The Analysis of a Generic Air-to-Air Missile Simulation Model

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Abstract

A generic missile model was developed to evaluate the benefits of using a dynamic missile fly-out simulation system versus a static missile launch envelope system for air-to-air combat simulation. This paper examines the performance of a launch envelope model and a missile fly-out model. The launch envelope model bases its probability of killing the target aircraft on the target aircraft's position at the launch time of the weapon. The missile's probability of kill is calculated by using either a mathematical function or a look-up table. This method presents several problems. The method does not account for any evasive maneuvers that the target aircraft attempts in order to maximize the miss distance of the missile to the aircraft. Most launch envelope implementations do not include the opponent's closing rate and Line-of-Sight (LOS) rate in the probability of kill computation. The benefits gained from a launch envelope model are the simplicity of implementation and the minimal computational overhead required. The missile's probability of kill is based strictly on the target's position at launch time. A missile fly-out model takes into account the physical characteristics of the missile as it simulates the guidance, propulsion, and movement of the missile. The missile's probability of kill is based on the missile miss distance (or the minimum distance between the missile and the target aircraft). This technique of modeling weapon launches rewards the target aircraft for any evasive maneuvers that it attempts in order to maximize the missile miss distance. The problems associated with this method of modeling are a larger computational overhead, the additional complexity required to determine the missile miss distance, and the additional complexity of determining the reason(s) the missile missed the target. This paper evaluates the two methods and compares the results of running each method on a comprehensive set of test conditions.

Nomenclature

t	Current time (seconds)
t_{BURN}	Time before fuel exhaustion (seconds)
Δt	Simulation time interval (seconds)
t_{impact}	Estimated time of missile's closest approach to target (seconds)
X_{Target}	Target position on the X axis (meters)
$X_{Missile}$	Missile position on the X axis (meters)
Y_{Target}	Target position on the Y axis (meters)
$Y_{Missile}$	Missile position on the Y axis (meters)
Z_{Target}	Target position on the Z axis (meters)
$Z_{Missile}$	Missile position on the Z axis (meters)
ΔX	Distance between X_{Target} and $X_{Missile}$ (meters)
ΔY	Distance between Y_{Target} and $Y_{Missile}$ (meters)
ΔZ	Distance between Z_{Target} and $Z_{Missile}$ (meters)
RANGE	Distance between the target and the missile (meters)
$RANGE_{Estimated}$	Estimated range at t_{impact} (meters)
D	Drag affecting missile
V	Velocity (meters/second)
A	Acceleration (meters/second^2)
Θ	Pitch angle (radians)
Ψ	Yaw angle (radians)
$\dot{\Theta}$	Pitch Velocity (radians/second)
$\dot{\Psi}$	Yaw Velocity (radians/second)
q	Pitch rate (radians/second)
r	Yaw rate (radians/second)
$\dot{q}$	Pitch acceleration(radians/second^2)
$\dot{r}$	Yaw acceleration (radians/second^2)
ρ	Density of air
s	Surface area of missile
C_{D0}	Coefficient of Drag
K	Constant of Drag
w	Weight of missile used in drag calculation (kilograms)
T	Thrust of missile (newtons)
G	Acceleration due to gravity (meters/second^2)

M	Mass of missile (kilograms)
M_{MAX}	Mass of missile at launch time (kilograms)
M_{MIN}	Mass of missile when fuel is expended (kilograms)
S_{Θ}	Pitch Signal
S_{Ψ}	Yaw Signal
C_{MT}	Missile time constant. Lag in control surfaces (seconds)
LOS	Line-of-Sight (LOS) angle (radians)
LOS_X	X component of the LOS angle (meters)
LOS_{YZ}	YZ component of the LOS angle (meters)
C_R	Closing rate between missile and target (meters/second)
C_{RX}	Closing rate between missile and target on the x axis (meters/second)
C_{RY}	Closing rate between missile and target on the y axis (meters/second)
C_{RZ}	Closing rate between missile and target on the z axis meters/second)
C_V	Closing velocity between missile and target (meters/second)
$V_{X_{Desired}}$	Desired velocity in the X axis to close with target (meters/second)
$V_{Y_{Desired}}$	Desired velocity in the Y axis to close with target (meters/second)
$V_{Z_{Desired}}$	Desired velocity in the Z axis to close with target (meters/second)
$q_{Desired}$	Desired pitch rate to close with target (radians/second)
$r_{Desired}$	Desired yaw rate to close with target (radians/second)

Introduction

Modern air combat simulations must perform in a greatly expanded and rapidly changing tactical environment. Such a simulation system must be able to model new aircraft and their advanced capabilities. The system requires a modular software structure so that new weapon systems or aircraft subsystems (e.g., sensors or propulsion systems), modifications to aircraft control systems, or changes to the aircraft configuration can be easily incorporated. In support of the study of aircraft with enhanced maneuverability at Langley Research Center (LaRC), a Tactical Guidance Research and Evaluation System (TiGRES) was developed. The design and development of TiGRES as well as its relationship to past and current air combat simulation systems are described in detail in reference 1.

The TiGRES system allows researchers to develop and evaluate aircraft systems in a tactical environment. The three main components of TiGRES are a Tactical Decision Generator (TDG), the Tactical Maneuver Simulator (TMS), and the Differential Maneuvering Simulator (DMS). A TDG is an intelligent system that selects the combat maneuvers to perform throughout an air combat engagement. Both the TMS and the DMS use a TDG as the automated opponent. The Paladin TDG was developed specifically for the TiGRES research.

This paper presents two methods for modeling weapons systems within TiGRES. The first method evaluated utilizes a missile launch envelope model. The missile launch envelope model utilizes the range and LOS angle between the target aircraft and firing aircraft. The missile's probability of kill is based on the range and LOS angle between the missile and the target aircraft at the time of missile launch. This technique of modeling weapon launches does not consider any evasive maneuvers that the target aircraft may attempt in order to maximize the missile miss distance. The second method evaluated is a missile fly-out model. The missile fly-out model includes the physical characteristics of the missile and simulates the guidance, propulsion, and movement of the missile. The missile's probability of kill is based on the missile miss distance, the minimum distance between the missile and the target aircraft. This technique of modeling weapon launches rewards the target aircraft for any evasive maneuvers that it attempts while trying to maximize the missile miss distance.

The Paladin System

Paladin is a knowledge-based TDG implemented using Artificial Intelligence (AI) techniques and a large amount of information about aircraft dynamics, flight control, and air combat. The system provides insight into both the tactical benefits and the costs of enhanced maneuverability. Paladin uses an object-oriented programming approach[3] to represent each aircraft in the simulation. Each aircraft object includes information on the current state of the aircraft's offensive systems (e.g., guns, missile systems, fire control radar, etc.), defensive systems (e.g., electronic counter–measures, chaff, etc.), and propulsion system. This state information is used to help guide Paladin's reasoning process.

Paladin models a combat engagement as a series of discrete decisions. Hence, at temporally regular decision points, the system must choose the "best" tactical maneuver to follow until the next decision point. To make this choice, Paladin uses information about its own state and estimated data about the opponent to calculate the relative geometry between the two aircraft. This relative geometry is used to perform a situation assessment and to select a new throttle position. After extrapolating the opponent's state a short time into the future, Paladin generates a situationally dependent set of trial maneuvers[5] and predicts a future engagement state for each trial maneuvers. These future engagement states are passed through a group of scoring functions that

evaluate various aspects of the tactical situation. The results of the scoring functions are weighted, based on the mode of operation, to compute the current best maneuver. Paladin executes the selected maneuver to direct the aircraft until the next decision interval.

The weapons model used has a direct effect on the air-to-air combat results produced by TiGRES. At each simulation execution interval Paladin computes the relative geometry between the opposing aircraft. The weapons model then uses the relative geometry information to compute the current weapons solutions.

Engagement Scoring Data

Evaluating an engagement requires information on aircraft relative geometry and Paladin's system status. This information is available in the form of participant-specific data maintained by Paladin. All data relating to the Paladin aircraft as well as Paladin sensor data (e.g., the opponent's relative position) are assumed to be known exactly. Other data required about the opponent must be estimated.

The engagement scoring module uses quantities which are based on exactly known data specific to the Paladin aircraft or relative values from the Paladin aircraft's point of view. Paladin's current throttle position and altitude are parameters taken directly from the current state. Range is the magnitude of a vector connecting the centers of gravity of the aircraft. The LOS angle is defined as the angle between the LOS vector and the ownship body x-axis (see figure 1); the deviation angle is defined as the angle between the LOS vector and the ownship velocity vector; and the LOS angle off is defined as the angle between the LOS vector and the opponent's body x-axis.

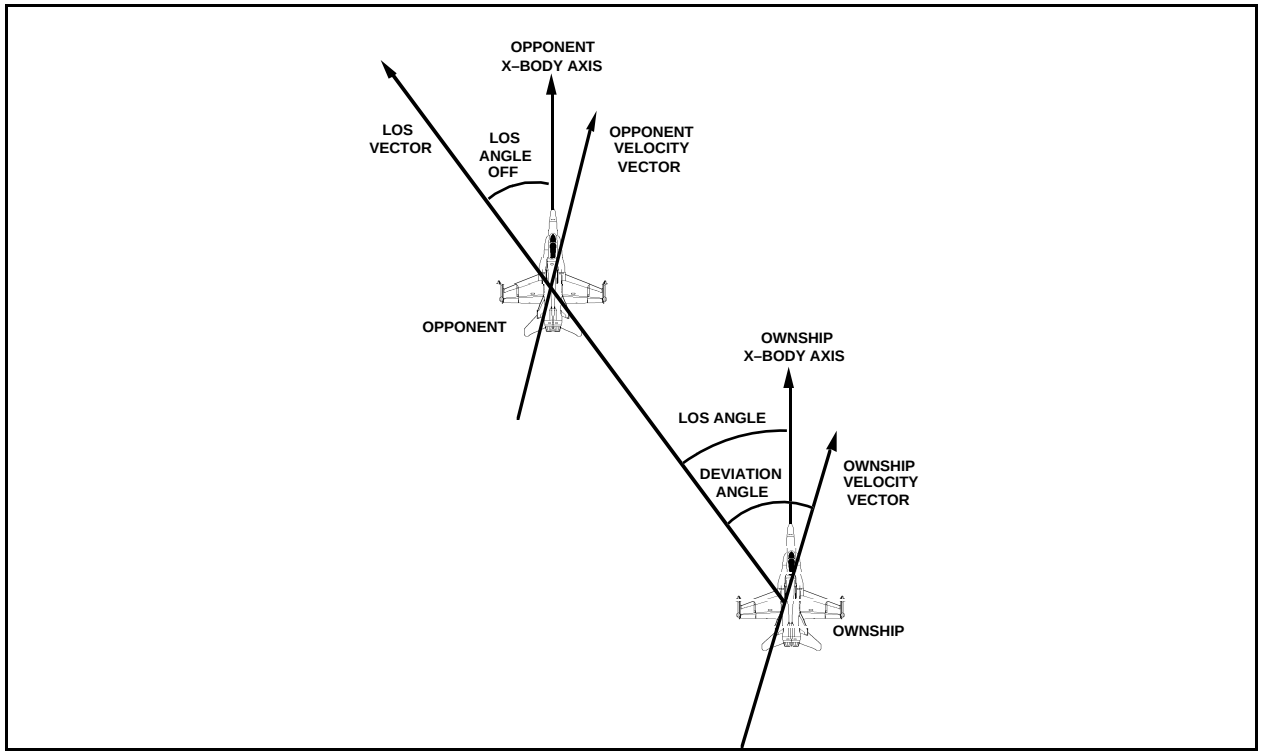

Figure 1. Angle Definitions

The deviation angle is calculated as the inverse cosine of the magnitude of the projection of the range onto the velocity vector divided by the range. In equation form,

deviation angle =

$$\arccos\left[\frac{\dot{x}\Delta x + \dot{y}\Delta y + \dot{z}\Delta z}{(\text{Range})\,|\text{Velocity}|}\right] \tag{1}$$

The LOS angle is the inverse cosine of the magnitude of the projection of the range onto the x-body axis divided by the range, or,

LOS angle =

$$\arccos\left[\frac{D(1,1)\Delta x + D(1,2)\Delta y + D(1,3)\Delta z}{\text{Range}}\right] \tag{2}$$

where Δx, Δy, and Δz represent the difference between the two aircraft positions. D(i, j) is the i, j element of the Paladin body axis direction cosine matrix. Then the LOS elevation is taken to be the inverse sine of minus the opponent's z-coordinate in the Paladin body axis system divided by the range, or,

LOS elevation =

$$\arcsin\left[\frac{-z_{\text{opponent in Paladin body axis system}}}{\text{Range}}\right] \tag{3}$$

The LOS azimuth is the inverse tangent of the opponent's y-coordinate divided by the opponent's x-coordinate, both in the Paladin body axis system.

LOS azimuth =

$$\arctan\left[\frac{y_{\text{opponent in Paladin body axis system}}}{x_{\text{opponent in Paladin body axis system}}}\right] \tag{4}$$

The velocity, acceleration, and orientation of the opponent are estimated, since this data would not be available from sensors. The required data values are estimated using a three point time history of the known position data and several assumptions about the opponent aircraft (weight, wing surface area, and flight characteristics). The current position of the opponent and the opponent's position at the preceding two decision cycles are used to find a quadratic curve fit for the position as a function of time. The first and second derivatives of this function at the current time yield an estimation of the opponent's instantaneous velocity and acceleration. By assuming aerodynamic characteristics of the opposing aircraft, and using the velocity and acceleration estimates, an estimated body-axis orientation for the opponent can be found.

The quantities used by the engagement scoring module which are based on estimated data are largely relative values from the opponent aircraft's point of view. Each of these quantities has

some error introduced by the estimation process. The range rate is the magnitude of the projection of the relative velocity onto the range axis (all in the inertial axis system).

$$\text{range rate} = \frac{\dot{\Delta x}\Delta x + \dot{\Delta y}\Delta y + \dot{\Delta z}\Delta z}{\text{Range}} \tag{5}$$

The opponent's deviation angle and LOS angle are calculated similarly to the Paladin aircraft parameters (equations 1 and 2), using the opponent's velocity and x-body axis. Paladin's LOS angle off is defined as 180° - opponent's LOS angle. References X and X1 present an evaluation of the error magnitudes (absolute value of the actual value minus the estimated value) during the course of a typical engagement. If the aerodynamics of the opponent aircraft are not well known, the error in the LOS angle should increase, since this error is strongly dependent on the aircraft flight characteristics.

Engagement Scoring Metrics

Paladin currently uses four scoring metrics, each computed at the aircraft simulation update rate of 32 times per second, to evaluate each air combat engagement. The first metric consists of the total time that each airplane has its weapons locked on its opponent, the probability that any weapons fired will hit the opponent, the distance between the opponents, the angle-off, and the deviation angle. The results are printed in a table format at the completion of each run.

The second scoring metric computes a Probability of survival (P_s) using the data computed by the first metric. The probability to hit for an all–aspect missile and for the cannon are computed using the range and LOS angle to the opponent. The probability to hit for a tail–aspect missile is computed using the range, the LOS angle to the opponent, and the LOS angle off. Aircraft missiles are treated as limited resources and a probability to hit of 0.65 is required to launch the first missile. The probability to hit threshold increases by 0.05 for each missile launched. An estimated fly-out time (the time it will take a missile to reach its target) for each missile is computed based on the launch parameters, and another missile cannot be fired until the fly-out time has passed. The P_s for an aircraft is:

$$P_s = 1.0 - \Sigma\,[\text{probability to hit} * P_s(f)] \tag{6}$$

summing over each weapon fired by the opposing aircraft. $P_s(f)$ represents the P_s of the aircraft firing the weapon at the time the weapon was fired.

The third scoring metric attempts to determine a Lethal Time (LT) advantage for each engagement. LT advantage attempts to weigh the lethality of each distinct type of weapons lock time.

$$\text{LT} = \frac{\text{Paladin Gun - Opponent Gun}}{2} +$$

$$(2 * (\text{Paladin Tail–Aspect - Opponent Tail–Aspect})) +$$

$$\backslash(\text{Paladin All–Aspect - Opponent All–Aspect }\backslash) \tag{7}$$

A positive LT value shows Paladin with a lethal time advantage, and a negative LT shows the opponent with an advantage.

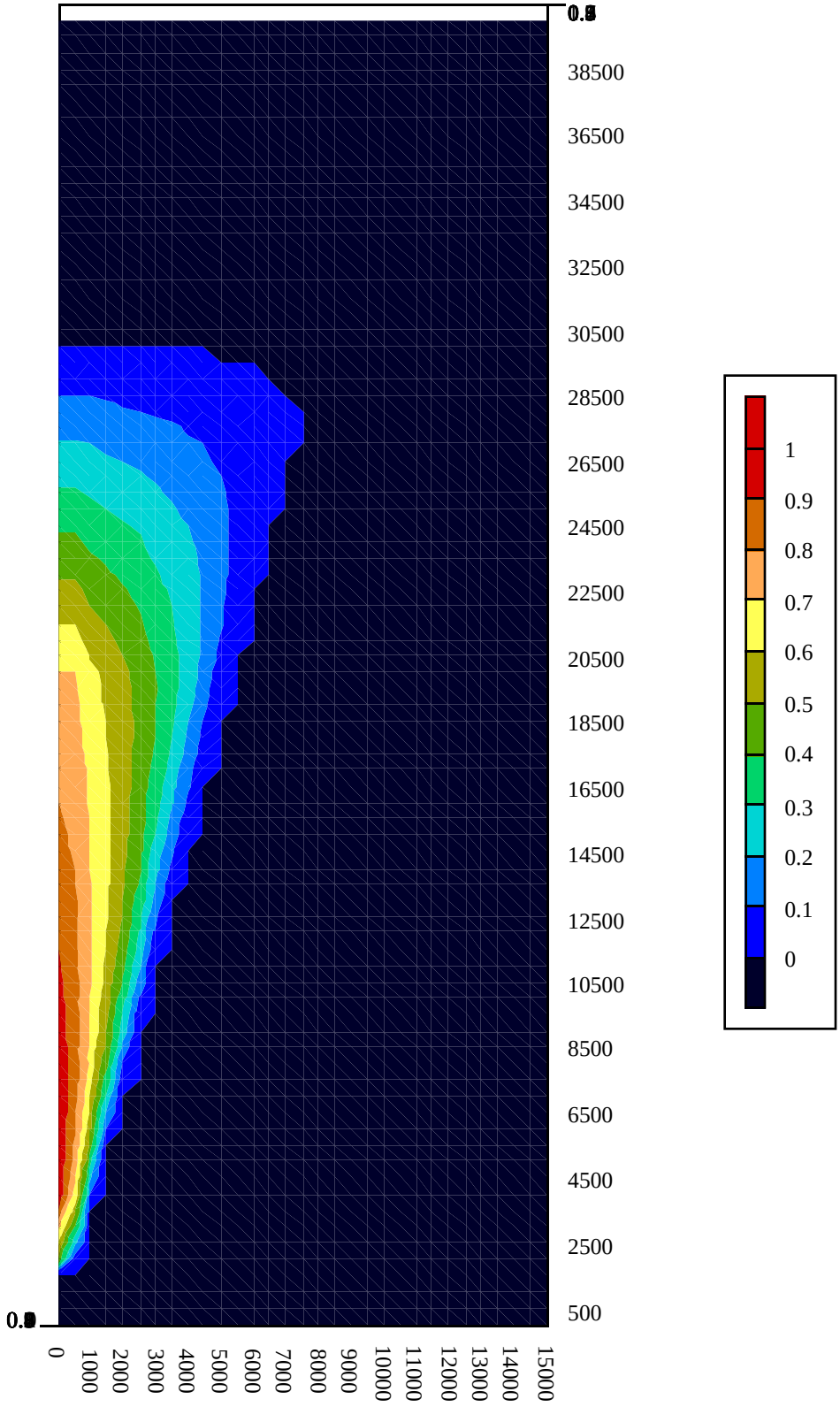

Figure 2 - Graphical Representation of A Launch Envelope Model

The fourth metric is Time on Offense (TOF).

$$TOF = (\text{Gun time} + \text{All-aspect time} + \text{Tail-aspect time}) \tag{8}$$

ΔTOF is computed as Paladin's TOF minus the opponent's TOF. A positive ΔTOF value shows Paladin with an time on offense advantage, and a negative ΔTOF shows the opponent with a time on offense advantage.

Missile Launch Envelope Method

The missile launch envelope model considers the range and LOS angle between the target and firing aircraft at launch. The missile's probability of kill is based on the range and LOS angle between the missile and the target aircraft at the time of missile launch. This technique of modeling weapon launches does not consider any evasive maneuvers that the target aircraft may attempt in order to maximize the missile miss distance. The problems associated with this method of modeling are the use of simplified scoring functions and the use of a "time of launch" probability of kill computation.

Missile Fly-out Method

The missile fly-out model includes the physical characteristics of the missile and simulates the guidance, propulsion, and movement of the missile. The missile's probability of kill is based on the missile miss distance, the minimum distance between the missile and the target aircraft. This technique of modeling weapon launches rewards the target aircraft for any evasive maneuvers that it may attempt in order to maximize the missile miss distance. Some of the problems associated with this method of modeling are a larger computational overhead, additional complexity in determining the missile's miss distance, and determining the reason(s) the missile missed the target. Missile miss distance may be caused by any combination of three reasons:

1) the missile failed to reach the target because of physical constraints (i.e., range, inability to quickly maneuver, etc.)
2) the missile's line of sight limitations were exceeded
3) the target aircraft performed a maneuver that generated an optimal miss distance

Model Characteristics

Several constraints were placed upon the implementation of the missile model. These constraints included:

1) the model must exhibit realistic physical properties (e.g., account for gravity, drag, etc.)
2) the guidance and control system must operate realistically
3) the model must require minimal computational intensity
4) the software must possess cross-platform capabilities
5) the subroutine must be re-entrant so multiple missiles may be in-flight against multiple targets

A point-mass missile model was developed based on aerodynamic equations provided in Reference 9. The model is generic so any missile's characteristic may be incorporated into it. The missile model selected for analysis is a generic radar guided missile with physical characteristics

similar to the AIM9 "Sidewinder." Table 1 presents the characteristics of the missile used for testing. The model takes into account the following physical features of the missile, including:

1) the missile can accelerate faster as the weight is reduced due to the rapid burning of fuel
2) the missile needs to accelerate to a sufficient velocity before it can begin to maneuver (i.e., the missile can not pull as many G's at low speeds as it can at high speeds)
3) the guidance controls in the missile use a proportional navigation system (i.e., they set a path to intercept the target, and not to track it)

Table 1 - Physical Characteristics of the Generic Test Missile

Weight at Launch	125 Lbs
Weight at Burnout	50 Lbs
Thrust	690 Lbs
Time of Motor Burn	8.0 seconds
Maximum Acceleration	30 G's
Range	2.5 Miles
Proportional Navigation	

Missile Simulation Computations

After initializing all variables with conditions suitable for launching the weapon, Paladin calls the missile subroutine. The first conditions computed are from the previous iteration. These conditions are used for the current iteration calculations.

The first variables to be computed are the differences in the X, Y, and Z axis. The ΔX, ΔY, and ΔZ all represent the difference between the missile's position and the target's position. Having computed the differences along each axis, the range is computed.

The difference in the X, Y, and Z axis, respectively, for the previous iteration in equation form is

$$\Delta X_{t-1} = X_{Target_{t-1}} - X_{Missile_{t-1}} \quad (9)$$

$$\Delta Y_{t-1} = Y_{Target_{t-1}} - Y_{Missile_{t-1}} \quad (10)$$

$$\Delta Z_{t-1} = Z_{Target_{t-1}} - Z_{Missile_{t-1}} \quad (11)$$

The range between the missile and the target for the previous iteration in equation form is

$$Range_{t-1} = \sqrt{\Delta X_{t-1}^2 + \Delta Y_{t-1}^2 + \Delta Z_{t-1}^2} \quad (12)$$

The subroutine then computes the forces which will effect the missile's flight path.

The missile's drag for the current iteration is computed by combining the profile drag and the drag due to lift drag. The drag, in equation form, is

$$D_t = (K_1 * V_{t-1}^2) + \frac{K_2 * (q_{t-1}^2 + r_{t-1}^2)}{V_{t-1}^2} \quad (13)$$

where

$$K_1 = \frac{1}{2} * \rho * s * C_{D_0} \tag{14}$$

$$K_2 = \frac{2 * K * w^2}{\rho * s} \tag{15}$$

p, s, C_{D_0}, and w are all assumed to be constant in the drag computation. When the weight has changed significantly enough to alter the drag, the missile's fuel will be exhausted. Having lost thrust, the missile will begin to quickly decelerate. This assumption was made to simplify the drag computations.

The missile's acceleration for the current iteration is computed by subtracting the drag from the thrust and dividing by the mass. Acceleration due to gravity must then be subtracted from the result.

The computation of the acceleration, in equation form, is

$$A_t = \frac{(T_{t-1} - D_{t-1})}{M_{t-1}} - G*\sin(\Theta_{t-1}) \tag{16}$$

The pitch and yaw accelerations are computed based upon the signals for the control surfaces minus pitch and yaw rates of the last iterations. These are then divided by the missile time constant representing the time necessary to move the missile's control surfaces.

The pitch and yaw accelerations, in equation form, respectively, are

$$\dot{q}_t = \frac{S_{\Theta_{t-1}} - q_{t-1}}{C_{MT}} \tag{17}$$

$$\dot{r}_t = \frac{S_{\Psi_{t-1}} - r_{t-1}}{C_{MT}} \tag{18}$$

The pitch velocity is computed based upon the previous iteration's pitch rate minus the cosine of the pitch angle. The result is then divided by the velocity to produce the pitch velocity.

The pitch velocity, in equation form, is

$$\dot{\Theta}_t = \frac{q_{t-1} - \cos(\Theta_{t-1})}{V_{t-1}} \tag{19}$$

The yaw velocity is computed dividing the previous iteration's yaw rate by the velocity multiplied by the cosine of the pitch.

The yaw velocity, in equation form, is

$$\dot{\Psi}_t = \frac{r_{t-1}}{V_{t-1} * \cos(\Theta_{t-1})} \tag{20}$$

The velocities for the X, Y, and Z axis are computed. This is done by multiplying the velocity by the components of the pitch and yaw angles that contribute to motion in the particular axis.

The computation for velocity in the X, Y, and Z axis respectively, in equation form, are

$$\dot{X}_t = V_{t-1} * \cos(\Theta_{t-1}) * \cos(\Psi_{t-1}) \quad (21)$$

$$\dot{Y}_t = V_{t-1} * \cos(\Theta_{t-1}) * \sin(\Psi_{t-1}) \quad (22)$$

$$\dot{Z}_t = V_{t-1} * \sin(\Theta_{t-1}) \quad (23)$$

The missile's velocity is computed by multiplying the missile's acceleration by the iteration rate and adding the result to the previous iteration's velocity.

The computation of the velocity, in equation form, is

$$V_t = V_{t-1} + A_t * \Delta t \quad (24)$$

The pitch and yaw rates for the current iteration are computed by multiplying the angle rate by the iteration rate and adding the result to the previous iteration's rate.

The computation of the pitch and yaw rates, respectively, in equation form, are

$$q_t = q_{t-1} + \dot{q}_t * \Delta t \quad (25)$$

$$r_t = r_{t-1} + \dot{r}_t * \Delta t \quad (26)$$

The pitch and yaw angles for the current iteration are computed by multiplying the angle velocity by the iteration rate and adding the result to the previous iteration's angle.

The computation of the pitch and yaw angle, respectively, in equation form, are

$$\Theta_t = \Theta_{t-1} + \dot{\Theta}_t * \Delta t \quad (27)$$

$$\Psi_t = \Psi_{t-1} + \dot{\Psi}_t * \Delta t \quad (28)$$

The X, Y, and Z position of the missile are computed for the current iteration by multiplying the axis' velocity by the iteration rate and adding the result to the previous iteration's position.

The computation of the X, Y, and Z position, respectively, in equation form, are

$$X_t = X_{t-1} + \dot{X}_t * \Delta t \quad (29)$$

$$Y_t = Y_{t-1} + \dot{Y}_t * \Delta t \quad (30)$$

$$Z_t = Z_{t-1} + \dot{Z}_t * \Delta t \quad (31)$$

If the fuel of the missile has not been exhausted, the mass is updated to reflect the mass lost due to oxidation. This is done by subtracting the mass at fuel exhaustion from the mass at missile launch and dividing the result by the time required to reach fuel exhaustion. This value represents the amount of mass lost per second. The amount of mass lost per second is then multiplied by the iteration rate to give the amount of mass lost per iteration. This is then subtracted from the previous iteration's mass. The resultant value is the current iteration's mass.

The computation of the mass, in equation form, is

$$M_t = M_{t-1} - \left(\left(\frac{M_{MAX} - M_{MIN}}{t_{BURN}}\right) * \Delta t\right) \quad (32)$$

The distances between the target and the missile along the axis are computed for the current iteration. This is done by subtracting the missile's position from the target's position.

The computation for the X, Y, and Z position, respectively, in equation form, are

$$\Delta X_t = X_{Target_t} - X_{Missile_t} \quad (33)$$

$$\Delta Y_t = Y_{Target_t} - Y_{Missile_t} \quad (34)$$

$$\Delta Z_t = Z_{Target_t} - Z_{Missile_t} \quad (35)$$

The range between the missile and the target for the current iteration in equation form is

$$Range_t = \sqrt{\Delta X_t^{\,2} + \Delta Y_t^{\,2} + \Delta Z_t^{\,2}} \quad (36)$$

Having computed the new distances between the missile and the target, the LOS components are computed. This is done to determine whether the target has exceeded the limitation of the seeker's radar.

The computation for the X component of the LOS, in equation form, is

$$LOS_X = \left|\Delta X_t\right| \quad (37)$$

The computation for the YZ component of the LOS, in equation form, is

$$LOS_{YZ} = \sqrt{\Delta Y_t^{\,2} + \Delta Z_t^{\,2}} \quad (38)$$

The LOS is computed by taking the inverse tangent of the YZ component of the LOS divided by the X component of the LOS.

The computation of the LOS, in equation form, is

$$LOS_t = \text{ARCTAN}\left(\frac{LOS_{YZ}}{LOS_X}\right) \quad (39)$$

Having computed the LOS angle between the missile and the target, the subroutine computes the closing rates as the missile tracks the target. This is done by subtracting the current iteration's distance between the missile and the target from the previous iteration's distance. The result is then multiplied by the iteration rate to give the closing rate for the current iteration.

The computation for the closing rates in X, Y, and Z, respectively, in equation form, are

$$CR_X = (\Delta X_{t-1} - \Delta X_t) * \Delta t \quad (40)$$

$$CR_Y = (\Delta Y_{t-1} - \Delta Y_t) * \Delta t \quad (41)$$

$$CR_Z = (\Delta Z_{t-1} - \Delta Z_t) * \Delta t \quad (42)$$

The relative closing rate computation, in equation form, is

$$CR = (RANGE_{t-1} - RANGE_t) * \Delta t \quad (43)$$

The closing velocity is the negation of the relative closing rate.

$$CV = -CR \quad (44)$$

Having computed all of the relative positions, the guidance algorithm of the missile can now be employed. The first computed variables are the desired velocities in the body axis that will lead to an intercept.

The computation of the desired velocities in the X, Y, and Z axis, respectively, presented in equation form, are

$$V_{X_{Desired}} = \frac{(\Delta Y_t * CR_Z) - (\Delta Z_t * CR_Y)}{\sqrt{\Delta X_t^2 + \Delta Y_t^2 + \Delta Z_t^2}} \quad (45)$$

$$V_{Y_{Desired}} = \frac{(\Delta Z_t * CR_X) - (\Delta X_t * CR_Z)}{\sqrt{\Delta X_t^2 + \Delta Y_t^2 + \Delta Z_t^2}} \quad (46)$$

$$V_{Z_{Desired}} = \frac{(\Delta X_t * CR_Y) - (\Delta Y_t * CR_X)}{\sqrt{\Delta X_t^2 + \Delta Y_t^2 + \Delta Z_t^2}} \quad (47)$$

With the desired velocities in the body axis computed, these are then transformed into equivalent desired pitch and yaw rates.

$$q_{Desired} = -\sin(\Psi) * V_{X_{Desired}} + \cos(\Psi) * V_{Y_{Desired}} \quad (48)$$

$$r_{Desired} = (\cos(\Theta) * V_{Y_{Desired}}) + \left[\sin(\Theta) * \left[(\cos(\Psi) * V_{X_{Desired}}) + (\sin(\Psi) * V_{Y_{Desired}})\right]\right] \quad (49)$$

The pitch and yaw signals are computed by multiplying the desired rates by the closing velocity and the navigational constant. The navigation constant adjust the signal so the missile will intercept the target instead of tracking it.

The computation of the pitch and yaw signals, respectively, in equation form, are

$$S_{\Theta} = C_{Nav} * CV * q_{Desired} \quad (50)$$

$$S_{\Psi} = C_{Nav} * CV * r_{Desired} \quad (51)$$

Missile Warhead Detonation Computations.

The missile's estimated time of closest approach is calculated, along with the estimated range at the time of closest approach.

$$t_{Impact} = \frac{-\left((\Delta X * CV_X) + (\Delta Y * CV_Y) + (\Delta Z * CV_Z)\right)}{CV_X^2 + CV_Y^2 + CV_Z^2} \quad (52)$$

$$RANGE_{Estimated} = \sqrt{(CV_X * t_{Impact} + \Delta X_t)^2 + (CV_Y * t_{Impact} + \Delta Y_t)^2 + (CV_Z * t_{Impact} + \Delta Z_t)^2} \quad (53)$$

By using the missile's detonation logic(see Appendix D), weapon detonation distance from the aircraft can be determined. One of three possible results are returned from the missile's detonation logic. The missile either missed the target, struck the target, or is still actively engaged in tracking the target.

Missile Simulation Testing.

To evaluate the model, extensive testing was performed. The launching aircraft was positioned at an altitude of 6,000 meters. A grid was set up in front of the launching aircraft that extended 5,000 meters down range, 4,000 meters to both sides of the aircraft, and 6,000 meters above and below the launching aircraft. Each of the axis were then broken down into 25 meter increments. Each point in the grid indicated a starting position for the target aircraft. The launching aircraft traveled down range in straight and level flight at a constant velocity of Mach 0.7. The target aircraft was also in straight and level flight at Mach 0.7. Mach 0.7 was chosen as the test velocity because the majority of tactical encounters occur in the subsonic range. The direction of travel for the target aircraft was away from the launching aircraft

number of possible starting conditions = (5000/25) * (8000/25) * (12000/25)

This works out to 30,720,000 possible starting positions for the target aircraft. The target aircraft was put into each of these starting position and the simulation was allowed to continue until one of three possible conditions occurred:

1) the seeker's line of sight limitation was exceed
2) a non-negative closure rate was achieved between the missile and the target aircraft
3) the missile scored a "hit" upon the target aircraft (a hit was denoted by the missile passing within 10 meters of the target aircraft)

Most modern air-to-air missiles inflict lethal damage upon their target by showering it with shrapnel. Detonation is achieved by passing within a predetermined distance of the target. Based upon various methods of producing shrapnel, 10 meters was judged to be an adequate distance to produce a mission kill. If a hit was scored, the starting position of the target aircraft was printed out to a file.

Several different simulations were run. The first denoted what areas the missile could hit by giving the seeker a perfect radar. This was done to determine the range and physical properties of the missile model. In Figure 3, a vertical slice was taken from the center of the volume generated by the simulation run. Several distinct features of this slice stand out. Each mark on the plot shows a starting position of the target aircraft that the missile was able to hit. The center of the slice forms a "peak" that leads to the position of the launching aircraft at zero X, zero Y, and 6,000 meters of altitude. This "peak" feature is primarily due to the fact that the missile cannot maneuver sufficiently at low speeds to hit the target aircraft. There exists a larger concentration of hits in the lower portion of the slice due to the effects of gravity on the missile.

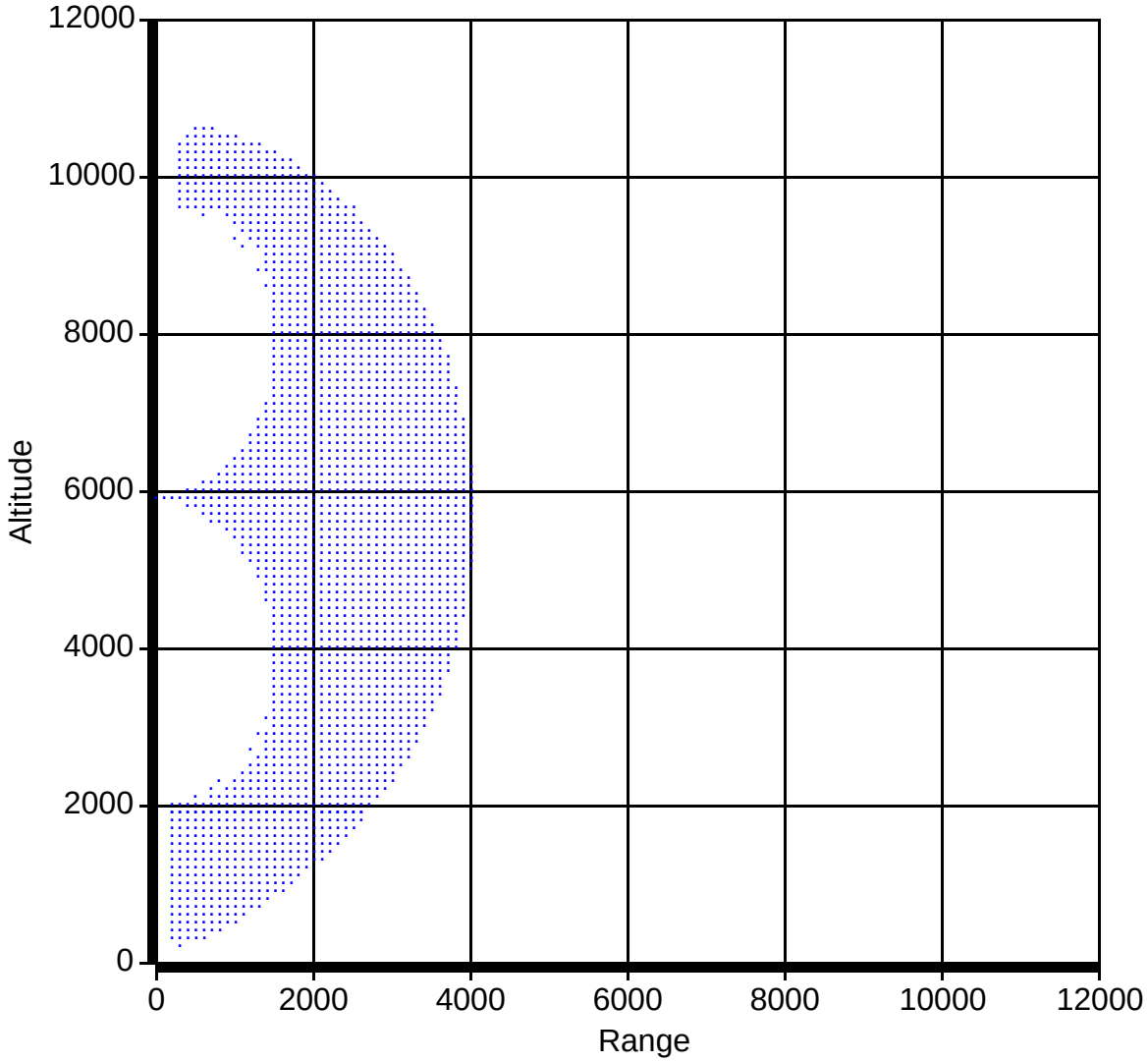

Figure 3 - Vertical Slice of Missile Fly-Out Simulation

The simulations that followed incorporated placing a LOS limitation upon the seeker. If the target was beyond this LOS limitation, then the seeker lost sight of the target and failed to track it, thus ending the simulation. Since TiGRES currently implements a 30˚ launch parameter, a 15˚ LOS limitation was placed upon the seeker(i.e. the missile's radar cone only extends 15˚s in any direction from a line projected out of the center of the seeker at the front of the missile). If this LOS limitation is rotated 360˚ in the X, Y, and Z axis, a 30˚ seeker cone in front of the missile is produced. This was done to see if TiGRES was over estimating the missile launch parameters. Running this simulation with a 15˚ LOS limitation produced a trumpet shaped cone (see Figure 3). The cone in Figure 4 was produced by running the simulation at an iteration rate of 32 times a second and taking a horizontal slice from the generated volume at the altitude of the launching aircraft. This cone closely resembles the shape of the launch envelope model. The narrow beginning of the cone was due to the missile's low speed at launch. In Figure 5 and Figure 6, the simulation was run at iteration rates of 64 and 128 times per second, respectively. The higher iteration rates allow the model to predict more accurately the missile's closest approach to the target aircraft. If the model estimates the missile will pass or overtake the target before the next iteration, it will detonate the warhead at the point of closest approach. If the model is run at lower iteration rates, it cannot predict accurately the closest approach distance. To determine whether a larger LOS limitation would affect performance, a 20 and 30˚ LOS limitation were tested. These limitations produced 40˚ and 60˚ cones, respectively. These simulations continued to reveal wider, yet similar, trumpet shaped cones as shown in Appendix E. Since the missile was tested against a non-maneuvering target, evasive maneuvering will raise the chance that the pilot can escape the kill range of the missile. The use of a non-maneuvering target in testing was done to insure the robustness of the missile model.

The missile's seeker relies on the target's relative position (X, Y, and Z). This is the only information that the launching aircraft is given about the target aircraft, so it is realistic to assume the missile will have access to similar information. The model is implemented as a re-entrant FORTRAN subroutine, so multiple missiles can be in-flight against multiple targets.

Conclusions

The results of this study show that a robust missile launch model envelope model will produce realistic results based on a non-maneuvering target. Simulations that include an active target require the additional features of a missile fly-out model to produce accurate results. The missile fly-out model considers the physical characteristics of the missile as it simulates its guidance system, propulsion, and movement. The missile's probability of kill is based on the missile miss distance, not the missile launch conditions. This technique of modeling weapon launches rewards the target aircraft for attempting evasive maneuvers to maximize the missile miss distance. The problems associated with this method of modeling are a larger computational overhead, the additional complexity required to determine the miss distance, and reason(s) why the missile missed the target. Achieving the maximum benefit of the fly-out model requires providing the target aircraft with visual or sensor information when the opponent launches a missile. This information allows the target to actively perform evasive maneuvers. Further research in this area requires adding missile avoidance logic to Paladin.

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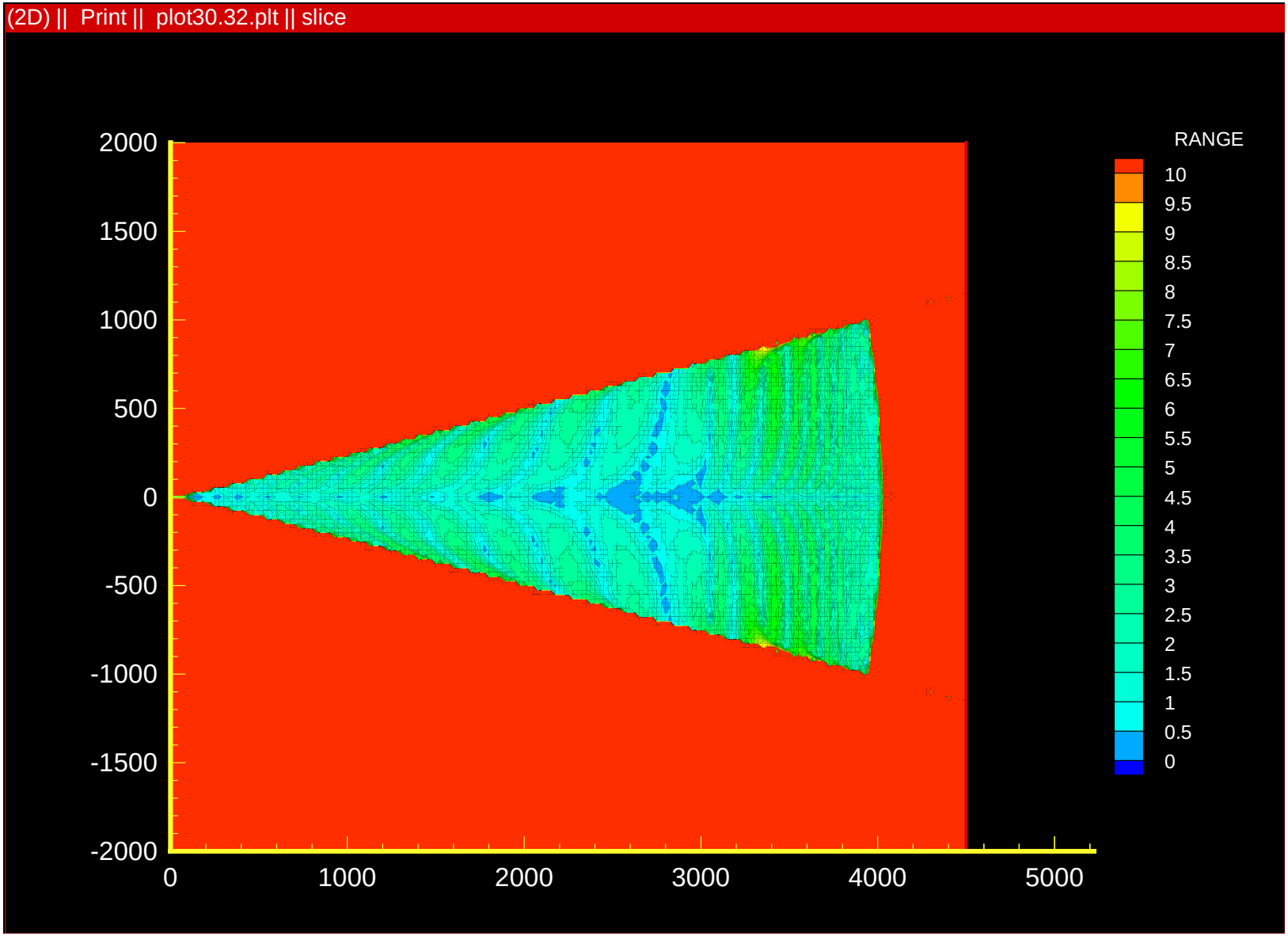

(2D) || Print || plot30.32.plt || slice
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1000
2000
3000
4000
5000
RANGE
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

Figure 4

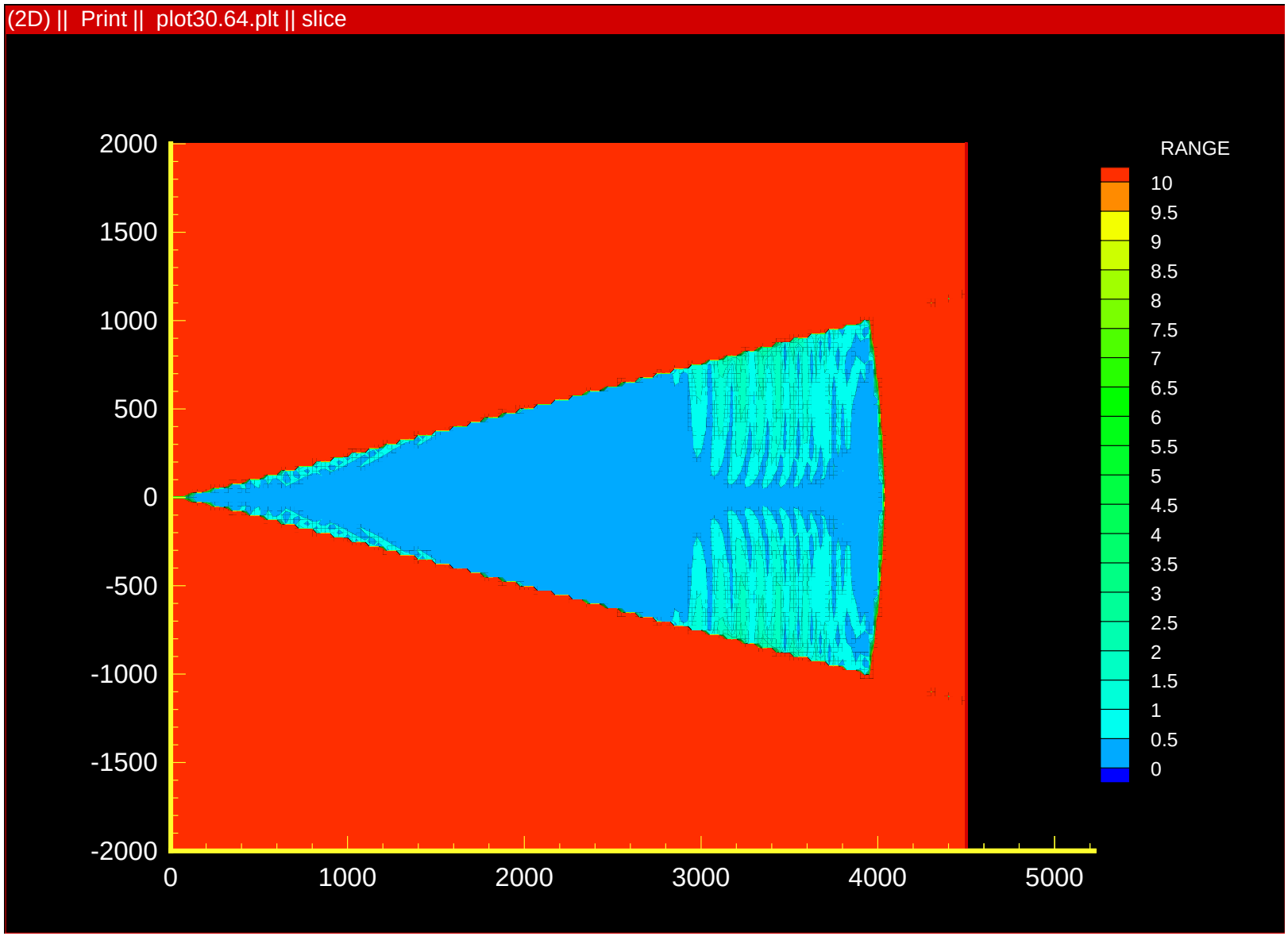

(2D) || Print || plot30.64.plt || slice
RANGE
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1000
2000
3000
4000
5000

Figure 5

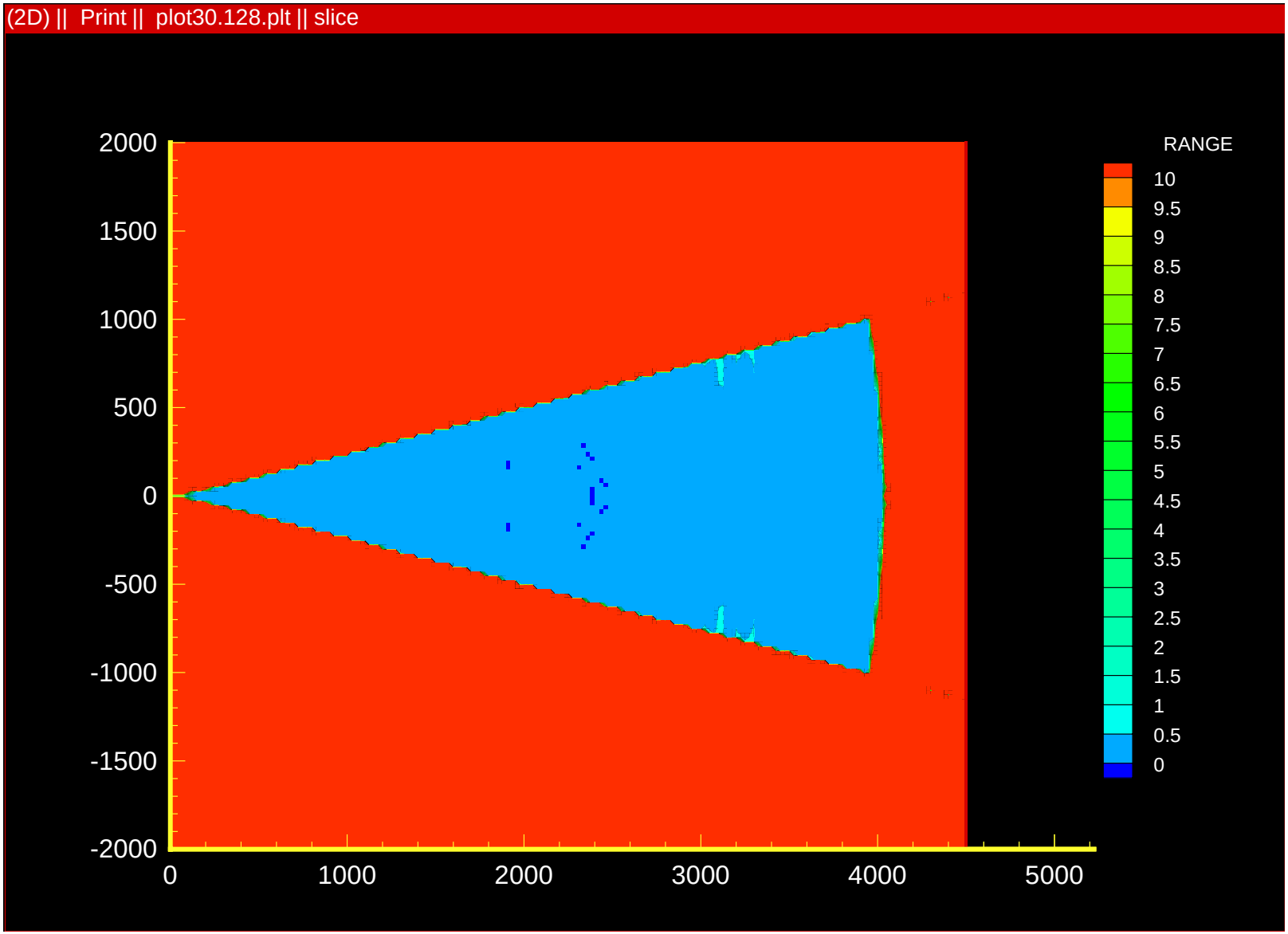

(2D) || Print || plot30.128.plt || slice
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1000
2000
3000
4000
5000
RANGE
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

Figure 6

Appendix A:

Format for Generic Missile Model

The model is implemented as a re-entrant subroutine. It has no concept of which missile it is calculating, the missile's target, or time. All these things must be passed to it. The model is just a single iteration calculator. By giving it the previous iteration's data, it can continue to calculate a course for the missile. The model calculates everything in metric units. If your program uses English units, several variables must be converted at missile initialization. The target's relative position (X, Y, and Z), old and new, must be converted every time.

Definition of Variables:

VELCTY	REAL	meters/second
PITCHR	REAL	radians/second
PTHSIG	REAL	radians/second**2
YAWR	REAL	radians/second
YAWSIG	REAL	radians/second**2
PITCH	REAL	radians
YAW	REAL	radians
X	REAL	earth-based x in meters
Y	REAL	earth-based y in meters
Z	REAL	earth-based z in meters
MASS	REAL	pounds
TARX	REAL	earth-based x in meters
TARY	REAL	earth-based y in meters
TARZ	REAL	earth-based z in meters
SEC	INTEGER	seconds
ITS	INTEGER	iteration # in current second
ITMIN	INTEGER	# of iterations per second
HIT	INTEGER	1 or 0
MISS	INTEGER	1 or 0
OTARX	REAL	earth-based x in meters
OTARY	REAL	earth-based y in meters
OTARZ	REAL	earth-based z in meters
RANGE	REAL	meters

Initialization of Variables:

VELCTY	Velocity	initialize to launching aircraft's velocity
PITCHR	Pitch rate	initialize to 0.0
PTHSIG	Pitch signal	initialize to 0.0
YAWR	Yaw rate	initialize to 0.0
YAWSIG	Yaw signal	initialize to 0.0
PITCH	Pitch	initialize to launching aircraft's alpha
YAW	Yaw or heading	initialize to launching aircraft's heading
X	X position of missile	initialize to launching aircraft's X position
Y	Y position of missile	initialize to launching aircraft's Y position
Z	Z position	initialize to launching aircraft's Z position
MASS	weight of missile	initialize to 56.7 kilograms
TARX	X position of target	initialize to target aircraft's X position
TARY	Y position of target	initialize to target aircraft's Y position
TARZ	Z position of target	initialize to target aircraft's Z position
SEC	# of secs of missile flight	initialize to 0

ITS	# of iterations in current sec	initialize to 0
ITMIN	# of iterations per sec	initialize to 32(if you are running at 32/sec)
HIT	hit determiner	initialize to 0(will change to 1 if hit scored)
MISS	miss determiner	initialize to 0(will change to 1 if miss scored)
OTARX	X pos of target last iteration	initialize to target's old X pos
OTARY	Y pos of target last iteration	initialize to target's old Y pos
OTARZ	Z pos of target last iteration	initialize to target's old Z pos
RANGE	distance of missile & target	initialize to -1.0

After all the variables have been initialized, the following variables must be update every iteration:

TARX	X position of target	set to target aircraft's X position
TARY	Y position of target	set to target aircraft's Y position
TARZ	Z position of target	set to target aircraft's Z position
OTARX	X pos of target last iteration	set to target's X pos from previous iteration
OTARY	Y pos of target last iteration	set to target's Y pos from previous iteration
OTARZ	Z pos of target last iteration	set to target's Z pos from previous iteration
SEC	Seconds of missile flight	
ITS	Number of iterations in current second	

Constants in program:

NAVC	navigational constant	4
PTHMAX	maximum pitch acceleration	30 G
YAWMAX	maximum yaw acceleration	30 G
TIMRNG	distance to fuse warhead at	100 meters
DETRNG	detonation range (hit score)	10 meters
SEEKER	seeker limitation	.261798 radians(15 degrees)
MXTIME	time of missile burn	8 seconds
MINWGT	minimum weight of missile	22.7 kilograms
MAXWGT	maximum weight of missile	56.7 kilograms
MAXTRT	Thrust during motor burn	6800 N
MINTRT	Thrust after motor burnout	0 N
G	Gravitational constant	9.8 meters per second^2
OPVEL	Optimal velocity of missile	700 meter per second

The managing software must keep track of the missiles in flight. It will also be responsible for updating the time of flight and the target for each missile. At every iteration, add one to the ITS variable until ITMIN is reached, then reset it to zero and add one to the SEC variable.

Appendix B - Test Program

```
      PROGRAM TMS_MISS_CALC
      IMPLICIT NONE

      REAL VELCTY,PITCHR,YAWR,PITCH,YAW
      REAL X,Y,Z,MASS,RANGE

      INTEGER LOOP1,LOOP2
      REAL TARX,TARY,TARZ

      INTEGER ITMIN
      PARAMETER (ITMIN = 128)

      INTEGER STEP
      REAL TARGTX,TARGTY,TARGTZ
      REAL PTHSIG,YAWSIG
      INTEGER TOPX,TOPY,TOPZ
      INTEGER BOTX,BOTY,BOTZ
      PARAMETER (TOPX = 4500)
      PARAMETER (TOPY = 4000)
      PARAMETER (TOPZ = 12000)
      PARAMETER (BOTX = 0)
      PARAMETER (BOTY = -4000)
      PARAMETER (BOTZ = 2000)
      PARAMETER (STEP = 25)
      INTEGER HIT,MISS
      REAL OTARX,OTARY,OTARZ

      OPEN(UNIT = 10,FILE = 'TEST_CONE',STATUS ='NEW')
      DO 3000 TARGTY=BOTY,TOPY,STEP
         DO 2000 TARGTZ=-BOTZ,-TOPZ,-STEP
C            PRINT *,'TARGTZ = ',TARGTZ,'TARGTX = ',TARGTX

            DO 1000 TARGTX=BOTX,TOPX,STEP

               VELCTY = 200.0
               PITCHR = 0.0
               YAWR = 0.0
               PTHSIG = 0.0
               YAWSIG = 0.0
               PITCH = 0.0
               YAW = 0.0
               X = 0.0
               Y = 0.0
               Z = -6000.0
               MASS = 56.7
               TARX = TARGTX
               TARY = TARGTY
               TARZ = TARGTZ
               HIT = 0
               MISS = 0
               RANGE = -1

               DO 200 LOOP1 = 1,30
                  DO 100 LOOP2 = 1,ITMIN
                  OTARX = TARX
```

```
                  OTARY = TARY
                  OTARZ = TARZ
                  CALL GETTAR(TARX,TARY,TARZ,ITMIN)
               CALL CALCULATIONS(VELCTY,PITCHR,PTHSIG,YAWR,YAWSIG,
     +                        PITCH,YAW,X,Y,Z,
     +                        MASS,TARX,TARY,TARZ,LOOP1,LOOP2,ITMIN,
     +                        HIT,MISS,OTARX,OTARY,OTARZ,RANGE)
 75                FORMAT(F8.2,',',F8.2,',',F8.2)
                  IF (HIT .EQ. 1) THEN
                     WRITE(10,75) TARGTX,TARGTY,-TARGTZ
                     HIT = 0
                     MISS = 0
                     GOTO 1000
                  END IF
                  IF (MISS .EQ. 1) THEN
                     MISS = 0
                     HIT = 0
                     GOTO 1000
                  END IF
100               CONTINUE
200            CONTINUE

1000  CONTINUE
2000  CONTINUE
3000  CONTINUE

      END
```

Appendix C - Missile Model

```
C*************************************************************
      SUBROUTINE CALCULATIONS(VELCTY,PITCHR,PTHSIG,YAWR,YAWSIG,
     +                        PITCH,YAW,
     +                        X,Y,Z,MASS,TARX,TARY,TARZ,SEC,
     +                        ITS,ITMIN,HIT,MISS,OTARX,OTARY,OTARZ,
     +                        RANGE)
C*************************************************************
C*    Name         - Subroutine Calculations
C*    Purpose      - Implements a missile simulation for the
C*                  Paladin tactical decision generator.
C*    Variables    -
C*    NAME         TYPE         UNITS
C*-----------------------------------------------------------------
C*    VELCTY       REAL         meters/second
C*    PITCHR       REAL         radians/second
C*    PTHSIG       REAL         radians/second**2
C*    YAWR         REAL         radians/second
C*    YAWSIG       REAL         radians/second**2
C*    PITCH        REAL         radians
C*    YAW          REAL         radians
C*    X            REAL         earth-based x in meters
C*    Y            REAL         earth-based y in meters
C*    Z            REAL         earth-based z in meters
C*    MASS         REAL         pounds
C*    TARX         REAL         earth-based x in meters
C*    TARY         REAL         earth-based y in meters
C*    TARZ         REAL         earth-based z in meters
C*    SEC          INTEGER      seconds
C*    ITS          INTEGER      iteration # in current second
C*    ITMIN        INTEGER      # of iterations per second
C*    HIT          INTEGER      1 or 0
C*    MISS         INTEGER      1 or 0
C*    OTARX        REAL         earth-based x in meters
C*    OTARY        REAL         earth-based y in meters
C*    OTARZ        REAL         earth-based z in meters
C*    RANGE        REAL         meters
c*************************************************************
      IMPLICIT NONE
      REAL VELCTY,PITCHR,YAWR,PITCH,YAW
      REAL THRUST,DRAG,YAWSIG,PTHSIG
      REAL X,Y,Z
      REAL ACCELR,PTCHRD,YAWRD,PITCHD,YAWD
      REAL XD,YD,ZD,MASS

      REAL CMPDIS,CMPSIG
      REAL CMPDRG,CMPTHT,ACCEL
      REAL PTHACC,YAWACC,CNGPTH,CNGYAW
      REAL CNGX,CNGY,CNGZ

      REAL TARX,TARY,TARZ
      REAL OTARX,OTARY,OTARZ
      REAL CURRR,CURRX,CURRY,CURRZ
      REAL NEWR,NEWX,NEWY,NEWZ
      REAL RESR,RESX,RESY,RESZ
      REAL CLSVEL,CMPOP,CMPOY
```

```
      REAL LINEX,LINEY,LINEZ
      REAL PITCHO,YAWO
      REAL RANGE,IMPTME,INTRVL
      INTEGER ITMIN,SEC,ITS,HIT,MISS
      REAL NAVC
      PARAMETER (NAVC = 4)
      REAL G
      PARAMETER (G = 9.8)
      REAL PTHMAX,YAWMAX
      PARAMETER (PTHMAX = 30.0)
      PARAMETER (YAWMAX = 30.0)
      REAL TIMRNG,DETRNG
      PARAMETER (TIMRNG = 100.0)
      PARAMETER (DETRNG = 10.0)
      REAL OPVEL,MATTRT,MINTRT
      PARAMETER (OPVEL = 700.0)
      PARAMETER (MATTRT = 6800.0)
      PARAMETER (MINTRT = 0.0)
      REAL BRNTME,MAXWGT,MINWGT
      PARAMETER (BRNTME = 8.0)
      PARAMETER (MAXWGT = 56.7)
      PARAMETER (MINWGT = 22.7)

      REAL SEEKER
C     degrees * .017453293 = radians
C     15 deg = .261798 radians
C     PARAMETER (SEEKER = .261798)
c     20 deg = .349064 radians
C     PARAMETER (SEEKER = .349064)
C     30 deg = .523596 radians
      PARAMETER (SEEKER = .523596)

      REAL XCOM,YZCOM
      REAL LNANG,ATAN

      INTRVL = 1/(ITMIN * 1.0)
      CURRX = (OTARX - X)
      CURRY = (OTARY - Y)
      CURRZ = (OTARZ - Z)

      CURRR = CMPDIS(CURRX,CURRY,CURRZ)

      THRUST = CMPTHT(SEC,MATTRT,BRNTME,MINTRT)
      DRAG = CMPDRG(VELCTY,PITCHR,YAWR)
      ACCELR = ACCEL(THRUST,DRAG,PITCH,MASS)
      PTCHRD = PTHACC(PTHSIG,PITCHR)
      YAWRD = YAWACC(YAWSIG,YAWR)
      PITCHD = CNGPTH(PITCHR,VELCTY,PITCH)
      YAWD = CNGYAW(YAWR,VELCTY,PITCH)
      XD = CNGX(VELCTY,PITCH,YAW)
      YD = CNGY(VELCTY,PITCH,YAW)
      ZD = CNGZ(VELCTY,PITCH)

      VELCTY = VELCTY + (ACCELR * 1/ITMIN)
      PITCHR = PITCHR + (PTCHRD * 1/ITMIN)
      YAWR = YAWR + (YAWRD * 1/ITMIN)
```

```
 PITCH = PITCH + (PITCHD * 1/ITMIN)
 YAW = YAW + (YAWD * 1/ITMIN)
 X = X + (XD * 1/ITMIN)
 Y = Y + (YD * 1/ITMIN)
 Z = Z - (ZD * 1/ITMIN)
 IF (SEC .LE. BRNTME) THEN
   MASS = MASS - (((MAXWGT-MINWGT)/BRNTME) * 1/ITMIN)
 END IF

 NEWX = (TARX - X)
 NEWY = (TARY - Y)
 NEWZ = (TARZ - Z)

 NEWR = CMPDIS(NEWX,NEWY,NEWZ)

 XCOM = CMPDIS(NEWX,0.0,0.0)
 YZCOM = CMPDIS(0.0,NEWY,NEWZ)

 LNANG = ATAN(YZCOM/XCOM)

 RESR = (CURRR - NEWR)*ITMIN
 RESX = (CURRX - NEWX)*ITMIN
 RESY = (CURRY - NEWY)*ITMIN
 RESZ = (CURRZ - NEWZ)*ITMIN

 CLSVEL = -RESR

 CALL LNOFST(NEWX,NEWY,NEWZ,RESX,RESY,RESZ,
+           LINEX,LINEY,LINEZ)

 PITCHO = CMPOP(YAW,LINEX,LINEY)
 YAWO = CMPOY(PITCH,YAW,LINEX,LINEY,LINEZ)

 PTHSIG = G * CMPSIG(NAVC,CLSVEL,PITCHO,PTHMAX,MASS,
+                    VELCTY,MINWGT,OPVEL)
 YAWSIG = G * CMPSIG(NAVC,CLSVEL,YAWO,YAWMAX,MASS,
+                    VELCTY,MINWGT,OPVEL)

 IF ((Z .GT. 0.0) .OR. (VELCTY .LE. 0.0)) THEN
    MISS = 1
    RETURN
 END IF

 IMPTME = -((NEWX*RESX)+(NEWY*RESY)+(NEWZ*RESZ))
 IMPTME = IMPTME/((RESX**2)+(RESY**2)+(RESZ**2))
 RANGE = (RESX*IMPTME + NEWX)**2
 RANGE = RANGE + (RESY*IMPTME + NEWY)**2
 RANGE = RANGE + (RESZ*IMPTME + NEWZ)**2
 RANGE = SQRT(RANGE)
 IF (RANGE .LT. DETRNG) THEN
   IF (ABS(IMPTME) .LE. INTRVL) THEN
      HIT = 1
      RETURN
   END IF
 END IF

 IF (ABS(LNANG) .GT. SEEKER) THEN
```

```
         IF (NEWR .LT. DETRNG) THEN
            HIT = 1
         ELSE
            MISS = 1
         END IF
         RETURN
      END IF

      IF ((CLSVEL .GT. 0) .AND. (SEC .GT.  BRNTME)) THEN
         IF (NEWR .LT. DETRNG) THEN
            HIT = 1
         ELSE
            MISS = 1
         END IF
         RETURN
      END IF

      RETURN
      END
C*************************************************************


C*************************************************************
C SUBROUTINES BEGIN HERE
C*************************************************************
C*************************************************************
      REAL FUNCTION CMPDRG(VELCTY,PITCHR,YAWR)
C*************************************************************
C*  Name           - Function CMPDRG
C*  Purpose        - Computes drag value for the missile simulation
C* Variables       -
C*    NAME         TYPE         UNITS
C*-----------------------------------------------------------
C*    VELCTY       REAL         meters/second
C*    PITCHR       REAL         radians/second
C*    YAWR         REAL         radians/second
C*************************************************************
      IMPLICIT NONE
      REAL VELCTY,PITCHR,YAWR
C
      REAL K1,K2
      PARAMETER (K1 = 0.009412)
      PARAMETER (K2 = 93850/(9.8**2))
C

      CMPDRG = K1 * VELCTY**2 + (K2 * (PITCHR**2 + YAWR**2))/VELCTY**2
      RETURN
      END
C*************************************************************

C*************************************************************
      REAL FUNCTION CMPSIG(NAVC,CLSVEL,LINEO,MAXTRN,MASS,
     +                     VELCTY,MNMASS,OPVEL)
C*************************************************************
C*    Name         - Function CMPSIG
C*    Purpose      - Computes steering signals for missile
C*    Variables    -
```

```
C*    NAME        TYPE        UNITS
C*-------------------------------------------------------------
C*    NAVC  I     NTEGER      Navigational constant.  Usually 4
C*    CLSVEL      REAL        Meters/second
C*    LINEO       REAL        radians (line of sight)
C*    MAXTRN      REAL        G's (max number of G's capable of pulling)
C*    VELCTY      REAL        meters/second
C       MASS      REAL        kilograms
C*************************************************************
      IMPLICIT NONE

      REAL NAVC,CLSVEL,LINEO,MAXTRN,MASS,VELCTY

      REAL SIGNAL,MAXSIG,MNMASS,VLCTY2,OPVEL,OPVEL2
      REAL VELSIG

      SIGNAL = NAVC * CLSVEL * LINEO

      VLCTY2 = VELCTY * VELCTY
      OPVEL2 = OPVEL * OPVEL

      VELSIG = (VLCTY2/OPVEL2)

      IF (VELSIG .GT. 1.0) THEN
         VELSIG = 1.0
      END IF

      MAXSIG = (MNMASS/MASS) * VELSIG * MAXTRN

      IF (ABS(SIGNAL) .GT. MAXSIG) THEN
         SIGNAL = MAXSIG * ABS(SIGNAL)/SIGNAL
      END IF

      IF (ABS(SIGNAL) .GT. MAXTRN) THEN
         SIGNAL = MAXTRN * ABS(SIGNAL)/SIGNAL
      END IF

      CMPSIG = SIGNAL

      RETURN
      END
C*************************************************************

C*************************************************************
      REAL FUNCTION CMPOP(YAW,LINEX,LINEY)
C*************************************************************
C*    Name        - Function CMPOP
C*    Purpose     - Computes an element used in computing
C*                  pitch signals from the seeker.
C*    Variables   -
C*    NAME        TYPE        UNITS
C*-------------------------------------------------------------
C*    YAW         REAL        radians
C*    LINEX       REAL        meters
C*    LINEY       REAL        meters
C*************************************************************
      IMPLICIT NONE
```

```
      REAL YAW,LINEX,LINEY

      CMPOP = (-1) * SIN(YAW) * LINEX + COS(YAW) * LINEY

      RETURN
      END
C*****************************************************************

C*****************************************************************
      REAL FUNCTION CMPOY(PITCH,YAW,LINEX,LINEY,LINEZ)
C*****************************************************************
C*    Name         - Function CMPOY
C*    Purpose      - Computes an element used in computing
C*                   yaw signals from the seeker.
C*    Variables    -
C*    NAME         TYPE         UNITS
C*-----------------------------------------------------------
C*    PITCH        REAL         radians
C*    YAW          REAL         radians
C*    LINEX        REAL         meters
C*    LINEY        REAL         meters
C*    LINEZ        REAL         meters
C*****************************************************************
      IMPLICIT NONE
      REAL PITCH,YAW
      REAL LINEX,LINEY,LINEZ

      CMPOY = SIN(PITCH) * (COS(YAW)*LINEX + SIN(YAW)*LINEY)
      CMPOY = CMPOY + COS(PITCH)*LINEZ

      RETURN
      END
C*****************************************************************

C*****************************************************************
      SUBROUTINE LNOFST(RX,RY,RZ,RESX,RESY,RESZ,
     +                  LINEX,LINEY,LINEZ)
C*****************************************************************
C*  Name           - Subroutine LNOFST
C*  Purpose        - Computes line of sight angles
C*  Variables      -
C*    NAME         TYPE         UNITS
C*-----------------------------------------------------------
C*    RX           REAL         meters
C*    RY           REAL         meters
C*    RZ           REAL         meters
C*    RESX         REAL         meters/second
C*    RESY         REAL         meters/second
C*    RESZ         REAL         meters/second
C*    LINEX        REAL         meters
C*    LINEY        REAL         meters
C*    LINEZ        REAL         meters
C*****************************************************************
      IMPLICIT NONE
      REAL RX,RY,RZ
      REAL RESX,RESY,RESZ
      REAL LINEX,LINEY,LINEZ
```

```
      REAL CMPDIS

      REAL R,R2

      R = CMPDIS(RX,RY,RZ)
      R2 = R * R

      LINEX = (RY * RESZ - RZ * RESY) / (R2)
      LINEY = (RZ * RESX - RX * RESZ) / (R2)
      LINEZ = (RX * RESY - RY * RESX) / (R2)

      RETURN
      END
C*****************************************************************

C*****************************************************************
      REAL FUNCTION CMPDIS(X,Y,Z)
C*****************************************************************
C*  Name          - Function CMPDIS
C*  Purpose       - Computes distance
C*  Variables           -
C*    NAME        TYPE        UNITS
C*-----------------------------------------------------------
C*    X           REAL        earth-based x
C*    Y           REAL        earth-based y
C*    Z           REAL        earth-based z
C*****************************************************************
      IMPLICIT NONE
      REAL X,Y,Z

      CMPDIS = SQRT(X*X + Y*Y + Z*Z)

      RETURN
      END
C*****************************************************************

C*****************************************************************
      SUBROUTINE GETTAR(TARX,TARY,TARZ,ITMIN)
C*****************************************************************
C*  Name          - Subroutine GETTAR
C*  Purpose       - Provides a moving target.
C*  Variables     -
C*    NAME        TYPE        UNITS
C*-------------------------------------------------------------
C*    TARX        REAL        earth-based X
C*    TARY        REAL        earth-based Y
C*    TARZ        REAL        earth-based Z
C*    ITMIN       INTEGER     (# of iterations per second)
C*****************************************************************
      IMPLICIT NONE
      REAL TARX,TARY,TARZ
      INTEGER ITMIN

      REAL MACH
      PARAMETER (MACH = 234.375)

      TARX = TARX + (MACH/ITMIN)
```

```
      TARY = TARY
      TARZ = TARZ

      RETURN
      END
C*****************************************************************

C*****************************************************************
      REAL FUNCTION CMPTHT(T,MAXTRT,MXTME,MINTRT)
C*****************************************************************
C*  Name           - Function CMPTHT
C*  Purpose        - Computes thrust for missile simulation
C*  Variables      -
C*    NAME         TYPE         UNITS
C*-----------------------------------------------------------------
C*    T            INTEGER      seconds (# of seconds missile has flown)
C*****************************************************************
      IMPLICIT NONE
      INTEGER T

      REAL MAXTRT,MXTME,MINTRT

      IF (T .LE. MXTME) THEN
         CMPTHT = MAXTRT
      ELSE
         CMPTHT = MINTRT
      END IF

      RETURN
      END

C*****************************************************************

C*****************************************************************
      REAL FUNCTION ACCEL(THRUST,DRAG,PITCH,MASS)
C*****************************************************************
C*  Name           -  Function Accel
C*  Purpose        -  Computes acceleration
C*  Variables      -
C*    NAME         TYPE         UNITS
C*-------------------------------------------------
C*    THRUST       REAL         newtons
C*    DRAG         REAL         newtons
C*    PITCH        REAL         radians
C*    MASS         REAL         kilograms
C*****************************************************************
      IMPLICIT NONE

      REAL THRUST,DRAG,PITCH
      REAL G,MASS

C ACCELERATION DUE TO GRAVITY IS 9.8 meters PER SECOND
      PARAMETER (G = 9.8)

      ACCEL = (THRUST-DRAG)/MASS - (G*(SIN(PITCH)))
      RETURN
      END
```

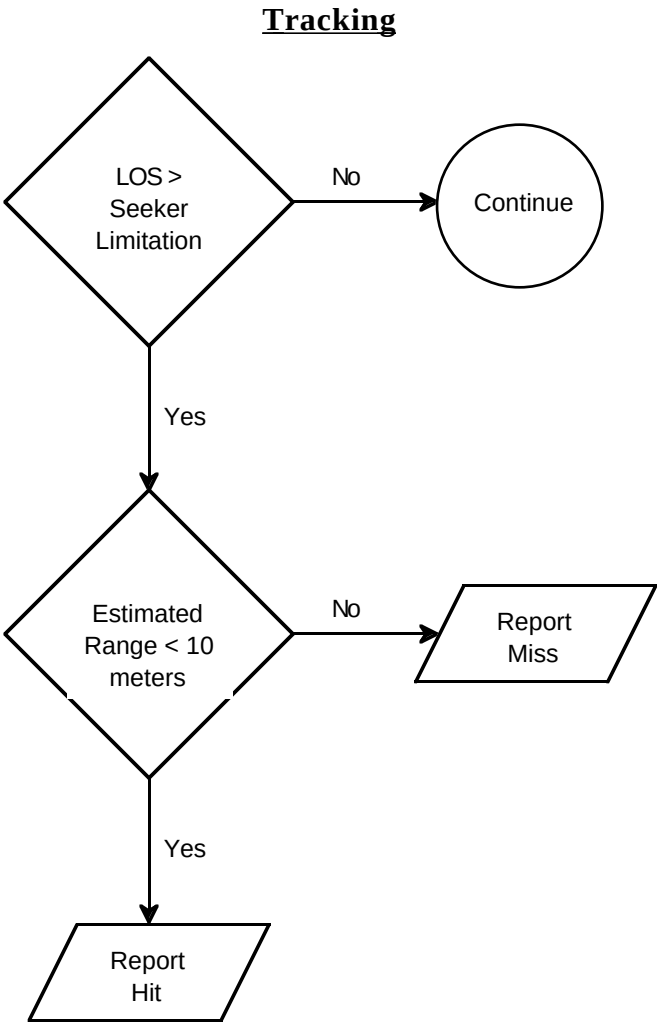
```
C*****************************************************************

C*****************************************************************
      REAL FUNCTION PTHACC(SIGNAL,PITCHR)
C*****************************************************************
C*  Name           -  Function PTHACC
C*  Purpose        - Computes pitch acceleration
C*  Variables      -
C*    NAME         TYPE         UNITS
C*-------------------------------------------------------
C*    SIGNAL       REAL         radians/sec**2
C*    PITCHR       REAL         radians/sec
C*****************************************************************
      IMPLICIT NONE

      REAL SIGNAL,PITCHR
      REAL MSSCST

C MISSLE TIME CONSTANT IS 0.25 SECONDS
      PARAMETER (MSSCST = 0.25)

      PTHACC = (SIGNAL - PITCHR)/MSSCST

      RETURN
      END
C*****************************************************************

C*****************************************************************
      REAL FUNCTION YAWACC(SIGNAL,YAWR)
C*****************************************************************
C*  Name           - Function YAWACC
C*  Purpose        - Computes Yaw acceleration
C*  Variables      -
C*    NAME         TYPE         UNITS
C*-------------------------------------------------------
C*    SIGNAL       REAL         radians/sec**2
C*    YAWR         REAL         radians/sec
C*****************************************************************
      IMPLICIT NONE

      REAL SIGNAL,YAWR
      REAL MSSCST

C MISSLE TIME CONSTANT IS 0.25 SECONDS
      PARAMETER (MSSCST = 0.25)

      YAWACC = (SIGNAL - YAWR)/MSSCST

      RETURN
      END
C*****************************************************************

C*****************************************************************
      REAL FUNCTION CNGPTH(PITCHR,VELCTY,PITCH)
C*****************************************************************
C*  Name           - Function CNGPTH
C*  Purpose        - Computes changes in the pitch angle
```

```
C*  Variables     -
C*    NAME        TYPE        UNITS
C*-------------------------------------------------
C*    PITCHR      REAL        radians/second
C*    VELCTY      REAL        meters/second
C*    PITCH       REAL        radians
C*****************************************************************
      IMPLICIT NONE

      REAL PITCHR,VELCTY,PITCH

      CNGPTH  = ((PITCHR - COS(PITCH))/VELCTY)

      RETURN
      END
C*****************************************************************

C*****************************************************************
      REAL FUNCTION CNGYAW(YAWR,VELCTY,PITCH)
C*****************************************************************
C*  Name    - Function CNGYAW
C*  Purpose     - Computes yaw changes
C*  Variables     -
C*    NAME        TYPE        UNITS
C*-------------------------------------------------
C*    YAWR        REAL        radians/second
C*    VELCTY      REAL        meters/second
C*    PITCH       REAL        radians
C*****************************************************************
      IMPLICIT NONE

      REAL YAWR,VELCTY,PITCH

      CNGYAW = ( YAWR / (VELCTY*(COS(PITCH))))

      RETURN
      END
C*****************************************************************

C*****************************************************************
      REAL FUNCTION CNGX(VELCTY,PITCH,YAW)
C*****************************************************************
C*  Name          - Function CNGX
C*  Purpose       - Computes changes in x direction
C*  Variables     -
C*    NAME        TYPE        UNITS
C*-------------------------------------------------
C*    VELCTY      REAL        meters/second
C*    PITCH       REAL        radians
C*    YAW         REAL        radians
C*****************************************************************
      IMPLICIT NONE

      REAL VELCTY,PITCH,YAW

      CNGX = VELCTY * COS(PITCH) * COS(YAW)
```

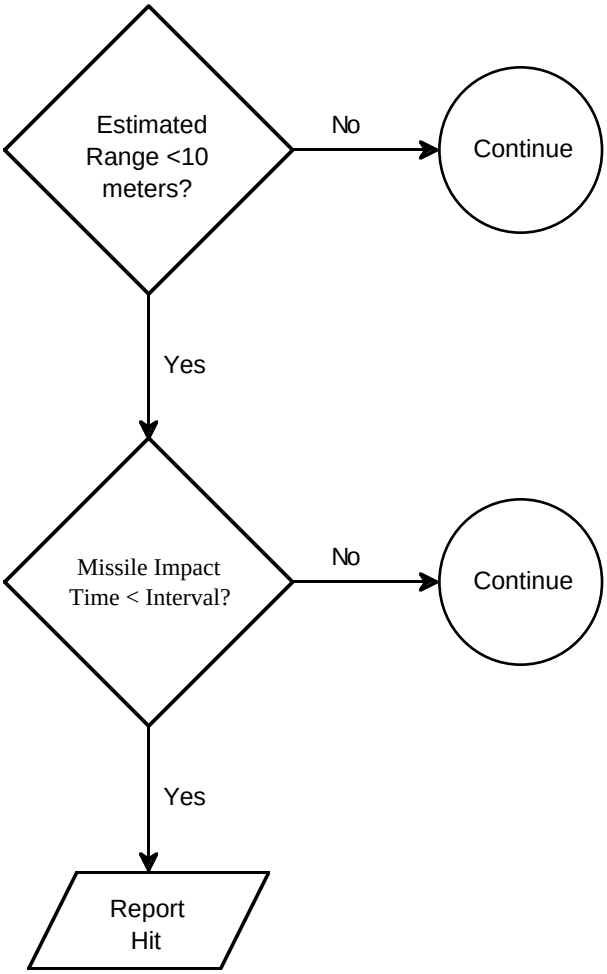
```
      RETURN
      END
C*****************************************************************

C*****************************************************************
      REAL FUNCTION CNGY(VELCTY,PITCH,YAW)
C*****************************************************************
C*  Name           - Function CNGY
C*  Purpose        - Computes changes in Ydirection
C*  Variables      -
C*    NAME         TYPE         UNITS
C*-----------------------------------------------------
C*    VELCTY       REAL         meters/second
C*    PITCH        REAL         radians
C*    YAW          REAL         radians
C*****************************************************************
      IMPLICIT NONE

      REAL VELCTY,PITCH,YAW

      CNGY = VELCTY * COS(PITCH) * SIN(YAW)

      RETURN
      END
C*****************************************************************


C*****************************************************************
      REAL FUNCTION CNGZ(VELCTY,PITCH)
C*****************************************************************
C*  Name    - Function CNGZ
C*  Purpose        - Computes changes in z direction
C*  Variables      -
C*    NAME         TYPE         UNITS
C*-----------------------------------------------------
C*    VELCTY       REAL         meters/second
C*    PITCH        REAL         radians
C*****************************************************************
      IMPLICIT NONE

      REAL VELCTY,PITCH

      CNGZ = VELCTY * SIN(PITCH)

      RETURN
      END
C*****************************************************************
```

Appendix D

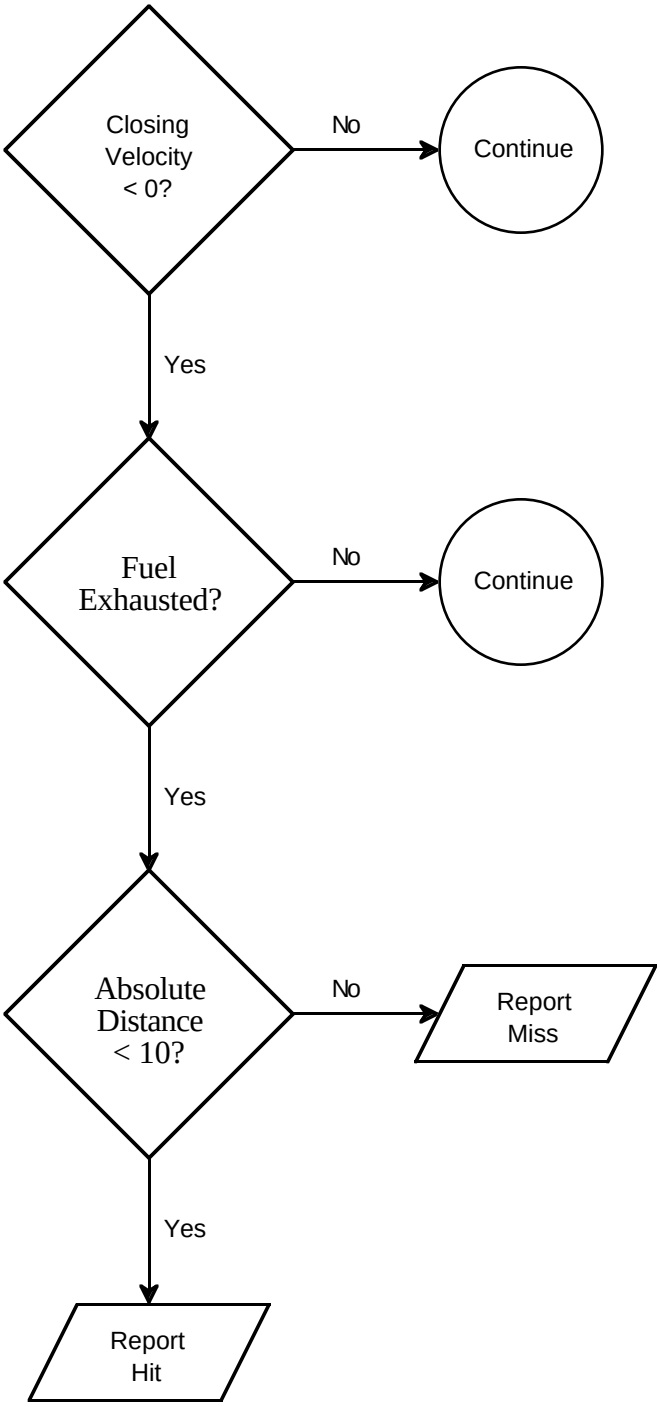
Missile Detonation Logic

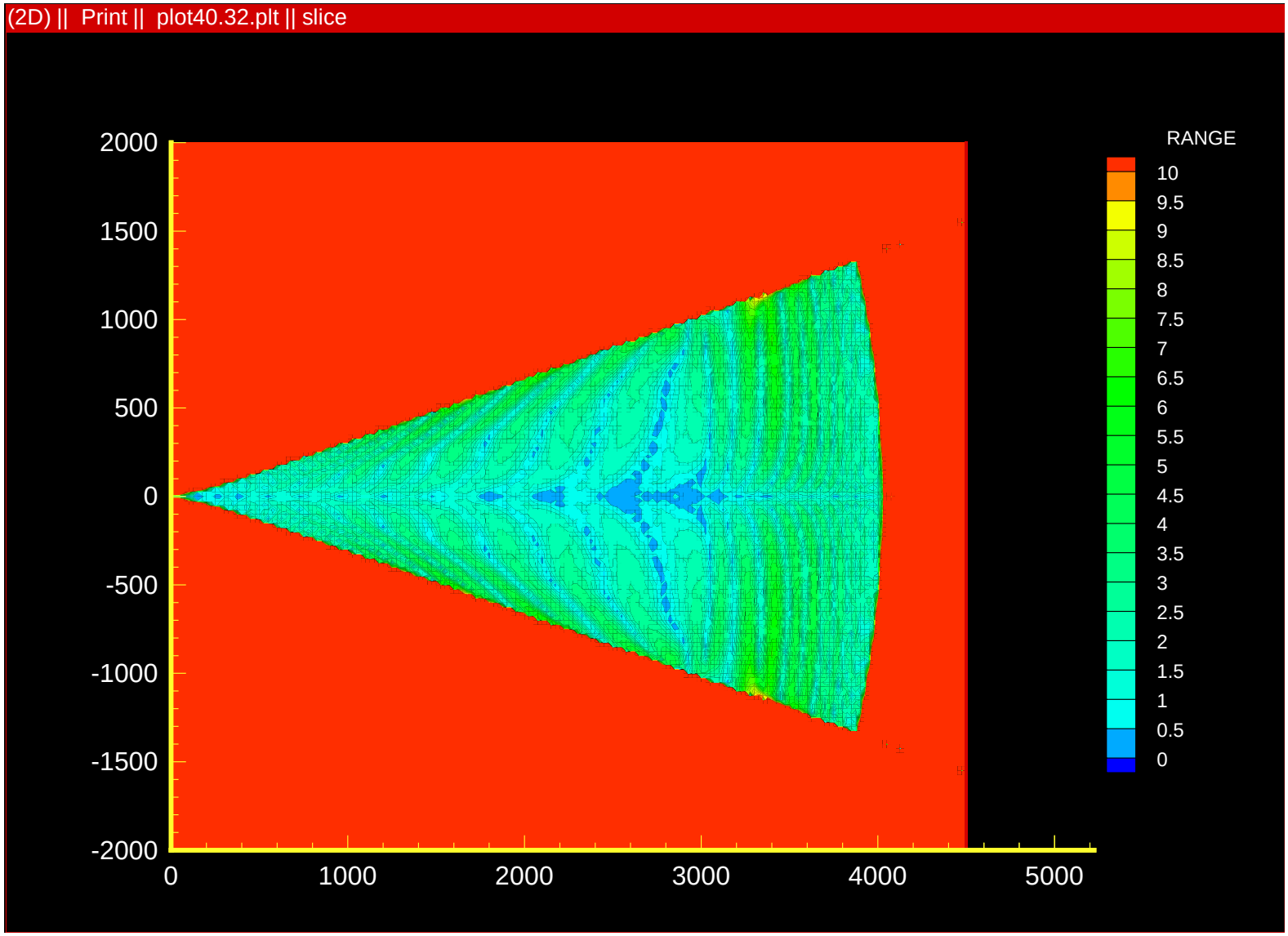


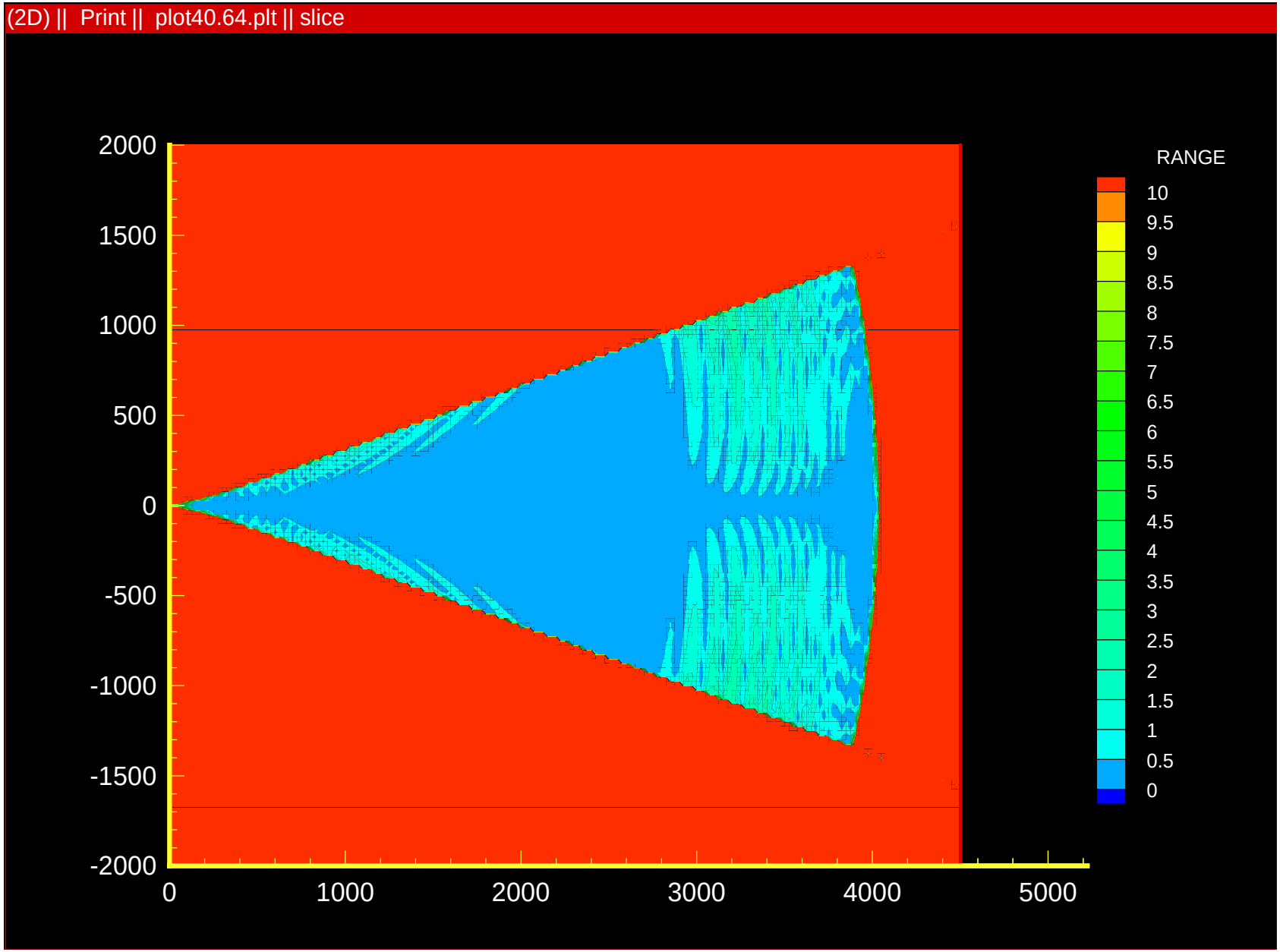
Impact

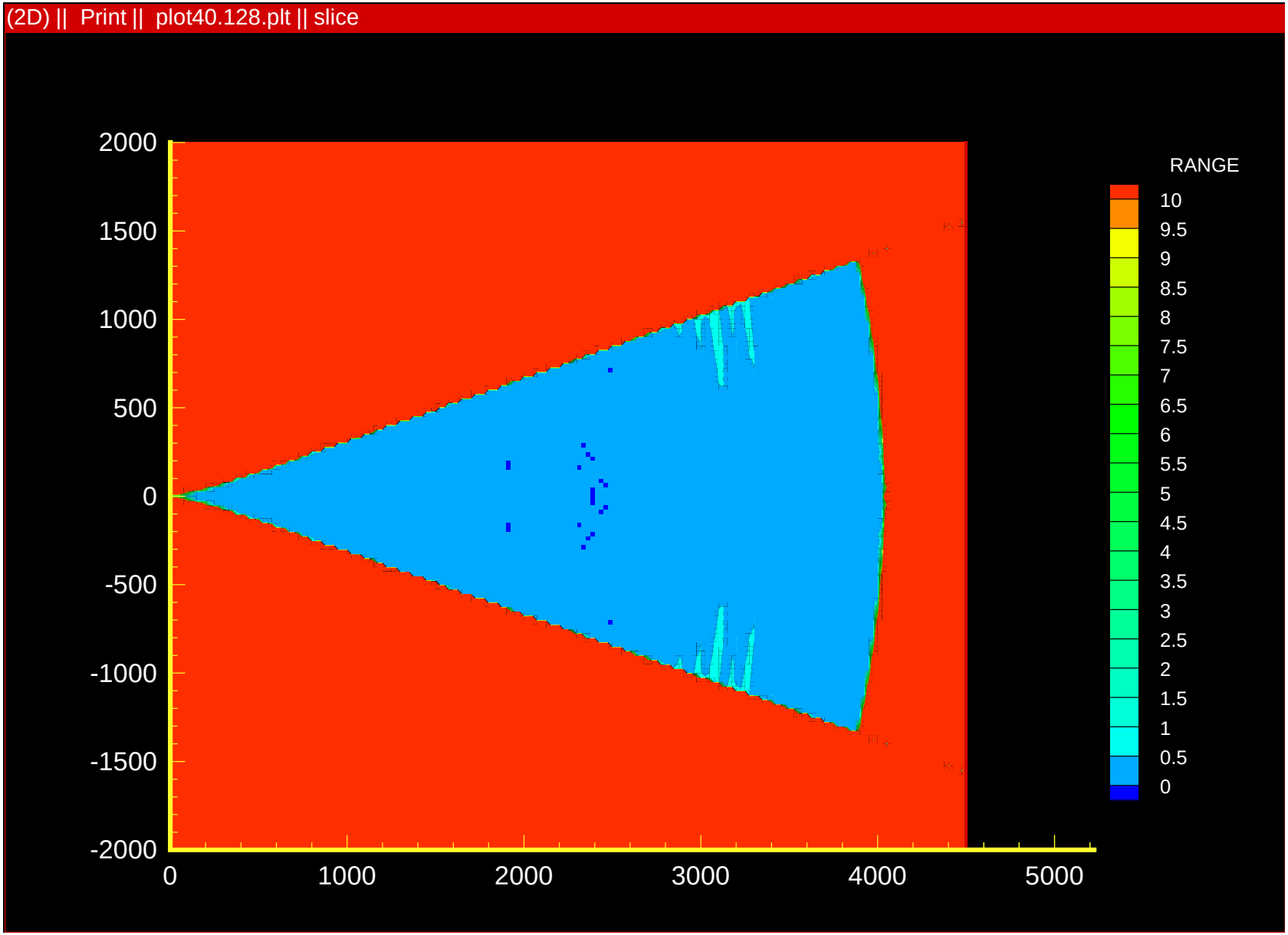

Estimated Range <10 meters?
No
Continue
Yes
Missile Impact Time < Interval?
No
Continue
Yes
Report Hit

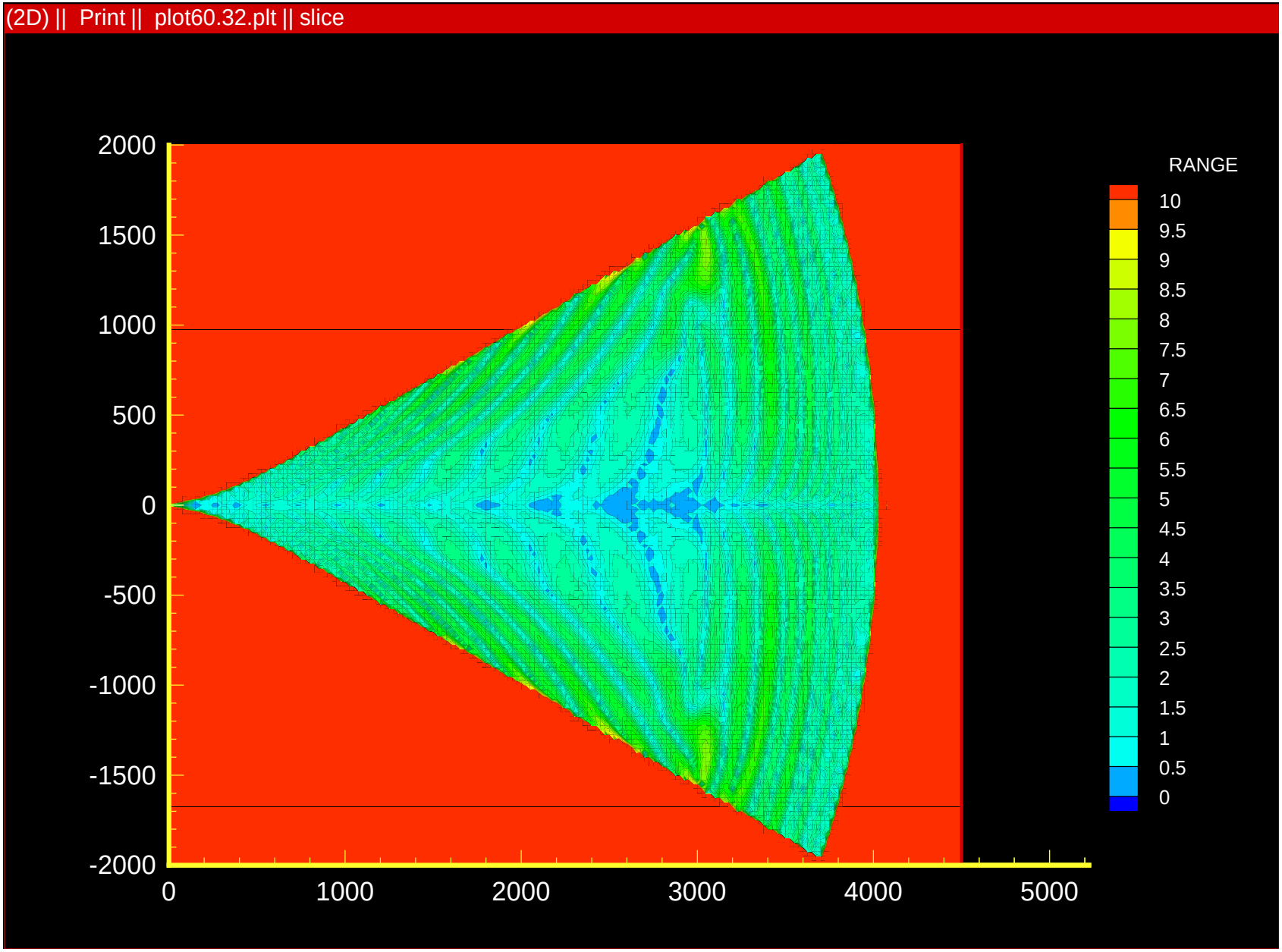
Fuel Exhausted

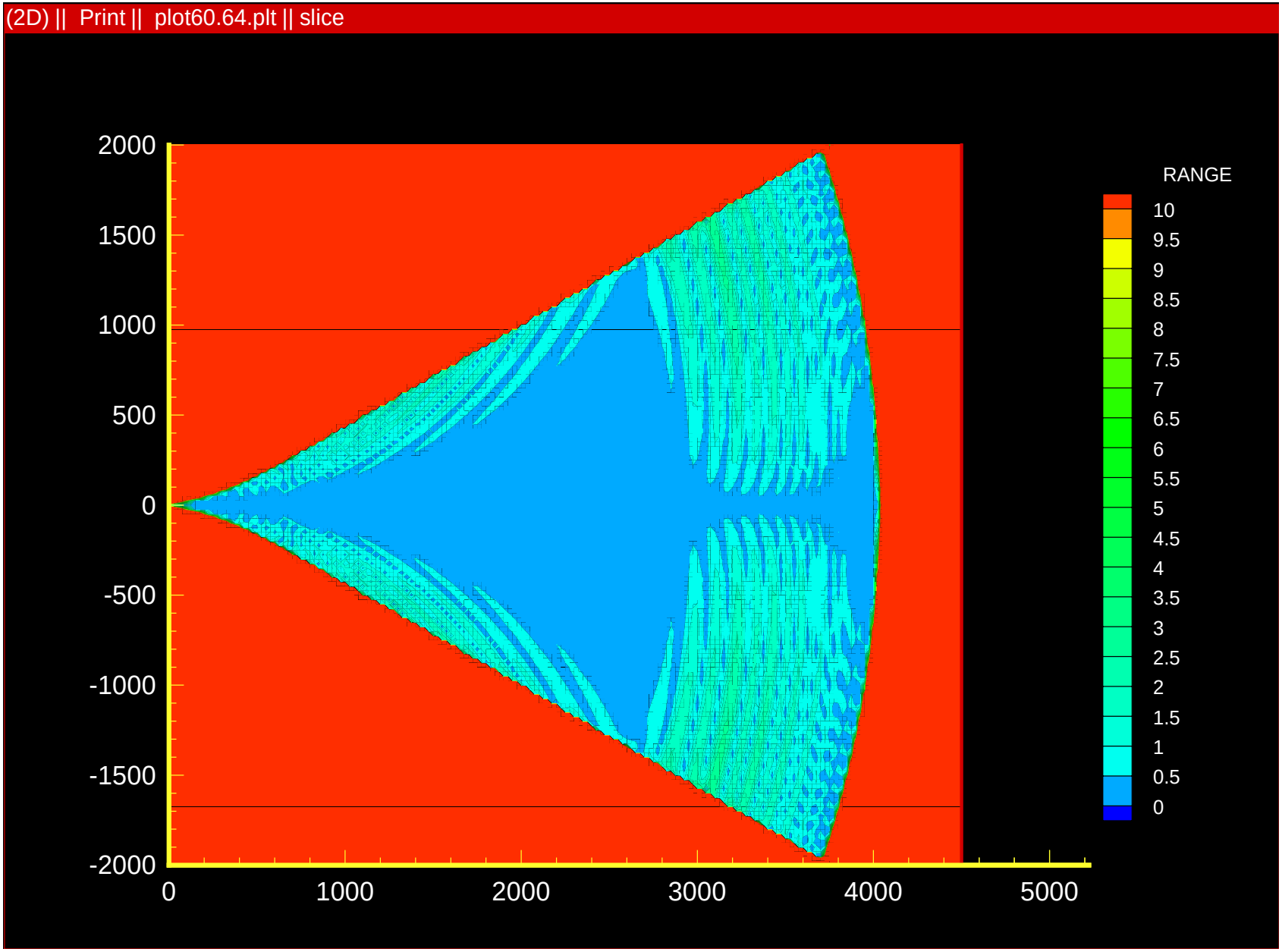


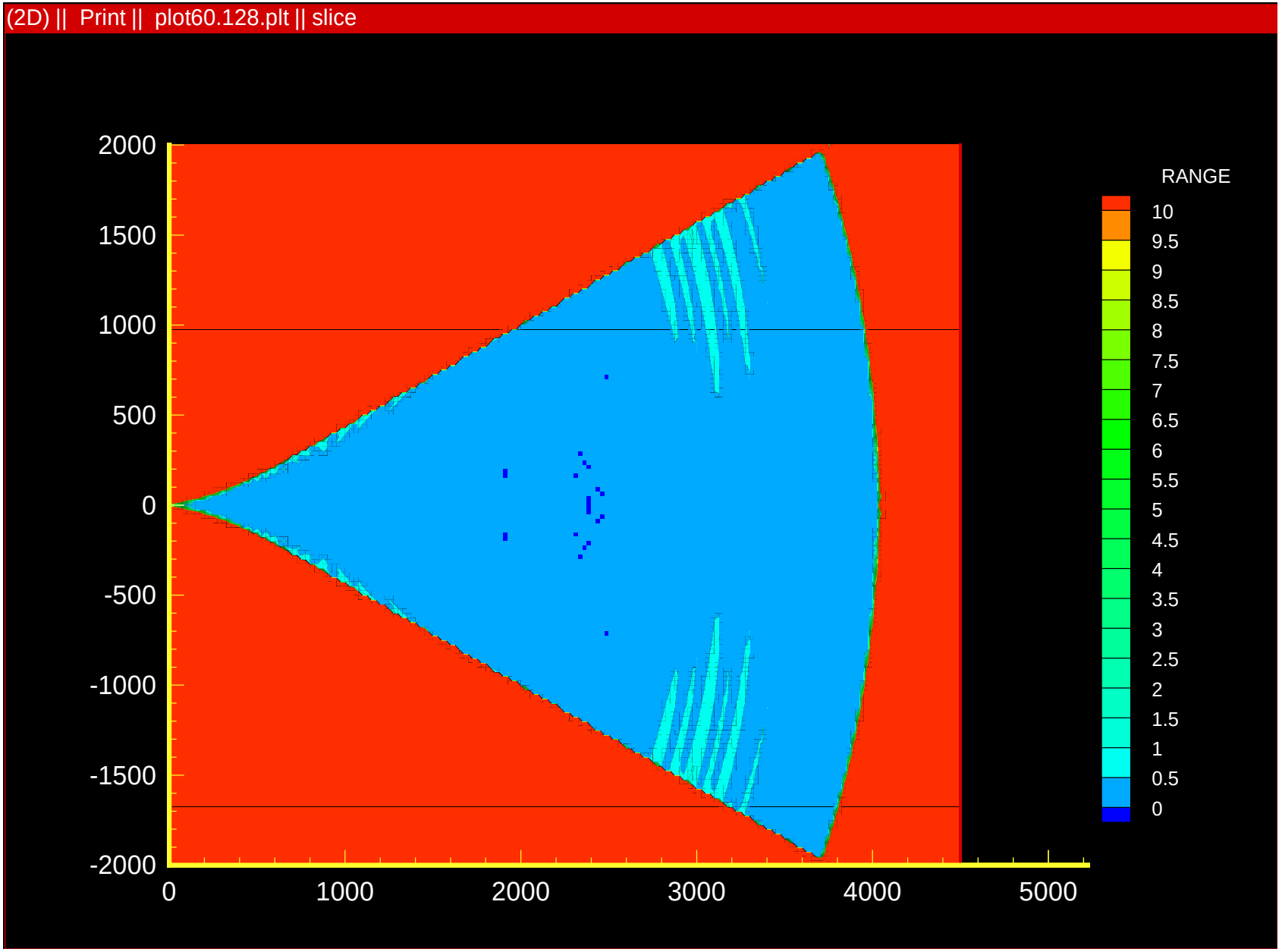

(2D) || Print || plot40.32.plt || slice
RANGE
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1000
2000
3000
4000
5000


(2D) || Print || plot40.64.plt || slice
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1000
2000
3000
4000
5000
RANGE
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0


(2D) || Print || plot40.128.plt || slice
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1000
2000
3000
4000
5000
RANGE
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0


(2D) || Print || plot60.32.plt || slice
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1000
2000
3000
4000
5000
RANGE
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0


(2D) || Print || plot60.64.plt || slice
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1000
2000
3000
4000
5000
RANGE
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0


(2D) || Print || plot60.128.plt || slice
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
1000
2000
3000
4000
5000
RANGE
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0