RADAR PERFORMANCE ANALYSIS APPROACHES FOR THE EVALUATION OF RADAR SYSTEMS

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RADAR PERFORMANCE ANALYSIS APPROACHES FOR THE EVALUATION OF RADAR SYSTEMS

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ABSTRACT

RADAR PERFORMANCE ANALYSIS APPROACHES FOR THE EVALUATION OF RADAR SYSTEMS

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In this thesis study, some approaches are proposed for radar performance analysis. It turns out that average power and antenna aperture area (equivalently, antenna gain) are the most important parameters for the assessment or comparison of radar systems. Search and track load concepts and the utilization trade between search and tracking tasks in multifunction radars are also presented. For long distance search / tracking tasks, performance of a two-radar system is analyzed, and it is shown that cross range accuracy and maximum detectable range of a single radar operated in X band can be improved by fusing it with a radar operated in V/UHF bands. Finally, two existing radars, namely AN/TPY-2 and 96L6E, are compared in terms of their performance in ballistic missile defense systems.

Keywords: Radar Performance Analysis, Search Radars, Tracking Radars, Radar Equation

ÖZ

RADAR SİSTEMLERİNİ DEĞERLENDİRMEK AMAÇLI RADAR BAŞARIM ANALİZİ YAKLAŞIMLARI

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Bu tez çalışmasında radar başarım analizi için bazı yaklaşımlar sunulmuştur. Radar sistemlerinin değerlendirilmesi ya da karşılaştırılması sırasında ortalama güç ve anten açıklığı alanının (eşdeğer olarak anten kazancı) en önemli parametreler olduğu görülmüştür. Çok fonksiyonlu radarlarda arama ve takip yükü kavramları ve arama ve takip görevlerinin kullanım oranı sunulmuştur. Uzun menzilli arama ve takip görevleri açısından iki-radarlı bir sistemin başarımı analiz edilmiş, X bandında çalışan bir radar V/UHF bandında çalışan başka bir radarla birleştirildiğinde açısal doğruluk ve en uzun menzil açısından iyileşme sağlandığı gösterilmiştir. Son olarak, şu anda var olan AN/TPY-2 ve 96L6E radarlarının balistik füze savunma sistemlerindeki başarımları karşılaştırılmıştır.

Anahtar Kelimeler: Radar Başarım Analizi, Arama Radarları, Takip Radarları, Radar Denklemi

To My Family

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I have the most generous mom and dad in the world in terms of their love, and I have one of the most encouraging sister in the world. I would like to thank all of my beloved family members who support me through this way. It was impossible to concentrate on the studies without their supports and feeling their breath on my back.

I would like to express my gratitude to my colleagues who brought me coffee and biscuits while I was working for this thesis, made me open my mind in the inextricable situations and were lost in football conversation with me for hours.

I count myself as a fortunate person since all of my friends have encouraged me to finish the study. I would like to express my gratitude to them for their support. However, the deepest gratitude is deserved by one of them who stayed with me in the library even she did not have anything to do there, made me wake up when I could not, and motivated me when I did not feel doing anything. Half of this thesis is yours my coffee mate, thank you!

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

During the past seventy years, Radar (**RA**dio **D**etection **A**nd **R**anging) has become a worldwide used detection system that uses electromagnetic waves to determine the range, direction, or velocity of objects. Among the fundamental functions of radar, the most important ones are detection and tracking of targets, geolocation, estimating the sizes and velocities of targets. The basic principle behind how a radar operates is quite straightforward. A transmitter with an antenna transmits electromagnetic waves through air and a receiver detects the echoes of the wave that has been sent by the transmitter. If a detectable echo signal exists, then the radar system claims that a target is present in the region being searched.

The performance of a radar system is generally evaluated by its maximum range, which is defined as the range at which a target with a specific radar cross section can be detected with a certain probability of detection. It is clear that maximization of this parameter is the goal of a radar designer, but, during the design stages, there are many constraints that must be taken into consideration. In fact, the radar designer can increase the maximum range by increasing the average power and the antenna gain (or, equivalently aperture area). Hence, power-aperture area product becomes a very important criterion to be able to meet the maximum range requirement. On the other hand, power-aperture area product cannot be increased arbitrarily, since it is limited by some design constraints (such as the physical size of the antenna, operation frequency, losses, etc.), hardware limitations and the technological abilities at the time when the system is constructed. The present study is directly related to the assessment of radar systems in terms of the two critical radar specifications, namely the average power of the radar, and the antenna gain. These specifications are depending on other parameters such as operating frequency, pulse width, pulse repetition frequency, etc. The aim of the thesis is to introduce methods to evaluate the performance of radar systems, compare the performances of two or more radars, and assess the performance of systems containing more than one radar.

The outline of the thesis is as follows:

In chapter 1 (Introduction), a typical radar system is explained, emphasizing how radars are classified in terms of functioning and frequency of operation and specific types of radars used in applications are mentioned. After a brief history of radar, fundamentals and operation concepts of radars are explained. The basic components of radars are given and described.

In Chapter 2, the important parameters of radars performing both search and track tasks are discussed. Since the radar must be able to carry out these tasks in a given period of time, this requirement brings a trade-off between search and track tasks. One of the problems arising during design phase of a radar is to handle this trade-off effectively. Each task must be evaluated in terms of importance and/or urgency in order to select the time percentages of the radar for search and track issues. To handle this trade-off, calculations that have to be done are introduced.

In chapter 3, power-aperture area products for both search and tracking radars are evaluated for different maximum ranges and for some parameters (frequency, search refresh time interval, etc.) that are to be used. The relationship between radar antenna size and half power azimuth and elevation beamwidths are investigated by also taking the radar frequency into account. Some existing radar systems are embedded in the obtained graphs for evaluation. Furthermore, for the maximum ranges evaluated in this chapter, search-track utilization trade is explained.

Another important problem encountered by radars is the difficulties associated with the detection and tracking of dim targets (i.e. targets that are far away from the radar and/or with small Radar Cross Section (RCS)). Detection task becomes difficult due to the reduced SNR value. Moreover, RCS reduction techniques are feasible as a counter measure for radars operating at higher frequencies, therefore, not only for dim targets but also for targets with reduced RCS, the radar designer has to take an action to meet the detection and tracking requirements.

In chapter 4, a solution is suggested for dim target detection and tracking. Since the RCS reduction techniques at lower frequencies are not as effective as the ones at microwave frequencies and the targets have larger RCS at lower frequencies, the microwave radar tasked for both search and track is used together with a low frequency radar. The microwave radar carries out the search task in a volume specified by the low frequency radar, after the low frequency radar detects the target(s). This implies that the overall system must handle a smaller search volume, which means an increase in the maximum range. Moreover, with the help of the high antenna gain of the microwave radar, the target(s) can be tracked with improved position accuracy.

Ballistic missiles follow a high altitude trajectory with long horizontal range compared to other ordinary missiles. In terms of their physical size, they are usually larger in size. Ballistic missiles are serious threats for many countries in the world, and the improvement in ballistic missile technology enforces the development of new ballistic missile defense systems. Radars play a very important role in ballistic missile detection and tracking in such systems. There are two worldwide known radars used in ballistic missile defense systems. The first is AN/TPY-2 (developed in USA) and the other one is 96L6E (developed in Russia).

In chapter 5, ballistic missiles, their types and flight stages are explained. Range performances of 96L6E and AN/TPY-2 are analyzed. Then, their usage in defense systems for different types of ballistic missiles is examined for different phases of ballistic missile flight. Furthermore, location accuracies of the targets detected by the two radars are compared.

1.1 Description of Radar

Radar stands for RAdio Detection And Ranging. As can be understood from the name of Radar, it detects some targets and finds their ranges by using electromagnetic waves in Radio Frequency range which covers a wide range of wavelength from 10^4 km to 1 cm. Operating frequency generally differs with respect to hardware requirements or different areas of application. Hardware requirements include the antenna size and power generation. Radars with bigger components are usually immobile. If the radar is required to be portable, frequency should be selected to satisfy mobility [1]. In terms of application areas, radars can be classified as military and civil. Some military and civil radar application examples are given in the following figure.

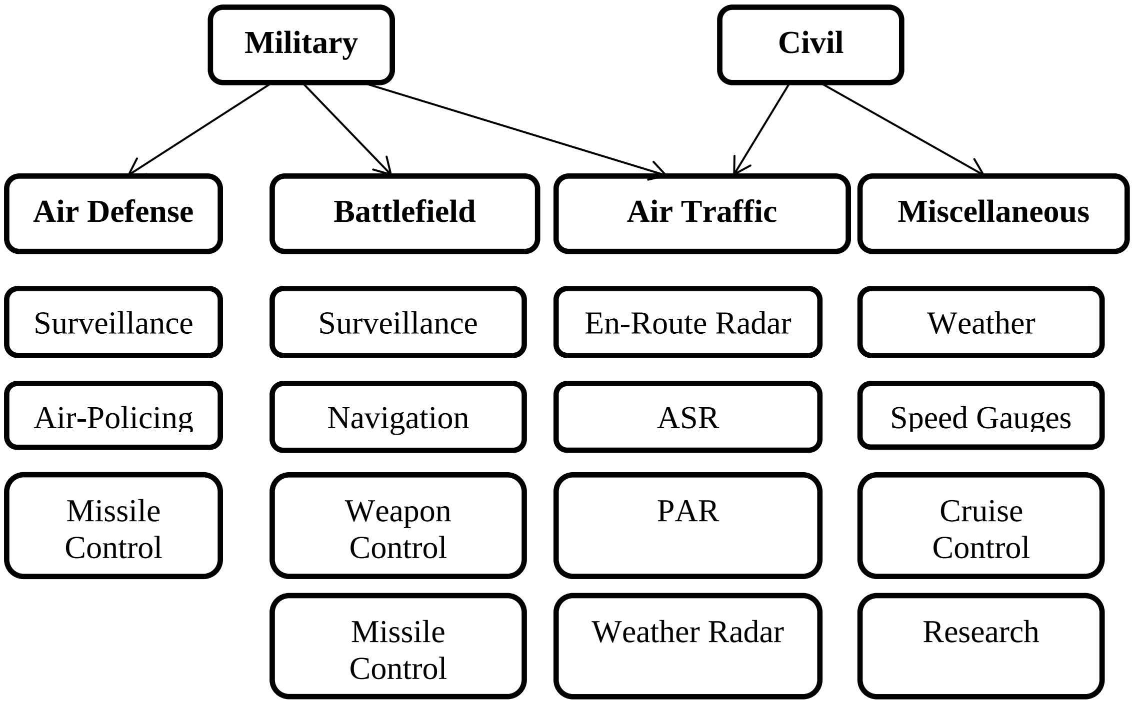

Fig. 1 Civil and Military Radar Applications

Besides the operational classification, radars are classified in terms of the location of their operating frequencies in the electromagnetic spectrum. Frequency spectrum which is generally used by radar systems is shown in **Fig. 2** [2]:

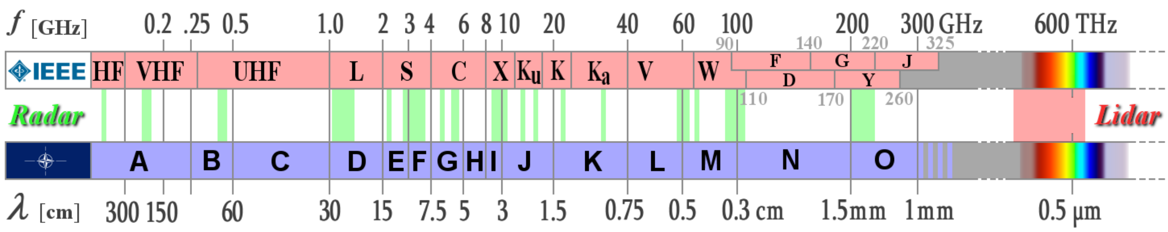

Fig. 2 Frequency Spectrum Used by Radars [2]

Radars can also be named by the name of the frequency band:

HF-VHF Radars: This radar frequency band covers 3 MHz – 300 MHz. At these frequencies, the attenuation of electromagnetic waves is smaller, the maximum power of the radar is larger and RCS of the target takes values larger than those at higher frequencies. However, the accuracy of target azimuth and elevation is poor owing to wider beamwidths and physically larger antennas must be built since the wavelength is larger. Hence, these frequencies are not feasible for mobile radars. This kind of radar is widely used in early warning systems [3].

UHF Radars: This radar frequency band covers 300 MHz – 3 GHz. The concept of operation of the radar operating in these frequencies is generally detection and tracking over a long range [3].

L-Band Radars: This radar frequency band covers 1 GHz – 2 GHz. These radars are used for long-range operation over 400 km [3].

S-Band Radars: This radar frequency band covers 2 GHz – 4 GHz. Since attenuation increases at these radar frequencies, the average transmitter power must also increase. To achieve higher average powers, signal power has to be amplified with physically larger sized amplifiers [3].

C-Band Radars: This radar frequency band covers 4 GHz – 8 GHz. This frequency band is generally used in mobile military applications because of the relatively small-sized antennas [3].

X and Ku Band Radars: X frequency band covers 8 GHz-12 GHz; Ku frequency band covers 12 GHz-18 GHz. The characteristics of the frequency bands are similar, hence they are categorized together. As the bearing angle accuracy is very high even for antennas with reduced size, these radars are generally used in missile guidance applications [3].

K and Ka-Band Radars: K frequency band covers 18 GHz-27 GHz; Ka frequency band is between 27 GHz-40 GHz. At these frequencies, atmospheric absorption is comparably high. Therefore, these radars are generally used in short range Automatic Take-off and Landing Systems of aircrafts, and in guided missiles [3].

1.2 Brief History of Radar [4]

Radar cannot be thought of being invented by a single individual. The development is a process starting from usage of electromagnetic waves. Therefore, there are some important steps taking part in improving the radar idea and usage. First; in 1865, the Scottish physicist James Clerk Maxwell showed that electric and magnetic fields are waves that travel through space at the constant speed of light. Then, the idea of using reflections of electromagnetic waves to detect metallic objects is attributed to Nicola Tesla. However, this idea was not supported, hence it could not be implemented. In 1904, German engineer Christian Hülsmeyer worked with this idea and invented "Telemobiloscope" to control Sea Traffic in bad weather conditions. This was the first milestone of the radar concept. Afterwards, it was needed to detect targets at longer ranges, however, the power of radar was not enough. Following the invention of Magnetron (1921) and Klystron (1936), it was possible to supply the radar with higher powers.

During and after World War II, nations tried to develop their own radars. Germany, USA, Great Britain and France were the countries playing very important roles during improvement of radar. In Germany, Dr. Rudolph Kühnold; in Great Britain, Sir Robert Watson-Watt; in USA Albert H. Taylor and Leo C. Young; in France, Pierre David conducted experiments and tried to develop radar.

1.3 Fundamentals of Radar

The basic working principle of radar is very simple to understand. However, operational requirements and practical problems may sometimes make the implementation of radar harder. If an electromagnetic wave transmitted from a known place hits a reflective object like metals, it scatters to the air. If the wave scattered from the reflective object turns back to the radar, the distance between the radar and the reflective object can be calculated from the time delay between the signals transmitted and received [5]. The following figure shows the operation concept of a radar:

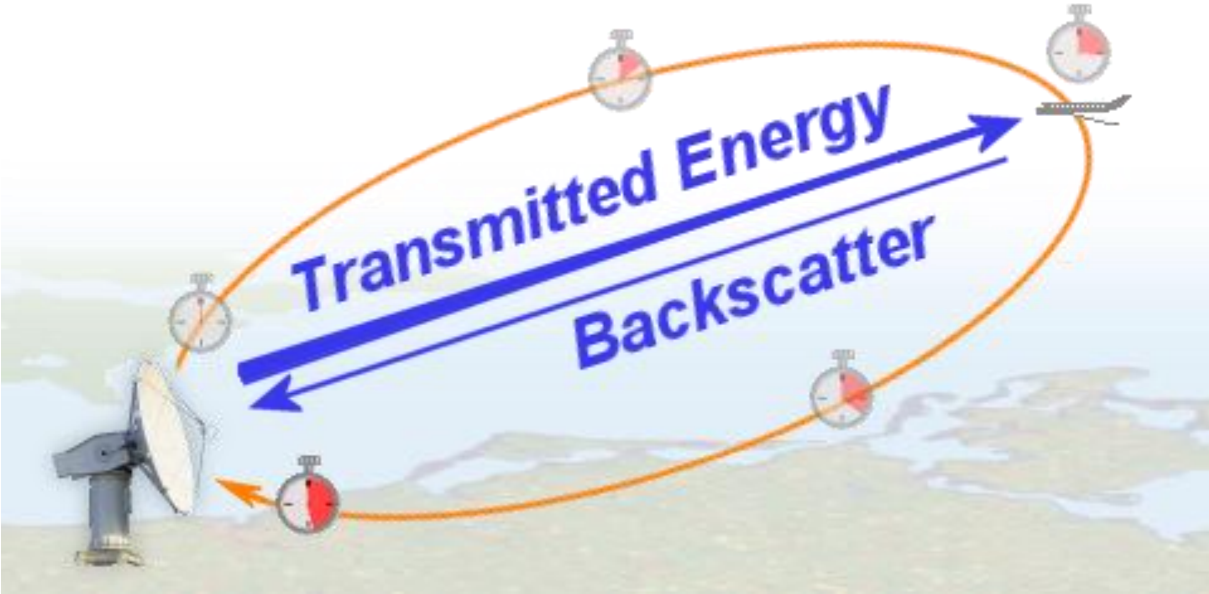

Fig. 3 Radar Operating Concept [5]

Radar involves some subsystems in order to be able to accomplish these operations. The fundamental block diagram of monostatic radar, which means using the same antenna for both transmitting and receiving, is the following:

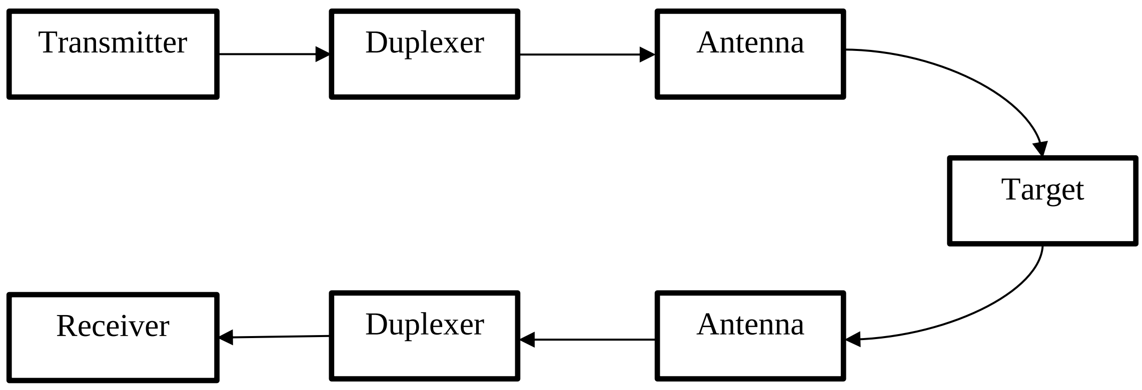

Fig. 4 Radar Block Diagram

Transmitter: Transmitter is where the signal energy is generated. Electromagnetic wave may be in the pulsed or continuous wave shape. If it is pulsed, transmitter arranges the time between pulses. To reach the required power, power amplifiers or the power oscillators are involved in the transmitter.

Duplexer: During transmission, a high power signal is sent to the antenna, and the receiver may be damaged. A duplexer is a device for isolating the transmitting and receiving processes from each other. It is essential for healthy radar operation.

Antenna: Antenna is a transducer which converts the electrical signal into radio waves or vice versa. Generally, radar antennas are directive antennas, therefore they have gains in the look direction while launching and and receiving the radio wave.

Receiver: The signal received from the antenna is processed in the receiver. The process in receiver includes to amplify the signal, to convert the echo signal to the intermediate frequency, to filter noise component of the signal and all the detection and parameter estimations. After receiver, the processed signal is sent to a displayer, which shows what the operator wants to see.

CHAPTER 2

RADAR PERFORMANCE ANALYSIS

Radar performance is mostly considered in terms of the radar`s maximum range for which detection and/or tracking is possible for a target having a specified radar cross section with a required probability of detection. Radar manufacturers focus on increasing the maximum range of the radar without violating the design requirements. It is well-known that the average power of the transmitted wave and the effective antenna aperture are the parameters that determine the performance of a radar. Even though it seems that radar range performance may be improved by increasing average transmitted power and effective antenna aperture, there are some constraints which must be satisfied during the design phase of the radar system. Some of these constraints are related to the current technology level in hardware design, physical size of the antenna, antenna size dependence on frequency, etc.

The radar designer starts by assessing the requirements / parameters / constraints of the radar system, such as the operation concept of the radar, typical target types and radar cross section values, required probability of detection for a given target, and typical target distance to the radar. These preliminary requirements affect the performance of the radar, since the radar designer / manufacturer has to determine the parameters such as average power, frequency, and antenna size to meet the requirements. These parameters are the parameters in terms of which the performance of a radar is directly specified.

The first reason why performance analysis is so important is that it enables the designer to carry out a feasibility study of the radar for a given requirement list. The radar manufacturer evaluates the requirements and decides whether it is feasible to build a radar system fulfilling the requirements. Secondly, in some cases it may be necessary to compare two or more radars operating for similar tasks and / or similar concepts. This case is important if a manufacturer is provided with two or more preliminary designs, and a comparison can be obtained via performance analysis. This case is also important for customers trying to select from a set of radar systems produced by different companies, and such a performance analysis will help the radar customer choose the right radar system meeting his / her requirements. Another case where performance analysis is critical, is the feasibility study related to the integration of two or more radars to carry out a specific task. If a single radar cannot satisfy the requirements, then the radar manufacturer can take the advantage of using two or more radars coherently.

2.1 Formulations

The most important performance criterion in radar system evaluation / comparison is the maximum range of the radar. For pulsed radars, the pulse repetition interval must be chosen to satisy the unambiguous range restriction. Ambiguity occurs if the echo signal created by a pulse is received after the next pulse is transmitted. In this case the radar processor cannot determine the range unambiguously. In **Fig. 5**, A shows the unambiguous case, while B shows a case where there is range ambiguity:

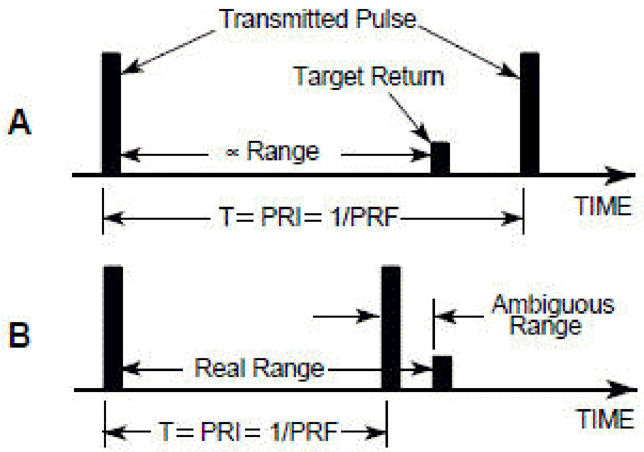

Fig. 5 Range Ambiguity

The radar equation is the fundamental relation to be used in performance analysis. The equation is the mathematical description of the two-way signal transmission from the radar to the target, and from the target back to the radar. The radar equation can be obtained by considering the power density at a given range created by a hypothetical isotropic transmitter antenna as given below:

$$P_R = \frac{P_t}{4\pi R^2}$$

P_t = Average pulse power radiated from an isotropic antenna (W)

P_R = Power density at range R (W/m^2)

Since P_t directly affects the maximum range of target that can be detected by the radar, radar manufacturers always look for methods to increase pulse power. For this purpose, many amplifier and oscillator systems (such as the magnetron, amplitron, klystron and TWT (Traveling Wave Tube)) have been invented and research is ongoing for improving such systems. The transmitter to be used in the radar is chosen in terms of its operating frequency, average/peak power ratio, which is equal to duty ratio[1], and bandwidth, [1]. Typical military radar peak pulse powers are around MW levels and average pulse powers are around a few hundreds of kW. It may seem that pulses with short duration are advantageous considering the better range resolution. However, decreasing pulse width increases signal bandwidth and results in higher receiver noise which reduces receiver sensitivity. Moreover, short pulses will shorten the life of amplifier tubes used in transmitter design because of the rapid temperature changes in transmitter.

In modern radars, active electronically scanned phased array antennas are often used to increase the gain of the antenna whilst lowering the side lobe levels. Each element used in the active electronically scanned array antenna is an individual antenna having

[1] Duty Cycle (Duty Ratio) is the time proportion that a device or system is on the operation.

a certain average power. By bringing them together, the average power of the transmitter can be increased considerably. Moreover, small sized elements, easy and fast beam steering (so that dwell time can be changed easily), increased stability of the beam through the look direction are the other reasons why most radars use active electronically scanned array antennas [6].

If the electromagnetic wave is radiated from a directive antenna, power is not radiated uniformly and it has a gain represented with G_T in the target direction. The power density at the range R becomes

$$P_R = \frac{P_t G_T}{4\pi R^2}$$

The wave incident on the target is scattered towards the radar, and the reflected power can be modeled as if the incident wave with the power density given above is intercepted by a target of area σ, and the power received by the radar antenna is then;

$$P_r = \frac{P_t G_T}{4\pi R^2} \frac{\sigma A_e}{4\pi R^2}$$

P_r = Received Power at Radar Antenna (W)

σ = Radar Cross Section (RCS) of a target (m^2)

A_e = Effective Aperture Area (m^2)

Radar Cross Section is a measure of an object`s reflectivity of radar signals and depends on the shape, aspect angle, material properties, etc. The concept is analogous to the antenna aperture area in receiving antennas in terms of the similarity of the interception of an incoming electromagnetic wave.

In terms of the minimum signal level that can be detected by the receiver, maximum range can be reached using the equations derived above.

$$R_{max} = [\frac{P_t G_T \sigma A_e}{(4\pi)^2 S_{min}}]^{1/4}$$

S_{min} = Minimum detectable signal power density

In addition to the expression above, instead of receiver power, signal-to-noise ratio (SNR) can be used. The reason behind implementation of the SNR to the calculations is the relationship between the SNR and the probability of detection.

Thermal noise in a radar receiver is expressed as below:

$$N_0 = kT_sB$$

k = Boltzmann`s constant

T_s = System noise temperature (K)

B = Receiver Bandwidth (Hz)

where $B\tau = 1$. τ is the pulse width.

Single pulse SNR for a required probability of detection is denoted as $(SNR)_1$. Moreover, N_p pulse SNR for the same probability of detection is denoted as $(SNR)_{Np}$ [7]. With a radar utilizing non-coherent integration, $(SNR)_{Np}$ is calculated as below.

$$E(N_p)(SNR)_{N_p} = \frac{(SNR)_1}{N_p}$$

$E(N_p)$ = Integration efficiency (=1 with perfect integrator)

$(SNR)_1$=SNR of a single pulse to satisfy probability of detection requirement

After losses are added into the equation and a perfect integrator is used in the system, range equation becomes

$$R_{max}{}^4 = \frac{P_{pk}\tau N_p G_T \sigma A_e}{(4\pi)^2 kT_s (SNR)_1 L}$$

P_{pk} = Peak Pulse Power (W)

N_p = Number of pulses integrated

L = Radar system losses

There are two important parameters that the radar manufacturer (or, performance evaluator) has to take into account: the probability of detection and probability of false alarm.

The probability of detection is equal to the probability that received signal from the target (echo) plus noise is over a threshold level which is specified to maximize the probability of detection for a constant probability of false alarm. It is denoted as P_d. In many applications, the radar should detect targets with probability greater than 0.8 [8]. Detection hypothesis is given below:

$$s(t) + n(t) > V_T$$

s(t) = Echo signal returned from the target

n(t) = Noise in the receiver

V_T = Threshold level

The probability of detection and signal to noise ratio relation can be understood from the detection hypothesis above. As the signal to noise ratio increases, the probability of detection increases. **Fig. 6** [9] shows Probability of Detection versus SNR for a sine-shaped signal for different false alarm probabilities. In this figure, Swerling 0 model is assumed.

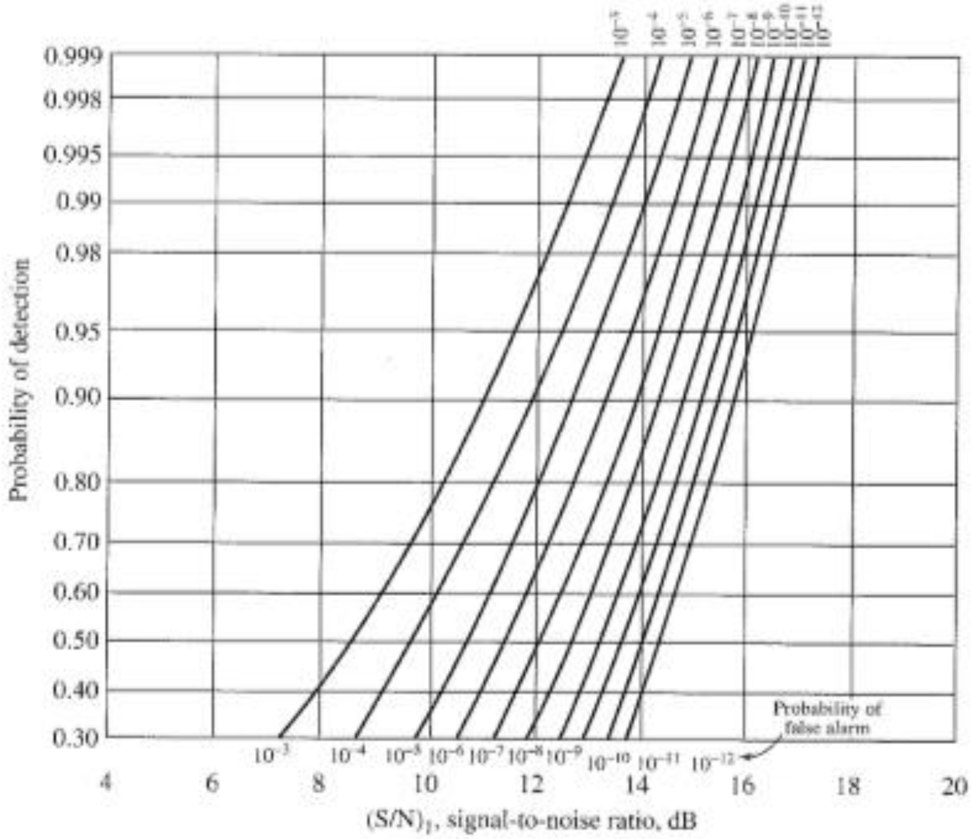

Fig. 6 SNR vs. Pd [9]

During probability of detection calculations, zero mean white Gaussian noise with constant variance is assumed. Probability density function of a Gaussian noise is known. Therefore, unless the RCS of the target changes pulse to pulse or scan to scan, it is easy to compute the probability of detection. However, RCS of a target may change unless it is an idealized object without any RCS fluctuation (such as a perfect sphere). There are 4 Swerling models describing probability density functions of RCS of the targets fluctuating pulse to pulse or scan to scan [10].

Swerling I Model: This model assumes that the magnitude of the signal received by the receiver changes from scan to scan. Therefore, during the entire pulse train in a scan period, RCS is a random variable with Rayleigh pdf.

$$P(\sigma) = \frac{1}{\sigma_{average}} \exp(\frac{-\sigma}{\sigma_{average}})$$

Swerling II Model: This model assumes that the magnitude of the signal received by the receiver changes from pulse to pulse since the change in the RCS value of the target is faster than the model I. However, the probability density function of the target RCS is the same as model I.

Swerling III Model: This model is similar to the model I. However, in Swerling I Model, the target is assumed to vary according to a Chi-Square probability density function with two degrees of freedom. In model III, it has four degrees of freedom, so probability density function becomes:

$$P(\sigma) = \frac{4\sigma}{{\sigma_{average}}^2} \exp(\frac{-2\sigma}{\sigma_{average}})$$

Swerling IV Model: This model is similar to the model II. However, as in model III, the target is assumed to vary according to a Chi-Square probability density function with four degrees of freedom.

In all the calculations that are given below, Swerling 0 model is assumed and the SNR value returned for the required probability of detection is taken from **Fig. 6.**

Trying to bring the radar range equation into a form that is convenient to be used for Average Power-Aperture product of the radar, the equations given below are used:

$$P_{pk}\tau N_p = \; P_{av}T_{dwell}$$

P_{pk} = Peak pulse power over dwell time (W)

T_{dwell} = Average dwell time for a beam (sec)

Assuming same dwell time for all beams, T_{dwell} can be obtained as

$$T_{dwell} = \frac{T_{FS}\delta_S}{N_{beams}}$$

T_{FS} = Total search time period (sec)

δ_s = Time fraction reserved for the search mission

N_{beams} = Number of beams used in search volume

Using independent and uniform beams assumption [11], N_{beams} can be found by

$$N_{beams} = \frac{\Omega}{\Delta\theta\Delta\emptyset}$$

Ω = Total volume searched (rad^2)

$\Delta\theta$, $\Delta\emptyset$ = Azimuth, Elevation beamwidth of one beam (rad)

Assuming a rectangular aperture antenna, azimuth and elevation beamwidths are calculated as below [11]:

$$\Delta\theta = \frac{\beta_\theta\lambda}{D_x} \qquad \Delta\emptyset = \frac{\beta_\emptyset\lambda}{D_y}$$

λ = Wavelength of the electromagnetic wave radiated (m)

β_θ,$\beta_\emptyset$ = Azimuth, Elevation beam broadening factor (rad)

D_x, D_y = Antenna width, height (m)

Antenna gain can be expressed as [11]

$$G_T = \frac{4\pi\rho D_x D_y}{\lambda^2} \qquad A = D_x D_y$$

ρ = Antenna efficiency

Assuming that the same radar operates for both search and track missions in a time period and taking the radar mission allocation into account, the Average Power-Aperture area product which is also called search load can be obtained as given below;

$$P_{av}A_e\delta_s \geq \frac{R^4\Omega(SNR)_1(4\pi)kT_sL}{T_{FS}\beta_\theta\beta_\emptyset\sigma}$$

The equations given above are derived and combined considering a search radar. In order to be able to use the equations for tracking radars, a modification is needed.

$$T_{dwell} = \frac{T_{FT}\delta_T}{N_T}$$

Here, T_{dwell} is not denoted for the dwell time for a beam but for a target.

N_T = Number of targets tracked

T_{FT} = Total track time period (sec)

δ_T = Time fraction divided for the track mission

Similar to the derivation of search load inequality; by combining the equations above, Average Power-Aperture Area-Transmitter Antenna Gain product inequality, which is also called track load inequality can be obtained as given below

$$P_{av}A_eG_T\delta_T \geq \frac{R^4N_T(SNR)_1(4\pi)^2kT_sL}{T_{FT}\sigma}$$

These equations enable one to either calculate maximum radar range using specified parameters or evaluate how parameters should be chosen to obtain the required radar range. Of course, maximum radar range should be between the unambiguous range and minimum range which occurs in monostatic radar systems[2]. The unambiguous range is related to the pulse repetition interval as shown in **Fig. 5**. The unambiguous range is calculated as given below:

$$R_{unam} = \frac{c * PRI}{2}$$

R_{unam} = Unambiguous range

c = Speed of light ($3*10^8$ m/s in air)

[2] Radar systems using only one antenna for both transmitting and receiving

PRI = Pulse repetition interval

Minimum measuring range limit in monostatic radar systems is due to the usage of a device called “duplexer” for switching transmission and reception times. Therefore, the radar cannot receive any electromagnetic wave during transmission which is named as minimum measuring range (also called “blind range”). This situation is shown in **Fig. 7** [12].

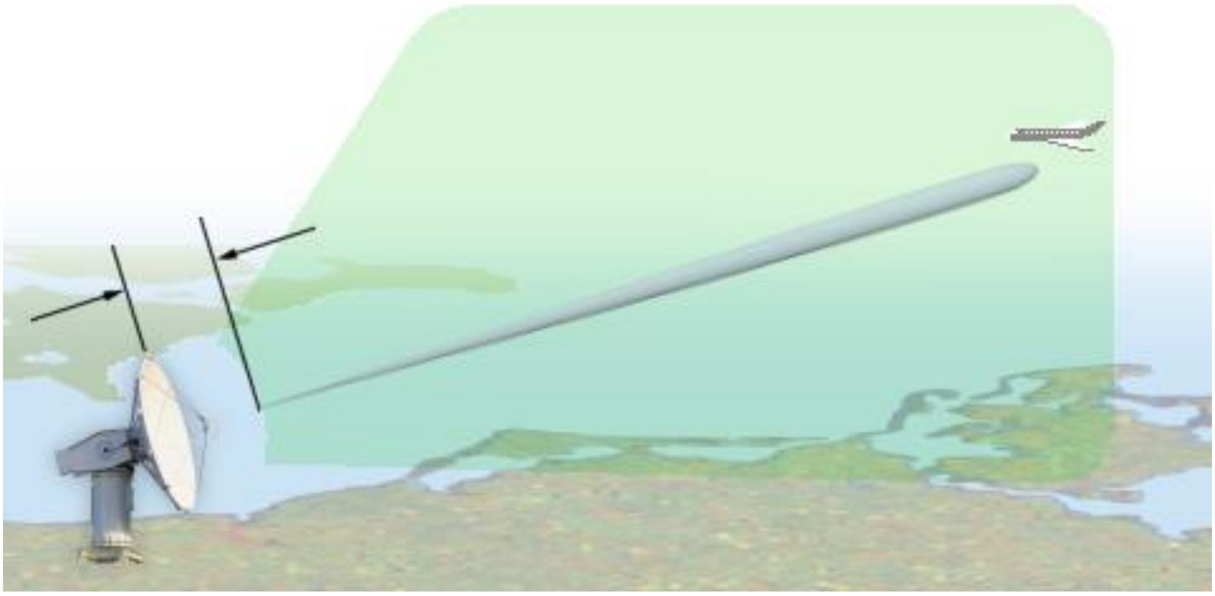

Fig. 7 Blind Range **[12]**

The blind range is calculated as follows:

$$R_{blnd} = \frac{c * \tau}{2}$$

R_{blnd} = Minimum measuring range (blind range)

While calculating the range of the radar, multipath effect[3](**Fig. 8** [13]) and limitation coming from the curvature of the surface of the Earth[4](**Fig. 9** [14]) should be taken into account. For lower frequencies the multipath effect is more significant since the waves with longer wavelengths tend to reflect more as compared to shorter wavelength waves.

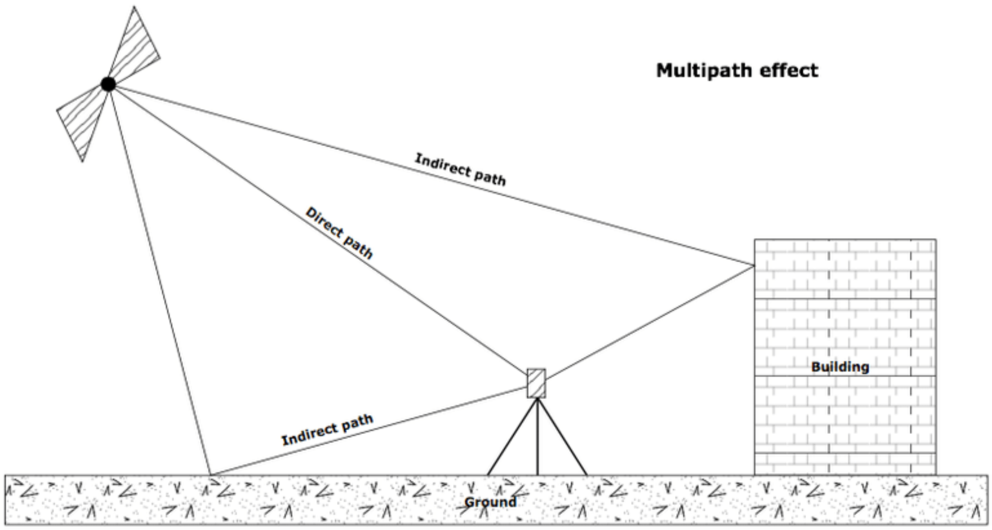

Fig. 8 Multipath Effect **[13]**

[3] Multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths.

[4] The circumstance that the target is not seen since it is below the radar line which is tangent to the Earth`s surface.

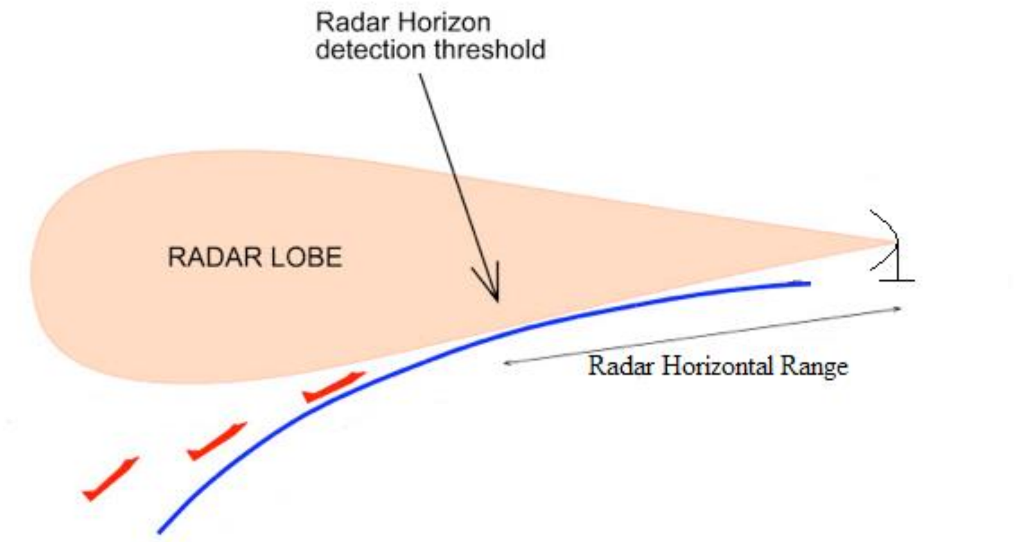

Fig. 9 Horizontal Range **[14]**

Radar range is limited by multipath effect as follows [15]:

$$R_m = \frac{4\pi h_R h_t}{\lambda}$$

R_m = Radar range limited by multipath effect (m)

h_R = Radar`s height with respect to the ground (m)

h_t = Target`s height with respect to the ground (m)

Radar range limited by the surface curvature of the Earth is calculated as follows [16]:

$$R_h = \sqrt{\frac{8}{3} R_{Earth}}(\sqrt{h_R} + \sqrt{h_t})$$

R_{Earth} = Earth`s radius (m)

Taking Earth`s radius as 6371 Km, the equation becomes:

$$R_h = 4120(\sqrt{h_R} + \sqrt{h_t})$$

R_h = Radar range limited by Earth`s horizon (m)

The other important parameters that must be taken into account during evaluation of radars are the range accuracy and angular track accuracy. Accuracy and resolution are parameters that should be carefully defined avoiding any confusion. Accuracy is how closely the radar determines the position of the target in range and azimuth / elevation angles. As can be understood from the description, position accuracy is a parameter which can be modeled as a probabilistic result and depends on the actual position of the target. As the target approaches to the radar, accuracy gets better. On the other hand, resolution is basically related to the ability of the radar to resolve two closely positioned targets in range or in azimuth / elevation angles.

Angular track accuracy is related to the SNR of the echo signal returning back from the target and is expressed as follows [17]:

$$\sigma_{\theta,\emptyset} = \frac{\Delta\theta,\emptyset}{\sqrt{2SNR}}$$

$\sigma_{\theta,\emptyset}$ = Azimuth and Elevation Angular Track Accuracy

$\Delta\theta,\emptyset$ = Azimuth and Elevation Beamwidth

The range accuracy of a radar is calculated as follows:

$$\sigma_R = \frac{c * \tau}{2\sqrt{2SNR}}$$

σ_R = Range accuracy (m)

In both angular and range accuracy expressions SNR plays an important role. It is intuitively clear that higher SNR values improve the accuracy values. It is also clear that angular track accuracy depends on the antenna beamwidths, which implies that a larger antenna aperture area improves angular accuracy. In range accuracy the pulse width seems to be an important parameter, but in modern radar systems pulse compression techniques are used providing wide bandwidth with long duration pulses. For example, when coding methods are used chip duration, which is much smaller than the pulse duration, becomes the important parameter in range resolution and accuracy.

In this thesis, range resolution and accuracy is not included in the performance analysis parameters, since the related performance is closely related by the pulse compression technique which is used in the radar system. Pulse duration is only used in assessing the duty ratio, which is important in the calculation of average power.

The equations which are named as search and track load inequalities are important not only in the preliminary design phase of radar systems, but also for the comparison of radar systems with similar missions. The following important conclusions can be drawn from these inequalities:

1. In both equations, the left-hand side of the inequalities are upper bounds of expressions containing parameters related to the specifications (or, requirements) of the radar system. For search radars, these parameters can be listed as radar range, search volume, SNR, system noise temperature, losses, search duration, azimuth / elevation beam broadening factors, and RCS of the target. In tracking radars, the parameters related to the requirements are radar range, number of targets being tracked, SNR, system noise temperature, losses, track duration, and RCS of the target. The fourth-power of the radar range is due to the attenuation of the electromagnetic wave during the two-way propagation and appears as the most critical term in these inequalities.
2. The left hand sides of the inequalities contain the product of the average power, and aperture area in search radars; and average power, aperture area, and antenna gain in tracking radars respectively. These terms are named as search and tracking loads, and they clearly show that the radar designer (or, the person carrying out a comparison of radar systems) must choose (or compare) these parameters so that the radar system with given specs is feasible. It is clear that increasing the average power, and constructing an antenna with increased aperture area (equivalently, increased gain) is crucial in building successful search and tracking radar systems, since these parameter appear in expressions which form the upper bounds of the expressions containing the radar specs.

However, there are restrictions for the achievable average power, and designing and constructing an antenna with large aperture area (high gain).

3. The peak power of the radar system is determined by the power supplied by the transmitter amplifier tubes, or the TR-modules used in radars with active array antennas. The average power is also related to the duty ratio and a high duty ratio is required to increase the average power. It is clear that there are technological limits in peak power, and there are technological as well as design constraints (i.e. choice of pulse duration and pulse repetition interval) in average power. Therefore, one must start with a feasible average power value in the preliminary design phase. In comparing radar systems with similar missions, one must favor the one with highest average power.
4. The antenna effective aperture area is determined by the physical area and the wavelength. In fact, the aperture area is determined in terms of the electrical dimensions (i.e. dimensions in terms of wavelength) of the antenna. This implies that the antennas turn out to be physically larger for lower operating frequencies. Many military radar systems operate at microwave frequencies, where the wavelength is in the order of a few centimeters up to a few tens of centimeters. So, the radar designer is faced with the constraint related to the antenna size. This is critical especially in transportable radar systems. In array antennas, the array elements must be located over the aperture and it is a real challenge to construct such an array antenna with TR modules connected to each array element in the background. As a result, there is an upper limit for the aperture size due to physical and technological constraints.
5. In multifunctional radars search and tracking tasks must be carried out during the operation of the radar. The radar must allocate time intervals for these two tasks during operation. Therefore, track and search loads must be assessed to perform this time allocation properly. This can be achieved in terms of the two-dimensional search-track load graphs. This approach is discussed in the next chapter.

CHAPTER 3

SEARCH-TRACK RADAR PERFORMANCES

In a search radar system, the range of the radar is the most critical performance parameter. Radar power and antenna aperture area are the parameters that must be set to reach the required range of the radar. Moreover, minimum SNR, search refresh time period and search volume are determined by the requirements.

Assuming a radar using a 100 % efficient antenna with a circular aperture, **Fig. 10** shows Antenna size (in terms of radius) versus average power required for some range options. The azimuth and elevation beamwidths versus radius graphs are also given for the same range options.

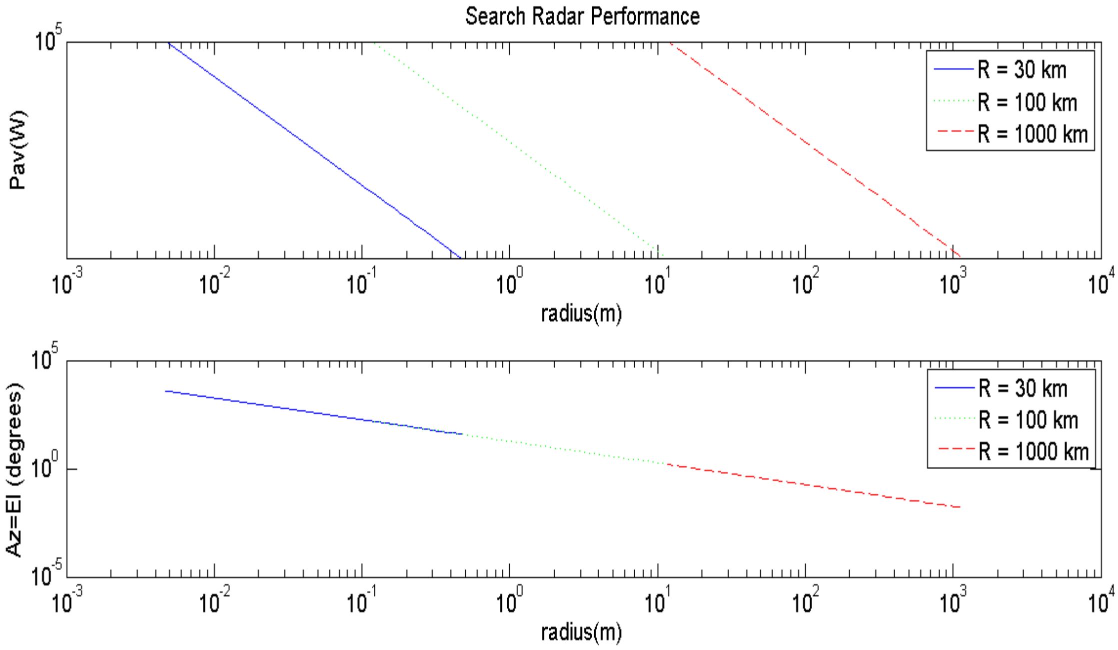

Fig. 10 Search Radar Performance

The other parameters are chosen as below:

f = 1 GHz,

Radar Cross Section = 0.7 m^2

Radar Search Refresh Time Period = 5 sec,

Doubling Radar Search Refresh Time Period, and taking frequency as 10 GHz, **Fig. 11** shows the new results:

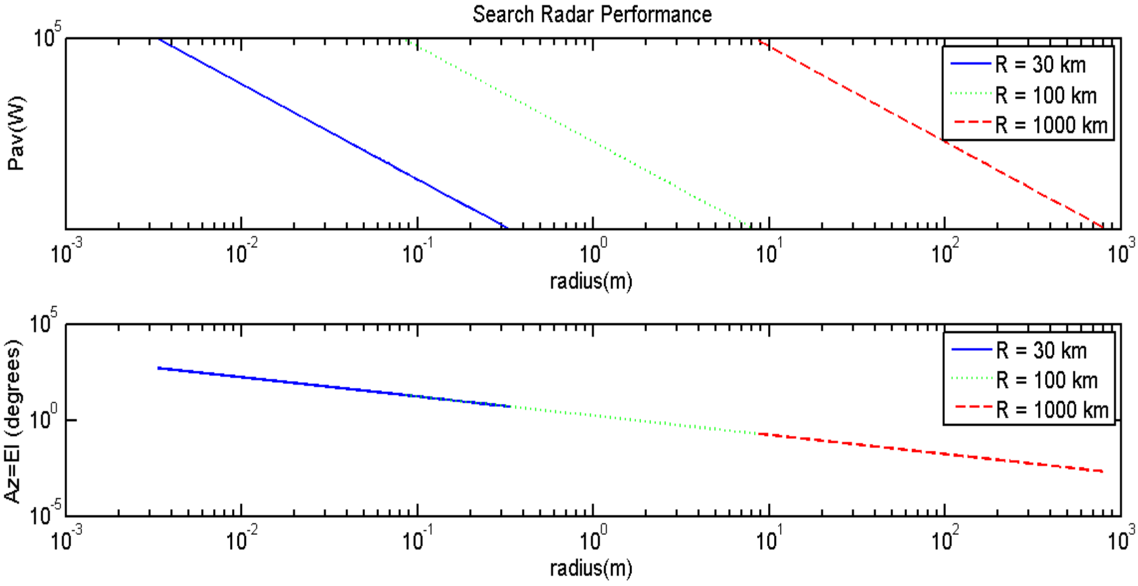

Fig. 11 Search Radar Performance

Fig. 12 illustrates the same results when operating frequency is chosen as 500 MHz and search refresh time period is 2.5 sec.

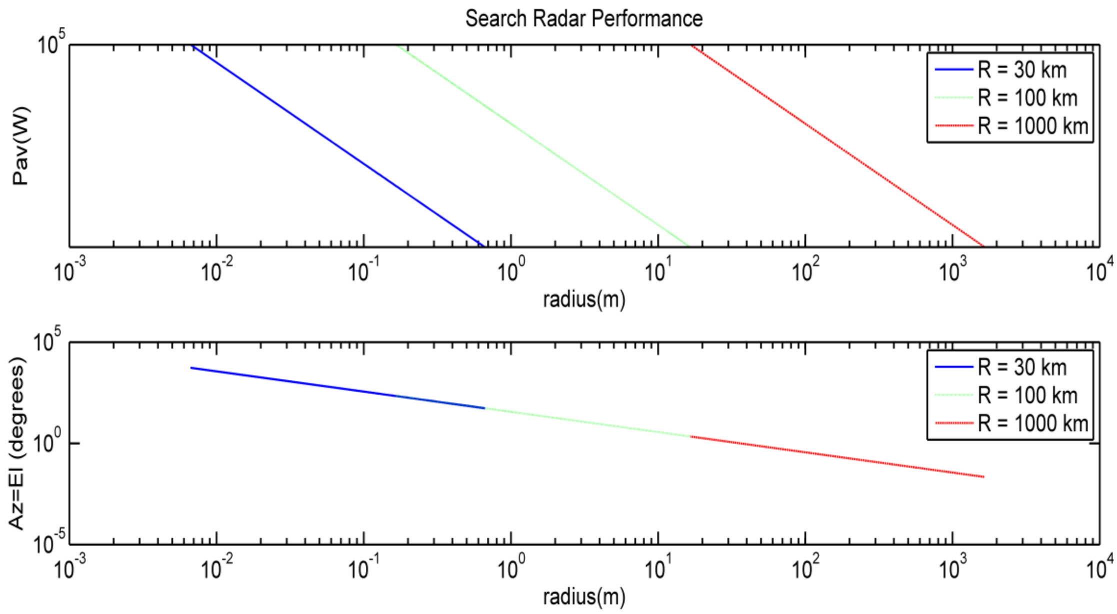

Fig. 12 Search Radar Performance

In these calculations atmospheric attenuation is taken into account. Standard atmospheric attenuation says that total attenuation at 1 GHz and at 10 GHz are 0.03 dB/km and 0.05 dB/km, respectively, considering only water vapor and dry weather attenuations [18]. However, these losses occur in the volume occupied by the stratosphere which extends 50 km above sea level. For a radar looking upwards with an elevation angle of 30°, atmospheric losses mostly occur within 100 km. **Fig. 13** [18] shows the atmospheric attenuation graph changing with frequency:

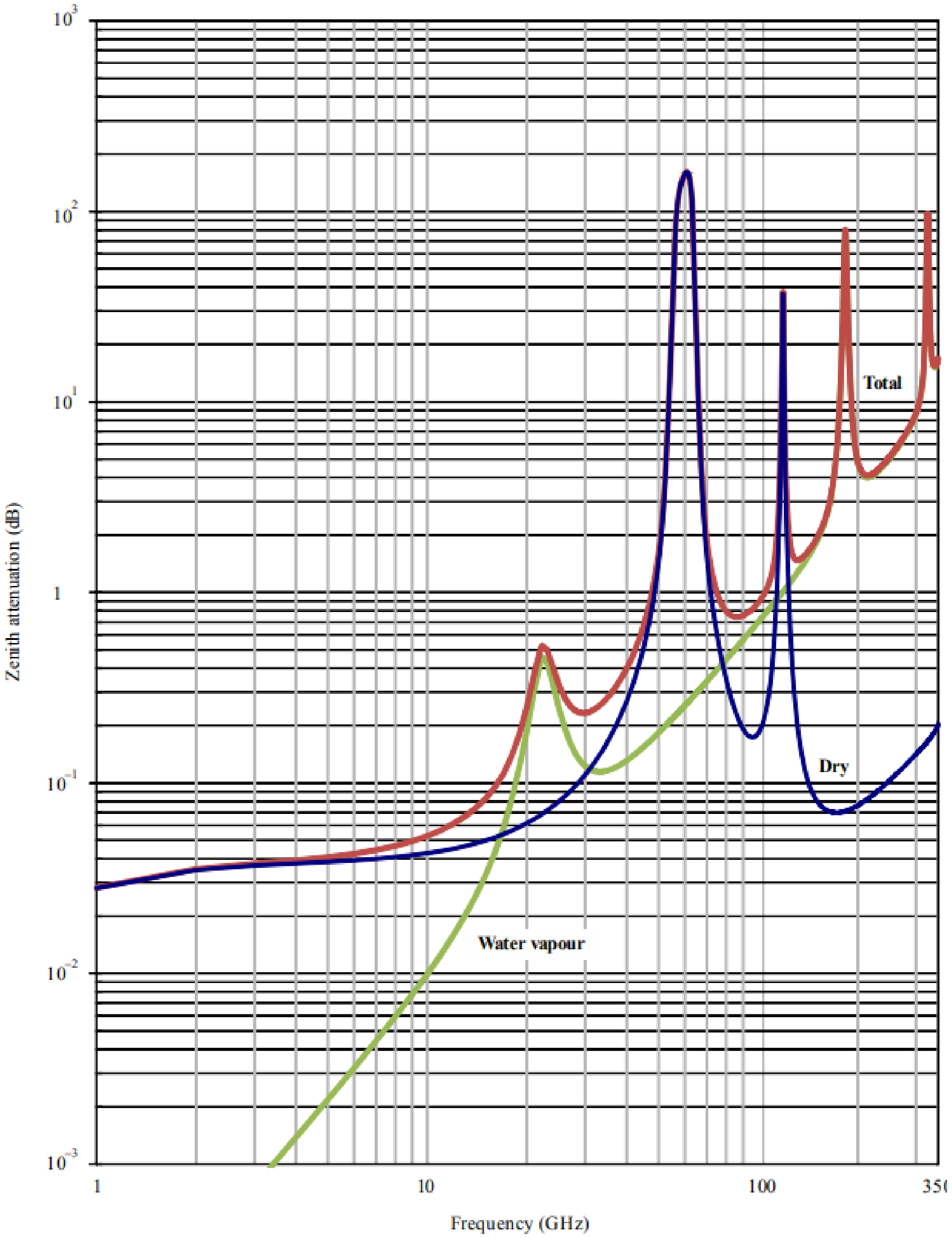

Fig. 13 Attenuation By Atmospheric Gases [18]

In **Fig. 10**, **Fig. 11** and **Fig. 12**, the RCS = 0.7 m^2 is a typical value for a stealth aircraft or a missile. RCS may change with the frequency of the signal, angle of incidence of the signal to the target and the size and / or shape of the target. Therefore, the average value of the RCS is more meaningful and RCS values of a standing man taken from [19] and [20] are about 0.7 m^2 at 10 GHz and 0.3 m^2 at 1 GHz. Table 1 shows average RCS values of some objects in X band.

Table 1 RCS Values

Target	**RCS (m^2)**
Bird (eagle, hawk etc.)	0.05
Cruise Missiles	0.5
Man	0.7
Small Fighter Aircrafts	2
Large Fighter Aircrafts	4
Medium Sized Airliners	40

The most important challenge for a radar designer is the physical size of the antenna if the radar is mobile. Since the antenna size depends on the wavelength, the choice of the operating frequency is critical. For example, in order to design a Search Radar having a range of 1000 km, it is more efficient to choose the frequency in X-band (say 10 GHz) for a transportable radar. Moreover, using high frequency signals in a radar provides narrower beamwidths for antennas having a fixed physical size. However, in search radars moderate antenna beamwidths are sufficient, since angular resolution is not the most critical criterion. While designing such a radar, it should not be forgotten that unambiguous range must be above the maximum range of the radar. To achieve 1000 km, 100 km and 30 km radar range, pulse repetition intervals must be greater than 6.66 ms, 0.66 ms and 0.2 ms, respectively. These PRI levels ideally satisfy unambiguous range, however practically there should be a margin above ideal PRI level or below maximum unambiguous range.

The average power-antenna radius graphs are useful to assess the performance of several radars on the same graph. Some popular worldwide used search radars are embedded in such a graph in **Fig. 14**.

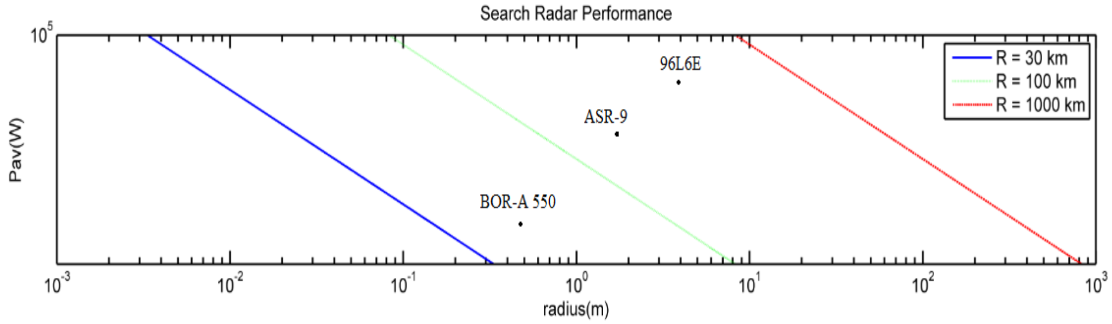

Fig. 14 Performance Evaluation of Commercial Radar Systems

BOR-A 550 is a commercial ground, sea and low level air surveillance radar operated at I band. It is developed by a company based in France. Its instrumented surveillance range is up to 80 km.

ASR-9 is an airport surveillance radar operated at S band. It is developed by a company based in the USA. Its instrumented surveillance range is up to 110 km.

96L6E which is also called “Cheese Board” is an early warning and acquisition radar operated in C band. It is developed in Russia. Its instrumented surveillance range is up to 300 km.

In a tracking radar system, the performance of the radar is determined by the number of targets being tracked, and again by its range. In these radars, since the critical point is not to lose the target which is being tracked, total track refresh time interval must be much smaller than the search refresh time interval used in search radar systems. If a radar is tracking multiple targets, the total track refresh interval is related to the number of targets being tracked and the method used in tracking. For instance, dwell time on a target in radars using the method of monopulse tracking[5] is equal to pulse repetition interval [21]. Therefore, total track refresh time interval is equal to pulse repetition interval multiplied by the total number of tracks.

In these radars, the beamwidth of the antenna should be narrower than that of search radars. Hence, it is advantageous to radiate high-frequency electromagnetic waves. Mostly, frequencies in X band are used in these radars. **Fig. 15** shows the requirements of a Track Radar tracking a single target and using 10 GHz frequency.

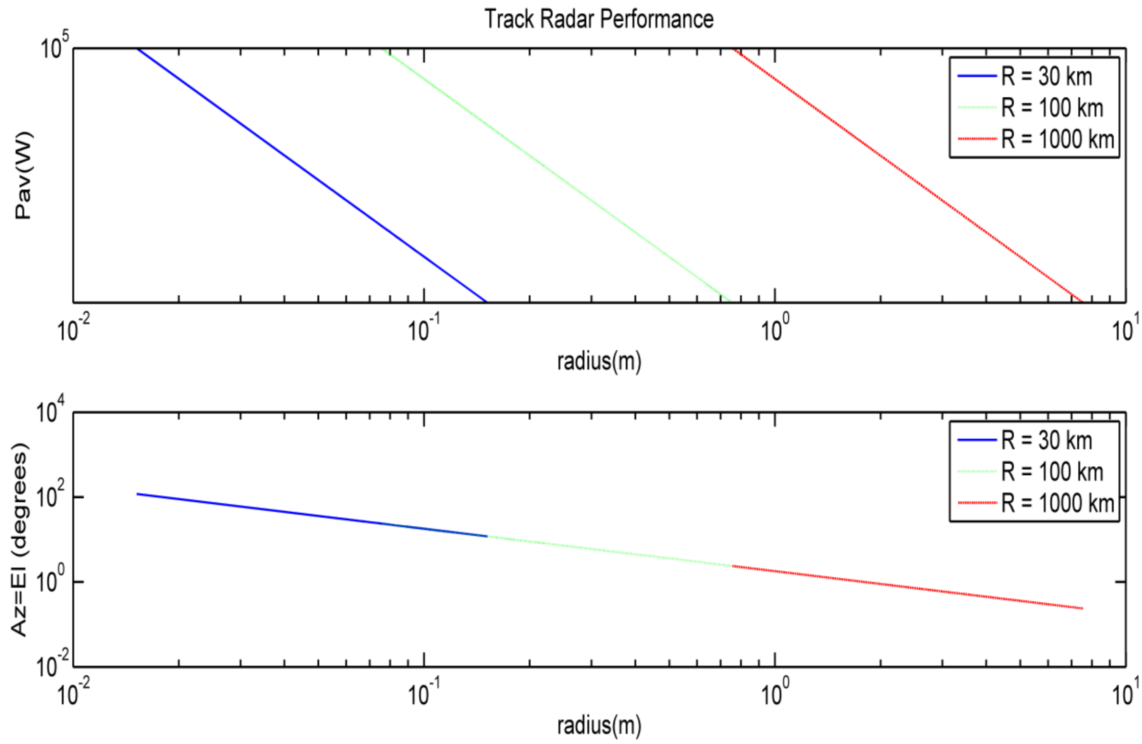

Fig. 15 Track Radar Performance

In this radar, a PRI of 10 ms is assumed and 20 pulses are integrated during the dwell time. The total number of target tracks is assumed to be 1. This PRI value provides the radar with an unambiguous range of 1500 km which is 1.5 fold of 1000 km radar range.

---

[5] Radar system comparing received the signal from a single radar pulse and hence finding the direction of beam incoming.

In all calculations, a circular aperture antenna having an effective antenna area of $A_e = \rho\pi r^2$ is assumed, therefore azimuth and elevation beamwidths are equal. For antennas with different aperture geometries, azimuth and elevation beamwidths will not be the same. The beamwidth of an antenna only depends on the antenna geometry and frequency. As can be interpreted from the figures, at higher frequencies beamwidths get narrower when the antenna size is kept fixed.

For multi-function radars performing both searching and tracking, there should be a trade-off between the tasks. Considering the time allocation and operational requirements for search and tracking, preliminary radar design studies can be carried out for 30, 100 and 1000 km ranges by using the graphs shown in **Fig. 16**, **Fig. 17** and **Fig. 18**. In these graphs the horizontal and vertical axes denote search and track loads. The line segment denotes the locus of search and track loads as a function of time percent of allocation to search (or, track) loads. The horizontal axis intercept denotes the search load when the radar performs only the search task. Similarly, the vertical axis intercept denotes the track load when the radar performs only the tracking task.

In all graphs, RCS of the target is taken as 0.7, probability of detection (Pd) is taken as 0.9 for 16 pulses integrated. Total search refresh time interval is assumed to be 5 sec during search of 60*20 degrees^2.

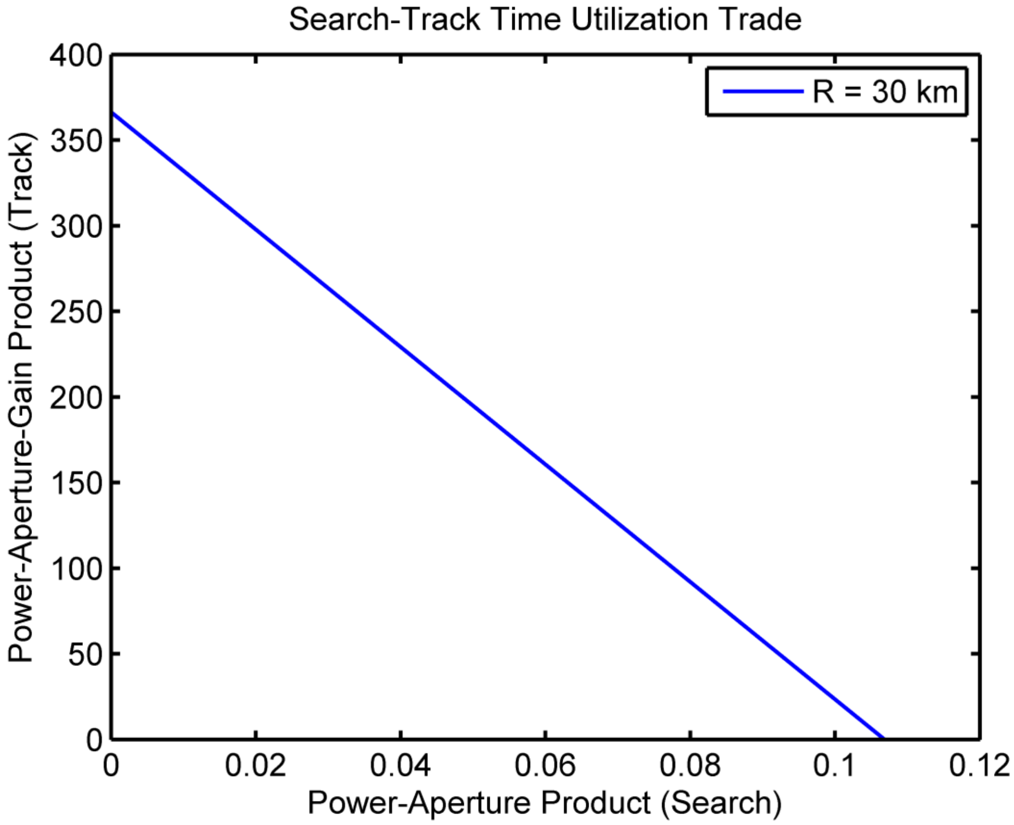

Fig. 16 Trade-Off Between Search And Track

From **Fig. 16**, it can be inferred that with a antenna aperture equal to 0.25 m^2 and with 0.5 W average power, 30 km range is achievable for a radar adopted only to searching. However, if the radar is performing search and tracking with a time fraction of 0.5 for both tasks, simultaneously; an antenna with a directive gain around 2500 must be used. Since the directive gain depends on the physical area as well as wavelength, the frequency choice will depend on such observations.

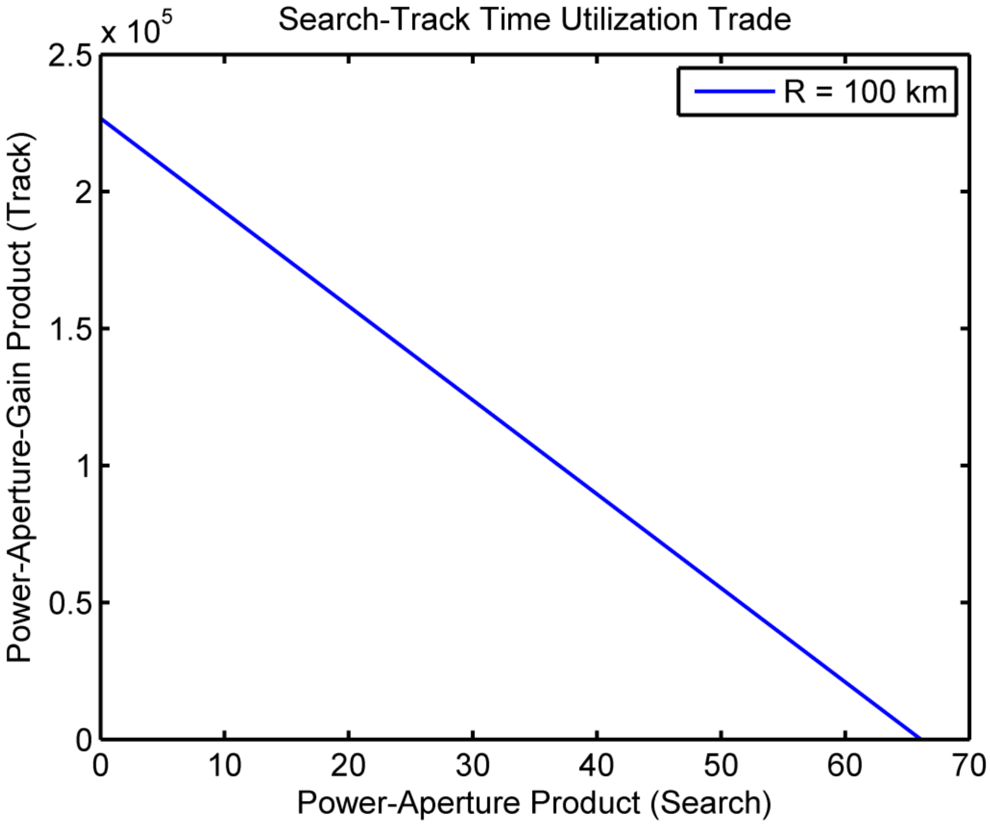

Fig. 17 Trade-Off Between Search And Track

Fig. 17 illustrates the role of average power in a radar system. For a search radar if we assume that the same antenna is used in Figs. 16 and 17, average power must be increased about 600-fold in order to increase the range about three-fold. This is an important observation, since for achieving longer ranges with an antenna with feasible size, the radar designer is forced to increase the average power.

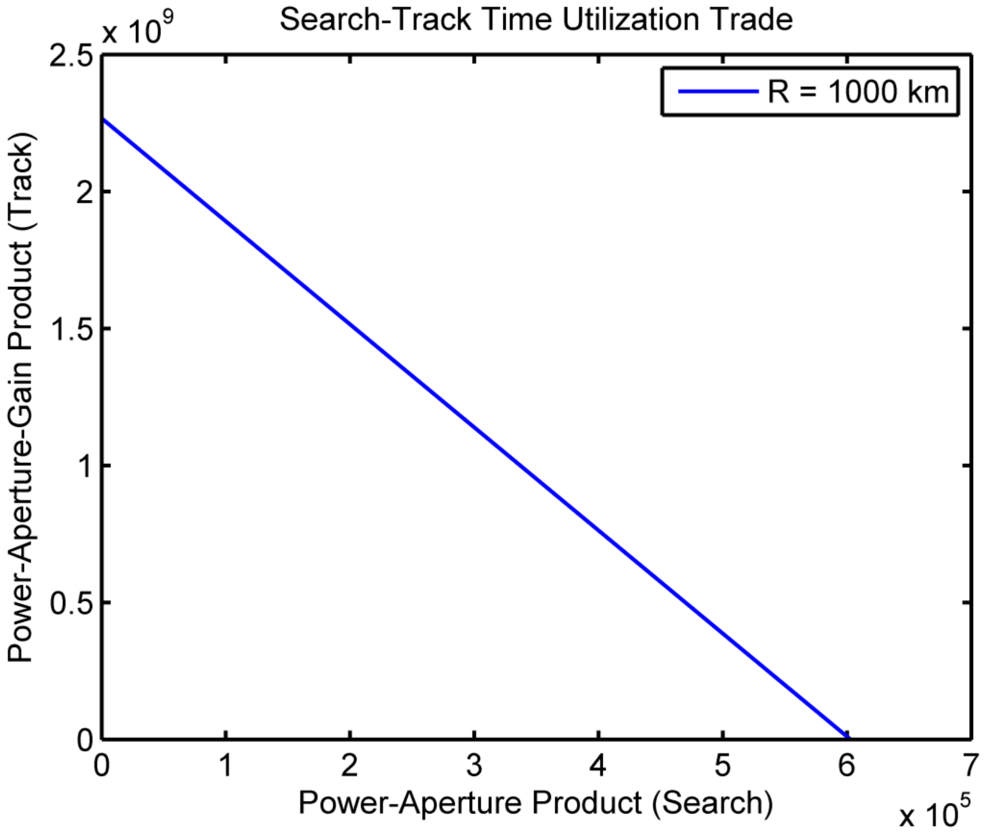

Fig. 18 Trade-Off Between Search And Track

A radar having an average power of 50 kW and 10 m^2 aperture area, fails to satisfy 1000 km range requirement. However, in these graphs RCS of the target is taken as 0.7 and total search refresh time interval is taken as 5 sec. Hence, with a radar having 50 kW average power and 10 m^2 aperture area, 1000 km range can be achieved for a target with higher RCS or by increasing the total search refresh time interval.

During the preliminary design phase of a multi-function radar, the designer may use the search load versus track load graphs to carry out some feasibility studies. Moreover, after determining the search radar parameters, the required transmit gain may be set in order to perform the required tasks properly. This, on the other hand, brings some constraints for the radar operating frequency.

CHAPTER 4

PERFORMANCE ANALYSIS OF MULTI-RADAR SYSTEMS

Modern radar systems carry out searching and tracking functions simultaneously. However, performing both tasks brings some tradeoff while selecting operating frequency. It is known that RCS values of some targets tend to increase at lower frequencies, especially in the VHF-UHF band [22]. Moreover, in the VHF-UHF band, RCS reduction techniques (i.e. Stealth techniques) via absorbing materials are not feasible since the material thickness is directly proportional to wavelength. The absorbing material applied to attenuate the high-frequency electromagnetic wave on target is not as thick as the one which is designed to attenuate the low-frequency electromagnetic wave. For instance, while an ideal absorber thickness at 10 GHz is about 0. 75 cm [23], an ideal absorber thickness at 300 MHz should be about 25 cm [23] to effectively absorb the incoming wave before it is incident on the target skin. The increased target RCS and the difficulties related to stealth techniques may seem to dictate the usage of low frequencies. However, for lower frequencies, the physical size of the antenna must be quite large to have a relatively narrow beamwidth to find the location of the target accurately. The constraint on the physical size of the antenna yields an accuracy loss in locating the target. Consequently, tracking a target by a VHF-UHF band low frequency radar is not as effective as an X-band microwave radar. On the other hand, microwave radar is faced with the fact that RCS reduction techniques are more effective at these frequencies. It is clear that the two radars operating at different frequencies are faced with different difficulties, and it is clear that designing a multi-radar system may increase the overall search-track performance with respect to the performances of the individual radars.

The two-radar system composed of a Microwave Radar (MR) and a Low Frequency Radar (LFR) is shown in **Fig. 19** [15]. Due to the physical constraints, the antenna sizes in both radars are close to each other. It is assumed that LFR has a parabolic reflector antenna with relatively wide beamwidth, whereas MR has an electronically scanned phased array antenna with narrow beamwidth. LFR is engaged to search and detect the targets in a wider search volume. LFR and MR can both be rotated by 360° and they must be synchronized if they need to rotate to satisfy the search volume requirement. When LFR detects a target in its search volume, MR takes the action and searches only the volume in which LFR detects the target. After MR detects the target in the reduced search volume dictated by the beamwidth of the LFR, it starts to track the target with a high location accuracy through its fast beam steering phased array antenna with narrow beamwidth.

In this two-radar system, MR operates at 10 GHz in X band. The operating frequency of the LFR is restricted to the VHF-UHF bands and the radar designer must choose the frequency of the LFR to optimize the range performance of the overall radar system.

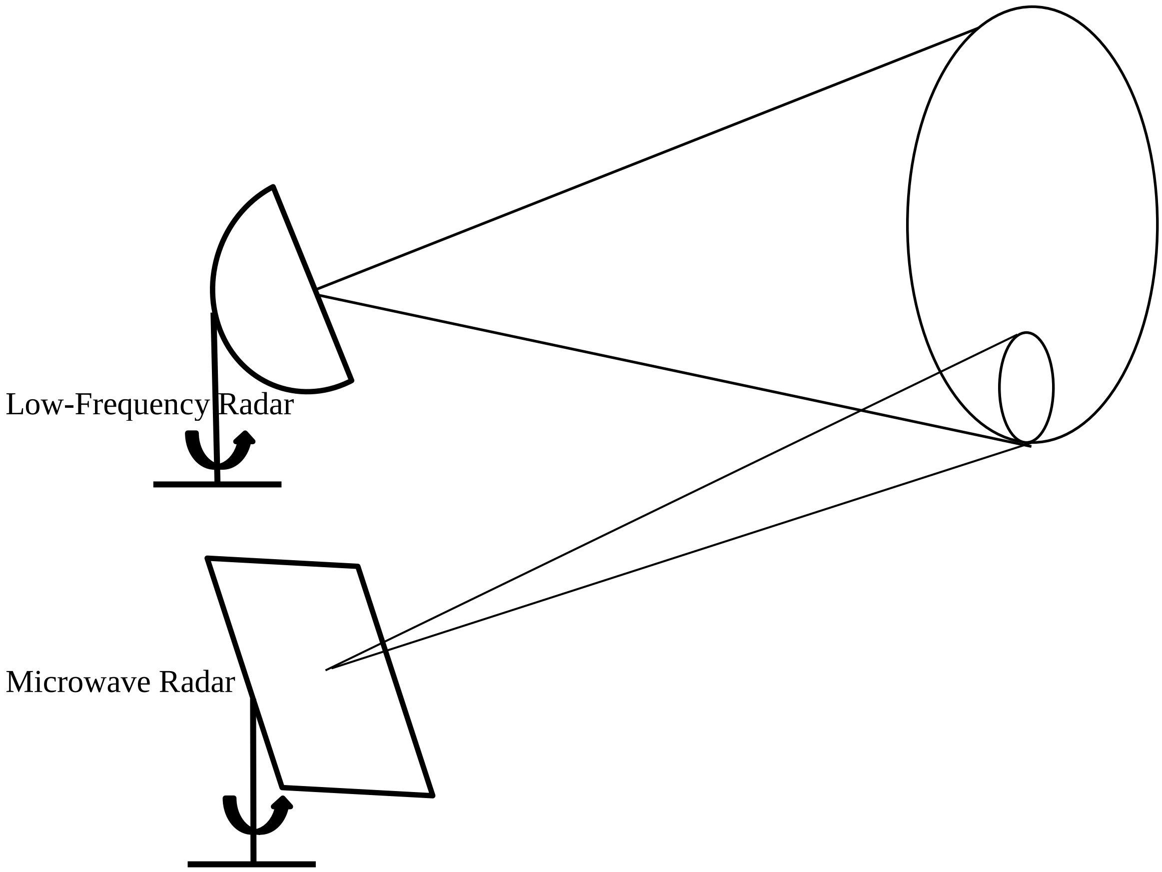

Fig. 19 MR Cued By LFR Scenario

The target is assumed to be a missile shown in **Fig. 20** with 60° head-on RCS values given in **Fig. 21** [24].

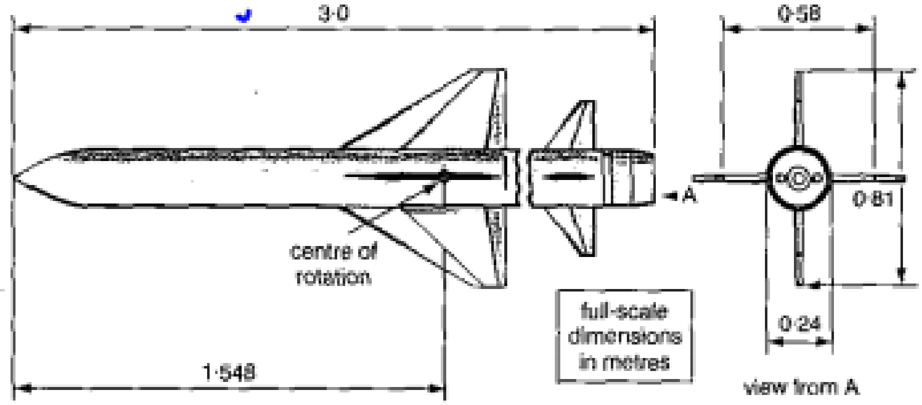

Fig. 20 Missile Example **[24]**

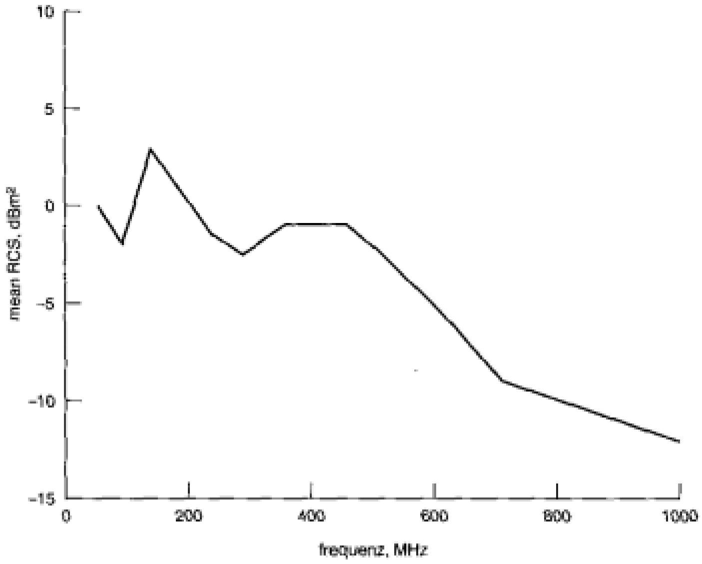

Fig. 21 60° Head-on RCS of the Missile in Fig. 20 **[24]**

Since our aim is to find the optimal value of the frequency of the LFR radar, feasible parameter values are proposed for both radars.

The average transmitter power in the LFR system is set to 77 dBm (50 kW) with a duty cycle of 0.2, which implies that the peak power is 250 kW.

In MR system, the average transmitter power is set to 77 dBm (50 kW) with the same duty cycle used in the LFR system, which leads to a peak power of 250 kW. Since the MR is engaged to both search and track, it is assumed that the same power level applies to both tasks.

The radius of the parabolic reflector antenna is chosen as 1.5 m because of operational reasons. Therefore, half-power azimuth and elevation beamwidths change as a function of frequency of the LFR. It is assumed that antenna in the LFR system is 100% efficient. **Fig. 22** shows the beamwidth for both azimuth and elevation of a 1.5 m radius parabolic antenna as a function of frequency.

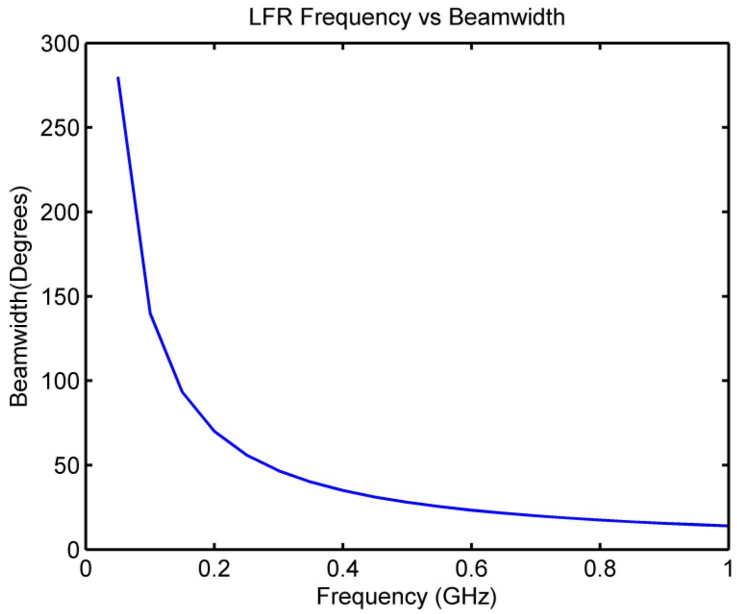

Fig. 22 Beamwidth Change with LFR Frequency

The electronically scanned phased array antenna of the MR has height and length chosen as 3 meters because of operational reasons. The electronically scanned phased array antenna efficiency is also assumed to be 100%. Therefore, it has an effective area of 9 m^2. In MR system, the wavelength of the transmitted wave is already fixed (3 cm), therefore the azimuth and elevation beamwidths are also fixed.

Search time refresh interval (T_{FS}) for LFR is chosen as 4 seconds. This is equivalent to 15 rpm in the motor speed of the antenna. Since LFR is only tasked with searching, time fraction allocated to search (δ_s) is equal to unity corresponding to 4 seconds.

In the MR system, T_{FS} should be smaller than that of LFR because of its smaller search volume coverage, faster scanning ability with the help of electronically scanned phased array antenna and its additional tracking task. T_{FS} for MR is taken as 1 second and only half of the time is devoted to searching, the other half is devoted to the tracking task.

Total atmospheric loss at VHF and UHF bands can be averaged to 0.02 dB/km and can be taken as 0.05 dB/km at X band [18]. Total two-way atmospheric attenuation in standard weather conditions is $0.02 * 2R$ dB for LFR and $0.05 * 2R$ dB for MR, respectively.

The RCS of the missile shown in Fig. 20 is about 0.1 m^2 in X band [25]. However, one of the reasons why MR cued by LFR is used is to handle RCS reduction techniques at higher frequencies. Therefore, it is assumed that the target is a missile whose RCS value is reduced by using stealth techniques, and reduced RCS value is taken as 0.01 m^2.

In Fig. 23, the red curve shows LFR search range versus its frequency. At low frequencies, the radar range is limited because of increasing multipath effect. During radar range calculations under multipath, the radar antenna is assumed to be placed at a height of 3.5 meters from the ground and the radar is searching for targets at the altitude of minimum 3 km. For targets with different altitudes, multipath calculations should be repeated.

The green curve stands for the MR range calculations if MR is used in stand-alone mode. In stand-alone mode, the MR does not get any information from LFR. MR stand-alone search range calculations are done with the same parameters used before.

The blue curve shows the range of MR cued by LFR versus frequency of the LFR. From the frequency of LFR increases, MR range increases as well. The reason behind this result is due to the decrease in the search volume of MR, since this volume is dictated by the beamwidth of the LFR as shown in **Fig. 19**.

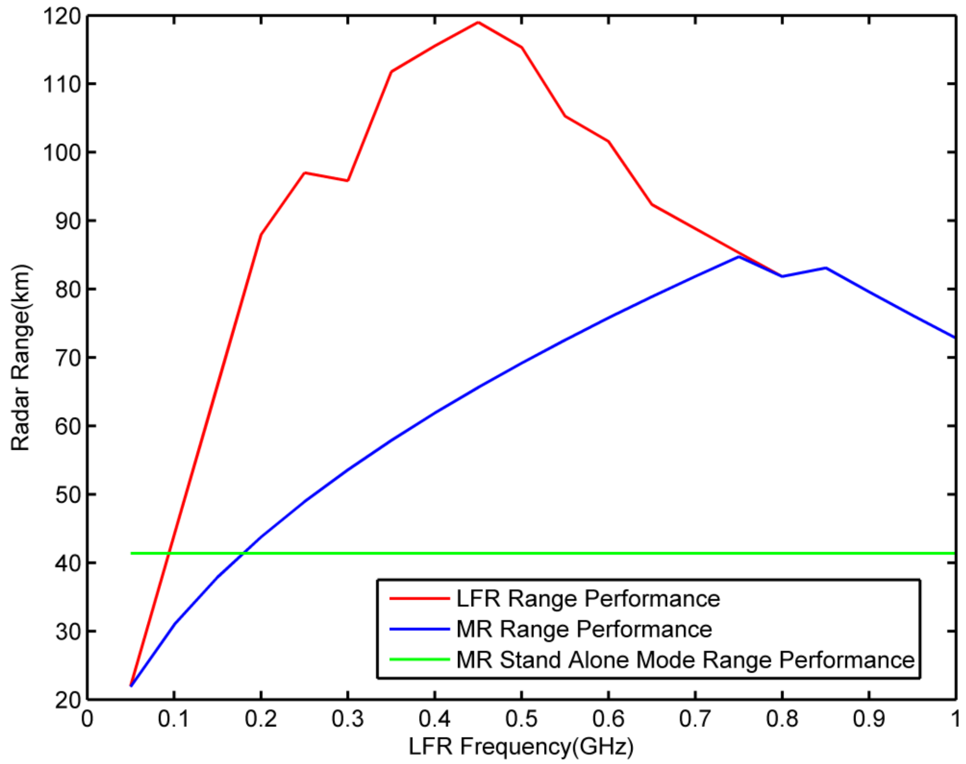

Fig. 23 MR Range versus LFR Frequency

Fig. 23 shows that MR in stand-alone mode range is greater than that of MR Cued by LFR for LFR frequencies less than 0.18 GHz. Although LFR reaches its maximum range at 0.45 GHz, MR cannot detect the targets at this range, and the MR Cued by LFR system cannot reach its purposes.

MR Cued by LFR reaches its peak range at the LFR frequency 0.75 GHz. At this frequency, maximum range of LFR is 86 km, whereas MR Cued by LFR has maximum range equal to 85 km. Since the maximum range of MR in stand-alone mode is only a 41.4 km, the improvement in the range performance when MR is cued by LFR is more than two-fold.

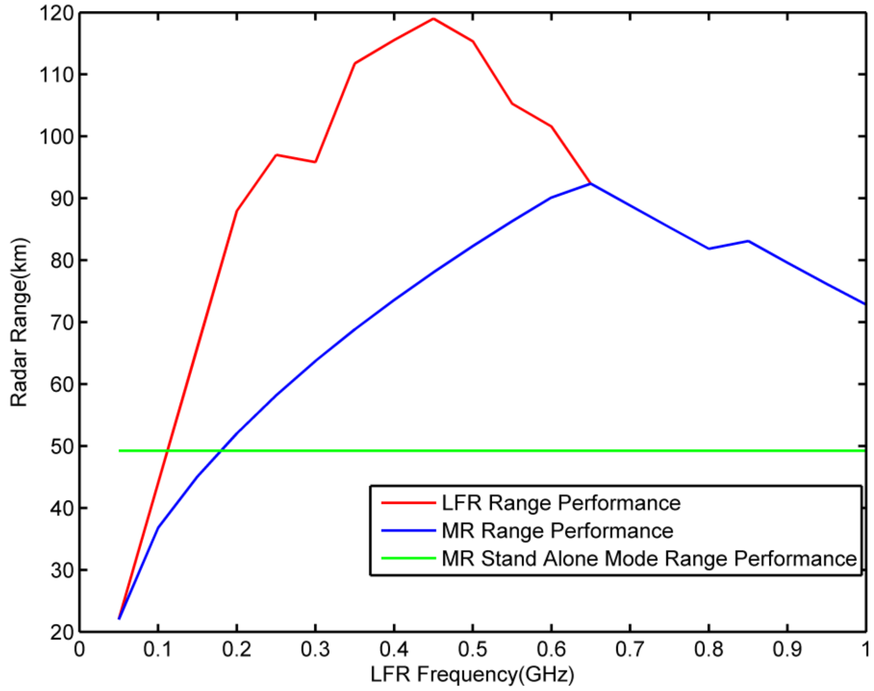

Fig. 24 MR Cued By LFR

Fig. 24 shows how much range performance can be increased if MR power is doubled. The change in the maximum range is about 5 km. The reason behind this insignificant rise compared to the two-fold rise in power is hidden in the range equation, given in CHAPTER 2. In order to double the maximum range, a sixteen-fold increase in average power is necessary.

One of the important parameters that is had to be taken into account is cross-range resolution of the tracking radar. Cross range resolution represents the uncertainty of target`s being in the stated horizontal interval of the beam. **Fig. 25** shows the Cross Range Resolution concept.

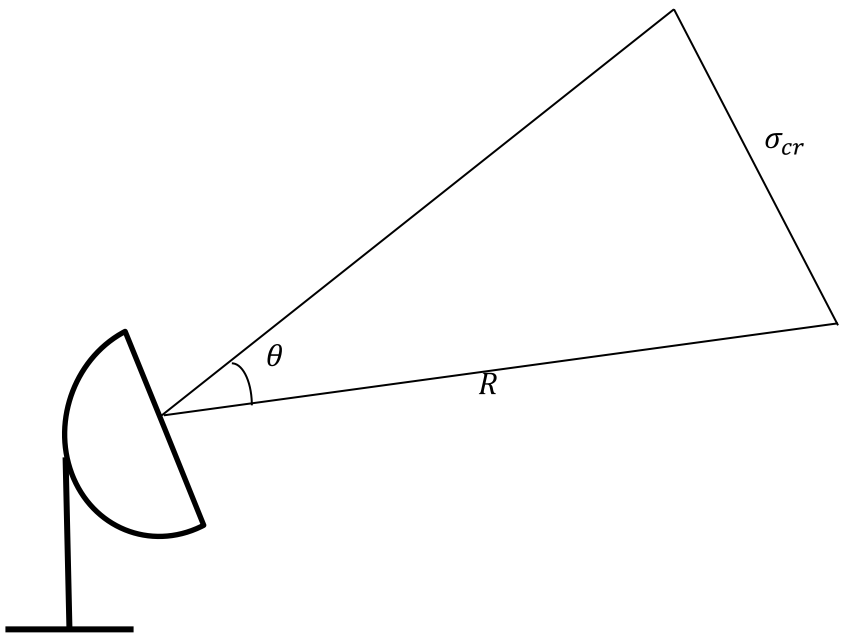

Fig. 25 Cross Range Resolution

It is formulized as follows:

$$\sigma_{cr} = \theta * R$$

σ_{cr} = Cross-range resolution

θ = Half-power beamwidth of the radar antenna

R = Distance between the target and the radar antenna

As the target gets closer to the radar, cross range resolution becomes better and target`s location can be estimated more precisely.

Another important parameter related to target`s location is range resolution. Range resolution is totally related to pulse width. **Fig. 26** is taken from [26] and shows range resolution of a radar.

Fig. 26 Range Resolution **[26]**

Range resolution is formulized as follows:

$$\Delta R = \frac{c * \tau}{2}$$

ΔR = Range resolution

Fig. 27 shows cross-range resolution analysis of the MR cued by LFR.

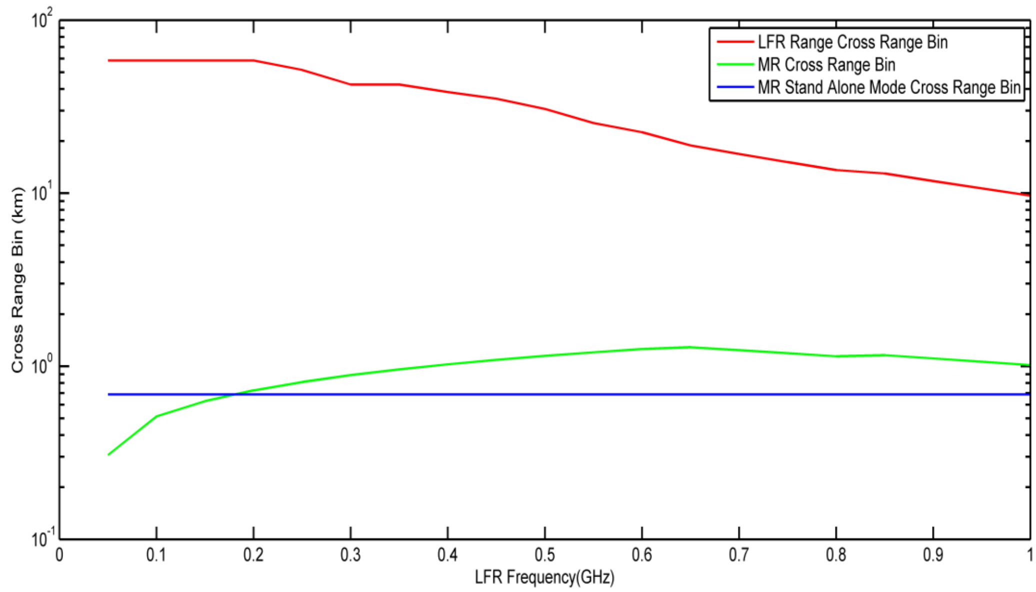

Fig. 27 Cross Range Bin of MR Cued By LFR

Location accuracy in the horizontal range is increased in MR Cued by LFR compared to LFR stand-alone mode since resolution is better. As stated in the beginning of the chapter, the system integrates LFR`s good detection capability and MR`s good location accuracy.

CHAPTER 5

RADAR PERFORMANCE ANALYSIS OF BALLISTIC MISSILE DEFENSE SYSTEMS: AN/TPY-2 AND 96L6E

Ballistic missile is a missile guided to its target, following a high altitude, elliptical trajectory. It may have one or more warheads[6] attached to the front part of the missile. Ballistic missiles are generally guided during only a short period of the whole flight. After guided session is finished, warhead is released and its trajectory is formed under the influence of natural forces, such as gravity and air resistance of the atmosphere. Ballistic missile trajectory is composed of 3 phases [27].

Boost Phase: Boost phase is the initial part of the trajectory during which the missile is powered and launched from the ground, as it can be understood from the name of the phase.

Midcourse Phase: In midcourse phase, the missile leaves the guide and warhead continues to move under the gravitational force. For long range ballistic missiles, warhead exits the atmosphere in midcourse phase.

Terminal Phase: Terminal phase is the final part of the trajectory where missile returns back to the atmosphere and hits the the target area.

Fig. 28 shows the trajectory phases of a ballistic missile.

[6] The part of a missile with the explosive, damaging materials.

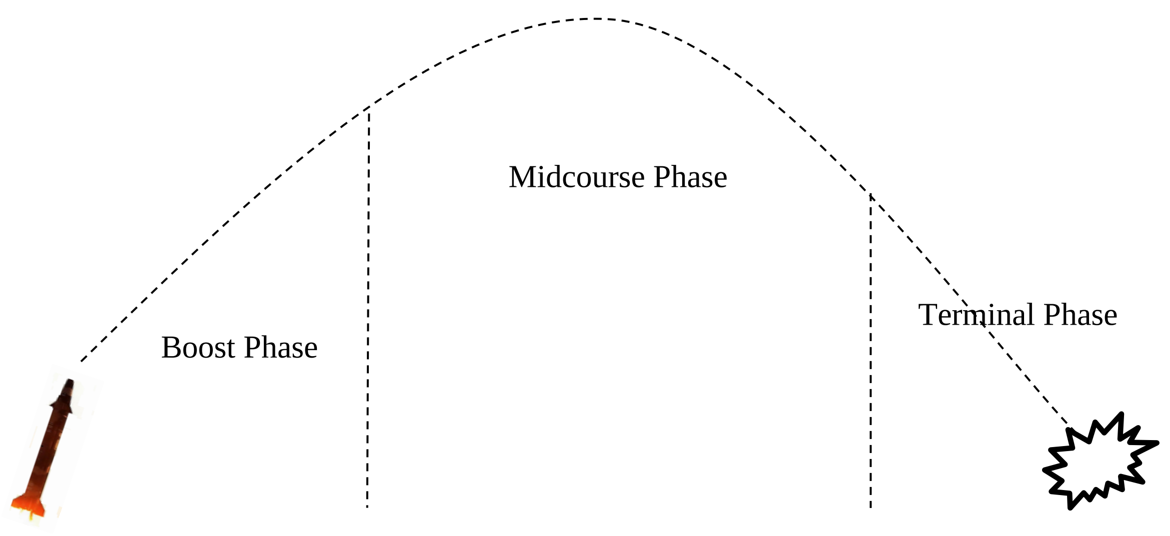

Fig. 28 Ballistic Missile Trajectory

Considering the range that the missile can travel in the horizontal plane, there are four main types of ballistic missiles:

Short Range Ballistic Missiles (SRBM): This kind of ballistic missile can travel up to 600 km away from where it is launched and it can reach to 50 km altitude.

Medium Range Ballistic Missiles (MRBM): This kind of ballistic missile can travel up to 1300 km away from where it is launched and it can reach to 100 km altitude.

Intermediate Range Ballistic Missile(IRBM): This kind of ballistic missile can travel up to 5500 km away from where it is launched and it can reach to 250 km altitude.

InterContinental Ballistic Missile(ICBM): This kind of ballistic missile can travel up to 10000 km away from where it is launched and it can reach to 500 km altitude.

Ballistic missile industry is still developing and ballistic missiles are becoming more dangerous threats. The improvement in ballistic missile technology will apparently not stop and these missiles always be a risk for border protection of the countries that do not have efficient Ballistic Missile Defense systems. Countries all over the world have to take precautions against this global threat.

Radars play a very important role in ballistic missile defense systems. The search and tracking radar systems in ballistic missile defense systems have more competitive / greedy requirements than the ones for aircraft detection and tracking because of the longer ranges that ballistic missile defense radar has to reach and smaller RCS values of the targets.

Two similar radars used in ballistic missile defense are American AN/TPY-2 and Russian 96L6E long range search and tracking radars.

Fig. 29 shows what the abbreviation (TPY) in AN/TPY-2 stands for in US army forces.

First Letter (Type of Installation)		Second Letter (Type of Equipment)		Third Letter (Purpose)	
A	Piloted aircraft	L	Countermeasures	D	Direction finder, reconnaissance, or surveillance
F	Fixed Ground	P	Radar	G	Fire control or searchlight directing
M	Ground, mobile (installed as operating unit in a vehicle which has no function other than transporting the equipment	Y	Signal/data processing	K	Computing
P	Pack or portable (animal or man)			N	Navigational aids (including altimeter, beacons, compasses, racons, depth sounding, approach, and landing)
S	Water surface craft			Q	Special, or combination of purposes
T	Ground, transportable			R	Receiving, passive detecting
U	Ground utility			S	Detecting or range and bearing, search
V	Ground, vehicular (installed in vehicle designed for functions other than carrying electronic equipment, etc., such as tanks			Y	Surveillance (search, detect, and multiple target tracking) and control (both fire control and air control)

Fig. 29 Subset of AN Nomenclature

In AN/TPY-2 radar, an active electronically scanned array (AESA) antenna is used. It is known that the antenna is composed of 25344 transmit/receive (TR) modules and it is supposed that each module has 3.2 W average power. Total average power of the radar is equal to 81 kW [28].

The antenna used in the radar is known to have an antenna aperture of 9.2 m^2 [28].

The radar is known to operate in X band. Hence, it is estimated that frequency of the transmitted electromagnetic wave is 10 GHz [28].

SNR values required to detect and track a target are taken as 13 dB and 20 dB, respectively.

In Russian 96L6E radar, the number of the antenna modules is less than the number of modules used in AN/TPY-2. It is estimated that total average power of the 96L6E radar is 50 kW.

This radar uses an active electronically scanned array whose dimensions are assumed to be 3 meters (width) and 4 meters (length). Its antenna has an aperture efficiency of 0.8.

The radar is known to operate in C band. Hence, it is estimated that frequency of the transmitted electromagnetic wave is 5 GHz [29].

Range comparison of the two radars is given in **Fig. 30**.

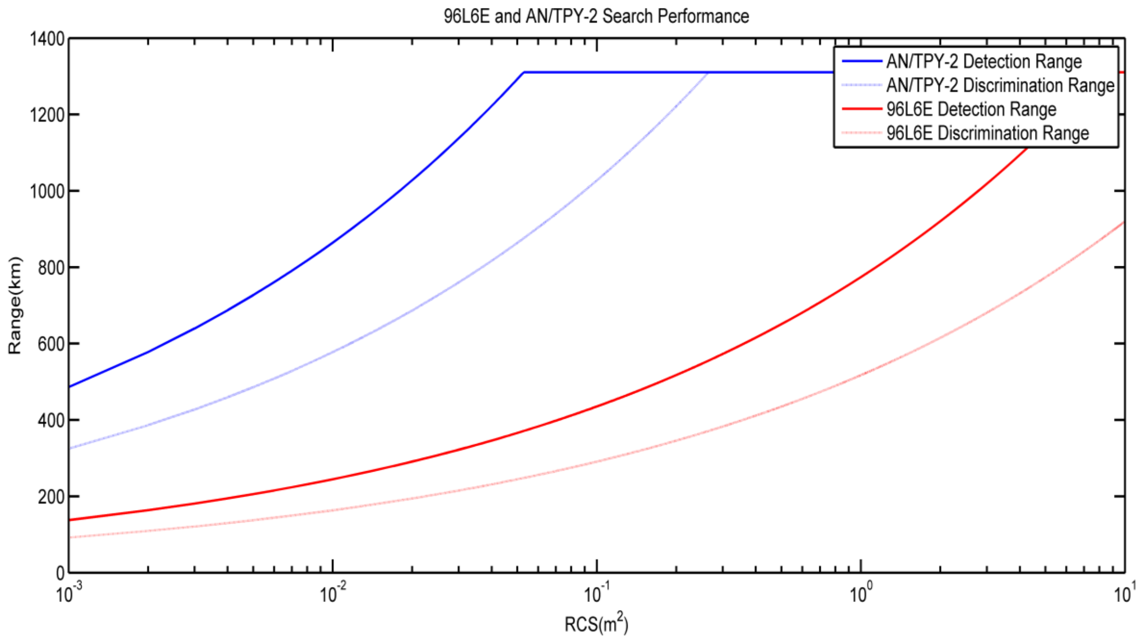

Fig. 30 Range Comparison Between AN/TPY-2 and 96L6E Radars

The upper range limit of the radars is due to radar horizon. The targets beyond this limit cannot be detected because of the curvature of the earth[7]. The radar is assumed to be placed 3.5 meters above the ground to enhance visibility.

For a radar placed 3.5 meters above the ground, **Fig. 31** shows how horizontal limit is affected by the altitude of the target.

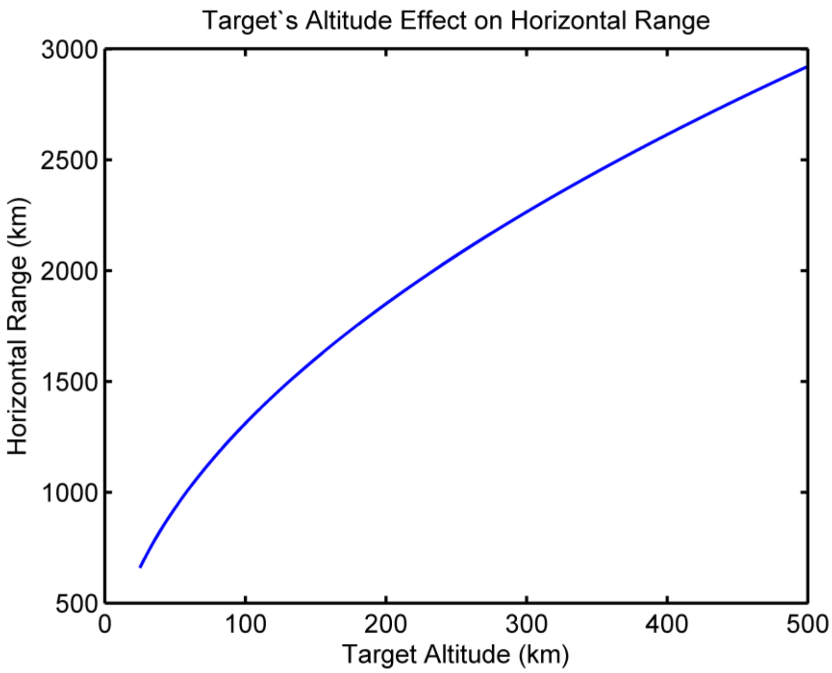

Fig. 31 Horizontal Range versus Target Altitude

RCS of a ballistic missile depends on three parameters. The first one is the phase of the flight, since the missile warhead separates from the main body after the boost phase, and the radar has to detect the warhead which is the smaller part. The second important parameter is the operating frequency. The RCS of the same target is smaller for AN/TPY-2 radar as compared to the RCS value seen by 96L6E. The third parameter is the type of ballistic missile. Assumed RCS values of ballistic missiles in

[7] The elevation of the target is assumed to be 100 km from the ground. The radars are assumed to be placed 3.5 meters above the ground.

boost phase used in the calculations are given in Table 2 RCS values of MRBM are taken from [25]. The RCS values of other ballistic missile types are approximated by using the size ratios.

Assumed RCS values in midcourse and terminal phase including only warhead are given in Table 3. RCS values of MRBM are taken from [30].

Table 2 RCS Assumptions of Warhead With Guide

RCS (m^2)	**96L6E (5 GHz)**	**AN/TPY-2 (10 GHz)**
SRBM	0.8	0.67
MRBM	1.2	1
IRBM	2	1.67
ICBM	3	2.5

Table 3 RCS Assumptions of Warhead Without Guide

RCS (m^2)	**96L6E (5 GHz)**	**AN/TPY-2 (10 GHz)**
SRBM	0,02	0.007
MRBM	0.03	0.01
IRBM	0.05	0.017
ICBM	0.075	0.025

Considering boost phase of the ballistic missiles, the scenarios should be as shown in **Fig. 32** and **Fig. 33**. By using the RCS values given in Table 2 and **Fig. 30**, the results given below in Table 4 are obtained.

Table 4 Detection and Tracking Ranges of the Radars

Detection Range (km)	Tracking Range (km)	**96L6E (5 GHz)**		**AN/TPY-2 (10 GHz)**	
SRBM		590	480	590	590
MRBM		810	540	930	930
IRBM		900	610	1310	1310
ICBM		1010	680	1310	1310

AN/TPY-2 Radar`s 1310 km detection and tracking ranges of ICBM and IRBM are caused due to the radar horizon limit. For ballistic missiles which cannot reach 100 km altitude, the limit will decrease. For SRBM and MRBM, since the maximum flight altitude is less than 100 km, they are not expected to reach such altitudes in the boost phase. Therefore, their range limits are less than those of IRBM and ICBM.

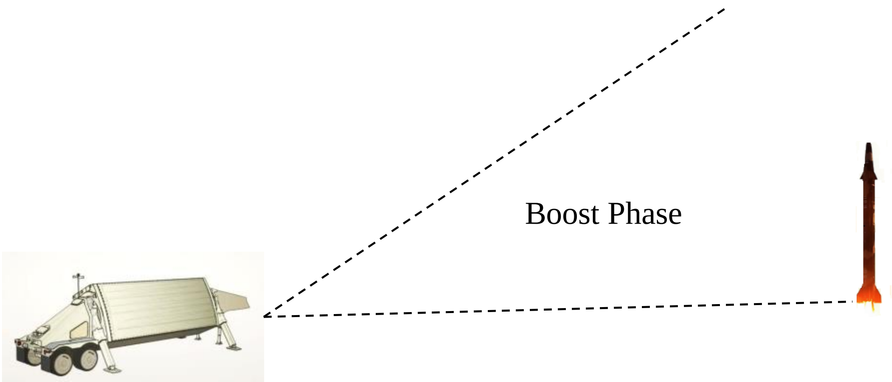

Fig. 32 AN/TPY-2 Radar Placement for a Boost Phase Detection

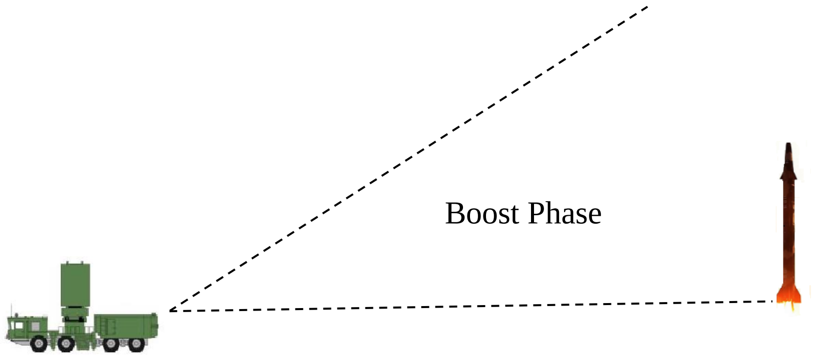

Fig. 33 96L6E Radar Placement for a Boost Phase Detection

Considering midcourse and terminal phases of the ballistic missiles, the scenarios should be as shown in **Fig. 34** and **Fig. 35**. By using the RCS values given in Table 3 and **Fig. 30**, the results given below in Table 5 are obtained.

Table 5 Detection and Tracking Ranges of the Radars

Detection Range (km)	Tracking Range (km)	**96L6E (5 GHz)**		**AN/TPY-2 (10 GHz)**	
SRBM		270	180	780	500
MRBM		310	210	820	550
IRBM		360	240	950	650
ICBM		410	270	1070	730

Detachment of the warhead from the ballistic missile makes detection and tracking harder. Since the RCS values of the warhead is much smaller, the maximum radar ranges decrease considerably.

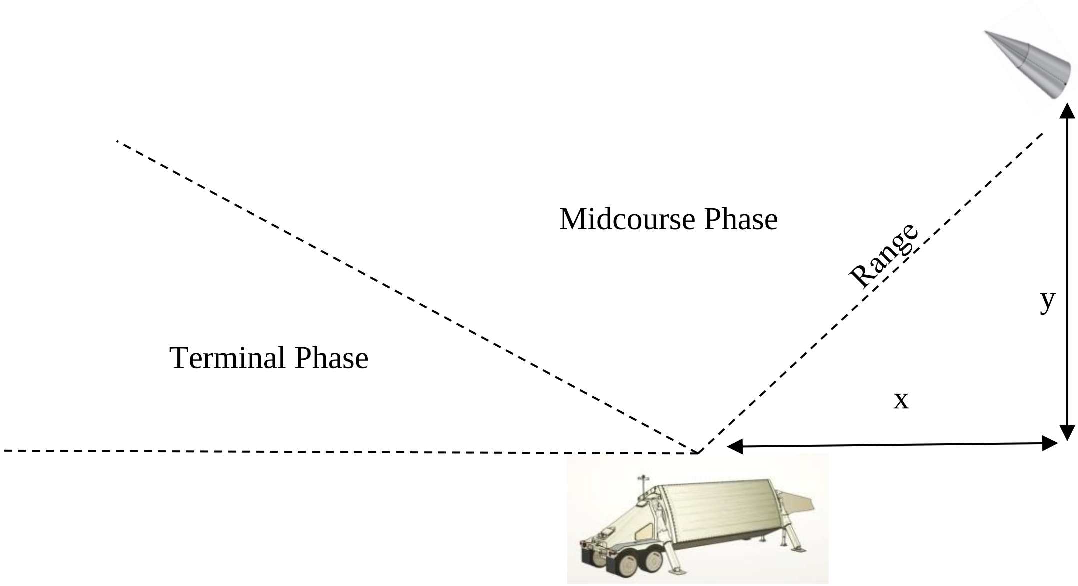

Fig. 34 AN/TPY-2 Radar Placement for Midcourse and Terminal Phase Detection

In **Fig. 34**, x and y values represent the horizontal distance from the radar to the warhead position projected to the ground, and altitude of the warhead which depends on the ballistic missile type. Table 6 shows the needed AN/TPY-2 Radar distance to projected position of the warhead on the ground.

Table 6 Maximum Horizontal Radar Placement

Detection Range (km)	Tracking Range (km)	**AN/TPY-2 (10 GHz)**				
		Range (km)		**Altitude (km)**	**Horizontal Range (km)**	
SRBM		780	500	50	778.4	497.5
MRBM		820	550	100	813.9	540.8
IRBM		950	650	250	916.5	600.0
ICBM		1070	730	500	946.0	531.9

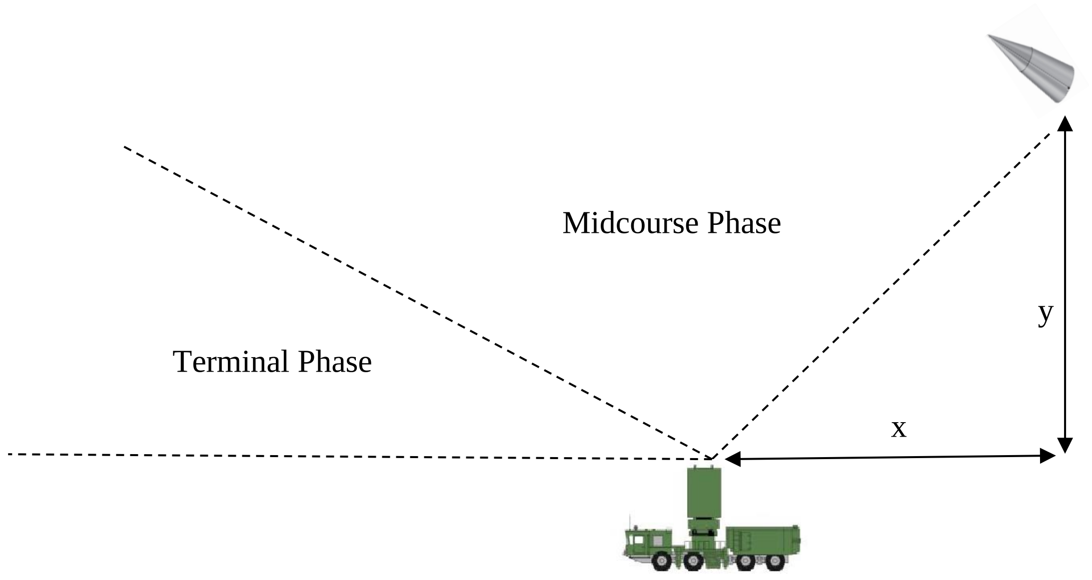

Fig. 35 96L6E Radar Placement for Midcourse and Terminal Phase Detection

Table 7 shows the needed 96L6E Radar distance to projected position of the warhead on the ground.

Table 7 Maximum Horizontal 96L6E Radar Placement

Detection Range (km)	Tracking Range (km)	**96L6E (5 GHz)**				
		Range (km)		**Altitude (km)**	**Horizontal Range (km)**	
SRBM		270	180	50	265.3	172.9
MRBM		310	210	100	293.4	184.7
IRBM		360	240	250	259.0	Unavailable
ICBM		410	270	500	Unavailable	Unavailable

Table 7 shows that it is not possible to detect and track the warhead of an ICBM by using 96L6E radar during the midcourse and the terminal phases, since the total range that radar can detect is lower than the altitude that the warhead flies. It is only possible to detect the ICBM warhead in the terminal phase, while it is below its flight altitude. Similarly, with the same radar, it is not possible to track the warhead of an IRBM, while detection is possible.

Another important parameter that must be taken into account during selection of radar to be used in a ballistic missile defense system is angular track accuracy. The location of the ballistic missile should be estimated with high accuracy to increase the collision probability when an anti-ballistic missile is launched by the ballistic missile defense system.

Fig. 36 shows the angular accuracies of the 96L6E and AN/TPY-2 radars.

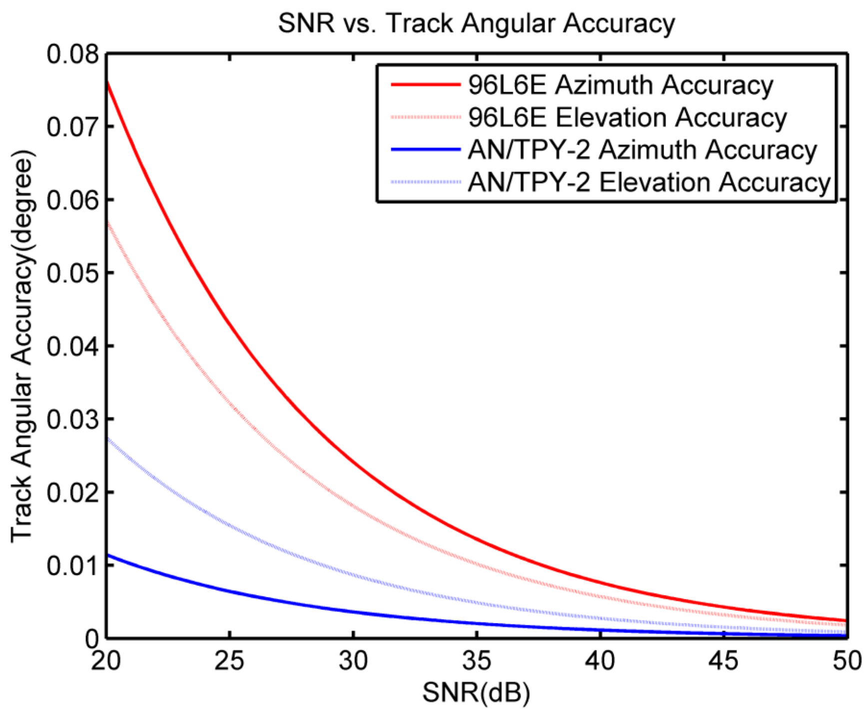

Fig. 36 SNR vs Angular Track Accuracy

Since AN/TPY-2 radar operates at a higher frequency and it has antenna with larger aperture area, as compared to 96L6E radar, the angular accuracy and resolution of AN/TPY-2 radar is better than those of 96L6E radar.

Cross range accuracy of the radars can be calculated by using angular elevation and azimuth accuracies given in **Fig. 36**. **Fig. 37** shows the cross range accuracies of 96L6E and AN/TPY-2 radars when the target range is 25 km and 50 km, respectively.

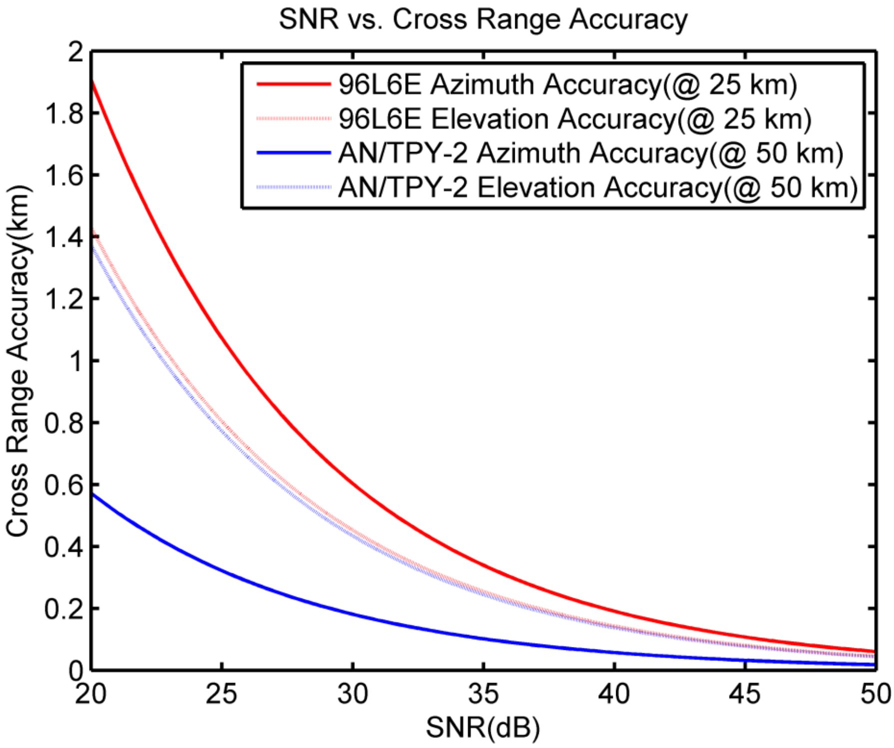

Fig. 37 Cross Range Accuracy

CHAPTER 6

CONCLUSION

Radars are devices for detecting and tracking objects, by transmitting a signal as an electromagnetic wave by a directive antenna and receiving and processing the echo signal. The range of the target is obtained from the time-delay measured in the echo signal, and the angular location of the object is obtained from the beam direction of the antenna and by using techniques such as monopulse processing. The range accuracy depends on the pulse-width as well as pulse compression techniques, which are outside the scope of this thesis. Angular accuracy depend on the antenna beamwidth and SNR. The performance of a radar is closely related to the maximum range parameter, which is the range where a target with a specified RCS is detected with a specified probability of detection. In this thesis, this concept lies at the center of the entire study.

In this thesis, a MATLAB tool is developed for the preliminary performance analysis of a radar (or, radars) in terms of the important radar parameters that should be taken into account during radar design to satisfy the requirements of the customer / end user / operator. The analysis is based on the fact that, average power and antenna aperture area (equivalently, antenna gain) are the two parameters that must be chosen during the preliminary design phase by the designer /manufacturer. For an existing radar system, these two parameters are again important (from the viewpoint of a customer or end-user) to assess the performance of the radar. The analysis is based on different versions of the radar equation for search and tracing radars. As an application, for a search radar scanning targets 30,100 and 1000 km away, the average power and the required antenna size to achieve maximum range is plotted as a graph. Moreover, for multi-tasking radars employed for both search and tracking, a utilization trade is drawn. By analyzing the graphs, the designer will be able to determine (or, assess) the time fraction allocated for search and tracking. It is clear that such graphical tools provide valuable information not only for designers in the preliminary phase, but also for customers trying to choose a radar system from a set of radar systems in the market.

The thesis contains two case studies for the performance analysis of (i) a two-radar system (ii) two existing radar systems used in ballistic missile defense systems. These case studies clearly show that the developed tools are adequate for assessing or comparing radar systems in terms of their functionalities.

The first case study is a two-radar system to detect and track dim targets. Targets whose RCSs are decreased by using RCS reduction (stealth) techniques are difficult to detect for radars operating in the microwave frequency (typically the X-band for military radars) band. However, it is known that RCS values increase for lower frequencies and especially in VHF/UHF bands radars have a good detection capability since stealth techniques are ineffective over this band of frequencies. By combining MR with a LFR operating in VHF and / or UHF band, a two-radar system can be designed with an improved detection range performance. Moreover, the insufficient location accuracy of LFR is compensated with the help of the narrow beamwidth of the MR. Therefore, such a two-radar system can be used for border protection, since it will be easier to locate the threat and the system is effective in early warning.

The second case study is the comparison of two existing long range radar systems used in ballistic missile defense systems. Ballistic missiles are getting more threatening all over the world. By using ICBMs, a country can hit a target point which is thousands of km away. Therefore, any country in the world that does not have ballistic missile defense system may be an easy target for ballistic missiles. Radars used in ballistic missile defense systems play an important role in early detection and in locating the ballistic missile before launching the anti-ballistic missile. There are two world-wide known radars used in ballistic missile defense systems: AN/TPY-2 being an American product and 96L6E being an Russian product. The range performances of these radars are analyzed for different portions of the missile trajectory. Lastly, the location accuracies and the angular track accuracies of the radars are compared.

As a consequence, the developed tools prove to be useful for assessing and / or comparing radar performances. The main goal of this thesis is to provide a performance analysis which is useful to gain some initial insight about the radar system. In terms of the designer, such an analysis is functional in the preliminary phase as a feasibility study. For the customer, performance analysis is essential to assess an existing radar system, and also for comparing two or more radar systems with similar functionalities. The two case studies demonstrate that the analysis can be extended to multi-radar systems and multifunction radars.

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