# CRUISE MISSILE MISSION REHEARSAL

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## CRUISE MISSILE MISSION REHEARSAL

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# ABSTRACT

## CRUISE MISSILE MISSION REHEARSAL

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Cruise missile mission planning is a key activity of cruise missile operations. Ground planning activities aim at low observable missions that have high probability of success. These activities include end game planning, route planning and launch planning. While end game planning tries to optimize end game parameters for maximum effectiveness, route planning tries to maximize survivability and enable navigational supports by determining the waypoints to from launch zone to target through a defended area. And lastly, planner tries to find the appropriate launch parameters that will prohibit platform to contact enemy agents. Mission rehearsal is the execution of the planned mission in a virtual environment that will be constructed with the data that drives the planning process. Mission rehearsal will support planners by providing possible results of the planned mission. Stochastic processes of the execution of the planned mission will be incorporated in the simulation of the combat. Along with platform, cruise missile and target, other players like SAM Sites or Search Radars (Early Warning Radars) will be incorporated in the rehearsal process.

Keywords: Mission Rehearsal, Cruise Missile, Weapon Systems, Radar Systems, Damage Assessments

# ÖZ

## SEYİR FÜZESİ GÖREV PROVASI

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Yüksek Lisans, Makina Mühendisliği Bölümü
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Seyir füzesi görev planlaması, seyir füze operasyonların kilit faaliyetlerinden biridir. Yer planlama aktiveteleri, yüksek başarı oranına sahip düşük görünürlüklü görevleri amaçlamaktadır. Bu aktiviler oyun sonu, rota ve bırakma planlamalarını içermektedir. Oyun sonu planlaması azami etkinlik için oyun sonu parametrelerini eniyilemeye çalışırken, rota planlaması azami hayatta kalabilirlik ve savunulan bir alan içinde atış bölgesinden hedefe olan bölgedeki yol noktalarını belirleyebilmek adına seyrüsefer desteklerini etkin kılma için uğraşmaktadır. Son olarak planlamacılar, platformun düşman unsurlarıyla temasını engelleyecek uygun bırakma parametrelerini bulmaya çalışmaktadır. Görev provası, planlama sürecini yürüten veri kullanılarak oluşturulacak görev planlamasının sanal ortamda uygulanmasıdır. Görev provası planlanmış görev için elde edilen olası sonuçlar ile planlamacıları destekleyecektir. Yürütülen görev planlamasının rastsal süreçleri muharebe benzetimlerine katılacaktır. Platformun yanısıra, seyir füzesi ve hedef ile karadan havaya füze konumları ve erken uyarı radarları gibi diğer unsurlar da prova sürecine dahil edilecektir.

Anahtar Kelimeler: Görev Provası, Seyir Füzesi, Silah Sistemleri, Radar Sistemleri, Mühimmat Etkinliği

To My Parents

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| | |
|---|---|
| $m_w$ | Weapon Mass |
| $\overline{F}$ | Total Force Vector of Weapon |
| $\overline{F}_L$ | Lift Force Vector of Weapon |
| $\overline{F}_D$ | Drag Force Vector of Weapon |
| $\overline{F}_T$ | Thrust Force Vector of Weapon |
| $\overline{F}_G$ | Gravity Force Vector of Weapon |
| $F_L$ | Magnitude of Lift Force |
| $F_D$ | Magnitude of Drag Force |
| $F_T$ | Magnitude of Thrust Force |
| $F_G$ | Magnitude of Gravity Force |
| $\vec{a}_w$ | Acceleration Vector of Weapon |
| $m_{w_{ref}}$ | Reference Mass (Weapon Mass without Fuel) |
| $m_{fuel}$ | Fuel Mass |
| $\vec{v}_w$ | Velocity Vector of Weapon |
| $\vec{x}_w$ | Position Vector of Weapon |
| $\vec{v}_{w_0}$ | Initial Velocity Vector of Weapon |
| $\vec{x}_{w_0}$ | Initial Position Vector of Weapon |
| $C_L$ | Coefficient of Lift Force |
| $\alpha_t$ | Angle of Attack |
| $C_{L_\alpha}$ | Coefficient of Lift Force Depends on Angle of Attack |
| $V_w$ | Magnitude of Weapon Velocity |
| Q | Dynamic Pressure |
| S | Reference Area |

| | |
|---|---|
| $\vec{u}_{v_w}$ | Unit Velocity Vector of Weapon |
| $\vec{u}_l$ | Unit Vector of Lift Force |
| $C_D$ | Coefficient of Drag Force |
| $C_{D_0}$ | Coefficient of Zero Drag Force |
| $C_{D_{\alpha^2}}$ | Coefficient of Second Order Drag Force |
| $F_{P_{ref}}$ | Reference Thrust Force |
| $p_{ref}$ | Reference Pressure |
| $p_a$ | Atmospheric Pressure |
| $A_e$ | Exhaust Area |
| $\vec{u}_b$ | Unit Vector of Weapon Orientation |
| $\dot{m}_{fuel}$ | Fuel Consumption with respect to Time |
| $I_{sp}$ | Specific Fuel Consumption |
| $\vec{g}$ | Gravity Acceleration Vector |
| $g_0$ | Reference Gravity Acceleration |
| P | Air Pressure |
| T | Air Temperature |
| c | Sound Speed |
| lat | Latitude of Weapon |
| lon | Longitude of Weapon |
| LOS | Line of Sight |
| NR | Navigation Ratio |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

A cruise missile is “a guided missile, the major portion of whose flight path to its target is conducted at approximately constant velocity; depends on the dynamic reaction of air for lift and upon propulsion forces to balance drag.”[1] In the Second World War, they were used by Nazi Germany for the first time. After that time, their development and use in combat could not be prevented. Today, they have every variety of destructive payloads known to man, from high-explosives to chemical, biological and nuclear weapons. [2]

A mission rehearsal, which is performed before force execution event, is a preparatory process in tactical operation cycle. Tactical operation cycle is the life-blood of the battle management. Mission rehearsal ensures whether mission planning is done properly in execution planning process by simulating almost all events which are likely to happen.

Tactical operation cycle, presented at Figure 1.1, is occurred from seven different processes. These are objectives, target development, weaponeering, execution planning, mission rehearsal, force execution, and combat assessment.

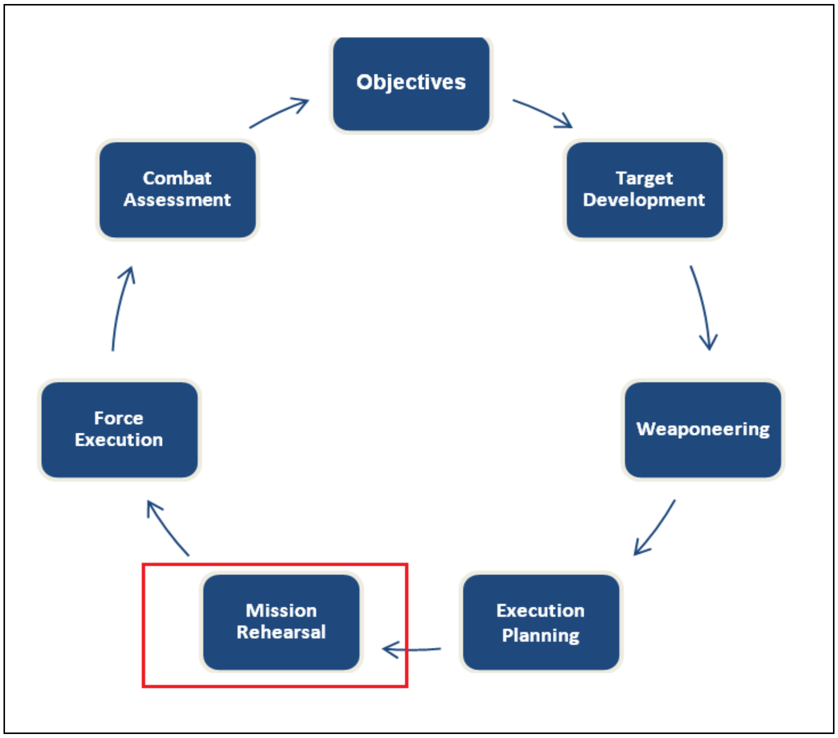

Figure 1.1 Tactical Operation Cycle

Objectives part is required to understand situation and to establish incident aims and strategy. In the target development part, available information of targets is gathered to select target for damaging. In weaponeering part, weapon is selected from available weapon lists to kill enemy. Mission planning, developing a route planner with low observable is performed in execution planning. Mission rehearsal is performed to understand how good current plan is. Strategy, tactics and assignments are interpreted in this stage. It gives information whether current plan is successful or not. In the case of not success, it gives chance to modify mission plan. Force execution is required to implement analyzed mission plan during operational period. Combat assessment is responsible to evaluate mission plan at various processes in its development and implementation. Then, the appropriate modification is made to ensure that effectiveness is guaranteed and objectives are met.

In this research, mission rehearsal tool with constructive simulation environment is developed to evaluate mission planning of cruise missile. Mission rehearsal tool is modeled according to discrete system simulation since in most military systems, events do not occur continuously but at isolated points in time. There are the two approaches for discrete system simulation [3]

- Event to event simulation (or Event-Driven Simulation)

- Constant-Time-Step Simulation (or Time-Driven-Simulation).

An appropriate approach for simulation depends on the nature of the inter-event intervals. Event-driven simulation is suitable for unequal or random intervals between consecutive events. However, in the case that the inter-event intervals are equal, time-driven simulation approach is suitable. [3]

Every aspect of a mission plan must be analyzed to examine the degree that it fulfills its objectives. Thus, the mission planner can decide whether mission plan is good or bad. In order to analyze the mission plan to determine its effectiveness in meeting the requirements of its tasking, some constraints shall be checked. These constraints are as follows [3]

- Flight performance constraints: Cruise missile shall carry enough fuel for the mission to reach required altitudes, perform the turns and achieve the various speed profiles specified along the flight paths. So the points that the plan exceeds the performance capabilities of the Cruise Missile shall be possible to determine.

- Survivability and effectiveness constraints: Cruise missile shall be planned to a survivable route that will avoid enemy SAM and AAA sites and engage its target in effectively. So the planner shall be situated with low survivability and effectiveness information as it is a possibility.

## 1.2 Movatiation and Objectives

Air defense system performance can be analyzed by three different approaches. As all explained in [4] the first one is to analyze data obtained from actual combat operations. The second one is to analyze data obtained from controlled system level tests. The last one is to analyze data taken from a simulation.

Analysis based on actual combat operations is performed by lessons learned from using actual combat. This analysis provides important information but it does not give response to whether existing military operation can perform the duty or not. Moreover, it can be too late for that plan after battle.

Much reliability is provided by analysis based on controlled system level tests owing to using actual hardware and software. However, the cost of system is so high and also it covers only a limited number of system configurations and tactical scenarios. Moreover, due to limitations of system and safety reasoning, natural state is diminished. This causes increasing erroneous results.

Analysis based on simulation of air defense system provides flexible system configurations and tactical scenarios. Moreover, this analysis supplies unlimited number of tests because the cost of system is so low. There is an opportunity to perform complex air defense system at computer simulation in the case of analyzing mission plan.

Due to reasons mentioned above, for mission rehearsal tool, computer simulation of all or part of the mission that is currently being planned, is picked as the methodology to assess mission effectiveness. [4]

The aim of mission rehearsal can be classified into two objectives.

- Mission optimization, through the possible identification of better solutions.

- Creating situation awareness for analyzer that specific mission.

In the thesis, we target at developing a mission rehearsal tool for cruise missiles that simulates the air defense systems and cruise missile in the tactical environment to analyze prepared mission plan. It will utilize visibility, feasibility and variability aspects. [5]

Owing to visibility technique, the mission rehearsal tool provides visualization of operational scenarios including cruise missile trajectory, terrain, launch vehicles trajectories, radars' coverage and interactions of air defences' units in 2D plane.

Mission rehearsal tool provides mission analyzer with the knowledge to determine if a mission can be achieved by using feasibility technique. This tool presents mission feasibility through ground assets, tracking line of sight to cruise missile or launch weapons, and analysis reports to meet mission success criteria.

Owing to variability technique, this tool provides ability to adjust tactical operating scenario which includes determining parameters of air defense system (red forces) to evaluate mission plan performance.

According to techniques mentioned above, the mission rehearsal tool is performed as Discrete System Simulation (Constant-Time-Step Simulation) with constructive simulation environment. Because, all models of it communicate with each other at every time step.

The outputs of mission rehearsal tool is probability of survivability, probability of hit and probability of kill of specific cruise missile at specified tactical environment consists of threats including early warnings, SAM and AAA sites.

## 1.3 Scope of the Thesis

This chapter presents a background to thesis topic and motivation and objectives. In background section, operation cycle and the importance of mission rehearsal in the operation cycle are explained. The general information about discrete system simulation and modeling mission rehearsal tool according to discrete system are given. The requirements to determine mission plan effectiveness are mentioned. In motivation and objectives section, the ways to analyze air defense performance are presented.

The theory behind air defense system structure is explained in Chapter 2. Air defense system consists of three top section; radar system, command and control center and weapon system, respectively. The relationships between these components and modeling hierarchy of these components are mentioned individually. In radar system, two types of radar, search and track radar, and sub-models of these radars and duties of radars in air defense system are explained. In command and control center part, the construction, the aim and the task of command and control center in air defense system are described. Weapon system includes two types of weapon, Surface to Air Missile (SAM) with command and line of sight guidance and proportional navigation guidance, and Antiaircraft Artillery (AAA) namely. Moreover, weapons have two different fuze type, proximity and point detonating namely.

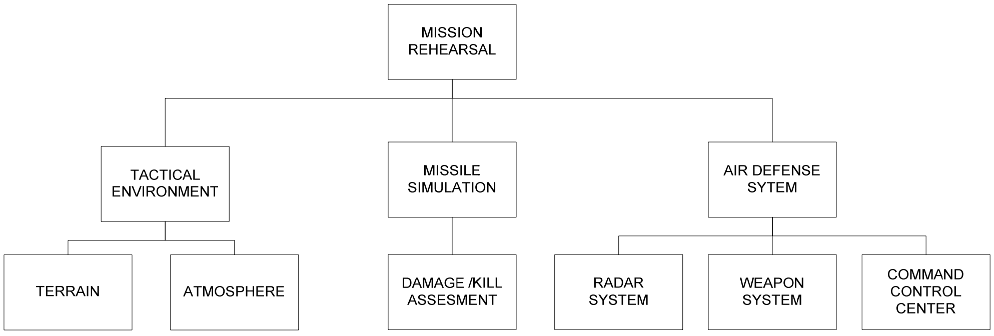

Figure 1.2 Mission Rehearsal Components

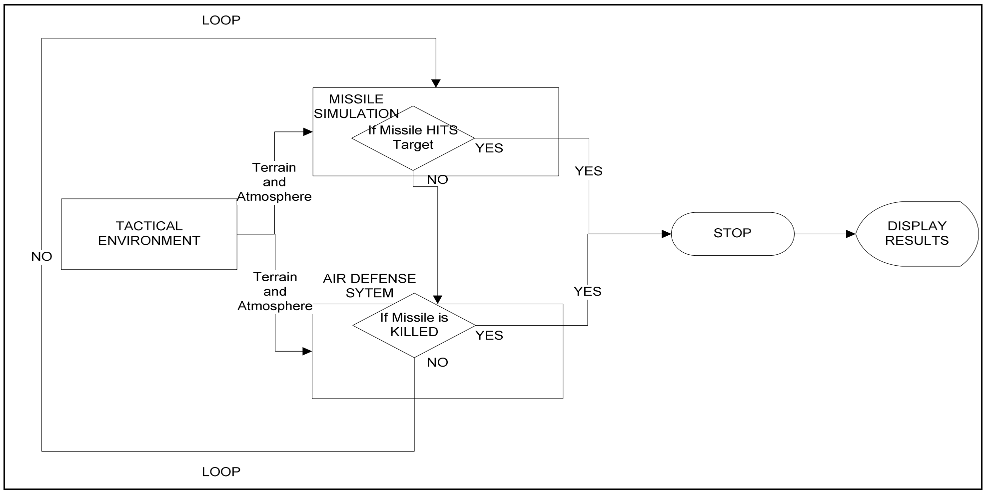

Figure 1.3 Flow Diagram of Mission Rehearsal

Chapter 3 gives brief information about cruise missile and task of it in mission rehearsal tool. Cruise missile simulation data required for analyzing mission plan is explained.

Tactical environment data required for analyzing mission plan is explained in Chapter 4. Tactical environment data includes terrain and atmosphere data. Moreover, the formats of terrain and atmosphere data are presented in this section.

Chapter 5 gives brief information about Monte Carlo Simulation and use of it in mission rehearsal tool. In the other words, it is explained why Monte Carlo is used in this research.

Case studies are employed by using mentioned theory are presented in Chapter 6. Inputs required for each case study and outputs of mission rehearsal with respect to sample run are presented.

The conclusion and future studies are given in Chapter 7 which is the final chapter of the thesis.

# CHAPTER 2

# AIR DEFENSE SYSTEM

## 2.1 A Brief Introduction to Air Defense System

Air defense system is designed to oppose missile by detecting and engaging processes through a specific airspace region. It consists of four different agents. These are:

- Radar System
- Weapon System
- Command Control Center
- Sub Air Defense System

Developed mission rehearsal tool has no limitation of numbers of radar, weapon system and sub air defense system into any air defense system. But, each air defense system has only one command control center. This hierarchical structure of air defense system is presented at Figure 2.1.

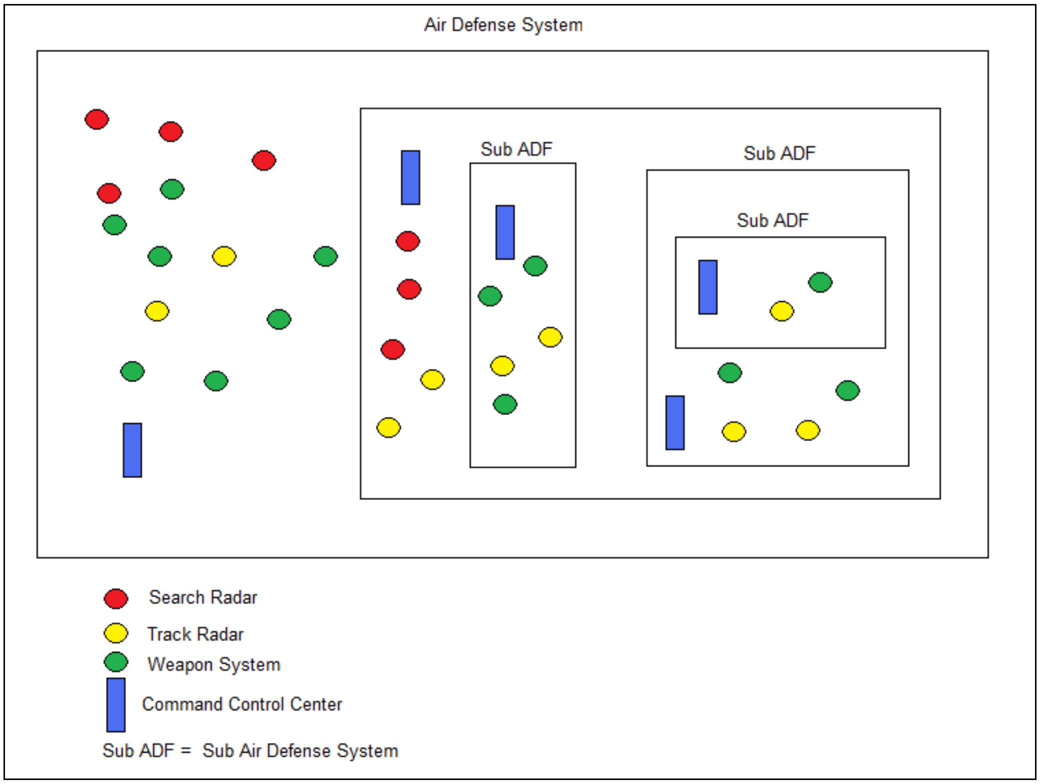

Figure 2.1 Hierarchical Structure of Air Defense System

Figure 2.2 shows the relationships between the Radars, the Command Center, and Weapon System.

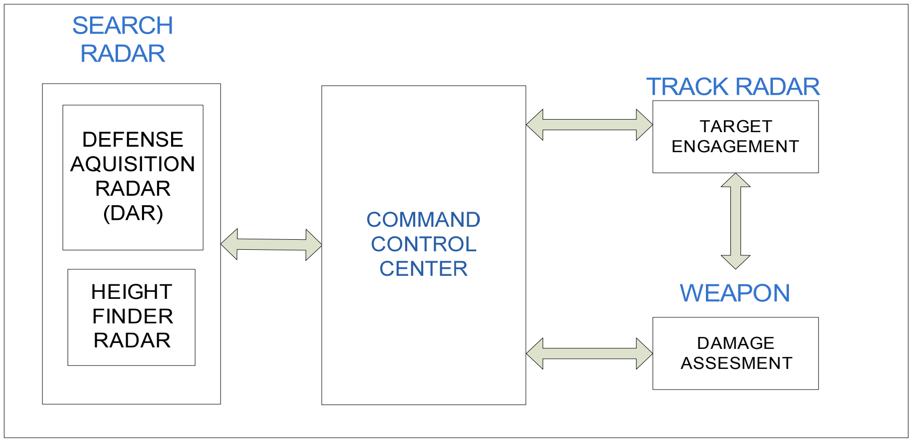

Figure 2.2 Relationships in Air Defense System

Command Control Center provides communication between Radar System and Weapon System. This agent is the decision box of the air defense system. All information about air defense system and threat is stored in it.

Radar System consists of target acquisition and target engagement processes. In the target acquisition processes, detection of target is accomplished. After finishing target acquisition part, target engagement is initiated by selecting weapon towards the target related to its type.

Weapon System is modeled as two different weapon types which are Surface-To-Air-Missile (SAM) and Antiaircraft Artillery (AAA). After performing target acquisition and engagement, damage assessment consisting of hit and kill probability calculation is done. And the type and number of weapon is determined based upon assessment. That is, if selected weapon does not succeed in killing missile, command control center select other appropriate weapons. This process continues until missile is killed. Figure 2.3 illustrates the processes in the air defense system.

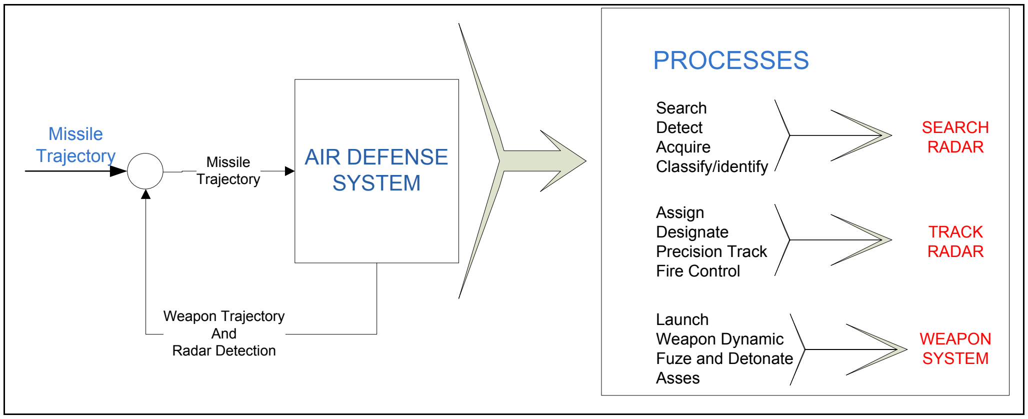

Figure 2.3 Air Defense System Processes [6]

Figure 2.4 shows that the communication model of air defense system is performed in this thesis. This figure illustrates communication network between different agents in the air defense system and also distribution of duty.

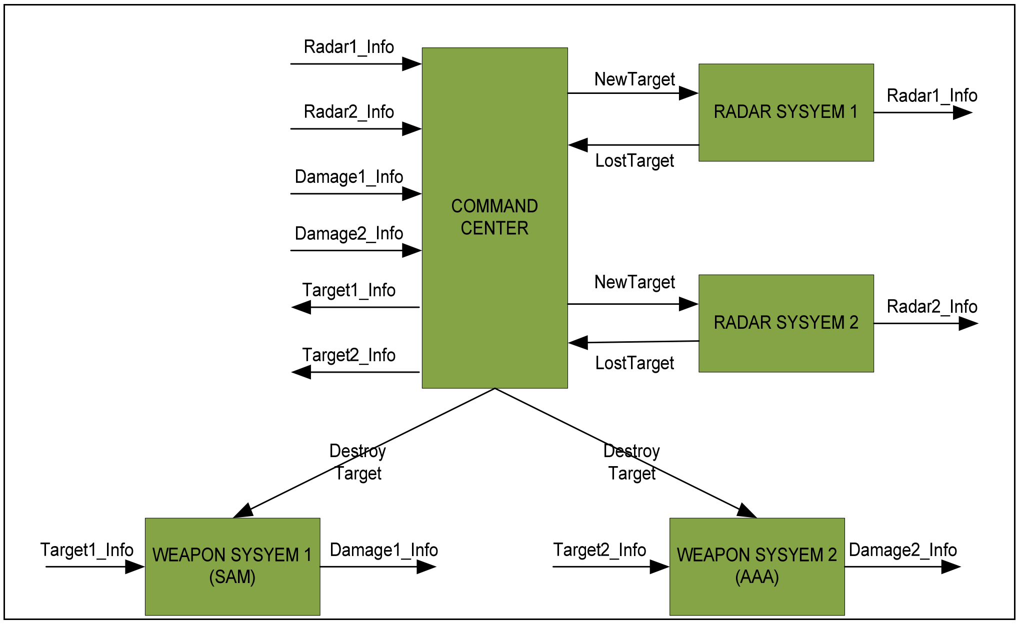

Figure 2.4 Communication Model of Air Defense System [6]

The generic order of tasks in air defense for cruise missile

- Early detection and warning of command and control center in own air defense system, and determination of location, direction of cruise missile.

- Target acquisition and tracking

- To protect its own defended area against foes by use of SAMs and AAAs (Defense Forces)

## 2.2 Subsystems of Air Defense System

### 2.2.1 Radar System

Radar System is mainly designed into two different types as Target Acquisition and Target Engagement. Target Acquisition and Engagement is done by Search and Track Radar respectively.

Target acquisition is the generic name of processes from search to identification of target. It consists of several parts:

- Search
- Detection
- Acquisition
- Recognition
- Identification

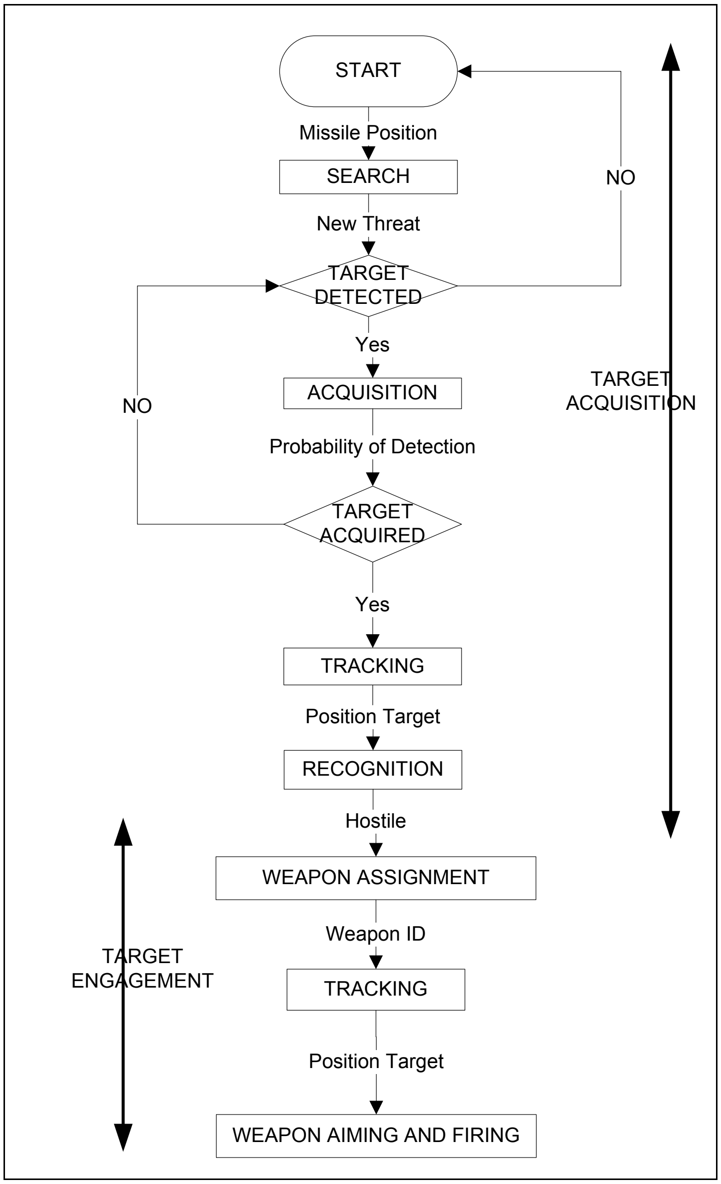

Figure 2.5 Flow Diagram of Target Acquisition and Engagement

Firstly, a search is made using sensors to detect a target. Secondly, after detecting target, it is acquired. This process is repeated during several scans of sensors. Finally, recognition and identification processes are performed. In the recognition process, the class of target such as tanks, guns is determined. If recognition is performed, identification is started to determine its specific type and identify whether the target is friendly or foe (IFF). Target Acquisition part is done used by Defense Acquisition

Radar (DAR). That is, DAR consists of search, detection, acquisition, and recognition and identification model. The inputs of DAR are taken from Command Control Center and the outputs of DAR which are azimuth and range of target are passed to target engagement part. DARs are mostly the Two-Dimensional-Radars, because of this; there also exist Height Finder Radar to obtain elevation of target. [3]

After obtaining a threat from search radar (Target Acquisition), Target Engagement is initiated as a number of control actions:

- Assignment
- Designation
- Precision Track
- Weapon Fire-Control And Aiming [7]

In the assignment part, the weapon (SAM or AAA) is selected related to coincidence of search sensor assignment. This air defense simulation is regarded as a one-on-one engagement simulation. That is only one weapon is launched according to activating track radar. In other words, each one is responsible for only one weapon.

Designation process includes the detection and acquires parts of search sensors. It is assumed that target data obtained from search radar is transferred to tracking sensor for activating sensor.

In the precision track process, accurate target state data is obtained for the weapon fire control process.

The Weapon Fire-Control and Aiming part provides target data to weapon before firing, based on available information about selected weapon.

In the air defense system, the radars are selected according to their range and area of usage. [7]. Table 2.1 shows some type of radars used in the air defense system.

Table 2.1 Radar Type [8]

| Radar | Type | Rated Range (nm(km)) |
|---|---|---|
| AN/FPS-36 | Defense Acquisition Radar | 200 (371) |
| AN/FPS-56 | Defense Acquisition Radar | 200 (371) |
| AN/FPS-61 | Defense Acquisition Radar | 200 (371) |
| AN/FPS-69 | Alternate Battery Acquisition Radar | 160 (297) |
| AN/FPS-71 | Defense Acquisition Radar | 160 (297) |
| AN/FPS-75 | Alternate Battery Acquisition Radar | 160 (297) |

#### 2.2.1.1 Radar Modeling

Radars are modeled by using Cookie-Cutter law which implies sure detection of target within the radar range and no detection beyond this range. [7] In this thesis, two radar types, namely search and track radar, are designed. As shown in the Figure 2.6, detection range of the search radar is longer than detection range of the track radar. And also detection range of the track radar is between the maximum effective and minimum weapon range.

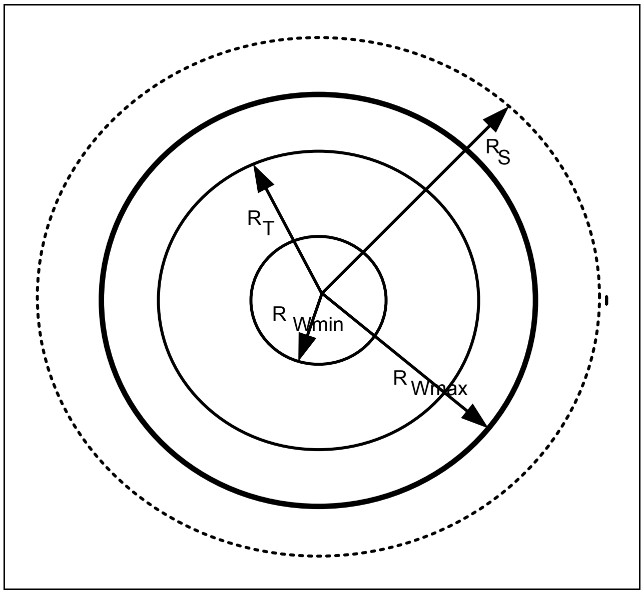

Figure 2.6 Engagement System Dimensions

$R_S$ : Detection Range of Search Sensor

$R_T$ : Detection Range of Track Sensor

$R_{Wmax}$ : Maximum Effective Range of Weapon

$R_{Wmin}$ : Minimum Range of Weapon

### 2.2.1.1.1 Radar Coverage Modeling

Radar coverage modeling determines LOS in 3D plane by using terrain variations. In the research, whole space from starting radar location to its maximum range is divided into many profiles along the azimuth direction. Each profile is divided many fragments to calculate LOS for each fragment. LOS values are limited between maximum and minimum altitude bounds of radar. It is assumed that missile is not detected by radar if LOS values are not in the range of these limits.

$$m = \frac{2\pi}{d\theta} \tag{2-1}$$

m= Number of profiles

$d\theta$= Azimuth angle increment

$$n = \frac{R_{\max} \times \sigma_{\max}}{dr} \tag{2-2}$$

n= Number of fragments for each profile

$R_{\max}$ = Maximum range of radar

$\sigma_{\max}$ = Maximum RCS value of missile

dr= Range increment

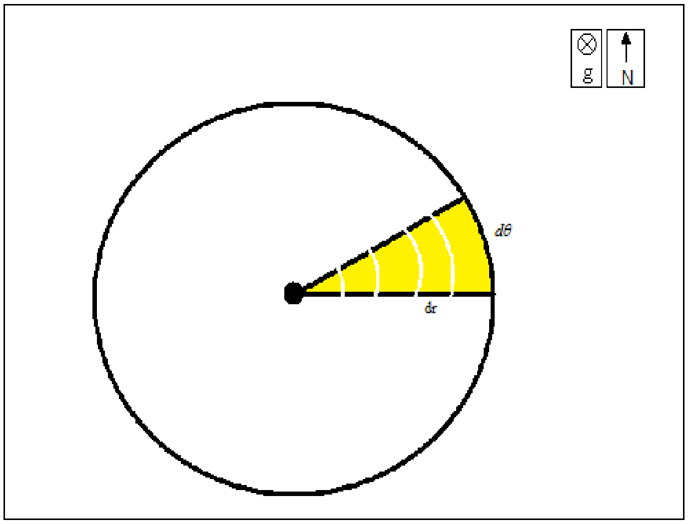

Figure 2.7 Demonstration of azimuth angle and range increment

Radar location contains data of radar geographic location in latitude, longitude and total altitude. Total attitude refers to the sum of radar elevation from sea level and system height and radar antenna height. These parameters are presented at Figure 2.8.

$$\text{Total Altitude} = \text{Radar Elevation} + \text{Radar's Antenna Height} + \text{System Height} \tag{2-3}$$

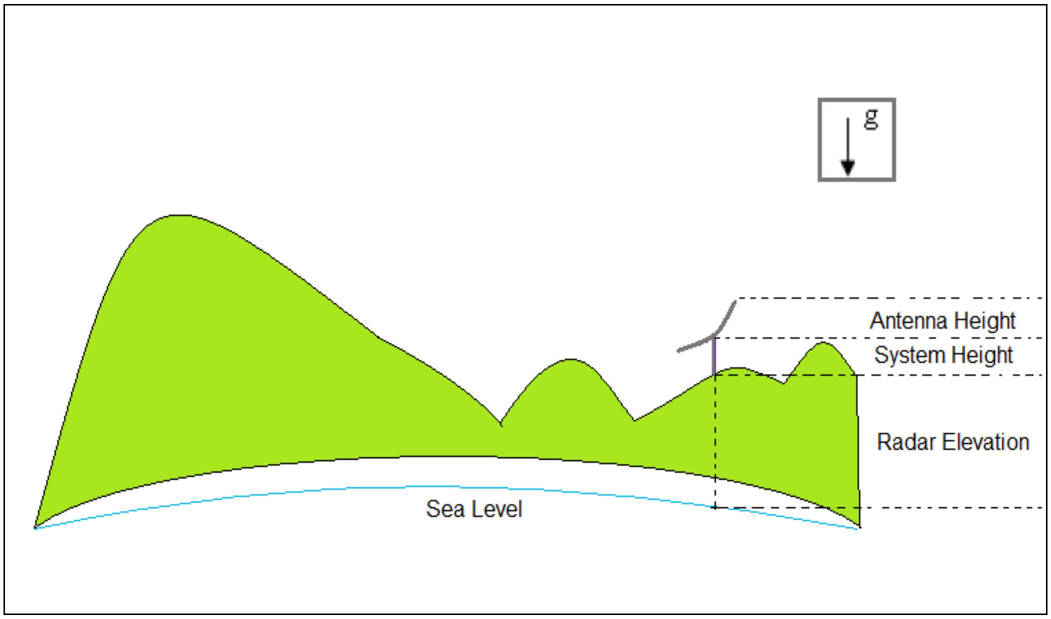

Figure 2.8 Illustration of Total Altitude Parameters

Radar coverage calculation is performed only once when scenario is begun for all radars in operating scenario and then is saved at database to use at all simulation time steps. It returns LOS value computed before when inquired according to current azimuth and range values. LOS values are not less than ground elevation for any location. Because they must be equal to ground elevation or be greater than it to see missile clearly. Therefore, firstly current elevation angle is calculated between ground elevation and radar's total elevation at the current range. Then, it is checked whether current elevation angle is greater than previous one determined by using previous range or not. If current elevation angle is greater than previous one, ground elevation at current range is set as LOS value. Otherwise, current LOS value is determined again by using previous elevation angle. It is illustrated at Figure 2.9 that LOS value for point C is calculated by using elevation angle of point B.

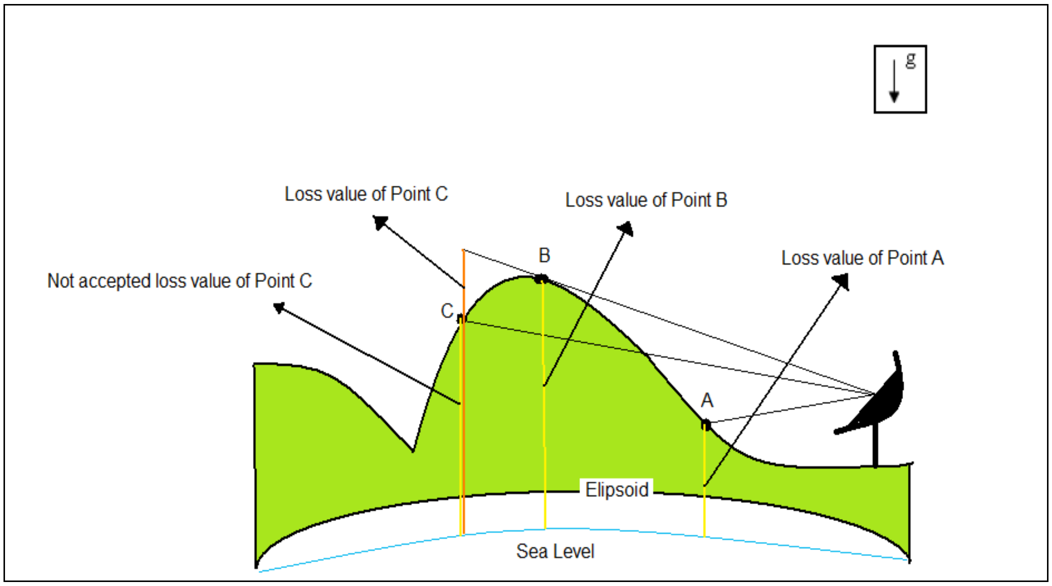

Figure 2.9 Loss values of points

#### 2.2.1.1.2 Search Radar (Early Warning Radar)

Search radar is the long-range radar whose primarily function is to provide target position data to alert command and control system. Its antenna is rotated through $360^{\circ}$ without knowing target position. It means that it scans whole space undirectionally. It is shown from Figure 2.10 that it consists of five different models.

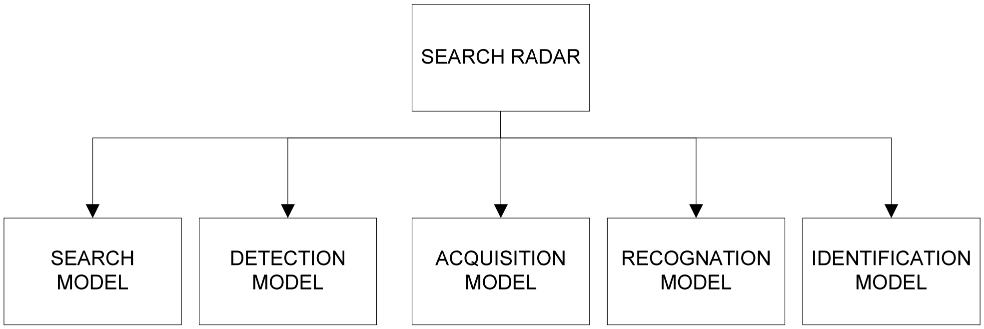

Figure 2.10 Models of Search Radar

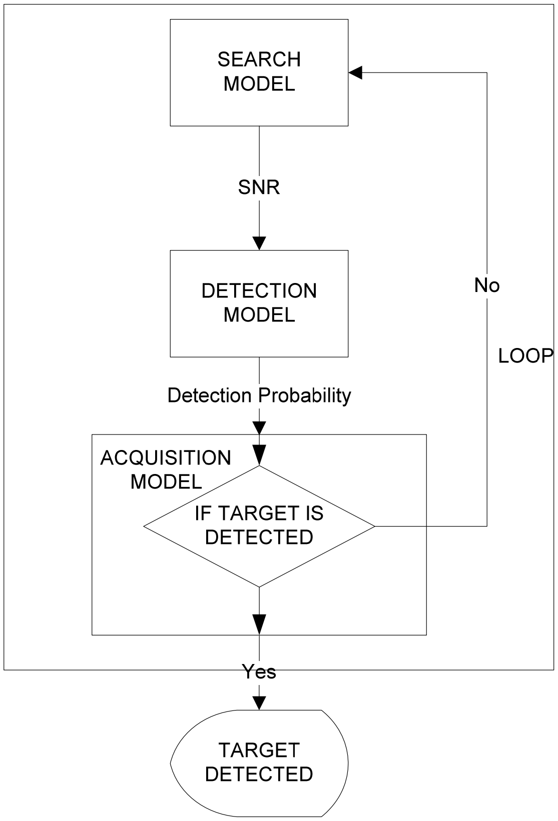

Figure 2.11-Processes of Search Radar Models

In this research, recognition and identification models are omitted, because only one missile is taken as threat and it always is accepted as hostile threat. Therefore, search radar's models are:

- Search Model
- Detection Model
- Acquisition Model

These models work in the loop until target to be detected.

#### 2.2.1.1.2.1 Search Model

This model decides in two stages to check whether threat approaches or not. Firstly, the range between threat and its position is determined to compare range of radar at each time increment.

$$\text{Range of Radar} = R_{\max} \times \sigma_{\max} \tag{2-4}$$

If calculated range is smaller than range of radar, it is passed to second stages to determine observability. In this stage, it is determined whether threat is within intervals of scanning angle or not. If it is within them, the flight altitude of threat is compared to loss value obtained from radar coverage at threat location to distinguish whether it hides behind terrain or not. In other words, terrain masking analysis is performed by line of sight. After all processes, if threat is observed, signal noise ratio is calculated to send designation model.

Equation to determine signal noise ratio can be written as [6]

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_0 N L B} \tag{2-5}$$

where

$G =$ Anttenna Gain

$\lambda =$ Wave lenght

$\sigma =$ Target cross section

$R =$ Range to target

$k =$ Boltzman constant

$T_0 =$ 290 Kelvin

$N =$ Noise factor of receiver

$L =$ System loss factor

$B =$ System bandwith of receiver

$P_t =$ Transmitted Power(watt)

$R_0$ Range to target at which signal noise ratio(S/N) is 1(0 db) is calculated by solving Equation (2.5). Then equation of S/N with a parameter of $R_0$ can be written as

$$\frac{\mathrm{S}}{\mathrm{N}} = (\frac{R_0}{R})^4 \tag{2-6}$$

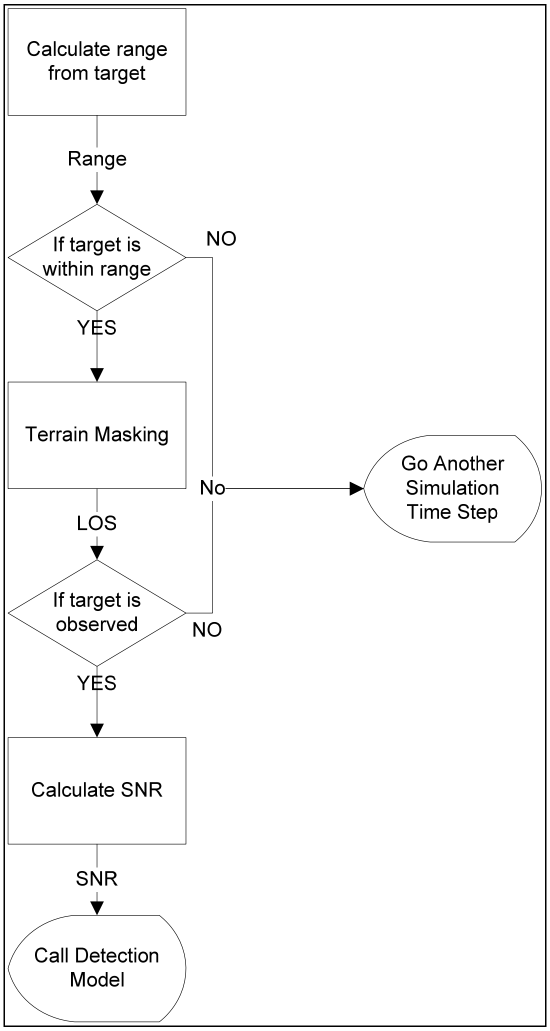

Figure 2.12-Processes of Search Model

#### 2.2.1.1.2.2 Detection Model

The detection process by radar consists of radiation of EM energy by a transmitter and electronic processing of the energy reflected back by target. The line of sight detection is done by this type detection. [3]

In this thesis, detection radar which is one of the electromagnetic sensors is examined.

The purpose of detection model is to obtain the detection probability of particular scan by using Signal-Noise-Ratio (SNR) taken from Search Model and Probability of False Alarm.

The typical range of false alarm values used in radar detection is $10^{-4}$ to $10^{-8}$ ; these numbers approximate false alarm times ranging from seconds to several minutes, respectively in the detection system. The basic procedure is to select a value for probability of false alarm ($P_{fa}$) and assume it is constant. $P_{fa} = 10^{-6}$ is a frequently used value. [3]

As a result, probability of false alarm will be assumed as constant and taken as $10^{-6}$ in this thesis.

$$p_d = 10^{-6^{\left(\frac{1}{1+S/N}\right)}} \tag{2-7}$$

After calculating probability of detection, target detection is determined in two ways. In the first one, a random number between zero and one is drawn. To determine whether target is detected or not, probability of detection is compared to it. If it is smaller than probability of detection obtained. It is assumed that target is detected. Otherwise, target is not detected. The second one, the probability of detection is compared to the threshold probability of detection for sensor used. For detecting target, the probability of detection is bigger than the threshold probability of detection for sensor. Otherwise, target is lost. In general, the first method is more realistic than the second one [7]. As a result of this, this model used the first decision criteria to detect target.

The output of detection model is the probability of target detection. If target is not detected, the probability of detection is assumed as zero at the particular scan. The value of probability detection is sent to Acquisition model at each simulation time step. The process of detection model is shown in the flow diagram of it at Figure 2.13 .

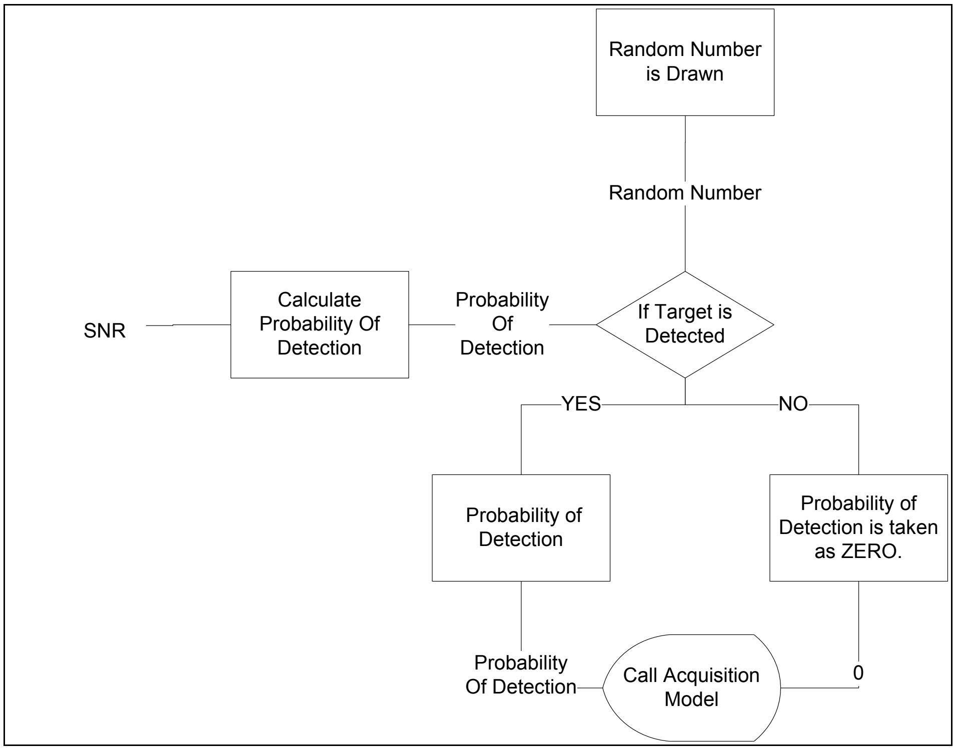

Figure 2.13 Flow Diagram of Detection Model

### 2.2.1.1.2.3 Acquisition Model

The probability of detection for all scans up to that simulation time is stored in acquisition Model. The criteria for acquisition is that the number of threshold detects is accomplished on number of successful detects of all scans. It works in two stages to make decision.

In the first stages, it is checked that the minimum detects out of the total scans exceed the threshold minimum number of successful detection. In this thesis, default threshold minimum number of successful detection can be adjusted from configuration file by user. If the minimum detects out of the total scans is less than the threshold, search model is called. That is, simulation goes on and skips to the next simulation time. Otherwise, the second stage starts. In this step, firstly the cumulative detection probability over all scans is calculated. It can be written as [7]

$$P_D = 1 - \prod_{i=1}^{n} (1 - p_i) \tag{2-8}$$

where

$P_D$ = T*he* cumulative detection over all scans

$p_i$ = single-scan probability of detection

n = the number of all scans

Secondly, a random number between zero and one draw to determine if detection occurs. The criterion for target detected is to exceed the cumulative detection of probability over threshold value.

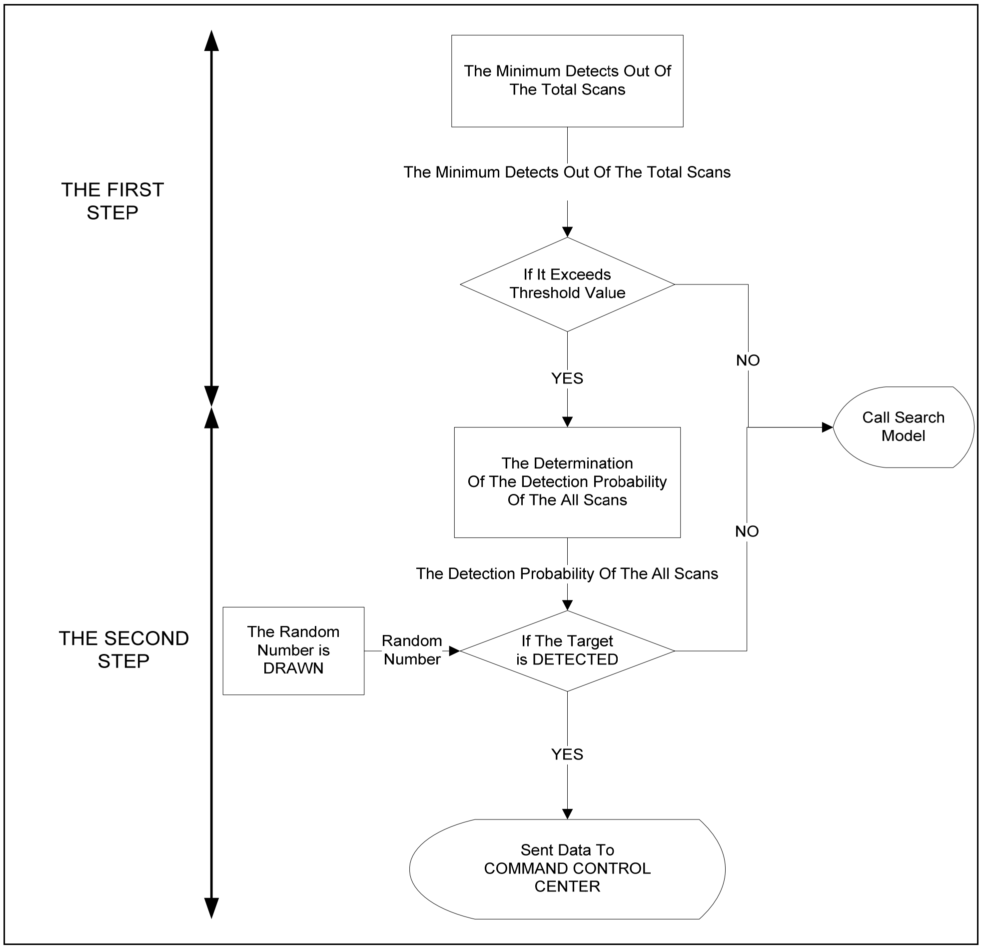

Figure 2.14 Flow Diagram of Acquisition Model

### 2.2.1.1.3 Track Radar

Track radar is the medium or short range radar whose primarily function is to follow threat for sending threat location to command and control system or weapon system related to operating situation. It is activated by command and control center to rotate towards threat. Because of its narrow beam width to minimize errors in measuring threat location, it scans only region where threat is likely to be. In most air defense system, track radar consists of five different models.

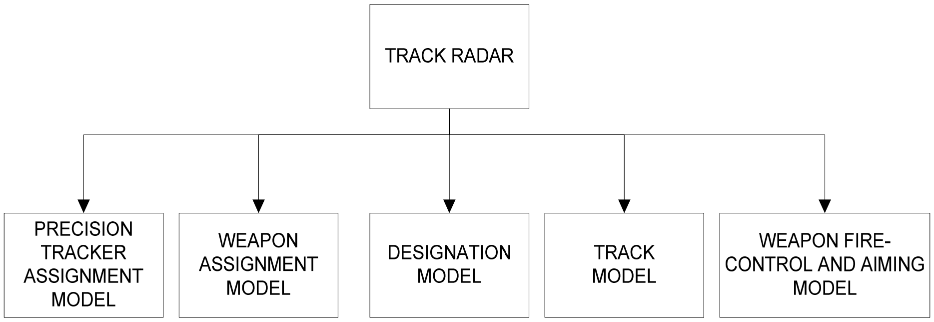

Figure 2.15 Models of Track Radar

Weapon Fire Control and Aiming model reproduces the aiming algorithm in the actual system, along with data that is sent to the weapon before firing. Aiming and weapon fire control errors are determined in it. And also dynamic and time- variable errors which are target prediction, ballistic closure and gun mount follow are calculated. In this research, these types of errors are negligible since it is assumed that track radar has perfect actual system, so this model is excluded.

These are models used for designing track radar:

- Precision Tracker Weapon Assignment Model
- Weapon Assignment Model
- Designation Model
- Track Model

Dependence of models is illustrated at Figure 2.16 .

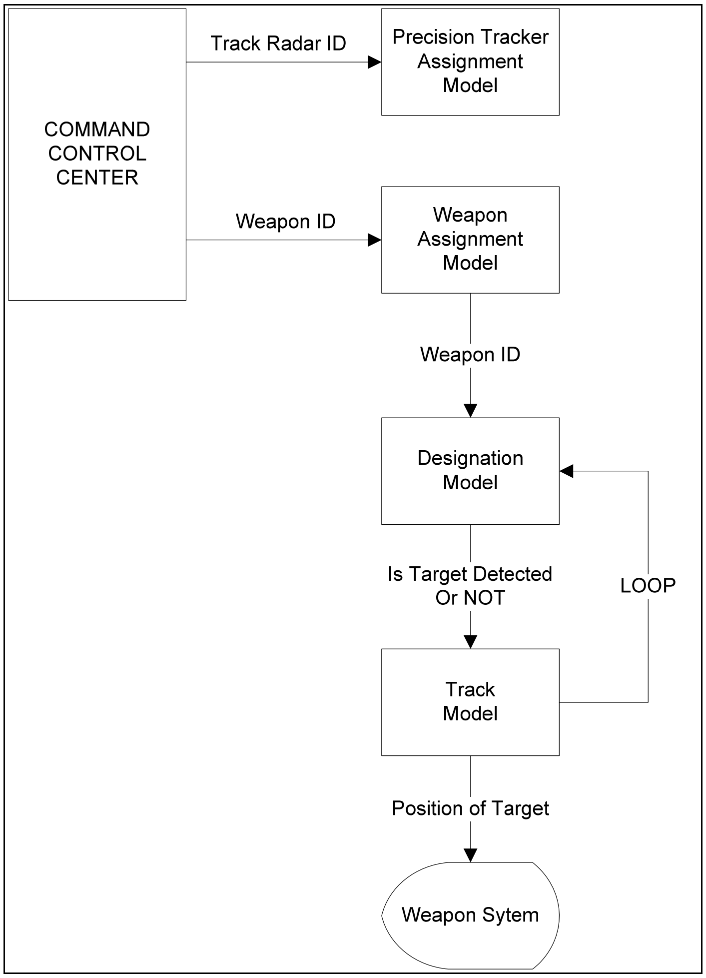

Figure 2.16 Flow Diagram of Track Radar

### 2.2.1.1.3.1 Precision Tracker Assignment Model

The aim of this model is to store track radar ID given from command control center. By doing this, the appropriate track radar in the air defense system is activated to initiate following target.

### 2.2.1.1.3.2 Weapon Assignment Model

This model is required in order to store weapon ID given from command control center. Therefore, the appropriate weapon in the air defense system is initiated to prepare firing. After activated, designation model is called.

### 2.2.1.1.3.3 Designation Model

Designation model is modeled as the scope of detection and acquisition model in the search radar mentioned above.

As it can be seen from Figure 2.17, Designation model is performed in three steps. In the first step, the slant range is calculated to make decision whether threat is within radar detection range or not.

In the second step, terrain masking analysis is done by line-of-sight analysis. The visibility of target is determined by result of it. The second step is finished when target is observed and then, the third step is started. Otherwise, track model is called to send information of the target disappeared.

In the third step, SNR and the probability of detection are determined by the same way mentioned in the search radar section. In this model, the probability of false alarm and the threshold value of detection probability, which be changed from configuration file by user, are assumed as constant. After obtaining probability of detection, it is compared with threshold value of detection probability to give information about target tracking.

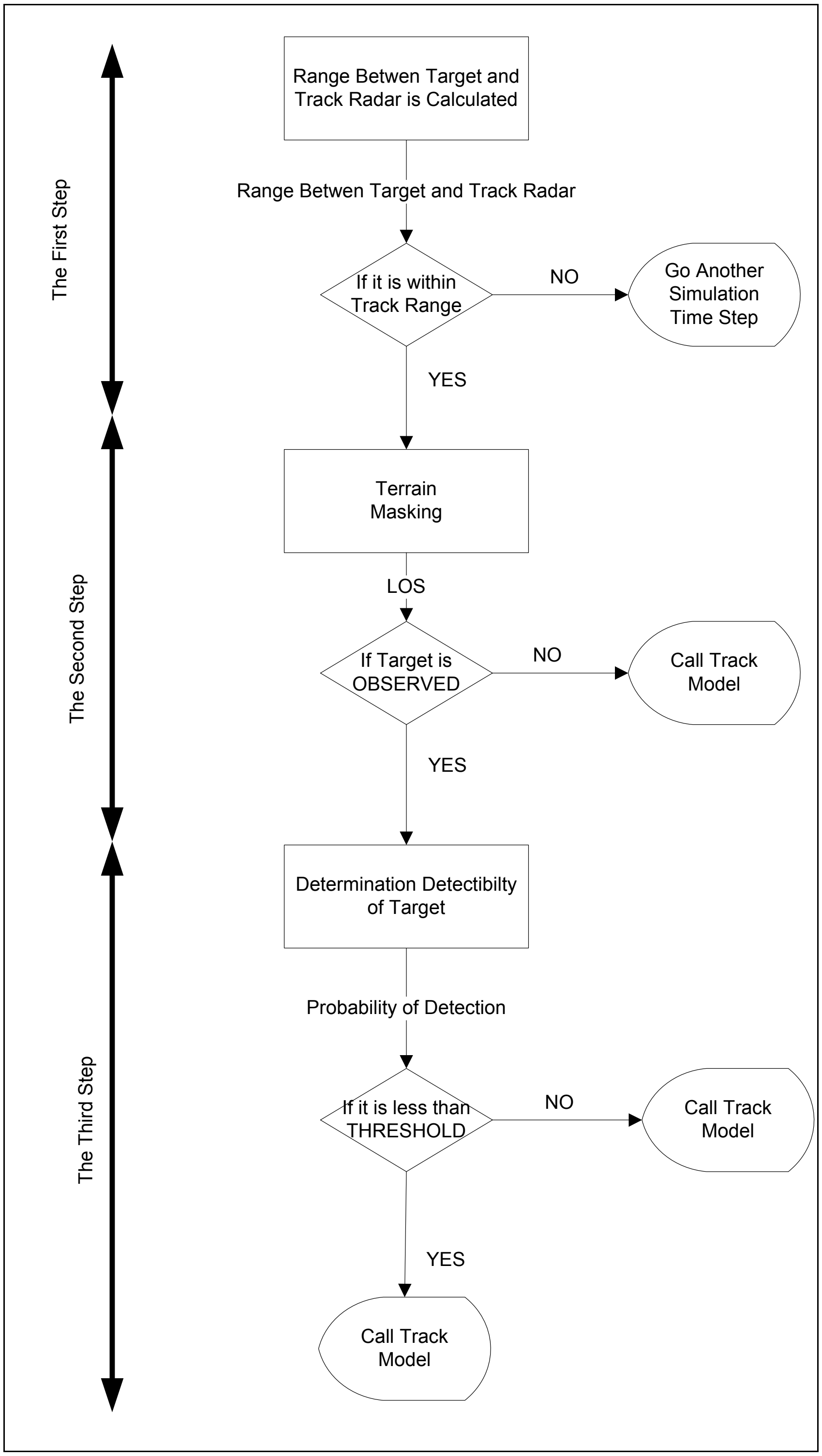

Figure 2.17 Flow Diagram of Designation Model

#### 2.2.1.1.3.4 Track Model

The main aim of track model is to supply target position data to weapon system in order to steer weapon towards threat. In this research, it is assumed that raw target data, which means missile range, azimuth and elevation, is directly taken from simulated missile. This data is converted to three dimensional positions in Cartesian coordinates in order to be used by weapon in track model.

Current target state data and previous target state data are supplied in order to send second one in case of losing target. This condition is illustrated at Figure 2.18.

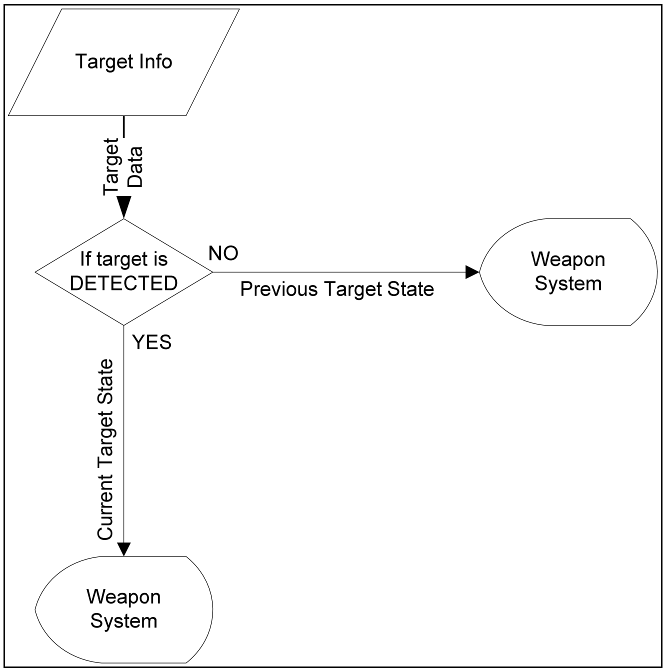

Figure 2.18 Process of Track Model

### 2.2.2 Weapon System

Weapon can be clarified as any thrown object carrying payload in order to protect defended area from enemy forces [10].

Different classifications of weapon can be done. According to its orientation towards threat, two major classes can be identified as guided and unguided weapons [11].
Guided missiles can be investigated in two major categories, tactical and strategic (ballistic, cruise) missiles [11].

Tactical missiles are short and medium range missiles which generally use seeker or ground based guidance. Unlike tactical missiles, strategic missiles are for long distance stationary targets.

In this research, weapon system covers guided and unguided weapons with 3D point mass model to be launched from ground to kill cruise missile (threat) and defend own operational area. Guided weapons include surface to air missile (SAM) which is medium or long range missile and unguided ones contain anti-aircraft artillery (AAA) which is short range projectile. Unguided weapons are fired towards estimated threat position because there is no chance for unguided weapon to be oriented towards threat. Unguided weapons are pointless towards fast and remote threats due to lack of steering commands.

As it can be seen from Figure 2.19 that weapon system occurs from four basic models.

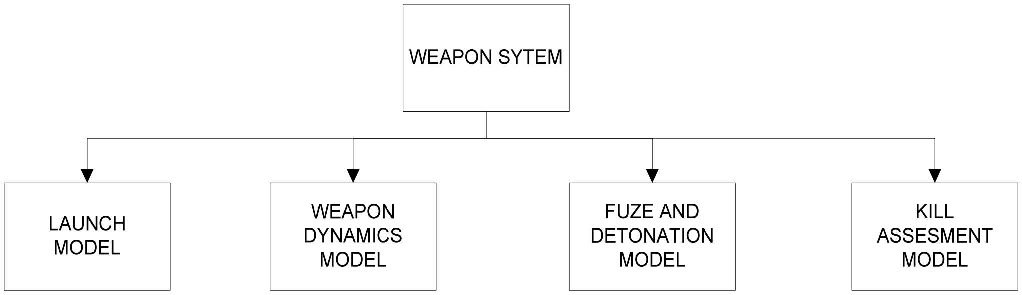

Figure 2.19 Models of Weapon System

In air defense system, weapon system makes preparation to fire according to information from command and control center. It keeps in contact with command and control center to send information about vulnerability of missile at end of its flight. Weapon dynamics and fuze and detonation models have different communication behavior with track radar to be assigned to it according to weapon types and weapon guidance types. For example, track radar keeps in contact with surface to air missile (SAM) with CLOS guidance during weapon flight. However, it is in communication with weapons including AAA and SAM with PN guidance until to be launched.

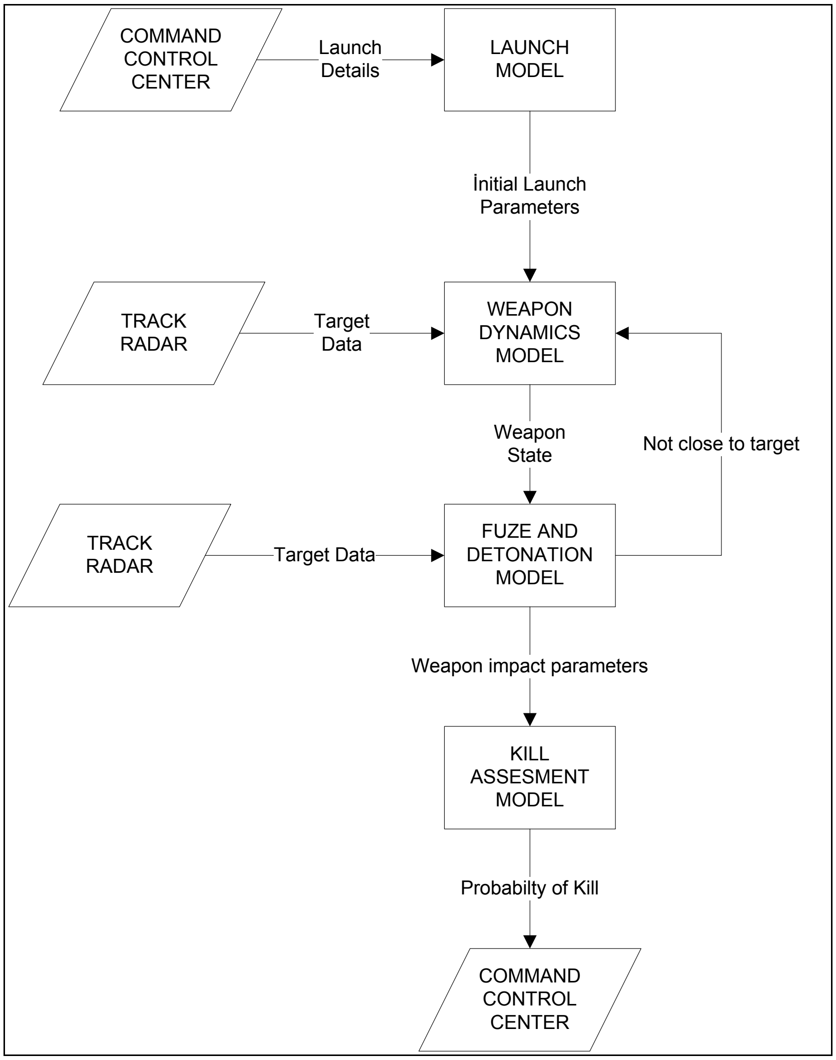

Figure 2.20 Flow Diagram of Weapon System

### 2.2.2.1 Launch Model

The launch model is necessary to adjust launch conditions which are azimuth and elevation of launcher and initial velocity vector of weapon taken from command and control center in order to increase the likelihood of hitting target. After making these preparations, it calls weapon dynamics model to initiate to weapon flight.

### 2.2.2.2 Weapon Dynamics Model

The purpose of this model is to clarify and model the behavior of weapon system during flight period [13]. Moreover, it is declared as the relation between the motion of weapon and the forces acting on weapon body.

The input and output of this model are target position and weapon trajectory at each simulation time step, respectively.

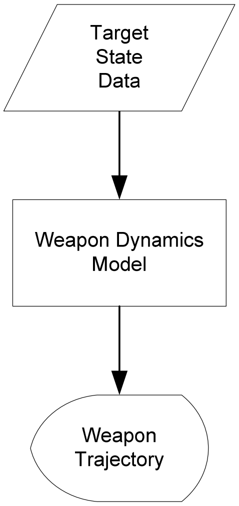

Figure 2.21 Input and Output of Weapon Dynamics Model

This model includes nine basic sub-models that will be described in later sections.

- Dynamic Model
- Aerodynamic Model
- Atmosphere Model
- Thrust Model

- Gravity Model

- Coriolis Model

- Guidance Model

- Autopilot Model

- Earth Model

In this research, two reference coordinate systems, fixed to earth surface, are used.

- Local Cartesian coordinate system

- Geographic coordinate system (Spherical earth coordinate system)

The origin of local Cartesian coordinate system ($e(x, y, z)$) with its X axis pointing towards north, Y axis pointing towards east and Z axis pointing towards down to the centre of the earth has zero height at the point that weapon simulation is launched. [14]

$X_e$ *Axis:* Ellipsoid North
$Y_e$ *Axis*: Ellipsoid East
$Z_e$ *Axis*: Ellipsoid Down

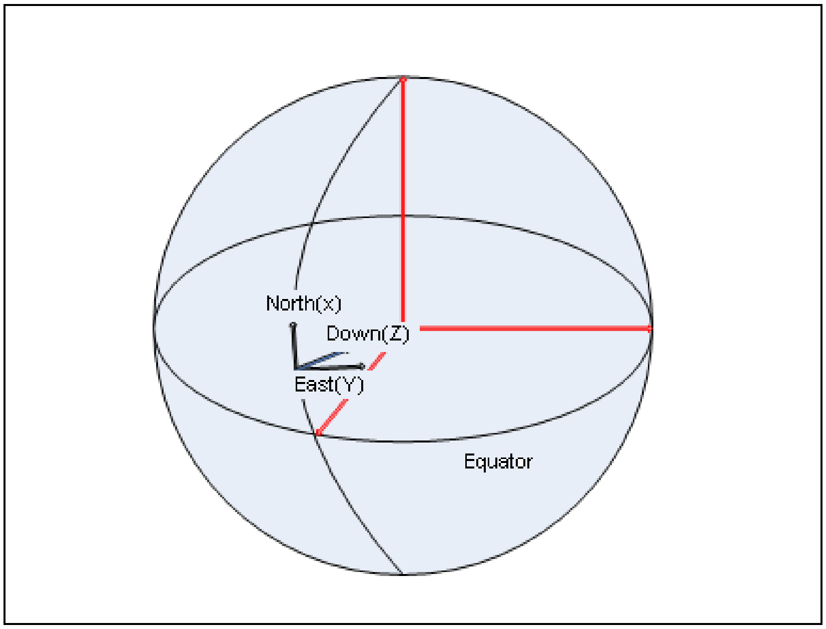

Figure 2.22 Local Coordinate System

Spherical earth coordinate system (c(x, y, z)), whose elevation of start location is equal to zero when weapon is fired, is required to determine elevation of weapon from earth surface during flight. [14]

$X_c$ *Axis:* Ellipsoid North

$Y_c$ *Axis*: Ellipsoid East

$Z_c$ *Axis*: The direction from earth surface to weapon position at any time

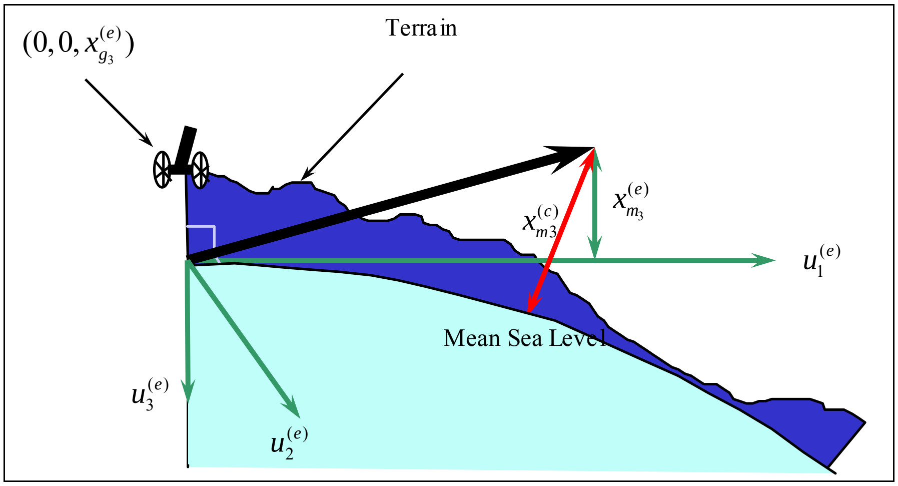

Figure 2.23 Spherical Earth Coordinate System

### 2.2.2.2.1 Dynamic Model

The purpose of dynamic model based on Newton’s second law is to obtain weapon position, velocity and acceleration during flight. A force acting weapon body frame, considering rigidly body, at each instant of flight time produces an instantaneous acceleration of the center of it. This instantaneous acceleration, calculated by using total forces on it and its instant mass, is directly proportional to the total force.

$$\bar{a}_w^{(e)} = \frac{\sum \bar{F}^{(e)}}{m_w} \tag{2-9}$$

Total force acting weapon can be categorized as [14],

- Lift force obtained from aerodynamic model
- Drag force obtained from aerodynamic model
- Gravity force obtained from gravity model

- Thrust force obtained from thrust model

- Coriolis force obtained from coriolis model

Total force acting on weapon is determined by summation of these vectorial forces.

$$\sum \bar{F}^{(e)} = \bar{F}_L^{(e)} + \bar{F}_D^{(e)} + \bar{F}_T^{(e)} + \bar{F}_G^{(e)} + \bar{F}_C^{(e)} \tag{2-10}$$

After obtaining total force, instantaneous acceleration is determined by the way that total force is divided by its instant mass.

$$\bar{a}_w^{(e)} = \begin{bmatrix} a_{w_1}^{(e)} \\ a_{w_2}^{(e)} \\ a_{w_3}^{(e)} \end{bmatrix} = \frac{1}{m_w}\left(\bar{F}_L^{(e)} + \bar{F}_D^{(e)} + \bar{F}_T^{(e)} + \bar{F}_G^{(e)} + \bar{F}_C^{(e)}\right) \tag{2-11}$$

Instant mass is determined by sum of reference mass and fuel mass. The reference mass refers to weapon mass without fuel mass.

$$m_w^{(e)} = m_{w_{ref}}^{(e)} + m_{fuel}^{(e)} \tag{2-12}$$

The equations of weapon velocity and position can be written as,

$$\bar{v}_w^{(e)} = \bar{v}_{w_0}^{(e)} + \int_0^t \bar{a}_w^{(e)} dt \tag{2-13}$$

$$\bar{x}_w^{(e)} = \bar{x}_{w_0}^{(e)} + \int_0^t \bar{v}_w^{(e)} dt \tag{2-14}$$

#### 2.2.2.2.2 Earth Model

Earth model is utilized in order to transform weapon position from local Cartesian coordinate system to earth coordinate system [14]. The equation required transformation can be written as

$$\overline{x}_m^{(c)} = \begin{bmatrix} x_{m_1}^{(e)} \\ x_{m_2}^{(e)} \\ \dfrac{(x_{m_1}^{(e)2} + x_{m_2}^{(e)2})}{2R} - x_{m_3}^{(e)} \end{bmatrix} \tag{2-15}$$

$R = 6.356766E6$ meter

#### 2.2.2.2.3 Atmosphere Model

This model is required to determine adverse atmosphere effects on weapon. Aerodynamic forces and moments, acting weapon body, are formed over surface of it by the stream of atmospheric air. [13].

The primary atmosphere properties used in determining aerodynamic forces are:

- Air density
- Air pressure
- Speed of sound
- Air Temperature
- Wind Speed

The aim of this model is to provide atmosphere properties at instantaneous altitude of weapon during simulation by using METCM format, defined in STANAG. 4082. [15]

The equation of air density can be written as

$$\rho = \frac{0.003483678761P}{T} \tag{2-16}$$

The speed of sound equation can be written as

$$c = 20.046796T^{1/2} \tag{2-17}$$

The unity of air pressure, temperature, density and sound of speed are Pascal, Kelvin, $kg/m^3$ and m/s respectively.

### 2.2.2.2.4 Aerodynamic Model

Pressure and shearing forces are two basic types of aerodynamic forces acting weapon body. Shearing force, tangential, is generally defined as friction force. Aerodynamic forces and moment on weapon body are occurred at each computation time of simulation from sum of these two forces.

In this research, aerodynamic model is responsible for calculating aerodynamic forces acting on weapon body. According to Mach number at each computation time of simulation, aerodynamic coefficients, used in determination of aerodynamic forces, are obtained from aerodynamic file illustrated at Table 2.2.

Table 2.2 Example of Aerodynamic File

| Mach | $C_{L_\alpha}$ | $C_{D_0}$ | $C_{D_{\alpha^2}}$ |
|---|---|---|---|
| 0.1 | 0.3471 | 0 | 107.9548743 |
| 0.33 | 0.3563 | 0 | 109.8452913 |
| 0.53 | 0.3626 | 0 | 112.2988111 |
| 0.71 | 0.362 | 0 | 114.7121093 |
| 0.86 | 0.4187 | 0 | 120.3833602 |
| 1 | 0.6075 | 0 | 135.8686905 |
| 1.05 | 0.6821 | 0 | 136.8340098 |
| 1.12 | 0.6427 | 0 | 135.4664742 |
| 1.19 | 0.5933 | 0 | 134.259825 |
| 1.27 | 0.5504 | 0 | 128.5483526 |
| 1.36 | 0.5208 | 0 | 125.0892918 |
| 1.46 | 0.501 | 0 | 119.2169327 |
| 1.58 | 0.4859 | 0 | 107.5526579 |
| 1.71 | 0.4809 | 0 | 100.7954229 |
| 1.87 | 0.4731 | 0 | 94.96328549 |
| 2.04 | 0.4812 | 0 | 89.21159136 |
| 2.23 | 0.4423 | 0 | 82.937016 |
| 2.46 | 0.4114 | 0 | 76.98421364 |
| 2.71 | 0.3819 | 0 | 71.43362771 |
| 3 | 0.3508 | 0 | 65.92326336 |

### 2.2.2.2.4.1 Lift Force

Lift force, defined as desirable quantity, is produced by the combined effects of airflow over weapon surface in order to maneuvering weapon towards to threat. The direction of lift force is perpendicular to direction of weapon velocity vector.

Angle of attack to carry out commanded acceleration obtained from weapon guided algorithm is calculated from autopilot model discussed in more detail in later section. This angle creates lift force in the direction of commanded acceleration vector. In other words, the lift force and commanded acceleration are in the same direction. Lift force can not be determined when angle of attack and direction of lift force are not produced by guided algorithm.

The equations to calculate lift force can be written as

$$C_L = C_{L_\alpha} \alpha_t \tag{2-18}$$

$$Q = 0.5 \rho V^2 \tag{2-19}$$

$$V_w = \left| \bar{v}_w^{(e)} \right| = \sqrt{v_{w_1}^{(e)2} + v_{w_2}^{(e)2} + v_{w_3}^{(e)2}} \tag{2-20}$$

.

$$\bar{v}_w^{(e)} = V_w \begin{bmatrix} u_{v_{w1}}^{(e)} \\ u_{v_{w2}}^{(e)} \\ u_{v_{w3}}^{(e)} \end{bmatrix} \tag{2-21}$$

By using values obtained from equations above, lift force are calculated with respect to following equations.

$$F_L = QSC_L \tag{2-22}$$

$$\bar{F}_L^{(e)} = F_L \begin{bmatrix} u_{l_1}^{(e)} \\ u_{l_2}^{(e)} \\ u_{l_3}^{(e)} \end{bmatrix} \tag{2-23}$$

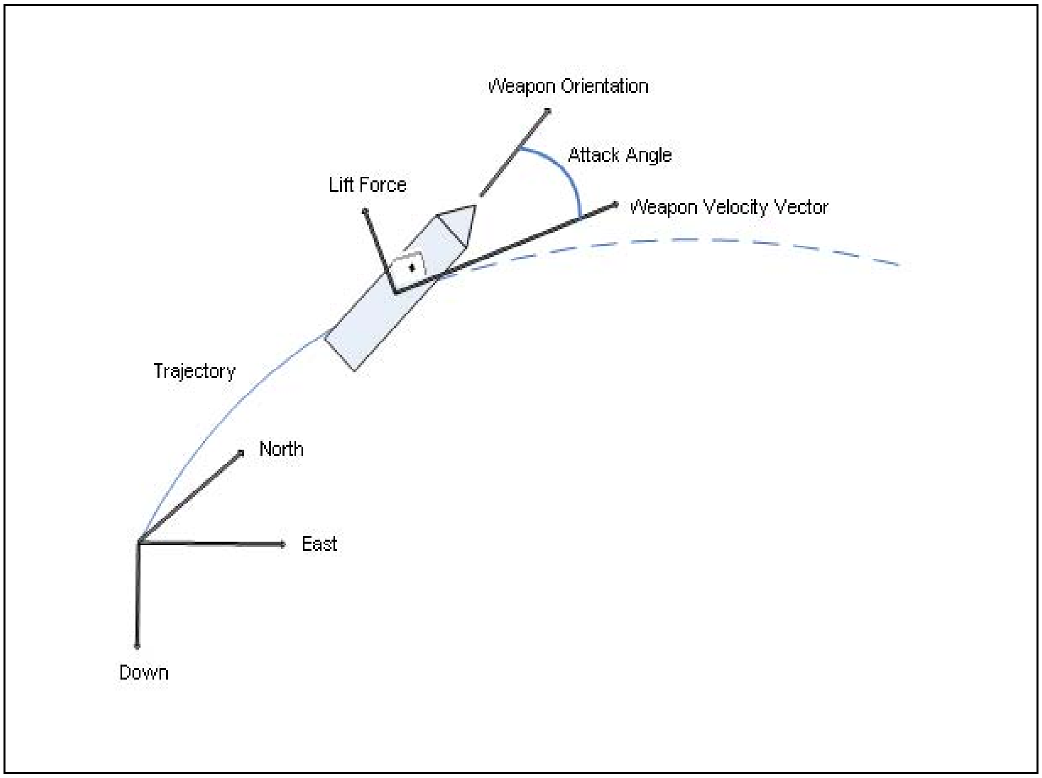

Figure 2.24 Lift Force

### 2.2.2.2.4.2 Drag Force

Drag force, defined as undesirable quantity, is the resistance force that oppose weapon through weapon velocity vector. The effects of angle of attack is taken into consideration on drag force at condition that weapon has guidance.

Equation to determine drag force can be represented as

$$C_D = C_{D_0} + C_{D_{\alpha^2}}(\alpha_t)^2 \qquad (2\text{-}24)$$

$$F_D = QSC_D \qquad (2\text{-}25)$$

$$\bar{F}_D = -F_D \begin{bmatrix} u_{v_{w_1}}^{(e)} \\ u_{v_{w_2}}^{(e)} \\ u_{v_{w_3}}^{(e)} \end{bmatrix} \tag{2-26}$$

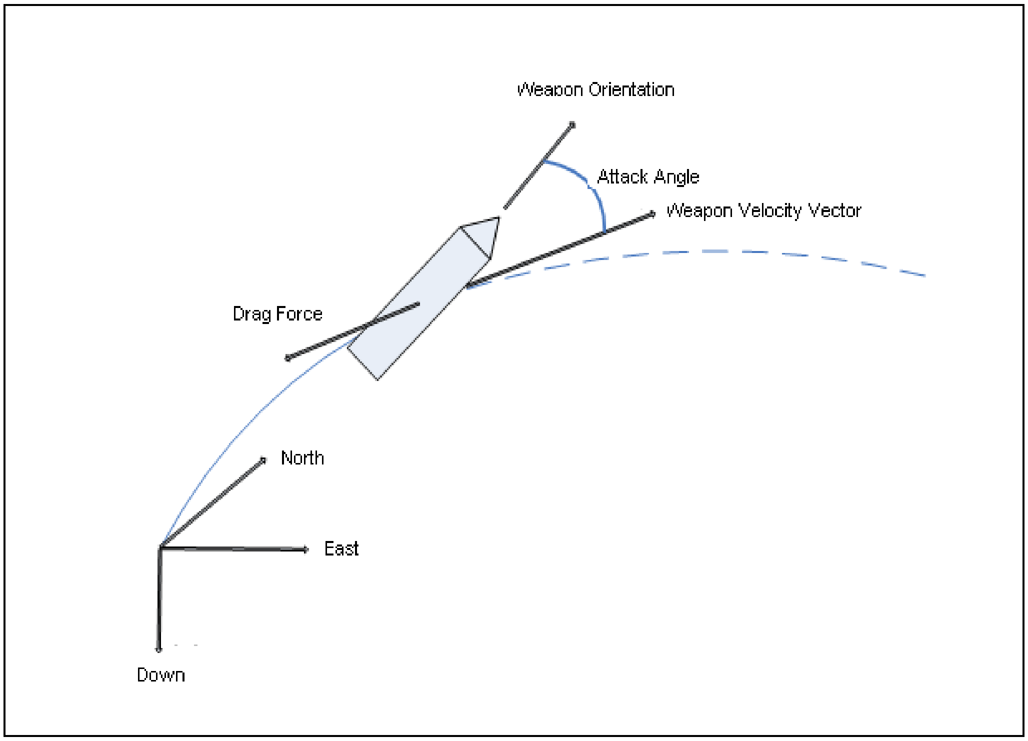

Figure 2.25 Drag Force

### 2.2.2.2.5 Thrust Model

The weapon propulsion system is required to generate thrust for overcoming drag force effects and accelerating weapon at each computation time of simulation. Moreover, decreasing fuel mass of weapon shifts the mass center of weapon, so the moment of inertia lessens.

In operational system, several motor types have been used as propellant power for weapon [13]. These are:

- propellant rocket motors
- air-augmented rockets
- liquid propellant rockets
- turbojet engines
- ramjet engines

The power of solid propellant rocket motor is only affected by on the design of the propellant grain and is not based on Mach number and weapon flight altitude. Moreover, solid propellant rocket motor has a capability of operating at high altitude due to not depending on weapon flight altitude. But the control of weapon speed is so difficult because there is no thrust control in this type [13].

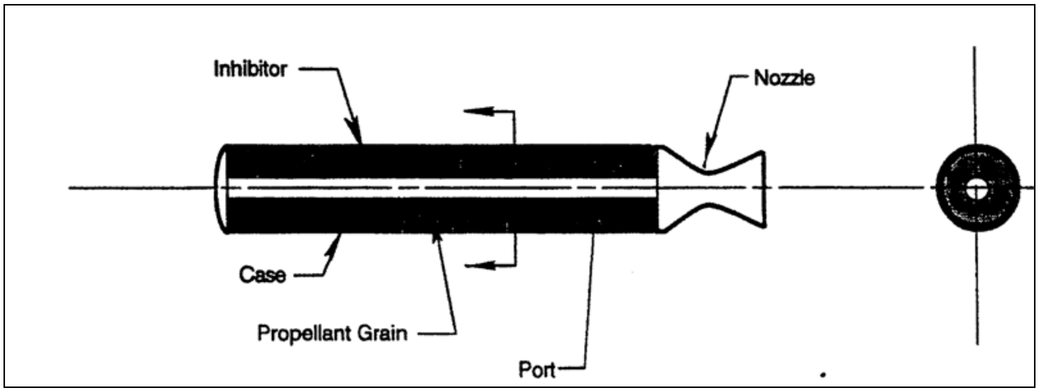

Figure 2.26 Typical Solid Propellant Rocket Motor [13]

The performance of air-augmented rocket is affected from air condition, operating flight conditions and design of propulsion system [13].

Unlike propellant rocket motors, turbojet engine, mainly used by subsonic cruise missiles, has a capability of controlling weapon thrust at instantaneous flight time [19]. Controlling weapon thrust gives a chance of changing weapon speed and range.

In this research, thrust model is utilized to provide a force against drag force.

Reference thrust force is attained by product of specific fuel consumption and the quantity of fuel consumption.

Equations to determine thrust force can be written as

$$F_{P_{ref}} = I_{sp}\dot{m}_{Fuel} \tag{2-27}$$

$$F_P = F_{P_{ref}} + (p_{ref} - p_a)A_e \tag{2-28}$$

$$\overline{F}_P^{(e)} = \begin{bmatrix} F_{P_1}^{(e)} \\ F_{P_2}^{(e)} \\ F_{P_3}^{(e)} \end{bmatrix} = F_P \begin{bmatrix} u_{b_1}^{(e)} \\ u_{b_2}^{(e)} \\ u_{b3}^{(e)} \end{bmatrix} \tag{2-29}$$

Total mass of weapon is decreased because of fuel mass reduction during flight simulation. The instantaneous mass can defined as

$$m_{fuel} = m_{fuel_0} - \int_0^t \dot{m}_{fuel} dt \tag{2-30}$$

In this model, it is assumed that fuel consumption time does not depend on fuel temperature, pressure at flight altitude and the rotation of weapon.

### 2.2.2.2.6 Gravity Model

Based on Newton's law of gravitation, there is an attraction force, depending on mass of particles and range between particles, in the universe. The direction of this force is the direction of the line connecting the particles.

In this system, gravity model is required to determine gravitational force. While calculating gravity force, the variations of reference gravity acceleration due to world flatness, and the instant distance between weapon and center of world is taken into consideration.

Gravity force is determined with respect to following equations [14].

$$\overline{F}_G^{(e)} = m_w . \overline{g} \tag{2-31}$$

$$R = 6.356766x10^6 m \tag{2-32}$$

$$\overline{g}^{(e)} = g_0 \begin{bmatrix} \frac{X_1}{R} \\ \frac{X_2}{R} \\ 1 - \frac{2X_3}{R} \end{bmatrix} \tag{2-33}$$

$$g_0 = 9.80665\left[1 - 0.0026\cos(2.\text{lat})\right] \tag{2-34}$$

### 2.2.2.2.7 Coriolis Model

The purpose of this model is to determine Coriolis force acting weapon body resulted from rotation of earth because the dynamics equations used in this thesis are based on coordinate frame with rotating earth.

Coriolis force is determined with respect to following equations [14].

$$\vec{F}_C = -2m_m(\vec{\omega} x \vec{v}_m) \tag{2-35}$$

$$\overline{\omega}^{(e)} = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} = \begin{bmatrix} \Omega\cos(lat)\cos(AZ) \\ -\Omega\cos(lat)\sin(AZ) \\ \Omega\sin(lat) \end{bmatrix} \tag{2-36}$$

$$AZ = \text{atan}\left(\frac{v_{m_2}^{(e)}}{v_{m_1}^{(e)}}\right) \tag{2-37}$$

$$\Omega = 7.292115x10^{-5}\,\text{rad/s} \tag{2-38}$$

$$\overline{F}_C^{(e)} = -2m_m(\tilde{\omega}^{(e)}.\overline{v}_m{}^{(e)}) = -2m_m \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix} \begin{bmatrix} v_{m_1}^{(e)} \\ v_{m_2}^{(e)} \\ v_{m_3}^{(e)} \end{bmatrix} \tag{2-39}$$

#### 2.2.2.2.8 Guidance Model

Guidance can be described as strategy that hardware, the functions, and the processes used to steer weapon towards threat, improving weapon accuracy.

Guidance system can be divided up into two basic groups. [13], [20].

- Ground Guidance and Tracking
- Homing Guidance and Tracking

Ground guidance and tracking refer to steer weapon by means of sensors and computer located on the ground. Devices, located on the ground, trace target position, interpret weapon position relative to target position, and then send commands to the weapon to head towards target. Therefore, a weapon with ground guidance should have instruments to receive these commands and control actuation system to perform the required control action.

The first reason for selecting ground guidance is to decrease cost of short range weapon since this type of weapon follow its flight path easily by means of this guidance system.

The second reason is that very large target tracking sensor is not required for long-range weapon, so the cost also decreases for this type of weapon.

The ground guidance system is divided into three basic types [13].

- Command
- Track-via-Missile
- Command to Line of Sight

Guidance processor, used in changing the weapon flight path, provides guidance command sending from weapon launch point and is submitted to weapon by command guidance system. This system is generally used for surface to air missile. The target and weapon position are the measurements of this system. This system, illustrated at Figure 2.27, has large measurement errors for long range weapons, so these types of weapon should have large warhead to damage target effectively.

Due to large measurement errors in command guidance, the sensor located on weapon is used to get weapon position in addition to target position in track-via-weapon guidance system. The relative distance between them, minimum range, is determined by means of weapon position and target position by computer located on the ground. The weapon is steered along the direction of this relative distance to intercept with target. This guidance system is shown at Figure 2.28.

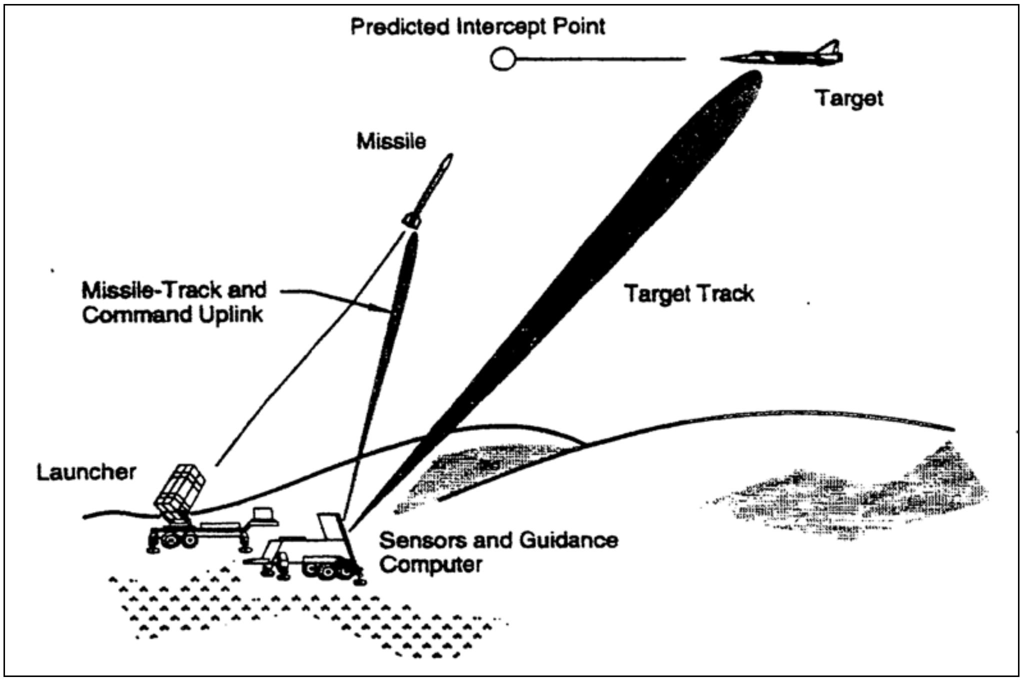

Figure 2.27 Command Guidance [13]

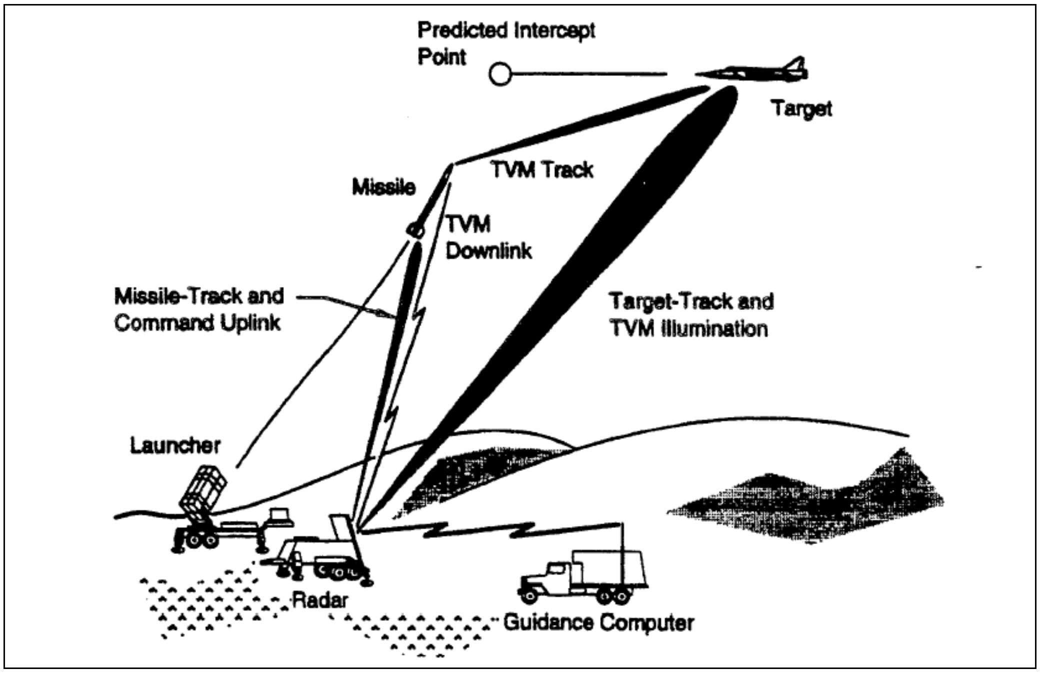

Figure 2.28 Track-via- Missile Guidance System [13]

Command line of sight guidance system, tracking target and holding weapon within the center of a controlled directional energy beam, is also a ground guidance system. This guidance type always tries to keep weapon at the center of beam.

In contrast to ground guidance system, weapon steers towards target by means of guidance devices located on weapon in homing guidance system. In other words, onboard seekers holds weapon within the seeker boresight axis towards target with gathering energy spreading from target. Components of homing weapon are shown at Figure 2.29.

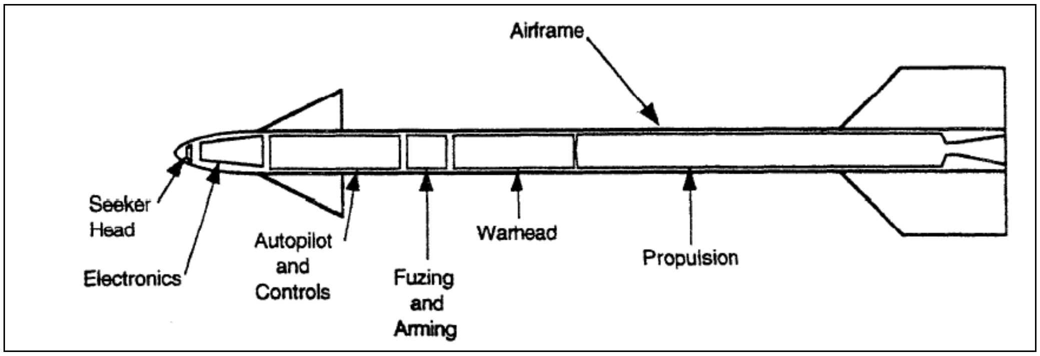

Figure 2.29 Components of Homing Weapons [13]

This guidance system can defined as two point guidance because the position of weapon and target are only considered to generate guidance commands.

Moreover, it can be categorized three main groups depending on how signal is produced.

- Active Homing
- Semi-Active Homing
- Passive Homing

An active homing guidance system produces signal for illuminating target and collects reflected energy from target onboard weapon. This system determines relative distance and bearing from weapon to target along the line of sight direction. And also it calculates rate of distance change to determine guidance command required for steering weapon towards target. An example of active homing guided missile is Harpoon AGM. [13]

A semi-active homing guidance system uses reflected energy produced by transmitter located on the ground. Transmitter continues sending signal to weapon by using the ground control continuous wave radar until the weapon hits target. This guidance system evaluates angular rates of line of sight from weapon to target and bearing between target and weapon. An example of semi-active homing guided missile is Bloodhound SAM. [13]

The source of a passive homing guidance is based on the natural signal (heat source) produced by IR and RF. After firing weapon, ground based launch system is not required to track target. This approach is known as “fire and forget” in literature. An example of passive homing guided missile is Mistral SAM. [13]

In this research, command line of sight guidance law (CLOS) for ground guidance system and proportional navigation guidance law (PN) for homing guidance are modeled for guidance system of surface to air missiles. As anti-aircraft artillery is not guided weapon, guidance system is not designed for these weapons.

## 2.2.2.2.8.1 Command to Line of Sight Guidance (CLOS)

The purpose of this guidance system is to generate guidance command for fixing weapon through line of sight between target and weapon launch point located on the ground. The cross range error is a distance between target and line of sight (LOS) [17].

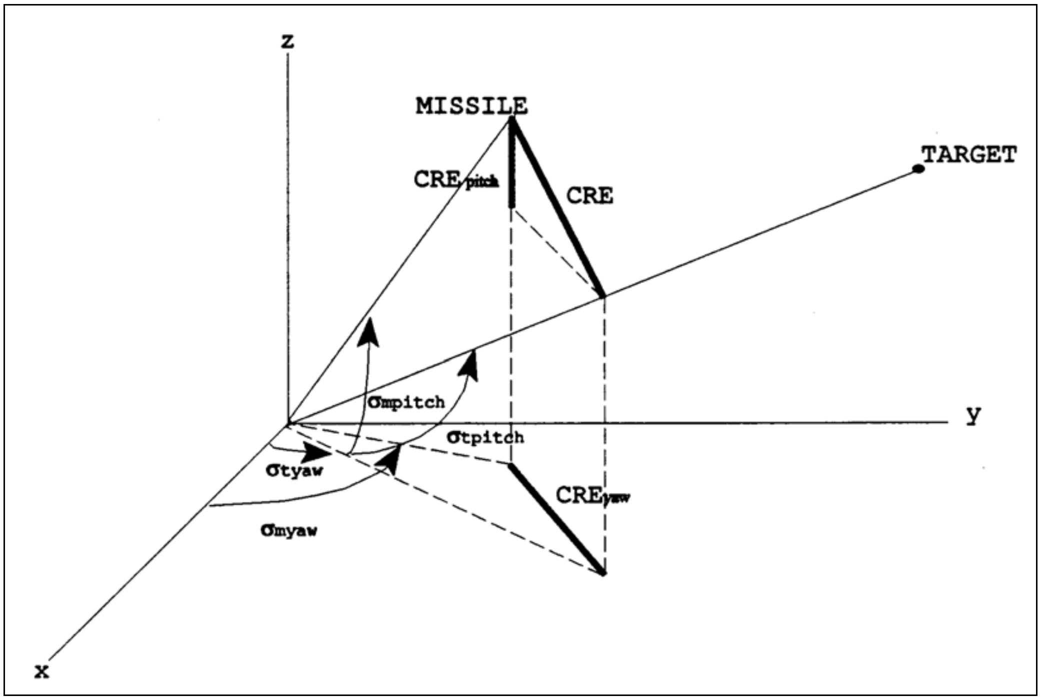

Figure 2.30 The Cross Range Error [17]

The equation for cross range error can be written as [17];

$$\left|\overrightarrow{CRE}\right| = \frac{\left|\overrightarrow{R_m} \times \overrightarrow{R_t}\right|}{\overrightarrow{R_t}} \tag{2-40}$$

The equation can be rearranged as [17],

$$\left|\overrightarrow{CRE}\right| = \frac{1}{\overrightarrow{R_t}}\sqrt{(y_m z_t - y_t z_m)^2 + (x_t z_m - x_m z_t)^2 + (x_m y_t - x_t y_m)^2} \tag{2-41}$$

As it can be seen from

Figure 2.30, cross range error consists of two components, yaw and pitch.

$$CRE_{yaw} = \sqrt{(x_m{}^2 + y_m{}^2)}\sin(\sigma_{t_{yaw}} - \sigma_{m_{yaw}}) \tag{2-42}$$

$$\mathrm{CRE}_{\mathrm{pitch}}=\sqrt{(\mathrm{CRE}^2\text{-}\mathrm{CRE}_{\mathrm{yaw}}{}^2)}\,\mathrm{sign}(\sigma_{t_{\mathrm{pitch}}}-\sigma_{m_{\mathrm{pitch}}}) \tag{2-43}$$

where

$\sigma_{m_{yaw}}$ =Missile Yaw Angle

$\sigma_{m_{pitch}}$ =Missile Pitch Angle

$\sigma_{t_{yaw}}$ =Target Yaw Angle

$\sigma_{t_{pitch}}$ =Target Pitch Angle

$\sigma_{yaw}$ =Missile to Target yaw plane

$\sigma_{pitch}$ =Missile to Target pitch plane

$R_m$ =Range between radar and missile

$R_t$ =Range between radar and target

R =Range between missile and target

Parameters, mentioned above, can be determined by using following equations.

$$\sigma_{m_{yaw}}=\arctan(\frac{y_m}{x_m}) \tag{2-44}$$

$$\sigma_{m_{pitch}}=\arctan(-\frac{z_m}{\sqrt{x_m^2+y_m^2}}) \tag{2-45}$$

$$\sigma_{t_{yaw}} = \arctan(\frac{y_t}{x_t}) \quad (2\text{-}46)$$

$$\sigma_{t_{pitch}} = \arctan(-\frac{z_t}{\sqrt{x_t^2 + y_t^2}}) \quad (2\text{-}47)$$

$$\sigma_m = \arctan(\frac{y_t - y_m}{x_t - x_m}) \quad (2\text{-}48)$$

$$\sigma_m = \arctan(-\frac{z_t - z_m}{\sqrt{(x_t - x_m)^2 + (y_t - y_m)^2}}) \quad (2\text{-}49)$$

$$R_m = \sqrt{x_m^2 + y_m^2 + z_m^2} \quad (2\text{-}50)$$

$$R_t = \sqrt{x_t^2 + y_t^2 + z_t^2} \quad (2\text{-}51)$$

$$R = \sqrt{(x_t - x_m)^2 + (y_t - y_m)^2 + (z_t - z_m)^2} \quad (2\text{-}52)$$

In command to line of sight guidance system, rate of change of cross range error refers to commanded acceleration required to determine angle of attack of weapon. The commanded acceleration is designed to steer weapon perfectly. To obtain perfect command, the equation of commanded acceleration must be of the form [17];

$$s^2 + (\alpha + \beta)s + \alpha\beta$$

As a result of this, damping is required, so the equation of commanded acceleration can be written as,

$$a_{cmd} = \ddot{CRE} = \alpha \dot{CRE} + \rho CRE \quad (2\text{-}53)$$

Let's take Laplace transform both side of equation.

$$\frac{a_{cmd}(s)}{CRE(s)} = s^2 + \alpha s + \rho \tag{2-54}$$

Two real roots are obtained at s = -5.7171 and s = -34.2829 with $\alpha = 40$ and $\rho = 196$, [17]

Two components of commanded acceleration can be determined as;

$$\begin{bmatrix} a_{cmd_{yaw}} \\ a_{cmd_{pitch}} \end{bmatrix} = \begin{bmatrix} 196 & 40 & 0 & 0 \\ 0 & 0 & 196 & 40 \end{bmatrix} \begin{bmatrix} CRE_{pitch} \\ \dot{CRE}_{pitch} \\ CRE_{yaw} \\ \dot{CRE}_{yaw} \end{bmatrix} \tag{2-55}$$

where

$$\dot{CRE}_{pitch} = \frac{CRE_{pitch}^{current} - CRE_{pitch}^{previous}}{\Delta t} \tag{2-56}$$

$$\dot{CRE}_{yaw} = \frac{CRE_{yaw}^{current} - CRE_{yaw}^{previous}}{\Delta t} \tag{2-57}$$

After all calculations are done, commanded acceleration in Cartesian coordinate system is determined by product of guidance gain and two components of commanded acceleration obtained from above equations. Each Cartesian coordinate frame of commanded acceleration is equal to sum of yaw and pitch components in that frame. Finally, gravitational acceleration, perpendicular to weapon velocity vector, is also considered.

Commanded acceleration in x axis can be written as;

$$a_x^{(e)} = G_{clos}(a_{x_{yaw}}^{(e)} + a_{x_{pitch}}^{(e)}) \tag{2-58}$$

where

$$a_{x_{pitch}}^{(e)} = (-a_{cmd_{pitch}})\cos(\sigma_{yaw})\sin(\sigma_{pitch}) \tag{2-59}$$

$$a_{x_{yaw}}^{(e)} = (-a_{cmd_{yaw}})\sin(\sigma_{yaw}) \tag{2-60}$$

Commanded acceleration in y axis can be written as;

$$a_y^{(e)} = G_{clos}(a_{y_{yaw}}^{(e)} + a_{y_{pitch}}^{(e)}) \tag{2-61}$$

where

$$a_{y_{pitch}}^{(e)} = (-a_{cmd_{pitch}})\sin(\sigma_{yaw})\sin(\sigma_{pitch}) \tag{2-62}$$

$$a_{y_{yaw}}^{(e)} = (a_{cmd_{yaw}})\cos(\sigma_{yaw}) \tag{2-63}$$

Commanded acceleration in z axis can be written as;

$$a_z^{(e)} = G_{clos}(a_{z_{pitch}}^{(e)}) \tag{2-64}$$

where

$$a_{z_{pitch}}^{(e)} = (-a_{cmd_{pitch}})\cos(\sigma_{pitch}) \tag{2-65}$$

Gravitational acceleration can be defined as;

$$\bar{g}_n^{(e)} = \bar{g}^{(e)} - (\bar{u}_w^{(e)} \times \bar{g}^{(e)})\bar{u}_w^{(e)} \tag{2-66}$$

Finally, commanded acceleration obtained from CLOS guidance system can be written as;

$$\overline{A}_c^{(e)} = \overline{a}^{(e)} - \overline{g}_n^{(e)} \tag{2-67}$$

where

$$\overline{a}^{(e)} = \begin{bmatrix} a_x^{(e)} \\ a_y^{(e)} \\ a_z^{(e)} \end{bmatrix} \tag{2-68}$$

### 2.2.2.2.8.2 Proportional Guidance Law (PN)

The purpose of this guidance system is to generate guidance command for steering weapon through line of sight between target and weapon position with onboard seeker, as it can be seen from Figure 2.31.

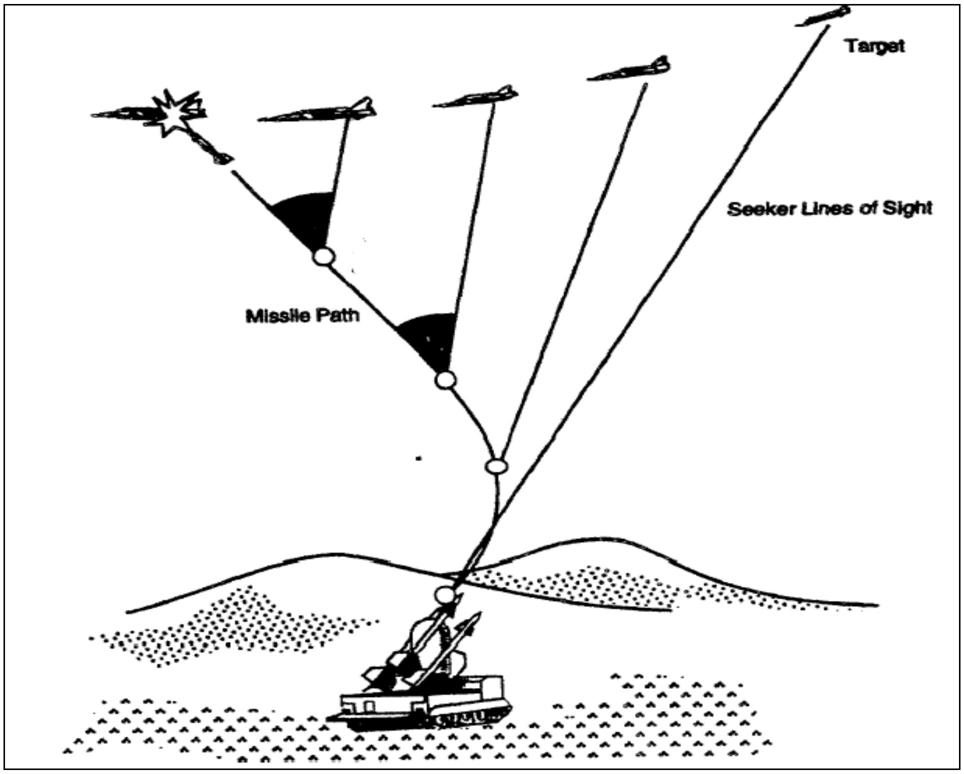

Figure 2.31 Proportional Navigation Guidance Law [13]

The principle of this guidance system depends on rate of change of line of sight. Commanded acceleration of weapon, required to determine angle of attack, is proportional to rate of change of line of sight, which can be defined as proportional navigation constant (PN). To keep weapon stable, proportionality factor must be greater than 2 [13], [17].

To determine guidance command, these parameters must be known:

- Position of target
- Position of weapon
- Speed of target

- Speed of weapon

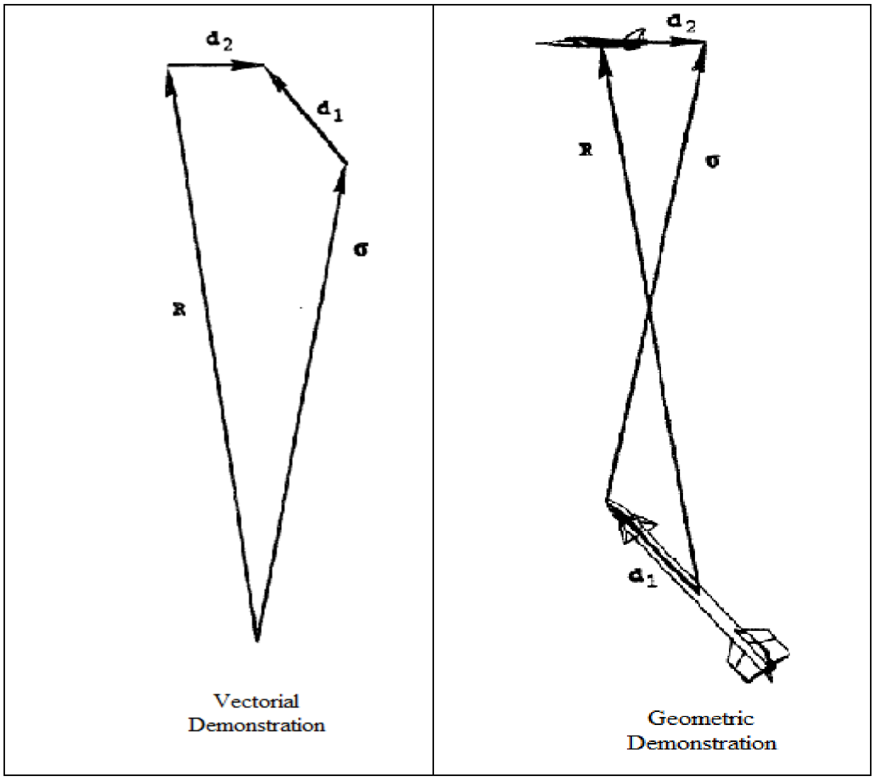

Figure 2.32 Demonstration of Line of Sight Vector [13]

According to Figure 2.32, the equation of line of sight vector can be written as;

$$\sigma = R - d_1 + d_2 \tag{2-69}$$

where

R = distance vector from weapon center of mass to target center of mass

$d_1$ = distance vector from weapon center of mass to seeker

$d_2$ = distance vector from target center of mass to seeker

$\sigma$ = line of sight vector between seeker and tracking point

In this research, the effect of seeker position is considered as insignificant, so distance vectors from target to seeker and from weapon to seeker are taken as zero. Therefore, the equation of line of sight vector is rearranged as

$$\sigma = R \tag{2-70}$$

The angular rate of line of sight vector is defined as,

$$w_{\sigma} = \frac{(\sigma \times V_{T/W})}{|\sigma|^2} \tag{2-71}$$

where

$V_{T/M}$ = Velocity vector target center of mass relative to weapon center of mass

$$V_{T/W} = V_T - V_W \tag{2-72}$$

$V_T$ = Target velocity vector relative to earth

$V_W$ = Weapon velocity vector relative to earth

Commanded acceleration is equal to the sum of commanded acceleration due to angular rate of line of sight and the effect of gravitational force. And also, the effect of wind speed on weapon speed is taken into account while obtaining it.

$$\overline{A}_c^{(e)} = NR(w_{\sigma} \times V_M) - \overline{g}_n^{(e)} \tag{2-73}$$

In this research, an instantaneous angle between the boresight axis of seeker and the weapon center line, known as gimbal angle, is determined at each instant of flight time. In the case that an instantaneous gimbal angle is not within intervals between maximum and minimum value of it, it is assumed that target can not be tracked by seeker. After this condition formed, there is no chance to track target anymore.

Instantaneous gimbal angle is determined as [13];

$$\lambda = \cos^{-1}(u_{sa} \bullet u_{cl}) \tag{2-74}$$

where

$u_{sa}$ =unit vector in the direction of seeker boresight axis

$u_{cl}$ =unit vector in the direction of weapon centerline

$u_{sa}$ is determined by normalizing line of sight vector.

$$u_{cl} = \mathrm{Norm}(u_{V_M} + \sin(\alpha_t) u_{A_c}) \tag{2-75}$$

where

$u_{V_M}$ = unit vector of weapon velocity vector

$\alpha_t$ =angle of attack

$u_{A_c}$ = unit vector of commanded acceleration vector

Norm() = normalizing function

#### 2.2.2.2.9 Autopilot Model

The objective of designing autopilot model is to determine angle of attack for performing commanded acceleration obtaining from guidance model and orientation of weapon. Moreover, it can be defined as bridge between weapon actuator system and guidance system.

In this research, the angle of attack is retained in the intervals of maximum angle of attack and minimum of angle attack due to aerodynamic limits. In other words, in case that angle of attack exceeds to maximum value, it is set to maximum value. Similarly, in the condition that it is smaller than minimum value, angle of attack is taken as minimum value according to aerodynamic limits.

Commanded acceleration due to lift force is assumed that its direction is perpendicular to weapon velocity vector relative to air.

During computation time of flight, delays in response to commanded acceleration are not taken into account. According to this assumption, weapon always fly under the conditions specified. In other words, there is no transition state during weapon flight.

According to these assumptions, attack angle required lift force is performed by using following equations [13].

$$\vec{F}_L = m_w \vec{A}_C \tag{2-76}$$

$$\overline{F}_L^{(e)} = \begin{bmatrix} F_{L_1}^{(e)} \\ F_{L_2}^{(e)} \\ F_{L_3}^{(e)} \end{bmatrix} = m_w \begin{bmatrix} A_{C_1}^{(e)} \\ A_{C_2}^{(e)} \\ A_{C_3}^{(e)} \end{bmatrix} \tag{2-77}$$

$$\bar{u}_l^{(e)} = \begin{bmatrix} u_{l_1}^{(e)} \\ u_{l_2}^{(e)} \\ u_{l3}^{(e)} \end{bmatrix} = \bar{u}_{a_c}^{(e)} = \begin{bmatrix} u_{a_{c_1}}^{(e)} \\ u_{a_{c_2}}^{(e)} \\ u_{a_{c_3}}^{(e)} \end{bmatrix} \tag{2-78}$$

$$F_L = \left|\vec{F}_L^{(e)}\right| = \sqrt{(F_{L_1}^{(e)})^2 + (F_{L_2}^{(e)})^2 + (F_{L_3}^{(e)})^2} \tag{2-79}$$

$$\alpha_t = \frac{F_L}{QSC_{L_\alpha}} \tag{2-80}$$

The angle of attack with the help of the above model can be defined as the absolute value of the angle between velocity vector of axi-symmetric weapon relative to air and its orientation vector. In this research, all weapons are considered to be axi-symmetric in flight simulation. In other words, the equivalent lift forces are assumed to occur at the equivalent pitch and side slip angles of weapon.

The unit vector of weapon orientation can be defined as;

$$\bar{u}_b^{(e)} = \bar{u}_{v_{air}}^{(e)} \cos(\alpha_t) + \bar{u}_l^{(e)} \sin(\alpha_t) \tag{2-81}$$

#### 2.2.2.3 Fuze and Detonation Model

The purpose of this model is to decide the interaction of weapon and target (cruise missile) by communicating with weapon dynamics model until that weapon hits target. In the case of hitting target, it calls kill assessment model. Otherwise, weapon dynamics model is called to skip next simulation time step.

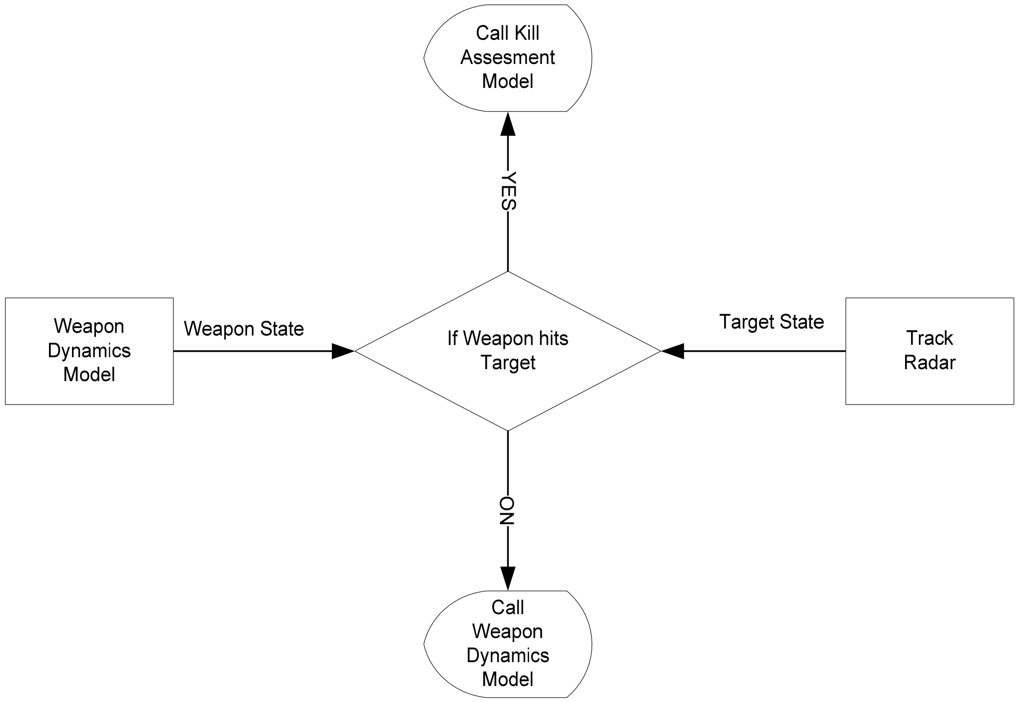

Figure 2.33 Flow Diagram of Fuze and Detonation Model

#### 2.2.2.4 Kill Assessment Model

The aim of this model is to make decision about survivability of target (cruise missile) according to determining single shot kill probability of weapon.

In this research, single shot kill probability of weapon is evaluated according to fuze type of weapon [21].

- Proximity fuze
- Point detonating fuze

The criterion for determining single shot kill probability is that the range between weapon and cruise missile must be within circular error probable (CEP). In both arms during the collision is treated as two-dimensional. This model is designed by using ‘Cookie-Cutter” damage function. It implies that the damage is complete in the case that weapon with point detonating fuze hits target, otherwise no damage occurs. Similarly, when cruise missile is within the effective radius of weapon with proximity fuze, target is destroyed completely.

In this research, it is assumed that normal distribution occurs around impact point with the standard deviation of weapon.

To calculate single shot kill probability, the parameters need to know can be divided into four basic groups.

- Parameters of cruise missile
- Parameters of weapon
- Impact point position
- Angle between cruise missile and weapon at impact point

Parameters of cruise missile required are length and radius of it.

Parameters of weapon for calculations can be categorized into three parts.

- Standard deviation of weapon in the case of impact
- Reliability factor of weapon system
- Lethality radius and radius of the fuze to be active for weapon with proximity fuze.

The probability of single shot kill can be defined as;

$$P_k = R \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} k(x,y)\, p(x,y)\, dx dy \tag{2-82}$$

where

$P_k$ = Probability of kill

k(x, y) = kill function in terms of x and y

p(x, y) = Normal probability distribution density function in term of x and y

R = Reliability factor

x, y = the origin of coordinate plane is the weapon mass center

$$p(x, y) = p(x)p(y) \tag{2-83}$$

p(x) = Normal probability distribution density function in x axis

p(y) = Normal probability distribution density function in y axis

Deviations in x axis and in y axis are considered to be independent of each other.

Normal probability distribution density function in x axis can be found as

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma_x} \exp\left( -\frac{(x-x_0)^2}{2\sigma_x^2} \right) \tag{2-84}$$

where

$\sigma_x$ = standard deviation through x axis

$x_0$=the distance from the y-axis

$$p(y) = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left( -\frac{(y-y_0)^2}{2\sigma_y^2} \right) \tag{2-85}$$

where

$\sigma_y$ = standard deviation through y axis

$y_0$=the distance from the x-axis

Normal distribution density function is rearranged as;

$$p(x,y)=\frac{1}{2\pi\sigma_x\sigma_y}\exp\left( -\frac{(x-x_0)^2}{2\sigma_x^2}-\frac{(y-y_0)^2}{2\sigma_y^2} \right) \tag{2-86}$$

Finally, the probability of single shot kill can be rearranged as

$$P_k=R\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} k(x,y)\frac{1}{2\pi\sigma_x\sigma_y}\exp\left( -\frac{(x-x_0)^2}{2\sigma_x^2}-\frac{(y-y_0)^2}{2\sigma_y^2} \right)dxdy \tag{2-87}$$

#### 2.2.2.4.1 Single Shot Kill Probability for Weapon with Point Detonating Fuze

Calculating the collision area, the projection of the field of cruise missile perpendicular to the direction of the weapon is considered. Projected area is calculated according to an angle between the two arms, and weapon size. The area of cruise missile damage around weapon refers to lethality are of weapon. [22]

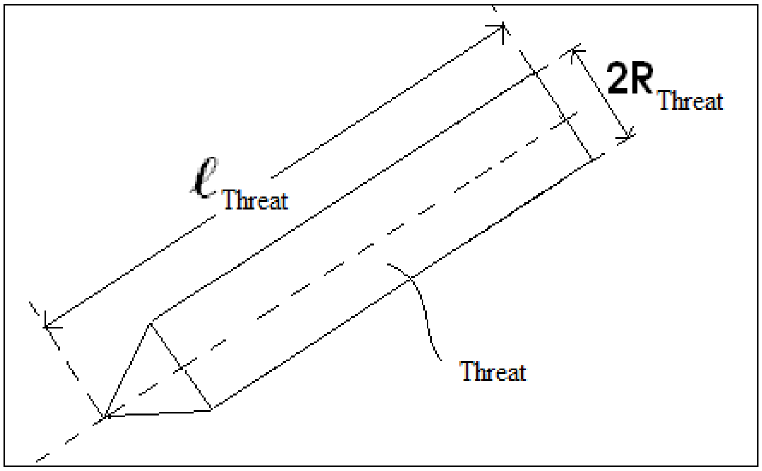

Figure 2.34 Dimensions of Threat

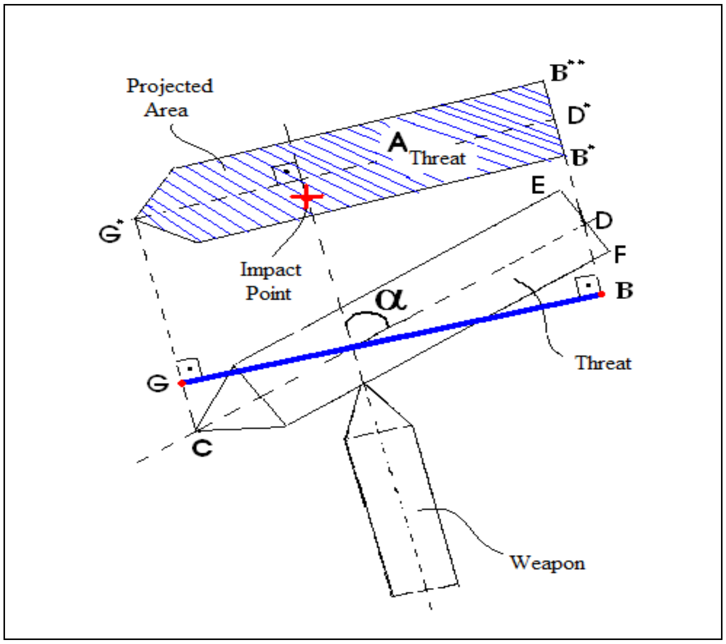

Figure 2.35 Impact Demonstration

As it can be seen at from Figure 2.35

Dimensions of threat:

$$Length = |CD| = l_{threat} \tag{2-88}$$

$$Width = |EF| = 2R_{threat} \tag{2-89}$$

Angle between weapon and threat: (α)

Angle between weapon and threat:

$$A_{Threat} \cong |G^{*}D^{*}| . |B^{*}B^{**}| \tag{2-90}$$

$$\left|G^{*}D^{*}\right| = \left|CD\right|\sin(\alpha) = l_{threat}\sin(\alpha) \tag{2-91}$$

$$\left|B^{*}B^{**}\right| = \left|EF\right| = 2R_{Threat} \tag{2-92}$$

$$A_{Threat} \cong 2R_{Threat}l_{Threat}\sin(\alpha) \tag{2-93}$$

According to Cookie-Cutter, kill function in terms of x and y can be written as;

$$R = \begin{cases} 1 & x, y \in A_{Threat} \\ 0 & x, y \notin A_{Threat} \end{cases} \tag{2-94}$$

where

$$A_{Threat} \cong \left\{ x, y \middle| -R_{Threat} \leq x \leq R_{Threat}, -\frac{\ell_{Threat}.\sin(\alpha)}{2} \leq y \leq \frac{\ell_{Threat}.\sin(\alpha)}{2} \right\}$$

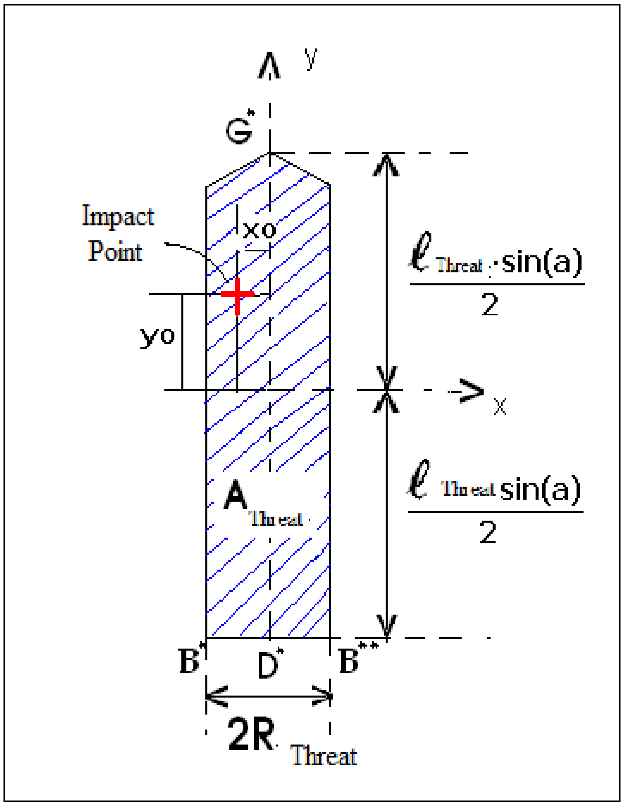

Figure 2.36 Parameters used in determining Single Kill Probability for Weapon with Point Detonating Fuze

The probability of single shot kill for weapon with Point Detonating Fuze can be written as;

$$P_k = R\int_{y1}^{y2}\int_{x1}^{x2}\frac{1}{2\pi\sigma_x\sigma_y}\exp\left(-\frac{(x-x_0)^2}{2\sigma_x^2}-\frac{(y-y_0)^2}{2\sigma_y^2}\right)dxdy \qquad (2\text{-}95)$$

where

$x_1 = -R_{Threat}$

$x_2 = R_{Threat}$

$$y_1 = -\frac{l_{Threat}\sin(\alpha)}{2}$$

$$y_2 = \frac{l_{Threat}\sin(\alpha)}{2}$$

The equation of the probability of single shot kill for weapon with Point Detonating Fuze is solved by using Maple 8.

$$P_k = \left[ \operatorname{erf}(\frac{\sqrt{2}(L*\sin(\alpha)-2y_0)}{4\sigma_y})+\operatorname{erf}(\frac{\sqrt{2}(L*\sin(\alpha)+2y_0)}{4\sigma_y}) \right] \left[ 0.25R(\operatorname{erf}(\frac{\sqrt{2}(R-x_0)}{2\sigma_x})+\operatorname{erf}(\frac{\sqrt{2}(R+x_0)}{2\sigma_x})) \right]$$

(2-96)

### 2.2.2.4.2 Single Shot Kill Probability for Weapon with Proximity Fuze

Weapon with Proximity Fuze kills any threat in the case that the threat is within the effective area of weapon. In other words, radius of this area is equal to radius in which fuze can active [22]. Radius required for killing threat, lethal radius, is assumed that it is identical to effective radius of weapon in this research.

According to Cookie-Cutter, kill function in terms of x and y can be written as;

$$R = \begin{cases} 1 & x,y\in A_{Lethality} \\ 0 & x,y\notin A_{Lethality} \end{cases} \tag{2-97}$$

$$A_{Lethality} = \left\{ x,y \middle| x^2+y^2\leq R^2_{Lethality} \right\} \tag{2-98}$$

So if the two equations are combined;

$$R = \begin{cases} 1 & x,y \in R_{Lethality} \\ 0 & \text{otherwise} \end{cases} \tag{2-99}$$

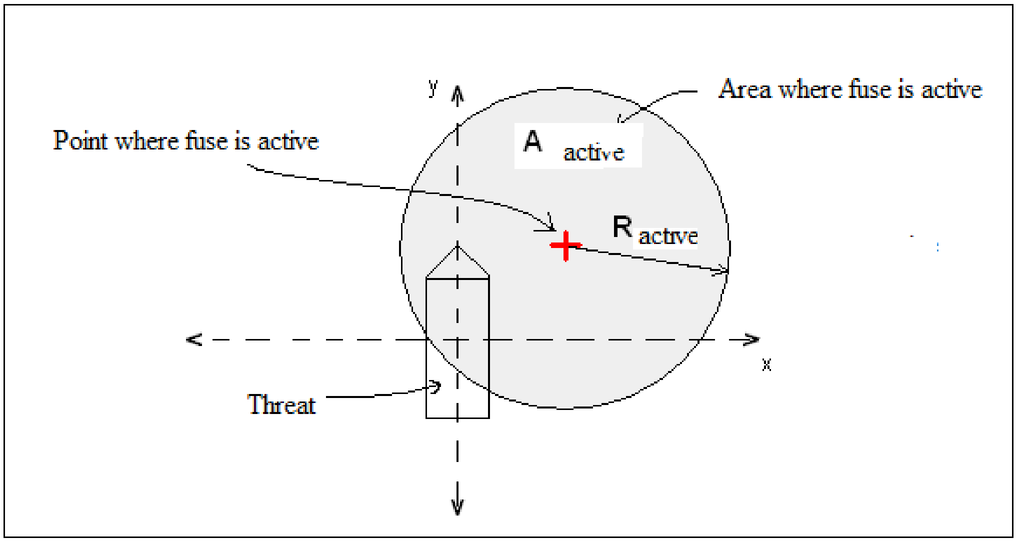

Figure 2.37 The values of fuze to be active

$$P_k = R \int_{y1}^{y2} \int_{x1}^{x2} \frac{1}{2\pi\sigma_x\sigma_y} \exp\left( -\frac{(x-x_0)^2}{2\sigma_x^2} - \frac{(y-y_0)^2}{2\sigma_y^2} \right) dxdy \tag{2-100}$$

where

$x_1 = -R_{Lethality}$

$x_2 = R_{Lethality}$

$y_1 = -\sqrt{R_{Lethality} - y^2}$

$$y_2 = \sqrt{R_{Lethality} - y^2}$$

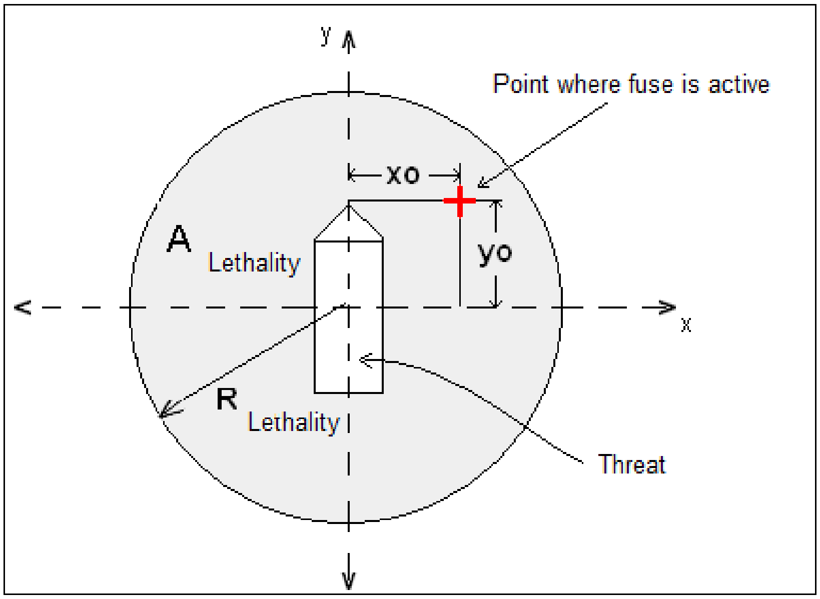

Figure 2.38 Parameters used in determining Single Kill Probability for Weapon with Proximity Fuze

$x_0$ and $y_0$ are the mean coordinates of the weapon impact distribution in the x and y axis. Moreover, $\sigma_x$ and $\sigma_y$ are the mean standard deviations in these axes.

In the literature, normal distribution density function can be determined in the case of following four cases. [21]

- Case 1: $x_0 = y_0 = 0$; $\sigma_x = \sigma_y = \sigma$
- Case 2: $x_0 \neq 0, y_0 \neq 0$; $\sigma_x = \sigma_y = \sigma$
- Case 3: $x_0 = y_0 = 0$; $\sigma_x \neq \sigma_y$
- Case 4: $x_0 \neq 0, y_0 \neq 0$; $\sigma_x \neq \sigma_y$

In this research, Case 1 and Case 2 are examined while obtaining single shot kill probability for weapon with proximity fuze.

#### 2.2.2.4.2.1 Zero Offset and Equal Variances

In this case;

$x_0 = y_0 = 0$; $\sigma_x = \sigma_y = \sigma$

The equations of single shot kill probability can be rearranged as:

$$P_k = R \iint_{A=A_{Lethality}} \frac{1}{2\pi\sigma^2} \exp\left( -\frac{x^2 + y^2}{2\sigma^2} \right) dxdy \tag{2-101}$$

where

$$R = \begin{cases} 1 & x,y \in R_{Lethality} \\ 0 & \text{otherwise} \end{cases} \tag{2-102}$$

The polar coordinate system is used in order to solve integral equation.

$$P_k = R \int_0^{2\pi} \int_0^{R_{Lethality}} \frac{1}{2\pi\sigma^2} \exp(-\frac{r^2}{2\sigma^2}) rdrd\theta \tag{2-103}$$

$$P_k = R \int_0^{R_{Lethality}} \frac{r}{\sigma^2} \exp(-\frac{r^2}{2\sigma^2}) dr = -R \exp(-\frac{r^2}{2\sigma^2}) \Big|_0^{R_{Lethality}} \tag{2-104}$$

$$P_k = R * \left[ 1 - \exp(-\frac{R_{Lethality}^{2}}{2\sigma^{2}}) \right] \qquad (2\text{-}105)$$

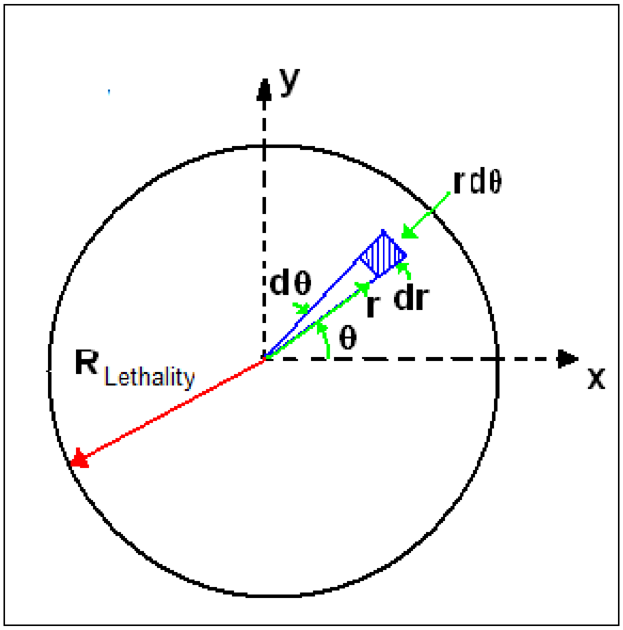

Figure 2.39 Polar Coordinate

### 2.2.2.4.2.2 Offset Distribution and Equal Variances

In this case;

$x_0 \neq 0, y_0 \neq 0;$ $\sigma_x = \sigma_y = \sigma$

The offset of the mean point of impact can be defined as

$$r_0 = \sqrt{x_0^2 + y_0^2} \qquad (2\text{-}106)$$

The coordinate axes are rotated so that the offset of the mean point of impact lies along the positive axis in order to simplify calculations. The equations of single shot kill probability can be rearranged as

$$P_k = R \iint_{A=A_{\text{Lethality}}} \frac{1}{2\pi\sigma^2} \exp\left( -\frac{(x-r_0)^2}{2\sigma^2} - \frac{y^2}{2\sigma^2} \right) dxdy \tag{2-107}$$

$$P_k = R\frac{1}{2\pi\sigma^2}\exp(-\frac{r_0}{2\sigma^2})\int_0^{R_{\text{Lethality}}}\int_0^{2\pi} r\exp(-\frac{r^2}{2\sigma^2}+\frac{rr_0\cos\theta}{\sigma^2})d\theta dr \tag{2-108}$$

The modified Bessel function of the first kind of order zero in Poisson's form is used in order to integrate equation above.

$$I_0(z) = \frac{1}{\pi}\int_0^{\pi}\cosh(z\cos\theta)d\theta = \frac{1}{\pi}\int_0^{\pi}\exp(z\cos\theta)d\theta \tag{2-109}$$

The equation above can be rearranged since $z\cos\theta$ is symmetrical about $\theta=\pi$ .

$$2I_0(z) = \frac{1}{\pi}\int_0^{2\pi}\exp(z\cos\theta)d\theta \tag{2-110}$$

Hence,

$$P_k = R\frac{1}{\sigma^2}\exp(-\frac{r_0}{2\sigma^2})\int_0^{R_{\text{Lethality}}} r\exp(-\frac{r^2}{2\sigma^2})I_0(\frac{rr_0}{\sigma^2})dr \tag{2-111}$$

Now new variable u can be defined as

$$r = R_{\text{Lethality}} u^{\frac{1}{2}} \tag{2-112}$$

$$dr = \frac{R_{\text{Lethality}}}{2u^{\frac{1}{2}}} du \tag{2-113}$$

As a result, the limits of integration 0 to R turn to 0 and 1.

$$P_k = R \frac{R^2_{\text{Lethality}}}{2\sigma^2} \exp(-\frac{r_0}{2\sigma^2}) \int_0^1 \exp(-\frac{R^2_{\text{Lethality}} u}{2\sigma^2}) I_0 (\frac{R_{\text{Lethality}} r_0 u^{\frac{1}{2}}}{\sigma^2}) du \tag{2-114}$$

By replacing Bessel function

$$I_0 (z) = \sum_{n=0}^{\infty} \frac{(\frac{1}{2} z)^{2n}}{(n!)^2} \tag{2-115}$$

$$I_0 (\frac{R_{\text{Lethality}} r_0 u^{\frac{1}{2}}}{\sigma^2}) = \sum_{n=0}^{\infty} (\frac{R^2_{\text{Lethality}}}{2\sigma^2})^n (\frac{r_0^2}{2\sigma^2})^n \frac{u^n}{(n!)^2} \tag{2-116}$$

The equation of single kill probability can be rearranged as

$$P_k = R \sum_{n=0}^{\infty} \frac{1}{n!} (\frac{r_0^2}{2\sigma^2})^n \exp(-\frac{r_0^2}{2\sigma^2}) \times \frac{1}{n!} (\frac{R^2_{\text{Lethality}}}{2\sigma^2})^{n+1} \int_0^1 u^n \exp(-\frac{R^2_{\text{Lethality}}}{2\sigma^2}) du$$

(2-117)

Finally

$$P_k = R\sum_{n=0}^{\infty} f_n \times g_n \tag{2-118}$$

where

$$f_n = \frac{1}{n!}\left(\frac{r_0^2}{2\sigma^2}\right)^n \exp\left(-\frac{r_0^2}{2\sigma^2}\right) = \frac{1}{n}\left(\frac{r_0^2}{2\sigma^2}\right)f_{n-1} \tag{2-119}$$

$$\begin{aligned} g_n &= \frac{1}{n!}\left(\frac{R_{\text{Lethality}}^2}{2\sigma^2}\right)^{n+1}\int_0^1 u^n \exp\left(-\frac{R_{\text{Lethality}}^2}{2\sigma^2}\right)du \\ &= -\frac{1}{n!}\left(\frac{R_{\text{Lethality}}^2}{2\sigma^2}\right)^n \exp\left(-\frac{R_{\text{Lethality}}^2}{2\sigma^2}\right) + g_{n-1} \end{aligned} \tag{2-120}$$

### 2.2.3 Command Control Center

In air defense system a command and control center is mainly required to make decision about tactical situation and protect defended areas which are its own air defense system against enemy threats by selecting most suitable weapon systems to engage them. It is known that rapid operational planning and evaluating tactical situation is required under severe stress operation conditions. Moreover, it can be defined as decision box.

The model of command and control center can be represented by Observe-Orient-Decide-Act (OODA) loop. [23]

As it can be seen from Figure 2.40, the decision cycle of command and control center (C2) occurs from four different phases.

Information from internal sources and information from external sources are collected at the observation stage. Information from internal sources is obtained from typically a feedback loop within the decision-making entity. Moreover, information from external sources means typically sensors or information sources outside the decision-making entity.

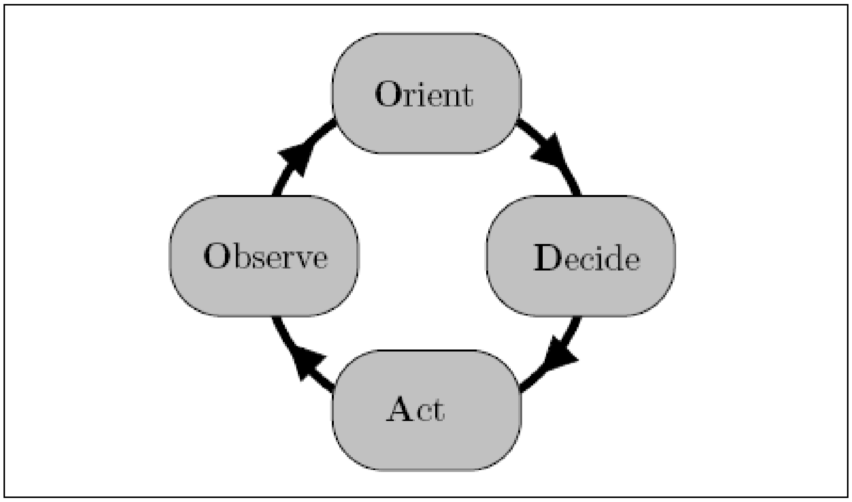

Figure 2.40 The OODA Loop [23]

The orient phase can be divided into two sub-phases: destruction and creation. In the destruction sub-phase, the problem is dissociated until the sub-problems are solved. In the creation sub-phase, in order to combining problems into an all action plan, problems are mapped with their alternative plans.

In the decision phase, plans obtained from orient phase are gathered in order to decide which plan is most suitable for special tactical environment situation.

The act phase consists of actions including a physical attack or movement, the issuance of an order, or a focus of effort on the sensors for a better observation during the next cycle of the process. [23]

In this research, command and control center consists of two different sub-models.

- Threat Engagement and Weapon Assignment (TEWA)

- Fire Control and Weapon Aiming

### 2.2.3.1 Threat Engagement and Weapon Assignment (TEWA)

TEWA is the semi-automated and automated decision process of C2 in the military air defense situation. It can be described as the optimization process to minimize threat survivability.

Threat engagement is required to determine risk if any entity aims to damage to the defending areas along with the ranking of such entities related to the level of threat they pose.

In this research, only one cruise missile is assumed as threat against the air defense system. In this part, track radars and weapons are ranking according to range from threat. After this, suitable track radars and suitable weapons from ranked lists are chosen in order to destroy threat.

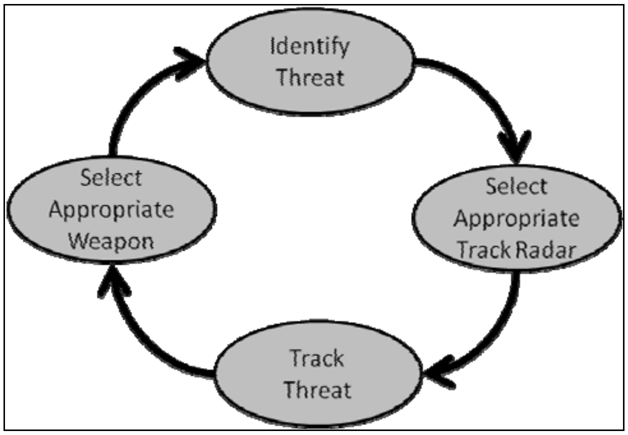

Figure 2.41 TEWA Loop

### 2.2.3.2 Fire Control and Weapon Aiming

This model is required to predict launch condition of weapon to kill target when fired. Launch condition of weapon

- Bearing angle of weapon
- Elevation angle of weapon
- Velocity of weapon
- Predicted position of threat (intercept point)
- Predicted time of flight of weapon ($T_2$)

For weapon fired towards target, some criteria must be met. These are

- Smooth target tracking
- A valid fire control solution and condition (eq: lag time)
- An intercept range within which the selected weapon can be effective

The velocities and positions of target at instantaneous simulation time are gathered during lag time of selected weapon to determine mean values. After obtaining mean of target velocity, it multiplies with predicted time of flight of weapon ($T_2$) to predict future target position (incept point).

$$P_{\mathrm{int\,ercept}} = V_{\mathrm{mean}} \times T_2 \tag{2-121}$$

By using future target position and weapon platform position, azimuth and elevation angle of weapon are obtained.

In this research, for Surface to Air Missile (SAM), predicted time of flight of weapon ($T_2$) is taken as guidance start time. Otherwise, for Antiaircraft Artillery (AAA), predicted time of flight of weapon ($T_2$) is obtained by using following equations. [7]

$$T_2 = \left( \frac{2m}{V_0 C_D \rho S} \right) \left[ e^{(C_D \rho S/2m)x} - 1 \right] \qquad (2\text{-}122)$$

where

$m = \text{weapon mass(kg)}$

$V_0$ = initial velocity of weapon (platform velocity) (m/s)

$C_D$ = Drag Coefficient

$\rho$ = air density ($\frac{kg}{m^3}$)

S = Presented frontal area of weapon ($m^2$)

x = distance travelled by the weapon (m)

Drag coefficient and air density are determined as same as calculated in the Atmosphere Model mentioned above.

# CHAPTER 3

# CRUISE MISSILE

Cruise missiles, designed against land and sea enemies, are high precision missiles. Moreover, it can be fired from sea, land and air platform. The types of cruise missiles can be divided into two common groups. These are:

- land-attack cruise missiles (LACMs)
- anti-ship cruise missiles (ASCMs)

Cruise missiles have global positioning system (GPS) and ground-map (terrain following) systems for following terrain at low altitude to destroy target. However, anti-ship cruise missiles also detect and hit their enemies by means of radar and heat-seeking sensors. [24]

## 3.1 Missile Simulation Model

This model stores cruise missile parameters obtained from own sub-models at each instantaneous flight simulation time and its physical parameters. These sub-models are:

- Missile's Radar Cross Section (RCS) Model
- Simulation Data Model
- Damage Assessment Model

### 3.1.1 Missile's Radar Cross Section (RCS) Model

Radar cross section (RCS) is the measure of a target's ability to reflect radar signals in the direction of the radar receiver, i.e. it is a measure of the ratio of backscatter power per steradian (unit solid angle) in the direction of the radar (from target) to the power density that is intercepted by the target [25]. Radar cross section has units of "$m^2$"and symbol of "σ". Radar cross sectional area can be determined by using:

Target external geometry

Frequency of radar transmitters

The direction of the illuminating radar

The used material types
Moreover, it can be expressed by as:

$$\sigma = \text{Geometric Cross Section} \times \text{Reflectivity} \times \text{Directivity} \tag{3-1}$$

Geometric cross section is a projected area the target presents to radar. It is defined as size of power transmitted by radar is intercepted by target. Its unit is "$m^2$".

$$\text{Geometric Cross Section} = \frac{P_{\text{intercepted}}}{P_{\text{transmitted}}} \tag{3-2}$$

Reflectivity is the ratio of power scattered by the target to the power intercepted by the target.

$$\text{Reflectivity} = \frac{P_{\text{scatter}}}{P_{\text{intercepted}}} \tag{3-3}$$

Directivity is defined as ratio of backscattered power to isotropic power. Backscattered power refers to reflected power toward the radar. The power that is scattered in a perfect sphere over a unit solid angle of that sphere is called isotropic.

$$\text{Directivity} = \frac{P_{\text{backscatter}}}{P_{\text{isotropic}}} \tag{3-4}$$

In literature, value of radar cross section is determined by using azimuth and elevation angles. But in this thesis, effects of elevation angle are omitted, that is, it is assumed that RCS values only depend on azimuth angles. And also, RCS values of missile related to azimuth angles are given as input parameters by user. The format of this data is presented at Table 3.1. First column represents azimuth angles and second one indicates RCS values with respect to these azimuth angles.

Table 3.1 The example of RCS Data

| **Azimuth Angles** | **The Values of RCS** |
|---|---|
| 0.0 | 0.025 |
| 30.0 | 0.05 |
| 60.0 | 0.075 |
| 90.0 | 0.1 |
| 120.0 | 0.075 |
| 150.0 | 0.05 |
| 180.0 | 0.025 |

This model is required to determine RCS value of cruise missile at each instantaneous flight simulation time.

### 3.1.2 Simulation Data Model

This model stores simulation data required for calculation at each instantaneous flight simulation time. Simulation data includes altitude above mean sea level, latitude, longitude, yaw angle, pitch angle, roll angle, velocity in x axis, velocity in y axis, velocity in z axis, and impact angle of missile. Their units are meter, degree, degree, radian, radian, radian, meter/second, meter/second, meter/second, and degree respectively.

### 3.1.3 Damage Assessment Model

This model is required to estimate damage caused to target by means of impact angle at impact time and type of target. Example of target probability of kill for various target type and impact angle used in this thesis is presented Table 3.2. Probability of kill for target type and impact angle at impact time is determined by means of cruise missile's kill probability given by analyzer. After obtaining probability of kill for target type and impact angle at final time, a random number between 0 and 1 is drawn for comparing to probability of kill determined. If random number drawn is less than probability of kill, it means that cruise missile damages its target completely. Otherwise, the effectiveness of cruise missile equals to zero.

Table 3.2 Example of Probability of Kill According to Target Type and Impact Angle

| **Target Type** | **Target Probability of Kill For Various Impact Angle** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **10** | **20** | **30** | **40** | **50** | **60** | **70** | **80** |
| **Airbase Operational Facility** | 0.75 | 0.65 | 0.8 | 0.7 | 0.65 | 0.74 | 0.7 | 0.65 |
| **Airbase Runway** | 0.65 | 0.75 | 0.8 | 0.65 | 0.7 | 0.725 | 0.65 | 0.75 |
| **Four Storey Masonry Office Building** | 0.65 | 0.8 | 0.7 | 0.75 | 0.65 | 0.7 | 0.75 | 0.7 |

# CHAPTER 4

# TACTICAL ENVIRONMENT

Ideal military operation performance is seldom accomplished since air defense systems operate in the real world. Those real world conditions are implied by the term “tactical environment”. Those conditions cover [7]

- Atmosphere
- Electromagnetic emitter density
- Jamming
- Vehicular traffic density
- Terrain

This chapter contains tactical environment data used at each instantaneous flight simulation time. Tactical environment data consists of

- Terrain
- Atmosphere

In this chapter, terrain and atmosphere data are discussed respectively.

## 4.1 Terrain

Flight simulation and air defense system performance are affected by terrain. This influence can be Maximum LOS range from given position, acting as an absolute constraint on, ranges of sensor detection. [7]

Terrain model covers real world's geographic attributes with Geographic Coordinate System (WGS84) and Digital Terrain Elevation Data (DTED). In this research, latitude and longitude of location are presented by Geographic Coordinate System (WGS84). Elevation of location from mean sea level (MSL) is obtained from Digital Terrain Elevation Data (DTED) by using "Open-Map" Tool.

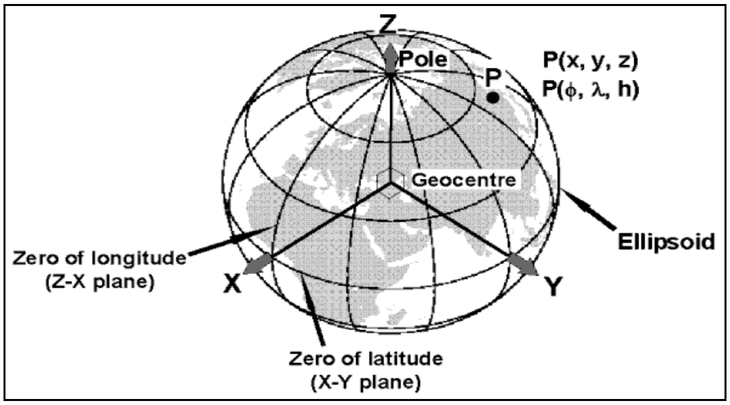

Figure 4.1 Geographic Coordinate System (WGS84)

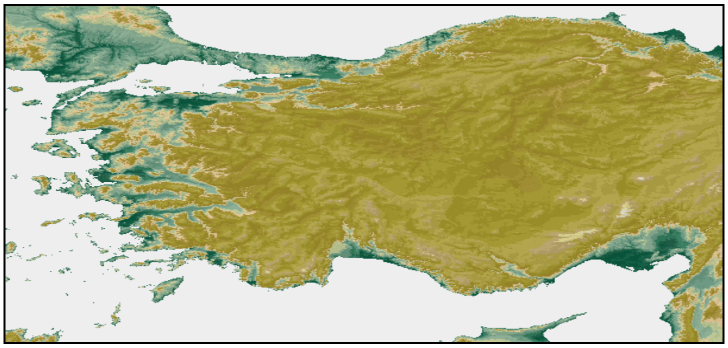

Figure 4.2 Digital Terrain Elevation Data (DTED) by using "Open-Map" Tool

"U.S. Military Specification Digital Terrain Elevation Data (DTED) MIL-PRF-89020B" describes DTED format file. According to it, Dted format for level is standardized with three levels. [26]

- Level 0 = a post spacing of 30 arc seconds in latitude direction (ca. 900 meters)
- Level 1 = a post spacing of 3 arc seconds (ca. 90 meters)
- Level 2 = a post spacing of 1 arc seconds (ca. 30 meters)

Increasing dted level results increasing resolution of DTED since resolution of it depends on dted level.

## 4.2 Atmosphere Data

Flight simulation and air defense system performance are influenced by atmosphere. As result of this, this model is required to store Atmosphere Data which is used at each instant of flight time. It has METCM format which is defined in STANAG. 4082. Atmosphere Data consists of

- Wind Direction
- Wind Speed Magnitude
- Temperature

- Pressure

at given flight altitude.

# CHAPTER 5

# MONTE CARLO

## 5.1 A Brief Introduction to Monte Carlo

Random numbers can be produced in software or hardware in computer environments. Monte Carlo technique models estimated systems such as physically or mathematical systems using these random values and analyses the effects of produced these random values. [27]

The first step in studying a system is to build a model from which one can obtain predictions concerning the systems' behavior. After that the models explains in mathematical or graphical nature. Once the model for the system at hand has been constructed, the next step is to derive a solution from this model. To this end, both analytical and numerical solutions methods may be invoked. An analytical solution is usually obtained directly from its mathematical representation in the form of formulas. A numerical solution directly is generally an approximation via a suitable approximation procedure. More precisely, this is called as *stochastic computer simulation* or *Monte Carlo Simulation*, which includes some randomness in the underlying mode, rather than deterministic computer simulation. [27]

## 5.2 Usage of Monte Carlo in Military Simulations

Monte Carlo simulation, the one of the most common types of simulation in the combat simulations, is required if there is randomness to the result of a particular event. The stochastic, or probabilistic, nature of a Monte Carlo process decreases degree of randomness in results. For example, if all circumstances are met for a unit to kill an enemy force, the final result is determined by random number generation. If

the decision criterion of simulation for killing enemy is %90, a random number between 0 and 1 is drawn for comparing to decision criteria (0.9). In the case that random number is less than decision criteria, it means that enemy force is killed. However, there is no method to estimate, whether enemy force is killed or not, thus randomness. [27]
The main advantage of Monte Carlo is that it supplies predictions of performance over a wide range situations rather than limited range as often obtained by analytical model. Moreover, it can be used to determine very complex probabilistic manners.

Mission rehearsal simulations occur from many sub-models. Owing to changing parameters of sub-models easily, there is the potential of conducting a sensivity analysis. If a sensivity analysis is done, Monte Carlo simulation increases accuracy of results that can be obtained from single run.

## 5.3 Usage of Monte Carlo in Mission Rehearsal Tool

Certain insights can be obtained from single scenario run, however significant analysis results are determined by multiple scenario runs. The probabilistic simulations require multiple runs for obtaining repeated tendencies which are anomalies. Moreover, multiple scenario runs are necessary according to idea that an event in battle will never replicate itself implicitly. [27]

According to the reasons mentioned above, this model is necessary to obtain statistically significant results by running simulation repeatedly in the case that random parameters are employed to simulate glint.

It is important to realize that development of scenario and taking outputs of scenario both take time. Time for taking mission rehearsal tool results depends on the details of analysis desired. Details of analysis desired can be adjusted by analyzer with determining confidence level and error margin. In other words, number of sample runs is determined according to confidence level and error margin entered by user in mission rehearsal tool.

By using standard normal distribution table, shown at Table 5.1, z-score value is determined according to confidence level. After finding z-score value, minimum number of sample runs to needed to satisfy confidence level and error margin entered by user is determined following equation.

$$\text{Number of Simulation} = \left( \frac{\text{z-score}}{2 \times (\text{error margin})} \right)^2 \tag{5-1}$$

Table 5.1 Standard Normal Distribution (Z Table) [29]

| Z | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.5000 | 0.5040 | 0.5080 | 0.5120 | 0.5160 | 0.5199 | 0.5239 | 0.5279 | 0.5319 | 0.5359 |
| 0.1 | 0.5398 | 0.5438 | 0.5478 | 0.5517 | 0.5557 | 0.5596 | 0.5636 | 0.5675 | 0.5714 | 0.5753 |
| 0.2 | 0.5793 | 0.5832 | 0.5871 | 0.5910 | 0.5948 | 0.5987 | 0.6026 | 0.6064 | 0.6103 | 0.6141 |
| 0.3 | 0.6179 | 0.6217 | 0.6255 | 0.6293 | 0.6331 | 0.6368 | 0.6406 | 0.6443 | 0.6480 | 0.6517 |
| 0.4 | 0.6554 | 0.6591 | 0.6628 | 0.6664 | 0.6700 | 0.6736 | 0.6772 | 0.6808 | 0.6844 | 0.6879 |
| 0.5 | 0.6915 | 0.6950 | 0.6985 | 0.7019 | 0.7054 | 0.7088 | 0.7123 | 0.7157 | 0.7190 | 0.7224 |
| 0.6 | 0.7257 | 0.7291 | 0.7324 | 0.7357 | 0.7389 | 0.7422 | 0.7454 | 0.7486 | 0.7517 | 0.7549 |
| 0.7 | 0.7580 | 0.7611 | 0.7642 | 0.7673 | 0.7704 | 0.7734 | 0.7764 | 0.7794 | 0.7823 | 0.7852 |
| 0.8 | 0.7881 | 0.7910 | 0.7939 | 0.7967 | 0.7995 | 0.8023 | 0.8051 | 0.8078 | 0.8106 | 0.8133 |
| 0.9 | 0.8159 | 0.8186 | 0.8212 | 0.8238 | 0.8264 | 0.8289 | 0.8315 | 0.8340 | 0.8365 | 0.8389 |
| 0.10 | 0.8413 | 0.8438 | 0.8461 | 0.8485 | 0.8508 | 0.8531 | 0.8554 | 0.8577 | 0.8599 | 0.8621 |
| 0.11 | 0.8643 | 0.8665 | 0.8686 | 0.8708 | 0.8729 | 0.8749 | 0.8770 | 0.8790 | 0.8810 | 0.8830 |
| 0.12 | 0.8849 | 0.8869 | 0.8888 | 0.8907 | 0.8925 | 0.8944 | 0.8962 | 0.8980 | 0.8997 | 0.9015 |
| 0.13 | 0.9032 | 0.9049 | 0.9066 | 0.9082 | 0.9099 | 0.9115 | 0.9131 | 0.9147 | 0.9162 | 0.9177 |
| 0.14 | 0.9192 | 0.9207 | 0.9222 | 0.9236 | 0.9251 | 0.9265 | 0.9279 | 0.9292 | 0.9306 | 0.9319 |
| 0.15 | 0.9332 | 0.9345 | 0.9357 | 0.9370 | 0.9382 | 0.9394 | 0.9406 | 0.9418 | 0.9429 | 0.9441 |
| 0.16 | 0.9452 | 0.9463 | 0.9474 | 0.9484 | 0.9495 | 0.9505 | 0.9515 | 0.9525 | 0.9535 | 0.9545 |
| 0.17 | 0.9554 | 0.9564 | 0.9573 | 0.9582 | 0.9591 | 0.9599 | 0.9608 | 0.9616 | 0.9625 | 0.9633 |
| 0.18 | 0.9641 | 0.9649 | 0.9656 | 0.9664 | 0.9671 | 0.9678 | 0.9686 | 0.9693 | 0.9699 | 0.9706 |
| 0.19 | 0.9713 | 0.9719 | 0.9726 | 0.9732 | 0.9738 | 0.9744 | 0.9750 | 0.9756 | 0.9761 | 0.9767 |

Table 5.1 (continued)

| Z | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|---|---|---|
| **0.20** | 0.9772 | 0.9778 | 0.9783 | 0.9788 | 0.9793 | 0.9798 | 0.9803 | 0.9808 | 0.9812 | 0.9817 |
| **0.21** | 0.9821 | 0.9826 | 0.9830 | 0.9834 | 0.9838 | 0.9842 | 0.9846 | 0.9850 | 0.9854 | 0.9857 |
| **0.22** | 0.9861 | 0.9864 | 0.9868 | 0.9871 | 0.9875 | 0.9878 | 0.9881 | 0.9884 | 0.9887 | 0.9890 |
| **0.23** | 0.9893 | 0.9896 | 0.9898 | 0.9901 | 0.9904 | 0.9906 | 0.9909 | 0.9911 | 0.9913 | 0.9916 |
| **0.24** | 0.9918 | 0.9920 | 0.9922 | 0.9925 | 0.9927 | 0.9929 | 0.9931 | 0.9932 | 0.9934 | 0.9936 |
| **0.25** | 0.9938 | 0.9940 | 0.9941 | 0.9943 | 0.9945 | 0.9946 | 0.9948 | 0.9949 | 0.9951 | 0.9952 |
| **0.26** | 0.9953 | 0.9955 | 0.9956 | 0.9957 | 0.9959 | 0.9960 | 0.9961 | 0.9962 | 0.9963 | 0.9964 |
| **0.27** | 0.9965 | 0.9966 | 0.9967 | 0.9968 | 0.9969 | 0.9970 | 0.9971 | 0.9972 | 0.9973 | 0.9974 |
| **0.28** | 0.9974 | 0.9975 | 0.9976 | 0.9977 | 0.9977 | 0.9978 | 0.9979 | 0.9979 | 0.9980 | 0.9981 |
| **0.29** | 0.9981 | 0.9982 | 0.9982 | 0.9983 | 0.9984 | 0.9984 | 0.9985 | 0.9985 | 0.9986 | 0.9986 |
| **0.30** | 0.9987 | 0.9987 | 0.9987 | 0.9988 | 0.9988 | 0.9989 | 0.9989 | 0.9989 | 0.9990 | 0.9990 |
| **0.31** | 0.9990 | 0.9991 | 0.9991 | 0.9991 | 0.9992 | 0.9992 | 0.9992 | 0.9992 | 0.9993 | 0.9993 |
| **0.32** | 0.9993 | 0.9993 | 0.9994 | 0.9994 | 0.9994 | 0.9994 | 0.9994 | 0.9995 | 0.9995 | 0.9995 |
| **0.34** | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9997 | 0.9998 |

# CHAPTER 6

# CASE STUDIES AND RESULTS

This chapter covers sample runs to analyze the outputs of cruise missile mission rehearsal tool developed in this thesis. While analyzing, data of units in air defense system used in all analyses is presented in Appendix C, D, and E. Note that, if there is a change in this data, it is presented in the part of interest. Analysis work is done into two major parts. At the first one, each units of air defense system is analyzed based on single run simulation. The second one presents some tactical operational scenarios with different weapon types based on multi simulation runs. Same cruise missile data is used in all analyses in order to evaluate performance of mission planning on different enemy forces. Cruise missile flight path is presented in Figure 6.1.

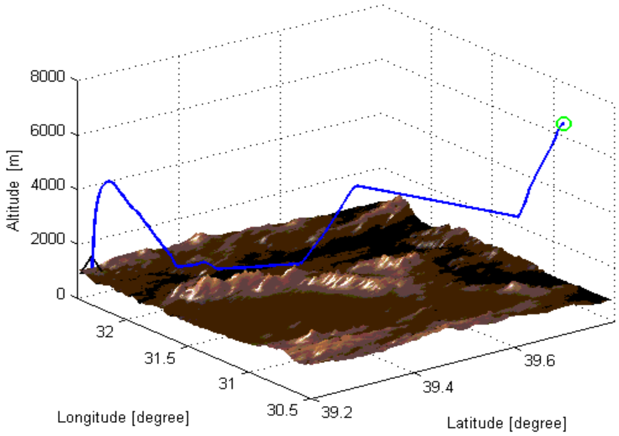

Figure 6.1 Cruise Missile Flight Path

## 6.1 Analysis of Each Main Units in Air Defense System Based on Single Run

All outputs given in this part are presented in the coordinate frame, which is X axis pointing towards north, Y axis pointing towards east and Z axis pointing towards down to the centre. X and Y axes of this coordinate frame are placed on the ground where weapon is fired. Z axis presents elevation of weapon from earth surface during flight.

Search radar is required to alert command and control center. Track radar is responsible to track cruise missile according to warning from C2. If weapons follow and catch cruise missile, these radars should be worked correctly. Air defense system must be occurred from at least one search radar, track radar, and weapon in order to damage enemy. Moreover, all main units in air defense system must be analyzed together. Therefore, in this section, search and track radar are not analyzed individually.

### 6.1.1 Anti-Aircraft Artillery (AAA)

This sample occurs from single anti-aircraft artillery, command and control center, search, and track radar. Locations of components and screenshot of scenario are presented in Table 6.1 and Figure 6.2 respectively. The initial speed of weapon is 823 m/s. The standard deviations in x axis and y axis are 10 m and 15 m, respectively.

Table 6.1 Locations of components in First Sample

| **Components** | **Location** | |
|---|---|---|
| | **Latitude[degree]** | **Longitude[degree]** |
| C2 | 39.22912 | 32.132084 |
| Search Radar | 39.349632 | 32.182438 |
| Track Radar | 39.276863 | 32.087048 |
| AAA | 39.22239 | 32.376053 |

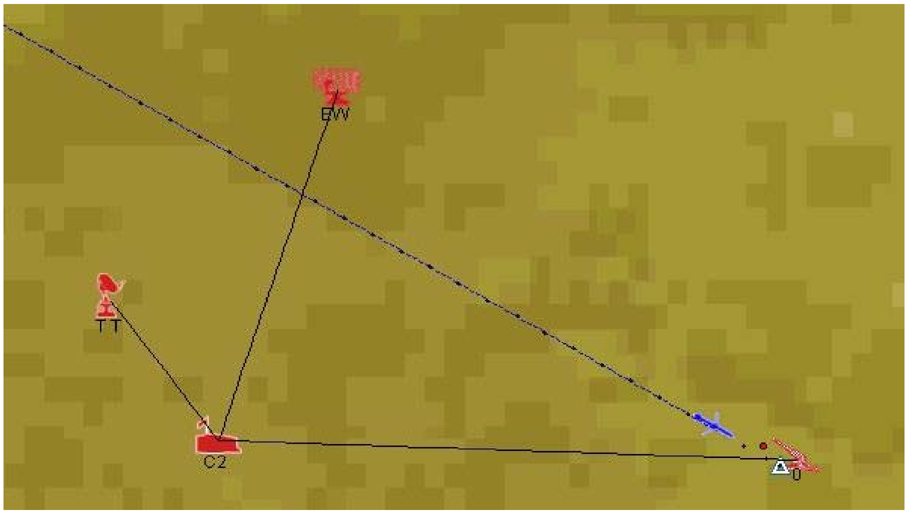

Figure 6.2 Screenshot of scenario while first sample is running

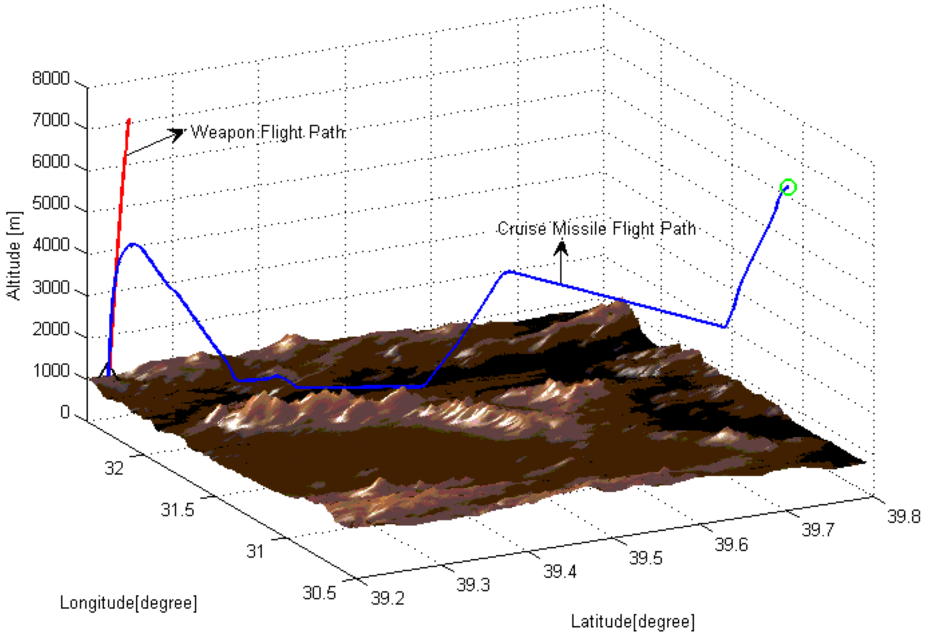

Figure 6.3 AAA's and cruise missile's flight path in 3D plane.

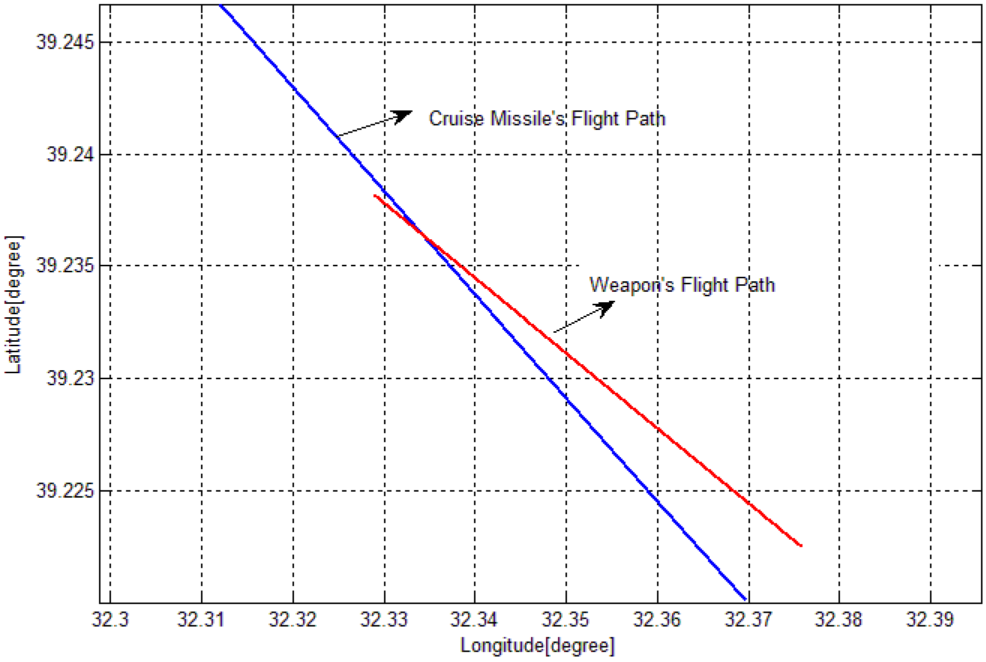

Figure 6.4 AAA's and cruise missile's flight path in latitude and longitude plane

It can be seen from Figure 6.3 and Figure 6.4 that weapon flights towards cruise missile, but it does not kill the cruise missile. It is difficult to damage target by only single AAA because weapon does not have guidance. As a result of this, lots of AAAs are fired against target with elevation and azimuth changes. Interception point is determined by C2 by using missile current location when weapon is fired, weapon's platform location, and predicted weapon's flight time based on weapon parameters. After obtaining interception point, launcher's elevation and azimuth angles are modified by means of enfilade angle, which is entered by user from configuration file.

It can be seen from Figure 6.4, Figure 6.5 and Figure 6.2, position of weapon along X axis increase in order to reach target. Moreover, Figure 6.4, Figure 6.6, and Figure 6.2 show that weapon moves towards west to meet target.

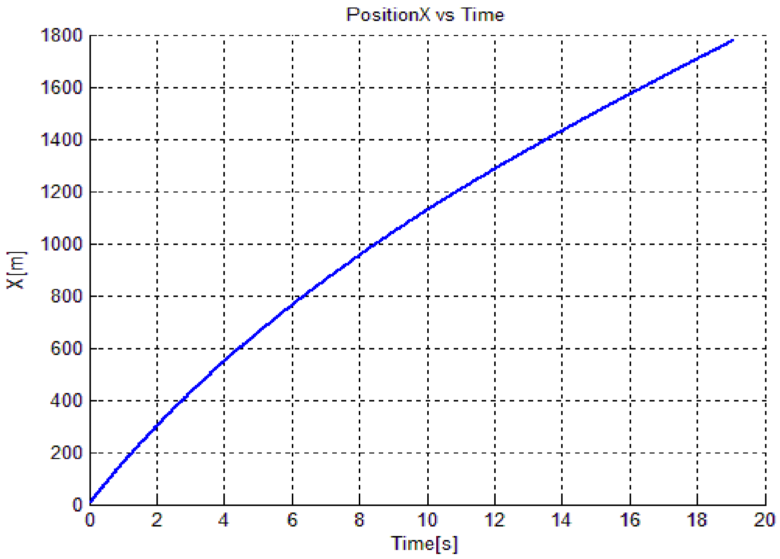

Figure 6.5 Position of weapon (AAA) in X axis

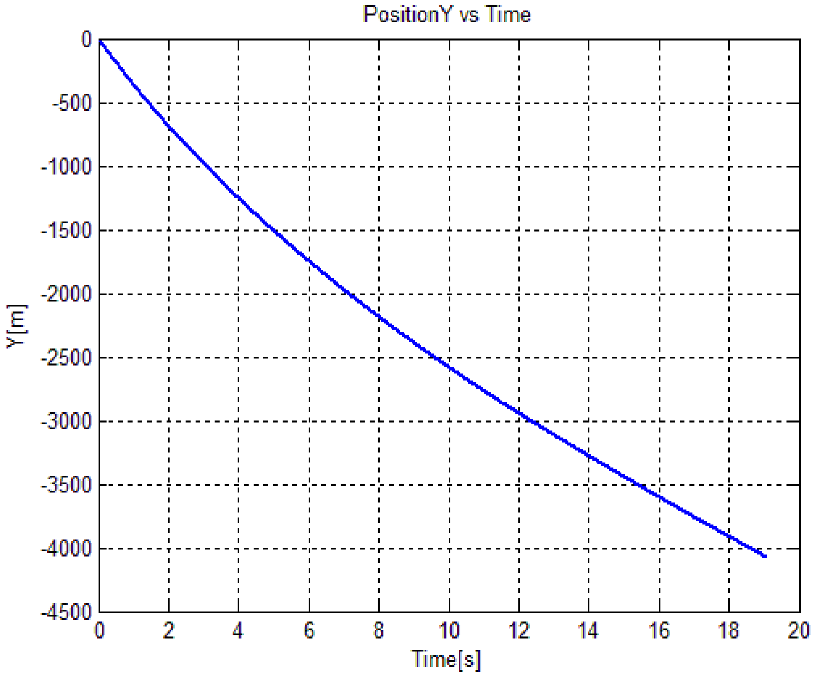

Figure 6.6 Position of weapon (AAA) in Y axis

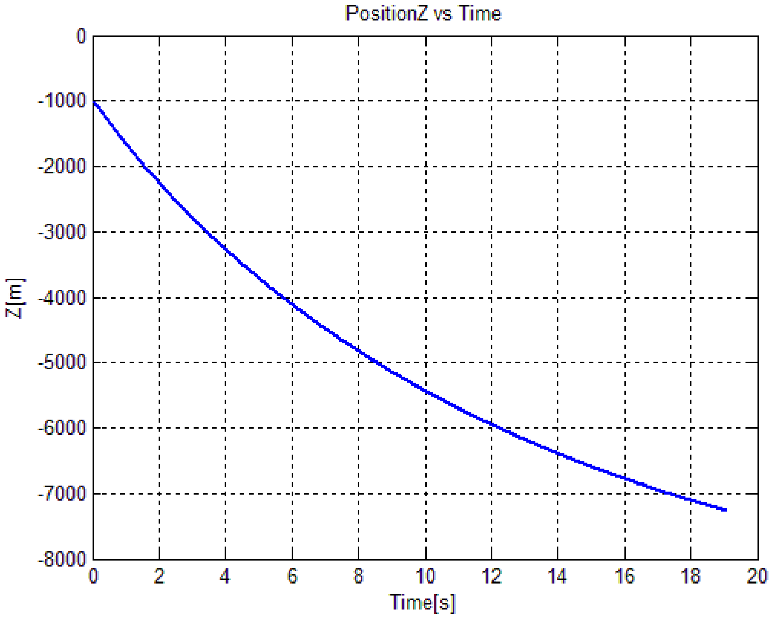

Figure 6.7 Position of weapon (AAA) in Z axis

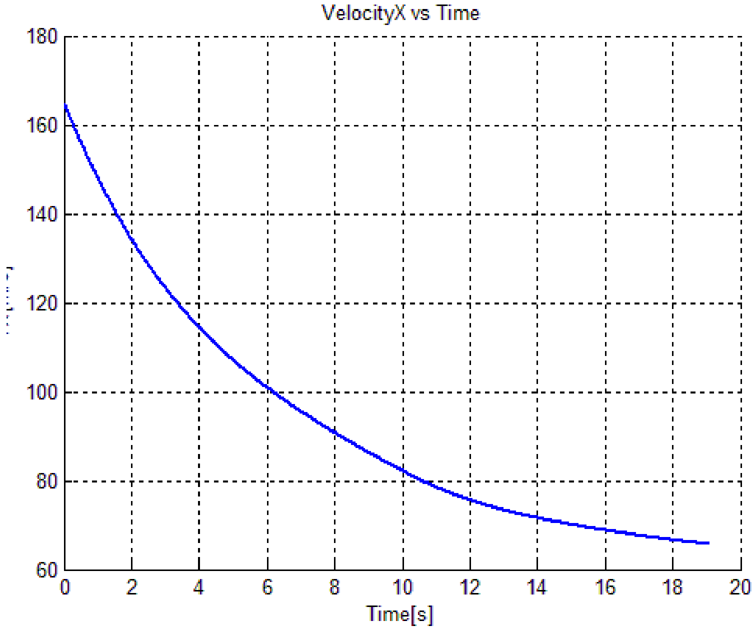

Figure 6.8 Velocity of weapon (AAA) in X axis

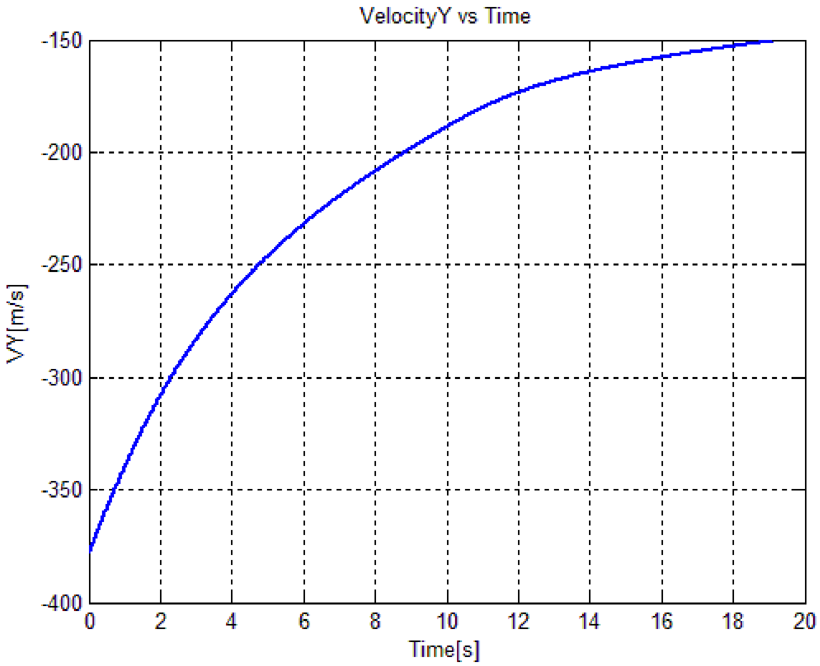

Figure 6.9 Velocity of weapon (AAA) in Y axis

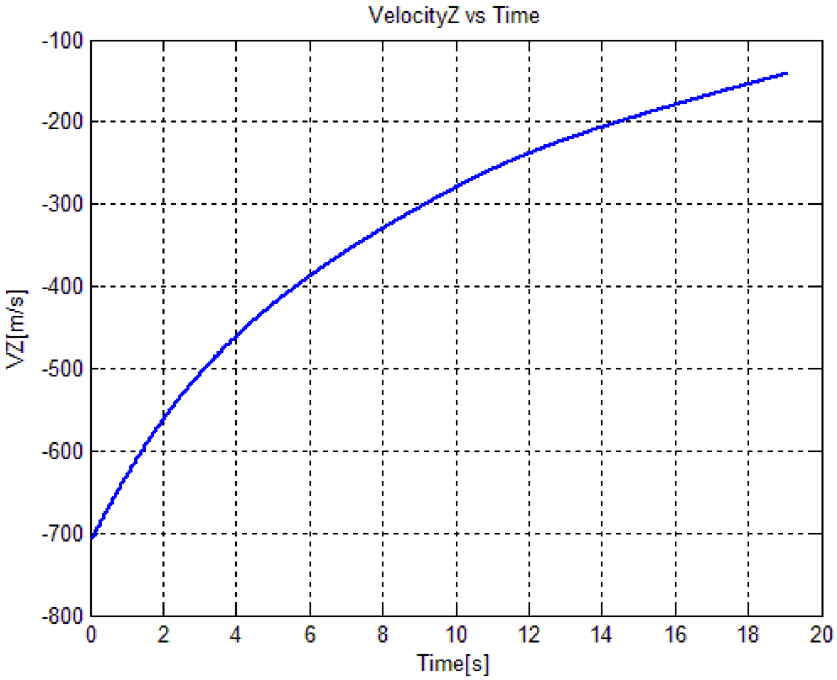

Figure 6.10 Velocity of weapon (AAA) in Z axis

It can be seen from Figure 6.8, Figure 6.9, and Figure 6.10 that velocity of weapon decreases during flight simulation due to air resistance.

### 6.1.2 Surface to Air Missile with Command Line of Sight Guidance (SAM with CLOS Guidance)

In this scenario, air defense system consists of single SAM with CLOS guidance, command and control center, search, and track radar. Locations of components and screenshot of scenario are presented in Table 6.2 and Figure 6.11 respectively. The maximum range of weapon equals to 100000 m. The standard deviations in x axis and y axis are 1 m.

Table 6.2 Locations of components in air defense system including SAM with CLOS

| **Components** | **Location** | |
|---|---|---|
| | **Latitude[degree]** | **Longitude[degree]** |
| C2 | 39.22912 | 32.132084 |
| Search Radar | 39.349632 | 32.182438 |
| Track Radar | 39.276863 | 32.087048 |
| SAM | 39.207294 | 32.19396 |

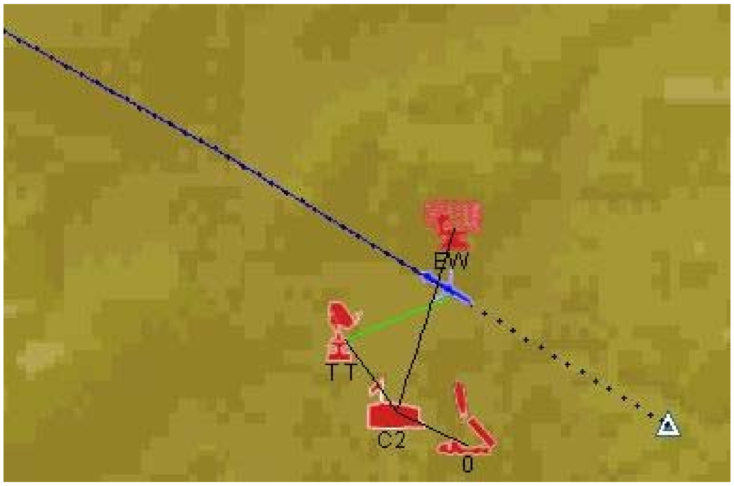

Figure 6.11 Screenshot of scenario while simulation is running

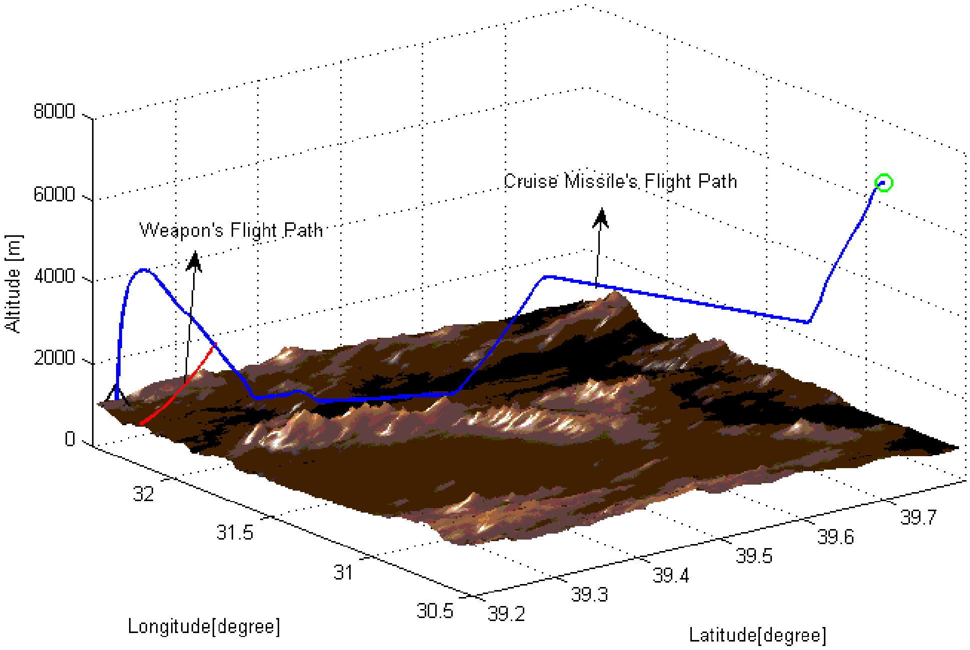

Figure 6.12 Flight paths of cruise missile and SAM with CLOS in 3D plane

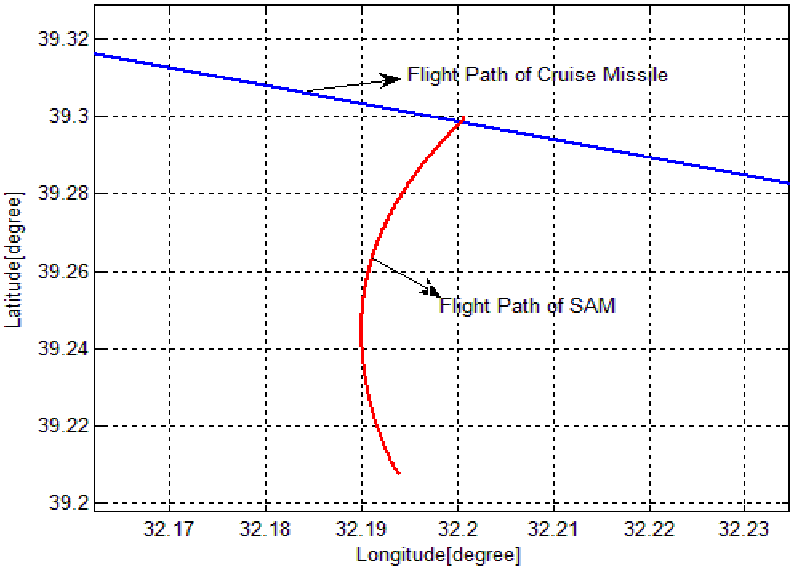

Figure 6.13 Flight paths of cruise missile and SAM with CLOS in 2D plane

As it can be seen from Figure 6.12, after SAM is fired, it begins to climb with cruise missile in order to catch cruise missile. Figure 6.13 shows that SAM is fired towards northwest, since it is located in the southeast with respect to cruise missile in that time. After guidance starts, it begins to direct towards cruise missile in order to damage it. In this case, SAM hits cruise missile, but it does not cruise missile due to low single shot kill probability.

Supplementary figures for this case are presented in APPENDIX F.1

### 6.1.3 Surface to Air Missile with Proportional Navigation Guidance (SAM with PN Guidance)

In this case, units of air defense system are single SAM with PN guidance, command and control center, search, and track radar. Their locations and screenshot of scenario are presented in Table 6.3 and Figure 6.14, respectively.

Table 6.3 Locations of components in air defense system including SAM with PN

| **Components** | **Location** | |
|---|---|---|
| | **Latitude[degree]** | **Longitude[degree]** |
| C2 | 39.22912 | 32.132084 |
| Search Radar | 39.349632 | 32.182438 |
| Track Radar | 39.276863 | 32.087048 |
| SAM | 39.365063 | 32.284416 |

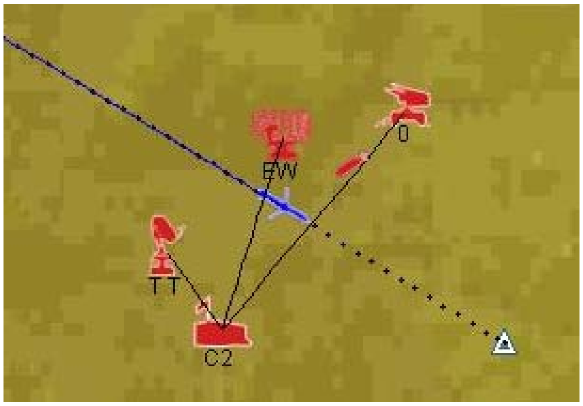

Figure 6.14 Screenshot of scenario with SAM PN while simulation is running

The maximum range of weapon equals to 45000 m. The standard deviations of SAM in x axis and y axis are 1 m. Its fuze type is point detonating.

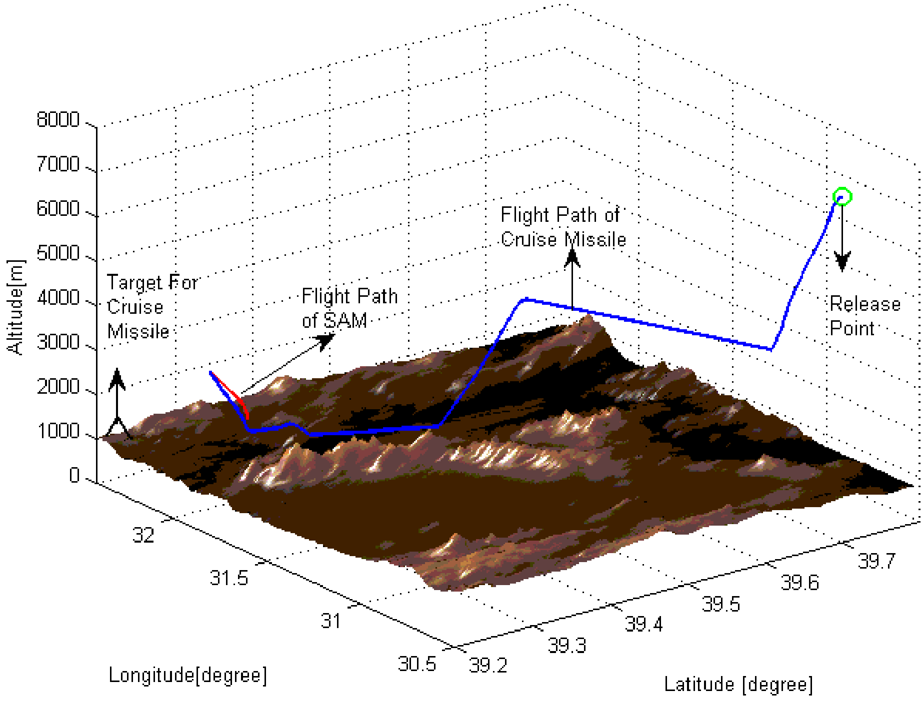

Figure 6.15 Flight paths of cruise missile and SAM with PN in 3D plane

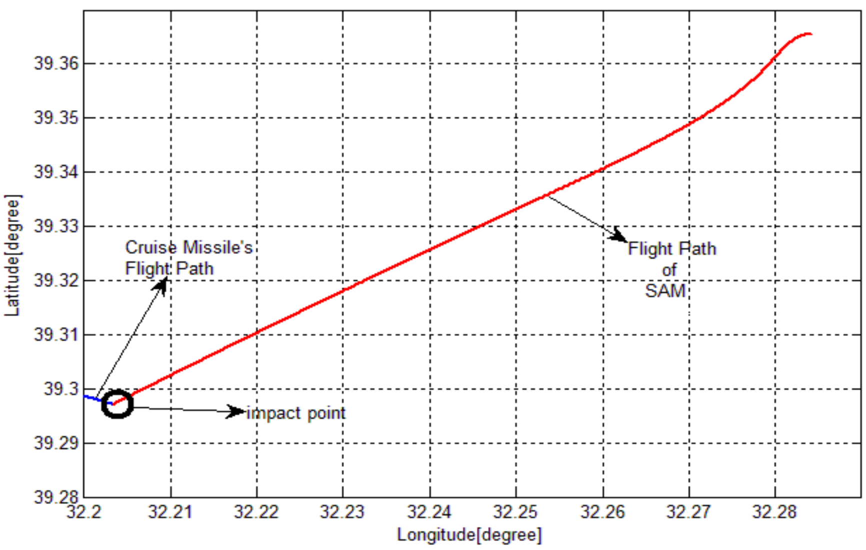

Figure 6.16 Flight paths of cruise missile and SAM with PN in 2D plane

SAM is launched towards southwest; since it is located in the northeast with respect to cruise missile in that time. It is illustrated in Figure 6.16 that weapon corrects orientation after guidance starts. Moreover, Figure 6.15 and Figure 6.16 show that SAM kills cruise missile in this case.

Supplementary figures for this case are presented in APPENDIX F.2

### 6.1.4 Command and Control Center (C2)

It is mentioned that C2 is responsible for evaluating tactical situation and defensing its own air defense system against threats by selecting most suitable weapon systems to engage them. Determining launcher’s azimuth and elevation are very important for weapon’s flight path, since if these parameters are obtained wrongly, the probability of target kill decreases due to the wrong orientation. Therefore, launch conditions of weapon determined by C2 are analyzed in this part. AAA is selected as weapon to analyze this event; because it has no guidance so determining initial condition is more crucial than other weapons.

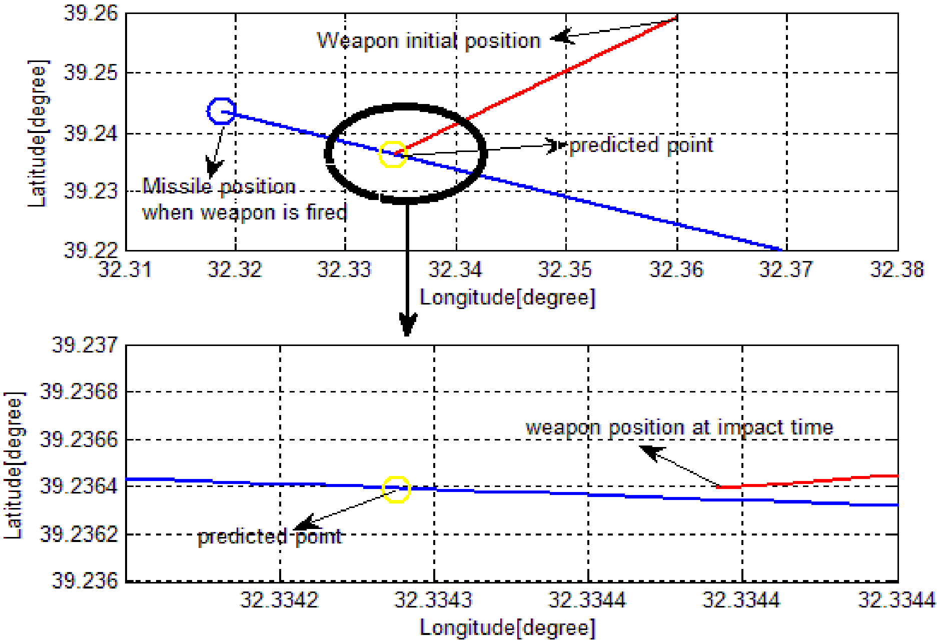

Figure 6.17 Interaction between missile and weapon in latitude and longitude axes

It is illustrated in Figure 6.17 that predicted position's latitude and longitude are placed on the cruise missile path. However, weapon failed to reach the cruise missile due to air resistance and motion of cruise missile.

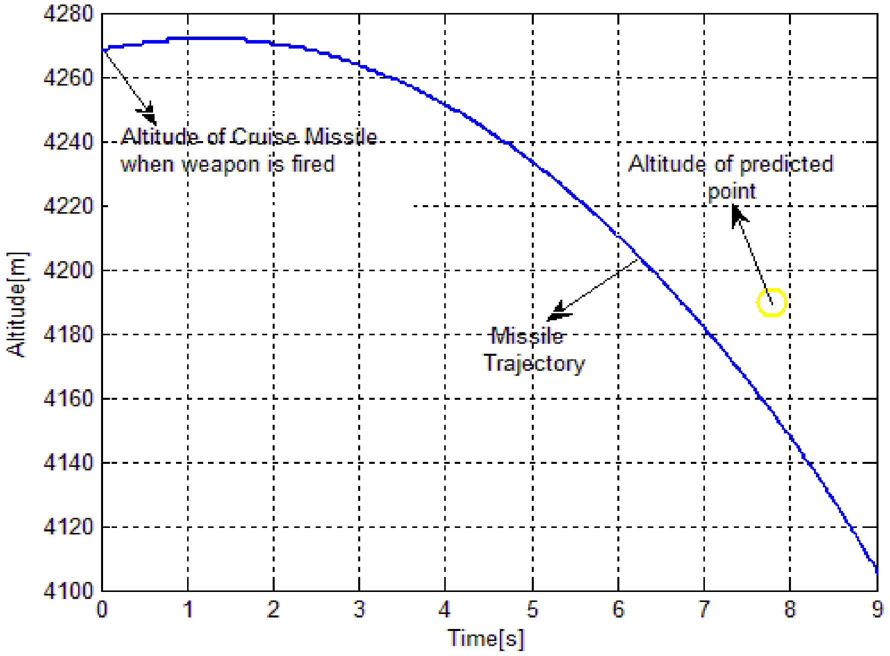

Figure 6.18 Illustration of missile trajectory and altitude of predicted point

Figure 6.18 shows that altitude of predicted interception point is above the altitude of cruise missile flight, because cruise missile begins to descend. As a result of this, firstly, predicted interception point is determined by C2 by using weapon's platform, location missile current location when weapon is fired, weapon's initial velocity and predicted weapon's flight time based on weapon parameters. Then, launcher's elevation and azimuth angles are modified according to enfilade angle, which is determined by user. Consequently, the probability of weapon's kill is increased.

## 6.2 Typical Operational Scenarios

This section covers evaluations of cruise missile mission planning's performance against typical air defense systems with various batteries. Monte Carlo simulation is done in order to obtain significant analysis results. The sampling number, which is determined according to confidence level = 0.95 and error margin = 0.05, equals to 268. Air defense system consists of single search radar and command and center, four track radar and batteries whose details are presented at section of interest. In spite of batteries' locations, locations of all units in air defense system are same. These locations are presented Table 6.4.

Table 6.4 Locations of all units in air defense system

| Components | Location | |
|---|---|---|
| | Latitude[degree] | Longitude[degree] |
| C2 | 39.219833 | 32.369457 |
| Search Radar | 39.294308 | 32.349514 |
| Track Radar 1 | 39.218086 | 32.34893 |
| Track Radar 2 | 39.227802 | 32.374203 |
| Track Radar 3 | 39.23029 | 32.3581 |
| Track Radar 4 | 39.213264 | 32.35918 |

### 6.2.1 Air Defense System Including Two SAM Batteries with CLOS Guidance

In this scenario, air defense system has two SAM batteries with CLOS guidance. Each battery has four missiles. The first one has a point denoting fuze according to that standard deviation is 3 m in x and y axes. The fuze type of the second battery is proximity with effective radius = 10 m and that standard deviation= 3 m in x and y axes. Parameters of batteries are presented in Table 6.5.

Table 6.5 Parameters of SAM Batteries with CLOS Guidance

| Batteries | Location[degree] | | # Missiles | Fuze Type |
|---|---|---|---|---|
| | Latitude | Longitude | | |
| SAM 1 | 39.216095 | 32.375423 | 4 | Point Detonating |
| SAM 2 | 39.233036 | 32.375423 | 4 | Proximity |

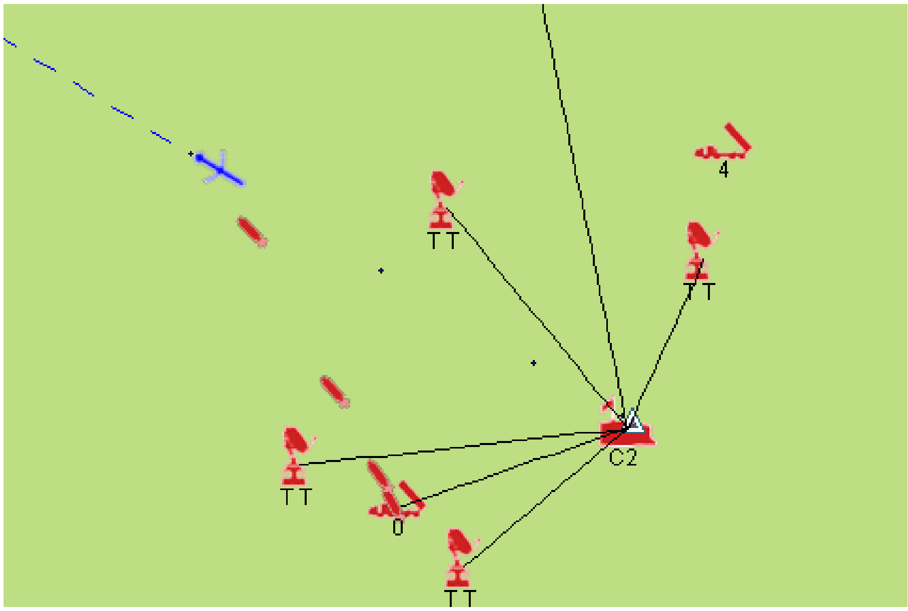

Figure 6.19 Screenshot of scenario with 2 SAM CLOS batteries while simulation is running

Figure 6.19 illustrates the screenshot of scenario taken from mission rehearsal tool while scenario is running. Plots of simulation's results are presented in following graphs.

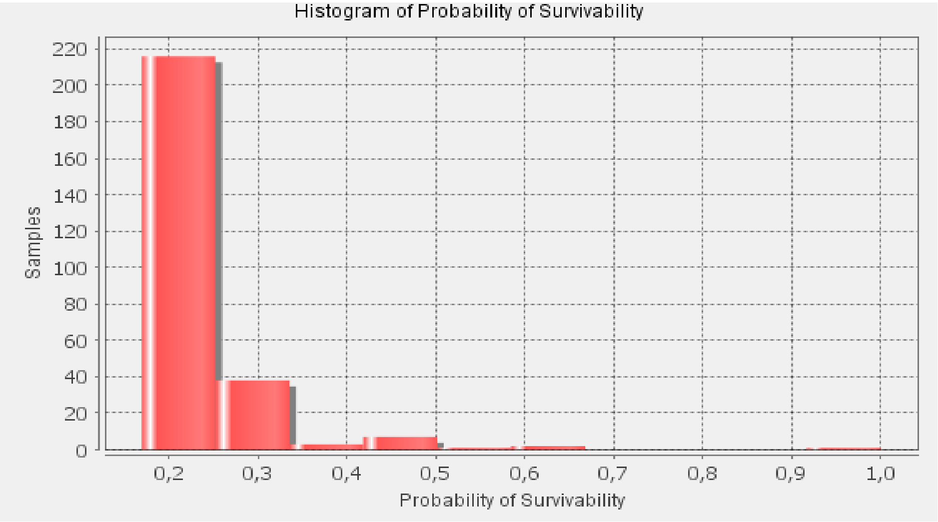

Figure 6.20 Histogram of Probability of Cruise Missile's Survivability

Figure 6.20 shows that probability of cruise missile's survivability against this air defense system is very low, which is nearly 0.2276.

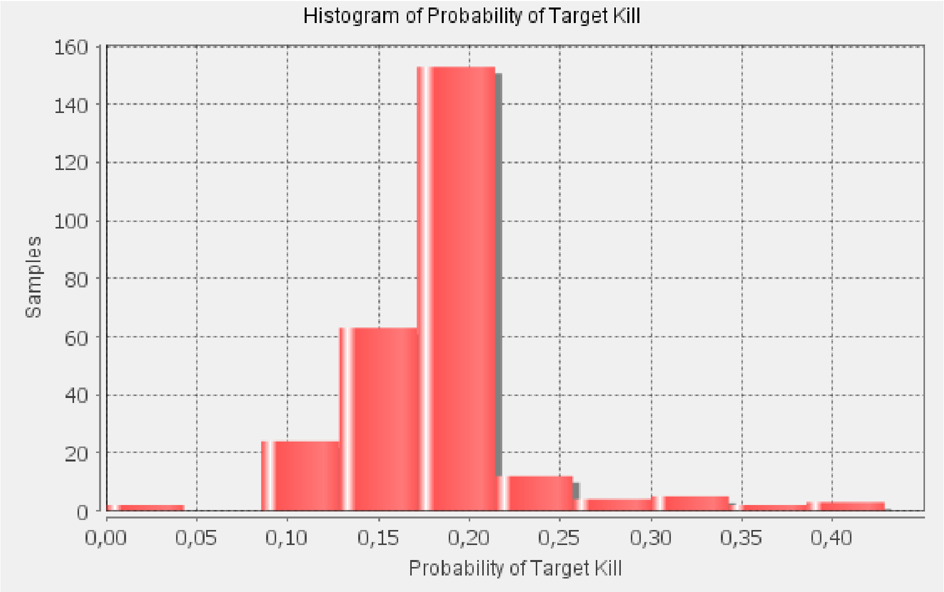

Figure 6.21 Histogram of Probability of Target Kill

It can be seen from Figure 6.21 that probability of target kill for cruise missile is nearly 0.1642. As expected, it also very low due to low cruise missile's survivability. Consequently, it can be declared that cruise missile is at high risk according to this operational scenario.

Supplementary plots for this case are presented in APPENDIX F.3

### 6.2.2 Air Defense System Including Two SAM Batteries with PN Guidance

Air defense system consists of two SAM batteries with PN guidance. The first one has a point denoting fuze based on that standard deviation is 5 m in x and y axes. The fuze type of the second battery is proximity with effective radius = 5 m and that standard deviation= 5 m in x and y axes. Parameters of batteries are provided in Table 6.6.

Table 6.6 Parameters of SAM Batteries with PN Guidance

| Batteries | Location[degree] | | # Missiles | Fuze Type |
|---|---|---|---|---|
| | Latitude | Longitude | | |
| SAM 1 | 39.215054 | 32.364075 | 3 | Point Detonating |
| SAM 2 | 39.22355 | 32.376656 | 3 | Proximity |

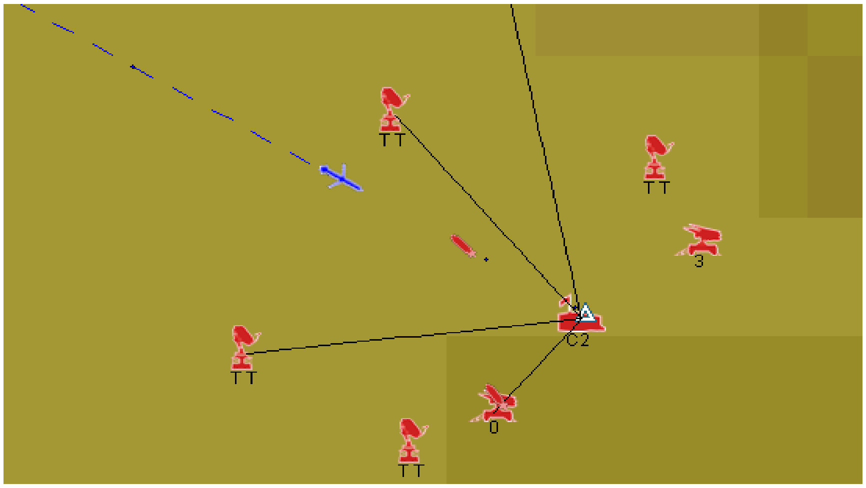

Figure 6.22 Screenshot of scenario with 2 SAM PN batteries while simulation is running

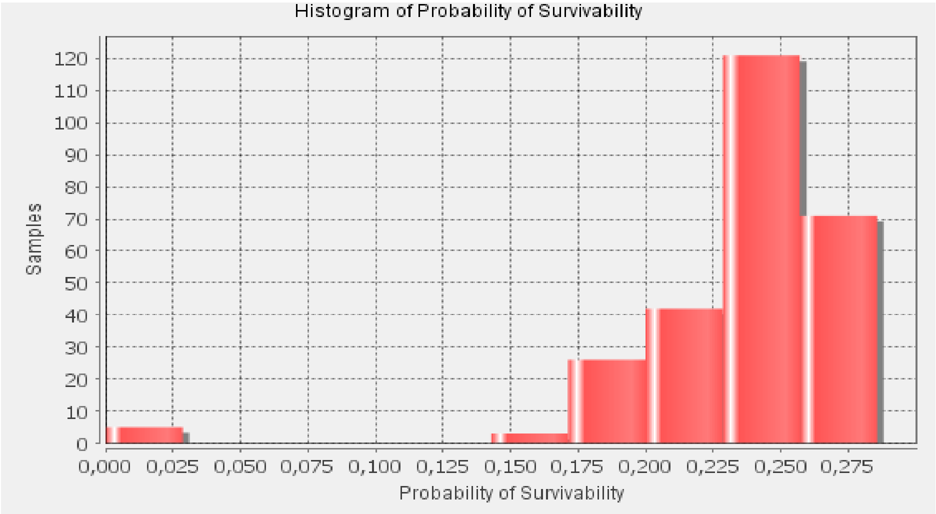

Figure 6.23 Histogram of Probability of Cruise Missile's Survivability in Air Defense with SAM PN

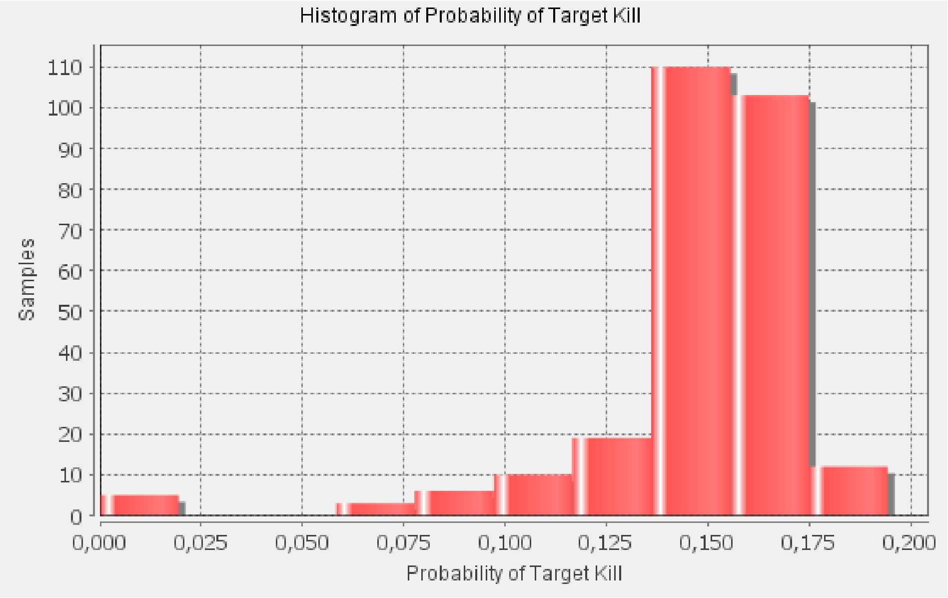

Figure 6.24 Histogram of Probability of Target Kill in Air Defense with SAM PN

As it can be seen from Figure 6.23 and Figure 6.24 that probability of missile survivability and missile's effectiveness on its target are nearly 0.25 and 0.153, respectively. As expected, probability of missile survivability is higher than probability of target kill. To sum up, it can be declared that cruise missile is unlikely to be successful according to this operational scenario.

Supplementary plots for this case are presented in APPENDIX F.4

### 6.2.3 Air Defense System Including Four AAA Batteries

In this case, air defense system occurs from four AAA batteries, which each one has 30 projectiles. Moreover, their standard deviations in x axis and y axis are taken as 10 m. Parameters of batteries are provided

Table 6.7 Parameters of AAA Batteries

| **Batteries** | **Location[degree]** | | **# Missiles** |
|---|---|---|---|
| | **Latitude** | **Longitude** | |
| AAA 1 | 39.22068 | 32.368248 | 30 |
| AAA 2 | 39.22172 | 32.367496 | 30 |
| AAA 3 | 39.22002 | 32.36703 | 30 |
| AAA 4 | 39.221203 | 32.369534 | 30 |

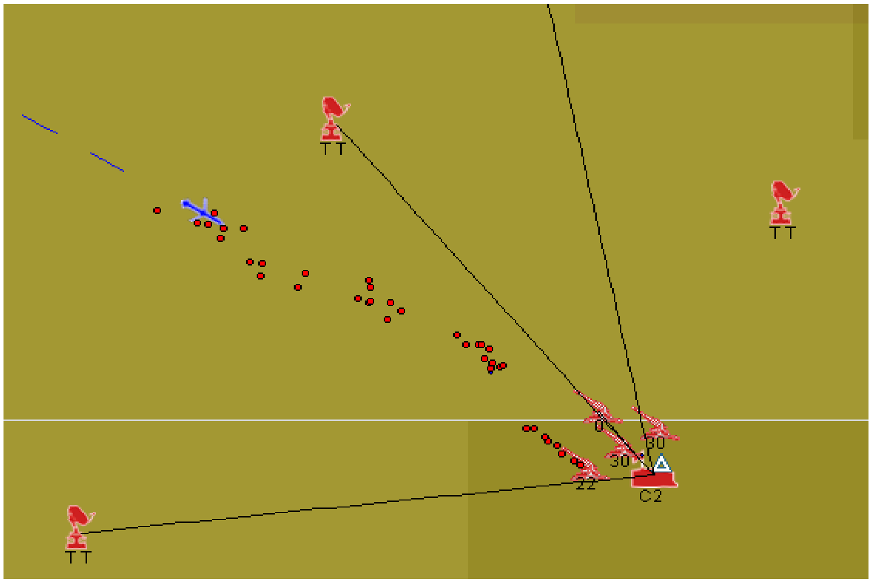

Figure 6.25 Screenshot of scenario with 4 AAA batteries while simulation is running

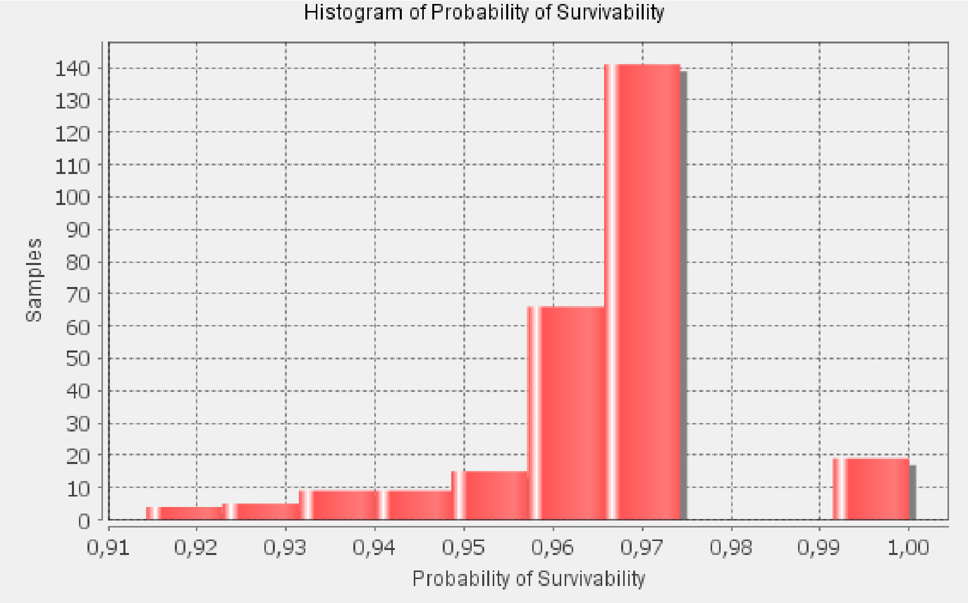

Figure 6.26 Histogram of Probability of Cruise Missile's Survivability in Air Defense with AAA

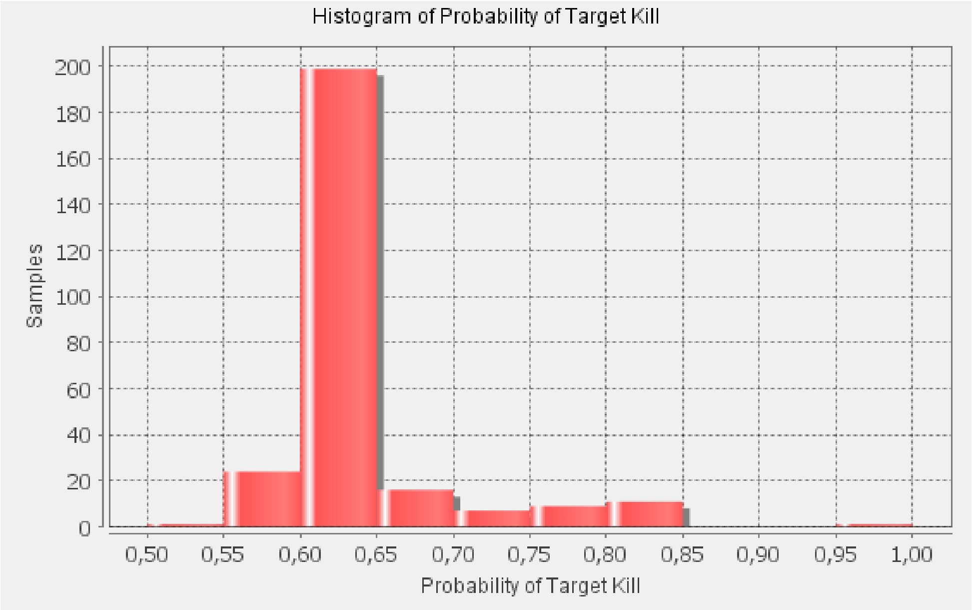

Figure 6.27 Histogram of Probability of Target Kill in Air Defense with AAA

Figure 6.26 and Figure 6.27 illustrate that probability of missile survivability and missile's effectiveness on its target is nearly 0.97 and 0.625, respectively. As expected, probability of target kill is lower than probability of missile survivability. To sum up, cruise missile is likely to be successful according to this operational scenario.

Supplementary plots for this case are presented in APPENDIX F.5

# CHAPTER 7

# CONCLUSION AND FUTURE WORK

## 7.1 Summary and Conclusion

In this thesis, the mission rehearsal tool is designed in order to assist in analyzing of planned mission by means of providing possible results of the planned mission and visualization of operational scenario in military operation. Moreover, it provides planner to identify potential risk and issues early in the tactical operating cycle. In other words, it allows planner to analyze enemy capabilities and to conduct risk assessment. According to outputs of mission rehearsal tool which are missile survivability and missile effectiveness, planner has an ability to evaluate feasibility of mission planning owing to visually rich environment that provides realistic simulation. As well as how well the planned mission works, it also goals at suggesting enhancement in the mission planning.

Tactical operating cycle includes seven different processes; objectives, target development, weaponeering, mission planning, mission rehearsal, force execution, combat assessment respectively. Mission rehearsal, one of most importance step in this cycle, offers possibility of revision of mission planning performed in the execution planning. This tool based on constructive simulation is modeled as Discrete System Simulation since there is an interaction between all models in it. It has three different techniques to evaluate performance of planned mission; visibility, feasibility, and variability techniques. Constructing complex air defense system is easy task because of having capability of flexible system configurations and tactical scenarios.

Mission rehearsal tool consists of three main models; air defense systems, cruise missile mission planning that will be analyzed and tactical environment.

Air defense system model refers to enemy forces (red forces) to damage cruise missile (blue force) by tracking and killing processes in its own defense area. Its constructive structure is based on four units such as radar system, weapon system, command and control center, and sub-air defense system. It has the ability to create multiple radar, weapon and sub-air defense systems. However, it only consists of a command and control center since command and control center is only decision-maker for all events which are held against its own defended area.

Radar system has two types of radar, such as search and track radar. Firstly, search radar (early warning radar), which is the long-range radar, is responsible for early target detection, warning of command and control center and attaining of target information. It has ability to scan all space undirectionally without knowing threat location. Search, detection, and acquisition models, which work together in order to alert command and control center in the case that threat is approaching to own defended area, are its sub-models. Secondly, the task of track radar is target tracking and acquisition according to warning sent from command and control center. It is the medium or short range radar with respect to search radar. It scans only limited space where threat is likely to be due to its narrow beam width to decrease errors in obtaining threat location. Its sub-models are precision weapon assignment, weapon assignment, designation, and track models. Inputs of precision weapon assignment, and weapon assignment, track radar's and weapon's id respectively are taken from command and control center. Designation model works in three steps, obtaining slant range to decide whether threat is within radar detection range or not, line of sight analysis to make decision about observability of threat, and determining probability of detection with using signal noise ratio to decide its traceability. Radar coverage modeling is necessary to terrain masking by means of determining loss value in 3D space. All area from starting radar location to its maximum range is disintegrated into many profiles throughout the direction of azimuth. Each profile is splitted into fragments to obtain loss values for each fragment. Loss values are restricted between maximum and minimum altitude bounds of radar. In this thesis, it is assumed that missile is not seen by radar at the out of these limits. Radar coverage of radars is determined at the initialization of scenario to speed up calculation, and then it is saved at database to be used in all flight simulation's time steps. Track model is required to supply threat data to weapon in order to aim of weapon to follow enemy.

In this thesis, weapon system includes guided and unguided weapons, surface to air missiles (SAMs) and anti-aircraft artilleries (AAAs) respectively. Guided weapons are divided into two groups with respect to guidance type, SAMs with command line of sight guidance, and SAMs with proportional navigation guidance, respectively. The principle of command line of guidance model is to produce commanded guidance acceleration for mounting weapon through line of sight between target and weapon launch point located on the ground. However, guidance command generated from proportional guidance model steers weapon through line of sight between target and weapon position with onboard seeker. Moreover, all weapons in weapon system are classified into two groups according to fuze type, point detonating and proximity fuze respectively.

The models of weapon system are launch, weapon dynamic, fuze and detonation, and kill assessment. The task of launch model is to determine launch data which are azimuth and elevation of launcher and initial velocity vector of weapon given from command and control center in order to raise the chance of killing target. The aim of weapon dynamic model is to determine manner of weapon during flight simulation. In other words, this model presents weapons' trajectory according to target data. Weapon dynamic model occurs from sub-models which are dynamic, atmosphere, aerodynamic, thrust, gravity, corios, guidance, autopilot and earth models. Fuze and detonation model makes decision whether weapon interacts with target (cruise missile) in the end condition. Kill assessment model is required to determine single shot kill probability of weapon.

The command control center is necessary to alert track radar for target tracking and acquisition, to determine attack details and weapon engagement. It consists of target engagement and weapon assignment, and fire control and weapon aiming models. Target engagement and weapon assignment model selects the most convenient track radar and weapon from ranked weapons' and radars' lists determined according to range from threat to increase damage of threat. Fire control and weapon aiming model determines launch data, which are bearing of weapon, azimuth of weapon, elevation of weapon, velocity of weapon, predicted location threat, and predicted time of weapon flight, to kill threat in the case of weapon fired.

In spite of single run, Monte Carlo method is used in this thesis since the probabilistic simulations require multiple runs for getting repeated tendencies. Owing to Monte Carlo, predictions of performance over a wide range situations rather than limited range as often obtained by analytical model is determined. Creating and analyzing scenario depends on the details of analysis desired both take time. The number of sampling is adjusted by analyzer with confidence level and error margin.

## 7.2 Recommendations for Future Work

In reality, behavior of simulation is affected by the vertical obstacles in the tactical environment. Therefore, the impact of vertical obstacles on mission planning, missile simulation, and mission rehearsal can be taken in order to obtain most realistic results. These obstacles can be buildings, and bridge etc.

Military Scenario Definiton Language (MSDL) is defined as the language between mission planning and mission rehearsal simulation to prepare military scenario file. Scenario file of mission rehearsal tool developed in this thesis can be organized according to MSDL standard.

The types of weapon could be extended to cover other types of missiles like air to air and surface to air missiles with different guidance types.

In this thesis, only one cruise missile is taken as threat, but in reality multi missiles attack towards defended area. The number of attacked missiles has an impact on units' behavior in air defense system. As a result of this, missile's survivability, effectiveness, and performance of air defense system can be changed.

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# APPENDIX A

# EXAMPLE OF SCENARIO FILE

```
<!-- Input File -->
<mission>
<!-- Environment -->
  <environment>
    <atmosphere>
      <atmosphere_file>./Atmosphere/meta.dat</atmosphere_file>
    </atmosphere>

    <terrain>
      <dted_data_path>./../dted/</dted_data_path>
      <variance_data_path>./sigmat/sigmatFile.txt</variance_data_path>
    </terrain>

   </environment>
 <!-- Blue Forces -->
   <blue_forces>
     <cruise_missile>
       <rcs_file>./Missile/missileRCSTable.rcs</rcs_file>
       <missileLength>4.0</missileLength>
       <missileRadius>0.5</missileRadius>
     </cruise_missile>
   </blue_forces>

<!-- Red Forces -->
   <red_forces>
```

```
      <air_defense>

         <air_defense_network >
            <file_dir>./AirDefenseNetwork/firstNetwork.xml</file_dir>
         </air_defense_network>

      </air_defense>
    </red_forces>

</mission>
```

# APPENDIX B

# EXAMPLE OF AIR DEFENSE FILE

```
<air_defense_network>

        <command_center>
          <latitude>39.67634</latitude>
          <longitude>31.045494</longitude>
        </command_center>

        <search_radar>
          <latitude>39.71</latitude>
          <longitude>31.0</longitude>
          <maxRange>100000</maxRange>
          <minRange>0</minRange>
          <systemHeight>10</systemHeight>
          <antennaHeight>2</antennaHeight>
          <transmittedPower>450</transmittedPower>
          <systemBandwidthReceiver>5</systemBandwidthReceiver>
          <Frequency>1.2</Frequency>
          <El_BeamWidth>12</El_BeamWidth>
          <Az_BeamWidth>2.4</Az_BeamWidth>
          <NoiseFigure>3.5</NoiseFigure>
          <SystemLoss>4</SystemLoss>
          <maxAltitudeBound>100000</maxAltitudeBound>
          <minAltitudeBound>0</minAltitudeBound>
          <scanRate>20</scanRate>
```

```
   <azimuthScanAngle>15</azimuthScanAngle>
</search_radar>

<track_radar>
            <latitude>39.61694</latitude>
             <longitude>30.92546</longitude>
             <maxRange>30000</maxRange>
             <minRange>0</minRange>
             <systemHeight>10</systemHeight>
             <antennaHeight>3</antennaHeight>
             <transmittedPower>450</transmittedPower>
             <systemBandwidthReceiver>5</systemBandwidthReceiver>
             <Frequency>1.2</Frequency>
             <El_BeamWidth>12</El_BeamWidth>
             <Az_BeamWidth>2.4</Az_BeamWidth>
             <NoiseFigure>3.5</NoiseFigure>
            <SystemLoss>4</SystemLoss>
             <maxAltitudeBound>100000</maxAltitudeBound>
            <minAltitudeBound>0</minAltitudeBound>
</track_radar>

<track_radar>
             <latitude>39.601665</latitude>
             <longitude>31.024563</longitude>
            <maxRange>45000</maxRange>
             <minRange>0</minRange>
             <systemHeight>10</systemHeight>
            <antennaHeight>3</antennaHeight>
           <transmittedPower>450</transmittedPower>
          <systemBandwidthReceiver>5</systemBandwidthReceiver>
          <Frequency>1.2</Frequency>
          <El_BeamWidth>12</El_BeamWidth>
```

```
        <Az_BeamWidth>2.4</Az_BeamWidth>
        <NoiseFigure>3.5</NoiseFigure>
        <SystemLoss>4</SystemLoss>
        <maxAltitudeBound>100000</maxAltitudeBound>
        <minAltitudeBound>0</minAltitudeBound>
</track_radar>
<weapon>
    <numberOfWeapon>3</numberOfWeapon>
    <type>AAA</type>
    <aeroFile>./Weapon/AAA/aeroFile.aero</aeroFile>
    <phyFile>./Weapon/AAA/phyFile.phy</phyFile>
    <tubeVelMag>100.0</tubeVelMag>
    <platformLat>39.6016657</platformLat>
    <platformLon>31.0245637</platformLon>
    <platformAlt>910</platformAlt>
    <lagTime >3.0</lagTime>
    <maxRange>5000</maxRange>
    <fuseType>converge</fuseType>
    <standartDeviationXY>10</standartDeviationXY>
     <effectiveRadius>20</effectiveRadius>
</weapon>

<weapon>
    <numberOfWeapon>1</numberOfWeapon>
        <type>SAM</type>
        <guidanceType>PN</guidanceType>
        <motorFile>./Weapon/SAM_PN/motorData.mot</motorFile>
        <massFile>./Weapon/SAM_PN/massFlow.mdot</massFile>
        <guidFile>./Weapon/SAM_PN/PNguidFile.guid</guidFile>
        <aeroFile>./Weapon/SAM_PN/aeroFile.aero</aeroFile>
        <phyFile>./Weapon/SAM_PN/phyFile.phy</phyFile>
        <tubeVelMag>100.0</tubeVelMag>
```

```
        <platformLat>39.665127</platformLat>
        <platformLon>31.171822</platformLon>
        <platformAlt>789</platformAlt>
        <lagTime >2.0</lagTime>
        <maxRange>80000</maxRange>
        <fuseType>impact</fuseType>
          <standartDeviationX>5</standartDeviationX>
        <standartDeviationY>5</standartDeviationY>
</weapon>

<weapon>
       <numberOfWeapon>1</numberOfWeapon>
       <type>SAM</type>
       <guidanceType>CLOS</guidanceType>
       <motorFile>./Weapon/SAM_CLOS/motorData.mot</motorFile>
      <massFile>./Weapon/SAM_CLOS/massFlow.mdot</massFile>
     <guidFile>./Weapon/SAM_CLOS/CLOSguidFile.guid</guidFile>
      <aeroFile>./Weapon/SAM_CLOS/aeroFile.aero</aeroFile>
      <phyFile>./Weapon/SAM_CLOS/phyFile.phy</phyFile>
      <tubeVelMag>100.0</tubeVelMag>
       <platformLat>39.594727</platformLat>
        <platformLon>31.14476</platformLon>
       <platformAlt>1020</platformAlt>
        <lagTime >1.0</lagTime>
        <maxRange>60000</maxRange>
        <fuseType>impact</fuseType>
      <standartDeviationX>5</standartDeviationX>
        <standartDeviationY>5</standartDeviationY>
</weapon>

 <air_defense_network >
        <file_dir>./AirDefenseNetwork/secondNetwork.xml</file_dir>
```

```
        </air_defense_network>
</air_defense_network>
```

# APPENDIX C

# EXAMPLE OF ATMOSPHERE FILE FORMAT

Table C. 1 Example of Atmosphere File

| Line Number | Wind Direction | Wind Magnitude | Temperature | Pressure |
|---|---|---|---|---|
| 0. | 0. | 0. | 2882. | 1013. |
| 1. | 0. | 0. | 2875. | 1001. |
| 2. | 0. | 0. | 2859. | 972. |
| 3. | 0. | 0. | 2833. | 926. |
| 4. | 0. | 0. | 2800. | 872. |
| 5. | 0. | 0. | 2768. | 820. |
| 6. | 0. | 0. | 2735. | 771. |
| 7. | 0. | 0. | 2703. | 724. |
| 8. | 0. | 0. | 2670. | 679. |
| 9. | 0. | 0. | 2638. | 637. |
| 10. | 0. | 0. | 2605. | 597. |
| 11. | 0. | 0. | 2573. | 559. |
| 12. | 0. | 0. | 2524. | 505. |
| 13. | 0. | 0. | 2459. | 441. |
| 14. | 0. | 0. | 2395. | 383. |
| 15. | 0. | 0. | 2330. | 332. |
| 16. | 0. | 0. | 2265. | 286. |
| 17. | 0. | 0. | 2200. | 245. |
| 18. | 0. | 0. | 2167. | 210. |
| 19. | 0. | 0. | 2167. | 179. |
| 20. | 0. | 0. | 2167. | 153. |
| 21. | 0. | 0. | 2167. | 131. |
| 22. | 0. | 0. | 2167. | 112. |
| 23. | 0. | 0. | 2167. | 96. |
| 24. | 0. | 0. | 2167. | 82. |
| 25. | 0. | 0. | 2167. | 70. |
| 26. | 0. | 0. | 2167. | 60. |
| 27. | 0. | 0. | 2176. | 47. |
| 28. | 0. | 0. | 2196. | 35. |
| 29. | 0. | 0. | 2216. | 25. |
| 30. | 0. | 0. | 2235. | 19. |
| 31. | 0. | 0. | 2255. | 14. |

# APPENDIX D

## EXAMPLE OF WEAPONS' DATA

Table D. 1 Example of Weapons' Aerodynamic File

| Mach | $CD_0$ | $CD_\alpha^2$ | $CL_\alpha$ |
|---|---|---|---|
| 0.10 | 0.35 | 0.00 | 107.95 |
| 0.33 | 0.36 | 0.00 | 109.85 |
| 0.53 | 0.36 | 0.00 | 112.30 |
| 0.71 | 0.36 | 0.00 | 114.71 |
| 0.86 | 0.42 | 0.00 | 120.38 |
| 1.00 | 0.61 | 0.00 | 135.87 |
| 1.05 | 0.68 | 0.00 | 136.83 |
| 1.12 | 0.64 | 0.00 | 135.47 |
| 1.19 | 0.59 | 0.00 | 134.26 |
| 1.27 | 0.55 | 0.00 | 128.55 |
| 1.36 | 0.52 | 0.00 | 125.09 |
| 1.46 | 0.50 | 0.00 | 119.22 |
| 1.58 | 0.49 | 0.00 | 107.55 |
| 1.71 | 0.48 | 0.00 | 100.80 |
| 1.87 | 0.47 | 0.00 | 94.96 |
| 2.04 | 0.48 | 0.00 | 89.21 |
| 2.23 | 0.44 | 0.00 | 82.94 |
| 2.46 | 0.41 | 0.00 | 76.98 |
| 2.71 | 0.38 | 0.00 | 71.43 |
| 3.00 | 0.35 | 0.00 | 65.92 |

Table D. 2 Example of Weapons' Physical File

| Mass(kg) | Surface Area($m^2$) | Length(m) |
|---|---|---|
| 250 | 0.040 | 2.7 |

Table D. 3 Example of Weapons’ Mass Flow Rate

| Time (s) | Mass Flow Rate(kg/s) | Time (s) | Mass Flow Rate(kg/s) |
|---:|:---:|:---:|:---:|
| 0 | 0 | 5.598 | 23.64568 |
| 0.098 | 30.29591 | 5.698 | 23.64568 |
| 0.198 | 29.5022 | 5.798 | 23.49541 |
| 0.298 | 28.78554 | 6.898 | 23.45689 |
| 0.398 | 28.33089 | 6.998 | 23.41836 |
| 0.498 | 27.9533 | 7.098 | 23.26809 |
| 0.598 | 27.61424 | 7.198 | 22.96756 |
| 0.698 | 27.27133 | 7.298 | 22.92903 |
| 1.798 | 26.97079 | 7.398 | 22.81729 |
| 1.898 | 26.51614 | 7.498 | 22.66317 |
| 1.998 | 26.21561 | 7.598 | 22.47438 |
| 2.098 | 25.83802 | 7.698 | 22.36264 |
| 2.198 | 25.57217 | 7.798 | 22.36264 |
| 2.298 | 25.4219 | 7.898 | 22.51291 |
| 2.398 | 25.15605 | 7.998 | 22.51291 |
| 2.498 | 25.08284 | 8.098 | 22.13532 |
| 2.598 | 25.00578 | 8.198 | 21.00254 |
| 2.698 | 24.85551 | 8.298 | 19.03753 |
| 2.798 | 24.77845 | 8.398 | 16.31733 |
| 2.898 | 24.62819 | 8.498 | 13.18487 |
| 2.998 | 24.58966 | 8.598 | 10.72667 |
| 3.098 | 24.55498 | 8.698 | 8.800185 |
| 4.198 | 24.40086 | 8.798 | 7.40541 |
| 4.298 | 24.28913 | 8.898 | 6.157047 |
| 4.398 | 24.21207 | 8.998 | 5.324805 |
| 4.498 | 24.0618 | 9.098 | 4.457887 |
| 4.598 | 24.2506 | 9.198 | 3.702705 |
| 4.698 | 23.95007 | 9.298 | 3.059259 |
| 4.798 | 23.95007 | 9.398 | 2.454342 |
| 4.898 | 23.87301 | 9.498 | 1.926485 |
| 4.998 | 23.87301 | 9.598 | 1.471835 |
| 5.098 | 23.83448 | 9.698 | 1.059567 |
| 5.198 | 23.76127 | 9.798 | 0.678123 |
| 5.298 | 23.68421 | 9.898 | 0.339061 |
| 5.398 | 23.68421 | 9.998 | 0.077059 |
| 5.498 | 23.68421 | 10.04 | 0 |

Table D. 4 Example of Weapons' Motor File

| **Specific Fuel Consumption (Ns/kg)** | **Reference Pressure (Pa)** | **Exit Area ($m^2$)** | **Fuel Mass (kg)** |
|---|---|---|---|
| 2100 | 101325.018 | 0.05 | 306.8608615 |

Table D. 5 Example of Weapons' Guidance File (CLOS)

| **CLOS Ratio** | **Guidance start Time** | **Minimum Angle of Attack** | **Maximum Angle of Attack** | **Minimum Gimbal Angle** | **Maximum Gimbal Angle** |
|---|---|---|---|---|---|
| 7 | 0,3 | -45 | 45 | -50 | 50 |

Table D. 6 Example of Weapons' Guidance File (PN)

| **NR** | **Guidance start Time** | **Minimum Angle of Attack** | **Maximum Angle of Attack** |
|---|---|---|---|
| 13 | 0,3 | -45 | 45 |

# APPENDIX E

# EXAMPLE OF RADARS' DATA

Table E. 1 Search Radar's Data

| **Parameters** | **Values** | **Units** |
|---|---|---|
| Maximum Range | 150000 | m |
| Minimum Range | 0 | m |
| System Height | 10 | m |
| Antenna Height | 2 | m |
| Transmitted Power | 450 | kW |
| System Bandwidth Receiver | 5 | mHZ |
| Frequency | 1.2 | Hz |
| Elevation Beamwidth | 12 | degree |
| Azimuth Beamwidth | 2.4 | degree |
| Noise Figure | 3.5 | dB |
| System Loss | 4 | dB |
| Maximum Altitude Bound | 100000 | m |
| Minimum Altitude Bound | 0 | m |
| Scan Rate | 20 | s |
| Azimuth Scan Angle | 15 | degree |
| Minumum Number Of TotalScans | 3 | |

Table E. 2 Track Radar’s Data

| **Parameters** | **Values** | **Units** |
|---|---|---|
| Maximum Range | 100000 | m |
| Minimum Range | 0 | m |
| System Height | 10 | m |
| Antenna Height | 2 | m |
| Transmitted Power | 450 | kW |
| System Bandwidth Receiver | 5 | mHZ |
| Frequency | 1.2 | Hz |
| Elevation Beamwidth | 12 | degree |
| Azimuth Beamwidth | 2.4 | degree |
| Noise Figure | 3.5 | dB |
| System Loss | 4 | dB |
| Maximum Altitude Bound | 100000 | m |
| Minimum Altitude Bound | 0 | m |
| Threshold Detection Factor Of Sensor | 0.9 | |

# APPENDIX F

# SUPPLEMENTERY FIGURES FOR CASE STUDIES

## F.1 Surface to Air Missile with Command Line of Sight Guidance (SAM with CLOS Guidance)

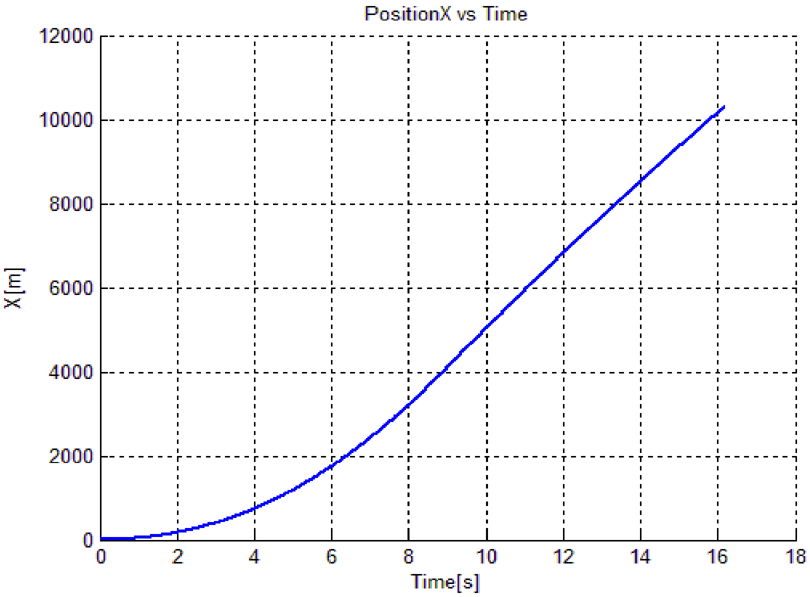

Figure F. 1 Position of weapon (SAM) in X axis

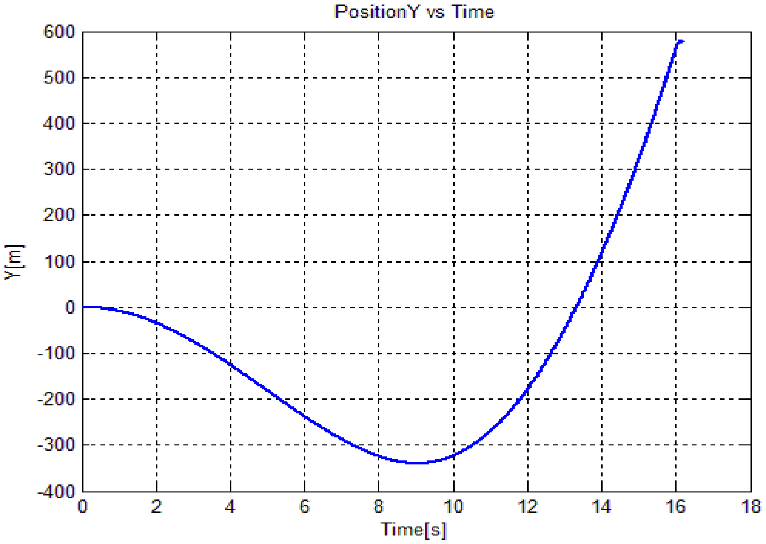

Figure F. 2 Position of weapon (SAM) in Y axis

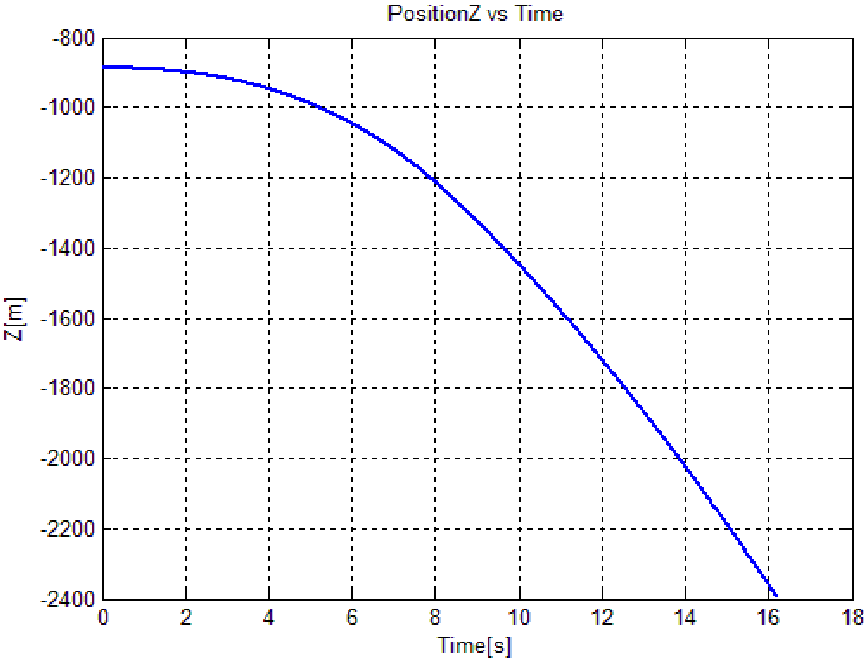

Figure F. 3 Position of weapon (SAM) in Z axis

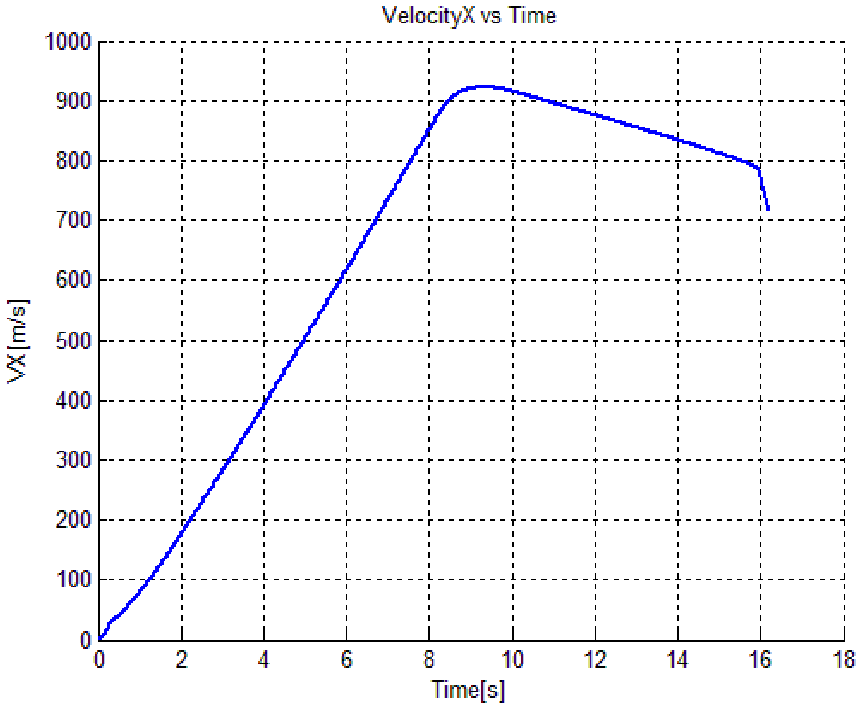

Figure F. 4 Velocity of weapon (SAM) in X axis

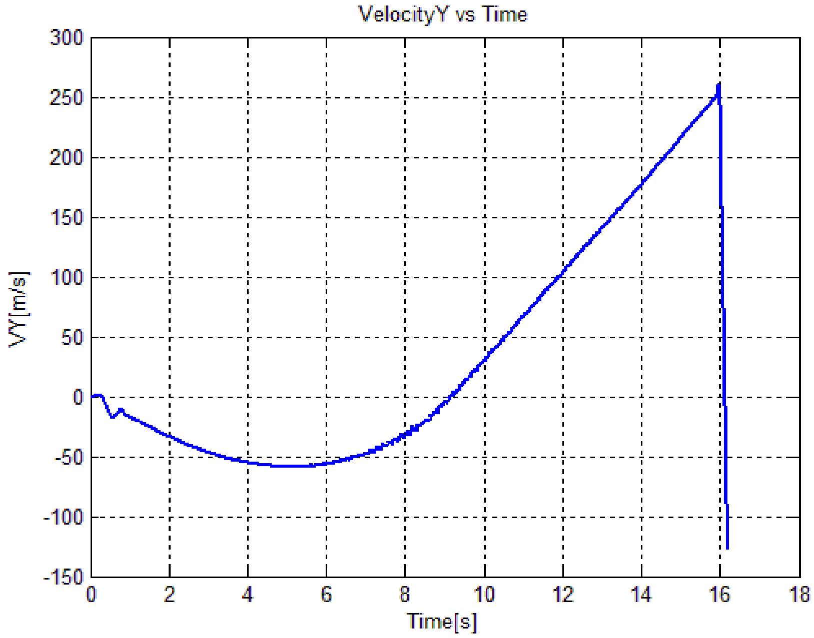

Figure F. 5 Velocity of weapon (SAM) in Y axis

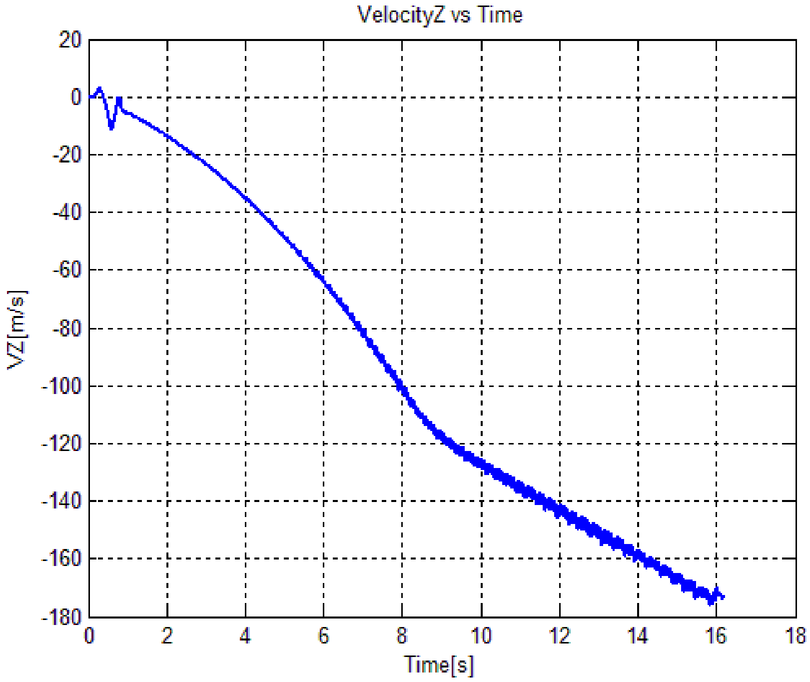

Figure F. 6 Velocity of weapon (SAM) in Z axis

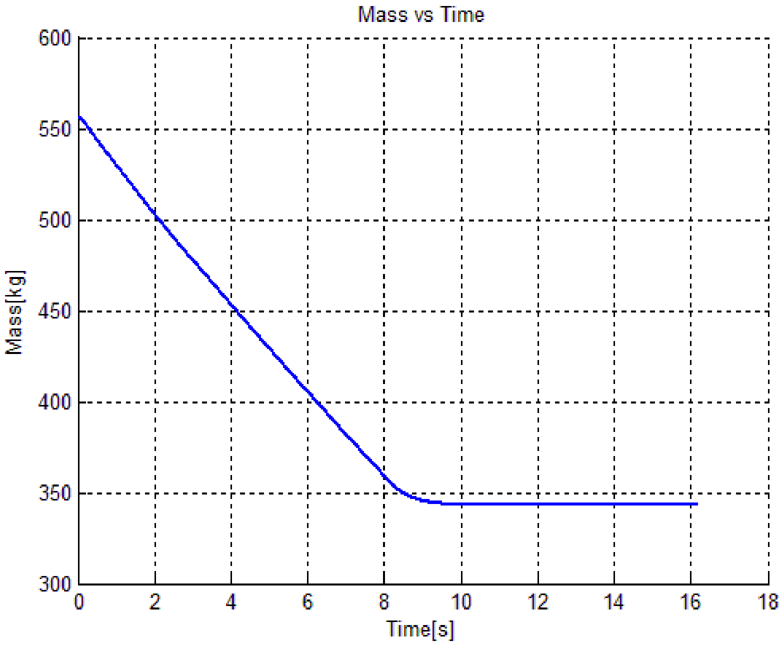

Figure F. 7 Total Mass of Weapon (SAM CLOS)

## F.2 Surface to Air Missile with Proportional Navigation Guidance (SAM with PN Guidance)

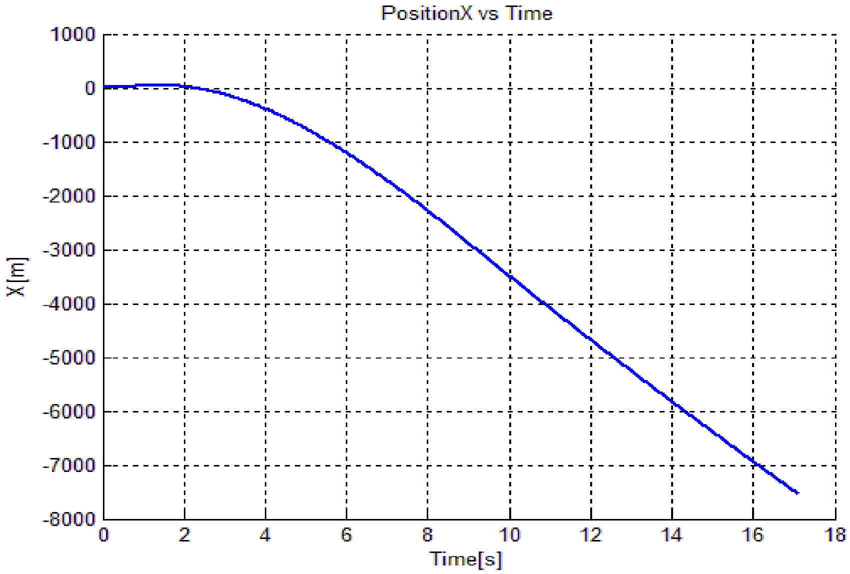

Figure F. 8 Position of weapon (SAM with PN) in X axis

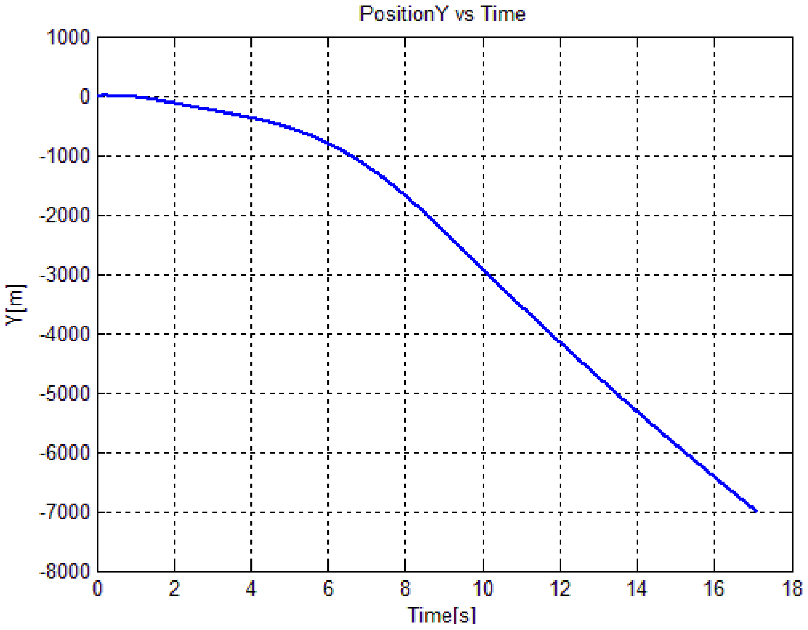

Figure F. 9 Position of weapon (SAM with PN) in Y axis

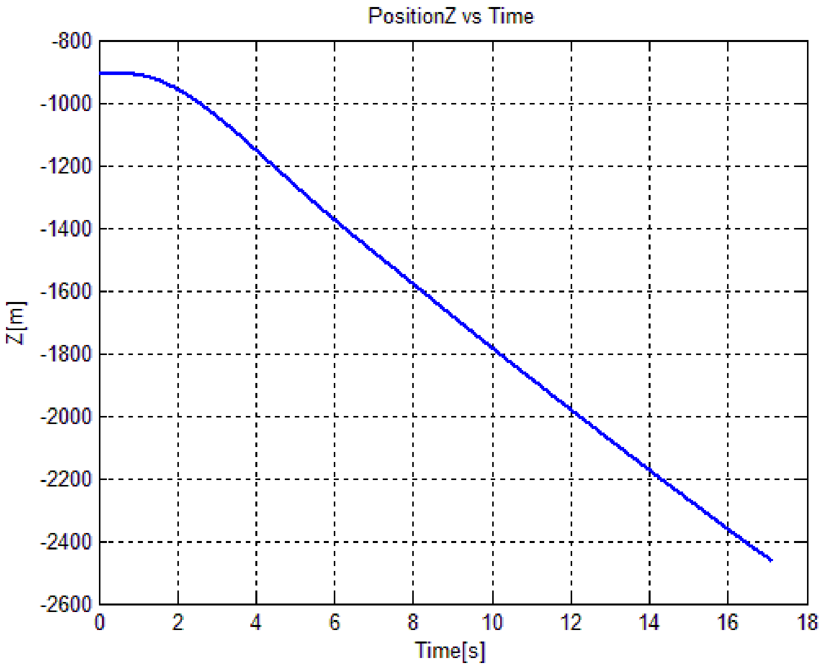

Figure F. 10 Position of weapon (SAM with PN) in Z axis

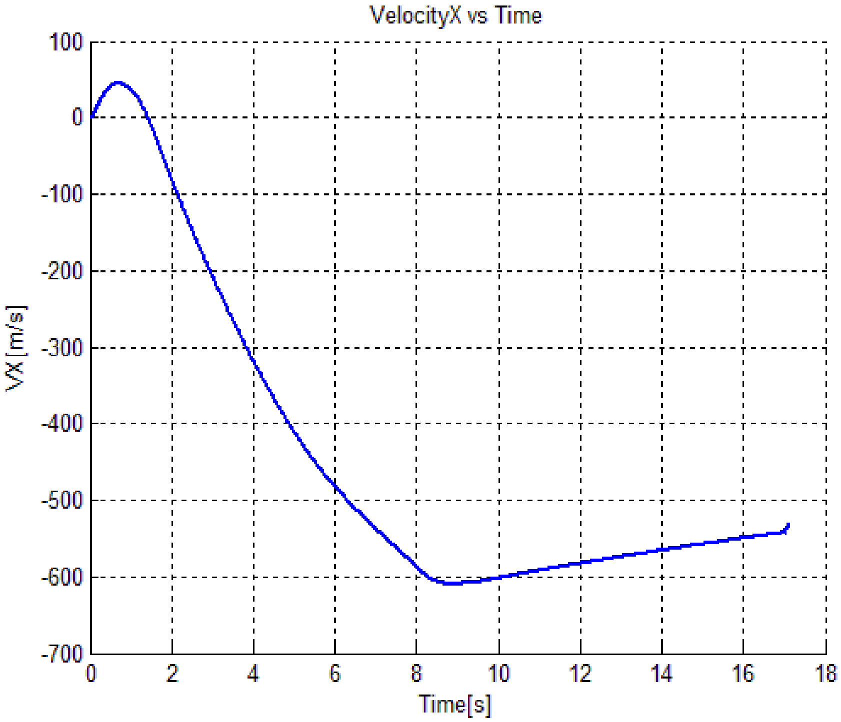

Figure F. 11 Velocity of weapon (SAM with PN) in X axis

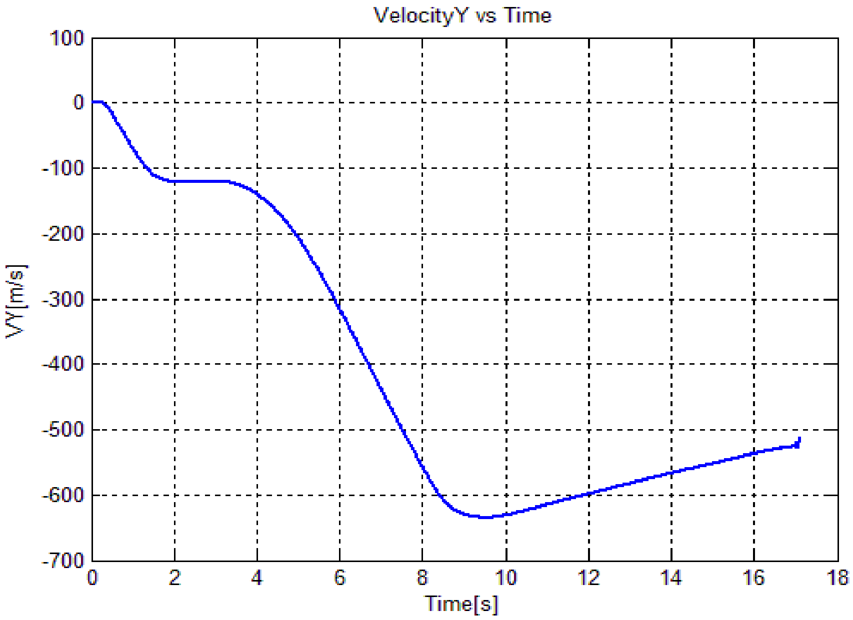

Figure F. 12 Velocity of weapon (SAM with PN) in Y axis

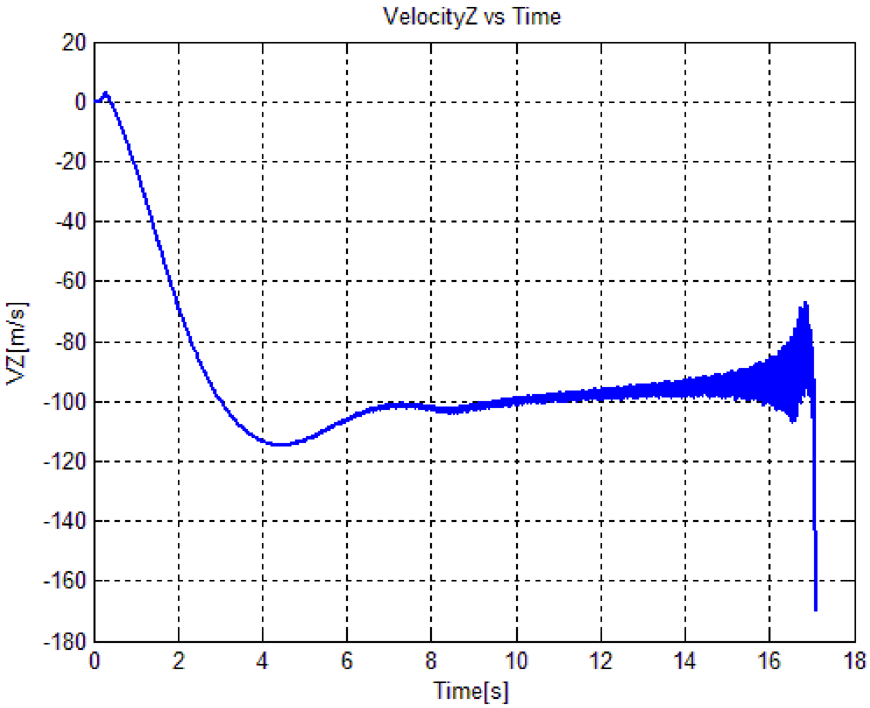

Figure F. 13 Velocity of weapon (SAM with PN) in Z axis

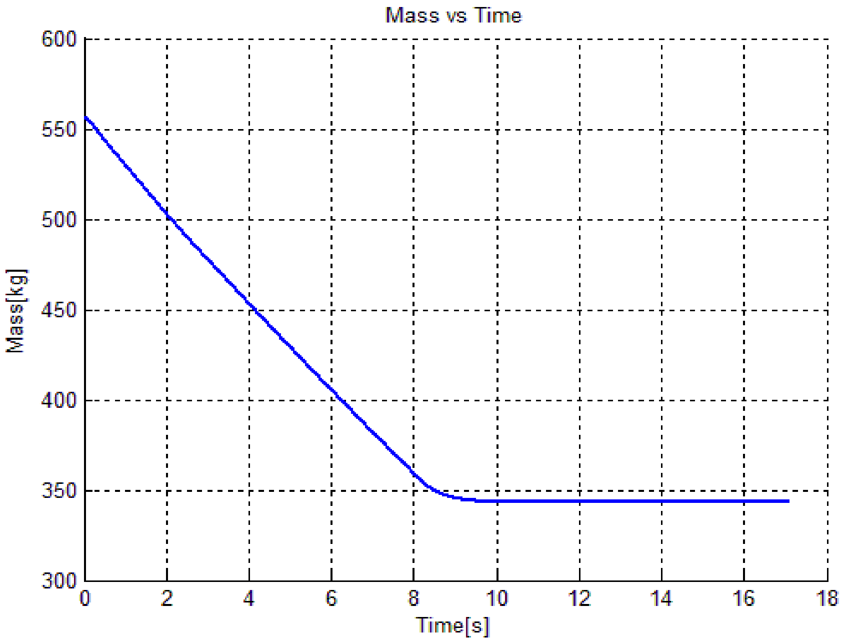

Figure F. 14 Total Mass of Weapon (SAM with PN)

### F.3 Air Defense System Including Two SAM Batteries with CLOS Guidance

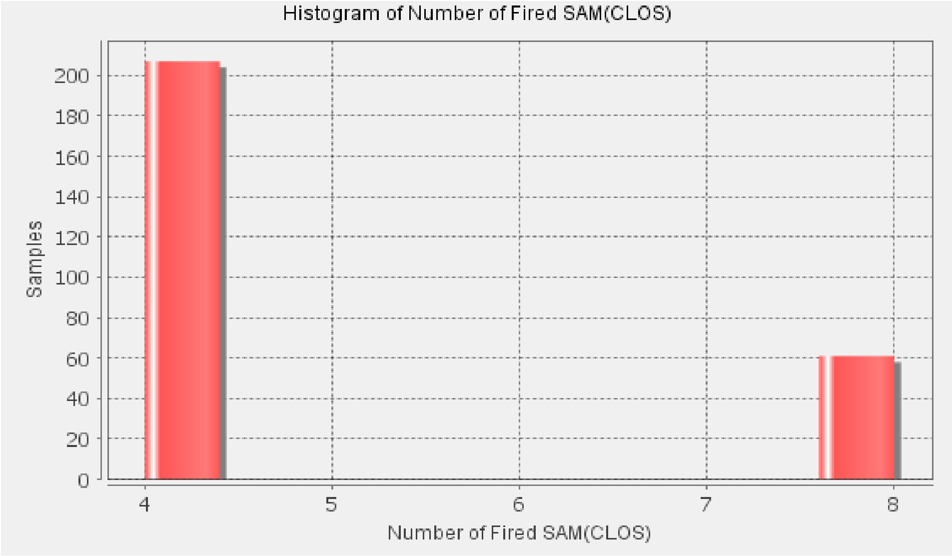

Figure F. 15 Histogram of Number of Fired SAM (CLOS)

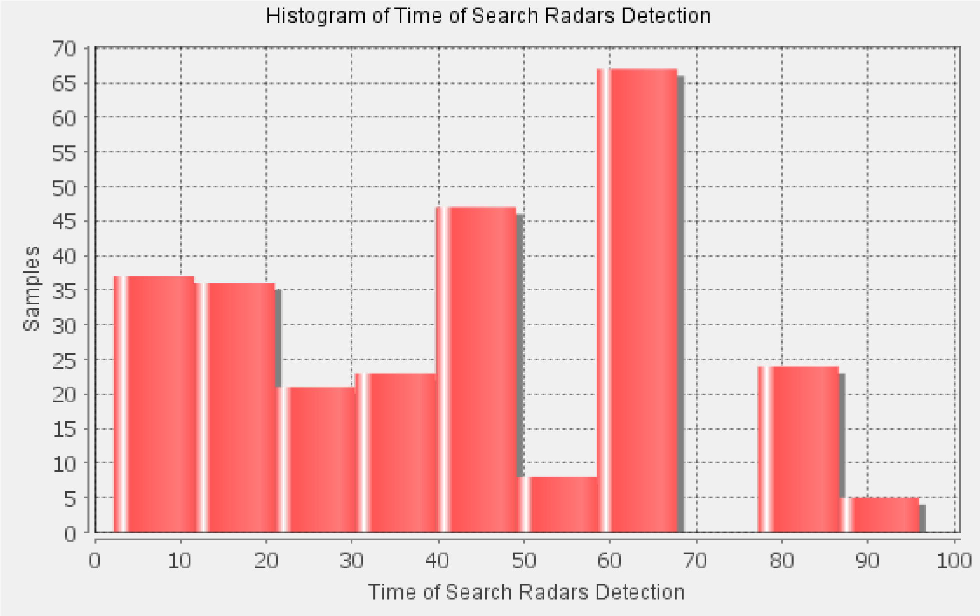

Figure F. 16 Histogram of Time of Search Radars Detection in Air Defense with SAM CLOS

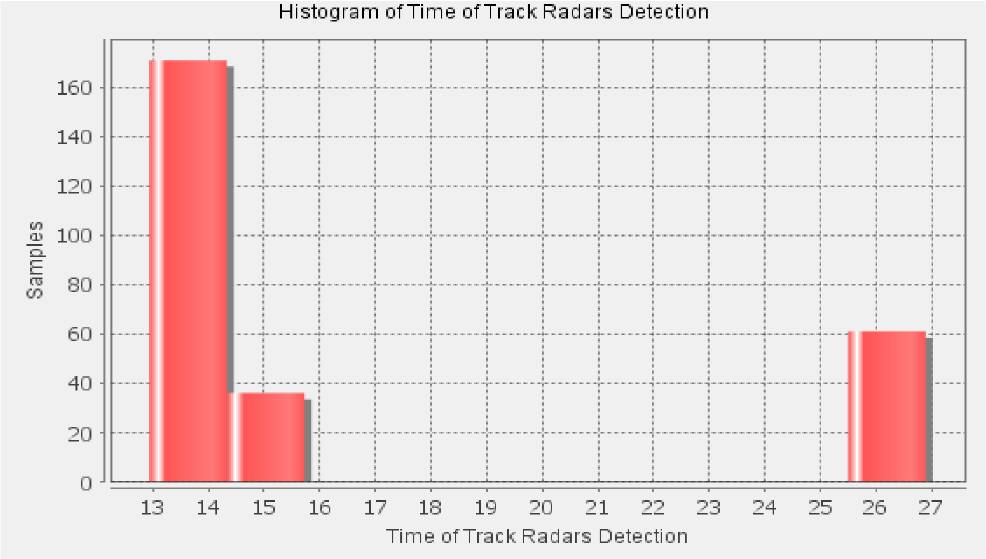

Figure F. 17 Histogram of Time of Track Radar Detection in Air Defense with SAM CLOS

## F.4 Air Defense System Including Two SAM Batteries with PN Guidance

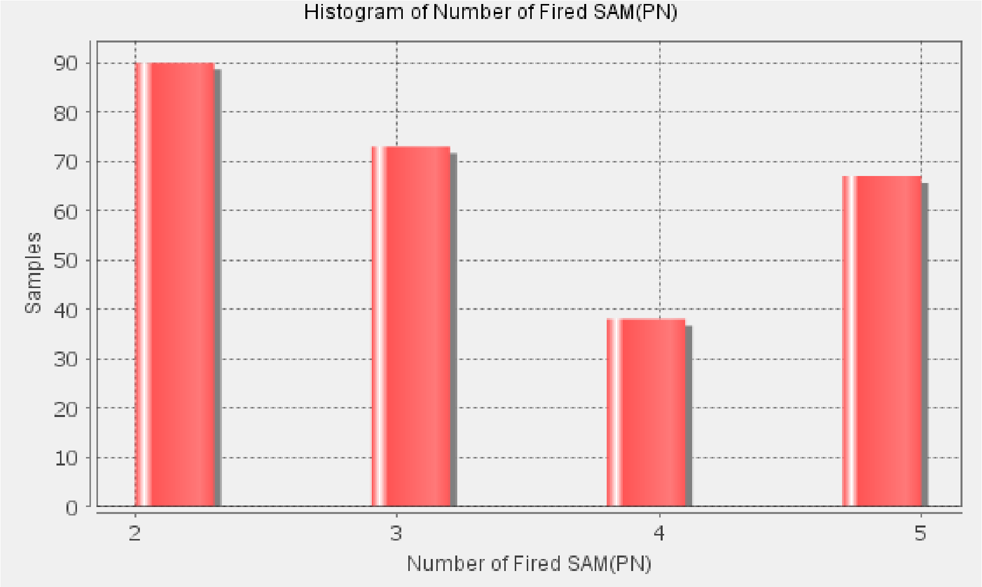

Figure F. 18 Histogram of Number of Fired SAM (PN)

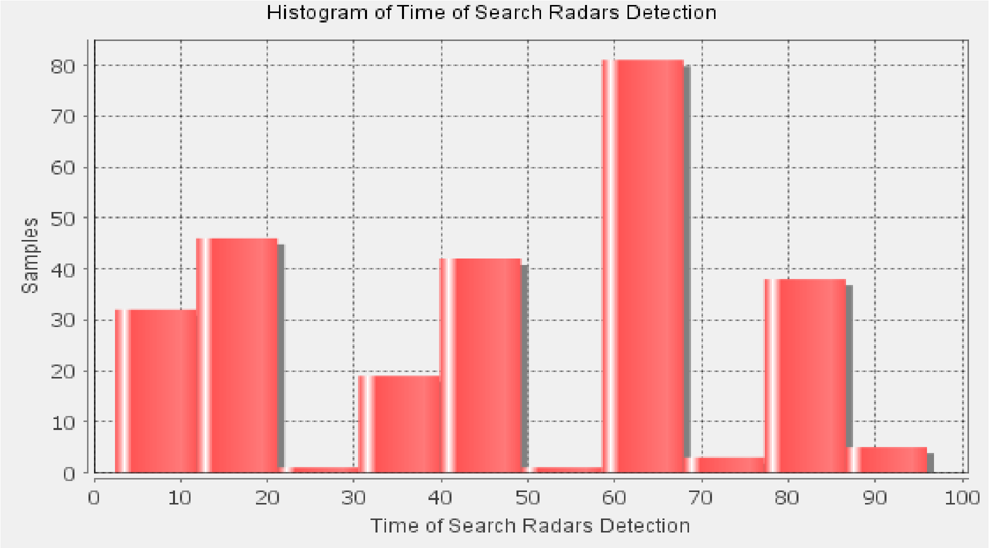

Figure F. 19 Histogram of Time of Search Radars Detection in Air Defense with SAM PN

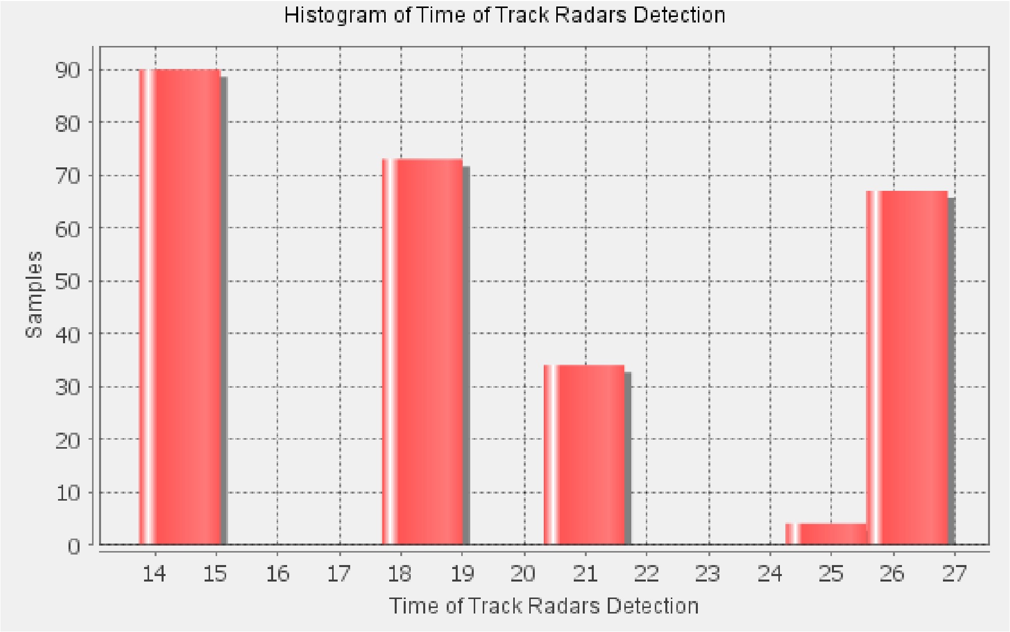

Figure F. 20 Histogram of Time of Track Radar Detection in Air Defense with SAM PN

## F.5 Air Defense System Including Four AAA Batteries

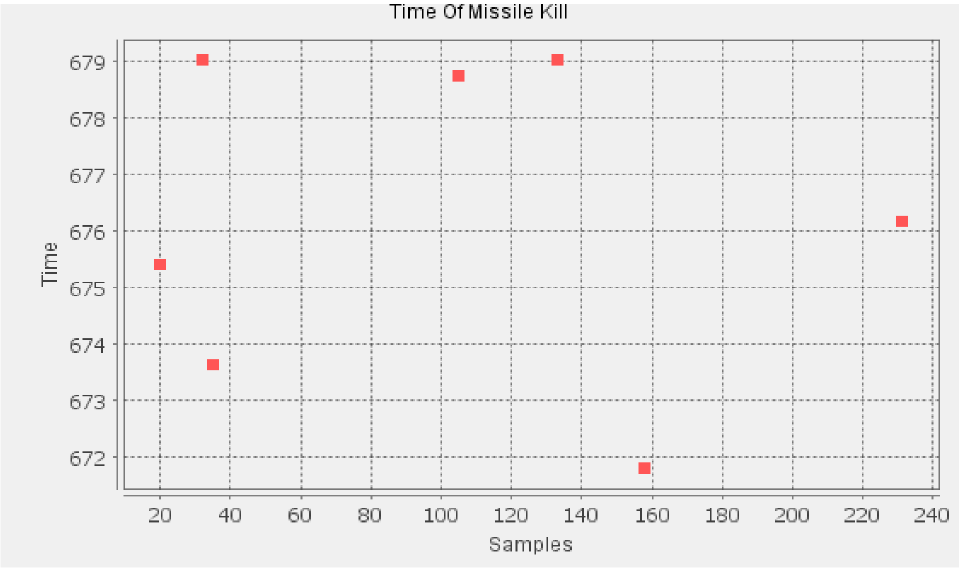

Figure F. 21 Time of Missile Kill

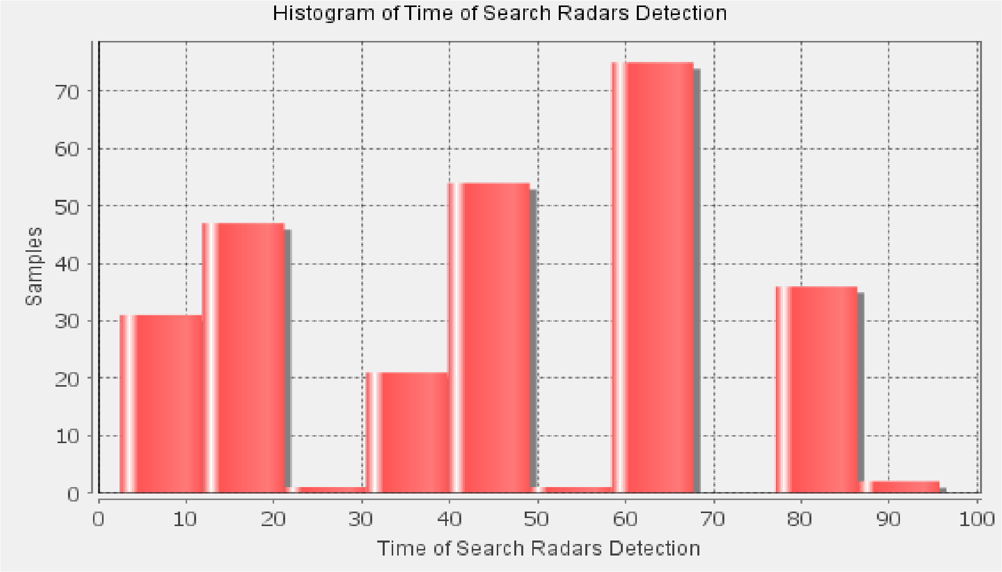

Figure F. 22 Histogram of Time of Search Radars Detection in Air Defense with Four AAA Batteries