy sight-line rate. One strategy for noise filtering involves modelling the colour noises and supplementing them with the process model of a Kalman filter[1].

**The Kalman filter** helps make sense of noisy and uncertain measurements, providing a more accurate and smooth estimate of the object's actual position and velocity. It combines current measurements with predictions based on the system's dynamics, constantly adjusting and refining its estimate as new information becomes available. Essentially, it assists in filtering out noise and refining the tracking information for more reliable target monitoring[6].

**Proportional Navigation (PN) guidance** enhances the seeker tracking capabilities of a missile by providing a guidance law that ensures a continuous and adaptive approach to intercepting the target. This approach ensures the missile continually closes in on the target by adapting its path based on the observed changes in the LOS[7].

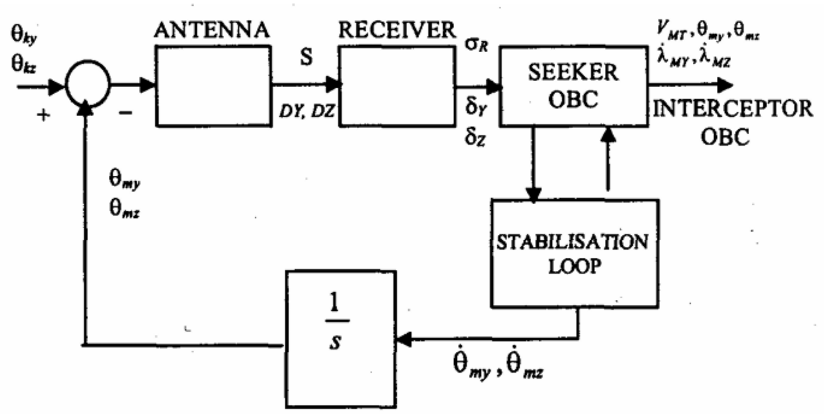



Figure 3.1: Functional Diagram of RF Seeker [1]

Consider an RF seeker equipped with a mono-pulse receiver, a critical component for precise guidance. The antenna model receives input in the form of boresight errors, representing the disparity between the kinematic gimbal angles ($\theta_{ky}, \theta_{kz}$) and the measured gimbal angles ($\theta_{my}, \theta_{mz}$). Leveraging the sum and difference antenna patterns, obtained experimentally, the antenna model generates signals for both channels based on these boresight errors. These sum and difference signals are then directed to the receiver block.

For simplicity, it is assumed that the difference signal is equivalent to the individual boresight errors, which are directly transmitted to the receiver model. The receiver block computes angle errors using the sum and difference signals, forwarding them to the digital signal processing (DSP) block. Within the DSP block, operations such as angle error accumulation and averaging take place. This DSP block is an integral part of the seeker's onboard computer.

The seeker's onboard computer issues commands to the antenna stabilization system, directing the antenna toward the target. Furthermore, the onboard computer performs various processing tasks, providing information on the line-of-sight rate, gimbal angles, and closing velocity between the interceptor and the target at a specific update rate.

Moreover, the seeker's onboard computer supplies data on the quality of seeker measurements. This includes angle error variance and signal-to-noise ratios in terms of log detector output, which prove valuable for seeker filtering purposes. In essence, this comprehensive system ensures accurate guidance and monitoring capabilities for the RF seeker[1].

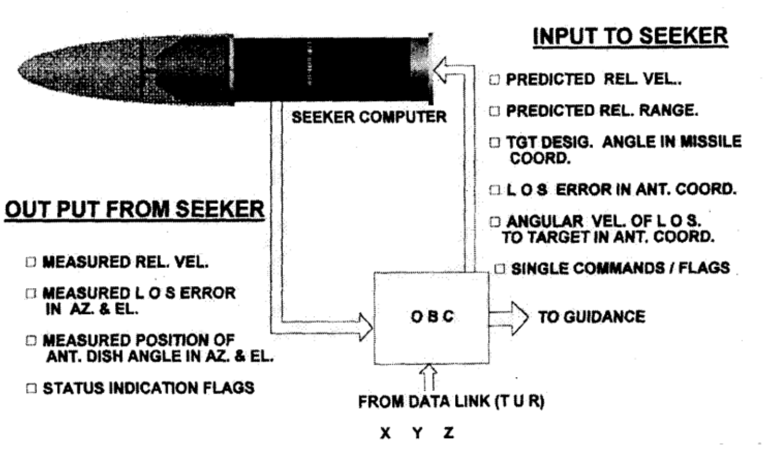



Figure 3.2: Active radar seeker operation with onboard computer[2]

## 3.1 Radar vs. Seeker

The seeker communicates the following information to the On-Board Computer (OBC):[2]

1. Measured Relative Velocity
2. Measured Line-of-Sight (LOS) in Azimuthal/Elevation
3. Measured Position of Antenna Dish Angle in Azimuthal/Elevation

4. Status of Indication Flags

## 3.2 Measurement of Radial Velocity

Radial velocity is calculated in terms of Doppler shift[2].The Doppler shift is an apparent alteration in frequency (or wavelength) resulting from the relative motion between two objects, where one or both may be in motion relative to the ground. Radar systems leverage the Doppler shift to gauge relative speed. When objects approach each other, the Doppler shift leads to a wavelength shortening or frequency increase. Conversely, when objects move away from each other, the Doppler shift causes a lengthening of wavelength or a decrease in frequency[8].

As the target approaches the seeker, the received echo's frequency increases, and when the target moves away, the frequency decreases. The difference between the transmitted and received frequencies is termed Doppler frequency ($fd$)[9].

The Doppler frequency shift ($f_d$) is given by the difference between the receiver frequency ($f_r$) and the transmitter frequency ($f_t$):

$$f_d = f_r - f_t$$

In terms of radial velocity ($V_r$), the Doppler frequency shift can be expressed as:[5]

$$f_d = \frac{f_t \cdot V_r}{c}$$

In practical applications, many Doppler radars measure phase shift ($\Delta\phi$) instead of directly measuring Doppler frequency ($\Delta f$)[10]. Doppler radars can determine the radial velocity component, representing the rate at which an object moves toward or away from an observer along the line of sight. A positive radial velocity indicates an increasing distance between objects, while a negative radial velocity suggests a decreasing distance between the source and observer.

In Figure 3.3, A is the transmitted wave, B is the received wave, R is the distance between the radar and the target at time t and R-D is the distance between the radar and the target at time (t+T).

Consider two successive pulses sent out by the radar[11]:

At time $t$, the radar sends Pulse 1, where the distance travelled by the pulse is $2R$, and the number of wavelengths along the path is $2R/\lambda$.

If the radar's pulse repetition time is $T$, then at time $t + T$, the radar sends out Pulse 2, where the distance travelled by the pulse is $2R-2D$, and the number of wavelengths along the path is $(2R - 2D)/\lambda$. Note that Pulse 2 has to travel a distance $2D$ lesser than Pulse 1.

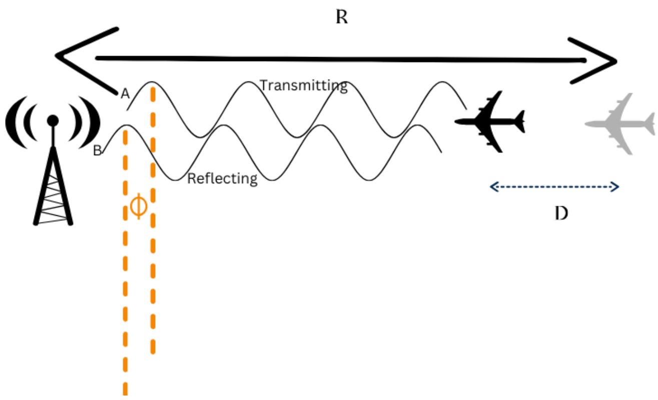



Figure 3.3: Radial Velocity Measurement

Pulse 2 has traveled $2D/\lambda$ wavelengths lesser than Pulse 1. The return from Pulse 2 reaching the radar will be phase-shifted by $2\pi(-2D/\lambda)$ radians compared to the return from Pulse 1.

The phase difference between the transmitted signal and the received signal, i.e., the phase shift ($\phi$), is given by $2\pi(-2D/\lambda)$[11].

The frequency ($f$) is the time derivative of the phase change:

$$\frac{d\phi}{dt} = \frac{4\pi dD}{\lambda dt}$$
$$\frac{d\phi}{dt} = \frac{4\pi V_r}{\lambda}$$

Here $V_r$ represents the radial velocity.

In practice, $\frac{d\phi}{dt}$ could be measured easily by transmitting lots of signals in unit time and measuring the $\frac{d\phi}{\Delta t}$[10].

## 3.3 Measurement of LOS

The Line of Sight (LOS) is an imaginary axis connecting an observer or sensor to a target, providing a fundamental reference for angular relationships. The behaviour of the LOS signal is influenced by interceptor-target geometry, showing gradual changes at higher ranges and pronounced fluctuations at lower ranges. Proportional Navigation (PN) principles use LOS measurements to guide interceptor missiles by adjusting their heading proportionally to nullify the LOS rate. Missile seekers accurately measure LOS angular rates, vital for PN guidance.

$$a_n = N \cdot V_c \cdot \frac{d\lambda}{dt}$$

$a_n$ = commanded normal acceleration

$N$ = effective navigation ratio

$V_c$ = closing velocity

$\frac{d\lambda}{dt}$ = LOS rate measured by the missile seeker[12].

To ensure the missile stays on the Line of Sight (LOS), it is crucial to have a perpendicular component of velocity ($V_{m_\perp}$). Any deviation from a perpendicular path can cause the missile to move off the direct line connecting the target and the control point.

Neglecting the case of a manoeuvring target, in Fig3.4, the relative closing velocity ($R'$) between the missile and target in terms of velocity components along the LOS of the target ($V_T$) and perpendicular to the LOS of the missile ($V_{m_\perp}$) is given by:

$$R' = V_t \cdot \cos(\lambda - \theta_t) - V_m \cdot \cos(\lambda - \theta_m)$$

The LOS rate of rotation ($\lambda$ ') is defined as:[7]

$$\lambda' = \frac{V_t - V_m}{R}$$

As the missile approaches the target closely, there's a risk of the target filling the entire field of view of the missile's seeker. This situation, known as the blind range, occurs when the seeker loses its ability to precisely ascertain the target's position and movement. To manage this, a predefined blind range law is necessary, outlining specific conditions under which the seeker may encounter limitations in accurately tracking the target[13].

For an ideal pursuit,in Fig3.5,

$\theta_M = \lambda'$, where $\lambda$ is the LOS angle ($q$).

Similarly, the linearized form for the LOS angle using the small-angle approximation can be expressed as:[13]

$$\frac{q_y}{R}$$

For a head-on case, the closing velocity $V_C$ can be approximated as:[13]

$$V_C = V_M + V_T$$

whereas in a tail chase case, $V_C$ can be approximated as:[13]

$$V_C = V_M - V_T$$

The linearized form for range $R$ with the time-varying is[13]

$$R = V_C(t_f - t)$$

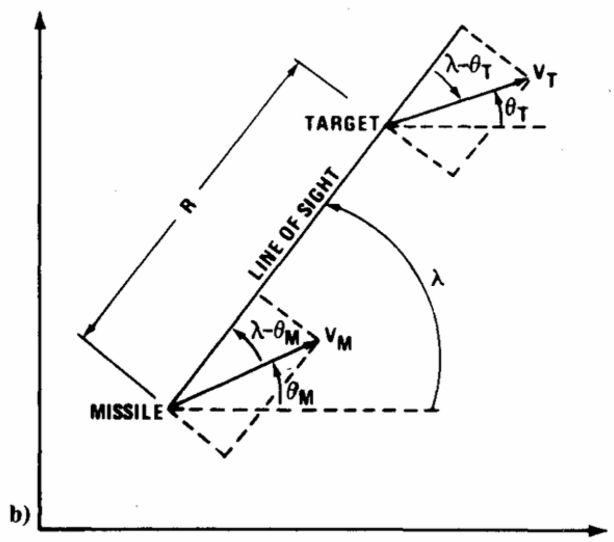



Figure 3.4: Relative Closing Velocity[7]

## 3.4 Measurement of Azimuthal / Elevation:

A monopulse tracking system represents a sophisticated radar technology that excels in precisely determining the azimuthal and elevation angles of a target. In contrast to conventional radar systems, monopulse employs multiple simultaneous beams, generated by multiple feedhorns or antennas, to measure both azimuth and elevation angles concurrently. This dual-angle measurement capability enhances tracking accuracy significantly. The term "monopulse" arises from the system's utilization of a single pulse to generate multiple beams.

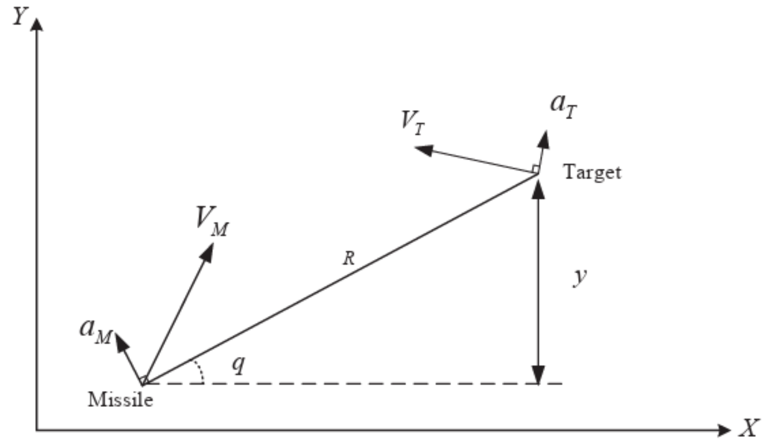



Figure 3.5: Ideal Pusuit[13]

Monopulse tracking systems find widespread applications in various fields, including air traffic control, missile guidance, and military surveillance, where precise target tracking is essential for effective operation. Chapter 4 explains further in detail about monopulse.

| **Feature** | **Radar** | **Seeker** |
|---|---|---|
| Range | Typically longer range (from meters to hundreds of kilometers). | Short to medium range (commonly used in missile guidance). |
| Frequency | Uses radio waves or microwaves (GHz range). | Depends on the type - could be radio, infrared, or other. |
| Working | Emits electromagnetic waves and detects reflections to identify and track targets. | A device that "seeks" or homes in on a target, often found in guided missiles. |
| Applications | Air traffic control, weather monitoring, military surveillance, navigation. | Primarily used in guided missile systems, anti-aircraft systems. |
| Resolution | Can achieve high resolution depending on the wavelength used. | Resolution depends on the specific sensor type; may be lower compared to radar. |
| Mobility | Ground-based, airborne, or space-based installations. | Mobile in the context of guided missiles; can be air-to-air, ground-to-air, etc. |
| Targets | Detects a wide range of objects (aircraft, ships, weather phenomena). | Targets specific objects, often guided missiles, aircraft, or other vehicles. |
| Cost | Can be expensive, especially for advanced systems. | Seekers are integral parts of missile systems, contributing to overall costs. |
| Stealth | Can be countered by stealth technology. | Seekers play a role in anti-stealth capabilities, but stealth is a factor in missile design. |
| History | Developed during World War II for military purposes. | Evolved as a component of guided missile systems, stemming from radar technology. |

Table 3.1: Comparison between Radar and Seeker

# Chapter 4

# MONOPULSE RADAR SYSTEM

One of the primary responsibilities of radiolocation is, as we all know, the direction finding of targets, which entails figuring out the direction of the target. Adopting the monopulse technique detailed information regarding the target's angular position can be extracted by the reflected signal. The amplitude variations of the reflected signal have no bearing on the precision of angular coordinate measurement because monopulse radars only use one pulse to determine the target's direction. Therefore, this explains the term "monopulse (single pulse)" direction finding. Therefore, the monopulse method is used for determining the coordination of targets. Monopulse is also known as simultaneous lobe comparison. It is a technique for measuring the direction of arrival of radiation that can be from an active source or passive source. Active sources could be:[14]

1. Distant transmitting antenna
2. Beacon
3. Jammer
4. Astronomical body

Passive sources include a target that reradiates some of the power incident on it. Finding the error signal in radar systems is essential for precise tracking and guiding of the missile or system toward the target, especially with monopulse radar[14].The discrepancy between the target's actual position as detected by the radar system and its intended or expected position is represented by the error signal. To guarantee precise targeting, this error signal is necessary to modify the missile's trajectory or guidance system. Hence there are two methods for obtaining an error signal[3].

1. Amplitude Method
2. Phase Method

## 4.1 Amplitude Method

The amplitude comparison method is one of the methods used in monopulse radar for determining a target's angle of arrival. To determine the target's **angular position**, this approach compares the amplitude or strength of signals received from several antennas or channels.

It is like the concept of lobe switching, but here we don't compare the target echoes obtained in four sequential beam positions. Here it forms the four receiving beams simultaneously and makes the comparisons on each pulse.

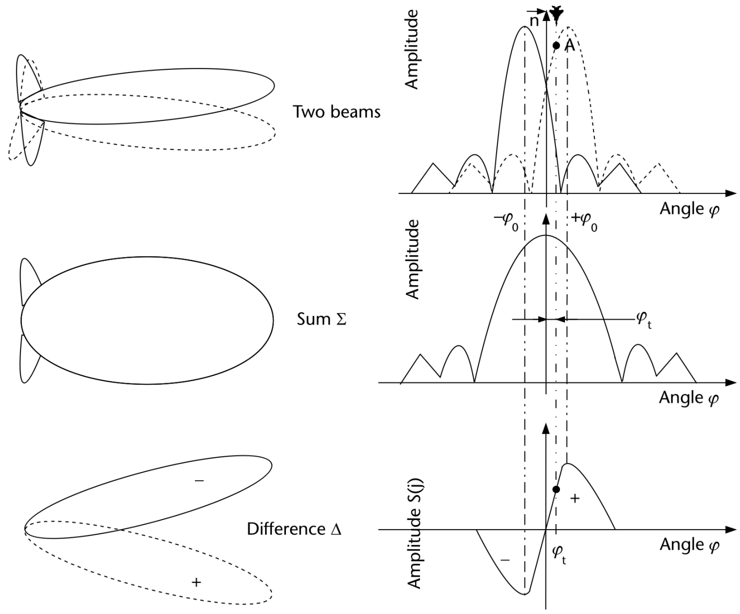



Figure 4.1: The principle of operation of the monopulse method for determining the target angular coordinates[3].

Using the amplitude approach, two intersecting radiation patterns are created, separated from one another by an angle of $\pm\theta_o$, concerning the equisignal direction, which is typically the normal n of a monopulse antenna. This allows for the determination of the angular coordinate in one plane, , for instance.

The signal received from the monopulse antenna's right partial radiation pattern is bigger than the signal received from the left partial radiation pattern when the target deviates by an angle of t from the equisignal direction n and is positioned at point A. The magnitude of the target's departure from the equisignal direction is indicated by the difference in the amplitudes of the received signals. The direction of displacement of the equisignal direc-

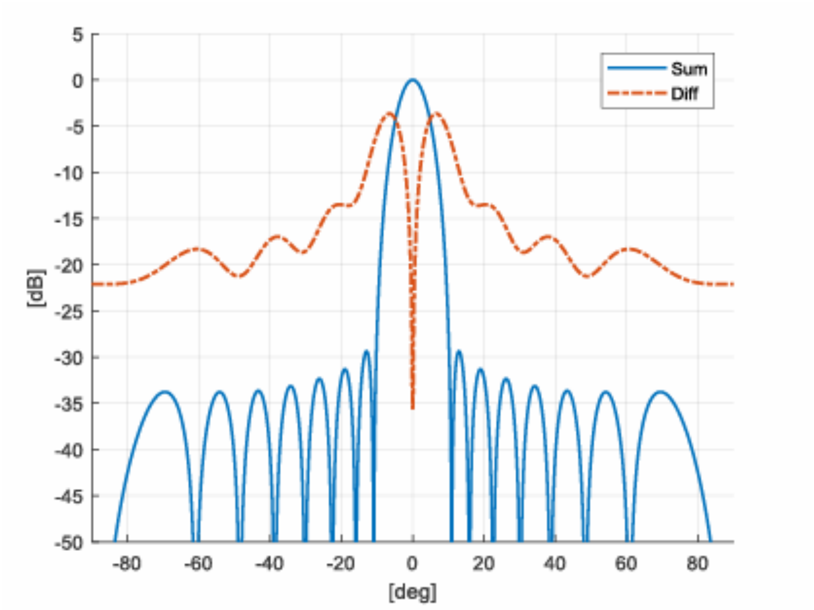



Figure 4.2: Sum and Difference [4]

tion concerning the target is indicated by the sign of this difference. The amplitudes of the reflected signals received in both partial radiation patterns are equal and their difference becomes zero when the equal-signal direction is aligned with the target[3].

## 4.2 Phase Method

In phase comparison monopulse, compared to sequential lobing, monopulse can offer a higher data rate since angle information is available from each received pulse, eliminating the need for a cycle of successive beam positions.

Similar methods are used to determine the target elevation angle $\epsilon_t$, employing two partial radiation patterns in the $\epsilon$ plane and two receiving channels. When using monopulse systems with phase direction finding, two antennas compare their signal phases to determine the direction of the target in a single-coordinate plane. Two antennas are shown in Figure 6.2, separated by a distance L. The target's line of sight and the $n$-axis, or normal $\mathbf{n}$ to the monopulse antenna, form an angle of $\epsilon_t$.

The target's distance from antenna 1 (R1) is

$R1 = R + \frac{L}{2} \cdot \sin(\epsilon_t)$

where the separation R2 between the target and antenna 2 is

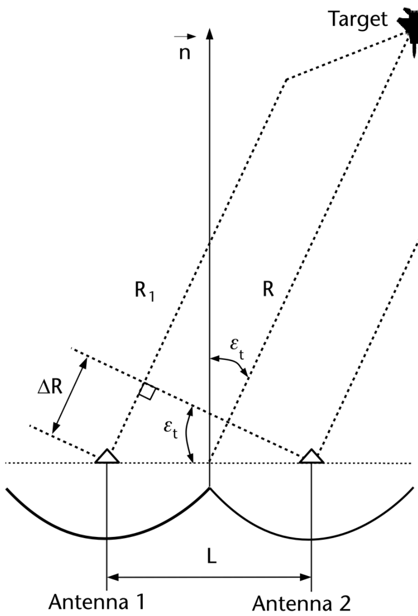


Figure 4.3: Phase method[3].

$R2 = R - \frac{L}{2} \cdot \sin(\epsilon_t)$

Consequently, the shape represents the difference in the distances between the target and the antennas.

$\Delta R = R_1 - R_2 = L \cdot \sin(\epsilon_t)$

and provide the phase difference's expression:

$\Delta\epsilon = \frac{2\pi}{\lambda} \cdot \Delta R = \frac{2\pi L}{\lambda} \cdot \sin(\epsilon_t)$

The wavelength is represented by $\lambda$. This enables two antennas positioned L apart to concurrently receive signals reflected from the target and detect their phase shifts, allowing the angle of arrival, $\epsilon_t$, to be found (see Figure 6.2). Remarkably, the above formula indicates that the phase shift of the $\sim \epsilon$ signals approach zero at other mismatch angles that correspond to the following conditions in addition to $\epsilon_t = 0$.

$\epsilon_t = \arcsin\left(\frac{2n\pi}{k_\lambda L}\right)$

for n to be 1, 2,..., $k_\lambda = \frac{2\pi}{\lambda}$and , also known as wavenumber.

Consequently, the error signal's dependence on the angle at which the signal C (phi) arrives, or the direction-finding characteristic, becomes sign-alternating and contains numerous incorrect directions in addition to the primary equal-signal direction[3].

# Chapter 5

# Simulation of Monopulse Seeker Operation

This chapter illustrates a fundamental simulation of monopulse functionality.

## 5.1 Sum and Difference Monopulse Radar

A main lobe sum beam and a difference beam with two main lobes are the intended outputs of the monopulse radar antenna. While the difference beam is in charge of detecting target azimuth and elevation angle information for angle tracking, the sum beam is in charge of detecting target distance and carrying out distance tracking. The signal received by the difference beam is very weak when the target is perfectly in line with the sum beam's greatest value direction. The difference beam receives a weak to strong signal from the moving target, which allows it to drive the servo mechanism for constant alignment with the target track[15].

The array factor, also known as the array radiation pattern or array response, represents the combined effect of individual antenna elements in an antenna array. It characterizes how the array radiates or receives electromagnetic waves in different directions. In a simplified form, the array factor or sum pattern (Sum) is defined as:

$$\text{Sum} = \sum_{n=1}^{N} w_o(n) \cdot \exp(jD_n u)$$

Here, $N$ is the number of antenna elements, $w_o(n)$ represents the quiescent weights for the sum channel given by $a(n) \cdot \exp(-jD_n u_s)$, where $a(n)$ is the amplitude of each antenna element assumed to be 1. The steering angle is denoted by $\theta_s$, $u_s = \sin(\theta_s)$, $u = \sin(\theta)$, $d_o$ is the element spacing in wavelengths ($d_o = \lambda/2$), and $D_n$ is calculated using the general formula $2\pi d_o(n - \frac{N}{2} - 0.5)$[16].

A more generalized equation is derived as:

$$\text{Sum} = \sum_{n=1}^{N} \exp(-jD_n(u_s - u))$$

Considering the sum pattern as an even function and the difference pattern as an odd function, weight perturbations creating nulls in the sum pattern do not necessarily result in nulls in the difference pattern, even with uniform amplitude distributions.

To create a difference pattern, half of the antenna elements receive a 180° phase shift. In this case, one-half of the elements have an amplitude of 1, and the other half has an amplitude of -1.

For a scenario with only 2 antenna elements ($N = 2$), $\theta_s = 0$, and very small $\theta$, the sum equation simplifies to $2\cos(D_n\theta)$, and the difference pattern becomes $2j\sin(D_n\theta)$.

The monopulse ratio, defined as the difference divided by the sum, is expressed as $k = j\tan(D_n\theta)$, proving to be a valuable parameter for determining the target's angular position.

In the computation of the element spacings ($D_n$), the formula $D_n[i] = 2\pi D_0(i - \frac{N}{2} - 0.5)$ is considered only for even $N$ to facilitate computational efficiency and phase shifting.

The summation pattern of the antenna elements can be expressed as $\sum_{j=1}^{N} e^{-jD_n y[i]}$, where $y$ is a phase shift factor defined as $y = \sin(\theta_s) - \sin(\theta_i)$.

To generate a difference pattern, half of the element signals undergo a 180° phase shift. This phase shift is implemented using the logic:

$$Dn1[i] = 2\pi D_0(i - \frac{N}{2} - 0.5)$$

$$Dn2[i] = 2\pi D_0(i + \frac{N}{2} - 0.5)$$

Finally, the difference pattern is obtained by subtracting the two half-patterns: $result1[i] - result2[i]$.

The monopulse ratio is calculated as the ratio of the difference pattern to the summation pattern and is subsequently plotted accordingly.

In this report, a simulation of the monopulse seeker has been conducted using both Python and MATLAB to enhance comprehension.

## 5.2 MATLAB Simulation

Listing 5.1: MATLAB code

```
clc
c = 3.0e8; % Speed of light in meters per second
f = 3.0e8; % Frequency of Rf in Hz
theta_s = 5; % Steering angle in degrees
theta_deg = linspace(-20, 20, 40); % Range of theta values in degrees
theta_rad = deg2rad(theta_deg); % Convert theta to radians
N = input("enter number of antenna elements to be considered: ");
% Number of antenna elements

Do = c / (2 * f); % Half-wavelength distance
% Calculate Dn for each antenna element
Dn = zeros(1, N);
if mod(N, 2) == 0
    Dn = 2 * pi * Do * ((1:N) - (N / 2) - 0.5);
end

y = sin(deg2rad(theta_s)) - sin(theta_rad);
% Calculate the summation for varying theta values
results = zeros(1, length(theta_rad));
for i = 1:length(theta_rad)
    results(i) = sum(exp(-1j * Dn * y(i)));
end

% To produce a difference pattern, one half the
element signals
% receive a 180" phase shift. So calculating Dn for this case
Dn1 = zeros(1, N/2);
Dn2 = zeros(1, N/2);
if mod(N, 2) == 0
    Dn1 = 2 * pi * Do * ((1:N/2) - (N / 2) - 0.5);
    Dn2 = 2 * pi * Do * ((N/2:N) - (N / 2) - 0.5);
end
```

```
y = sin(deg2rad(theta_s)) - sin(theta_rad);

% Calculate the difference for varying theta values
result1 = zeros(1, length(theta_rad));
result2 = zeros(1, length(theta_rad));
resultd = zeros(1, length(theta_rad));
for i = 1:length(theta_rad)
    result1(i) = sum(exp(-1j * Dn1 * y(i)));
    result2(i) = sum(exp(-1j * Dn2 * y(i)));
    resultd(i) = result1(i) - result2(i); % have antenna elements 180"
end
%in db
results_db=db(results);
resultd_db=db(resultd);

%monopulse ratio
for i = 1:length(theta_rad)
    k(i)=resultd(i)/results(i);
end

% Plotting
figure
plot(theta_deg, abs(results),'color','r'); hold on
plot(theta_deg, abs(resultd),'color','b'); hold off
title('Sum and Difference');
xlabel('Theta (degrees)');
ylabel('Amplitude');
grid on;
figure
plot(theta_deg, abs(k),'color','g');
title('Monopulse Ratio ');
xlabel('Theta (degrees)');
ylabel('k');
grid on;
figure
plot(theta_deg, abs(results_db),'color','r'); hold on
```

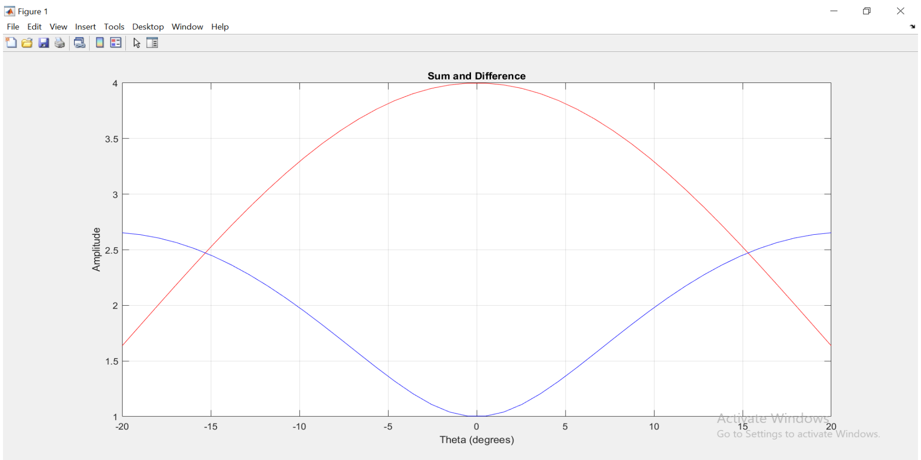
```
plot(theta_deg, abs(resultd_db),'color','b'); hold off
title('Sum and Difference');
xlabel('Theta (degrees)');
ylabel('Amplitude in db');
grid on;
```

## 5.3 Python Simulation

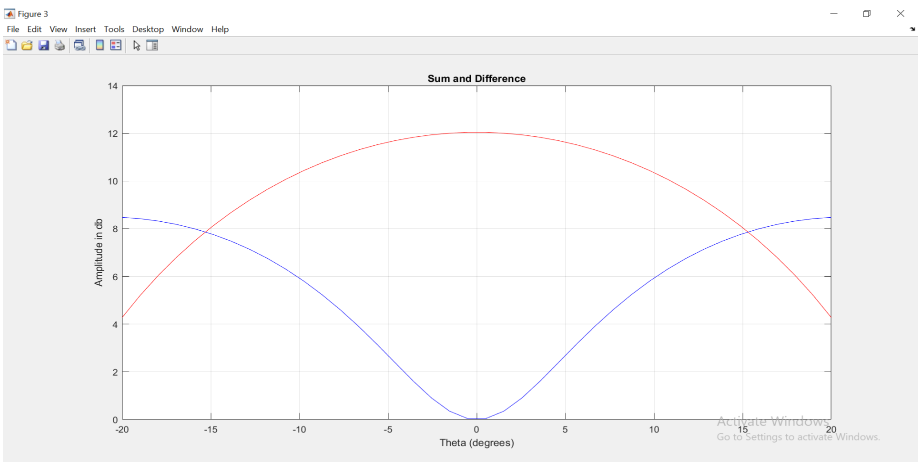
Listing 5.2: Python code

```
import numpy as np
import matplotlib.pyplot as plt

c = 3.0e8  # Speed of light in meters per second
f = 3.0e8  # Frequency in Hz
theta_s = 0  # Reference angle in degrees
theta_deg = np.linspace(-20, 20, 40)  # Range of theta
# values in degrees
theta_rad = np.deg2rad(theta_deg)  # Convert theta to radians
N = 30  # Number of antenna elements

Do = c / (2 * f)  # Half-wavelength distance

# Calculate Dn for Sum
Dn = np.zeros(N)
if N % 2 == 0:
    Dn = 2 * np.pi * Do * (np.arange(1, N + 1) - (N / 2) - 0.5)

# Calculate Dn for Difference
Dn1 = np.zeros(int(N/2))
Dn2 = np.zeros(int(N/2))
if N % 2 == 0:
    Dn1 = 2 * np.pi * Do * (np.arange(1, (int(N/2)+1))\
                           - (N / 2) - 0.5)
    Dn2 = 2 * np.pi * Do * (np.arange(int(N/2), N+1) \
                           - (N / 2) - 0.5)

y = np.sin(np.deg2rad(theta_s)) - np.sin(theta_rad)

# Calculate the summation for varying theta values (Sum and
#                                                  Difference)
result_sum = np.zeros(len(theta_rad), dtype=np.complex128)
result_diff = np.zeros(len(theta_rad), dtype=np.complex128)
```

```
for i, angle in enumerate(theta_rad):
    result_sum[i] = np.sum(np.exp(-1j * Dn * y[i]))
    result_diff[i] = np.sum(np.exp(-1j * Dn2 * y[i])) \
    - np.sum(np.exp(-1j * Dn1 * y[i]))

# Convert result_diff and result_sum to dB for better comparison
result_sum_db = 10 * np.log10(np.abs(result_sum))
result_diff_db = 10 * np.log10(np.abs(result_diff))

# Calculate ratio of Difference to Sum
ratio = result_diff / result_sum
ratio_db = 10 * np.log10(np.abs(ratio))

# Plotting
plt.figure(figsize=(10, 6))

# Plot Sum and Difference results
plt.plot(theta_deg, np.abs(result_sum), label='Sum')
plt.plot(theta_deg, np.abs(result_diff), label='Difference')
plt.plot(theta_deg, np.abs(ratio), label='Ratio')

# Plot Sum and Difference results in dB for better visualization
plt.plot(theta_deg, np.abs(result_sum_db), linestyle='--',\
        label='Sum (dB)')
plt.plot(theta_deg, np.abs(result_diff_db), linestyle='--',\
        label='Difference (dB)')

# Set plot labels, title, legend, and grid
plt.title('Monopulse Sum and Difference Plots')
plt.xlabel('Theta (degrees)')
plt.ylabel('Amplitude / Amplitude (dB)')
plt.legend()
plt.grid(True)

plt.show()
```

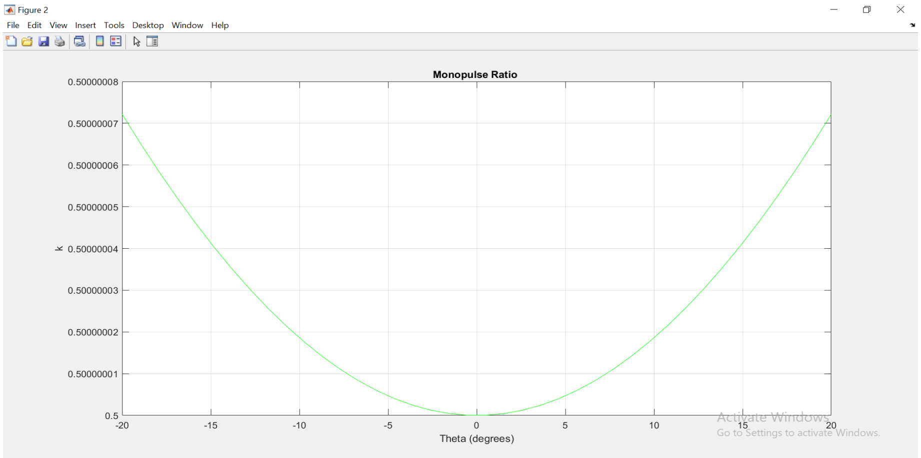



(a) Steering angle 0

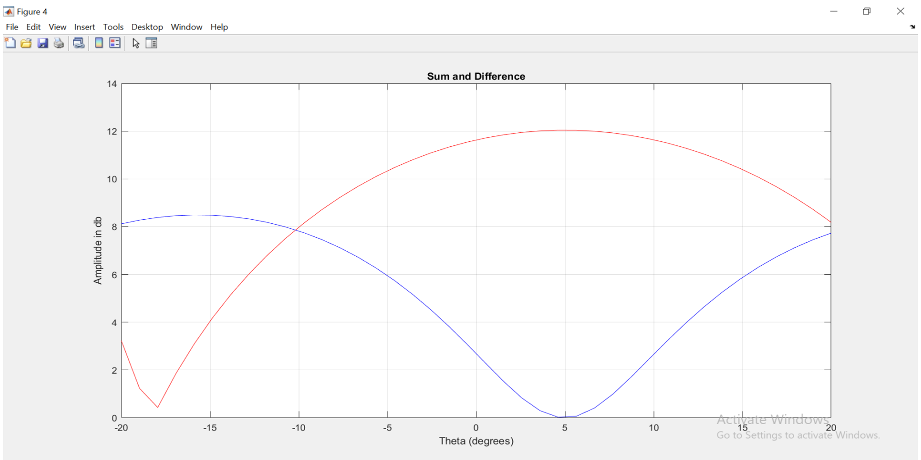



(b) Steering angle 0 in dB

Figure 5.1: MATLAB o/p

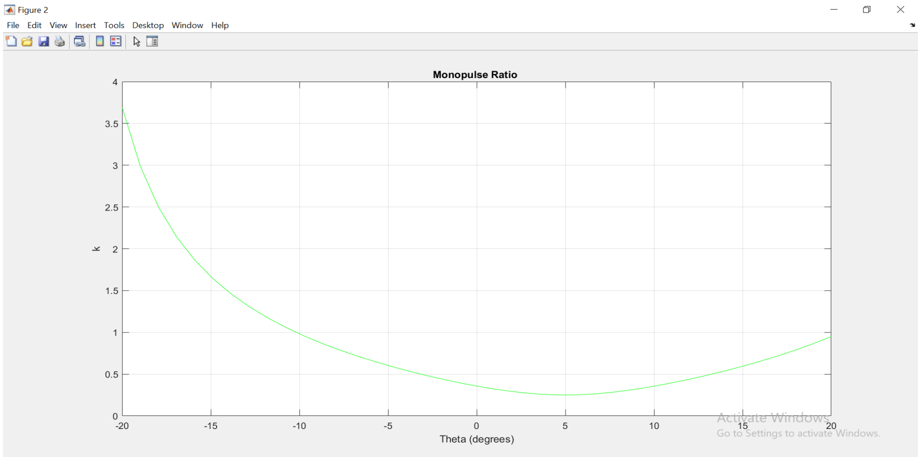



(a) Steering angle 0 Ratio

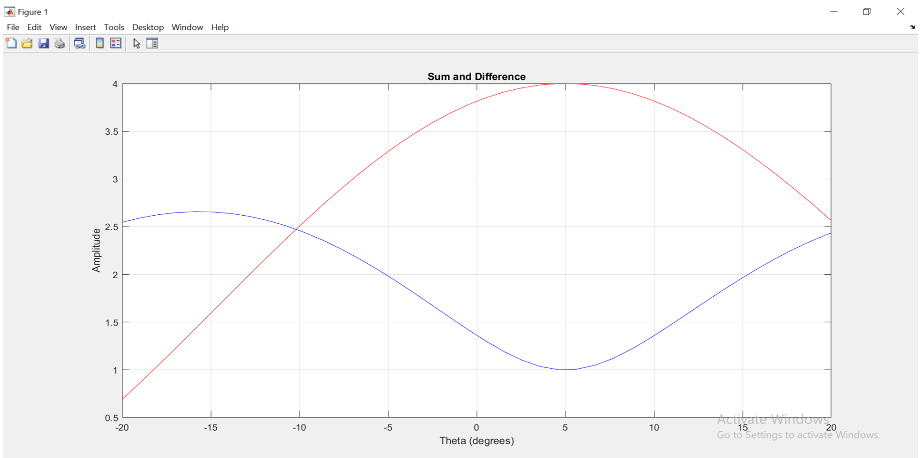



(b) Steering angle 5 in dB

Figure 5.2: MATLAB o/p




(a) Steering angle 5 ratio




(b) Steering angle 5

Figure 5.3: MATLAB o/p

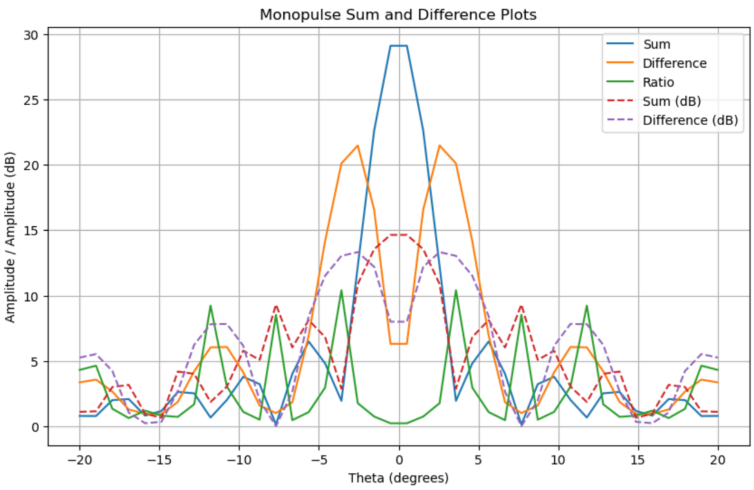



Figure 5.4: Monopulse Sum and Difference plot at Steering angle 0 (Python o/p)

# Conclusion

In conclusion, this report has provided an introductory exploration into the fundamental aspects of monopulse seeker operation, shedding light on its foundational principles. The study has centred around the essential relationship between radar technology and seekers, underscoring the crucial role seekers play in enhancing guidance and control mechanisms within radar-guided systems.

The report initiated a simplified derivation of the radar range equation, establishing a basic understanding of radar principles. Further, it delved into the specific inputs contributed by seekers to guidance and control systems, unravelling their essential roles in improving overall functionality and accuracy.

A significant focus of the study was on monopulse technology, a straightforward yet sophisticated radar technique employed by seekers. The report introduced basic concepts related to simulating sum and difference patterns using both Python and MATLAB, facilitating a rudimentary comprehension of these fundamental aspects.

Additionally, the concept of the monopulse ratio, serving as a rudimentary metric for assessing the performance of monopulse seekers, was introduced. The basic simulation of the monopulse ratio using Python and MATLAB served as a practical demonstration, providing fundamental insights into the operational characteristics of monopulse seekers.

# Bibliography


[1] Vora, P., Tiwari, P., Bhattacharjee, R., Bhattacharyya, A., and Jyothi, M., "Radio frequency seeker modelling and seeker filter design," *Defence Science Journal*, Vol. 55, No. 3, 2005, p. 337.

[2] Das, R., "Advances in active radar seeker technology," *Defence Science Journal*, Vol. 55, No. 3, 2005, p. 329.

[3] Markin, E., *Principles of Modern Radar Missile Seekers*, Artech House, 2022.

[4] Rim, J.-W., and Koh, I.-S., "Survivability simulation of airborne platform with expendable active decoy countering RF missile," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 56, No. 1, 2019, pp. 196–207.

[5] Richards, M. A., Scheer, J., Holm, W. A., and Melvin, W. L., "Principles of modern radar," 2010.

[6] Tapas, A. M., Rao, V. S., and Prabhakar, N., "Adaptive estimation of line-of-sight rate measurement from a radio frequency seeker," *Defence Science Journal*, Vol. 55, No. 3, 2005, p. 307.

[7] Pastrick, H., Seltzer, S., and Warren, M., "Guidance laws for short-range tactical missiles," *Journal of Guidance and Control*, Vol. 4, No. 2, 1981, pp. 98–108.

[8] MIT News, "Explained: the Doppler effect," `https://news.mit.edu/2010/explained-doppler-0803`, 2010. [Accessed on December 21, 2023].

[9] Singh, A., Shah, V., and Sarnaik, A., "Moving Target Indication Radar," *International Journal of*, 2013.

[10] Lei Mao, "Doppler Effect Phase Shift," `https://leimao.github.io/blog/Doppler-Effect-Phase-Shift/`, Year. [Accessed on December 21, 2023].

[11] "Velocity Determination," `https://courses.comet.ucar.edu/pluginfile.php/3788/mod_imscp/content/1/velocity_determination.html`, Year. [Accessed on December 21, 2023].

[12] Raj, K. D. S., and Ganesh, I. S. S., "Estimation of line-of-sight rate in a homing Missile Guidance loop using optimal filters," *2015 International Conference on Communications and Signal Processing (ICCSP)*, IEEE, 2015, pp. 0398–0402.

[13] Quancheng, L., Yonghua, F., Shizheng, W., and Jie, Y., "Influence of the seeker blind range guidance policy on guidance precision," *2019 IEEE 9th Annual International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER)*, IEEE, 2019, pp. 1120–1124.

[14] Sherman, S. M., and Barton, D. K., *Monopulse principles and techniques*, Artech House, 2011.

[15] Dong, X., Li, H., Tan, J., Hu, J., and Jiang, Y., "A PSO-CVX Algorithm of Sum and Difference Beam Patterns for Time-Modulated Antenna Array," *International Journal of Antennas and Propagation*, Vol. 2021, 2021, pp. 1–9.

[16] Haupt, R., "Simultaneous nulling in the sum and difference patterns of a monopulse antenna," *IEEE transactions on antennas and propagation*, Vol. 32, No. 5, 1984, pp. 486–493.