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*UNCLASSIFIED*
THESIS

A COMPUTER STUDY OF AIR DEFENSE GUN EFFECTIVENESS

by

Hyun Dae, Jung

December 1987

Thesis Advisor

Robert E. Ball

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A COMPUTER STUDY OF AIR DEFENSE GUN EFFECTIVENESS

This study describes the continuing development of a computer model for the simulation of burst kill probabilities for air defense gun systems firing projectiles at maneuvering aircraft. The computer simulation developed by Keeling is modified by adding a high explosive proximity and contact fuzed round to the simulation. The objective of this thesis is to develop and analyze the shipboard anti-air defense problem in order to choose the best air defense gun system. The air defense gun system studied consists of a 40 mm gun, firing fragmenting proximity and contact fuzed projectiles, an early warning radar system, and a fire control system. The aircraft vulnerability and the gun data used in this thesis are entirely synthetic to avoid security classification problems.
A Computer Study of Air Defense Gun Effectiveness

by

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ABSTRACT

This study describes the continuing development of a computer model for the simulation of burst kill probabilities for air defense gun systems firing projectiles at maneuvering aircraft. The computer simulation developed by Keeling is modified by adding a high explosive proximity and contact fuzed round to the simulation. The objective of this thesis is to develop and analyze the shipboard anti-air defense problem in order to choose the best air defense gun system. The air defense gun system studied consists of a 40 mm gun, firing fragmenting proximity and contact fuzed projectiles, an early warning radar system, and a fire control system. The aircraft vulnerability and the gun data used in this thesis are entirely synthetic to avoid security classification problems.
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I. INTRODUCTION

A. BACKGROUND

In modern times it often occurs that during battle, friendly ships are threatened by enemy aircraft. This thesis focuses on a ship's ability to defend itself against aircraft with a 40 mm gun system. The computer program presented in this paper is a modification of a simulation written in the A Programming Language (APL) by Capt. C. Keeling. [Ref. 1] Keeling's program simulates engagements between air defense gun systems firing non-explosive projectiles at maneuvering aircraft. In his thesis, Keeling suggested further research on proximity fused and contact fused high explosive (HE) rounds. This paper expands Keeling's simulation to include the HE round with both a contact fuze and a proximity fuze.

The simulation shows how changing gun parameters can affect a gun system's probability of kill against an aircraft. These parameters include: target range, projectile size, ballistic dispersion, muzzle velocity, firing rate, radar error, linear fire control, type of fuze (a new feature) and aircraft probability of kill given a hit or warhead lethal radius (a new feature). The use of this program increases the information available on the effectiveness of gun systems with and without HE warheads. The ultimate measure of success in the design and performance of an air defense gun system is the ability of the system to shoot down low-flying hostile aircraft within the combat environment.

B. OBJECTIVE

The objective of this thesis is to continue the development of a computer model that will be helpful in making decisions regarding the design and operation of an air defense gun system. In this thesis, the program is used to gain insight into how each of the design parameters of the gun system affect the probability of kill and which of the parameters are most important in the gun system design for air defense. In particular, the influence of the HE round on gun effectiveness will be studied.
C. APPROACHING THE PROBLEM

The gun system is located on a ship at the origin of an X, Y, and Z coordinate system. The playing area for the model is the quarter of a hemi-sphere entirely within the first quadrant of the X, Y and Z plane as shown in Figure 1.1. The size of the playing area may be adjusted by modifying the program's source code.

Figure 1.1 Playing Area of The X, Y & Z Plane.
The model assumes one-on-one engagements, no suppressive fire from the aircraft, and no terrain effects. The target is not necessarily attacking the gun system and may or may not maneuver while within the gun’s effective range.

D. ORGANIZATION OF THE MODEL

The air defense system consists of an early warning system, a tracking radar, a weapon control system and a gun with one or more barrels. The model studied here is a twin 40 mm gun using high explosive rounds located onboard the ship at the origin of the playing area. As an aircraft enters into the radar detection envelope of the early warning radar, the aircraft is detected and identified as hostile by the ship. The tracking radar is given the target’s position. This radar tracks the aircraft and continuously computes the target range, elevation, azimuth, and velocity. The gun fire control computer solves for the lead angle in azimuth and elevation based on the calculated target positional data assuming no target maneuvering. The gun is positioned at the lead angle and fires a burst of proximity or contact fuzed high explosive rounds. The projectiles fly out toward the moving target. The target continues on its randomly selected flight path. The miss distance and assumed ballistic dispersion are used in the model to determine the probability of aircraft kill for each round $P_{KSS}$. For the proximity fuzed warheads, the projectiles do not have to hit the target to cause damage. The probability of aircraft kill given a detonation, $P_{KD}$, is determined using the Carlton diffused Gaussian kill function. For the contact fuzed warheads, the projectiles must hit the target in order to cause damage. The probability the aircraft is killed given the hit on the target, $P_{KH}$, is represented by the two-dimensional Carlton hit function.

1. Scenario

The general approach in this model is the development of the kill probability for one gun system firing one burst at one randomly maneuvering target. The probability of kill for each round is used to compute a burst kill probability. The gun system computes target flight path characteristics, predicts a time-dependent intercept point in space, positions the gun and fires the projectiles. For contact fuzed IIE rounds, the target vulnerability is represented by a vulnerable area ($A_v$) in a plane in space that is perpendicular to the slant range ($R$) between the gun and the center of the target. For the proximity fuzed warhead, the target vulnerability is represented by a lethal radius.
2. Model Input

Inputs are required for the gun, the fuze, the target, and ranges of engagement. Gun inputs are muzzle velocity, projectile coefficient of drag, burst size, rate of fire, and angular ballistic dispersion. The fuze input is the probability of fuzing, which is independent of range. Aircraft inputs are velocity, altitude, acceleration performance capabilities, and vulnerability data based on the type and size of projectile and fuze being used. A flight path generates, for several different types of aircraft, maneuvers using a Monte Carlo simulation.
II. PROXIMITY FUZED WARHEAD

A. BASIC THEORY

A proximity fuze detects the target and causes detonation of the high explosive warhead in the vicinity of the target. A warhead usually contains a powerful but relatively insensitive high-explosive that can only be initiated by the heat and energy from the primary explosive in the fuze [Ref. 3]. Proximity fuzes accomplish their purpose through “influence sensing” with no contact between the projectile and the target. These fuzes are actuated by some characteristic feature of the target, such as a reflected radio signal, an induced magnetic field, an interrupted light wave, a pressure measurement, or an acoustical impulse. “Proximity sensing” results in detonation of the bursting charge in the vicinity of the target or targets. A direct hit is not necessary to disable an aircraft and achieve the desired effect. An aircraft may be damaged in any part of the large volume occupied by fragments from the exploding round. Since several air targets may exist simultaneously, the sensing equipment must be able to isolate a selected target. Proximity fuzing had its origins in England early in World War II. Proximity fuizing is represented as VT fuzing (a code name used during World War II to imply variable time fuzing) [Ref. 2 p. 76].

B. TARGET SUSCEPTIBILITY

The modeling and quantification of the individual events and elements in an air defense encounter is referred to as a susceptibility assessment. Susceptibility is the inability of an aircraft to avoid being damaged in the pursuit of its mission, to its probability of being hit [Ref. 2] The level of susceptibility of an aircraft in encounter with a threat is dependent upon three major factors:

- The scenario includes the physical environment in which the encounter takes place, the air defense deployment and activity, and the aircraft flight path and tactics, including any supporting forces.
- The air defense characteristics, operations, and lethality.
- The aircraft observables or detectable signatures, any countermeasures used, the aircraft performance capabilities, and any self-protection armament are the important factors associated with the aircraft itself.
One of the most important susceptibility measures is the closest point of approach or miss distance of a projectile to a maneuvering target.

In general, the smaller the miss distance, the more likely the aircraft will be hit. Whether or not the aircraft is hit depends upon the presented area of the aircraft. This study assumed the presented area $A_p$ of the aircraft is based on the six cardinal sides. The most the projectile can see in the intercept plane is part of three sides. The threat aircraft used in the study has a presented area from the area of the top $A_{top}$ (50 m$^2$, equal to the bottom), the area of the side $A_{side}$ (30 m$^2$, the same on each side), and the area of the front $A_{front}$ (5 m$^2$, equal to the rear).

C. MISS DISTANCE

As shown in Figure 2.1, the CPA is the mean value for an assumed Gaussian distribution of the projectile miss distance and the ballistic dispersion is the round to round variance about that point.

![Figure 2.1 Ballistic Dispersion, Bias, and CPA.](image)

The miss distance form for the round is given by

$$\mu_{bx}^2 + \mu_{by}^2 = CPA^2$$  (eqn 2.1)
where
- \((\mu_{bx}, \mu_{by})\) is the mean or bias in the x and y direction.

D. THE FUZE

The function of the fuze is to initiate the detonation of a warhead at a time and place such that maximum damage will be inflicted upon the target. Since the warhead damage volume is preset, the achievement of maximum damage depends on the time of fuze initiation [Ref. 3]. The fuze package consists of a safety-and-arming device to keep the weapon safe until it is deployed and clear of friendly forces, a detonator to initiate the HE charge detonation, a device that senses the presence of a target (known as the target detection device (TDD)), and a logic circuit that initiates detonation at the proper time.

The functioning of a fuze can be represented by the probability \(P_f\) which may or may not be dependent upon the miss distance. For example, a proximity fuze with an 80% probability of detonating the warhead within a miss distance range \(r_c\) of 100 ft and a 0% probability beyond \(r_c\) can be modeled in the form

\[ \begin{align*}
P_f(x,y) &= 0.8 \text{ when } (x^2 + y^2)^{1/2} \leq 100 \text{ft} \\
P_f(x,y) &= 0 \text{ when } (x^2 + y^2)^{1/2} > 100 \text{ft} 
\end{align*} \]

E. TARGET VULNERABILITY

Vulnerability refers to the inability of the aircraft to withstand one or more hits by the damage mechanisms, to its vincibility, to its liability to serious damage or destruction when hit by gun fire [Ref. 2]. The critical components on an aircraft are those components which, if either damaged or destroyed, would lead to an aircraft kill. A general procedure has been developed for determining the critical components, their possible damage or failure modes, and the effects of the component damage or failure upon the continued operation of the aircraft. The procedure consists of

- A selection of the aircraft kill levels or categories to be considered.
- An assembly of the technical and functional description of the aircraft.
- The determination of the aircraft components of the aircraft and their damage caused failure modes for the selected kill levels.
1. State Transition Matrix Method

The study by Keeling used the state transition matrix method to describe the damage state of the aircraft after one or more hits. This method allows the consideration of redundancy in the critical components and accounts for the fact that a single shot cannot kill more than one redundant critical component. This method states that a sequence of independent events can be modeled as a Markov process. The state space of the Markov process includes kill of the aircraft, no kill of the aircraft, a state space for a kill of each of the critical redundant components, and combinations of kills of redundant critical components that eventually lead to a kill of the aircraft. The state of the target at the beginning of the engagement is represented as the initial state vector $S^0$. One transition represents the state of the target after one random hit on the aircraft, and $S_{j+1}$ represents the state of the target after the $j$th hit. The matrix that accounts for the transition is $T_{M!}$. Thus

$$S_{j+1} = T_{M!} S_j \quad \text{(eqn 2.2)}$$

The state transition matrix method is not appropriate for the HE round.

2. Vulnerability Model for Externally Detonating Warheads

For the proximity fused HE rounds, the aircraft's vulnerability can be represented by a $P_KD$ function of $x$ and $y$ proposed by Carlton

$$P_KD = \exp(-x^2 r_0^2) \exp(-y^2 r_0^2) \quad \text{(eqn 2.3)}$$

The scaling parameter $r_0$ can be related to the warhead lethal radius $r_l$, such that when $r = r_l$, $P_KD = 0.5$. Collocating the one-dimensional Carlton kill function through 0.5 when $r = r_l$ gives $r_0 = 1.20 r_l$ as shown in Figure 2.2.

F. $P_{KSS}$

This simulation uses the circular Carlton kill function method as presented by Ball [Ref. 2 p. 320]. The equation for $P_{KSS}$ is

$$P_{KSS} = r_0^2 p_r(\alpha^1 \beta^1 \beta^2)^2 \exp(-\mu_{bx}^2 \alpha - \mu_{by}^2 \beta) \quad \text{(eqn 2.4)}$$

where
The calculation of the probability of kill for a variety of ranges is made simpler by using angular errors for the dispersion errors. From the Figure 2.3 it can be seen that \( \alpha_{X1} \) and \( \alpha_{X2} \) are the angles representing the angular standard deviation of the dispersion errors about the closest point of approach. Figure 2.3 shows that

\[
\sigma_{dx} = \alpha_{dx} R \quad \text{(eqn 2.5)}
\]

where

- \( \alpha_{dx1} = \alpha_{dx2} = \alpha_{dx} \)
- \( \alpha_{dx} \) is the angular ballistic dispersion in the x direction.

By the same theory in the y direction can be shown to be
\sigma_{dy} = \sigma_{dy} R

where \sigma_{dy} is the angular ballistic dispersion in the y direction.

Furthermore, the assumption is made that the angular ballistic dispersion as shown in Figure 2.2 is the same in both directions, hence

\sigma_{dx} = \sigma_{dy} = \sigma

The equation for the Carlton kill function model, Equation 2.3, simplifies to

\[ P_{KSS} = (r_0^2 P_f \gamma) \cdot \exp(-((\mu_{bx}^2 + \mu_{by}^2) \gamma)) \] (eqn 2.6)

where

- \gamma is \(2 \sigma^2 R^2 + r_0^2\)

The final form for the probability of kill is obtained by using Equation 2.1, giving

\[ P_{KSS} = (r_0^2 P_f \gamma) \cdot \exp(-CPA^2 \gamma) \] (eqn 2.7)

For this study, \(r_1\) is taken as five meters. Thus, \(r_0\) is six meters.
G. PROBABILITY OF KILL GIVEN A BURST

The probability of an aircraft kill for a burst of rounds is directly proportional to the probability there is a clear line of sight from the detecting element to the aircraft. Given that the aircraft has been detected, the probability that one or more propagators will be fired at the aircraft is detonated by \( P_F \). Thus, the probability that the aircraft is killed by one shot in an encounter, \( P_{KE} \), is given [Ref. 2. p. 320] by

\[
P_{KE} = P_D \times P_F \times P_{KSS}
\]  

(eqn 2.8)

- \( P_D \) is the probability that the aircraft has been detected from the start of a search up to the present time \( t \).
- \( P_F \) is the probability that a propagator will be fired at the aircraft.
- This study assumes that \( P_D \times P_F = 1 \).

The probability that the aircraft is killed by the sequence of \( N \) gun shots is unity minus the product of the individual probabilities of survival for each shot. Thus, for the burst of \( N \) rounds \( P_{KSS} \) in Equation 2.8 is replaced with

\[
P_{KE/\text{burst}} = 1 - \prod_{i=1}^{N} \left( 1 - P_{KSS} \right)
\]

(eqn 2.9)

where the subscript \( i \) denotes the \( i \)th shot.
III. CONTACT FUZED WARHEAD

Contact fuzes detonate the HE warhead upon contact with the target. Detonation can be made to occur on the surface or inside the target, depending upon the design of the fuze.

A. TARGET SUSCEPTIBILITY

The presented area $A_p$ of the aircraft is defined to be the area of the aircraft seen by the projectile in a plane normal to the path of the projectile at intercept. The procedure for determining the presented area seen by the round is determined based upon the difference between the projectile's velocity and the relative velocity of the projectile with respect to the aircraft. This procedure is described in detail in [Ref. 1].

B. TARGET VULNERABILITY

For warheads that do not use a proximity fuze, such as small arms and HE warheads with contact fuzes, a hit on the aircraft must occur to cause damage. Thus, the kill function that defines the probability the target is killed due to a propagator becomes $P_{K_H}$ for random hits, and integration is carried out over the extent of the aircraft. In this approach, the probability the aircraft is hit by the propagator, $P_{H}$, is computed and multiplied by the probability the aircraft is killed given the random hit on the aircraft, $P_{K_H}$. The computation of $P_{H}$ is developed by Keeling and accomplished using the Carlton hit function. The aircraft vulnerability is represented by its vulnerable area $A_V$, centered at the aim point, and any hit on the vulnerable area causes a kill. The computation for the vulnerable area is the product of presented area $A_p$ and the probability the aircraft is killed given the random hit on the aircraft $P_{K_H}$ [Ref. 2]

$$A_V = P_{K_H} A_p \quad \text{(eqn 3.1)}$$

This model assumes the $P_{K_H}$ value for the round is 0.25, and $A_V$ is given as

$$A_V = 0.25 A_p \quad \text{(eqn 3.2)}$$
C. \( P_{KSS} \)

This simulation uses the Carton kill function for the \( P_{KSS} \) as presented in [Ref. 2]:

\[
P_{KSS} = \frac{A_y}{(2\pi\sigma_x^2 + x_0^2)^{1/2}(2\pi\sigma_y^2 + y_0^2)^{1/2}} \exp \left[ \frac{-\pi\mu_x^2}{(2\pi\sigma_x^2 + x_0^2)} + \frac{-\pi\mu_y^2}{(2\pi\sigma_y^2 + y_0^2)} \right] \tag{eqn 3.3}
\]

The product of \( x_0 \) and \( y_0 \) can be taken as (1) equal to the presented area, \( A_p \), or (2) equal to the vulnerable area, \( A_y \) (see Ref. 2, PP 316-315). This study assumes \( x_0 = y_0 \) and uses \( A_p \) for the product. The means and deviations in Equation 3.3 are determined in the same manners as was done for the proximity fuzed round in Chapter II. Thus, the final form for the probability of kill given a single shot becomes

\[
P_{KSS} = (0.25)A_p (2\pi\alpha^2R^2 + A_p^2)\exp(-\pi CPA^2(2\pi\alpha^2R^2 + A_p^2)) \tag{eqn 3.4}
\]

D. PROBABILITY OF KILL GIVEN A BURST

When multiple shots are considered, the single hit \( P_{KH} \) is used for each shot. To determine the probability of an aircraft kill for a burst of rounds, the same procedure uses for the proximity fuzed warhead is used. Thus,

\[
P_{K/burst} = 1 - \prod_{i=1}^{N} (1 - P_{KSS}) \tag{eqn 3.5}
\]

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IV. COMPUTER PROGRAM

Keeling’s program is modified by adding subroutines PROXFUZE, CONTFUZE, BURSTKILL, and by changing the appropriate data to a 40 mm gun. This computer program consists of a main program and utilizes fifteen subroutines. The program was written in the A Programming Language (APL). The computer program listing is shown in APPENDIX A, and a flowchart of the program is depicted in Figure 4.1.

A. MAIN PROGRAM

The main program uses a DRIVER program for initiating simulation and probes the user for inputs. The program DRIVER calls the GUN subroutine for simulating gun fire solution. After the simulation has been initiated, subroutine GUN simulates the air defense engagement by utilizing the appropriate subroutines necessary to simulate the engagement of an aircraft by the on-board ship air defense gun. Subroutine GUN collects statistics on the probability of kill and where the actual slant range of intercept occurred. These data are then sent back to the main program DRIVER.

B. SUBROUTINES

1. Initiation

Subroutine GUN simulates the air defense engagement by calling the appropriate subroutines necessary to simulate the engagement of the aircraft by the on-board ship air defense gun.

2. Generation

The generation of a situation for air defense, aircraft’s position, the radar located position with radar errors, and flight path maneuver of aircraft is subroutines RANGECHK, RADAR, and AIRCRAFT.

3. Calculation

Subroutines INTERCEPT, MISSDIST, and MISSVECTOR are used to determine the predicted intercept point for the median round in the burst and the closest point of approach for each round in the burst.
4. Susceptibility

Subroutines APDATA, PKVECTOR, CONTFUZE, and PROXFUZE are used in determining the susceptibility of the aircraft. APDATA determines the
presented area of the aircraft that is used in the Carlton kill function model in subroutine CONTFUZE. PKVECTOR stores the data for each round in the burst.

5. **Vulnerability**

Subroutines PKVECTOR, CONTFUZE, PROXFUZE, and BURSTKILL are used in determining the vulnerability of the aircraft. Subroutine PKVECTOR stores the data for each round in the probability of kill. Subroutine CONTFUZE and PROXFUZE are used in determining the probability of kill for a single shot whether or not the projectile hit the target.

6. **Random Number**

Subroutines UNIF, UNIRAND, and NORRAND are used to generate the random number required in the simulation. Subroutine UNIF generates uniform random numbers in the interval (a, b). UNIRAND generates pseudo-uniform random numbers. NORRAND is the generation of normal random numbers.

**C. SUBROUTINE PROXFUZE**

Subroutine PROXFUZE is used in determining the probability of kill for a single shot of the HE proximity fused round. This vulnerability data is used by subroutine BURSTKILL to determine the probability of kill given burst.

**D. SUBROUTINE CONTFUZE**

Subroutine CONTFUZE is used in determining the probability of kill for a single shot of the HE contact fused round. This vulnerability data is used in subroutine BURSTKILL to determine the probability of kill given burst.

**E. SUBROUTINE BURSTKILL**

Subroutine BURSTKILL determined the probability of kill for a given burst. This probability of kill data uses the vulnerability of the aircraft.
V. ANALYSIS AND CONCLUSIONS

This program model was initiated with the realization that the probability of kill is one measure of effectiveness that has a broad base application in the field of air defense gun system evaluation. This program for determining gun system probability of kill has simulated several parameters. These parameters describe the gun, target environments, and engagement procedures whereby one gun system encounters one maneuvering target. The data used is given in APPENDIX D. This study uses a box plot to illustrate the effects of several important parameters. This graphical information gives a quick sense for the distribution of $P_K$ for the individual test values of each of the parameters. The vertical box contains the middle fifty percent of the distribution, and the individual dots show all the outliers. The mean value of the probability of kill at each of the test value settings are connected with a line. The result of each simulation is listed with the Empirical Statistics table in APPENDIX E.

A. TYPE OF FUZE

The probability of kill of the aircraft in a one-on-one encounter with both the proximity fuzed warhead and the contact fuzed warhead, $P_K$, is shown in Figure 5.1. The effects that a proximity and a contact fuzed warhead have on the lethality of the 40 mm gun using a HE rounds can be seen in this Figure. The proximity fuzed warhead shows a higher probability of kill given a burst than the contact fuzed warhead against a maneuvering target. Consequently, the remaining studies concentrate on the proximity fuzed warhead.

B. BALLISTIC DISPERSION

Figure 5.2 shows an example of how the 40 mm gun probability of kill changes with angular dispersion. The degree of dispersion can immediately be seen, as well as how many of the data points were considered as outliers. Since the dispersion settings for optimality is arbitrary in this range, the assumption is made that the dispersion angle for the gun is 1.0 milliradians.

C. RANGE EVALUATION

The evaluation of the $P_K$ for different range values was conducted for the maneuvering target. The maneuvering target was engaged by one burst for each range
Figure 5.1 Graphical Comparison of Fuze on 40 MM gun Lethality.

value. The gun produced the highest probability of kill at the 700 meters, and the effective range was 1300 meters against the maneuvering target. The air defense for a real situation requires about 2000 meters for successful engagement.
D. EFFECTS OF TARGET MANEUVERS

Figure 5.4 shows the effects that a maneuvering and non-maneuvering target have on the lethality of the 40 mm gun. Against the non-maneuvering aircraft, the probability of kill given a burst is about twice that for the maneuvering target. That means that the lethality of the air defense gun requires a non-linear fire control predictor based upon the tactical air combat maneuver (TACM).

E. EFFECTS OF RADAR ERROR

Figure 5.5 shows the effect of radar error on the 40 mm gun. In today's combat environment, the radar accuracy is an important factor. That means a large improvement in lethality can be obtained by reducing the radar error. The 100 percent error represents the current state of the radar system, so greater or less than 100 percent reflects great differences in lethality due to technological improvements to today's radar system.

Figure 5.2 Effects of Ballistic Dispersion on 40 MM gun lethality.
F. EFFECTS OF MUZZLE VELOCITY AND RATE OF FIRE

Increased rate of fire and muzzle velocity can significantly improve the probability of kill for the rounds in the burst, as shown in Figures 5.6 and 5.7. Increasing the rate of fire decreases the time between projectiles, which means there are more projectiles in the area of where the aircraft is at intercept. Thus, the probability of kill is increased for each round in the burst. Increasing muzzle velocity decreases the time required to get to the target, and thereby reduces the effects of target maneuver.

G. CONCLUSIONS

This study has been conducted from a theoretical and intuitive point of view with conclusions withheld in many cases pending validation. The execution of this program demonstrated what appear to be some clear improvements is gun lethality. The sample results in each of the graphs show the difference in the probability of kill values. They represent a convenient and practical base from which to study or perform parametric analyses on existing systems or on systems still on the drawing board. The 40 mm gun with the proximity fuzed warhead considered here for the given scenario and target
vulnerability data has an effective range of about 1300 meters against a maneuvering target. This gun can be improved by improving the radar, the fire control computer, projectile muzzle velocity, gun system rate of fire. These improvements should be attempted in the order given.
Another air defense gun system study should be conducted to determine the synergistic effects of changing more than one parameter simultaneously. The model should be further developed to account for non linear fire control. This can be easily done by changing the radar and intercept section of this program.

Figure 5.5 Effects of Radar Error on 40 MM Gun Lethality.
Figure 5.6  Effects of Muzzle Velocity on 40 MM Gun Lethality.
Figure 5.7 Effects of Firing Rate on 40 MM Gun Lethality.
APPENDIX A
APL COMPUTER PROGRAM

1. KEELING'S PROGRAM

```
*/ DRIVER; COUNT; I
*/
```
RADAR
AIRCRAFT
INTERCEPT
MISSVECTOR
PVVECTOR
PROBKLl
RANGEI+RANGEI,RTGT
PKDATA=PKDATA;PK
I=I+1
->(I<DATA)/LOOP3

\[ \nabla \text{RANGECHECK:R;O:D:MAXALT;MINALT} \n\]
*** DETERMINES A/C POSITION AT TIME OF FIRING ***
*** DETERMINES A/C POSITION AT TIME OF FIRING ***
\[ \text{WHAT IS THE MAXIMUM ALTITUDE IN METERS?}' \]
MAXALT+100
\[ \text{WHAT IS THE MINIMUM ALTITUDE IN METERS?}' \]
MINALT=90
\[ \text{R RANGE} \]
\[ \text{O}<0.1.5707963 \text{UNIF 1} \]
\[ \text{2F+ R RANGE/R RANGE) UNIF 1} \]
\[ \text{LOOP1:2F+ (MINALT,MAXALT) UNIF 1} \]
\[ \text{LOOP2:D+((R*2)-(2F*2))*0.5} \]
\[ \text{IF+D+{2C0} \n} \]

\[ \nabla \text{RADAR;S2;THETAA;R;DELRANGE;DTHETA;THETAE} \n\]
*** DETERMINES RADAR LOCATED TARGET BASED ***
*** ON ERRORS INDUCED BY RADAR ***
\[ \text{S2+0.0012+(2+RANGE)} \]
\[ \text{DELRANGE+1 NORRAND 0 6.2} \]
\[ \text{DTHETA+2 NORRAND(0,52)} \]
\[ \text{THETAE+THETAE+1} \]
\[ \text{THETAE+10(THETAE+R RANGE)} \]
\[ \text{THETAE+THETAE} \]
\[ \text{VR+R+{2C0(THETAE[2]+THETAE)}+{10(THETAE[1]+THETAE)}} \]
\[ \text{VR+R+{2C0(THETAE[2]+THETAE)}+{10(THETAE[1]+THETAE)}} \]

\[ \nabla \text{AIRCRAFT;VMIN;AXMAX;AXMIN;AZMIN;AZMAX;D;O;VZ1} \]
*** A/C PERFORMANCE DATA INPUTS ***
*** A/C PERFORMANCE DATA INPUTS ***
\[ \text{WHAT IS THE MIN ALT THE A/C IS ALLOWED TO FLY?}' \]
MINALT=90
\[ \text{WHAT IS THE MAX ALT THE GUN WILL ENGAGE?}' \]
MAXALT+100
\[ \text{WHAT IS THE MIN VELOCITY OF A/C IN METERS/SEC?}' \]
VMIN+150
\[ \text{WHAT IS THE MAX VELOCITY OF A/C IN METERS/SEC?}' \]
VMAX+225
\[ \text{WHAT IS THE MAX A/C ACCELERATION IN Z DIRECTION IN M/SEC2?'}' \]
AZMAX+43
\[ \text{WHAT IS THE MAX A/C ACCELERATION IN Z DIRECTION IN M/SEC2?'}' \]
AZMIN+39.2
a 'MAX ACCELERATION IN X OR Y DIRECTION IN M/SEC2?'
AXY+0.4*AXMAX

**** DETERMINES A/C FLIGHT PATH MANEUVER ****
AT TIME OF FIRING ****

VA+(VMIN, VMAX) UNIF 1
0*0.6,0831853 UNIF 2
VZ2=((VA*2)+2)*0.5
VZ2=(VZ1+VZ2) UNIF 1
D=((VA-1)-(VZ*2))*0.5
VX+((X(2000))
VY+((X(1000))
AZ1=(MAXALT-MINALT)+(MAXALT-MINALT)+(AZMIN*0.6))
AZ2+=(A21,A22) UNIF 1
O*0.6,0831853 UNIF 1
AX+AX=0.0001

VRX+1 NORMAND(VZ;0.1,VZ)
VRX+1 NORMAND(VX;0.1;VX)
VRX+1 NORMAND(VY;0.1;VY)

\INTERCEPT;F1TN;BURSTIME;XP1;YP1;ZP1;RPROJ;N;FTN

**** DETERMINES PREDICTED INTERCEPT POINT BASED ****
ON LINEAR FIRE CONTROL COMPUTATIONS ****
AND THE NEWTON-RAPHSON TECHNIQUE ********

LEVEL+1+(FIRERATE+60)
BURSTIME=BURST+0.6(FIRERATE+60)
N+1+(BURST*2)
TC=N×DELT

TAU=0

LOOP1:XP1+XR+(VRX×TAU)+(VRX×TAU)
YP1+XR+(VRY×TAU)+(VRX×TAU)
ZP1+X+R+(VRZ×TAU)+(VRX×TAU)
RTGT=((XP1*2)+(YP1*2)+(ZP1*2))*0.5
RPROJ=(V0×TAU)+(B×TAU)+1
F1TN=RTGT-RPROJ
F1TN=(INIT VELOC)+(YPI, VRT)+(ZPI×VRZ)+RTGT
F1TN=(V0*TAU)*((B×TAU)+1)

AIRRAFT

LOOP3:->((F1TN)<0.0001)/LOOP2

TAU+TAU=(FTN+F1TN)

LOOP1

\MISSVECTOR

**** CALCULATES DISTANCE FROM A/C TO MEAN THEORETICAL ****
** INTERCEPT POINT FOR EACH PROJECTILE ****

APN=10
VIMP=10
CPAN=10
N+1
TAU+0.1

LOOP:MISSDIST

**** COLLECTS STATISTICS ON BIS, PRESENTED AREA, ****
BURST VELOCITY, **
** USED TO DETERMINE PHIT AND PHILL ****

CPAN+CPAN,CPA
\[ \text{APDATA}: \text{AP1}, \text{AP2} \]

\[ \text{VIMP} = \text{VIMP}, \text{VIMP} \]

\[ N = N + 1 \]

\[ + (N < \text{BURST}) / \text{LOOP} \]

\[ \text{VMISSDIST} = A; F1; F2; F3; XA; YA; ZA; F1T; F2T; BT2; BT; XA; YA; ZA; F1T; F2T; BT2; BT; XP; YAP; ZAP; T0 \]

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\textbf{PBVECTOR}

Stores probability of kill for each round

\[ \text{PHIT} = 0 \]

\[ N = \text{CPAN} \]

\[ I = 1 \]

\textbf{LOOP: CPA = CPAN[I]}

\textbf{PROBHIT}

\[ \text{PHIT} = \text{PHIT}, \text{PH} \]

\[ I = I + 1 \]

\[ \rightarrow (I \leq N) / \text{LOOP} \]

\textbf{PROBIT: I = N}

Calculates prob of hit for a single round

\[ R = \text{RANGE} \]

\[ A = (6.2831 \times (R \times R) \times (\text{DISP} \times \text{DISP})) + \text{AP} \]

\[ B = (-3.1421 \times (\text{CPA} \times \text{CPA})) \]

\[ C = (2 \times (R \times R) \times (\text{DISP} \times \text{DISP})) + \text{AP} \]

\[ D = B + C \]

\[ \text{PHIT} = (\text{AP} + A) \times (\ast D) \]

\textbf{PROBKILL: I}

Determines probability for a given burst

\[ I = 0 \ 0 \ 0 \ 1 \]

\[ I = 1 \]

\textbf{LOOP: VIMP + VIMPN[I]}

\[ \rightarrow \text{VIMP} / \text{STOP} \]

\[ \text{AVDATA} \]

\[ \rightarrow (\text{PHIT} < 8) / \text{LOOP2} \]

\[ \rightarrow ((+/X) = 0) / \text{LOOP2} \]

\textbf{MARKOV}

\[ \text{LOOP2: I = I + 1} \]

\[ \rightarrow (I < \text{BURST}) / \text{LOOP1} \]

\[ \text{STOP: PK} = (y) / \text{AVDATA} \]

\textbf{AVDATA; VMIN; MAXV; AVMAX; AVMIN}

Builds transition matrix for velocity at burst

\[ \text{AVMIN} = 1 \ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]

\[ 0.8897\ 0.028\ 0\ 0.00\ 0.8617 \]

\[ 0.0823\ 0.8897\ 0.0421\ 0\ 0.8104 \]

\[ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]

\[ 0.8897\ 0.028\ 0\ 0.00\ 0.8617 \]

\[ 0.0823\ 0.8897\ 0.0421\ 0\ 0.8104 \]

\[ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]

\[ 0.8897\ 0.028\ 0\ 0.00\ 0.8617 \]

\[ 0.0823\ 0.8897\ 0.0421\ 0\ 0.8104 \]

\[ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]

\[ 0.8897\ 0.028\ 0\ 0.00\ 0.8617 \]

\[ 0.0823\ 0.8897\ 0.0421\ 0\ 0.8104 \]

\[ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]

\[ 0.8897\ 0.028\ 0\ 0.00\ 0.8617 \]

\[ 0.0823\ 0.8897\ 0.0421\ 0\ 0.8104 \]

\[ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]

\[ 0.8897\ 0.028\ 0\ 0.00\ 0.8617 \]

\[ 0.0823\ 0.8897\ 0.0421\ 0\ 0.8104 \]

\[ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]

\[ 0.8897\ 0.028\ 0\ 0.00\ 0.8617 \]

\[ 0.0823\ 0.8897\ 0.0421\ 0\ 0.8104 \]

\[ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]

\[ 0.8897\ 0.028\ 0\ 0.00\ 0.8617 \]

\[ 0.0823\ 0.8897\ 0.0421\ 0\ 0.8104 \]

\[ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]

\[ 0.8897\ 0.028\ 0\ 0.00\ 0.8617 \]

\[ 0.0823\ 0.8897\ 0.0421\ 0\ 0.8104 \]

\[ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]

\[ 0.8897\ 0.028\ 0\ 0.00\ 0.8617 \]

\[ 0.0823\ 0.8897\ 0.0421\ 0\ 0.8104 \]

\[ 0.1103\ 0.1103\ 0.0823\ 0\ 0.8897\ 0\ 0.028\ 0 \]
WHAT IS THE MINIMUM VELOCITY?

WHAT IS THE MAXIMUM VELOCITY?

\[
X = ((V_{\text{BUST}} - V_{\text{MIN}}) \times (A_{\text{VMAX}} - A_{\text{VMIN}})) + A_{\text{VMIN}}
\]
\[ V \]

\[ V R+N \text{ UNIRAND} B \]

\[ V \]

\[ V 2+N \text{ NORRAND} P; S; I; T \]
\[ P+2+P,1 \]
\[ Z+(N)\times 0 \]
\[ I+1 \]
\[ P10; T+2 \text{ UNIRAND} 0.5 \times 0.5 \]
\[ T+(2\times T)-1 \]
\[ S+(T[1]\times 2)+T[2]\times 2 \]
\[ Z[I]+P[1]+P[2]\times(T[1]\times((-2\times S)+S)\times 0.5) \]
\[ Z P10\times 1 \times (I+1) \leq N \]

**CORRECTIONS MADE TO KEELING'S PROGRAM IN:**

Subroutine AIRCRAFT (36, 37, 38)

Subroutine MISSVECTOR (9)

Subroutine MISSDIST (5, 30, 31, 37)

Subroutine PROBHIT (6)
APPENDIX B
APL COMPUTER PROGRAM

1. NEW PROGRAM

```
7 DRIVER; COUNT; I
10 INPUT DATA
11 
12 'HOW MANY DATA POINTS DO YOU WANT PER RANGE?' 
13 DATA+25 
14 DATA+DATA-1 
15 'WHAT IS THE GUN FIRING RATE IN_rounds per minute?' 
16 FIRE_RATE+600 
17 'WHAT IS THE MUZZLE VELOCITY?' 
18 VO+1005 
19 'WHAT IS THE BURST SIZE?' 
20 BURST+5 
21 'WHAT IS THE ANGULAR DISPERSION IN RADIANS?' 
22 DISP+0.001 
23 'WHAT IS THE DRAG FACTOR B=CDxVO*0.5?' 
24 B+.163 
25 'WHAT ARE THE RANGES YOU WANT TO LOOK AT?' 
26 RANGES+ 1900 1300 700 100 
27 'WHAT ARE THE AREAS OF THE AIRCRAFT?' 
28 AFR+5 
29 ASIDE+30 
30 ATOP+50 
31 RL+5 
32 PK/R+0.25 
33 
34 *** PROGRAM EXECUTION AND DATA COLLECTION *** 
35 *** P IS PROBABILITY OF KILL *** 
36 *** R SLANT IS RANGE OF TARGET AT INTERCEPT *** 
37 R+10 
38 I+10 
39 
40 COUNT+RANGES 
41 LOOP: RANGE=RANGES[I] 
42 GUN 
43 P+P, PKDATA 
44 R+R, RANGEI 
45 I+1 
46 +(I,COUNT)/LOOP 
47 * DATA CONTROL VECTOR USED FOR GRAPHS IN GRAFSTAT ** 
48 PK=1 
49 ' RANGE=1 
50 P+5 0 u 10 pR 
51 P+((DATA+1),P RANGES)P RANGES 
52 P+ , (QC) 
```

7 GUN; I; VAC; BODY; TOP; SIDE; VRX; VRY; VRZ

* SIMulates air defense gun by calling appropriate subroutines *

RANGEI+10

I+0
PKDATA=10

LOOP3: RANGECHEK
RADAR
AIRCRAFT
INTERCEPT
MISSVECTOR
PKVECTOR
BURSTKILL
RANGEI+RANGEI, RTCT
PKDATA+PKDATA,PK
I+4
+(I<DATA)/LOOP3

\[ \nabla \text{RANGECHEK: R; O; D; MAXALT; MINALT} \]

\[ \text{**** DETERMINES A/C POSITION AT TIME OF FIRING} \]

\[ \text{**** WHAT IS THE MAXIMUM ALTITUDE IN METERS?} \]
MAXALT+1100

\[ \text{**** WHAT IS THE MINIMUM ALTITUDE IN METERS?} \]
MINALT+90

\[ R=\text{RANGE} \]

\[ O=0.5707963\text{ UNIF 1} \]

\[ \rightarrow (R>\text{MAXALT})/\text{LOOP1} \]

\[ ZF+(\text{MINALT}, R) \text{ UNIF 1} \]

\[ \text{LOOP2: ZE}+(\text{MINALT}, \text{MAXALT}) \text{ UNIF 1} \]

\[ \text{LOOP2: B}+(R*2)-(ZF*2)*0.5 \]

\[ XF+D*(200) \]

\[ YF+D*(100) \]

\[ \nabla \text{RADAR: S2; THETAA; R; DELRANGE; DTHETA; THETAE} \]

\[ \text{**** DETERMINES RADAR LOCATED TARGET BASED} \]

\[ \text{**** ON ERRORS INDUCED BY RADAR} \]

\[ S2=0.0012+(2*\text{RANGE}) \]

\[ \text{DELRANGE}=\text{NORRAND 0, 2} \]

\[ \text{DTHETA}=\text{NORRAND}(0, S2) \]

\[ \text{THETAA}=\text{THETAA} \]

\[ \text{THETAE}=\text{THETAE} \]

\[ \text{THETAE}+(200) \]

\[ \text{THETAE}+(100) \]

\[ \nabla \text{AIRCRAFT: VMIN; AMAX; AZMIN; AZMAX; D; O; VZ1} \]

\[ \text{VZ2; MINALT; MAXALT; AXY; AZ1; AZ2; 01} \]

\[ \text{**** A/C PERFORMANCE DATA INPUTS} \]

\[ \text{**** WHAT IS THE MIN ALT THE A/C IS ALLOWED TO FLY?} \]

\[ \text{**** MINALT}=90 \]

\[ \text{**** WHAT IS THE MAX ALT THE GUN WILL ENGAGE?} \]

\[ \text{**** MAXALT}=1100 \]

\[ \text{**** WHAT IS THE MIN VELOCITY OF A/C IN METERS/SEC?} \]

\[ \text{**** VMIN}=150 \]

\[ \text{**** WHAT IS THE MAX VELOCITY OF A/C IN METERS/SEC?} \]

\[ \text{**** VMAX}=220 \]

\[ \text{**** MAX A/C ACCELERATION IN Z DIRECTION IN M/SEC2?} \]

\[ \text{**** AZMAX}=4.9 \]
**A/C ACCELERATION IN Z DIRECTION IN M/SEC²?**

AZMIN+39.2

**A/C MAX ACCELERATION IN X OR Y DIRECTION IN M/SEC²?**

AXY+0.4×AZMAX

**DETERMINES A/C FLIGHT PATH MANEUVER AT TIME OF FIRING**

VA=((VMAX, VMAX) UNIF 1

O+0.6, 2831853 UNIF 2

VZ=((MINALT-ZF)+((MAXALT-MINALT))×VZ2

VZ=(VZ2, V22) UNIF 1

D=(2×(V2×2)-V2×2)×0.5

VX=(VX(2×0.11))

VY=(VY(1×0.11))

AZ=((MINALT-ZF)+((MAXALT-MINALT)+(AZMIN×0.6))

AZ+0.6×AZMAX

A2=(A22, A22) UNIF 1

O+0.6, 2831853 UNIF 1

AX=AX×1.001

AY=AY×1.001

VRZ+1 NORRAND(VZ, (0, 0.1, VZ))

VRX+1 NORRAND(VX, (0, 0.1, VX))

VRZ+1 NORRAND(VZ, (0.1, VX))

**DETERMINES PREDICTED INTERCEPT POINT BASED ON LINEAR FIRE CONTROL COMPUTATIONS AND THE NEWTON-RAPHSON TECHNIQUE**

**DELT=+((FIRERATE)×60)

BRSTIME+Burst+((FIRERATE)+60)

L(BURST+2)

TAU1+N×DELT

L(XPI=XR+(VRX×TO)+(VRX×TAU)

YPI=vr+(VRX×TO)+(VRX×TAU)

ZPI+VR+(VRZ×TO)+(VRZ×TAU)

RTGT=((XPI×2)+(YPI×2)+(ZPI×2))×0.5

RPROJ+(V0×TAU)+(B×TAU)+1

FITN−RTGT−RPROJ

FITN=−RTGT<3000)/LOOP3

AIRCRAFT

LOOP3=+((FITN×0.0001)/LOOP2

TAU=TAU−(FITN+FITN)

LOOP2=0

**MISSVECTOR**

**DETERMINES DISTANCE FROM A/C TO MEAN THEORETICAL INTERCEPT POINT FOR EACH PROJECTILE**

APN+i0

CPMN+i0

CPAV+i0

N+1

TAU=−0.1

LOOP:MISSDIST

**COLLECTS STATISTICS ON BIS, PRESENTED AREA, AND BURST VELOCITY.**

**USED TO DETERMINE PKSS AND PK/BURST**
**APN, CPA, AP1, AP2**

**V MISSDIST:**

\[ A; F1; F2; F3; XA; YA; ZA; F1TN; F2TN; BT2; BT; XAP; TAP; ZAP; TO \]

**V APDATA: VXIMP, VYIMP, VZIMP, AP1, AP2**

```
/*---------*/
CPAN, CPA
APN, AP
VIMP, VIMP, VIMP
N++
(MSBRST)/LOOP

\[ V MISSDIST; A; F1; F2; F3; XA; YA; ZA; F1TN; F2TN; BT2; BT; \\
XAP; TAP; ZAP; TO \]

\[ V APDATA: VXIMP, VYIMP, VZIMP, AP1, AP2 \]
```

**V APDATA: VXIMP, VYIMP, VZIMP, AP1, AP2**

```
---
\[ V MISSDIST; A; F1; F2; F3; XA; YA; ZA; F1TN; F2TN; BT2; BT; \\
XAP; TAP; ZAP; TO \]

\[ V APDATA: VXIMP, VYIMP, VZIMP, AP1, AP2 \]
```
V PKVECTOR; I; N

** STORES PROBABILITY OF KILL FOR EACH ROUND **

PKSSN+10
N+cCPAN

LOOP: CPA+CPAN[I]

** OPTIONAL SELECTION FOR TYPE OF FUZE **

** FOR PROXIMITY FUZE, USE PROXFUZE **

** FOR CONTACT FUZE, USE CONTFUZE **

PROXFUZE

PKSSN+PKSSN,PKSS

I+=1

V PROXFUZE: A; B; C; D; R; RL; RO; AL; PF

** PROXIMITY FUZED WARHEAD STORES PROBABILITY **

** OF KILL FOR SINGLE SHOT **

R=RANGE
PF+1
RL+.5
RO+(1.2xRL)
A+((RO*2))xPF
B+((2x(DISP*2)x(R*2))+(RO*2))
C=A+B
D+((-1x(CPA*2)) (((2x(DISP*2)x(R*2))+(RO*2))
PKS+*Cx(*D)

V CONTFUZE: A; B; C; D; R

** CONTACT FUZED WARHEAD CALCULATES **

** PROBABILITY OF KILL FOR SINGLE SHOT **

R=RANGE
A=0.25xAP
B=((2x3.142x(DIS*2)x(R*2))+(AP*2))
C=A+B
D=((-3.142x(CPA*2)))+B
PKS+*Cx(*D)

V BURSTKILL: AK; BK

** PROBABILITY OF KILL GIVEN BURST **

** (CHANGES), (DATA+2))>PKSS

AK=PKSSN
BK+=AK
CK=+BK
EK+=+CK
PK+PK

** PROBABILITY OF KILL ENCOUNTER **

** ASSUMED PDxPF=1 **

** PK/E EQUAL TO PKBURST **
RAB UNIF N:A;B

GENERATES N UNIFORM RANDOM NUMBERS

ON INTERVAL(A,B)

A=AB[1]
B=AB[2]

R=A+(B-A)*((2147483647)*?Np2147483646)

RAB UNIRAND B

GENERATES N PSEUDO UNIFORM RANDOM NUMBERS


Z-N NORRAND P;S;I;T

GENERATES N NORMAL RANDOM NUMBERS

P=2+P,1

T=2-(N)p0

F10:T+2 UNIRAND 0.5 0.5

T=2*+T-1

S=2*I[1]*2+I[2]*2


10:1(I+I+1)SN
### APPENDIX C

#### SYMBOL NOTATION

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DEFINITION</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{ft}$</td>
<td>area of aircraft front</td>
<td>meters$^2$</td>
</tr>
<tr>
<td>$A_{top}$</td>
<td>area of aircraft top</td>
<td>meters$^2$</td>
</tr>
<tr>
<td>$A_{side}$</td>
<td>area of aircraft side</td>
<td>meters$^2$</td>
</tr>
<tr>
<td>$A_{max}$</td>
<td>max aircraft acceleration</td>
<td>meters sec$^2$</td>
</tr>
<tr>
<td>$A_{min}$</td>
<td>min aircraft acceleration</td>
<td>meters sec$^2$</td>
</tr>
<tr>
<td>$A_P$</td>
<td>aircraft presented area</td>
<td>meters$^2$</td>
</tr>
<tr>
<td>$A_v$</td>
<td>aircraft vulnerable area</td>
<td>meters$^2$</td>
</tr>
<tr>
<td>$A_{z1-A_{z2}}$</td>
<td>range of $A_z$</td>
<td>meters sec$^2$</td>
</tr>
<tr>
<td>$A_{x-A_{y-A_{z}}}$</td>
<td>acceleration of aircraft</td>
<td>meters sec$^2$</td>
</tr>
<tr>
<td>$C_d$</td>
<td>coefficient of drag</td>
<td>1 meters</td>
</tr>
<tr>
<td>$g$</td>
<td>gravitational constant</td>
<td>meters sec$^2$</td>
</tr>
<tr>
<td>$GD$</td>
<td>gravity drop</td>
<td>meters</td>
</tr>
<tr>
<td>$LM$</td>
<td>lethality matrix</td>
<td>n a</td>
</tr>
<tr>
<td>$P_{H}$</td>
<td>probability of aircraft hit</td>
<td>n a</td>
</tr>
<tr>
<td>$P_{h}$</td>
<td>probability of component hit</td>
<td>n a</td>
</tr>
<tr>
<td>$P_k$</td>
<td>probability of kill</td>
<td>n a</td>
</tr>
<tr>
<td>$P_{ke}$</td>
<td>probability of kill engagement</td>
<td>n a</td>
</tr>
<tr>
<td>$P_{k,h}$</td>
<td>probability of kill given hit</td>
<td>n a</td>
</tr>
<tr>
<td>$R$</td>
<td>slant range</td>
<td>meters</td>
</tr>
<tr>
<td>$R_p$</td>
<td>projectile range</td>
<td>meters</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
<td>sec</td>
</tr>
<tr>
<td>$V_a$</td>
<td>aircraft total velocity</td>
<td>meters sec</td>
</tr>
<tr>
<td>$V_{bust}$</td>
<td>burst velocity</td>
<td>meters sec</td>
</tr>
<tr>
<td>$V_0$</td>
<td>muzzle velocity</td>
<td>meters sec</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>(V_p)</td>
<td>projectile velocity</td>
<td>meters/sec</td>
</tr>
<tr>
<td>(V_{px}, V_{py}, V_{pz})</td>
<td>projectile velocity components</td>
<td>meters/sec</td>
</tr>
<tr>
<td>(V_{rx}, V_{ry}, V_{rz})</td>
<td>radar aircraft velocity</td>
<td>meters/sec</td>
</tr>
<tr>
<td>(V_x, V_y, V_z)</td>
<td>aircraft velocity components</td>
<td>meters/sec</td>
</tr>
<tr>
<td>(V_{zl}, V_{z2})</td>
<td>range of (V_z)</td>
<td>meters/sec</td>
</tr>
<tr>
<td>(W_i)</td>
<td>uncorrected wind</td>
<td>meters/sec</td>
</tr>
<tr>
<td>(X_a, Y_a, Z_a)</td>
<td>aircraft position at time (t)</td>
<td>meters</td>
</tr>
<tr>
<td>(X_f, Y_f, Z_f)</td>
<td>aircraft position at firing</td>
<td>meters</td>
</tr>
<tr>
<td>(X_p, Y_p, Z_p)</td>
<td>projectile location</td>
<td>meters</td>
</tr>
<tr>
<td>(X_r, Y_r, Z_r)</td>
<td>radar located target</td>
<td>meters</td>
</tr>
<tr>
<td>(\alpha_{dx}, \alpha_{dy})</td>
<td>angular ballistic dispersion</td>
<td>radians</td>
</tr>
<tr>
<td>(\Delta X_p)</td>
<td>projectile displacement</td>
<td>meters</td>
</tr>
<tr>
<td>(\varepsilon_R)</td>
<td>range error</td>
<td>meters</td>
</tr>
<tr>
<td>(\varepsilon_{\theta_e}, \varepsilon_{\theta_a})</td>
<td>azimuth and elevation error</td>
<td>radian</td>
</tr>
<tr>
<td>(\mu_{bx}, \mu_{by})</td>
<td>linear mean bias</td>
<td>meters</td>
</tr>
<tr>
<td>((\omega_e, \omega_a))</td>
<td>gun azimuth and elevation</td>
<td>milliradians</td>
</tr>
<tr>
<td>(\rho)</td>
<td>projectile linear range</td>
<td>meters</td>
</tr>
<tr>
<td>(\sigma_{dx}, \sigma_{dy})</td>
<td>linear ballistic dispersion</td>
<td>meters</td>
</tr>
<tr>
<td>(\tau)</td>
<td>projectile flight time</td>
<td>sec</td>
</tr>
<tr>
<td>(\theta_{bx}, \theta_{by})</td>
<td>angular mean bias</td>
<td>radians</td>
</tr>
<tr>
<td>(\theta_e, \theta_a)</td>
<td>target azimuth and elevation</td>
<td>milliradians</td>
</tr>
</tbody>
</table>
APPENDIX D
EQUATIONS AND DATA

1. GOVERNING EQUATIONS

a. The Siacci Formula

This equation used here to determine the velocity of the projectile at a point in time is

\[ V_p = V_0 \left( C_d V_0 \frac{1}{2} \tau - 1 \right)^2 \]  
(eqn D.1)

Where these two equation can be seen [Ref. 1].

- \( C_d \) is the coefficient of drag of the projectile.
- \( V_p \) is the velocity of the projectile.
- \( V_0 \) is the muzzle velocity.
- \( \tau \) is the time of flight of the projectile.

b. Range of the Projectile

The formula for determine the range of the projectile at a point in time is taken as

\[ R_g = V_0 \tau \left( C_d V_0 \frac{1}{2} \tau - 1 \right) \]  
(eqn D.2)

The derivation of these formula can be found in [Ref. 4].

c. Gravity Drop

\[ GD = (-1.6) g \tau^2 (1 + 2 V_p V_0 \frac{1}{2}) \]  
(eqn D.3)

2. DATA

This study looked at 40 mm gun system, and firing high explosive round with both a contact fuze and a proximity fuze. The unclassified system characteristics were obtained from [Ref. 5].
All references to vulnerable area data for specific air threats to these guns are classified, therefore aircraft probability of kill given a hit and warhead lethal radius is entirely synthetic. Vulnerable area data for many different aircrafts and many different gun systems is readily available for personnel with appropriate clearances. The optimal angular ballistic dispersion was determined using the computer simulation and the coefficient of drag for the projectiles are assumed. The other data was from Jane's Weapon System. The aircraft's vulnerability measure \( r_I \) is assumed as discussed in Chapt 2, and \( A_V \) is determined by using the probability the aircraft is killed given the random hit on the aircraft \( P_{KH} \) as discussed in Chapt 3.

<table>
<thead>
<tr>
<th>TABLE 1</th>
</tr>
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<tbody>
<tr>
<td><strong>40 MM GUN CHARACTERISTICS</strong></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>parameters</th>
<th>unit</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>firing rate</td>
<td>rds/min</td>
<td>600</td>
</tr>
<tr>
<td>muzzle velocity</td>
<td>m/sec</td>
<td>1005</td>
</tr>
<tr>
<td>coefficient of drag</td>
<td>1/sec</td>
<td>0.00515</td>
</tr>
<tr>
<td>maximum range</td>
<td>km</td>
<td>12</td>
</tr>
<tr>
<td>angular dispersion</td>
<td>mrad</td>
<td>1.0</td>
</tr>
</tbody>
</table>
APPENDIX E
EMPIRICAL COMPARISON OF MARGINAL DISTRIBUTIONS

1. TYPE OF FUZE
   a. Proximity Fuzed Warhead

   **TABLE 2**
   PROXIMITY FUZED WARHEAD

   | PARAMETER VALUES: (100);(700);(1300);(1900) |
   | POPULATIONS  : RG14:RG13:RG12:RG11 |
   | WEIGHTS      : 0 |
   | X LABEL      : RANGE IN METERS |
   | Y LABEL      : PROBABILITY OF KILL |
   | POPULATION NO. OF NUMBER POINTS | Y MEAN | Y STD DEV | 0.25 | 0.5  | 0.75 |
   | POPULATION NO. OF NUMBER POINTS | Y MEAN | Y STD DEV | 0.25 | 0.5  | 0.75 |
   | 100 50 | 0.06613 | 0.1907 | 0.72854 | 8.6001E-1 | 9.4777E-1 |
   | 700 50 | 0.2179 | 0.23669 | 0.021002 | 1.3836E-1 | 3.2233E-1 |
   | 1300 50 | 0.051488 | 0.15441 | 0 |
   | 1900 50 | 0.0094727 | 0.065348 | 0 |
   POOLED STANDARD DEVIATION ESTIMATE: 0.17357

   b. Contact Fuzed Warhead

   **TABLE 3**
   CONTACT FUZED WARHEAD

   | PARAMETER VALUES: (100);(700);(1300);(1900) |
   | WEIGHTS      : 0 |
   | X LABEL      : RANGE IN METERS |
   | Y LABEL      : PROBABILITY OF KILL |
   | POPULATION NO. OF NUMBER POINTS | Y MEAN | Y STD DEV | 0.25 | 0.5  | 0.75 |
   | POPULATION NO. OF NUMBER POINTS | Y MEAN | Y STD DEV | 0.25 | 0.5  | 0.75 |
   | 100 60 | 0.017203 | 0.0058264 | 0.013458 | 0.016796 | 1.9509E-2 |
   | 700 60 | 0.0092551 | 0.0053786 | 0.005805 | 0.010485 | 1.2478E-2 |
   | 1300 60 | 0.003111 | 0.0057373 | 0 |
   | 1900 60 | 0.00048311 | 0.002269 | 0 |
   POOLED STANDARD DEVIATION ESTIMATE: 0.0049179
2. BALLISTIC DISPERSION

### TABLE 4
#### BALLISTIC DISPERSION

<table>
<thead>
<tr>
<th>Parameter Values: (0);(0.0005);(0.001);(0.0015);(0.002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Populations: AP1;AP2;AP3;AP4;AP5</td>
</tr>
<tr>
<td>Weights: 0</td>
</tr>
<tr>
<td>X Label: Angular dispersion in radians</td>
</tr>
<tr>
<td>Y Label: Probability of kill</td>
</tr>
<tr>
<td>Population No. of</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>0.0005</td>
</tr>
<tr>
<td>0.001</td>
</tr>
<tr>
<td>0.0015</td>
</tr>
<tr>
<td>0.002</td>
</tr>
</tbody>
</table>

Pooled standard deviation estimate: 0.29559

3. RANGE EVALUATION

### TABLE 5
#### RANGE EVALUATION

<table>
<thead>
<tr>
<th>Parameter Values: (100);(700);(1300);(1900)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Populations: RG14;RG13;RG12;RG11</td>
</tr>
<tr>
<td>Weights: 0</td>
</tr>
<tr>
<td>X Label: Range in meters</td>
</tr>
<tr>
<td>Y Label: Probability of kill</td>
</tr>
<tr>
<td>Population No. of</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>700</td>
</tr>
<tr>
<td>1300</td>
</tr>
<tr>
<td>1900</td>
</tr>
</tbody>
</table>

Pooled standard deviation estimate: 0.16975
4. EFFECTS OF TARGET MANEUVERS

a. Maneuvering Target

**TABLE 6**
MANEUVERING TARGET

<table>
<thead>
<tr>
<th>PARAMETER VALUES:</th>
<th>POPULATIONS: RG14; RG13; RG12; RG11</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEIGHTS: 0</td>
<td>X LABEL: RANGE IN METERS</td>
</tr>
<tr>
<td>Y LABEL: PROBABILITY OF KILL</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POPULATION NO. OF</th>
<th>NUMBER POINTS</th>
<th>Y MEAN</th>
<th>Y STD DEV</th>
<th>0.25</th>
<th>0.5</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>50</td>
<td>0.80613</td>
<td>0.1907</td>
<td>8.6001E-1</td>
<td>9.4777E-1</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>50</td>
<td>0.2179</td>
<td>0.23669</td>
<td>1.3836E-1</td>
<td>3.2233E-1</td>
<td></td>
</tr>
<tr>
<td>1300</td>
<td>50</td>
<td>0.051488</td>
<td>0.15441</td>
<td>9.2321E-13</td>
<td>7.8509E-3</td>
<td></td>
</tr>
<tr>
<td>1900</td>
<td>50</td>
<td>0.0094727</td>
<td>0.065348</td>
<td>0.00000E0</td>
<td>6.1062E-16</td>
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</tr>
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</table>

POOLED STANDARD DEVIATION ESTIMATE: 0.17357

b. Non-maneuvering Target

**TABLE 7**
NON-MANEUVERING TARGET

<table>
<thead>
<tr>
<th>PARAMETER VALUES:</th>
<th>POPULATIONS: NOM1; NOM2; NOM3; NOM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEIGHTS: 0</td>
<td>X LABEL: RANGE IN METRES</td>
</tr>
<tr>
<td>Y LABEL: PROBABILITY OF KILL</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POPULATION NO. OF</th>
<th>NUMBER POINTS</th>
<th>Y MEAN</th>
<th>Y STD DEV</th>
<th>0.25</th>
<th>0.5</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>50</td>
<td>0.97438</td>
<td>0.009994</td>
<td>9.6751E-1</td>
<td>0.97309</td>
<td>0.98113</td>
</tr>
<tr>
<td>700</td>
<td>50</td>
<td>0.46539</td>
<td>0.25853</td>
<td>2.2858E-1</td>
<td>0.41486</td>
<td>0.6943</td>
</tr>
<tr>
<td>1300</td>
<td>50</td>
<td>0.16126</td>
<td>0.27431</td>
<td>6.3071E-11</td>
<td>0.0013258</td>
<td>0.28581</td>
</tr>
<tr>
<td>1900</td>
<td>50</td>
<td>0.012354</td>
<td>0.075884</td>
<td>0.00000E0</td>
<td>0</td>
<td>0</td>
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</tbody>
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POOLED STANDARD DEVIATION ESTIMATE: 0.19231

53
5. EFFECTS OF RADAR ERROR

TABLE 8
RADAR ERROR

<table>
<thead>
<tr>
<th>PARAMETER VALUES: (0);(50);(100);(150)</th>
<th>POPULATIONS : RD21;RD22;RD23;RD24</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEIGHTS : 0</td>
<td>&amp; LABEL : PERCENT RADAR ERROR</td>
</tr>
<tr>
<td>Y LABEL : PROBABILITY OF KILL</td>
<td></td>
</tr>
<tr>
<td>POPULATION NO. OF NUMBER POINTS Y MEAN Y STD DEV 0.25 0.5 0.75</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>60 0.3013 0.41684 1.4979E-12 0.014739 0.804</td>
</tr>
<tr>
<td>50</td>
<td>60 0.2246 0.33077 0.0000E0 0.0000149 0.44578</td>
</tr>
<tr>
<td>100</td>
<td>60 0.13527 0.25116 1.3878E-17 0.00014144 0.12566</td>
</tr>
<tr>
<td>150</td>
<td>60 0.083055 0.1728 0.0000E0 0.0017942 0.078821</td>
</tr>
<tr>
<td>POOLED STANDARD DEVIATION ESTIMATE: 0.29038</td>
<td></td>
</tr>
</tbody>
</table>

6. EFFECTS OF MUZZLE VELOCITY AND RATE OF FIRE
a. Muzzle Velocity

TABLE 9
MUZZLE VELOCITY

<table>
<thead>
<tr>
<th>PARAMETER VALUES: (1000);(1500);(2000);(2500)</th>
<th>POPULATIONS : MV1;MV2;MV3;MV4</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEIGHTS : 0</td>
<td>X LABEL : MUZZLE VELOCITY(METERS/SEC)</td>
</tr>
<tr>
<td>Y LABEL : PROBABILITY OF KILL</td>
<td></td>
</tr>
<tr>
<td>POPULATION NO. OF NUMBER POINTS Y MEAN Y STD DEV 0.25 0.5 0.75</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>60 0.11223 0.23417 0 0.000029386 0.055264</td>
</tr>
<tr>
<td>1500</td>
<td>60 0.24198 0.29665 0.0022309 0.1129 0.39962</td>
</tr>
<tr>
<td>2000</td>
<td>60 0.35197 0.27194 0.09949 0.31493 0.57484</td>
</tr>
<tr>
<td>2500</td>
<td>60 0.51254 0.2572 0.28252 0.3894 0.70919</td>
</tr>
<tr>
<td>POOLED STANDARD DEVIATION ESTIMATE: 0.26596</td>
<td></td>
</tr>
</tbody>
</table>
b. Rate of Fire

**TABLE 10**
RATE OF FIRE

| PARAMETER VALUES: (400);(600);(800);(1000) |
| POPULATIONS : FR21;FR22;FR23;FR24 |
| WEIGHTS : 0 |
| X LABEL : FIRING RATE(RDS/MIN) |
| Y LABEL : PROBABILITY OF KILL |

| POPULATION NO. OF |
| NUMBER | POINTS | Y MEAN | Y STD DEV | 0.25 | 0.50 | 0.75 |
| 400    | 60     | 0.1513 | 0.2581    | 0.0003 | 0.0217 | 0.1931 |
| 600    | 60     | 0.2113 | 0.2704    | 0.0007 | 0.0584 | 0.3934 |
| 800    | 60     | 0.3069 | 0.3067    | 0.0028 | 0.2385 | 0.5513 |
| 1000   | 60     | 0.4055 | 0.3249    | 0.0399 | 0.3805 | 0.7492 |

POOLED STANDARD DEVIATION ESTIMATE: 0.29132
LIST OF REFERENCES


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      Dept. of Aeronautics Engineering  
      Naval Postgraduate School  
      Monterey, CA 93943-5000 |
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| 10. | 1      | Naval Staff College  
      Jehwangsan-dong. Jinhae City. Gyungnam 602-00  
      Republic of Korea |
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Logistic Supply Center. Hyundong.  
Jinhae City, Gyungnam 602-00  
Republic of Korea

12. Commander of BuORD.  
Naval Shipyard. Hyundong.  
Jinhae City, Gyungnam 602-00  
Republic of Korea

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Monterey, CA 93943

16. LCDR Shin. Dong Ryong  
SMC =1732 NPS  
Monterey, CA 93943

17. LT Sur. Joo No  
SMC =1655 NPS  
Monterey, CA 93943
END
DATE
FILMED
APRIL
1988
DTIC