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Cooperative Behavior Schemes for Improving the Effectiveness of Autonomous Wide Area Search Munitions

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COOPERATIVE BEHAVIOR SCHEMES FOR IMPROVING THE EFFECTIVENESS OF AUTONOMOUS WIDE AREA SEARCH MUNITIONS

THESIS

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Abstract

The problem being addressed is how to best find and engage an unknown number of targets in unknown locations (some moving) using multiple autonomous wide area search munitions. In this research cooperative behavior is being investigated to improve the overall mission effectiveness. A computer simulation was used to emulate the behavior of autonomous wide area search munitions and measure their overall expected performance. This code was modified to incorporate the capability for cooperative engagement based on a parameterized decision rule. Using Design of Experiments (DOE) and Response Surface Methodologies (RSM), the simulation was run to achieve optimal decision rule parameters for given scenarios and to determine the sensitivities of those parameters to the precision of the Autonomous Target Recognition (ATR) algorithm, guidance precision and lethality of the warhead, and the characteristics of the battlefield.

Results show that the form of cooperative engagement used in this study is most useful in overcoming the limitations on warhead lethality and, to a lesser degree, probability of target report (P_{TR}). However, cooperative engagement alone is not able to compensate for higher false target attack rates. Also, the selection of the optimal weights in the decision algorithm are very sensitive to all battlefield characteristics.

COOPERATIVE BEHAVIOR SCHEMES FOR IMPROVING THE EFFECTIVENESS OF AUTONOMOUS WIDE AREA SEARCH MUNITIONS

I. Introduction

1.1 General

The problem being addressed is how to best find and engage an unknown number of targets in unknown locations (some moving) using multiple cooperating autonomous wide area search munitions. The problem is exacerbated by the fact that not all target priorities are the same, the munition target discrimination capability is never perfect, and target destruction is never a certainty even once engaged. Further, factors such as clutter density throughout the battlefield and ratio of targets to civilian or military non-targets create even more complications for these smart, yet simple-minded, munitions.

This research does not provide a precise solution to this rather ambiguous and complex problem; rather, this research provides a possible methodology for how to attack this problem using different optimization methodologies and shows some sample results.

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1.2 Background

The United States Air Force has significantly reduced the size of its military forces as a response to changing national military objectives and diminishing budgets. This reality has forced the Air Force to look for more cost effective ways of achieving its extremely crucial mission. One advancement has been the development of small, lightweight, low-cost, autonomous munitions fully equipped with INS/GPS navigation and seekers capable of

Autonomous Target Recognition (ATR). The intent in using these autonomous munitions is to employ larger numbers of cheaper, less sophisticated munitions as opposed to fewer numbers of expensive, complex munitions. However, in order to realize the full capabilities of a system composed of large numbers of smaller subsystems (or agents), the individual agents must behave cooperatively. Methods of evaluating mission effectiveness of these munitions have previously been developed for the case of non-cooperating munitions. In this research cooperative behavior is being investigated to improve the overall mission effectiveness.

Both the Air Force and Army are very interested in evaluating the expected effectiveness of the inclusion of cooperative behavior in these systems. The Air Force's primary wide area search munition in laboratory development is the Low Cost Autonomous Attack System (LOCAAS). The Army, in collaboration with the Defense Advance Research Projects Agency (DARPA), is investigating similar technologies with their Net Fires program. Systems such as this are specifically designed to autonomously detect, identify and destroy a number of different types of mobile and relocatable targets. The primary targets to be destroyed are Surface-to-Air Missile (SAM) sites, tactical Surface-to-Surface Missile (SSM) launchers, and interdiction targets such as tanks and artillery. The main difference between the Air Force and Army systems is that they are deployed from aircraft and ground launchers, respectively. Conceptually, both systems would deploy multiple munitions or submunitions which would execute complementary search patterns once they reached the target area. Current technology is limited to autonomous search and engagement on the part of the submunitions, but it has long been suspected that overall system effectiveness could be improved through cooperative behavior.

In a study performed by RAND [7], a rationale was developed for investigating cooperative behavior between Proliferated Autonomous Weapons (PRAWNs). They showed by implementing a cooperative weapon behavior logic into a computer simulation that there was a definite added potential when cooperation was incorporated into the logic of PRAWNs. This study supported the hypothesis that while the individual weapons may be less capable than conventional weapons under development today, through communications across the swarm of weapons, the group exhibits behaviors and capabilities that can exceed those of more conventional systems that do not employ communications between weapons. The benefits which come about through shared knowledge include possible relaxed sensor performance requirements, robustness to increases in Target Location Errors (TLE), and adaptivity to attrition and poor target characterization.

In this study, however, a fixed decision rule (called "swarming algorithm") was used. This algorithm was based on the foundations of two areas of study: ethology (the science of animal behavior) and robotics. The collective intelligence that seems to emerge from what are often large groups of relatively simple agents is what the engineers of the RAND study tried to capture in their swarming algorithm. While this algorithm worked for what they were doing, the research did not show how this decision algorithm compared to other possible decision algorithms. Also, the RAND study concentrated on a very specific battlefield layout that was composed of large clusters of targets and no possibility of encounters with non-targets or clutter. By not taking into account non-targets or clutter, the munitions had no false target attacks. According to Jacques [9], methods and models for evaluating the effectiveness of wide area search munitions must take into account the degradation due to false target attacks.

1.2.1 Ethology. Scientists studying animal behavior have identified and analytically modeled many behaviors of natural organisms that have parallels to the tasks that weapons must achieve in order to search for, acquire, and attack targets. These tasks include cooperative search, cooperative engagement, protection of each individual agent, and optimal path planning. Particularly, those animals which exhibit improvement in task performance when they interact as a group are of the highest interest. These include (but are certainly not limited to) bird flocks, animal herds, schools of fish, bee swarms, and ant colonies. When looked at as aggregate motions, these behaviors are usually referred to as swarm behaviors.

Reynolds considered the formation of flocks, herds, and schools in simulations in which multiple autonomous agents were repulsed by one another and attracted to one another (and other foreign objects) by inverse square law forces [16]. He believed each agent (bird, animal, or fish) was responding only to its limited-range local perception of the world and that natural flocks seemed to consist of two balanced, yet opposing, forces: a desire to stay close to the flock and a desire to avoid collisions within the flock.

Foraging is the mechanism by which ants gather food. Over the years, ants have adopted a foraging process which is optimal through the use of simple communications (in the form of chemical hormone deposits). The behavior of the ants in this process is characteristic of swarm behavior in that simple agents are able to work together and achieve greater accomplishments as a group than as a number of individuals. According to the Ant Colony Optimization Home Page [6], the ants lay down pheromone trails (chemical hormones) when food is discovered and carried back to the nest. The amount of pheromone dispensed decreases as the nest is approached so that a natural gradient of pheromone density indicates the direction of the food source. The more ants involved in the harvesting of the food, the more chemical is deposited. The simple behavior of the ants is to move toward increasing pheromone. Over a short period of time, the path from the nest to the source of food becomes optimal by these two simple processes (depositing pheromones and moving in the direction of higher pheromones).

These processes are simple examples of how groups of animals working together are able to achieve more than animals working alone. Some of these basic principals have been applied to multiple agents in the field of robotics to achieve some of the same group dynamics exhibited by natural organisms.

1.2.2 Robotics. Scientists in the field of robotics have developed architectures for the controlling of individual robots or agents, which allow groups of individuals to experience the benefits of group or swarm behaviors. There are basically two ways in robotics to communicate information between agents. One is to have each communicate locally to its neighbors, and, therefore, the receipt of information is limited to within a certain communication range. The other is to have a centralized station that collects all information from individual agents and transmits to all individual agents. This latter method is less enticing to the munition application because of the increased reliability of the "dumb" munitions on the one "smart" station, making that station a higher priority target for the enemy. The value of the first method is that its effectiveness does not rely on a single point of contact.

Arkin studied an approach to cooperation among multiple mobile robots without communications [1]. In this study a multi-agent simulation was used to emulate the behavior of ant foraging by having robots retrieve objects in a hostile environment. The robots had simple behavioral rules that they were required to follow, and they emitted signals with different gains in a manner very similar to the depositing of pheromones by ants. Arkin's research showed that swarm behavior characteristics could be achieved without any explicit communication between the agents. He also showed that centralized master/slave or hierarchy-based approaches have many disadvantages including communication bottlenecks, less robustness, and increased complexity when compared to completely decentralized approaches where each agent follows the same laws and behaviors autonomously. Kube and Zhang also researched the use of decentralized robots performing various tasks without explicit communication [10]. Much of their research was comparing the applications of different social insect behaviors to robots accomplishing tasks. In another contributing work to the field, Asama sums up the challenge in choosing the right behaviors for your agents by saying that "an autonomous and decentralized system has two essentially contradictory characteristics, autonomy and cooperativeness, and the biggest problem in the study of distibuted autonomous robotic systems is how to reconcile these two features" [2].

Kwok considered the problem of causing multiple (100's) of autonomous mobile robots to converge to a target using an on-board, limited range sensor for sensing the target and a larger but also limited-range robot-to-robot communication capability [11]. One of his goals was to keep the logic as simple as possible aboard each robot, so he implemented a "follow-the-leader" approach where each robot followed the robot with the best quality of information concerning the location of the target.

While much of the research in the field of cooperative control of robotics has been able to apply some of the basic principals learned from ethology, the application to cooperative engagement with autonomous weapons is rather limited. Since each of the munitions has a specific Field of View (FOV) on the order of a half mile in width, the munitions are normally programmed to fly a half mile from each other in order to limit the FOV overlap. Scenarios exist where large FOV overlap is desired in the interest of redundant coverage and higher probabilities of success, but the study of these scenarios is more applicable to the cooperative search problem than the cooperative engagement problem. Therefore, the protection and drag efficiencies gained by flocking, schooling or herding are not applicable to this study. However, the concept of ant foraging does have application to the problem at hand. Moreover, what if the ants had the ability to *choose* to follow the pheromone deposits to the known source of food or to *choose* to seek out a different area for a possible larger, better, or closer food source? By what criteria could this decision be made? Is the decision criteria the same for all situations? Taking this analogy one step further (and maybe a little beyond reality), what happens when an ant falsely identifies a poisonous food source as a good food source and causes the colony to subsist off of this unknown danger? These questions have not been answered in the applied research of robotics but are extremely important questions for the application of cooperative control of autonomous wide area search munitions.

1.3 Objectives

The primary objective of this study was to investigate the use of cooperative behavior to improve the overall mission effectiveness of autonomous wide area search munitions. The specific objectives were to:

1. Establish a methodology for measuring the expected effectiveness of a cooperative system of wide area search munitions
2. Develop optimal cooperative engagement decision rules for a variety of realistic scenarios
3. Analyze the sensitivities of the decision rule parameters to the precision of the submunition's ATR algorithm, the lethality of the warhead, and the characteristics of the battlefield (clutter density, target layout, etc.)

1.4 Approach

A computer simulation was used to emulate the behavior of autonomous wide area search munitions and measure their overall expected performance. This code was modified to incorporate the capability for cooperative engagement based on a parameterized decision rule. Using a number of Design of Experiments (DOE) and Response Surface Methodologies (RSM), the simulation was run to achieve optimal decision rule parameters for given scenarios and to determine the sensitivities of those parameters to the precision of the ATR algorithm, lethality of the warhead, and the characteristics of the battlefield.

1.5 Scope

This research is not limited to any particular type of wide area search munition and was consciously completed using parameters that describe a very generic wide area search munition. This research, therefore, applies to all wide area search munitions and more specific results can be achieved for any specific system by simply modifying the parameters in the effectiveness simulation. Further, the methods developed as part of this research have applications in the more general area of cooperative behavior and control.

II. Wide Area Search Munitions

2.1 General Characteristics and Operations

According to Jacques [9], autonomous wide area search munitions show great promise in being able to locate and engage widely dispersed and/or highly mobile or relocatable ground targets. They have the effect of decentralizing the search process from the strike aircraft or surveillance sensors to greater numbers of small, smart munitions with high resolution seekers operating at relatively short ranges. Wide area search munitions equipped with ATR algorithms can be delivered with very relaxed TLE requirements due to their ability to search large areas and make autonomous target attack decisions.

In measuring the effectiveness of wide area search munitions, Jacques [9] defines two metrics as the most crucial measures of ATR performance: False Target Attack Rate (FTAR) and probability of target report (P_{TR}). FTAR is defined as the average rate ($/km^2$) at which munitions are expended on falsely confirmed targets. The FTAR is driven by the target being searched for, the environment being searched, and the type of seeker and ATR algorithm being used to search. The numerical expression to define FTAR is shown in equation (2.1). P_{TR} is the probability that a correct attack decision is made given that a real target is encountered. The expression for this parameter is shown in equation (2.2). Note that the degree of discrimination on the part of the munition seeker does not have to be specified.

$$\text{FTAR} = \eta \cdot P_{FTA|FTE} \tag{2.1}$$

where

η = Clutter Density

$P_{FTA|FTE}$ = Probability of false target attack given a false target encounter

$$P_{TR} = P_{acq} \cdot P_{ID} \tag{2.2}$$

where

$$P_{acq} = \text{Probability of acquisition}$$

$$P_{ID} = \text{Probability of correct identification (or classification)}$$

A generic wide area search munition is shown in Figure 2.1. Some parameters that describe the wide area search munition used in this research are:

- Reliability < 1
- False Target Attack Rate > 0
- Probability of Target Report < 1
- Probability of Kill < 1
- Maneuver Capability ≈ 2 g's
- Guidance - GPS/INS

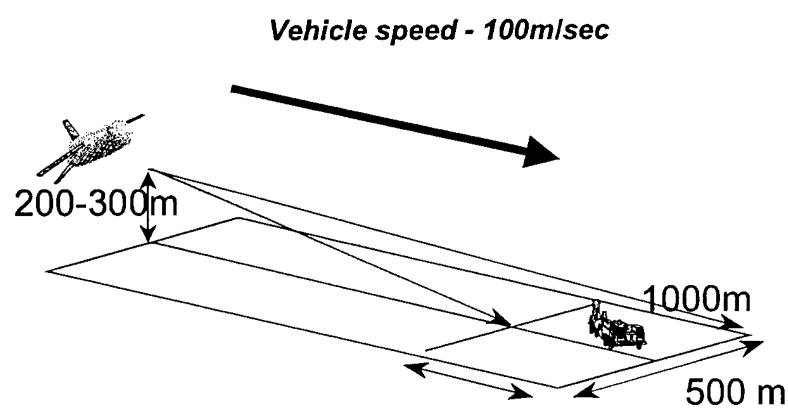

Figure 2.1 Candidate Wide Area Search Munition

There are many different conceptual search patterns for wide area search munitions including line, circle, spiral, and serpentine. The pattern chosen for this study was the serpentine pattern demonstrated by four munitions in Figure 2.2.

The notional attack operations concept for wide area search munitions is illustrated in Figure 2.3. The concept demonstrated here is the deployment of the munitions in an attempt to find a relocatable missile launcher. The event that triggers this entire

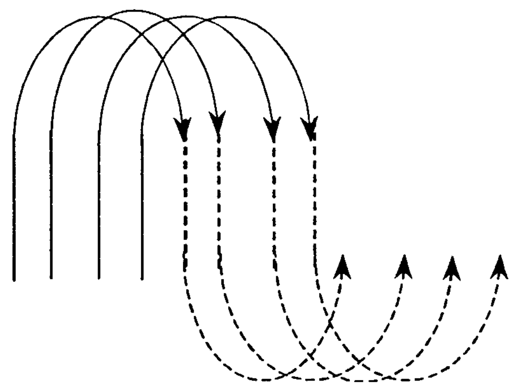

Figure 2.2 Serpentine Search Pattern

operation is a missile launch. Reconnaissance satellites detect the launch and transmit estimated coordinates of the launcher to a C^3I aircraft. That aircraft then communicates the information to the ground and any aircraft in the area in an attempt to task resources to attack the target. A combat air patrol aircraft carrying the wide area search munitions is then notified of the target. That aircraft ingresses to the target location and deploys the search munitions. As the figure shows, all of these events take time, and the area of uncertainty containing the missile launcher increases quadratically with respect to time (assuming the target is free to move in any direction). In order to overcome this increase in uncertainty area for the single target in this example, at least four submunitions must be deployed to cover the required area.

2.2 ATR Algorithm

How a particular ATR works in reality is very dependent on the system and discrimination level. However, for purposes of effectiveness analysis, this information is not required. According to Jacques [8], the typical means for describing the ability of an ATR based system to make correct decisions is the confusion matrix. To start, consider the simplest confusion matrix where the only discrimination is between target and non-target. The confusion matrix for this simple case is shown in Table 2.1. In a simulation, the numbers in the confusion matrix are used to determine the outcome of a random draw each time an object, target or otherwise, is encountered. As usual, the probability numbers in the matrix can vary between zero and one, with a perfect algorithm having a value of one

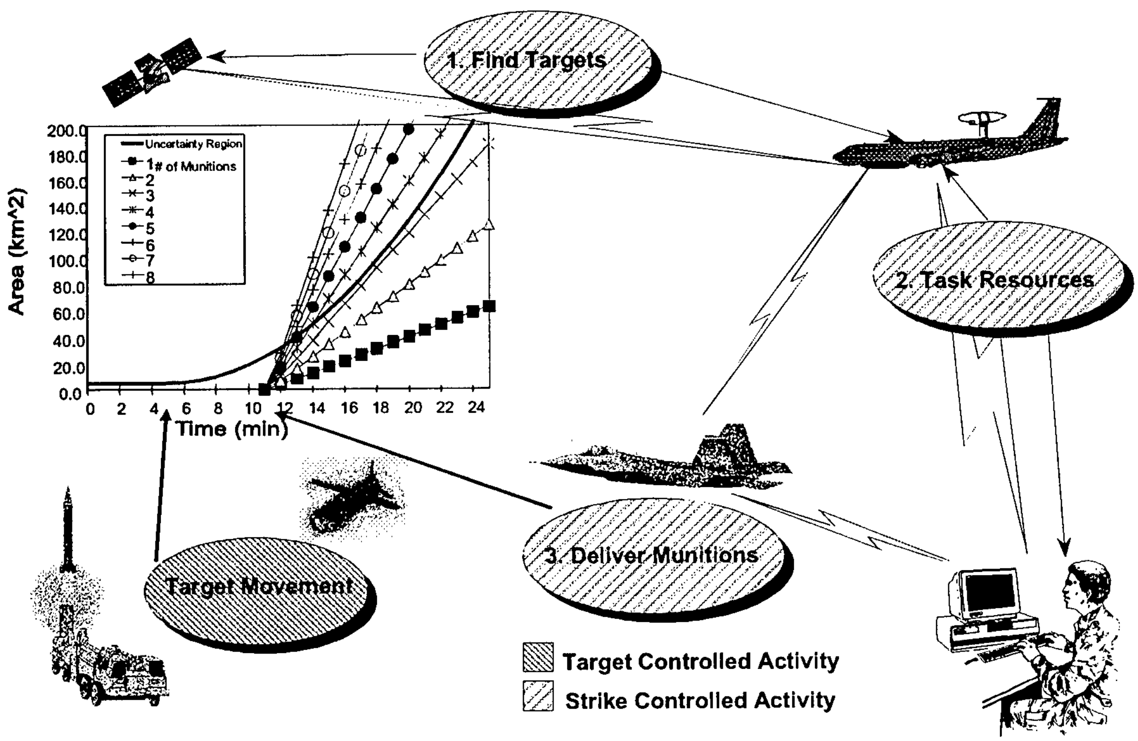

Figure 2.3 Notional Attack Operations Concept

for P_{TR} and a value of zero for $P_{FTA|FTE}$. Note that since an encountered target must be declared either a target or a non-target, the sum of the probabilities in any row must sum to one.

Table 2.1 Binary Confusion Matrix

	Declared As:	
Encountered	*Target*	*Non-Target*
Target	P_{TR}	$(1-P_{TR})$
Non-Target	$P_{FTA\|FTE}$	$(1-P_{FTA\|FTE})$

In this research, two real-target types, a non-target type, and clutter were used resulting in a more complex confusion matrix shown in Table 2.2. Target 1 represents a high priority target and Target 2 represents a low priority target. As stated previously, all rows sum to one since all encountered objects must be declared to be something. Notice that this confusion matrix takes into account the possible situation that a non-target more closely resembles a low priority target such as a bus or cargo truck than a high priority target such as a missile launcher or tank.

Table 2.2 Implemented Confusion Matrix

	Declared As:			
Encountered	*Target 1*	*Target 2*	*Non-Target*	*Clutter*
Target 1	P_{TR}	$\frac{1-P_{TR}}{3}$	$\frac{1-P_{TR}}{3}$	$\frac{1-P_{TR}}{3}$
Target 2	$\frac{1-P_{TR}}{4}$	P_{TR}	$\frac{1-P_{TR}}{2}$	$\frac{1-P_{TR}}{4}$
Non-Target	$\frac{1-P_{TR}}{4}$	$\frac{1-P_{TR}}{2}$	P_{TR}	$\frac{1-P_{TR}}{4}$
Clutter	$\frac{P_{FTA\|FTE}}{2}$	$\frac{P_{FTA\|FTE}}{2}$	0	$1-P_{FTA\|FTE}$

The two seeker parameters this study is most interested in are FTAR and P_{TR}, the latter of which is specifically identified in the confusion matrix. The FTAR is computed by the expression shown in equation (2.3). The first part of the expression represents the incorrect identification of clutter as a real target, and the second part of the expression represents identifying a non-target as a real target (both situations contributing to an overall FTAR).

$$\text{FTAR} = \eta \cdot \text{P}_{FTA|FTE} + \frac{\#\text{Non Targets}}{\text{Battlefield Area}} \cdot \left(\frac{1 - \text{P}_{TR}}{4} + \frac{1 - \text{P}_{TR}}{2} \right) \tag{2.3}$$

2.3 Non-Cooperating Sensitivities

According to the wide area search munition effectiveness analysis completed by Jacques [9], the performance of non-cooperating munitions is extremely sensitive to FTAR. Figures 2.4 and 2.5 illustrate this sensitivity for a very simple scenario. The scenario used was that which was described in Figure 2.3, that of a single mobile missile launcher fleeing its launch location. The different lines in Figure 2.4 represent the size of the search area required to guarantee an encounter with the target. The number of munitions required to achieve an expected mission success greater than 80% is plotted versus a varying FTAR. It is easy to see the extreme sensitivity to an increasing FTAR.

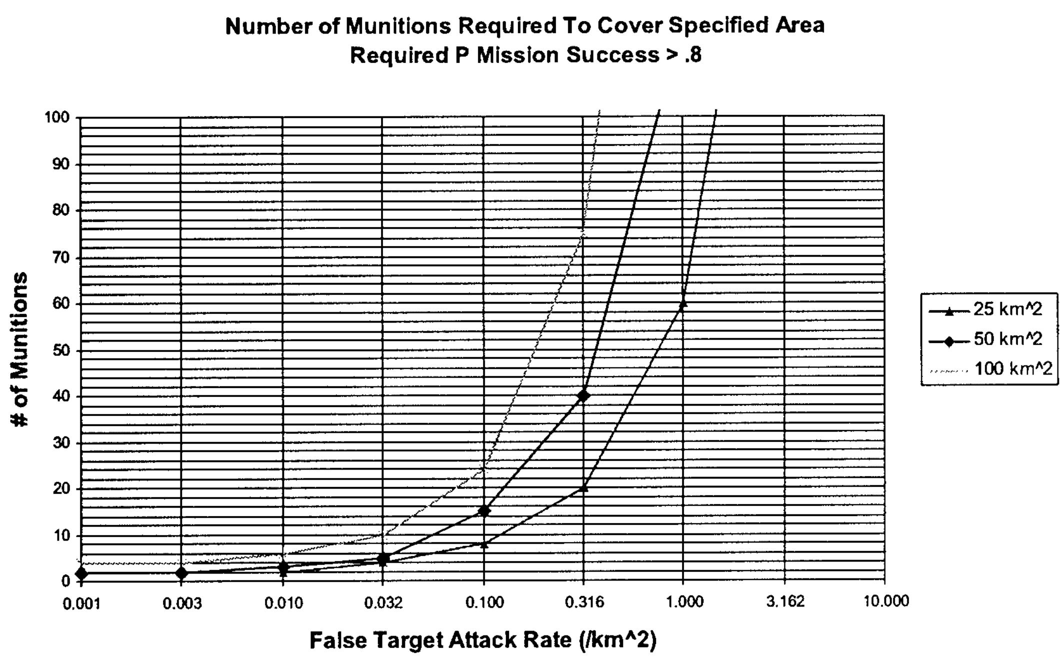

Figure 2.4 Munition #'s vs. FTAR and Area Coverage

Figure 2.5 once again shows the sensitivity to FTAR, but this time parameterized around P_{TR} for a given level of mission success required (80%) and a given search area (50 km^2). It is interesting to note that the single fleeing target scenario is relatively insensitive to P_{TR} when compared to the sensitivity to FTAR.

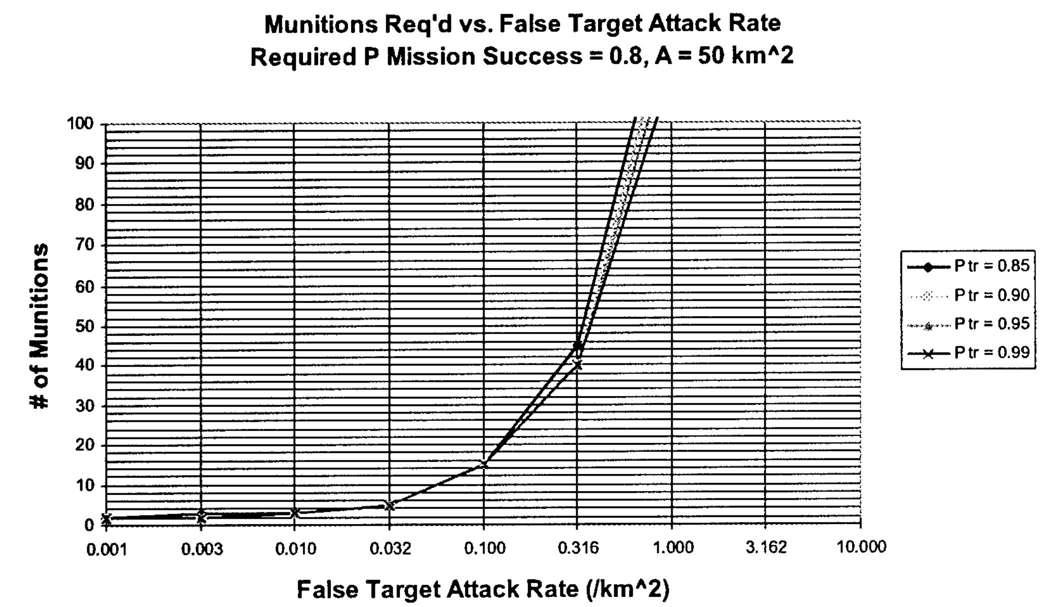

Figure 2.5 Munition #'s vs. FTAR and Probability of Target Report

2.4 Effectiveness Prediction Methods

When predicting the effectiveness of wide area search munitions with the inclusion of these two key parameters (FTAR and P_{TR}) in a multi-target/multi-munition scenario, analytic or deterministic methods are simply infeasible. For the single target, single munition case, a P_k could be determined by equation (2.4).

$$P_{K|ENC} = P_{LOS} \cdot P_{TR} \cdot P_{H|TR} \cdot P_{K|H} \tag{2.4}$$

where

$P_{K|ENC}$ = Probability of kill given a real target encounter

P_{LOS} = Probability of having a clear line of sight

$P_{H|TR}$ = Probability of hitting the target given that you found it and correctly recognized it (primarily a guidance parameter)

$P_{K|H}$ = Probability of killing the target given you hit it (a warhead parameter)

Although not shown, equation (2.4) could be generalized to accommodate reliability factors, and this typically is done for most effeciveness models.

However, given that the scenario is not that simple, how does one deterministically model a group of munitions wading through a number of non-targets and/or clutter on their way to a number of real targets that they might not be able to correctly identify when they get there? Then the addition of cooperative behavior among the munitions would make any analytic solutions simply impossible. Therefore, an appropriate method for measuring the effectiveness of wide area search munitions is the use of a stochastic, Monte Carlo based computer simulation. The computer simulation allows the incorporation of all desired cooperative behaviors, the setting of desired probabilities and FTARs, and the measurement of expected effectiveness values. Having the simulation Monte Carlo based provides a means for measuring the expected performance over many random probability draws. This was the method chosen to accomplish all effectiveness analysis in this research.

III. The Computer Simulation

3.1 Baseline Simulation

The Monte Carlo based Fortran program employed by this research was originally developed by Lockheed Martin Vought Systems [12] as an effectiveness model for the LOCAAS. However, it is versatile enough to be used for any generic wide area search munition. The simulation makes no attempt to model the aerodynamics, guidance, etc. of the submunitions, however, it does model multiple submunitions in a coordinated search for multiple targets. Prior to the modifications made through this research, this program had the capability to simulate the following events of the submunition "life cycle":

- Round dispense (any number of rounds)
- Submunition dispense (any number of submunitions per round)
- Submunition flies a user supplied pattern by following predetermined waypoints and looks for targets on the ground
- If a target enters a submunition's FOV, the submunition may acquire it based on the precision of the ATR algorithm
- Once acquired, the submunition can select that target to engage
- Once engaged, the submunition attempts to hit the target
- Once the target is hit, an assessment is made as to whether the target has been completely destroyed (dead) or is still in working condition (alive)

The simulation allows for any number of targets with varying priority levels, the addition of non-targets (military or civilian), and a user supplied clutter density per square kilometer of battlefield. The baseline code also has an option to incorporate some cooperation among the submunitions. This option has the following limited capabilities:

- When a target is engaged by a submunition, send just one, all, $\frac{1}{2}$, $\frac{1}{3}$, etc. of the remaining submunitions to engage that target

- Once called to cooperate, the submunitions could go immediately or at the end of the current search leg

When a submunition is redirected off of its initial user supplied flight path (due to a cooperative engagement attempt) but does not see the target it is supposed to engage, that submunition will fly a straight line for twenty seconds beyond the expected target location and then expire. The submunition might not see the target it's redirected toward for a number of possible reasons:

1. The submunition's detection mechanism does not acquire the target
2. The submunition acquires the target but falsely identifies it as either clutter or a non-target and, therefore, does not select (engage) that target
3. The submunition that originally engages the target falsely identified a non-target or clutter as a real target and communicates the position of this object as a real target to the other submunitions; consequently, the submunition that is redirected as a result of that information is sent to an area where there are no real targets

The simulation is extremely flexible in its capabilities to handle a multitude of input parameters and supplies comprehensive results as output files at the conclusion of each run.

3.1.1 Inputs to the Simulation. To run the simulation, two separate input files are required. The first contains the information concerning the user supplied flight paths for the submunitions once dispensed from the rounds including waypoints, altitude and velocity (see appendix A, page A-5 for an example). The second input file contains all the parameters characterizing the submunitions and the parameters required to run the simulation (see appendix A, page A-1 for an example). Table 3.1 shows a summary of some of the input parameters that must be entered regarding the characteristics of the submunitions and targets:

Since the simulation is based on the ability to do Monte Carlo runs, the user also has the ability to pick the number of Monte Carlo trials and a Monte Carlo baseline random number stream seed (which is modified for every repetition in a series).

Table 3.1 Input Parameters to Baseline Simulation

Parameter	*Description*
Numbers:	
Rounds	Total number of rounds dispensed
Submunitions	Total number of submunitions (and submunitions per round
Target Types	Priority 1, priority 2, non-targets, etc.
Targets	Total number of targets and how many of each type
Discrete:	
Random Targets	Either targets are placed in specific locations or random within a specified area $\leq$ total battlefield area
Blind in Turns	Submunition's target detection is turned off when turning
Live	Submunition can tell if target was killed by another submunition already
Correlate Targets	Submunition can tell if it has seen a target before
Reliabilities:	
Round	Probability that round will not fail
Submunition	Probability that submunition will not fail
Probabilities:	(Input for each target type)
Acquisition	Submunition will acquire the target when it enters its FOV
Hit	Submunition will hit the target once its acquired
Kill	Submunition will kill the target once its hit
Correct Identification	Submunition will identify the target correctly or incorrectly (incorrect identifications are distributed among all target types as desired)
Seeker Data:	
Foot Print Width	Width of the FOV on the ground
Beam Width	Beam width in degrees used for vertical FOV
Boresight Angle	Angle at which the LADAR points down from the horizon
Scan Time	Time for the FOV to sweep the entire foot print width
Flyback Time	Time for the FOV to return at the completion of each sweep
Submunition Data:	
Min Turn Radius	Minimum turn radius the submunition can fly
Time of Flight	Total Time of flight from submunition dispense time to expiration
Target Data:	
Locations	Specific locations of all targets if using non-random target layout
Mobility Data	If mobile: start time, heading, speed, acceleration time

3.1.2 Outputs of the Simulation.

The simulation offers four different output files. The main output file first lists all of the input parameters used to run the simulation for tracking purposes. Then for each Monte Carlo repetition, a brief history of what each submunition did during that repetition is displayed. Finally, at the end of the main output file, all Monte Carlo repetitions are summarized showing a breakdown, per target type and per individual target, of the number of acquisitions, selections, hits, and kills, as well as the total number of kills and unique kills for that simulation run. An example of this output file for 10 Monte Carlo runs (as opposed to 200 used for all testing) is located in appendix A on page A-18.

The following files can be created for any number of individual repetitions within a Monte Carlo cycle. The history output file recaps everything that happened during the repetition in chronological order in a manner similar to that of a sports announcer providing play by play action (see appendix A, page A-29 for an example). The next output file is a summary of the cuts for each submunition. A cut occurs anytime a submunition sees something on the ground and the ATR algorithm takes a "cut" at classifying it. The cuts output file is broken down by submunition, and provides specific information about each cut that submunition had during that repetition (see appendix A, page A-31 for an example). Finally, the playback output file is a data file for a Visual Basic program that provides a post-processed visual representation of the entire repetition (see appendix A, page A-32 for a sample screen capture).

3.2 Simulation Modifications

Modification of the simulation was accomplished in three steps:

- Define and provide shared information for use by the individual submunitions
- Implement the cooperative engagement decision algorithm
- Implement other small changes to best achieve all objectives

Once the code was pretty well understood, the following modifications were made.

3.2.1 Shared Information.

The first step in the modification process was to be able to redirect any number of submunitions at any time toward any found targets. The way this was accomplished was using a structured array to store all target information on the targets found. This structured array stored the x, y and z coordinates of the target (if the target was a moving target, these coordinates would be those corresponding to the position of the target at the time it was acquired and selected), and the type of target found. A very important distinction which needs to be made at this point is that the target type stored is not necessarily the correct identification of the target found; it is the identification of the target type determined by the munition that identified that target. Therefore, the type of target found which is stored in this target array may not be the true type of target located at the stored coordinates.

Once the target information was stored, a method for distributing that information had to be determined. Obviously, since this was just a simulation, it would be easy to just provide all submunitions access to all entries in the aforementioned structured array. But is this feasible, realistic or even advantageous? Since this study hoped to gain some insight into the trade-offs between local and global communication, a mechanism for determining whether a submunition received the communicated information had to be implemented. First of all, in this study incomplete communications were not considered, i.e., either a submunition receives all the information about the target or none. However, communications reliability based solely on whether or not the submunition was within a certain maximum communications range did not seem too realistic either. Therefore, a communications reliability function was developed. In order to keep it relatively simple, this function was based solely on the probability of communication failures increasing as maximum communications range was approached. The function used is shown in equation 3.1. Another way of doing this (and possibly a more realistic way) could have been to assign 50% reliability (possibly representing a 3dB degradation in signal power) at the maximum communications range and then continue the function down to 0% reliability some distance beyond the maximum communications range. This would make the maximum communications range more of a "soft" constraint, allowing some communications to be received beyond that distance, rather than a "hard" constraint as done in this study.

$$\text{Comm Rel} = \begin{cases} 1 & \text{if range} \leq \frac{\text{max comm range}}{2} \\ \left(\frac{\text{max comm range} - \text{range}}{\frac{\text{max comm range}}{2}}\right)^{0.1} & \text{if range} > \frac{\text{max comm range}}{2} \end{cases} \tag{3.1}$$

Figure 3.1 illustrates an example of this communications reliability function for a maximum communications range of 10,000 meters.

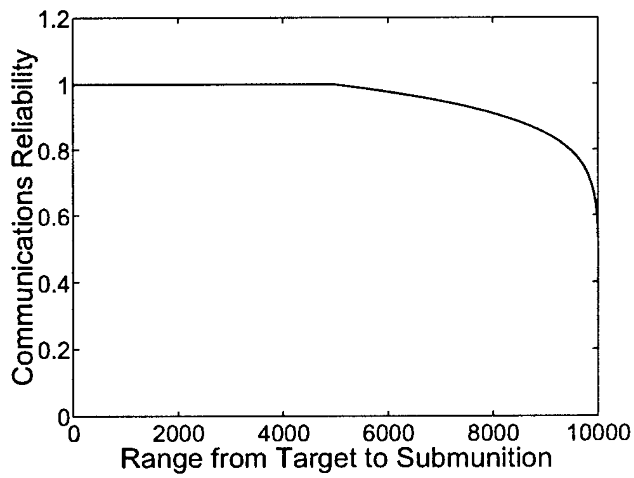

Figure 3.1 Communications Reliability Function

In order to implement the decision algorithm described in the following section, the amount of information that had to be shared among the submunitions had to be determined. For this study, the following three pieces of information were determined to be important and were communicated for each target found

- Location of the target
- Type of target
- Specific target to be engaged

The location of the target was communicated as the precise x and y coordinates of the target. The type of target was communicated as either a high priority (priority 1) or a low priority (priority 2). Once again, this communicated target type is the target type as identified by the ATR algorithm and, therefore, not necessarily a correct classification (or priority identification) of the target. The specific target to be engaged is, in reality, a very difficult piece of information to communicate and keep track of reliably, especially with non-global and non-perfect communications. In particular, multiple targets within a small area can cause ambiguities as to which target is really being seen. However, in this study, the target registration problem was not considered.

3.2.2 Decision Algorithm. The purpose of the decision algorithm was to provide a criteria by which the submunitions could "decide" whether or not to participate in a cooperative engagement. In developing the algorithm, the goals were to incorporate all important factors that should be taken into account for making a cooperative engagement decision and to keep it simple since the available computing power aboard these submunitions is likely to be minimal. After many long brainstorming sessions, the following (in no particular order) were determined to be the most important factors that needed to be included in the decision algorithm:

- Fuel Remaining
- Target Priority
- Range Rate from submunition to target
- Range from submunition to target
- Number of submunitions that have already engaged a particular target

To keep the decision algorithm simple, the basic first order expression shown in equation 3.2 was used.

$$\text{Threshold} = \alpha_1 * x_1 + \alpha_2 * x_2 + \alpha_3 * x_3 - \alpha_4 * x_4. \tag{3.2}$$

where

$$\begin{aligned}
x_1 &= \text{Normalized Fuel Remaining} \\
x_2 &= \text{Normalized Target Priority} \\
x_3 &= \text{Normalized Range Rate} \\
x_4 &= \text{Normalized Number of Engaged Submunitions on a particular target}
\end{aligned}$$

α_i = Weighting Parameters

Note that the actual range from the submunition to a specific target is not explicitly used in this decision algorithm, however, a range check was added as a final go/no-go criteria to ensure that a submunition is not redirected toward a target that cannot be reached based on insufficient fuel remaining.

All factors in the decision algorithm were normalized with the sense that values approaching unity encouraged a cooperative attack, while values approaching zero provided a discouragement. One exception to this is the x_4 parameter which is explained below. Normalization of fuel remaining in the simulation was easily accomplished by normalizing time of flight or search time. Since each submunition was assumed to have a twenty minute total search time, the normalized time of flight was the time in search divided by 1200 seconds. Target priority was normalized by assigning a value of one to a priority one target, one-half to a priority 2 target and zero for anything else.

The purpose of incorporating a range rate parameter in the decision rule was to apply little influence on the decision (or even discourage a cooperative engagement) when the range rate was negative (the submunition is moving towards the target) and to encourage a cooperative engagement when the range rate is positive (the submunition is moving away from the target). This provided a means for allowing the submunition to continue its predetermined search pattern if it was flying toward a known target location. The expression used to normalize range rate is shown in equation 3.3 with $\dot{r}$ defined by a backward difference.

$$\text{normalized range rate} = \left|\frac{\dot{r} - \text{vel}}{2 * \text{vel}}\right| \tag{3.3}$$

where

$$\dot{r} = \frac{\text{range}_i - \text{range}_{i-1}}{\text{time}_i - \text{time}_{i-1}}$$

Figure 3.2 illustrates the function for normalized range rate shown in equation (3.3). Note that equation (3.3) and Figure 3.2 correspond to an assumed munition speed of 100 m/sec.

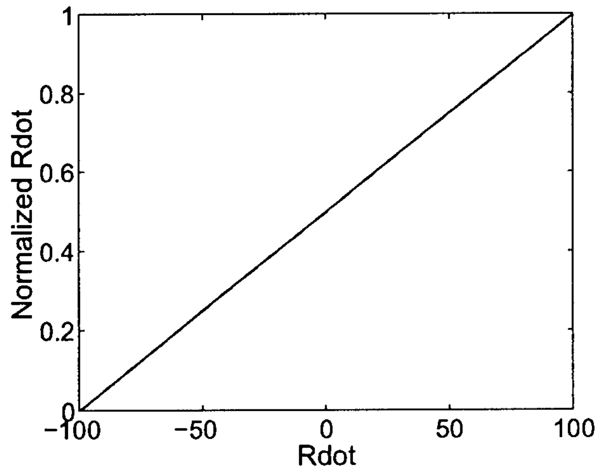

Figure 3.2   Normalized Range Rate

Finally, the last parameter in the decision algorithm is the normalized number of engaged submunitions on a specific target. The purpose of this parameter is to discourage multiple cooperative engagements on a single target in an attempt to spread out the total hits and not send all submunitions after the same target. When a target has been engaged by only a single submunition, then this parameter should not be discouraging a cooperative engagament on that target. However, once one submunition has cooperatively engaged a target (resulting in a total of two munitions attempting to hit that specific target), this parameter should be invoked to discourage any additional submunitions from choosing to cooperatively engage that target. Equation 3.4 was used to normalize this parameter.

$$\text{Normalized Parameter} = \text{Number of engaged submunitions} - 1 \qquad (3.4)$$

Note that in equation 3.2 a "-" sign is implemented in front of this parameter in order to *discourage* a cooperative engagement as this parameter increases. As desired, this parameter equals zero when only one submunition has engaged a specific target but then increases in value as more submunitions cooperatively engage that target.

The implementation of the decision rule in equation 3.2 was rather simple. Once a target is found, the information about that target is communicated by the submunition that identified the target. Then at all subsequent time steps, every submunition that received the communication and is not in an engaged status will calculate all of the normalized parameters and the decision algorithm. When multiple targets are found and communicated, then at all subsequent time steps the normalized parameters and the decision algorithm are calulated by each submunition for each target individually. If the total for the decision algorithm exceeds the decision threshold, then a cooperative engagement on that target by that submunition occurs. That submunition then communicates globally with 100% reliability that it has engaged that specific target (ignoring all target registration issues).

3.2.3 Additional Modifications. In order to best achieve the objectives of this study, a few additional changes needed to be made to the simulation. The first was a simple modification to the main output file to include the values of each normalized parameter as well as the weights on the parameters every time a cooperative engagement was invoked. This provided a means to track all cooperative engagements, and ensure the decision algorithm was being implemented properly.

A second change was an attempt to answer the following question: what should happen to a submunition that is sent off its original search pattern to cooperatively engage a target that it cannot find? Three possible scenarios that could cause this situation were listed on page 3-2. This issue was not addressed in the baseline code. In order to resolve this, an attempt was made to create a new search pattern for the redirected submunition that focused on the location of the target that was cooperatively engaged. The new pattern used was a growing figure-8 centered on the communicated target location. This pattern would initially turn the submunition around after it crossed the expected target location to fly right back over it as an attempt to acquire and classify the target if it simply "missed" it the first time. If the target was still not selected on this second pass, then the submunition would continue flying past the target, but this time farther past the target, in the opposite direction in which the submunition first approached the target area. It would then turnaround and fly back toward the target until the submunition engages a target or expires (search time depletes)–the submunition cannot participate in a second cooperative engagement on a different target. The behavior chosen to handle this situation is not necessarily that which would be implemented operationally, nor was any research completed that showed this behavior would produce optimal results. This situation was deemed outside the scope of the research and could better be addressed by a study in cooperative search.

IV. Applied RSM

4.1 Introduction

Response surface methodology is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes. Most applications include situations where several input variables potentially influence some performance measure or quality characteristic of the system. The purpose of RSM is to approximate the measures of performance, referred to as response functions, in terms of the most critical factors (or independent variables) that influence those responses. In doing this, a response surface can then be mapped out (hypersurface for the general n-dimensional case) showing how variations in the independent variables affect the responses.

A typical RSM according to Myers and Montgomery [14] is broken into phases. The first experiment is usually designed to investigate which factors are most influential to the responses with the intent of eliminating the unimportant ones. This type of experiment is called a screening experiment and is typically referred to as phase zero of a response surface study. Once the important independent variables are identified, phase one begins with the intent of determining if the current levels or settings of the independent variables result in values of the responses near optimum. If the current settings or levels of the independent variables are not consistent with optimum performance, then adjustments to the input variables that will move the responses toward the optimum must be made. To do this a first order model and the optimization technique called the method of steepest ascent are employed. Phase two of the response surface study begins when the process is near the optimum. At this point models that will accurately approximate the true response functions are desired. Because the true response surfaces usually exhibits curvature near the optimum, models of at least second order must be used. Finally, the models of the various responses must be analyzed to determine the settings for the independent variables that provide the optimal expected performance over all responses.

4.2 Application

For this study, RSM was used to determine the optimal settings for the α_i's in the cooperative engagement decision algorithm shown in equation 3.2 as well as the maximum communications range. The optimal α_i's were simply the weights on the parameters used in the decision rules. A high weight on a parameter means that that parameter is of high importance in making the decision to cooperatively engage, whereas a low weight on a parameter can be interpreted to mean that that parameter is less important (or even insignificant) in making the decision to cooperatively engage. A low maximum communications range implies that only local communications are employed, whereas a high maximum communications range implies global communications.

4.2.1 Independent Variables.

Because of the relatively small number of input variables, the phase zero screening experiments were not necessary for this study. Therefore, the first step was to choose the ranges of the independent variables to begin the RSM. To do this effectively, a decision threshold from equation 3.2 had to first be determined and fixed. Without loss of generality, a threshold of one was chosen and remained constant for all simulations. In picking the ranges for the independent variables, careful consideration was made to ensure the RSM studies would be investigating the effects of different cooperative engagement decision rules. Therefore, the values for the independent variables when chosen at their extremes had to be able to result in the possible triggering of the decision algorithm. Since the first three parameters in the decision rule (as described on page 3-7) were normalized to have maximum values of one, the weights on these parameters could not be all less than one-third or else a cooperative engagament would be impossible. This would, therefore, result in an RSM study investigating the effects of different cooperative engagament decision rules *and* no cooperation at all. Since this was not the goal, minimum values for the first three parameters had to be chosen greater than one third. Table 4.1 shows the values used for each independent variable.

The values chosen in Table 4.1 ensure that even when the independent variables are chosen at their extremes, cooperative engagements are still possible. The maximum communications range values were chosen based on a battlefield that was approximately 300 square kilometers in size.

Table 4.1 Independent Variable Ranges for RSM

Variable	*Weight on*	*Minimum*	*Maximum*
α_1	Time of Flight	0.4	0.8
α_2	Target Priority	0.4	0.8
α_3	Range Rate	0.4	0.8
α_4	Number of Munitions	0.4	0.8
Maximum Communications Range		5 km	15 km

4.2.2 Responses.

The responses had to be chosen to somehow accurately measure the expected mission effectiveness for wide area search munitions. Four responses were chosen:

- Unique Kills
- Total Kills
- Total Hits
- Target Formula

Unique kills was defined as the expected number of unique, real targets killed (each target can be killed only once). Total kills was defined as the number of submunitions expected to achieve lethal hits on real targets. Total hits was defined as the expected number of real target hits. Finally, the target formula response was used as a means of measuring the hits on high priority targets (priority one) versus hits on low priority targets (priority two) and incorporating a penalty for any hits on non-targets. This target formula is shown in equation 4.1 where "# prior 1 hits" means the number of hits on priority one targets, "# prior 2 hits" means the number of hits on priority two targets, and "# non-target hits" means the number of hits on any non-targets.

$$\text{Target Formula} = 2 * (\#\text{ prior 1 hits}) + \#\text{ prior 2 hits} - \#\text{ non-target hits} \tag{4.1}$$

A simple example can be used to distinguish and better understand these responses. This example has five submunitions, 2 real targets (one high priority and one low priority) and one non-target. Submunition #1 hits target #1, a high priority target, but does not kill it. Submunition #2 hits that same target (target #1) but kills it. Submunition #3 hits and kills target #2, a low priority target. Then submunition #4 also hits target #2, and this engagement is also deemed a kill (even though the target was already dead) . Finally, submunition #5 hits the non-target. The responses for this example are shown in Table 4.2.

Table 4.2 Responses for Example

Response	*Explanation*	*Value*
Unique Kills	targets #1 and #2	2
Total Kills	submunitions #2, #3, and #4	3
Total Hits	submunitions #1, #2, #3, and #4	4
Target Formula	2 hits on target #1 (high priority target)	
	2 hits on target #2 (low priority target)	
	1 hit on a non-target	5

4.2.3 Phase 1. The purpose of phase one is to determine if the current ranges for the independent variables shown in Table 4.1 result in responses that are near optimal. To accomplish this a 2^{5-1} fractional factorial design was used. This design is both orthogonal and resolution V. Orthogonality is often a desired property for ease and convenience of calculations and the avoidance of singularities. A resolution V design is a design in which no main effect or two-factor interaction is aliased with any other main effect or two-factor interaction, but two-factor interactions are aliased with three-factor interactions. In general, the resolution of a two-level fractional factorial design is equal to the smallest number of letters in any word in the defining relation. Usually, the fractional design having the highest possible resolution consistent with the degree of fractionation required is desired. This provides a design with less restrictive assumptions regarding which interactions are negligible in order to obtain a unique interpretation of the data. This property is most desired for Phase 2 described below and is therefore used in this phase to best garner the benefits of sequential testing. This design required a total of 16 runs to complete. Each design was augmented with four center runs resulting in a total of 20 runs. For each run the values for each of the four responses were recorded. Using an analysis of variance (ANOVA) for each response, an attempt to fit first order models to each response was made. Whenever a first order model was appropriate, the method of steepest ascent was used to traverse the response surface to a new operating region that was closer to the optimal design point. The method of steepest ascent is summarized by the following few steps.

1. Fit a planar (first-order) model using an orthogonal design
2. Compute a path of steepest ascent where the movement in each design variable direction is proportional to the magnitude of the regression coefficient corresponding to that design variable with the direction taken being the sign of the coefficient
3. Conduct experimental runs along the path
4. Choose a new design location where an approximation of the maximum response is located on the path
5. Conduct a second fractional factorial experiment centered at the new design location and attempt to fit another first order model

If a second first order model is accurately fit, then a second path of steepest ascent can be computed and traversed until a region is reached where a higher-order model is required to accurately predict system behavior.

In this study, after the initial fractional factorial design was completed, a first order model was never adequate. Therefore, the method of steepest ascent was never required because the starting region of design seemed to always be close enough to the optimal point over all responses.

4.2.4 Phase 2. The purpose of this phase is to build second (or higher) order models to accurately predict all responses and choose the settings for the independent variables that will result in the optimal expected performance over all responses. Since the resolution V fractional factorial was already completed at the appropriate design point, the ideal second order design would be able to simply augment the first design to decrease the total number of runs, thereby saving time and money. Therefore, the central composite design (CCD) was used. A sample of this design is located in appendix B on page B-1. This design requires three parts:

- Two-level factorial design or resolution V fraction

- 2k axial or star runs (k = # of independent variables)
- Center runs

The resolution V fraction contributes to the estimation of the linear terms and two-factor interactions. It is variance-optimal for these terms. The axial points contribute to the estimation of the quadratic terms. The center runs provide an internal estimate of error (pure error) and contribute toward the estimation of quadratic terms. Since the phase one experiments required the fractional factorial design and the center runs, to complete the CCD the axial runs were all that was required.

The areas of flexibility in the use of the central composite design resides in the selection of α, the axial distance, and the number of center runs. According to Myers and Montgomery [14] and Box and Draper [3], the CCD that is most effective from a variance point of view is to use $\alpha = \sqrt{k}$ and three to five center runs. This design is not necessarily rotatable but is near-rotatable. Therefore, the four center runs completed in the initial augmented fractional factorial design were sufficient for the CCD, and the 10 additional axial runs at $\alpha = \sqrt{5} = 2.236$ were all that were required to complete the CCD.

The result of the CCD is four models, one for each of the individual responses. Each model will be a maximum of second order. Sample models and their accompanying ANOVA tables are located in appendix B, starting on page B-2.

Once all models were determined, a mechanism for choosing the values of the independent variables that would result in the most-optimal mission effectiveness for all responses had to be determined. Because of the complexity and multi-dimensionality of the response surfaces, a simple overlaying of contour plots to graphically choose the point which appeared to be optimal over all responses was not applicable. Therefore, the Derringer and Suich [5] desirability function for optimizing over multiple responses was employed. This method allows for the creation of desirability functions (d_1, d_2, d_3, d_4) for each response where the desirability function can target a specific value, minimize or maximize a response. Since all the responses in this study were measures of mission effectiveness, the desirability functions used were all maximizing. The shape of each desirability function is based on the weight assigned to it in accordance with Figure 4.1. Notice that as the weight increases, the desirability assigned is lower until the value nearly approaches the goal (maximum), and vice versa as the weight decreases.

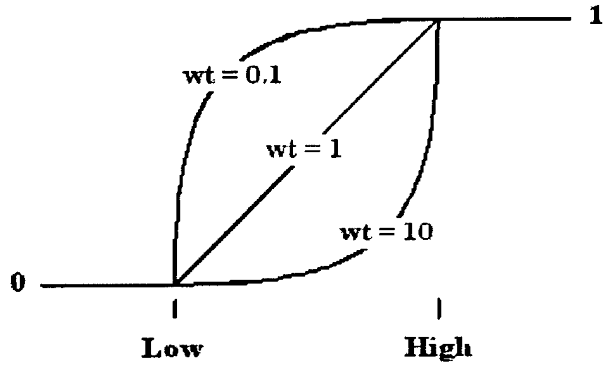

Figure 4.1 Desirability Curves for Goal is Maximum

Once each individual desirability function is determined, a single composite response (D) is developed which is a weighted mean of the desirabilities of the individual responses. The weights in the composite response allow more emphasis on specific individual responses as specified by their importance. If all four responses were of equal importance, D would be computed by equation (4.2).

$$D = \left(d_1 \cdot d_2 \cdot d_3 \cdot d_4\right)^{\frac{1}{4}} = \left(\prod_{i=1}^{4} d_i\right)^{\frac{1}{4}} \tag{4.2}$$

In this study, extra emphasis was placed on two of the responses: the number of unique kills and the number of hits on priority one targets (target formula). Table 4.3 shows the ratings using a scale of one to five of the importance of each of the responses.

Table 4.3 Importance Ratings for Each Response

#	*Response*	*Importance*
1	Unique Kills	4
2	Total Kills	3
3	Total Hits	3
4	Target Formula	5

The composite response (D) was then computed using equation (4.3) taking into account the appropriate weights on importance.

$$D = \left(d_1{}^{r_1} \cdot d_2{}^{r_2} \cdot d_3{}^{r_3} \cdot d_4{}^{r_4}\right)^{\frac{1}{\sum r_i}} = \left(\prod_{i=1}^{4} d_i{}^{r_i}\right)^{\frac{1}{\sum r_i}} = \left(d_1{}^4 \cdot d_2{}^3 \cdot d_3{}^3 \cdot d_4{}^5\right)^{\frac{1}{15}} \tag{4.3}$$

To determine the "optimal" conditions, the following non-linear algorithm with constraints was used:

1. Let X be a vector of x_i for $i = 1 \ldots n$ representing the design variables over the optimization space which is a subset of the design space (in this case $n = 5$).

2. Let y_j, U_j, and L_j for $j = 1 \ldots m$ be responses with upper and/or lower bounds serving as constraints (in this case $m = 4$).

3. Let $D(X)$ be the response to be optimized. Then $f(X) = -D(X)$ for maximization.

4. Define the constraints as a series of discontinuous functions:

$$g_j(X) = \begin{cases} y_j(X) - U_j & \text{for } y_j > U_j \\ 0 & \text{for } L_j \leq y_j \leq U_j \\ L_j - y_j(X) & \text{for } y_j < L_j \end{cases}$$

   This produces a system of m constraints that can be solved as an unconstrained problem via a penalty function approach.

5. Define the cost function as:

$$J = \left\{f(X) + p^{\sum g_j(X)}\right\} \tag{4.4}$$

   where p is a penalty parameter greater than zero for $j = 1 \ldots m$.

Finding an initial feasible region can be difficult. The design software used starts with a small value of a penalty function in a downhill simplex (Nelder-Mead) multi-dimensional pattern search which converges at either a stationary point or a design space boundary [15]. The search around the initial convergence point is restarted using a larger penalty function. Convergence is achieved when the distance moved or objective function change is less than a 10^{-6} ratio.

The starting N+1 simplex points are constructed by adding or subtracting a fraction of each of the N factor ranges to the initial starting point [15]. The decision to add or subtract is made to maintain a maximum distance from the factor limits.

V. Results and Analysis

5.1 Quantitative Results and Analysis

Specific numerical results are shown for four scenarios where a cooperative engagement decision algorithm employing the optimal settings resulted in overall improvement over baseline (non-cooperative) performance. Each scenario was defined by three general characteristics:

1. Warhead lethality
2. ATR precision
3. Battlefield characteristics

The specific parameters that were varied in the simulation to define the three general characteristics above were:

1. Probability of Kill (P_k)
2. False target attack rate (FTAR) and probability of target report (P_{TR})
3. Clutter density (η) and whether the targets were clustered or widely dispersed

The battlefield used for all simulations was approximately 300 square kilometers in size. Two groups of four submunitions each (totaling eight submunitions) where employed in all scenarios. Each of the groups flew a serpentine pattern that covered the entire battlefield in approximately 20 minutes. Each scenario had a total of eight real targets (three high priority and five low priority). Also, two non-targets were employed in the vicinity of the real targets and a battlefield η of 0.05 per square kilometer were randomly placed throughout the battlefield in all scenarios (this value was changed during the FTAR sensitivity analysis described in Section 5.2).

Table 5.1 shows the parameters defining scenario 1. This submunition has a relatively non-lethal warhead and is searching for targets clustered in a four square kilometer region of the battlefield.

Table 5.1 Scenario 1 Defining Parameters

Parameter	*Value*
P_k	0.5
FTAR	0.0053 per square km
P_{TR}	0.95
Target Layout	Cluster

The RSM described in section 4.2 was performed on this scenario to determine the ideal weighting parameters for the decision rule shown in equation (3.2). When performing the RSM, each simulation run required was reported as a summary of 200 Monte Carlo runs. Each repetition was completed using a different baseline seed for the Monte Carlo simulation. The resulting parameters are shown in Table 5.2. Note that time of flight is by far the dominant term in the optimal decision rule for this scenario, whereas target priority and number of engaged munitions have little to no influence.

Table 5.2 Ideal Parameters for Scenario 1 Decision Algorithm

Variable	*Weight on*	*Ideal Value*
α_1	Time of Flight	0.77
α_2	Target Priority	0.14
α_3	Range Rate	0.35
α_4	Number of Munitions	0.0
Maximum Communications Range		9.8 km

The expected performance of the wide area search munitions employing the decision algorithm with the ideal weighting parameters and ideal maximum communications range was then compared to their baseline performance (no cooperation). Table 5.3 shows these results for each of the responses. The overall percent improvement is simply an average of the percent improvements corresponding to each of the four responses. This scenario showed significant room for improvement through cooperative behavior.

Table 5.4 shows the parameters defining scenario 2. This submunition has a *lethal* warhead and is searching for targets clustered in a four square kilometer region of the battlefield (same battlefield as scenario 1).

The RSM described in section 4.2 was performed on this scenario to determine the ideal weighting parameters for the decision rule in a similar manner to that for scenario 1.

Table 5.3 Scenario 1 Results

Response	*No Cooperation*	*Ideal Cooperation*	*Improvement*
Unique Kills	2.7	2.81	4.07%
Total Kills	3.06	3.37	10.13%
Total Hits	6.08	6.515	7.15%
Formula	8.04	8.72	8.46%
Overall			7.45%

Table 5.4 Scenario 2 Defining Parameters

Parameter	*Value*
P_k	0.8
FTAR	0.0053 per square km
P_{TR}	0.95
Target Layout	Cluster

The resulting parameters are shown in Table 5.5. Note a more even distribution amongst the first three weighting parameters with number of engaged munitions having no influence.

Table 5.5 Ideal Parameters for Scenario 2 Decision Algorithm

Variable	*Weight on*	*Ideal Value*
α_1	Time of Flight	0.30
α_2	Target Priority	0.36
α_3	Range Rate	0.42
α_4	Number of Munitions	0.0
Maximum Communications Range		20.3 km

The same performance measurements as in scenario 1 were analyzed for this scenario. Table 5.6 shows these results for each of the responses. While the performance gains were not as significant for this case, improvement of 5-8% was still possible.

The only difference between the first two scenarios was the parameter describing the warhead lethality (P_k). Therefore, one would expect the number of hits on targets for both scenarios to be approximately the same (variations arise from stochastics), and this is the case. However, the number of kills would logically increase as the lethality of the warhead is increased. Therefore, the number of targets killed is greater in scenario 2 than in scenario 1, but the incorporation of cooperation engagement does not appear as useful to scenario 2. This is also explained by the difference in warhead lethality. The system

Table 5.6 Scenario 2 Results

Response	*No Cooperation*	*Ideal Cooperation*	*Improvement*
Unique Kills	4.13	4.18	1.21%
Total Kills	4.95	5.25	6.06%
Total Hits	6.145	6.53	6.27%
Formula	8.11	8.77	8.11%
Overall			5.42%

with the non-lethal warhead can benefit most when additional strikes are made against the same targets in order to increase the probability of killing them. However, in the case where the warhead is more lethal, these additional strikes are not as necessary and often result in wasted submunitions attacking targets that are already dead. An interesting point is that warhead lethality is often "traded off" with size and cost in order to achieve smaller and cheaper munitions. Employing smaller munitions provides the aircraft the capability to carry more munitions. The results from these scenarios demonstrate that cooperative engagement may be able to compensate for some of the lethality lost by choosing smaller, cheaper munitions.

Table 5.7 shows the parameters defining scenario 3. This submunition has a relatively non-lethal warhead and is searching for targets widely dispersed throughout the entire battlefield.

Table 5.7 Scenario 3 Defining Parameters

Parameter	*Value*
P_k	0.5
FTAR	0.0053 per square km
P_{TR}	0.95
Target Layout	Widely Dispersed

The same RSM as the previous scenarios was performed on this scenario. The resulting parameters are shown in Table 5.8. Time of flight is still the most important parameter, just as in scenario 1, but for this scenario target priority becomes more important than range rate.

Table 5.9 shows the results for each of the responses.

Table 5.8 Ideal Parameters for Scenario 3 Decision Algorithm

Variable	*Weight on*	*Ideal Value*
α_1	Time of Flight	0.71
α_2	Target Priority	0.48
α_3	Range Rate	0.1
α_4	Number of Munitions	0.1
Maximum Communications Range		13.3 km

Table 5.9 Scenario 3 Results

Response	*No Cooperation*	*Ideal Cooperation*	*Improvement*
Unique Kills	2.72	2.70	-0.74%
Total Kills	3.07	3.35	9.12%
Total Hits	6.295	6.52	3.57%
Formula	8.56	9.245	8.00%
Overall			4.99%

In this scenario where the targets were widely dispersed, cooperative engagement appears to have less utility than when the targets were clustered (scenarios 1 and 2). This is mostly due to the number of unique kills. The cooperative engagements are good for putting additional hits on known targets, but they limit the total search area covered by the submunitions. When the targets are widely dispersed, the unique kills are increased not only by putting additional hits on known targets, but also by searching the entire battlefield. It appears that the increase in hits on targets is slightly less beneficial (in terms of unique kills) than continuing to search the entire battlefield for more targets when the targets are widely dispersed. When the targets are clustered, a submunition that cooperatively engages a known target area has a pretty good chance of encountering a unique target in the vicinity of the known target. This results in more unique hits, but this is not apparent in any of the four responses evaluated in this study. Therefore, the total number of kills and hits are pretty similar for the clustered target scenarios and the widely dispersed target scenarios.

Table 5.10 shows the parameters defining scenario 4. This submunition has a *lethal* warhead and is searching for targets that are widely dispersed throughout the entire battlefield (same battlefield as scenario 3).

Table 5.10 Scenario 4 Defining Parameters

Parameter	*Value*
P_k	0.8
FTAR	0.0053 per square km
P_{TR}	0.95
Target Layout	Widely Dispersed

The resulting parameters after completing the RSM are shown in Table 5.11. Note that this scenario has the most evenly distributed weighting parameters of all the scenarios considered.

Table 5.11 Ideal Parameters for Scenario 4 Decision Algorithm

Variable	*Weight on*	*Ideal Value*
α_1	Time of Flight	0.31
α_2	Target Priority	0.35
α_3	Range Rate	0.40
α_4	Number of Munitions	0.15
Maximum Communications Range		19.7 km

Table 5.12 shows the results for each of the responses.

Table 5.12 Scenario 4 Results

Response	*No Cooperation*	*Ideal Cooperation*	*Improvement*
Unique Kills	3.93	3.99	1.53%
Total Kills	4.97	5.3	6.64%
Total Hits	6.225	6.555	5.30%
Formula	8.38	9.03	7.76%
Overall			5.31%

The results from scenario 4 corroborate the results from the previous scenarios very well. The increase in the warhead lethality over that for scenario 3 results in some improvement in the number of unique kills, even when cooperative behavior is employed. When the submunitions cooperatively engaged in scenario 3, the additional hits often did not result in a dead target–therefore, not only did the number of kills not increase, but less of the battlefield was searched. In scenario 4, more of these cooperative engagements resulted in dead targets, therefore making the tradeoff of searching less area a little more enticing. However, for the same reasons as stated earlier on page 5-3, the increase in hits on known targets when the submunition's warhead is more lethal often results in more wasted submunitions. This accounts for a lower utility in using cooperative engagement for scenario 4 than scenario 3, but apparently the benefits described earlier slightly outweigh this detriment.

5.2 Sensitivity Analysis

As the precision of the ATR is degraded and/or the clutter density increases, this form of cooperative engagement does not offer any advantages and often deteriorates the overall performance of the wide area search munitions. This is because of the hyper-sensitivity to the false target attack rate. By degrading the ATR precision and/or increasing the clutter density, FTAR increases. Therefore, what often occurs is that a submunition falsely identifies a clutter or non-target as a real target and then communicates to some of the other munitions the existence of a *real*-target that doesn't actually exist. Then one or more of the other submunitions will decide to cooperatively engage that false target. Now the best event that could occur for that redirected submunition is that it just happens to encounter a real target on its flight path to the false target (the chances of that event occurring being no better than if the submunition would have just stayed on its original search pattern). However, if that does not happen, the submunition is guaranteed to encounter that false target that it thinks is a real target. Upon encountering the false target, the submunition may correctly identify it and not engage it, but as FTAR increases, this is less and less likely. Therefore, cooperative engagement alone cannot overcome the hyper-sensitivity in wide area search munition effectiveness to increasing FTAR.

For a given scenario, if the weights in the decision algorithm are chosen wisely, degraded performance due to cooperative engagement can be minimized. To demonstrate this, a sensitivity analysis was performed to investigate the mission effectiveness versus a varying FTAR. Scenario 1 was chosen for this analysis because cooperative engagement seemed to be most beneficial to this scenario. The simulation was run for varying FTAR's and the two most critical responses were measured and analyzed: unique kills and target formula (equation (4.1)). The weights in the decision algorithm (α_i's) remained constant for all runs and were assigned the optimal values for scenario 1 shown in Table 5.2. For this FTAR sensitivity analysis, the P_{TR} remained constant at 0.95 and the P_k was either 0.5 (non-lethal warhead) or 0.8 (lethal warhead). The results for the unique kills are shown in Figure 5.1, and the results for the target formula are shown in Figure 5.2. The curves representing varying P_k are not in Figure 5.2 because warhead lethality does not affect whether or not the munition hits the target.

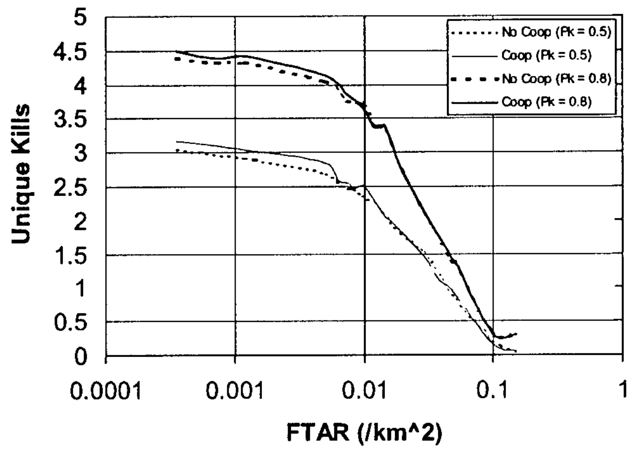

Figure 5.1 Unique Kills Sensitivity to FTAR for 2 Warheads

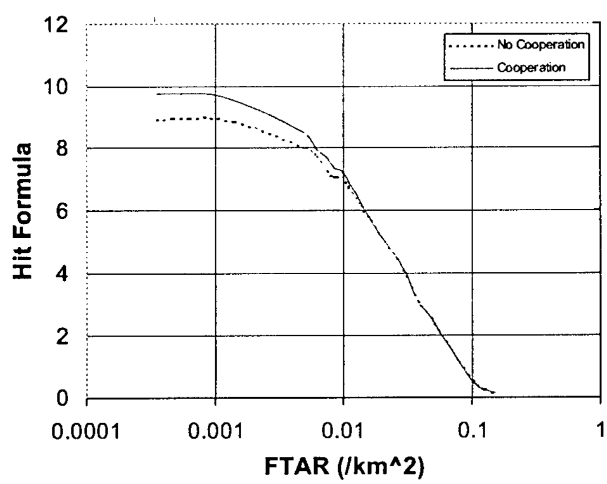

Figure 5.2 Target Formula Sensitivity to FTAR

In both Figures 5.1 and 5.2, cooperative engagement very rarely deteriorates the performance of the submunitions when compared to the baseline (no cooperation). This is because of the choice of weight in the decision algorithm. Notice that the weight on the time of flight parameter in Table 5.2 is relatively high (0.77). Because of the relative importance on this parameter versus the others, the submunitions are basing the majority of their cooperative engagement decision on time. Scenario 1 is defined by all targets clustered in a small area in the center of the battlefield. Therefore, as FTAR gets higher and higher (worse and worse), the submunitions aren't lasting long enough into the total search time to even participate in cooperative engagements because they are falling for clutter targets. Therefore, for the cases of high FTAR, cooperative engagements are very infrequent resulting in similar outcomes for the cooperative behavior and baseline situations. For this case, if the time of flight weight in the decision rule is dropped in importance and any of the other weights are increased, more cooperative engagements occur early in the search patterns resulting in deteriorated performance.

What happens when FTAR remains low, but P_{TR} decreases? This means that given real target encounters, the probability that the ATR is correctly identifying the real targets is decreasing, i.e., there is an increase in submunitions not engaging real targets because they are falsely identifying them as non-targets. This situation is realistic because often in ATR algorithm precision tuning, P_{TR} is traded off with FTAR. In this situation, as long as FTAR remains low (favorable), cooperation can still improve overall effectiveness. This is because a submunition may later encounter and correctly identify (and therefore communicate and engage) a real target that another submunition may have previously incorrectly identified as a false target. Then through cooperation, the submunition that originally made the incorrect identification could go back and get a second look at that target and possibly correctly identify and engage it. A scenario such as this will also benefit from redundant area coverage with the initial search patterns at the expense of reduced total area coverage rate.

A sensitivity analysis to P_{TR} was completed in a similar manner to that for FTAR. This analysis was completed on scenario 1 using the ideal decision rule weighting parameters shown in Table 5.2. For all runs, FTAR remained constant at a very low value of 0.007 /km^2. The same two responses were looked at. The results for the unique kills are shown in Figure 5.3, and the results for the target formula are shown in Figure 5.4. The curves representing varying P_k are not in Figure 5.4 because warhead lethality does not affect whether or not the munition hits the target.

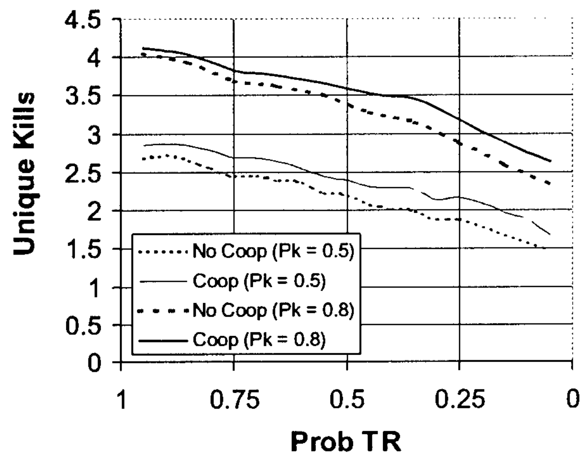

Figure 5.3 Unique Kills Sensitivity to P_{TR} for 2 Warheads

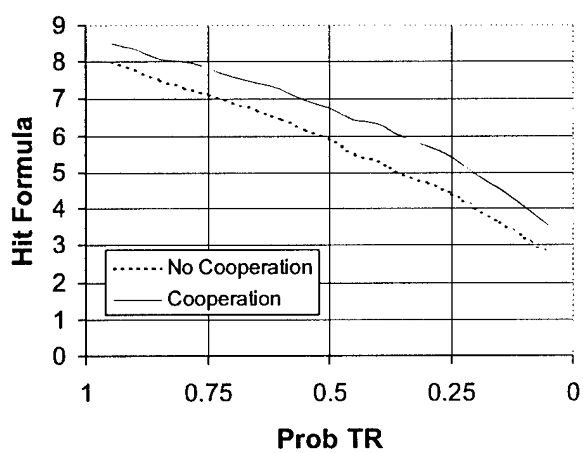

Figure 5.4 Target Formula Sensitivity to P_{TR}

The sensitivity analyses described here could be considered robustness analyses of the weights in the decision algorithm to varying ATR algorithms. What might be of interest for future work is to repeat the previous sensitivity analyses but not keep the decision algorithm the same throughout. Instead, for each ATR algorithm analyzed, determine the ideal weighting parameters for the decision rule using the RSM techniques described in Section 4.2. Doing this should provide an increase in the performance of the cooperative systems over the baseline and may provide some additional insight into these sensitivities.

A final analysis was completed to see the sensitivity to target density. For this analysis, a scenario very similar to that of scenario 3 was used with a few variations. Table 5.13 shows the specific characteristics of this scenario.

Table 5.13 Target Density Sensitivity Scenario Defining Parameters

Parameter	*Value*
P_k	0.5
FTAR	0.009 per square km
P_{TR}	0.80
Target Layout	Widely Dispersed

To do this analysis, the target density was increased by simply increasing the number of targets in the simulation. A total of nine sets of runs were examined using the specific target distribution described in Table 5.14. The number of high priority targets was set equal to the set number. The number of low priority targets was equal to two times the number of high priority targets minus one. The number of non-targets was equal to one less than the number of high priority targets.

Table 5.14 Target Distribution for Each Set of Runs

Set #	*High Priority*	*Low Priority*	*Total Real Targets*	*Non-Target*
1	1	1	2	0
2	2	3	5	1
3	3	5	8	2
4	4	7	11	3
5	5	9	14	4
6	6	11	17	5
7	7	13	20	6
8	8	15	23	7
9	9	17	26	8

Each set of runs consisted of 200 Monte Carlo runs with eight submunitions, and the number of unique kills and the target formula from equation 4.1 were measured for both cooperative behavior and non-cooperative behavior (baseline). Since the battlefield characteristics for this scenario were similar to that of scenario 3, the weights used in the cooperative engagement decision rule were those determined to be ideal for scenario 3 (listed in Table 5.8). The results for the unique kill sensitivity are shown in Figure 5.5, and the results for the target formula sensitivity are shown in Figure 5.6.

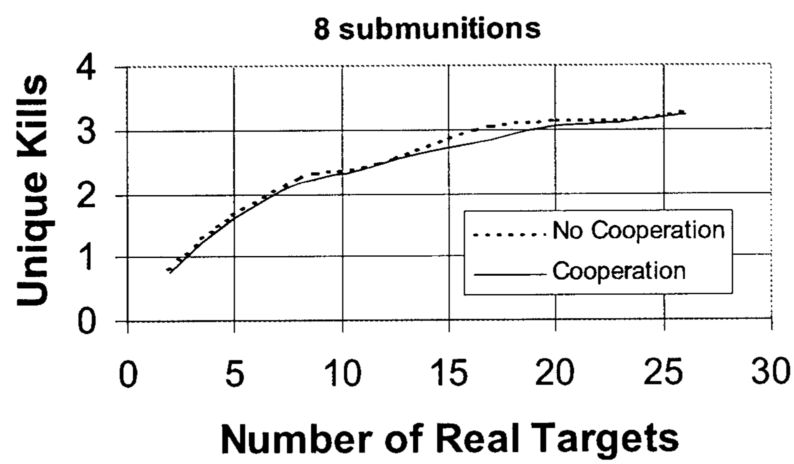

Figure 5.5 Unique Kills Sensitivity to Target Density

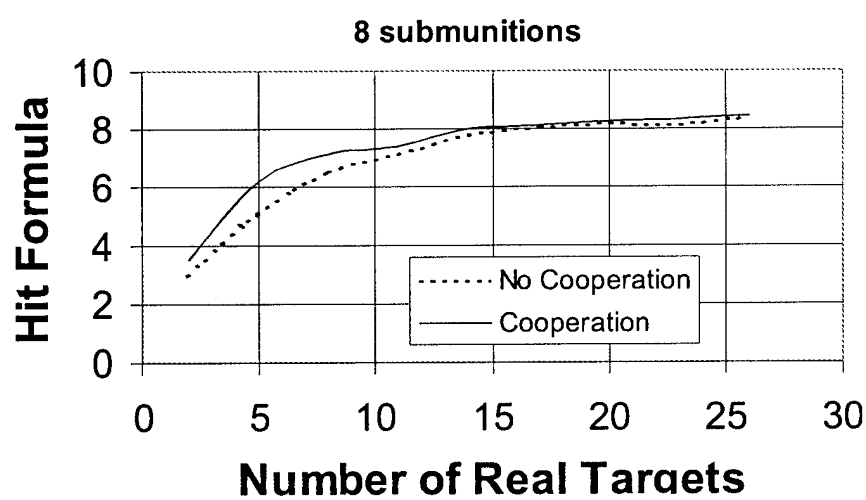

Figure 5.6 Target Formula Sensitivity to Target Density

Looking back at the final results from scenario 3, it is interesting to note that the number of unique kills with cooperation was less than the baseline performance (see Table 5.9).

Therefore, it is not too surprising to see that in Figure 5.5 the results from incorporating cooperation remain slightly worse than the baseline performance results across all target densities. However, Figure 5.6 shows that the target formula (which emphasizes hits on high priority targets) is always greater for the cooperating case than the baseline case. It is especially interesting to note that the greatest improvement seen by the incorporation of cooperative behavior is when the number of real targets in the battlefield is approximately 75% of the number of submunitions employed.

A different way of doing the previous sensitivity analysis would be to vary the number of munitions in the simulation as well as the number of targets. Additional munitions with more overlapping search patterns should provide improved performance, but how much is unknown. This information would be very useful for better understanding the relationships between mission effectiveness, target densities and target-to-munition ratios.

5.3 Robustness

To test the robustness of the optimal decision parameters determined for each scenario, the optimal decision rule for one scenario was run on a different scenario and then compared to the baseline performance. For example, the optimal decision parameters for scenario 1 (as defined in Table 5.2) were implemented in the simulation setup to run scenario 2 (as defined by the parameters listed in Table 5.4). This was done for all combinations of the four scenarios described in the quantitative results section (section 5.1). In general, the results proved very little robustness to the selection of the optimal decision parameters. In most cases, the performance with the sub-optimal decision parameters resulted in a zero to two percent overall improvement over baseline performance, but sometimes resulted in deteriorated performance when compared to the baseline.

With these results an attempt was then made to correlate the values of the optimal weighting parameters to the parameters used to define the different scenarios. The results showed some correlation of the general distribution of weights in the decision algorithms to whether the targets were clustered or widely dispersed, but, due to the diversity in the optimal weighting parameters across all four scenarios, no specific correlations were recognized. The only parameter that displayed some sort of consistency was that associated with the fuel remaining or time of flight–there appears to be some value in waiting until the latter part of the search pattern to choose to cooperatively engage a known target. This, of course, makes sense and allows for the greatest exploration of the entire battlefield.

VI. Conclusions and Recommendations

This research established a methodology for measuring the expected effectiveness of a cooperative system of wide area search munitions. The methods used in this research are not limited to any particular type of wide area search munition and were consciously completed using parameters that describe a very generic wide area search munition. This research, therefore, applies to all wide area search munitions and other cooperative vehicles, and more specific results can be achieved for any specific system by simply modifying the parameters in the effectiveness simulation. Further, the methods developed as part of this research have applications in the more general area of cooperative behavior and control.

The form of cooperative engagement used in this study is most useful in overcoming the limitations on warhead lethality. As the munition size and cost are decreased, the warhead is likely to become less and less lethal. This research shows that some of this loss in lethality can be made up by the use of cooperative engagement. Also, as submunition size decreases, the number of weapons carried by an aircraft increases. This research hints at the possibility of achieving greater results with higher numbers of cooperative munitions carrying non-lethal warheads rather than fewer submunitions with larger, more lethal warheads.

Cooperative engagement employed in this study demonstrated the potential ability to overcome lower P_{TR}'s. However, cooperative engagement alone is not able to compensate for higher false target attack rates. When tuning the precision of an ATR algorithm, the FTAR is often traded-off with P_{TR}. As the algorithm is opened up allowing less of a match to predetermined target images for target identification purposes, then P_{TR} is increased but the number of false alarms is also increased. On the other hand, when the algorithm is tuned so tight requiring almost perfect matches, the FTAR is decreased but some real targets are missed (P_{TR} is decreased). This research hints that when the ATR is being tuned, low FTAR should be favored and the decrease in P_{TR} can possibly be overcome through cooperative engagement. Also, the selection of the optimal weights in the decision algorithm are very sensitive to all battlefield characteristics.

Sensitivity analyses show that for most scenarios, cooperative engagement can provide improvement over completely autonomous performance when the weighting parameters in the decision algorithm are chosen wisely. These analyses specifically identify regions of operation where this form of cooperative engagement is most effective.

To improve the results of this research, additional studies on cooperative search and cooperative discrimination must be included with the cooperative engagement algorithm to better achieve the full synergistic value of cooperative wide area search munitions. Additionally, various decision algorithms should be explored. For example, different parameters could be included in the decision algorithm such as range from target to submunition, and different decision rule forms (second order, inclusion of interaction terms, etc.) can be explored to improve the effectiveness of cooperative engagement. Further, the methods by which each of the specific parameters in the simulation were normalized can be evaluated to possibly reduce the sensitivities of the ideal weights in the decision algorithms. However, even without any of these modifications, some scenarios most likely do exist where the form of cooperative engagement employed by this research will provide more significant improvement than actually demonstrated by the results of this study. Although little investigation has been completed, this research hints at improved performance in a more target-rich scenario with multiple groups of clustered targets where the warhead lethality of the munitions is low. More investigations into diverse scenarios could possibly identify cases where this form of cooperative engagement can be more useful; and equally important, more scenarios can be identified where this form of cooperative engagement is not applicable and causes a deterioration in overall mission effectiveness.

An interesting modification to the simulation could be to allow a submunition to find a target and communicate it, but not engage it. As the simulation currently runs, once a target is identified, the munitions automatically engages it. Altering this behavior could allow multiple munitions to take additional "looks" at targets to better identify them before engaging them and can allow individual submunitions to explore larger portions of the battlefield prior to making an engagement.

Additional methods of optimization could be explored for choosing the ideal weights in the decision algorithm. For example, the parameters resulting in a maximum for one of the responses (found by simple stationary point analysis) can be compared to those found by the Derringer and Suich desirability function method. Also, variations in the choice of weights for each response in the optimization routine used in this research could be explored to possibly find "more optimal" solutions.

Further sensitivity analyses could be conducted using the ideal weights in the decision rule for each variation in the precision of the ATR algorithm instead of keeping the weights constant. Additionally, the sensitivity analysis for the target density could be improved by varying the number of submunitions in addition to varying the number of targets. This can also be modified using various distributions of high and low priority targets and non-targets as well as varying the number of mobile versus stationary targets. Finally, more sensitivity information could be garnered using various RSM techniques to better understand how to choose the weights in the decision algorithm based on the scenario characteristics without having to go through an entire DOE and RSM study.

Appendix A. Sample PSub Files

A.1 Input Files

A.1.1 Main Input File.

```
$RUN_DATA
  RUN_COMMENTS       = 'DOE Test #1'
  DIS                = .F.,  ! RUNNING Distributed Interactive Simulation
  BLIND_IN_TURNS     = .T.,  ! switch to turn on/off seeker in turns
  no_sub_types       = 1,    ! if dis = .t., # seeker_inp sections in this file
  no_pattern_types   = 4,    ! if dis = .t., # patt_inp sections in this file
  NO_REPS            = 200,    ! NUMBER OF MONTE CARLO TRIALS
  XSEED               = '012342' ! MONTE CARLO SEED (TRIAL # WILL BE APPENDED)  JCS MODIFIED FROM SEED
  SIM_TIME_STEP      = 1.0, ! SIMULATION TIME STEP
  OUTPUT_TGT_STATS   = .T., ! OUTPUT ACQ,HIT,KILL DATA FOR TARGET
  OUTPUT_HIST        = 1,   ! TRIAL # for OUTPUT ENTIRE BATTLE HISTORY
  OUTPUT_CUTS        = 1,   ! TRIAL # for OUTPUT ENTIRE ENTRY AND EXIT TIMING
  OUTPUT_PLAYBACK    = 0,   ! TRIAL # for OUTPUT PLAYBACK TRAJECTORIES.
  PRNT_INTRVL        = 1000,   ! MONITOR MONTE CARLO MOD NUMBER
  NO_ROUNDS          = 1,   ! NUMBER OF ROUNDS OR DISPENSERS
  ROUND_REL          = 1.0, ! ROUND RELIABILITY
  USE_CEP            = .T., ! IF .T., 1ST VALUES IN CEP .F. - BOTH VALUES
  TLE(1)             = 100.0,100.0,    ! TLE RANGE AND DEFLECTION
  DISP_CEP(1)        = 13.0,0.0,          ! CEP OR MPI BIAS RANGE AND DEFLECTION
  DISP_PREC(1)       = 1.0,1.0,          ! PREC. RANGE AND DEFLECTION
  AIMX(1)            = 0.0,          ! DISPENSER(OR ROUND) AIM X
  AIMY(1)            = 0.0,         ! DISPENSER(OR ROUND) AIM Y
  PCLOS              = 1.00
  RND_TIME_DISP(1)   = 0,           ! DISPENSER(OR ROUND)TIME FROM DISPENSE TO BEGIN SEARCH
  TGT_AREA_DEF       = 225000,         ! TGT AREA DEFINITION:0-DISREGARD,POS-USE AREA,NEG-CHECK TGTS
  XBFMAX             = 15000.0,        ! BATTLEFIELD DIMENSIONS
  XBFMIN             =-2000.0,
  YBFMAX             = 15000.0,
  YBFMIN             =-2500.0,
  RANDOM_TARGETS     = .T.,  ! PLACE TARGETS RANDOMLY WITHIN A TARGET AREA INPUT BELOW
  TARGET_XMAX        = 5000.0,
  TARGET_XMIN        = 7000.0,
  TARGET_YMAX        = 5000.0,
  TARGET_YMIN        = 7000.0,
  NO_TARGETS         = 10,
$END

$SEEKER_INP  ! SUBMUNITION TYPE / SEEKER DATA INPUT...
  ROUNDS(1)          =-1,      ! ROUNDS THAT USE THIS SUB/SEEK DATA -1 ALL
```

```
   SUB_TYPE            = 'LC'     ! SUBMUNITION TYPE NAME
   SEEKER_TYPE         = 'broomsweep',    ! STARE; BROOMSWEEP; CURVESWEEP
   SUB_REL             = 0.95,    ! SUBMUNITION RELIABILITY
   FTP_WIDTH           = 500.,    ! FOOT PRINT WIDTH
   SEEK_BMW            = 3.4,     ! BEAM WIDTH (DEG.)
   SEEK_DEPRSS         = 13.0,    ! BORESIGHT ANGLES MEAS. +DOWN OFF HORIZ.
   SEEK_SCAN_TIME      = 1.8,   ! TIME fov TO SWEEP FTP_WIDTH
   SEEK_FLYBACK_TIME   = 0.2,
   OVERLAP_DESIRED(1)  = 0.,100.,200.,    ! OVERLAP DIST. FOR SWEEP DESIRED @ this vel & ALT
   MIN_TIME_ACQ        = 0.001,   ! MINIMUM TIME IN FOV TO ACQUIRE A TARGET
   MIN_TURN_RADIUS     = 270.,    ! MINIMUM TURN RADIUS OF SUBMUNITION.
   COOP = 1,   ! Added By Dan Gillen, 15 Sep 00, for unique cooperative rule
RANGEPAR = 0.1,! Added By Dan Gillen, Range Parameter for decision rule
TOFPAR = 0.71,! Added By Dan Gillen, Time Parameter for decision rule
PRIORPAR = 0.48,! Added By Dan Gillen, Priority Parameter for decision rule
NO_ENG_PAR = 0.1,! Added By Dan Gillen, # Engaged Parameter for decision rule
COMM_RANGE = 9806.6,! Added By Dan Gillen
   COOPERATIVE(1)      = 0,       ! 0 - NO COOP; 1-GO NOW; 2-GO @ END OF FP
   COOPERATIVE(2)      = 0,       ! # SUBS CALL: 0 - 1/TGT SEEN; 1-ALL; 2-HALF;3-THIRD...
   COOPERATIVE(3)      = 0,       ! 1 - @ END OF FP,SEND REMAINING SUBS TO FIRST TARGET AREA; 0 - DON'T
   SELECT_COUNTER(1)   = 1,1,
   SELECT_AFT_HDNG     = 0, ! HDNG CHANGE THAT TGT SELECTION SHOULD BEGIN AFTER
   CORRELATE_TGTS      = .F.,    ! CAN SUBMUNITION TELL IF IT'S SEEN A TGT BEFORE
   NTGT_TYPES          = 4,
   TGT_TYPE(1)         = 'PRI1E',  'PRI2L','PRI3A',   'CLUTTER',
   TGT_PLIVE(1)        = 0.0,0.0,0.0,0.0,
   TGT_PRIOR(1)        = 1,2,99,99,
   TGT_PA(1)           = 1.0,1.0,1.0,1.0,
   TGT_PH(1)           = 1.0,1.0,1.0,1.0,
   TGT_PK(1)           = 0.5,0.5,0.5,0.5,
   TGT_PID(1,1)        = 0.95,0.016666,0.016666,0.016666,
TGT_PID(1,2)        = 0.0125,0.95,0.025,0.0125,
   TGT_PID(1,3) = 0.0125,0.025,0.95,0.0125,
TGT_PID(1,4) = 0.0475,0.0475,0.0,0.905,
   CLUTTER_DENSITY     = 0.05,           ! CLUTTER TARGET DENS. (PER KM**2)
 $END

 $PATT_INP   ! PATTERN DATA INPUT...
   ROUNDS(1)           = 0,          ! ROUNDS THAT USE THIS PATTERN DATA -1 ALL
   TYPE                = 'RACETRAK',  ! SPIRAL; CIRCLE; LINE; RACETRAK; DUMB
   RED_TGT_HDNG        = .F.,
   POWERED             = .T.,        ! ARE SUBS POWERED ( .false. = glide or dumb)
   RACETRACK_LENGTH    = 4500.,
   RACETRACK_WIDTH     = 4000.,
   RACETRACK_NO_REVS   = 2,
   FTP_TOF             = 1680.,      ! or END OF FOOT PRINT CUT OFF; TOF
```

```
   SUB_ALT            = 300.,       ! SUBMUNITION ALTITUDE
   SUB_VEL            = 100.,       ! METERS/SEC.
   NO_SUBS_IN_PAT     = 4,          ! # SUBMUNIIONS IN PATTERN/ROUND
   DISP_OPTION        = 'U_RLINE', ! BIVNORML; R_RLINE; U_RLINE;R_DLINE; U_DLINE; NONE
   DISP_RNGE          = 1500.,
   DISP_DEFL          = 0.,
   DISP_HEADING       = 0.,         ! DISPENSE HEADING (SUB'S INITIAL HDNG)
   DISP_DELAY         = 0.0,        ! DELAY BETWEEN SUBS OUT OF DISPENSER
$END
$PATT_INP
   ROUNDS(1)          = 0,          ! ROUNDS THAT USE THIS PATTERN DATA -1 ALL
   TYPE               = 'DUMB',     ! SPIRAL; CIRCLE; LINE; RACETRAK; DUMB
   RED_TGT_HDNG       = .F.,
   POWERED            = .F.,        ! ARE SUBS POWERED ( .false. = glide or dumb)
   LETHAL_RADIUS      = 25.0,       ! for dumb munitions
   NO_SUBS_IN_PAT     = 380,        ! # SUBMUNIIONS IN PATTERN/ROUND
   DISP_OPTION        ='bivnorml', ! BIVNORML; R_RLINE; U_RLINE;R_DLINE; U_DLINE; NONE
   DISP_RNGE          = 200.,
   DISP_DEFL          = 200.,
   DISP_DELAY         = 0.0,        ! DELAY BETWEEN SUBS OUT OF DISPENSER
$END
$PATT_INP
   ROUNDS(1)          = -1,         ! ROUNDS THAT USE THIS PATTERN DATA -1 ALL
   TYPE               = 'LINE',     ! SPIRAL; CIRCLE; LINE; RACETRAK; DUMB
   POWERED            = .T.,        ! ARE SUBS POWERED ( .false. = glide or dumb)
   FTP_TOF            = 1200,    ! or END OF FOOT PRINT CUT OFF; TOF
   SUB_ALT            = 200.,       ! SUBMUNITION ALTITUDE
   SUB_VEL            = 100.,        ! METERS/SEC.
   NO_SUBS_IN_PAT     = 8,          ! # SUBMUNIIONS IN PATTERN/ROUND
   DISP_OPTION        = 'U_DLINE', ! BIVNORML; R_RLINE; U_RLINE;R_DLINE; U_DLINE; NONE
   DISP_RNGE          = 0.,
   DISP_DEFL          = 3000.,
   DISP_HEADING       = 90.0,         ! DISPENSE HEADING (SUB'S INITIAL HDNG)
   DISP_DELAY         = 0.5,        ! DELAY BETWEEN SUBS OUT OF DISPENSER
   DISP_SUB_CEP       = 3.0,
$END
$PATT_INP
   ROUNDS(1)          =  0,         ! ROUNDS THAT USE THIS PATTERN DATA -1 ALL
   TYPE               = 'CIRCLE4', ! SPIRAL; CIRCLE; LINE; RACETRAK; DUMB
   RED_TGT_HDNG       = .F.,
   POWERED            = .T.,        ! ARE SUBS POWERED ( .false. = glide or dumb)
   FTP_TOF            = 1800.,      ! or END OF FOOT PRINT CUT OFF; TOF
   SUB_ALT            = 300.,       ! SUBMUNITION ALTITUDE
   SUB_VEL            = 100.,       ! METERS/SEC.
   CENTERX            = 0.,         ! CENTER OF SPIRAL OR CIRCLE X  relative
   CENTERY            = 1500.,      ! CENTER OF SPIRAL OR CIRCLE Y  relative
```

```
  START_RADIUS        = 1500.,       ! START POINT IN SPIRAL OR CIRCLE FOR 1st SUB.
  SCALE               = 1.,          ! Scale the circle size
  NO_SUBS_IN_PAT      = 4,           ! # SUBMUNIIONS IN PATTERN/ROUND
  START_ANGLE(1)      = 315.,135.,-135.,-315.,  ! Circle : each sub
  START_TIME(1)       = 4*-1., !4*94.16,     ! Circle : each sub  -1 for calculated time
  JOIN_ANGLE(1)       = 315.,135.,135.,315.,    ! Circle : each sub
  JOIN_RADIUS(1)      = 500.,500.,500.,500.,    ! Circle : each sub
  FRAC_CIRC           = 1.0,         ! FRACTION OF CIRCLE COVERED.
  SUB_SEPARATION      = 700.,        ! DIST BETWEEN SUCCESSIVE "RINGS" IN SPIRAL OR CIRCLE
  SPIRAL_MOVE         = 0,           ! 0 - MOVES OUTWARD; 1 - INWARD
  DISP_OPTION         = 'U_DLINE',   ! BIVNORML; R_RLINE; U_RLINE;R_DLINE; U_DLINE; NONE
  DISP_RNGE           = 0.,
  DISP_DEFL           = 1200.,
  DISP_HEADING        = 90.,         ! DISPENSE HEADING (SUB'S INITIAL HDNG)
  DISP_DELAY          = 0.0,         ! DELAY BETWEEN SUBS OUT OF DISPENSER
$END

/* TARGET DATA INPUT */
                                                  HEADING SPEED START   ACCEL
TARGET   TYPE        X       Y        Z      (DEG.)  (K/H) TIME(S) TIME
-------  ------    -----   -----    -----   ------- ----- ------- ----
'TGT1E'  'PRI1E'   2084.   3910.    0.0     45.0     10.  0.  0.  5.
'TGT2E'  'PRI1E'   5200    5950     0.0     0.0      0.   0.  0.  5.
'TGT3E'  'PRI1E'   6200    5950     0.0     0.0      0.   0.  0.  5.
'TGT4L'  'PRI2L'   5900.   6100.    0.0     135.0    10.  0.  0.  5.
'TGT5L'  'PRI2L'   5900.   5930.    0.0     215.0    10.  0.  0.  5.
'TGT6L'  'PRI2L'   6100.   6100.    0.0     0.0      0.   0.  0.  5.
'TGT7L'  'PRI2L'   5100.   6100.    0.0     0.0      0.   0.  0.  5.
'TGT8L'  'PRI2L'   6100.   5940.    0.0     0.0      0.   0.  0.  5.
'TGT9A'  'PRI3A'   6000.   6120.    0.0     315.0    10.  0.  0.  5.
'TGT10A' 'PRI3A' 5800    6050     0.0     0.0      0.   0.  0.  5.


                      LENGTH   WIDTH
  TYPE      R OR F     (M)      (M)    # ALT TYPES
  -----     ------    ------   -----   -----------
  'PRI1E'     'R'      0.1      0.1      0
  'PRI2L'     'R'      0.1      0.1      0
  'PRI3A'     'F'      0.1      0.1      0
  'CLUTTER'  'F'   0.1   0.1     0
```

A.1.2 Flight Path Input File for 8 Submunitions.

```
LINE        ! Pattern Name
0              ! file contains :  0 - # subs per round; 1 - all subs in game
1, 2, 3, 4,       Munition #
200.0 100 90.0   Altitude, Velocity & Heading(0 along +X axis(i.e.,deflection))
RANGE
     13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
      13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
     -180.
GO
RANGE
```

```
    13200.
GO
RADIUS
     850.
THETA
     180.
GO
RANGE
     13200.
GO
RADIUS
     850.
THETA
    -180.
GO
RANGE
    13200.
GO
 RADIUS
     850.
THETA
     180. !end of first sweep
GO
RANGE
    13200.
GO
RADIUS
     850. ! Offset next sweep by 0 meters
THETA
     180.
GO
RANGE
     13200.
GO
RADIUS
     850.
THETA
    -180.
GO
RANGE
    13200.
GO
 RADIUS
     850.
THETA
     180.
```

```
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
     -180.  ! end of second sweep
GO
RANGE
     13200.
GO
RADIUS
      850.
```

```
THETA
     -180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
```

```
 RADIUS
       850.
 THETA
      -180.
 GO
 RANGE
      13200.
 GO
 RADIUS
       850.
 THETA
       180. !end of third sweep
GO
 RANGE
      13200.
 GO
 RADIUS
       850.
 THETA
       180.
 GO
 RANGE
      13200.
 GO
 RADIUS
       850.
 THETA
      -180.
GO
 RANGE
      13200.
 GO
 RADIUS
       850.
 THETA
       180.
 GO
 RANGE
      13200.
 GO
 RADIUS
       850.
 THETA
      -180.
 GO
 RANGE
```

```
      13200.
 GO
 RADIUS
       850.
 THETA
       180.
GO
 RANGE
      13200.
 GO
 RADIUS
       850.
 THETA
      -180.
 GO
 RANGE
      13200.
 GO
 RADIUS
       850.
 THETA
       180.
 GO
 RANGE
      13200.
 GO
 RADIUS
       850.
 THETA
      -180. !end of forth sweep
GO
EXIT
5,       Munition #
 200.0 100 0.0   Altitude, Velocity & Heading(0 along +X axis(i.e.,deflection))
 RANGE
       13200.
 GO
 RADIUS
       850.
 THETA
      180.
 GO
 RANGE
      13200.
 GO
  RADIUS
```

```
      850.
THETA
      -180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
     180.
GO
RANGE
      13200.
GO
RADIUS
      850.
THETA
      -180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
     180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
      -180.
GO
RANGE
      13200.
GO
RADIUS
      850.
THETA
     180.
GO
RANGE
     13200.
```

```
GO
 RADIUS
      850.
THETA
      -180. !end of first sweep
GO
EXIT
6,        Munition #
200.0 100 90.0   Altitude, Velocity & Heading(0 along +X axis(i.e.,deflection))
RANGE
      200.
GO
RADIUS
      270.
THETA
     -90.
GO
RANGE
     12500.
GO
 RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
      13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
```

```
THETA
     -180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
      13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
      -180. !end of first sweep
GO
EXIT
7,       Munition #
200.0 100 90.0   Altitude, Velocity & Heading(0 along +X axis(i.e.,deflection))
RANGE
      600.
GO
RADIUS
      270.
THETA
     -90.
GO
```

```
RANGE
     12050.
GO
 RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
      13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
     -180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
      13200.
GO
RADIUS
      850.
THETA
```

```
     -180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
      -180. !end of first sweep
GO
EXIT
8,      Munition #
200.0 100 90.0   Altitude, Velocity & Heading(0 along +X axis(i.e.,deflection))
RANGE
      1000.
GO
RADIUS
      270.
THETA
     -90.
GO
RANGE
     11600.
GO
 RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
```

```
      13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
     -180.
GO
RANGE
     13200.
GO
RADIUS
      850.
THETA
      180.
GO
RANGE
      13200.
GO
RADIUS
      850.
THETA
     -180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
      180.
GO
RANGE
     13200.
GO
 RADIUS
      850.
THETA
      -180. !end of first sweep
```

```
GO
EXIT
```

A.2 Output Files

A.2.1 Main Output File for Example of 10 (instead of 200) Monte Carlo Runs.

```
*****************************************************************************************************
                        POWERED SUBMUNITION MODEL, VERSION 4A

SUBMUNITION INPUT FILE IS: thesis.in
SUBMUNITION SEARCH PATTERN FILE IS: 8sub.cmd
RUN BEGAN: Tue Feb 13 14:57:12 2001
*****************************************************************************************************
*** DOE Test #1
RANDUM SEED: 012342
DISPENSER RELIABILITY: 1.00
TARGET LOCATION ERROR CEP (METERS):   100.00
DISPENSER CEP (METERS):    13.00
DISPENSER PRECISION ERROR:  1.00 ,  1.00
PCLOS: 1.00
INGRESS TIME (SECONDS):     0.00
AIM POINT (X):      0.00
AIM POINT (Y):      0.00
NUMBER OF TARGETS:  10
RANDOM TARGETS?:  T
TARGET AREA XMAX:  5000.00
TARGET AREA XMIN:  7000.00
TARGET AREA YMAX:  5000.00
TARGET AREA YMIN:  7000.00
NUMBER OF TARGETS:  10
Value for Dans Variable is   1.000000
RANGEPAR =   0.1000000     TOFPAR =   0.7100000     PRIORPAR =   0.4800000
 NO_ENG_PAR =   0.1000000
Communications Max Range =    9806.600
 FOR CURRENT SUB VEL & SCAN TIME, OVERLAP IS :   38.54754
SUBMUNITION RELIABILITY: 0.95
SEEKER FOOT PRINT WIDTH (METERS): 500.0
SEEKER BEAM WIDTH:  3.4
SEEKER DEPRESSION ANGLE: 13.0
SEEKER SCAN TIME: 1.800
SEEKER FLYBACK TIME: 0.200
MINIMUM TURN RADIUS (METERS): 270.00
COOPERATIVE ENGAGEMENT IS NOT IMPLEMENTED
COUNTER LOGIC IS:   1 ,   1
SUBMUNITION TOTAL SEARCH TIME: 1200.00
SUBMUNITION SEARCH ALTITUDE (METERS): 200.0
SUBMUNITION SEARCH VELOCITY (M/S): 100.0
NUMBER OF SUBMUNITIONS IN PATTERN:  8
SUBMUNITION DISPENSE DEFLECTION (METERS):  3000.00
SUBMUNITION INITIAL HEADING (DEGS): 90.00
SUBMUNITION DISPENSE DELAY(SECS):  0.50
SUBMUNITION DISPENSE CEP (METERS):  3.00
```

TARGET	TYPE	X	Y	Z	HDNG	SPEED	START	TIMES	ACCEL TIME
TGT1E	PRI1E	2084.00	3910.00	0.00	45.0	10.0	0.0	0.0	5.0
TGT2E	PRI1E	5200.00	5950.00	0.00	0.0	0.0	0.0	0.0	5.0
TGT3E	PRI1E	6200.00	5950.00	0.00	0.0	0.0	0.0	0.0	5.0
TGT4L	PRI2L	5900.00	6100.00	0.00	135.0	10.0	0.0	0.0	5.0
TGT5L	PRI2L	5900.00	5930.00	0.00	215.0	10.0	0.0	0.0	5.0
TGT6L	PRI2L	6100.00	6100.00	0.00	0.0	0.0	0.0	0.0	5.0
TGT7L	PRI2L	5100.00	6100.00	0.00	0.0	0.0	0.0	0.0	5.0
TGT8L	PRI2L	6100.00	5940.00	0.00	0.0	0.0	0.0	0.0	5.0
TGT9A	PRI3A	6000.00	6120.00	0.00	315.0	10.0	0.0	0.0	5.0
TGT10A	PRI3A	5800.00	6050.00	0.00	0.0	0.0	0.0	0.0	5.0

PRI1E	R	0.10	0.10
PRI2L	R	0.10	0.10
PRI3A	F	0.10	0.10

****

REP NO = 1

**** COOP ENGAGEMENT (DECISION RULE) SUMMARY ****

	RANGE RATE		TIME		PRIORITY		NO_ENGAGE		(THRESHOLD = 1.00)
SUB #	PARAM	NORM	PARAM	NORM	PARAM	NORM	PARAM	NORM	DECISION
5	0.10	0.9754	0.71	0.5954	0.48	1.0000	0.10	0.0000	1.00
2	0.10	0.9843	0.71	0.5958	0.48	1.0000	0.10	0.0000	1.00
1	0.10	0.9805	0.71	0.7354	0.48	1.0000	0.10	1.0000	1.00

**** SMART SUB SUMMARY ****

SUB#	RND#	REL FAIL	#CUTS	#ACQ	SEL#	ACQ SLCTD	TGT# SLCTD	#PRI. TGTS ACQ	ACQ SLCTD HI PRI	HIT	KILL	FLS	CLT	#NOT ENUF TIME
1	1	F	1	1	1	0	2	0	0	T	F	F	F	0
2	1	F	2	2	1	0	3	1	0	T	F	F	F	0
3	1	F	2	2	1	0	5	1	0	T	T	F	F	0
4	1	F	2	2	1	0	4	1	0	T	F	F	F	0
5	1	F	4	4	1	0	3	0	0	T	T	F	F	0
6	1	F	2	2	1	0	2	0	0	T	T	F	F	0
7	1	F	1	1	1	0	105	0	0	F	F	F	T	0
8	1	F	4	4	1	0	3	0	0	T	F	F	F	0

**** SMART SUB LOSS ****

REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RND REL F

0	0	0	0	0	1	0	2	2	0
0.0	0.0	0.0	0.0	0.0	12.5	0.0	25.0	25.0	0.0

TOTAL LOST : 5 62.5

DG: End of Rep 1
DG: Total # of Reps = 10

****

REP NO = 2

**** COOP ENGAGEMENT (DECISION RULE) SUMMARY ****

	RANGE RATE		TIME		PRIORITY		NO_ENGAGE		(THRESHOLD = 1.00)
SUB #	PARAM	NORM	PARAM	NORM	PARAM	NORM	PARAM	NORM	DECISION

**** SMART SUB SUMMARY ****

								#PRI.	ACQ					#NOT
		REL				ACQ	TGT#	TGTS	SLCTD					ENUF
SUB#	RND#	FAIL	#CUTS	#ACQ	SEL#	SLCTD	SLCTD	ACQ	HI PRI	HIT	KILL	FLS	CLT	TIME
1	1	F	2	2	1	0	5	1	0	T	T	F	F	0
2	1	F	3	3	1	0	7	1	0	T	F	F	F	0
3	1	F	2	2	1	0	3	0	0	T	T	F	F	0
4	1	F	2	2	1	0	2	0	0	T	F	F	F	0
5	1	F	1	1	1	0	3	0	0	T	F	F	F	0
6	1	F	3	3	1	0	8	1	0	T	F	F	F	0
7	1	F	1	1	1	0	108	0	0	F	F	F	T	0
8	1	F	3	3	1	0	6	1	0	T	T	F	F	0

**** SMART SUB LOSS ****

REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RND REL F
0	0	0	0	0	1	0	0	4	0
0.0	0.0	0.0	0.0	0.0	12.5	0.0	0.0	50.0	0.0

TOTAL LOST : 5 62.5

DG: End of Rep 2
DG: Total # of Reps = 10

****

REP NO = 3

**** COOP ENGAGEMENT (DECISION RULE) SUMMARY ****

	RANGE RATE		TIME		PRIORITY		NO_ENGAGE		(THRESHOLD = 1.00)
SUB #	PARAM	NORM	PARAM	NORM	PARAM	NORM	PARAM	NORM	DECISION

**** SMART SUB SUMMARY ****

								#PRI.	ACQ					#NOT
		REL				ACQ	TGT#	TGTS	SLCTD					ENUF
SUB#	RND#	FAIL	#CUTS	#ACQ	SEL#	SLCTD	SLCTD	ACQ	HI PRI	HIT	KILL	FLS	CLT	TIME
1	1	F	3	3	1	0	8	1	0	T	F	F	F	0
2	1	F	2	2	1	0	7	1	0	T	T	F	F	0
3	1	F	1	1	1	0	4	1	0	T	T	F	F	0
4	1	F	1	1	1	0	111	0	0	F	F	F	T	0
5	1	F	2	2	1	0	8	1	0	T	F	F	F	0
6	1	F	4	4	1	0	3	0	0	T	F	F	F	0
7	1	F	1	1	1	0	102	0	0	F	F	F	T	0
8	1	F	1	1	1	0	6	1	0	T	F	F	F	0

**** SMART SUB LOSS ****

REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RND REL F
0	0	0	0	0	2	0	0	4	0
0.0	0.0	0.0	0.0	0.0	25.0	0.0	0.0	50.0	0.0

TOTAL LOST : 6 75.0

DG: End of Rep 3

DG: Total # of Reps = 10

****

REP NO = 4

**** COOP ENGAGEMENT (DECISION RULE) SUMMARY ****

	RANGE RATE		TIME		PRIORITY		NO_ENGAGE		(THRESHOLD = 1.00)
SUB #	PARAM	NORM	PARAM	NORM	PARAM	NORM	PARAM	NORM	DECISION
3	0.10	0.9876	0.71	0.5946	0.48	1.0000	0.10	0.0000	1.00

**** SMART SUB SUMMARY ****

								#PRI.	ACQ					#NOT
		REL				ACQ	TGT#	TGTS	SLCTD					ENUF
SUB#	RND#	FAIL	#CUTS	#ACQ	SEL#	SLCTD	SLCTD	ACQ	HI PRI	HIT	KILL	FLS	CLT	TIME
1	1	F	2	2	1	0	8	1	0	T	F	F	F	0
2	1	F	2	2	1	0	5	1	0	T	F	F	F	0
3	1	F	4	4	1	0	2	0	0	T	F	F	F	0

4	1	F	4	4	1	0	2	0	0	T	F	F	F	0
5	1	F	4	4	1	0	5	1	0	T	F	F	F	0
6	1	F	2	2	1	0	2	0	0	T	T	F	F	0
7	1	F	3	3	1	0	3	0	0	T	F	F	F	0
8	1	F	3	3	1	0	6	1	0	T	T	F	F	0

**** SMART SUB LOSS ****

REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RND REL F
0	0	0	0	0	0	0	2	4	0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0	50.0	0.0

TOTAL LOST : 6 75.0

DG: End of Rep 4

DG: Total # of Reps = 10

****

REP NO = 5

**** COOP ENGAGEMENT (DECISION RULE) SUMMARY ****

	RANGE RATE		TIME		PRIORITY		NO_ENGAGE		(THRESHOLD = 1.00)
SUB #	PARAM	NORM	PARAM	NORM	PARAM	NORM	PARAM	NORM	DECISION

**** SMART SUB SUMMARY ****

								#PRI.	ACQ					#NOT
		REL				ACQ	TGT#	TGTS	SLCTD					ENUF
SUB#	RND#	FAIL	#CUTS	#ACQ	SEL#	SLCTD	SLCTD	ACQ	HI PRI	HIT	KILL	FLS	CLT	TIME
1	1	F	5	5	1	0	101	0	0	F	F	F	T	0
2	1	T	0	0	1	0	0	0	0	F	F	F	F	0
3	1	F	2	2	1	0	8	1	0	T	T	F	F	0
4	1	F	6	6	1	0	0	1	0	F	F	F	F	0
5	1	F	6	6	1	0	2	0	0	T	F	F	F	0
6	1	F	3	3	1	0	7	1	0	T	F	F	F	0
7	1	F	1	1	1	0	106	0	0	F	F	F	T	0
8	1	F	1	1	1	0	8	1	0	T	F	F	F	0

**** SMART SUB LOSS ****

REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RND REL F
1	0	0	1	0	2	0	0	3	0
12.5	0.0	0.0	12.5	0.0	25.0	0.0	0.0	37.5	0.0

TOTAL LOST : 7 87.5

DG: End of Rep 5
DG: Total # of Reps = 10

****

REP NO = 6

**** COOP ENGAGEMENT (DECISION RULE) SUMMARY ****

	RANGE RATE		TIME		PRIORITY		NO_ENGAGE		(THRESHOLD = 1.00)
SUB #	PARAM	NORM	PARAM	NORM	PARAM	NORM	PARAM	NORM	DECISION

**** SMART SUB SUMMARY ****

SUB#	RND#	REL FAIL	#CUTS	#ACQ	SEL#	ACQ SLCTD	TGT# SLCTD	#PRI. TGTS ACQ	ACQ SLCTD HI PRI	HIT	KILL	FLS	CLT	#NOT ENUF TIME
1	1	F	5	5	1	0	6	1	0	T	F	F	F	0
2	1	F	2	2	1	0	7	1	0	T	T	F	F	0
3	1	F	1	1	1	0	5	1	0	T	F	F	F	0
4	1	F	1	1	1	0	4	1	0	T	F	F	F	0
5	1	F	4	4	1	0	7	1	0	T	F	F	F	0
6	1	F	2	2	1	0	10	0	0	F	F	T	F	0
7	1	F	1	1	1	0	8	1	0	T	F	F	F	0
8	1	F	3	3	1	0	103	0	0	F	F	F	T	0

**** SMART SUB LOSS ****

REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RND REL F
0	0	0	0	1	1	0	0	5	0
0.0	0.0	0.0	0.0	12.5	12.5	0.0	0.0	62.5	0.0

TOTAL LOST : 7 87.5

DG: End of Rep 6
DG: Total # of Reps = 10

****

REP NO = 7

**** COOP ENGAGEMENT (DECISION RULE) SUMMARY ****

	RANGE RATE		TIME		PRIORITY		NO_ENGAGE		(THRESHOLD = 1.00)
SUB #	PARAM	NORM	PARAM	NORM	PARAM	NORM	PARAM	NORM	DECISION
3	0.10	0.9684	0.71	0.5962	0.48	1.0000	0.10	0.0000	1.00

**** SMART SUB SUMMARY ****

SUB#	RND#	REL FAIL	#CUTS	#ACQ	SEL#	ACQ SLCTD	TGT# SLCTD	#PRI. TGTS ACQ	ACQ SLCTD HI PRI	HIT	KILL	FLS	CLT	#NOT ENUF TIME
1	1	F	1	1	1	0	102	0	0	F	F	F	T	0
2	1	F	3	3	1	0	8	1	0	T	F	F	F	0
3	1	F	4	4	1	0	2	0	0	T	F	F	F	0
4	1	F	1	1	1	0	3	0	0	T	F	F	F	0
5	1	F	6	5	1	0	8	1	0	T	T	F	F	0
6	1	F	3	3	1	0	6	1	0	T	T	F	F	0
7	1	F	1	1	1	0	2	0	0	T	T	F	F	0
8	1	F	1	1	1	0	5	1	0	T	F	F	F	0

**** SMART SUB LOSS ****

REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RND REL F
0	0	0	0	0	1	0	2	2	0
0.0	0.0	0.0	0.0	0.0	12.5	0.0	25.0	25.0	0.0

TOTAL LOST : 5 62.5

DG: End of Rep 7

DG: Total # of Reps = 10

****

REP NO = 8

**** COOP ENGAGEMENT (DECISION RULE) SUMMARY ****

SUB #	RANGE RATE PARAM	RANGE RATE NORM	TIME PARAM	TIME NORM	PRIORITY PARAM	PRIORITY NORM	NO_ENGAGE PARAM	NO_ENGAGE NORM	(THRESHOLD = 1.00) DECISION

**** SMART SUB SUMMARY ****

SUB#	RND#	REL FAIL	#CUTS	#ACQ	SEL#	ACQ SLCTD	TGT# SLCTD	#PRI. TGTS ACQ	ACQ SLCTD HI PRI	HIT	KILL	FLS	CLT	#NOT ENUF TIME
1	1	F	1	1	1	0	7	1	0	T	T	F	F	0
2	1	F	2	2	1	0	2	0	0	T	F	F	F	0
3	1	F	1	1	1	0	107	0	0	F	F	F	T	0
4	1	F	3	3	1	0	8	1	0	T	T	F	F	0
5	1	F	1	1	1	0	2	0	0	T	T	F	F	0
6	1	F	1	1	1	0	6	1	0	T	F	F	F	0

7	1	F	4	4	1	0	7	1	0	T	F	F	F	0
8	1	F	4	4	1	0	4	1	0	T	F	F	F	0

**** SMART SUB LOSS ****

REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RND REL F
0	0	0	0	0	1	0	1	3	0
0.0	0.0	0.0	0.0	0.0	12.5	0.0	12.5	37.5	0.0

TOTAL LOST : 5 62.5

DG: End of Rep 8
DG: Total # of Reps = 10

****

REP NO = 9

**** COOP ENGAGEMENT (DECISION RULE) SUMMARY ****

	RANGE RATE		TIME		PRIORITY		NO_ENGAGE		(THRESHOLD = 1.00)
SUB #	PARAM	NORM	PARAM	NORM	PARAM	NORM	PARAM	NORM	DECISION
3	0.10	0.9913	0.71	0.5946	0.48	1.0000	0.10	0.0000	1.00
6	0.10	0.9249	0.71	0.6025	0.48	1.0000	0.10	0.0000	1.00

**** SMART SUB SUMMARY ****

SUB#	RND#	REL FAIL	#CUTS	#ACQ	SEL#	ACQ SLCTD	TGT# SLCTD	#PRI. TGTS ACQ	ACQ SLCTD HI PRI	HIT	KILL	FLS	CLT	#NOT ENUF TIME
1	1	F	1	1	1	0	113	0	0	F	F	F	T	0
2	1	F	3	3	1	0	6	1	0	T	F	F	F	0
3	1	F	5	5	1	0	8	1	0	T	F	F	F	0
4	1	T	0	0	1	0	0	0	0	F	F	F	F	0
5	1	F	2	2	1	0	3	0	0	T	F	F	F	0
6	1	F	4	4	1	0	3	0	0	T	F	F	F	0
7	1	F	4	3	1	0	5	1	0	T	F	F	F	0
8	1	F	3	3	1	0	8	1	0	T	T	F	F	0

**** SMART SUB LOSS ****

REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RND REL F
1	0	0	0	0	1	0	1	4	0
12.5	0.0	0.0	0.0	0.0	12.5	0.0	12.5	50.0	0.0

TOTAL LOST : 7 87.5

DG: End of Rep 9
DG: Total # of Reps = 10

****

REP NO = 10

**** COOP ENGAGEMENT (DECISION RULE) SUMMARY ****

	RANGE RATE		TIME		PRIORITY		NO_ENGAGE		(THRESHOLD = 1.00)
SUB #	PARAM	NORM	PARAM	NORM	PARAM	NORM	PARAM	NORM	DECISION
4	0.10	0.9810	0.71	0.5950	0.48	1.0000	0.10	0.0000	1.00

**** SMART SUB SUMMARY ****

SUB#	RND#	REL FAIL	#CUTS	#ACQ	SEL#	ACQ SLCTD	TGT# SLCTD	#PRI. TGTS ACQ	ACQ SLCTD HI PRI	HIT	KILL	FLS	CLT	#NOT ENUF TIME
1	1	F	5	5	1	0	7	1	0	T	F	F	F	0
2	1	F	1	1	1	0	105	0	0	F	F	F	T	0
3	1	F	4	4	1	0	5	2	0	T	F	F	F	0
4	1	F	5	5	1	0	3	0	0	T	F	F	F	0
5	1	F	2	2	1	0	6	1	0	T	F	F	F	0
6	1	F	2	2	1	0	2	0	0	T	F	F	F	0
7	1	F	4	4	1	0	3	0	0	T	T	F	F	0
8	1	F	1	1	1	0	3	0	0	T	F	F	F	0

**** SMART SUB LOSS ****

REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RND REL F
0	0	0	0	0	1	0	1	5	0
0.0	0.0	0.0	0.0	0.0	12.5	0.0	12.5	62.5	0.0

TOTAL LOST : 7 87.5

DG: End of Rep 10
DG: Total # of Reps = 10

HIT/KILL FREQ		
4	1	0
6	3	0
7	5	0
8	1	0

**** SMART SUB LOSS AVG ****

THE AVERAGE NUMBER OF SUBMUNITIONS LOST BY CAUSE

	REL F	NO CUT	NO ACQ	NO SEL	FLSTGT	CLTTGT	NO HIT	DEDTGT	NO KIL	RFAIL
AVG	0.200	0.000	0.000	0.100	0.100	1.100	0.000	0.900	3.600	0.000
TOT	2.500	0.000	0.000	1.250	1.250	13.750	0.000	11.250	45.000	0.000

TOTAL LOST : 6.0 75.0

	# ACQUISITIONS		# SELECTIONS		# HITS		# KILLS		# UNIQUE KILLS	
TARGET	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV
1 TGT1E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2 TGT2E	1.50	1.18	1.20	1.03	1.20	1.03	0.60	0.84	0.40	0.52
3 TGT3E	1.40	1.07	1.30	1.16	1.30	1.16	0.40	0.70	0.30	0.48
4 TGT4L	0.50	0.53	0.40	0.52	0.40	0.52	0.10	0.32	0.10	0.32
5 TGT5L	0.90	0.57	0.80	0.63	0.80	0.63	0.20	0.42	0.20	0.42
6 TGT6L	0.80	0.42	0.80	0.42	0.80	0.42	0.30	0.48	0.30	0.48
7 TGT7L	0.90	0.74	0.80	0.79	0.80	0.79	0.30	0.48	0.30	0.48
8 TGT8L	1.20	0.79	1.20	0.79	1.20	0.79	0.40	0.52	0.40	0.52
9 TGT9A	1.10	1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 TGT10A	1.00	0.94	0.10	0.32	0.00	0.00	0.00	0.00	0.00	0.00

TOTAL # OF UNIQUE KILLS WAS : 2.00

	# ACQUISITIONS		# SELECTIONS		# HITS		# KILLS		# UNIQUE KILLS	
TARGET	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV
PRI1E	2.900	1.792	2.500	1.581	2.500	1.581	1.000	0.943	0.700	0.675

```
*  PRI2L     4.300   0.823   4.000   1.155   4.000   1.155   1.300   0.675   1.300   0.675  *
*  PRI3A     2.100   1.792   0.100   0.316   0.000   0.000   0.000   0.000   0.000   0.000  *
*                                                                                           *
*                                                                                           *
*  TOTAL # OF UNIQUE KILLS WAS :   2.00                                                     *
*  TOTAL # OF KILLS WAS :   2.30                                                            *
*                                                                                           *
*                                                                                           *
*********************************************************************************************

TOTAL NUMBER OF ROUND FAILURES :    0 OUT OF :   10   RES. REL. : 1.00
TOTAL NUMBER OF SUB   FAILURES :    2 OUT OF :   78   RES. REL. : 0.97
TOTAL NUMBER OF PK    FAILURES :   42 OUT OF :   65   RES. PK   : 0.35
*********************************************************************************************
RUN FINISHED: Tue Feb 13 14:57:20 2001
*********************************************************************************************
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A.2.2 History Output File for 1 Repetition.

TIME	TARGET				SUBMUN		ID		EVENT	THREAT COORDINATES		
(SEC.)	#	TYPENAME	X	Y	#	TYPENAME	#	TYPENAME	DESCRIPTION	X	Y	Z
0.500	0	--------	-9999.00	-9999.00	1	SUB	0	--------	SUB: DISPENSED	-1564.22	219.73	200.00
1.000	0	--------	-9999.00	-9999.00	2	SUB	0	--------	SUB: DISPENSED	-1130.60	215.13	200.00
1.500	0	--------	-9999.00	-9999.00	3	SUB	0	--------	SUB: DISPENSED	-704.78	211.80	200.00
2.000	0	--------	-9999.00	-9999.00	4	SUB	0	--------	SUB: DISPENSED	-273.17	216.85	200.00
2.500	0	--------	-9999.00	-9999.00	5	SUB	0	--------	SUB: DISPENSED	152.56	216.82	200.00
3.000	0	--------	-9999.00	-9999.00	6	SUB	0	--------	SUB: DISPENSED	584.37	219.36	200.00
3.500	0	--------	-9999.00	-9999.00	7	SUB	0	--------	SUB: DISPENSED	1006.76	216.38	200.00
4.000	0	--------	-9999.00	-9999.00	8	SUB	0	--------	SUB: DISPENSED	1442.70	217.98	200.00
84.581	102	CLUTTER	-9999.00	-9999.00	5	SUB	0	--------	TGT: ENTERED FOV	8360.62	216.82	200.00
84.582	102	CLUTTER	-9999.00	-9999.00	5	SUB	0	--------	TGT: ACQUIRED	8360.72	216.82	200.00
84.582	102	CLUTTER	-9999.00	-9999.00	5	SUB	4	CLUTTER	TGT: ID CORRECT	8360.72	216.82	200.00
178.662	111	CLUTTER	-9999.00	-9999.00	3	SUB	0	--------	TGT: ENTERED FOV	995.22	11565.95	200.00
178.663	111	CLUTTER	-9999.00	-9999.00	3	SUB	0	--------	TGT: ACQUIRED	995.22	11565.85	200.00
178.663	111	CLUTTER	-9999.00	-9999.00	3	SUB	4	CLUTTER	TGT: ID CORRECT	995.22	11565.85	200.00
255.495	105	CLUTTER	-9999.00	-9999.00	4	SUB	0	--------	TGT: ENTERED FOV	1426.83	3937.70	200.00
255.496	105	CLUTTER	-9999.00	-9999.00	4	SUB	0	--------	TGT: ACQUIRED	1426.83	3937.60	200.00
255.496	105	CLUTTER	-9999.00	-9999.00	4	SUB	4	CLUTTER	TGT: ID CORRECT	1426.83	3937.60	200.00
272.059	105	CLUTTER	-9999.00	-9999.00	8	SUB	0	--------	TGT: ENTERED FOV	2201.23	3187.98	200.00
272.060	105	CLUTTER	-9999.00	-9999.00	8	SUB	0	--------	TGT: ACQUIRED	2201.13	3187.98	200.00
272.060	105	CLUTTER	-9999.00	-9999.00	8	SUB	4	CLUTTER	TGT: ID CORRECT	2201.13	3187.98	200.00
273.129	105	CLUTTER	-9999.00	-9999.00	7	SUB	0	--------	TGT: ENTERED FOV	2108.36	2786.38	200.00
273.130	105	CLUTTER	-9999.00	-9999.00	7	SUB	0	--------	TGT: ACQUIRED	2108.26	2786.38	200.00
273.130	105	CLUTTER	-9999.00	-9999.00	7	SUB	2	PRI2L	TGT: ID INCORRECT	2108.26	2786.38	200.00
273.130	105	CLUTTER	-9999.00	-9999.00	7	SUB	0	--------	TGT: PRIORITY ACQUIRED	2108.26	2786.38	200.00
274.129	105	CLUTTER	-9999.00	-9999.00	7	SUB	0	--------	TGT: SELECTED	2008.36	2786.38	200.00
274.129	105	CLUTTER	-9999.00	-9999.00	7	SUB	0	--------	TGT: SLCTD WAS CLUT TGT	2008.36	2786.38	200.00
412.920	107	CLUTTER	-9999.00	-9999.00	8	SUB	0	--------	TGT: ENTERED FOV	9439.88	4887.98	200.00
412.921	107	CLUTTER	-9999.00	-9999.00	8	SUB	0	--------	TGT: ACQUIRED	9439.98	4887.98	200.00
412.921	107	CLUTTER	-9999.00	-9999.00	8	SUB	4	CLUTTER	TGT: ID CORRECT	9439.98	4887.98	200.00
426.463	112	CLUTTER	-9999.00	-9999.00	6	SUB	0	--------	TGT: ENTERED FOV	10835.84	4089.36	200.00
426.464	112	CLUTTER	-9999.00	-9999.00	6	SUB	0	--------	TGT: ACQUIRED	10835.94	4089.36	200.00
426.464	112	CLUTTER	-9999.00	-9999.00	6	SUB	4	CLUTTER	TGT: ID CORRECT	10835.94	4089.36	200.00
506.498	113	CLUTTER	-9999.00	-9999.00	8	SUB	0	--------	TGT: ENTERED FOV	10498.04	6587.98	200.00
506.499	113	CLUTTER	-9999.00	-9999.00	8	SUB	0	--------	TGT: ACQUIRED	10497.94	6587.98	200.00
506.499	113	CLUTTER	-9999.00	-9999.00	8	SUB	4	CLUTTER	TGT: ID CORRECT	10497.94	6587.98	200.00
529.268	115	CLUTTER	-9999.00	-9999.00	5	SUB	0	--------	TGT: ENTERED FOV	8286.87	5316.82	200.00
529.269	115	CLUTTER	-9999.00	-9999.00	5	SUB	0	--------	TGT: ACQUIRED	8286.77	5316.82	200.00
529.269	115	CLUTTER	-9999.00	-9999.00	5	SUB	4	CLUTTER	TGT: ID CORRECT	8286.77	5316.82	200.00
535.908	10	PRI3A	6641.49	5472.88	5	SUB	0	--------	TGT: ENTERED FOV	7622.82	5316.82	200.00
535.909	10	PRI3A	6641.49	5472.88	5	SUB	0	--------	TGT: ACQUIRED	7622.72	5316.82	200.00
535.909	10	PRI3A	6641.49	5472.88	5	SUB	3	PRI3A	TGT: ID CORRECT	7622.72	5316.82	200.00
535.909	10	PRI3A	6641.49	5472.88	5	SUB	0	--------	TGT: NOT SLCTD, PRIOR=99	7622.72	5316.82	200.00
538.713	3	PRI1E	6391.06	6567.98	8	SUB	0	--------	TGT: ENTERED FOV	7276.62	6587.98	200.00
538.714	3	PRI1E	6391.06	6567.98	8	SUB	0	--------	TGT: ACQUIRED	7276.53	6587.98	200.00
538.714	3	PRI1E	6391.06	6567.98	8	SUB	1	PRI1E	TGT: ID CORRECT	7276.53	6587.98	200.00
538.714	3	PRI1E	6391.06	6567.98	8	SUB	0	--------	TGT: PRIORITY ACQUIRED	7276.53	6587.98	200.00
538.919	3	PRI1E	6391.06	6567.98	8	SUB	0	--------	TGT: SELECTED	7255.94	6587.98	200.00
538.919	3	PRI1E	6391.06	6567.98	8	SUB	0	--------	TGT: HIT	7255.94	6587.98	200.00
538.919	3	PRI1E	6391.06	6567.98	8	SUB	0	--------	TGT: NOT KILLED	7255.94	6587.98	200.00
539.761	2	PRI1E	6248.57	5775.71	6	SUB	0	--------	TGT: ENTERED FOV	7213.42	5789.36	200.00
539.762	2	PRI1E	6248.57	5775.71	6	SUB	0	--------	TGT: ACQUIRED	7213.33	5789.36	200.00
539.762	2	PRI1E	6248.57	5775.71	6	SUB	1	PRI1E	TGT: ID CORRECT	7213.33	5789.36	200.00
539.762	2	PRI1E	6248.57	5775.71	6	SUB	0	--------	TGT: PRIORITY ACQUIRED	7213.33	5789.36	200.00
539.945	2	PRI1E	6248.57	5775.71	6	SUB	0	--------	TGT: SELECTED	7195.07	5789.36	200.00
539.945	2	PRI1E	6248.57	5775.71	6	SUB	0	--------	TGT: HIT	7195.07	5789.36	200.00
539.945	2	PRI1E	6248.57	5775.71	6	SUB	0	--------	TGT: KILLED	7195.07	5789.36	200.00
540.469	4	PRI2L	4909.72	6261.75	4	SUB	0	--------	TGT: ENTERED FOV	4826.83	7181.05	200.00
540.470	4	PRI2L	4909.72	6261.75	4	SUB	0	--------	TGT: ACQUIRED	4826.83	7180.96	200.00
540.470	4	PRI2L	4909.72	6261.75	4	SUB	2	PRI2L	TGT: ID CORRECT	4826.83	7180.96	200.00
540.470	4	PRI2L	4909.72	6261.75	4	SUB	0	--------	TGT: PRIORITY ACQUIRED	4826.83	7180.96	200.00
540.673	4	PRI2L	4909.32	6262.15	4	SUB	0	--------	TGT: SELECTED	4826.83	7160.58	200.00
540.673	4	PRI2L	4909.32	6262.15	4	SUB	0	--------	TGT: HIT	4826.83	7160.58	200.00
540.673	4	PRI2L	4909.32	6262.15	4	SUB	0	--------	TGT: NOT KILLED	4826.83	7160.58	200.00
545.884	5	PRI2L	4492.65	5737.45	3	SUB	0	--------	TGT: ENTERED FOV	4395.22	6584.48	200.00

545.885	5	PRI2L	4492.65	5737.45	3	SUB	0	--------	TGT: ACQUIRED	4395.22	6584.38	200.00
545.885	5	PRI2L	4492.65	5737.45	3	SUB	2	PRI2L	TGT: ID CORRECT	4395.22	6584.38	200.00
545.885	5	PRI2L	4492.65	5737.45	3	SUB	0	--------	TGT: PRIORITY ACQUIRED	4395.22	6584.38	200.00
546.065	5	PRI2L	4492.24	5737.16	3	SUB	0	--------	TGT: SELECTED	4395.22	6566.34	200.00
546.065	5	PRI2L	4492.24	5737.16	3	SUB	0	--------	TGT: HIT	4395.22	6566.34	200.00
546.065	5	PRI2L	4492.24	5737.16	3	SUB	0	--------	TGT: KILLED	4395.22	6566.34	200.00
688.577	7	PRI2L	5841.63	6303.46	2	SUB	0	--------	TGT: ENTERED FOV	5669.40	5491.44	200.00
688.578	7	PRI2L	5841.63	6303.46	2	SUB	0	--------	TGT: ACQUIRED	5669.40	5491.54	200.00
688.578	7	PRI2L	5841.63	6303.46	2	SUB	3	PRI3A	TGT: ID INCORRECT	5669.40	5491.54	200.00
688.578	7	PRI2L	5841.63	6303.46	2	SUB	0	--------	TGT: NOT SLCTD, PRIOR=99	5669.40	5491.54	200.00
714.500	0	--------	-9999.00	-9999.00	5	PRIMARY	5	CALLED	SUB: NOTIFIED OF TGTS	7871.14	7016.82	200.00
714.500	0	--------	-9999.00	-9999.00	5	SUB	0	--------	SUB: REDIRECTED	7871.14	7016.82	200.00
715.000	0	--------	-9999.00	-9999.00	2	PRIMARY	2	CALLED	SUB: NOTIFIED OF TGTS	5669.40	8133.71	200.00
715.000	0	--------	-9999.00	-9999.00	2	SUB	0	--------	SUB: REDIRECTED	5669.40	8133.71	200.00
729.223	3	PRI1E	6391.06	6567.98	5	SUB	0	--------	TGT: ENTERED FOV	7248.74	6522.37	200.00
729.224	3	PRI1E	6391.06	6567.98	5	SUB	0	--------	TGT: ACQUIRED	7248.65	6522.38	200.00
729.224	3	PRI1E	6391.06	6567.98	5	SUB	1	PRI1E	TGT: ID CORRECT	7248.65	6522.38	200.00
729.224	3	PRI1E	6391.06	6567.98	5	SUB	0	--------	TGT: PRIORITY ACQUIRED	7248.65	6522.38	200.00
729.224	3	PRI1E	6391.06	6567.98	5	SUB	0	--------	TGT: SELECTED	7248.65	6522.38	200.00
729.224	3	PRI1E	6391.06	6567.98	5	SUB	0	--------	TGT: HIT	7248.65	6522.38	200.00
729.224	3	PRI1E	6391.06	6567.98	5	SUB	0	--------	TGT: KILLED	7248.65	6522.38	200.00
729.257	3	PRI1E	6391.06	6567.98	2	SUB	0	--------	TGT: ENTERED FOV	6217.31	7556.33	200.00
729.258	3	PRI1E	6391.06	6567.98	2	SUB	0	--------	TGT: ACQUIRED	6217.31	7556.23	200.00
729.258	3	PRI1E	6391.06	6567.98	2	SUB	1	PRI1E	TGT: ID CORRECT	6217.31	7556.23	200.00
729.258	3	PRI1E	6391.06	6567.98	2	SUB	0	--------	TGT: PRIORITY ACQUIRED	6217.31	7556.23	200.00
729.258	3	PRI1E	6391.06	6567.98	2	SUB	0	--------	TGT: SELECTED	6217.31	7556.23	200.00
729.258	3	PRI1E	6391.06	6567.98	2	SUB	0	--------	TGT: HIT	6217.31	7556.23	200.00
729.258	3	PRI1E	6391.06	6567.98	2	SUB	0	--------	TGT: HIT ALREADY DEAD	6217.31	7556.23	200.00
729.258	3	PRI1E	6391.06	6567.98	2	SUB	0	--------	TGT: NOT KILLED	6217.31	7556.23	200.00
882.500	0	--------	-9999.00	-9999.00	1	PRIMARY	1	CALLED	SUB: NOTIFIED OF TGTS	6935.78	4571.51	200.00
882.500	0	--------	-9999.00	-9999.00	1	SUB	0	--------	SUB: REDIRECTED	6935.78	4571.51	200.00
892.880	2	PRI1E	6248.57	5775.71	1	SUB	0	--------	TGT: ENTERED FOV	6394.47	4761.23	200.00
892.880	2	PRI1E	6248.57	5775.71	1	SUB	0	--------	TGT: ACQUIRED	6394.47	4761.32	200.00
892.880	2	PRI1E	6248.57	5775.71	1	SUB	1	PRI1E	TGT: ID CORRECT	6394.47	4761.32	200.00
892.880	2	PRI1E	6248.57	5775.71	1	SUB	0	--------	TGT: PRIORITY ACQUIRED	6394.47	4761.32	200.00
892.880	2	PRI1E	6248.57	5775.71	1	SUB	0	--------	TGT: SELECTED	6394.47	4761.32	200.00
892.880	2	PRI1E	6248.57	5775.71	1	SUB	0	--------	TGT: HIT	6394.47	4761.32	200.00
892.880	2	PRI1E	6248.57	5775.71	1	SUB	0	--------	TGT: HIT ALREADY DEAD	6394.47	4761.32	200.00
892.880	2	PRI1E	6248.57	5775.71	1	SUB	0	--------	TGT: NOT KILLED	6394.47	4761.32	200.00

A.2.3 Cuts Output File for 1 Repetition.

```
 SUBM NO :         1
 TARGET     |------- LOCATION ------|                            |------- SUB FOV --------| |------- SUB LOC -------|
NO. NAME       X        Y        H     TENTER   ID     TEXIT   ID   TINFOV     X        Y        H        X      Y         Z
--- -------- ------- -------- -------- --------  --  --------   --  -------- -------- -------- -------- -------- -------- -------
  2 TGT2E    6248.57  5775.71     0.00   892.88          892.94          0.06  6170.27  5627.37   104.51  6394.47  4761.23   200.00
 SUBM NO :         2
 TARGET     |------- LOCATION ------|                            |------- SUB FOV --------| |------- SUB LOC -------|
NO. NAME       X        Y        H     TENTER   ID     TEXIT   ID   TINFOV     X        Y        H        X      Y         Z
--- -------- ------- -------- -------- --------  --  --------   --  -------- -------- -------- -------- -------- -------- -------
  3 TGT3E    6391.06  6567.98     0.00   729.26          729.38          0.12  6447.37  6691.73   284.90  6217.31  7556.33   200.00
  7 TGT7L    5841.63  6303.46     0.00   688.58          688.75          0.17  5887.62  6359.11    75.88  5669.40  5491.44   200.00
 SUBM NO :         3
 TARGET     |------- LOCATION ------|                            |------- SUB FOV --------| |------- SUB LOC -------|
NO. NAME       X        Y        H     TENTER   ID     TEXIT   ID   TINFOV     X        Y        H        X      Y         Z
--- -------- ------- -------- -------- --------  --  --------   --  -------- -------- -------- -------- -------- -------- -------
  5 TGT5L    4492.65  5737.45   215.00   545.88          546.07          0.18  4613.45  5716.81   284.12  4395.22  6584.48   200.00
111 CLUTTER   906.75 10570.40     0.00   178.66          178.81          0.14   777.00 10698.28   255.88   995.22 11565.95   200.00
 SUBM NO :         4
 TARGET     |------- LOCATION ------|                            |------- SUB FOV --------| |------- SUB LOC -------|
NO. NAME       X        Y        H     TENTER   ID     TEXIT   ID   TINFOV     X        Y        H        X      Y         Z
--- -------- ------- -------- -------- --------  --  --------   --  -------- -------- -------- -------- -------- -------- -------
  4 TGT4L    4909.72  6261.75   135.00   540.47          540.67          0.21  5045.06  6313.39   284.12  4826.83  7181.05   200.00
105 CLUTTER  1247.18  2986.72     0.00   255.50          255.69          0.20  1208.60  3070.04   255.88  1426.83  3937.70   200.00
 SUBM NO :         5
 TARGET     |------- LOCATION ------|                            |------- SUB FOV --------| |------- SUB LOC -------|
NO. NAME       X        Y        H     TENTER   ID     TEXIT   ID   TINFOV     X        Y        H        X      Y         Z
--- -------- ------- -------- -------- --------  --  --------   --  -------- -------- -------- -------- -------- -------- -------
  3 TGT3E    6391.06  6567.98     0.00   729.22          729.41          0.19  6367.28  6369.11   189.86  7248.74  6522.37   200.00
 10 TGT10A   6641.49  5472.88     0.00   535.91          536.07          0.16  6755.15  5535.04   165.88  7622.82  5316.82   200.00
102 CLUTTER  9212.46   386.26     0.00    84.58           84.77          0.19  9228.29   435.04    14.12  8360.62   216.82   200.00
115 CLUTTER  7298.01  5300.63     0.00   529.27          529.42          0.16  7419.20  5535.04   165.88  8286.87  5316.82   200.00
 SUBM NO :         6
 TARGET     |------- LOCATION ------|                            |------- SUB FOV --------| |------- SUB LOC -------|
NO. NAME       X        Y        H     TENTER   ID     TEXIT   ID   TINFOV     X        Y        H        X      Y         Z
--- -------- ------- -------- -------- --------  --  --------   --  -------- -------- -------- -------- -------- -------- -------
  2 TGT2E    6248.57  5775.71     0.00   539.76          539.95          0.18  6345.76  5571.13   194.12  7213.42  5789.36   200.00
112 CLUTTER 11779.81  3918.87     0.00   426.46          426.67          0.20 11703.50  3871.13   -14.12 10835.84  4089.36   200.00
 SUBM NO :         7
 TARGET     |------- LOCATION ------|                            |------- SUB FOV --------| |------- SUB LOC -------|
NO. NAME       X        Y        H     TENTER   ID     TEXIT   ID   TINFOV     X        Y        H        X      Y         Z
--- -------- ------- -------- -------- --------  --  --------   --  -------- -------- -------- -------- -------- -------- -------
105 CLUTTER  1247.18  2986.72     0.00   273.13        ********      ********  1240.70  2568.15   194.12  2108.36  2786.38   200.00
 SUBM NO :         8
 TARGET     |------- LOCATION ------|                            |------- SUB FOV --------| |------- SUB LOC -------|
NO. NAME       X        Y        H     TENTER   ID     TEXIT   ID   TINFOV     X        Y        H        X      Y         Z
--- -------- ------- -------- -------- --------  --  --------   --  -------- -------- -------- -------- -------- -------- -------
  3 TGT3E    6391.06  6567.98     0.00   538.71          538.92          0.21  6408.96  6369.76   194.12  7276.62  6587.98   200.00
105 CLUTTER  1247.18  2986.72     0.00   272.06          272.22          0.16  1333.56  3406.21   165.88  2201.23  3187.98   200.00
107 CLUTTER 10337.49  4857.01     0.00   412.92          413.14          0.22 10307.55  5106.21    14.12  9439.88  4887.98   200.00
113 CLUTTER  9643.71  6516.95     0.00   506.50          506.68          0.18  9630.37  6806.21   165.88 10498.04  6587.98   200.00
```

A.2.4 Sample Playback Output. Circles are targets (four of which are moving). Eight submunitions are searching the area in two sets of four.

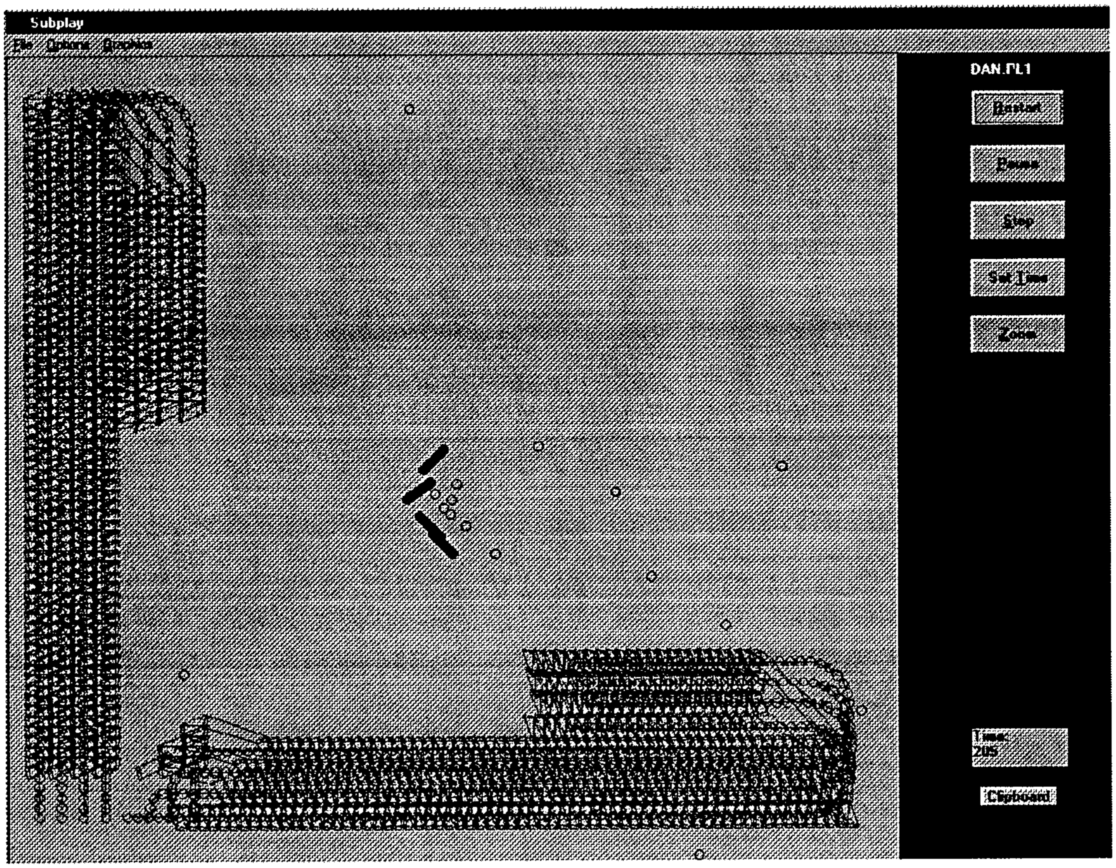

Figure A.1 Screen Capture of a Sample Playback

Appendix B. Design of Experiments Files

B.1 Example Design

Std	Run	Block	Factor 1 A:RDOT	Factor 2 B:TOF	Factor 3 C:Prior	Factor 4 D:Engage	Factor 5 E:Comm Range	Response 1 unique K	Response 2 total K	Response 3 total H	Response 4 formula
1	5	Block 1	0.80	0.80	0.40	0.80	5000.00	2.42	2.97	5.805	7.78
2	21	Block 1	0.80	0.40	0.80	0.80	5000.00	2.35	2.94	5.82	7.96
3	2	Block 1	0.40	0.80	0.80	0.40	15000.00	2.15	3.07	5.895	8.005
4	15	Block 1	0.80	0.80	0.80	0.40	5000.00	2.16	2.81	5.6	7.68
5	17	Block 1	0.80	0.80	0.40	0.40	15000.00	1.99	2.87	5.63	7.715
6	22	Block 1	0.80	0.40	0.40	0.80	15000.00	2.38	3.1	5.935	7.955
7	16	Block 1	0.40	0.40	0.80	0.80	15000.00	2.34	3.16	6.06	8.425
8	11	Block 1	0.40	0.80	0.40	0.80	15000.00	2.4	3.21	6.11	8.54
9	26	Block 1	0.80	0.40	0.80	0.40	15000.00	2.01	2.95	5.76	8.1
10	6	Block 1	0.40	0.80	0.80	0.80	5000.00	2.47	3.1	5.97	7.985
11	4	Block 1	0.40	0.40	0.40	0.40	5000.00	2.69	3.07	6.075	8.35
12	19	Block 1	0.24	0.60	0.60	0.60	10000.00	2.41	2.95	6.1	8.67
13	13	Block 1	0.96	0.60	0.60	0.60	10000.00	2.15	2.9	5.625	7.725
14	1	Block 1	0.60	0.24	0.60	0.60	10000.00	2.39	3.03	5.99	8.25
15	8	Block 1	0.60	0.96	0.60	0.60	10000.00	2.22	2.93	5.815	7.795
16	24	Block 1	0.60	0.60	0.24	0.60	10000.00	2.49	3.09	6.02	8.41
17	9	Block 1	0.60	0.60	0.96	0.60	10000.00	2.16	2.84	5.675	7.8
18	23	Block 1	0.60	0.60	0.60	0.24	10000.00	2.17	2.89	5.725	7.94
19	20	Block 1	0.60	0.60	0.60	0.96	10000.00	2.24	2.93	5.85	7.89
20	12	Block 1	0.60	0.60	0.60	0.60	894.20	2.67	3.16	6.05	8.255
21	3	Block 1	0.60	0.60	0.60	0.60	19105.80	2.26	3.14	5.905	7.8
22	18	Block 1	0.60	0.60	0.60	0.60	10000.00	2.25	2.99	5.89	7.955
23	7	Block 1	0.60	0.60	0.60	0.60	10000.00	2.3	3.06	5.89	7.79
24	25	Block 1	0.60	0.60	0.60	0.60	10000.00	2.25	2.96	5.88	7.985
25	14	Block 1	0.60	0.60	0.60	0.60	10000.00	2.27	3.01	5.9	8
26	10	Block 1	0.60	0.60	0.60	0.60	10000.00	2.25	2.97	5.86	7.905

B.2 Example ANOVA for Unique Kills Response

Response: unique K

ANOVA for Response Surface Quadratic Model

Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.708355	20	0.03542	89.2733	< 0.0001	significant
A	0.0338	1	0.03380	85.1956	0.0003	
B	0.01445	1	0.01445	36.4224	0.0018	
C	0.05445	1	0.05445	137.2456	< 0.0001	
D	0.00245	1	0.00245	6.1754	0.0555	
E	0.08405	1	0.08405	211.8548	< 0.0001	
A2	0.000305	1	0.00030	0.7681	0.4209	
B2	0.00268	1	0.00268	6.7560	0.0483	
C2	0.006277	1	0.00628	15.8204	0.0106	
D2	0.007309	1	0.00731	18.4221	0.0078	
E2	0.073654	1	0.07365	185.6501	< 0.0001	
AB	0.009365	1	0.00936	23.6050	0.0046	
AC	0.00175	1	0.00175	4.4104	0.0897	
AD	0.001724	1	0.00172	4.3460	0.0915	
AE	0.004176	1	0.00418	10.5252	0.0228	
BC	0.000818	1	0.00082	2.0625	0.2104	
BD	0.003542	1	0.00354	8.9275	0.0305	
BE	0.001436	1	0.00144	3.6185	0.1155	
CD	0.006319	1	0.00632	15.9274	0.0104	
CE	0.000459	1	0.00046	1.1569	0.3312	
DE	0.010082	1	0.01008	25.4115	0.0040	
Residual	0.001984	5	0.00040			
Lack of Fit	6.37E-05	1	0.00006	0.1326	0.7341	not significant
Pure Error	0.00192	4	0.00048			
Cor Total	0.710338	25				

The Model F-value of 89.27 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant.
In this case A, B, C, E, B^2, C^2, D^2, E^2, AB, AE, BD, CD, DE are significant model terms.
Values greater than 0.1000 indicate the model terms are not significant.
If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of 0.13 implies the Lack of Fit is not significant relative to the pur error. There is a 73.41% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

Std. Dev.	0.019918	R-Squared	0.9972074
Mean	2.301538	Adj R-Squ	0.9860372
C.V.	0.865429	Pred R-Sq	0.9314578
PRESS	0.048688	Adeq Prec	39.164955

The "Pred R-Squared" of 0.9315 is in reasonable agreement with the "Adj R-Squared" of 0.9860.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 39.165 indicates an adequate signal. This model can be used to navigate the design spa

Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF
Intercept	2.265321	1	0.0083	2.2440	2.2866	
A-RDOT	-0.07138	1	0.0077	-0.0913	-0.0515	2.6525
B-TOF	-0.04667	1	0.0077	-0.0666	-0.0268	2.6525
C-Prior	-0.0906	1	0.0077	-0.1105	-0.0707	2.6525
D-Engage	0.019219	1	0.0077	-0.0007	0.0391	2.6525
E-Comm Range	-0.11257	1	0.0077	-0.1324	-0.0927	2.6525
A2	0.003834	1	0.0044	-0.0074	0.0151	1.0152
B2	0.011372	1	0.0044	0.0001	0.0226	1.0152
C2	0.017402	1	0.0044	0.0062	0.0286	1.0152
D2	-0.01878	1	0.0044	-0.0300	-0.0075	1.0152
E2	0.059614	1	0.0044	0.0484	0.0709	1.0152
AB	-0.05536	1	0.0114	-0.0846	-0.0261	3.5867
AC	-0.02393	1	0.0114	-0.0532	0.0054	3.5867
AD	0.023752	1	0.0114	-0.0055	0.0530	3.5867
AE	-0.03696	1	0.0114	-0.0663	-0.0077	3.5867
BC	0.016363	1	0.0114	-0.0129	0.0457	3.5867
BD	0.034043	1	0.0114	0.0048	0.0633	3.5867
BE	-0.02167	1	0.0114	-0.0510	0.0076	3.5867
CD	0.045471	1	0.0114	0.0162	0.0748	3.5867
CE	0.012255	1	0.0114	-0.0170	0.0415	3.5867
DE	0.057435	1	0.0114	0.0281	0.0867	3.5867

Final Equation in Terms of Coded Factors:

unique K =

2.265321
-0.07138 * A
-0.04667 * B
-0.0906 * C
0.019219 * D
-0.11257 * E
0.003834 * A2
0.011372 * B2
0.017402 * C2
-0.01878 * D2
0.059614 * E2
-0.05536 * A * B
-0.02393 * A * C
0.023752 * A * D
-0.03696 * A * E
0.016363 * B * C
0.034043 * B * D
-0.02167 * B * E
0.045471 * C * D
0.012255 * C * E
0.057435 * D * E

Final Equation in Terms of Actual Factors:

unique K =
3.851125
0.730653 * RDOT
-0.28355 * TOF
-1.66622 * Prior
-1.46388 * Engage
-7.7E-05 * Comm Range
0.095861 * RDOT2
0.284305 * TOF2
0.435061 * Prior2
-0.46947 * Engage2
2.38E-09 * Comm Range2
-1.38389 * RDOT * TOF
-0.59819 * RDOT * Prior
0.593807 * RDOT * Engage
-3.7E-05 * RDOT * Comm Range
0.409071 * TOF * Prior
0.851069 * TOF * Engage

-2.2E-05 * TOF * Comm Range
1.13677 * Prior * Engage
1.23E-05 * Prior * Comm Range
5.74E-05 * Engage * Comm Range

Diagnostics Case Statistics

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	2.42	2.42108	-0.00108	0.98153	-0.40061	0.40615	-0.36421	5
2	2.35	2.35108	-0.00108	0.98153	-0.40061	0.40615	-0.36421	21
3	2.15	2.15108	-0.00108	0.98153	-0.40061	0.40615	-0.36421	2
4	2.16	2.16108	-0.00108	0.98153	-0.40061	0.40615	-0.36421	15
5	1.99	1.99108	-0.00108	0.98153	-0.40061	0.40615	-0.36421	17
6	2.38	2.38108	-0.00108	0.98153	-0.40061	0.40615	-0.36421	22
7	2.34	2.34108	-0.00108	0.98153	-0.40061	0.40615	-0.36421	16
8	2.4	2.40108	-0.00108	0.98153	-0.40061	0.40615	-0.36421	11
9	2.01	2.01108	-0.00108	0.98153	-0.40061	0.40615	-0.36421	26
10	2.47	2.47108	-0.00108	0.98153	-0.40061	0.40615	-0.36421	6
11	2.69	2.69217	-0.00217	0.92613	-0.40061	0.09581	-0.36421	4
12	2.41	2.40804	0.00196	0.93956	0.40061	0.11880	0.36421	19
13	2.15	2.14804	0.00196	0.93956	0.40061	0.11880	0.36421	13
14	2.39	2.38804	0.00196	0.93956	0.40061	0.11880	0.36421	1
15	2.22	2.21804	0.00196	0.93956	0.40061	0.11880	0.36421	8
16	2.49	2.48804	0.00196	0.93956	0.40061	0.11880	0.36421	24
17	2.16	2.15804	0.00196	0.93956	0.40061	0.11880	0.36421	9
18	2.17	2.16804	0.00196	0.93956	0.40061	0.11880	0.36421	23
19	2.24	2.23804	0.00196	0.93956	0.40061	0.11880	0.36421	20
20	2.67	2.66804	0.00196	0.93956	0.40061	0.11880	0.36421	12
21	2.26	2.25804	0.00196	0.93956	0.40061	0.11880	0.36421	3
22	2.25	2.26532	-0.01532	0.17260	-0.84562	0.00710	-0.81702	18
23	2.3	2.26532	0.03468	0.17260	1.91407	0.03639	3.31157	7
24	2.25	2.26532	-0.01532	0.17260	-0.84562	0.00710	-0.81702	25
25	2.27	2.26532	0.00468	0.17260	0.25826	0.00066	0.23255	14
26	2.25	2.26532	-0.01532	0.17260	-0.84562	0.00710	-0.81702	10

B.3 Example ANOVA for Total Kills Response

Responsetotal K

ANOVA for Response Surface Linear Model

Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.13676	5	0.0274	3.8293	0.0135	significant
A	0.06395	1	0.0640	8.9531	0.0072	
B	0.00982	1	0.0098	1.3753	0.2547	
C	0.02563	1	0.0256	3.5878	0.0728	
D	0.02518	1	0.0252	3.5249	0.0751	
E	0.00652	1	0.0065	0.9122	0.3509	
Residual	0.14286	20	0.0071			
Lack of	0.13658	16	0.0085	5.4370	0.0566	not significant
Pure Err	0.00628	4	0.0016			
Cor Tota	0.27962	25				

The Model F-value of 3.83 implies the model is significant. There is only a 1.35% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant.
In this case A are significant model terms.
Values greater than 0.1000 indicate the model terms are not significant.
If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of 5.44 implies there is a 5.66% chance that a "Lack of Fit F-value" this large could occur due to noise. Lack of fit is bad -- we want the model to fit.

Std. Dev	0.08452	R-Square	0.48910
Mean	3.00385	Adj R-Sq	0.36137
C.V.	2.81357	Pred R-S	0.10725
PRESS	0.24963	Adeq Pre	7.72702

The "Pred R-Squared" of 0.1073 is not as close to the "Adj R-Squared" of 0.3614 as one might normally expect. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response tranformation, outliers, etc.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 7.727 indicates an adequate signal. This model can be used to navigate the design spac

Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF
Intercep	3.0064	1	0.0167	2.9715	3.0412	
A-RDOT	-0.0608	1	0.0203	-0.1032	-0.0184	1.0172
B-TOF	-0.0238	1	0.0203	-0.0662	0.0186	1.0172
C-Prior	-0.0385	1	0.0203	-0.0809	0.0039	1.0172
D-Engage	0.0382	1	0.0203	-0.0042	0.0805	1.0172
E-Comm R	0.0194	1	0.0203	-0.0230	0.0618	1.0172

Final Equation in Terms of Coded Factors:

total K =
3.006368
-0.0608 * A
-0.02383 * B
-0.03849 * C
0.038153 * D
0.019408 * E

Final Equation in Terms of Actual Factors:

total K =
3.222475
-0.30402 * RDOT
-0.11916 * TOF
-0.19246 * Prior
0.190764 * Engage
3.88E-06 * Comm Range

Diagnostics Case Statistics

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	2.97	2.9790	-0.0090	0.3058	-0.1274	0.0012	-0.1242	5
2	2.94	2.9496	-0.0096	0.3058	-0.1370	0.0014	-0.1336	21
3	3.07	2.9861	0.0839	0.3058	1.1914	0.1042	1.2047	2
4	2.81	2.8257	-0.0157	0.3058	-0.2227	0.0036	-0.2173	15
5	2.87	2.9415	-0.0715	0.3058	-1.0151	0.0756	-1.0159	17
6	3.1	3.0654	0.0346	0.3058	0.4907	0.0177	0.4812	22
7	3.16	3.1101	0.0499	0.3058	0.7090	0.0369	0.6999	16
8	3.21	3.1394	0.0706	0.3058	1.0027	0.0738	1.0028	11

9	2.95	2.9122	0.0378	0.3058	0.5374	0.0212	0.5276	26
10	3.1	3.0236	0.0764	0.3058	1.0850	0.0864	1.0901	6
11	3.07	3.0719	-0.0019	0.4396	-0.0306	0.0001	-0.0298	4
12	2.95	3.1171	-0.1671	0.2412	-2.2698	0.2729	-2.5676	19
13	2.9	2.8956	0.0044	0.2203	0.0585	0.0002	0.0570	13
14	3.03	3.0498	-0.0198	0.2412	-0.2685	0.0038	-0.2622	1
15	2.93	2.9630	-0.0330	0.2203	-0.4418	0.0092	-0.4327	8
16	3.09	3.0765	0.0135	0.2412	0.1838	0.0018	0.1793	24
17	2.84	2.9363	-0.0963	0.2203	-1.2900	0.0784	-1.3132	9
18	2.89	2.9369	-0.0469	0.2412	-0.6368	0.0215	-0.6271	23
19	2.93	3.0759	-0.1459	0.2203	-1.9544	0.1799	-2.1179	20
20	3.16	2.9710	0.1890	0.2412	2.5669	0.3490	3.0553	12
21	3.14	3.0417	0.0983	0.2203	1.3171	0.0817	1.3433	3
22	2.99	3.0064	-0.0164	0.0390	-0.1976	0.0003	-0.1927	18
23	3.06	3.0064	0.0536	0.0390	0.6473	0.0028	0.6377	7
24	2.96	3.0064	-0.0464	0.0390	-0.5597	0.0021	-0.5498	25
25	3.01	3.0064	0.0036	0.0390	0.0438	0.0000	0.0427	14
26	2.97	3.0064	-0.0364	0.0390	-0.4390	0.0013	-0.4299	10

B.4 Example ANOVA for Total Hits Response

Response: total H

ANOVA for Response Surface Quadratic Model

Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.54357	20	0.02718	57.1962	0.0001	significant
A	0.11281	1	0.11281	237.4095	< 0.0001	
B	0.01531	1	0.01531	32.2246	0.0024	
C	0.05951	1	0.05951	125.2418	< 0.0001	
D	0.00781	1	0.00781	16.4411	0.0098	
E	0.01051	1	0.01051	22.1231	0.0053	
A2	0.00006	1	0.00006	0.1335	0.7298	
B2	0.00220	1	0.00220	4.6369	0.0839	
C2	0.00082	1	0.00082	1.7159	0.2472	
D2	0.01230	1	0.01230	25.8880	0.0038	
E2	0.02247	1	0.02247	47.2791	0.0010	
AB	0.01878	1	0.01878	39.5243	0.0015	
AC	0.00006	1	0.00006	0.1321	0.7312	
AD	0.00266	1	0.00266	5.5998	0.0642	
AE	0.00061	1	0.00061	1.2839	0.3086	
BC	0.00013	1	0.00013	0.2788	0.6201	
BD	0.00287	1	0.00287	6.0311	0.0575	
BE	0.00110	1	0.00110	2.3203	0.1882	
CD	0.00016	1	0.00016	0.3429	0.5836	
CE	0.00695	1	0.00695	14.6215	0.0123	
DE	0.00080	1	0.00080	1.6757	0.2521	
Residual	0.00238	5	0.00048			
Lack of Fit	0.00146	1	0.00146	6.33002	0.0656	not significant
Pure Error	0.00092	4	0.00023			
Cor Total	0.54595	25				

The Model F-value of 57.20 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant.
In this case A, B, C, D, E, D^2, E^2, AB, CE are significant model terms.
Values greater than 0.1000 indicate the model terms are not significant.
If there are many insignificant model terms (not counting those required to support hierarchy),
model reduction may improve your model.

The "Lack of Fit F-value" of 6.33 implies there is a 6.56% chance that a "Lack of Fit F-value" this large could occur due to noise. Lack of fit is bad -- we want the model to fit.

Std. Dev.	0.02180	R-Square	0.99565
Mean	5.87827	Adj R-Sq	0.97824
C.V.	0.37083	Pred R-S	-0.92426
PRESS	1.05054	Adeq Pre	26.26568

A negative "Pred R-Squared" implies that the overall mean is a better predictor of your response than the current model.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 26.266 indicates an adequate signal. This model can be used to navigate the design spa

Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF
Intercept	5.87768	1	0.00906	5.85440	5.90096	
A-RDOT	-0.13041	1	0.00846	-0.15217	-0.10865	2.65251
B-TOF	-0.04805	1	0.00846	-0.06980	-0.02629	2.65251
C-Prior	-0.09472	1	0.00846	-0.11648	-0.07296	2.65251
D-Engage	0.03432	1	0.00846	0.01256	0.05608	2.65251
E-Comm Rang	-0.03981	1	0.00846	-0.06157	-0.01805	2.65251
A2	-0.00175	1	0.00479	-0.01406	0.01056	1.01524
B2	0.01031	1	0.00479	-0.00200	0.02262	1.01524
C2	-0.00627	1	0.00479	-0.01858	0.00604	1.01524
D2	-0.02436	1	0.00479	-0.03667	-0.01205	1.01524
E2	0.03292	1	0.00479	0.02062	0.04523	1.01524
AB	-0.07839	1	0.01247	-0.11045	-0.04634	3.58667
AC	0.00453	1	0.01247	-0.02752	0.03658	3.58667
AD	-0.02951	1	0.01247	-0.06156	0.00255	3.58667
AE	-0.01413	1	0.01247	-0.04618	0.01792	3.58667
BC	-0.00658	1	0.01247	-0.03864	0.02547	3.58667
BD	-0.03062	1	0.01247	-0.06268	0.00143	3.58667
BE	-0.01899	1	0.01247	-0.05105	0.01306	3.58667
CD	0.00730	1	0.01247	-0.02475	0.03935	3.58667
CE	0.04768	1	0.01247	0.01563	0.07973	3.58667
DE	0.01614	1	0.01247	-0.01591	0.04819	3.58667

Final Equation in Terms of Coded Factors:

total H =

5.877683
-0.13041 * A
-0.04805 * B
-0.09472 * C
0.034319 * D
-0.03981 * E
-0.00175 * A2
0.010311 * B2
-0.00627 * C2
-0.02436 * D2
0.032924 * E2
-0.07839 * A * B
0.004532 * A * C
-0.02951 * A * D
-0.01413 * A * E
-0.00658 * B * C
-0.03062 * B * D
-0.01899 * B * E
0.007301 * C * D
0.04768 * C * E
0.016141 * D * E

Final Equation in Terms of Actual Factors:

total H =
5.591656
1.092231 * RDOT
1.374346 * TOF
-0.84097 * Prior
1.533489 * Engage
-5.3E-05 * Comm Range
-0.04374 * RDOT2
0.257771 * TOF2
-0.15681 * Prior2
-0.60907 * Engage2
1.32E-09 * Comm Range2
-1.9598 * RDOT * TOF
0.113288 * RDOT * Prior
-0.73768 * RDOT * Engage
-1.4E-05 * RDOT * Comm Range
-0.16459 * TOF * Prior
-0.76555 * TOF * Engage

-1.9E-05 * TOF * Comm Range
0.182534 * Prior * Engage
4.77E-05 * Prior * Comm Range
1.61E-05 * Engage * Comm Range

Diagnostics Case Statistics

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	5.805	5.79981	0.00519	0.98153	1.75040	7.75407	2.51595	5
2	5.82	5.81481	0.00519	0.98153	1.75040	7.75407	2.51595	21
3	5.895	5.88981	0.00519	0.98153	1.75040	7.75407	2.51595	2
4	5.6	5.59481	0.00519	0.98153	1.75040	7.75407	2.51595	15
5	5.63	5.62481	0.00519	0.98153	1.75040	7.75407	2.51595	17
6	5.935	5.92981	0.00519	0.98153	1.75040	7.75407	2.51595	22
7	6.06	6.05481	0.00519	0.98153	1.75040	7.75407	2.51595	16
8	6.11	6.10481	0.00519	0.98153	1.75040	7.75407	2.51595	11
9	5.76	5.75481	0.00519	0.98153	1.75040	7.75407	2.51595	26
10	5.97	5.96481	0.00519	0.98153	1.75040	7.75407	2.51595	6
11	6.075	6.06463	0.01037	0.92613	1.75040	1.82909	2.51595	4
12	6.1	6.10938	-0.00938	0.93956	-1.75040	2.26798	-2.51595	19
13	5.625	5.63438	-0.00938	0.93956	-1.75040	2.26798	-2.51595	13
14	5.99	5.99938	-0.00938	0.93956	-1.75040	2.26798	-2.51595	1
15	5.815	5.82438	-0.00938	0.93956	-1.75040	2.26798	-2.51595	8
16	6.02	6.02938	-0.00938	0.93956	-1.75040	2.26798	-2.51595	24
17	5.675	5.68438	-0.00938	0.93956	-1.75040	2.26798	-2.51595	9
18	5.725	5.73438	-0.00938	0.93956	-1.75040	2.26798	-2.51595	23
19	5.85	5.85938	-0.00938	0.93956	-1.75040	2.26798	-2.51595	20
20	6.05	6.05938	-0.00938	0.93956	-1.75040	2.26798	-2.51595	12
21	5.905	5.91438	-0.00938	0.93956	-1.75040	2.26798	-2.51595	3
22	5.89	5.87768	0.01232	0.17260	0.62115	0.00383	0.57834	18
23	5.89	5.87768	0.01232	0.17260	0.62115	0.00383	0.57834	7
24	5.88	5.87768	0.00232	0.17260	0.11683	0.00014	0.10464	25
25	5.9	5.87768	0.02232	0.17260	1.12548	0.01258	1.16499	14
26	5.86	5.87768	-0.01768	0.17260	-0.89182	0.00790	-0.86985	10

B.5 Example ANOVA for Target Formula Response

Responseformula

ANOVA for Response Surface Linear Model

Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1.2867	5	0.2573	9.3546	0.0001	significant
A	0.9424	1	0.9424	34.2578	< 0.0001	
B	0.2934	1	0.2934	10.6670	0.0039	
C	0.1631	1	0.1631	5.9280	0.0244	
D	0.0018	1	0.0018	0.0658	0.8002	
E	0.0063	1	0.0063	0.2308	0.6362	
Residual	0.5502	20	0.0275			
Lack of	0.5215	16	0.0326	4.5375	0.0769	not significant
Pure Err	0.0287	4	0.0072			
Cor Tota	1.8369	25				

The Model F-value of 9.35 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate model terms are significant.
In this case A, B, C are significant model terms.
Values greater than 0.1000 indicate the model terms are not significant.
If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of 4.54 implies there is a 7.69% chance that a "Lack of Fit F-value" this large could occur due to noise. Lack of fit is bad -- we want the model to fit.

Std. Dev	0.16586	R-Square	0.70048
Mean	8.02558	Adj R-Sq	0.62560
C.V.	2.06662	Pred R-S	0.45684
PRESS	0.99770	Adeq Pre	11.56597

The "Pred R-Squared" of 0.4568 is in reasonable agreement with the "Adj R-Squared" of 0.6256.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 11.566 indicates an adequate signal. This model can be used to navigate the design spa

Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF

Intercep	8.0436	1	0.0328	7.9753	8.1120	
A-RDOT	-0.2334	1	0.0399	-0.3166	-0.1502	1.0172
B-TOF	-0.1302	1	0.0399	-0.2134	-0.0471	1.0172
C-Prior	-0.0971	1	0.0399	-0.1803	-0.0139	1.0172
D-Engage	0.0102	1	0.0399	-0.0730	0.0934	1.0172
E-Comm R	-0.0192	1	0.0399	-0.1023	0.0640	1.0172

Final Equation in Terms of Coded Factors:

formula =
8.043642
-0.23342 * A
-0.13025 * B
-0.0971 * C
0.010229 * D
-0.01916 * E

Final Equation in Terms of Actual Factors:

formula =
9.433561
-1.16709 * RDOT
-0.65124 * TOF
-0.48549 * Prior
0.051147 * Engage
-3.8E-06 * Comm Range

Diagnostics Case Statistics

Standard Order	Actual Value	Predicted Value	Residual	Leverage	Student Residual	Cook's Distance	Outlier t	Run Order
1	7.78	7.8065	-0.0265	0.3058	-0.1915	0.0027	-0.1868	5
2	7.96	7.8728	0.0872	0.3058	0.6313	0.0293	0.6215	21
3	8.005	8.0203	-0.0153	0.3058	-0.1109	0.0009	-0.1081	2
4	7.68	7.5918	0.0882	0.3058	0.6382	0.0299	0.6285	15
5	7.715	7.7477	-0.0327	0.3058	-0.2365	0.0041	-0.2309	17
6	7.955	8.0286	-0.0736	0.3058	-0.5329	0.0208	-0.5231	22
7	8.425	8.3013	0.1237	0.3058	0.8952	0.0588	0.8906	16
8	8.54	8.2350	0.3050	0.3058	2.2072	0.3576	2.4735	11
9	8.1	7.8140	0.2860	0.3058	2.0696	0.3144	2.2756	26
10	7.985	8.0791	-0.0941	0.3058	-0.6809	0.0340	-0.6715	6

11	8.35	8.5133	-0.1633	0.4396	-1.3155	0.2263	-1.3416	4
12	8.67	8.4687	0.2013	0.2412	1.3930	0.1028	1.4289	19
13	7.725	7.6186	0.1064	0.2203	0.7269	0.0249	0.7180	13
14	8.25	8.2808	-0.0308	0.2412	-0.2135	0.0024	-0.2083	1
15	7.795	7.8064	-0.0114	0.2203	-0.0781	0.0003	-0.0761	8
16	8.41	8.2205	0.1895	0.2412	1.3118	0.0912	1.3374	24
17	7.8	7.8668	-0.0668	0.2203	-0.4562	0.0098	-0.4470	9
18	7.94	8.0250	-0.0850	0.2412	-0.5884	0.0183	-0.5785	23
19	7.89	8.0623	-0.1723	0.2203	-1.1763	0.0652	-1.1884	20
20	8.255	8.0785	0.1765	0.2412	1.2214	0.0790	1.2375	12
21	7.8	8.0088	-0.2088	0.2203	-1.4254	0.0957	-1.4658	3
22	7.955	8.0436	-0.0886	0.0390	-0.5452	0.0020	-0.5354	18
23	7.79	8.0436	-0.2536	0.0390	-1.5600	0.0165	-1.6224	7
24	7.985	8.0436	-0.0586	0.0390	-0.3607	0.0009	-0.3527	25
25	8	8.0436	-0.0436	0.0390	-0.2684	0.0005	-0.2621	14
26	7.905	8.0436	-0.1386	0.0390	-0.8527	0.0049	-0.8466	10

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Vita

Captain Daniel P. Gillen was born and raised in Smithtown, New York. He graduated from Smithtown High School West in 1992. He went on to become a Distinguished Graduate from the United States Air Force Academy in 1996 where he earned a Bachelor of Science degree in Engineering Sciences with a concentration in Astronautical Engineering Controls Theory.

After graduation he was assigned as a flight test engineer to the GPS Center of Expertise at the 746th Test Squadron, Holloman AFB, New Mexico. There he was responsible for the lab, field, and flight testing of a wide variety of GPS and INS components for Department of Defense applications.

He entered the Air Force Institute of Technology master's degree program in August of 1999. This thesis provides the final document required for him to earn his Master of Sciences Degree in Aeronautical Engineering.

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14. ABSTRACT
The problem being addressed is how to best find and engage an unknown number of targets in unknown locations using multiple autonomous wide area search munitions. In this research cooperative behavior is being investigated to improve the overall mission effectiveness. A simulation was used to emulate the behavior of autonomous wide area search munitions and measure their overall expected performance. This code was modified to incorporate the capability for cooperative engagement based on a parameterized decision rule. Using Design of Experiments and Response Surface Methodologies, the simulation was run to achieve optimal decision rule parameters for given scenarios and to determine the sensitivities of those parameters to the precision of the Autonomous Target Recognition algorithm, lethality of the warhead, and the characteristics of the battlefield.
Results show that the form of cooperative engagement used in this study is most useful in overcoming the limitations on warhead lethality and, to a lesser degree, probability of target report. However, cooperative engagement alone is not able to compensate for higher false target attack rates. Also, the selection of the optimal weights in the decision algorithm are very sensitive to all battlefield characteristics.

15. SUBJECT TERMS
Cooperative Engagement, Cooperative Behavior, Autonomous Munitions, Wide Area Search Munitions

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