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COOPERATIVE CONTROL SIMULATION VALIDATION USING APPLIED  
PROBABILITY THEORY

THESIS

Christopher S. Schulz, Captain, USAF

AFIT/GAE/ENY/03S-14

DEPARTMENT OF THE AIR FORCE  
AIR UNIVERSITY

**AIR FORCE INSTITUTE OF TECHNOLOGY**

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Wright-Patterson Air Force Base, Ohio

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AFIT/GAE/ENY/03S-14

COOPERATIVE CONTROL SIMULATION VALIDATION USING APPLIED  
PROBABILITY THEORY

THESIS

Presented to the Faculty

Department of Aeronautical and Astronautical Engineering

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the  
Degree of Master of Science in Aeronautical Engineering

Christopher S. Schulz, BS

Captain, USAF

Aug 2003

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COOPERATIVE CONTROL SIMULATION VALIDATION USING APPLIED  
PROBABILITY THEORY

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## List of Abbreviations and Symbols

$\alpha$	False Target density
$\beta$	Real Target density
$\Delta A$	Differential increase in the area searched by a munition
$\Delta P_E$	Probability of encountering a target within $\Delta A$
$\eta$	Target, False Target Density
$\lambda$	Poisson Probability Law Parameter
$\lambda_T$	Real Target Poisson Probability Law Parameter
$\lambda_{FT}$	False Target Poisson Probability Law Parameter
$\sigma_{loc}$	Standard Deviation of Target location
$\mu_{loc}$	Mean target location
$A$	Area already searched by a munition
$\bar{A}$	Target not attacked
$A_s$	Battle Space Search Area
<i>AFIT</i>	Air Force Institute of Technology
<i>AFRL</i>	Air Force Research Laboratory
<i>ATR</i>	Automatic Target Recognition
$\bar{C}$	Target not classified
$\bar{D}$	Target not detected
<i>DARPA</i>	Defense Advanced Research Projects Agency
$f^{[M,N]}(t)$	Target longevity probability distribution function

$F$	False Target
$g^{[M,N]}(\tau)$	False target longevity probability distribution function
$\bar{K}$	Target not killed
$M$	Number of Munitions on an individual WASM
$N$	Number of WASMs
$N_{tgt}$	Number of Targets
$PAD$	Persistent Area Denial
$P_{A_T}$	Probability of real target attack
$P_{A_{FT}}$	Probability of false target attack
$P_{FTA E}$	Probability of a false target attack given a false target encounter
$P_{FTk}$	Probability of false target kill
$P_{FTR}$	Probability of false target report
$P_k$	Warhead Probability of Kill
$P_{Tk}$	Probability of target kill

$P_{TR}$	Probability of target report
$s$	Time of attack
$\frac{\bar{s}}{T}$	Longevity of WASM given attack occurs, where $s$ is time of attack
$\frac{\bar{t}}{T}$	Longevity of a target given attack, where $t$ is time attacked
$T$	Real Target
$T_s$	Total time required performing a search of the battle space
$USAF$	United States Air Force
$V$	Munition velocity
$\bar{V}$	Target not verified destroyed
$W$	Munition sensor footprint width
$WASM$	Wide Area Search Munition

## **Abstract**

Several research simulations have been created to support development and refinement of teamed autonomous agents using decentralized cooperative control algorithms. Simulation is the necessary tool to evaluate the performance of decentralized cooperative control algorithms, however these simulations lack a method to validate their output. This research presents a method to validate the performance of a decentralized cooperative control simulation environment for an autonomous Wide Area Search Munition (WASM). Rigorous analytical methods for six wide area search and engagement scenarios involving Uniform, Normal, and Poisson distributions of  $N$  real targets and  $M$  false target objects are formulated to generate expected numbers of target attacks and kills for a searching WASM. The mean value based on the number of target attack and kills from Monte Carlo simulations representative of the individual scenarios are compared to the analytically derived expected values. Emphasis is placed on Wide Area Search Munitions (WASMs) operating in a multiple target environment where a percentage of the total targets are either false targets or may be misconstrued as false by varying the capability of the WASM's Automatic Target Recognition (ATR) capability.

INVESTIGATION OF COOPERATIVE BEHAVIOR IN AUTONOMOUS WIDE  
AREA SEARCH MUNITIONS

## I. Introduction

### **1.1 General**

Unmanned Air Vehicles are quickly becoming an indispensable force multiplier for commanders to conquer complex battlefield scenarios. As the use of these vehicles increases, however, battlefield users envision more complex tasks for these vehicles to perform. This includes vehicles that work cooperatively together, with little or no human intervention, to perform complex tasks such as Suppression of Enemy Air Defenses (SEAD), Persistent Area Denial (PAD), or Urban Battlefield Surveillance (UBS). Furthermore, autonomous aircraft capable of performing these types of missions reduce the total number of combat forces a battlefield commander must commit to the theater of operations. These requirements are driving the ongoing efforts to develop autonomous Wide Area Search Munitions (WASMs) capable of cooperative task execution.

Several simulations have been created to support developmental research on teamed autonomous agents using decentralized cooperative control algorithms. Simulation is a necessary tool to evaluate the performance of decentralized cooperative control algorithms; however, these simulations lack a method to validate their predictions.



The work presented here is concerned with the development of a method to validate the performance of a decentralized cooperative control simulation for autonomous wide area search munitions. A rigorous analytical treatment of six persistent area denial scenarios involving  $M$  targets and  $N$  munitions are used to validate the results of identical simulation runs. Emphasis is placed on WASMs operating in a multiple target environment where a percentage of the total targets are either decoys or targets that may be misconstrued as false targets by the WASM's Automatic Target Recognition (ATR) software.

## **1.2 Background**

The United States Department of Defense (DoD) is investigating opportunities to expand the future battlefield capabilities through the use of cooperative WASMs. Current emphasis is placed on exploiting a WASMs' ability to search, detect, identify, and attack a host of targets autonomously. Work by the RAND Corporation [1] has researched the effectiveness of possible WASM configurations along with methods of battlefield employment for SEAD and PAD like missions. This study focused on assessing the benefit of cooperative behavior of WASM like vehicles.

The conclusions made by the RAND study indicate a low complexity and thus potentially inexpensive munition could perform as an effective autonomous munition for PAD and SEAD type scenarios. These vehicles have capabilities such as INS aided GPS navigation systems, target acquisition sensors capable of Autonomous Target Recognition (ATR), and communications systems capable of sending and receiving current battlespace information. An example of this class munition is the USAF

LOCAAS [2], as seen in Figure 1-1. This munition embodies the capabilities, size, and level of complexity recommended by [1].



**Figure 1-1 USAF LOCAAS Design Concept**

The concept of wide area search munitions is also currently under consideration by DARPA and the US Army under the NetFires [21] program. NetFires is a technology demonstration program focused on beyond line-of-sight fires for the Army's Future Combat System incorporating LAM, a LOCAAS like munition. The LAM is an expendable loitering, hunter-killer, that is seven inches in diameter and weighs about 100 pounds. It is capable of searching a large area using a laser radar (LADAR) seeker with automatic target recognition. It will have a 45-minute cruise capability using a micro turbojet engine and a multi mode warhead.

Current research has focused on how to expand the capabilities of autonomous WASMs by incorporating team behavior through cooperative decision-making and task allocation. Emphasis has been placed on evaluating these concepts in the context of cooperative search, classification, and attack in order to discern improved munition

battlefield effectiveness. The following overview briefly covers the findings of current efforts in these areas.

In the area of *cooperative attack*, Gillen [3] investigated how cooperative behavior based on governing rules would benefit a group of munitions searching an area. He formulated decision rules based on weighted parameters representative of an individual munitions perceived environment. In this effort each munition relied on pre-optimized decision rule parameters, with each munition executing decisions based on prior knowledge of other munition results, but without further negotiations by the team. While this approach did not focus on cooperatively determined decisions, Gillen demonstrated that a group following similar decision rules would operate cohesively and effectively by each munition making actions that benefit the group as a whole.

Dunkel [13] and Gozaydin [15] expand on this work by incorporating *cooperative classification* of a target in conjunction with cooperative target attack. Additionally, Dunkel and Gozaydin have improved the decision process to control the actions of the group rather than the individual. Furthermore, the decision methodology was based upon a mathematically rigorous approach, [9], which eliminated the need for pre-optimized decision rules tuned for specific scenarios. Using this formulation, Dunkel and Gozaydin demonstrated that while cooperative attack alone does not always improve mission effectiveness, cooperative classification used in conjunction with cooperative attack does improve overall group efficiency. This is because multiple munitions cooperatively teamed to provide target identification have been shown to provide higher levels of target declaration accuracy. This equates to more munitions attacking true targets rather than false or non targets.

The effect of *cooperatively searching teams* has been explored by Flint[20]. This work focused on generating near optimal trajectories to follow in order for several UAV's to cooperatively search for targets in a given area for which some a priori knowledge about a target distribution is available. A dynamic programming based search algorithm was employed to facilitate multiple vehicle cooperation through consideration of other vehicles as stochastic elements. This method was shown to generate efficient search paths and thus perform the target finding role substantially better than non-cooperative vehicle formations.

Park [11] has identified the process a WASM will perform for non-cooperative behavior. The following reflects these steps for a generic ground attack role:

1. Begin searching: Activate ATR/sensors and search for targets.
2. Encounter/Engage Target: Munition locates target, communicates target information, and attacks target.

Dunkel and Park note that other weapons that are in communication range and meet certain proximity requirements will also converge on the target and commit attacks. Finally, munitions that are out of range will continue to search for another target. The non-cooperative process, as seen above, does not rely on external information for target information, nor does it rely on additional munitions to perform an attack on any encountered target. This process is similar to swarm or flock systems [7], [8], and related to classical optimal search methods [10].

Cooperatively controlled munitions, however, leverage the assistance of a team when performing a search/attack process. The following cooperative team process [11] is intended to contrast the differences to the non-cooperative case.

1. Begin searching: Activate ATR/sensors and search for targets
2. Target Encounter: A searching resource locates a target and passes the location and type of target to the command and control center.
3. Cooperative Decision Process: The command and control center processes this information and assigns a resource to engage and destroy the target
4. Encounter/Engage Target: An assigned resource engages the target with location and characteristics passed via the command and control center.

A cooperative search/attack process leverages the capabilities of the team as a whole when performing the ground attack role. The main difference between the cooperative and non-cooperative case is in the cooperative decision step, seen in item 3 above. This allows for an optimal solution to the target attack problem by using the team resources in the most efficient way.

Cooperative control relies on three main elements for success;

1. Communication
2. Decision Control/Task Allocation
3. Management of Uncertainty

Current research [3],[9],[14],[16],[13] has explored the affects these three items can have on cooperative control. Item 3 is of special interest for successfully employing cooperative teams to perform tasks. This is due to the fact that cooperative team tasking relies heavily on information perceived by one munition and then disseminated to the group for processing and future actions.

Target location and target identification via ATR is the source of greatest information uncertainty for cooperatively teamed WASMs. ATR algorithms can and do

misidentify real targets as false, and vice versa. Thus, a searching WASM can misidentify a target or non-target object and then pass this information to its teammates. This scenario will occur in battle, as enemy forces will deploy decoys intermingled with real vehicles specifically to increase the searching WASMs information uncertainty. Even without the presence of deliberate decoys, ATR algorithms will generally exhibit a non-zero false target declaration rate. Recent research [3], [13], [15] has verified that the false target attack rate has the greatest effect in the mission effectiveness for both cooperative and non-cooperative wide-area search munitions. Cooperative classification by multiple vehicles can reduce but not eliminate false target misidentification; however, this also will reduce the total number of targets encountered by the searching WASMs due to multiple vehicles having to return to a single target to verify its identity. A greater percentage of missed targets will also occur as a result of requiring confirmation before attack.

Several research simulations have been developed for evaluating the effectiveness of cooperative and non-cooperative teams of autonomous search and attack munitions. Simulations, such as the AFRL MultiUAV [19] allow for the user to vary the capabilities and complexity of the munitions along with varying the type, number, and distribution of real and false targets in the battlespace. Simulation tools can be used to investigate and validate the effectiveness of teamed munitions in varying conditions. These simulations, however, must be compared to an analytic benchmark to validate their statistical results.

### **1.3 Objectives**

The objective of this research is to establish an analytic validation methodology for the MultiUAV simulation. This effort will focus on characterizing the probabilities for real and false target attacks and kills made by a single searching munition. More specific objectives are:

1. Develop analytic scenarios to model varying battlespace conditions and munition capabilities.
2. Investigate the validity of the MultiUAV simulation via direct comparison of empirical vs. analytic results.
3. Identify simulation deficiencies (if any) resulting from the validity investigation.

### **1.4 Approach and Scope**

This work presents a method to validate the MultiUAV simulation environment via comparison of simulation results to six analytically derived solutions for Wide Area Search scenarios. The validation methodology was performed by comparing 5 test parameters in the analytic and simulation formulations. These test parameters are; the average number vs. probability of successful target attack, average number vs. probability of false target attack, average number vs. probability of successful target kill, average number vs. probability of false target kill, average time vs. expected time spent searching the battlespace before engaging either a target or false target. The values of the five parameters were evaluated analytically by way of closed form solution, and in simulation via Monte Carlo analysis.

Six identical analytical and simulation test scenarios were created to provide unique test cases involving realistic target distributions. Each test case varies the real and decoy target locations by way of either Uniform, Normal, or Poisson distributions. The individual distribution types approximate physically realizable situations, such as targets clustered around a certain location, as in the case of a Normal distribution. Additionally, a single WASM is considered as the searching agent in the six scenarios. Stochastic uncertainty in the performance of the ATR algorithm is considered, thus allowing for misidentification of encountered targets. Finally, in all cases both targets and false targets are modeled as stationary.

## **1.5 Relevance**

This research is intended to investigate the validity of target engagement performance for a generic cooperative control simulation. It is not intended to evaluate specific cooperative control algorithms, but rather to evaluate the validity of the simulation environment in which the cooperative control algorithms are used. Furthermore, this evaluation is not focused on modeling a specific searching munition, target, or specific geographical battlefield. Search munitions modeled in this research are not representative of a specific vehicle, nor are the targets.



## **II. Modeling Persistent Area Denial Scenarios for Wide Area Search Munitions**

### ***2.1 Operational Concepts for Persistent Area Denial Munitions***

The success of attacking ground targets can vary depending on both the capabilities of the attacking vehicle, the characteristics of the targets, and how the target and non-target objects are distributed throughout the search area. One method of quantifying the success of such an attack is to construct a simulation resembling such an environment. Simulations, however, can introduce variances into the results via actions not accounted for in the intended environment setup. Direct comparison to closed form analytic solutions can provide an independent validation method for the simulation results

This section covers the development of six distinct analytic closed form probabilistic models for a Wide Area Search Munitions (WASM) performing search, classify, and attack role.

#### **2.1.1 Analytical Theory for Search, Classification, and Attack**

Simulation tools such as MultiUAV provide the means for demonstrating success in decentralized cooperative control development. However, before any controller development can take place, an independent baseline performance comparison is necessary to ensure the proper operation of the simulation environment. Pachter and Jacques [12] provide a method of system analysis based on applied probability theory for vehicles performing search, classification, and attack on encountered targets within a search area. For the multi-target, multi-false target case a progression of analytical

expressions for six search, classify, and attack scenarios is presented that consider both real and false target distributions in the defined battle space. This work represents the foundation for the baseline comparison used for the MultiUAV simulation validation. The baseline comparison outlined in this work focuses on a single WASM armed with a single munition. The scenarios vary the amount of real and false targets, and in addition vary the type of target distribution (Uniform, Gaussian, or Poisson field). Uniform distributions provide for a known quantity of true or false targets in a given area. Gaussian distributions are used to distribute a known number of targets, with their locations set via a mean,  $\mu_{loc}$ , and standard deviation,  $\sigma_{loc}$ . Thus, a random target location assigned from such a Gaussian distribution may not always place the target within the battle space. Poisson distributions will be further explained below.

### 2.1.2 Poisson Field of Targets

Poisson fields, by their definition, do not provide a constant quantity of expected targets over a specified battle space,  $A_s$ . Instead, they provide an average rate of target encounters while searching over  $A_s$ . The Poisson field of targets or false targets [12] is characterized by the target probability density,  $\alpha \left[ \frac{1}{km^2} \right]$ . As an area  $A$  is searched, the

Poisson probability law parameter is specified as

$$(1 - P_{FTR})\lambda \tag{1}$$

where  $\lambda$  is defined as the expected number of targets in  $A_s$ . The Poisson probability function  $P(\cdot)$  is defined by

$$P(\{k\}) = e^{-\lambda(1-P_{FTR})} \frac{(\lambda(1-P_{FTR}))^k}{k!} \tag{2}$$

Equation (2) specifies the probability of encountering  $k$  total targets based on the parameter  $\lambda$ . The Poisson field provides a scenario of uniform targets/false target density where it is not guaranteed that any number of any target (or false target) encounters will occur in any given area.

### 2.1.3 Scenario Comparison Parameters

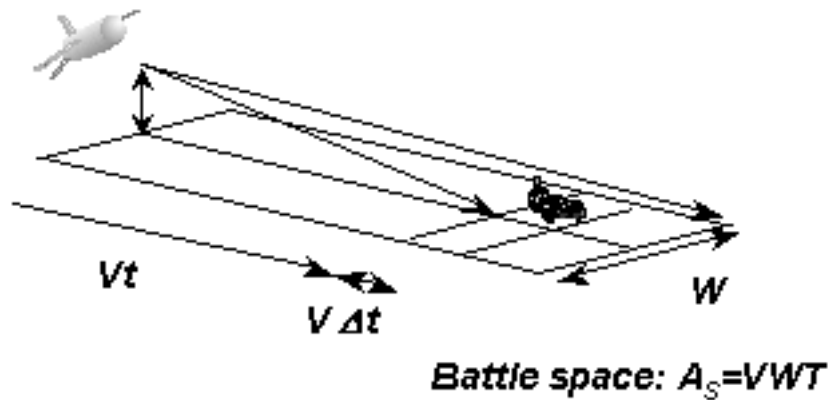
The baseline comparisons for all six scenarios will focus on five parameters :

- Probability of real target attacks,  $P_{A_r}$
- Probability of false target attacks,  $P_{A_{FT}}$
- Probability of successful target kills,  $P_{TK}$
- Probability of successful false target kills,  $P_{FTK}$
- Longevity of WASM given attack occurs,  $\frac{s}{T_s}$ , where  $s$  is time of attack

These probabilities allow for the formulation of expected attacks and kills of both real and false targets. As a note,  $T_s$  is defined as the total time available to search the battle space.

### 2.1.4 Search Area Definition

Scenarios 1-6 assume the WASM searches over a linearly defined area, as represented in Figure 2-1 Linear Search Path.



**Figure 2-1 Linear Search Path**

Here, the WASM has the parameters of forward velocity  $V$ , and sensor swath width  $W$  to define search rate and the total search area,  $A_S$ . Section 2.3 will cover the details of scenarios 1-6, however the methodology used to determine the probability for target report must first be explained.

## **2.2 Probability of Target Report**

WASMs rely on Automatic Target Recognition systems to perform target identification and classification. This process is not 100% accurate, and thus introduces error into the vehicle's decision algorithms. In order to more accurately represent the error in Automatic Target Recognition (ATR) a *confusion matrix* is used to represent the probability of both correct and incorrect target reports. When a WASM encounters a target, error associated with ATR has the possibility of causing false target detections or missed target declarations. The confusion matrix models the ATR function based on probability of target report,  $P_{TR}$ , and probability of false target attack given false target

encounter,  $P_{FTA/E}$ . An example of a binary confusion matrix for the single target type case is shown in Figure 2-2 Binary Confusion Matrix.

		Encountered Object	
		Target	Non-Target
Declared Object	Target	$P_{TR}$	$1 - P_{FTR}$
	Non-Target	$1 - P_{TR}$	$P_{FTR}$

**Figure 2-2 Binary Confusion Matrix**

The confusion matrix provides a simple method to determine the probability of falsely declared target. This is represented by the probabilities of target and false target detection in the rows of the matrix. Because an encountered object will be declared either a target or non-target, the columns of the matrix sum to one.

### 2.2.1 Confusion Matrix Implications in Poisson Modeling of Targets

The confusion matrix represents the potential for misinformation from the ATR function, which in turn will cause a vehicle to misinterpret a real target as false, or vice versa. If the munition is destroyed after attacking a target, such as a missile, then the probability of engaging a target in  $\Delta A$  is conditioned on not having engaged a false target prior to arriving at its current position. For the single target scenario, the probability of encountering a target within  $\Delta A$  is defined as

$$\Delta P_E = P_{FTA}(A) \frac{\Delta A}{A_s} \quad (3)$$

where  $\frac{\Delta A}{A_s}$  is defined as the probability of a target being present in  $\Delta A$ . Furthermore,

$P_{FTA}(A)$  is the probability of no false target attacks occurring before the munition has arrived at its present location. By assuming a non-zero false target report rate,  $P_{FTR}$ , the probability of no false target attacks in the searched area leading up to  $\Delta A$  can be expressed as

$$P_{FTA}(A) = e^{-\alpha A} \quad (4)$$

This states the probability of not employing the weapon while searching an area  $A$  in a Poisson field of false targets.

### **2.3 Persistent Area Denial Evaluation Scenarios**

This research focused on developing six test scenarios [12] to characterize several distributions of real and false targets over the battlespace,  $A_s$ . Scenarios 1 and 2 depict a Poisson distribution of false targets, while varying the real target distribution with Uniform or Poisson fields, respectively. Scenarios 3 and 4 model false targets with Poisson or Uniform fields, respectively, and real targets with a Uniform field. Finally, scenarios 5 and 6 model false targets with Poisson or Normal fields, respectively, while real targets are modeled via a Normal field.

#### **2.3.1 . Scenario 1 ( Single Uniform T, Poisson FTs)**

Scenario 1 presents a single target (T) uniformly distributed amongst a Poisson field of false targets (FTs) in a battlespace of area  $A_s$ . For the Poisson field of FTs assuming a non-zero  $P_{FTR}$ ,  $\alpha$  is modified as follows:

$$\alpha := (1 - P_{FTR})\alpha \quad (5)$$

Let  $f(t)$  be the probability density function (p.d.f) of the random variable  $t$  representing an attack on a real target. The probability of real target attack is formulated by

$$f(t) = P_{TR} \frac{V \cdot W}{A_s} P_{FTA}(A) \quad (6)$$

Noting equation (4),  $f(t)$  is expressed as

$$f(t) = P_{TR} \frac{V \cdot W}{A_s} e^{-(1-P_{FTR})\alpha A} \quad (7)$$

Also,  $A_s = VWT$ , and  $A = VWt$ , so

$$A = A_s \frac{t}{T} \quad (8)$$

and

$$\frac{V \cdot W}{A_s} = \frac{1}{T} \quad (9)$$

Now, by defining the Poisson parameter,  $\lambda = \alpha A_s$ , equation (8) can be reformed as

$$\alpha A = \lambda \frac{t}{T} \quad (10)$$

Using the above, equation (6) can now be expressed as

$$f(t) = \frac{1}{T} P_{TR} e^{-(1-P_{FTR})\lambda \frac{t}{T}} \quad (11)$$

To determine the expectation of target attack the above can be integrated for the entire battle sweep,  $T$ , as represented below.

$$P_{AT} = \int_0^T f(t) dt \quad (12)$$

which results in

$$P_{AT}(A_s) = P_{TR} \frac{(1 - e^{-(1-P_{FTR})\lambda})}{(1 - P_{FTR})\lambda} \quad (13)$$

Additionally, the probability of false target attack,  $P_{AFT}$ , is defined using the p.d.f for false target attacks

$$g(t) = e^{-(1-P_{FTR})\lambda\frac{t}{T}} \left[ \frac{A_s - VWt}{A_s} + (1-P_{TR})\frac{VWt}{A_s} \right] \alpha VW(1-P_{FTR}) \quad (14)$$

which simplifies to

$$g(t) = \frac{1}{T} \lambda(1-P_{FTR})(1-P_{TR})\frac{t}{T} e^{-(1-P_{FTR})\lambda\frac{t}{T}} \quad (15)$$

By integration the expectation of a false target attack can be represented as

$$P_{AFT} = \int_0^T g(t) dt \quad (16)$$

and is

$$P_{AFT}(A_s) = \left( 1 - \frac{P_{TR}}{(1-P_{FTR})\lambda} \right) (1 - e^{-(1-P_{FTR})\lambda}) + P_{TR} e^{-(1-P_{FTR})\lambda} \quad (17)$$

To calculate the lifetime of a target, assuming an attack has occurred, let  $s$  be the time of either a real or false target attack. To calculate the probability of either a real or false target attack not occurring before time  $s$  the p.d.f,  $h(s)$ , of the random variable  $s$

$$h(s) = -\frac{d}{ds} H(s) \quad (18)$$

is formed where  $H(s)$ , the probability of either a a T or FT attack not happening before time  $s$  is defined as

$$\begin{aligned} H(s) &= e^{-(1-P_{FTR})\lambda\frac{s}{T}} \left[ 1 - \frac{s}{T} + (1-P_{TR})\frac{s}{T} \right] \\ &= e^{-(1-P_{FTR})\lambda\frac{s}{T}} (1-P_{TR})\frac{s}{T} \end{aligned} \quad (19)$$

This allows the formulation of an expression,  $\bar{s}$ , for the longevity of the munition in the case where the munition engages a target and subsequently is destroyed.

$$\bar{s} = \int_0^T \frac{sh(s)ds}{(1-P_s)} \quad (20)$$

where  $P_s = H(T)$ . Through integration by parts the above is now



$$\bar{s} = \frac{\int_0^T H(s) ds - T P_s}{(1 - P_s)} \quad (21)$$

and is then

$$\begin{aligned} \frac{\bar{s}}{T} = & \frac{(1 - P_{FTR})\lambda - P_{TR}}{[1 - P_{FTR}\lambda]^2 [1 - (1 - P_{TR})e^{-(1 - P_{FTR})\lambda}]} \\ & + \frac{[P_{TR} - (1 - P_{TR})(1 - P_{FTR})\lambda(1 + \lambda - P_{FTR}\lambda)]e^{-(1 - P_{FTR})\lambda}}{[(1 - P_{FTR})\lambda]^2 [1 - (1 - P_{TR})e^{-(1 - P_{FTR})\lambda}]} \end{aligned} \quad (22)$$

### 2.3.2 Scenario 2 ( Poisson T, Poisson FT )

For the second scenario considered a search environment consisting of both a Poisson field of targets, Ts, and false targets, FTs, is considered. For the Poisson field of real targets, the Poisson probability law parameter describing real targets,  $\lambda_T$ , is defined as

$$\lambda_T = \beta A_S \quad (23)$$

Here, the Poisson field target declarations of real targets is parameterized by  $\beta \left[ \frac{1}{km^2} \right]$  and

false targets by  $\alpha \left[ \frac{1}{km^2} \right]$ . The parameter  $\beta$  is defined as

$$\beta = \eta_T P_{TR} \quad (24)$$

where  $\eta_T$  is defined as the real target object probability density. So, recognizing the following p.d.fs,  $f(t)$  and  $g(t)$ , of the random variable  $t$  for real and false target attack are

$$f(t) = \frac{1}{T} P_{TR} \lambda_T e^{-[(1 - P_{FTR})\lambda_{FT} + P_{TR}\lambda_T] \frac{t}{T}} \quad (25)$$

$$g(t) = \frac{1}{T} (1 - P_{FTR}) \lambda_{FT} e^{-[(1 - P_{FTR})\lambda_{FT} + P_{TR}\lambda_T] \frac{t}{T}} \quad (26)$$

By integration as demonstrated in scenario 1 the respective probabilities of a T and FT attack are

$$P_{A_T} = \frac{P_{TR} \lambda_T}{(1 - P_{FTR}) \lambda_{FT} + P_{TR} \lambda_T} \left(1 - e^{-[(1 - P_{FTR}) \lambda_{FT} + P_{TR} \lambda_T]}\right) \quad (27)$$

$$P_{A_{FT}} = \frac{(1 - P_{FTR}) \lambda_{FT}}{(1 - P_{FTR}) \lambda_{FT} + P_{TR} \lambda_T} \left(1 - e^{-[(1 - P_{FTR}) \lambda_{FT} + P_{TR} \lambda_T]}\right) \quad (28)$$

Furthermore, by recognizing the probability of either a real or false target attack not occurring before time  $s$  as

$$H(s) = e^{-[(1 - P_{FTR}) \lambda_{FT} + P_{TR} \lambda_T] \frac{s}{T}} \quad (29)$$

the expression for the lifetime of a target is then

$$\frac{\bar{s}}{T} = \frac{1 - (1 + (1 - P_{FTR}) \lambda_{FT} + P_{TR} \lambda_T) e^{-[(1 - P_{FTR}) \lambda_{FT} + P_{TR} \lambda_T]}}{((1 - P_{FTR}) \lambda_{FT} + P_{TR} \lambda_T) (1 - e^{-[(1 - P_{FTR}) \lambda_{FT} + P_{TR} \lambda_T]})} \quad (30)$$

### 2.3.3 Scenario 3 ( N Uniform Ts, Poisson FT )

Scenario 3 presents a search environment represented by a Poisson field of FTs, with a uniform distribution of  $N$  real targets, Ts. As in scenario 1 and 2, the Poisson field of FTs is parameterized by  $\alpha \left[ \frac{1}{km^2} \right]$ . A recursive form is used to present cases where

$N \geq 2$ . Therefore, for  $N$  real targets the probability of real target attack,  $P_{A_T}$ , is defined as

$$P_{A_T}^{[N]} = \frac{P_{TR} N}{(1 - P_{FTR}) \lambda_{FT}} \left(1 - (1 - P_{TR})^{N-1} e^{-(1 - P_{FTR}) \lambda_{FT}} - P_{A_T}^{[N-1]}\right); \quad (31)$$

$P_{A_T}^{[1]}$  given in scenario 1

Also, for false targets the probability of false target attack,  $P_{A_{FT}}$ ,

$$P_{A_{FT}}^{[N]} = 1 - (1 - P_{TR})^N e^{-(1 - P_{FTR}) \lambda_{FT}} - P_{A_{FT}}^{[N-1]}; \quad (32)$$

$P_{A_{FT}}^{[1]}$  given in scenario 1

To calculate the longevity of the munition,  $\frac{\bar{s}}{T}$ , given the munition has attacked a target or false target, use the probability density function,  $h^N(t)$ , and the probability that an attack occurred

$$1 - H^N(T) = 1 - e^{-(1-P_{FTR})\lambda_{FT}} \quad (33)$$

where

$$H^N(s) = (1 - P_{TR} \frac{s}{T})^N e^{-(1-P_{FTR})\lambda_{FT} \frac{s}{T}} \quad (34)$$

### 2.3.4 Scenario 4 ( N Uniform Ts, M Uniform FTs )

In scenario 4, a uniform distribution environment is used to ensure real and false target encounters. The search environment consists of N uniformly distributed targets and M uniformly distributed false targets. Scenario 4 is unique in that the analytical solution for the probability of false target attack,  $P_{A_{FT}}$ , and the probability of real target attack,  $P_{A_T}$ , is represented by a system of partial differential equations with given boundary conditions. This system is represented by

$$P_{A_T}^{[M,N]} = 1 - (1 - P_{TR})^N P_{FTA/E}^M - P_{A_{FT}}^{[M,N]} \quad (35)$$

Also, for false targets the probability of false target attack,  $P_{A_{FT}}$ ,

$$P_{A_{FT}}^{[M,N]} = \frac{N}{(N+1)} \frac{P_{TR}}{(1-P_{FTR})} \left[ 1 - (1 - P_{TR})^{N-1} P_{FTR}^{M+1} - P_{AT}^{(M+1,N-1)} \right] \quad (36)$$

With boundary conditions

$$P_{A_T}^{[M,1]} = \frac{1}{M+1} \frac{P_{TR}}{(1-P_{FTR})} (1 - P_{FTR}^{M+1}) \quad (37)$$

$$P_{A_{FT}}^{[1,N]} = \frac{1 - P_{FTR}}{P_{TR}} \frac{1}{N+1} (1 - (1 - P_{TR})^{N+1}) \quad (38)$$

And finally, for scenario 4, the longevity of the WASM, assuming a performed attack on target, is calculated by the following probability distribution function,  $g^{[M,N]}(\tau)$ .

$$g^{[M,N]}(\tau) = \frac{(1 - P_{FTR})M}{T} \left( 1 - P_{TR} \frac{\tau}{T} \right)^N \left( 1 - (1 - P_{FTR}) \frac{\tau}{T} \right)^{M-1} ; 0 \leq \tau \leq T \quad (39)$$

and the probability

$$1 - H^{(M,N)}(T) = 1 - (1 - P_{TR})^N P_{FTR}^M \quad (40)$$

### 2.3.5 Scenario 5 ( N Normal Ts, Poisson FTs)

In scenario 5, a circular battlespace of radius  $r$  centered at the origin is considered. The search area contains  $N$  Normally distributed targets with variance  $\sigma$  and  $M$  Poisson distributed false targets parameterized by  $\alpha \left[ \frac{1}{km^2} \right]$ . Scenario 5 and later 6 are different from the previous 4 scenarios in that they search in a spiral pattern from the outside of the circle inward. [12] presents the probability of attack and false target attack for this case as

$$P_{AT}^N(r) = P_{TR} N \int_0^{r^2/2\sigma^2} x e^{-[1+2(1-P_{FTR})\alpha\pi\sigma^2]x} (1 - P_{TR} + P_{TR} e^{-x})^{N-1} dx \quad (41)$$

$$P_{AFT}(r) = \int_0^r (1 - P_{FTR}) 2\pi\alpha\rho e^{-(1-P_{FTR})\alpha\pi\rho^2} [1 - P_{TR} + P_{TR} e^{-\frac{\rho^2}{2\sigma^2}}]^N d\rho \quad (42)$$

Similarly, the probability of an attack occurring is characterized as

$$1 - H^N(r) = 1 - \left[ 1 - P_{TR} + P_{TR} e^{-\frac{r^2}{2\sigma^2}} \right]^N e^{-\alpha\pi(1-P_{FTR})r^2} \quad (43)$$

where

$$H^N(r) = e^{-(1-P_{FTR})\alpha\pi r^2} \left[ 1 - P_{TR} + P_{TR} e^{-\frac{r^2}{2\sigma^2}} \right]^N \quad (44)$$

### 2.3.6 Scenario 6 ( N Normal Ts, M Circular FTs )

Scenario 6 consists of a similar battlespace configuration as scenario 5, with the exception that false targets are distributed according to a Normal distribution with variance  $\sigma_{FT}$ . As with scenario 5, the munition search path starts from the outer rim of the circular battlespace and searches inward. The p.d.f.s of interest are

$$f^{(M,N)}(\rho) = P_{TR} N \frac{1}{\sigma_T^2} \rho e^{-\frac{\rho^2}{2\sigma_{FT}^2}} \left( 1 - P_{TR} + P_{TR} e^{-\frac{\rho^2}{2\sigma_T^2}} \right)^{N-1} \cdot \left[ P_{FTR} + (1 - P_{FTR}) e^{-\frac{\rho^2}{2\sigma_{FT}^2}} \right]^M \quad (45)$$

$$g^{(M,N)}(\rho) = (1 - P_{FTR}) M \frac{1}{\sigma_{FT}^2} \rho e^{-\frac{\rho^2}{2\sigma_{FT}^2}} \left( 1 - P_{TR} + P_{TR} e^{-\frac{\rho^2}{2\sigma_T^2}} \right)^N \cdot \left[ P_{FTR} + (1 - P_{FTR}) e^{-\frac{\rho^2}{2\sigma_{FT}^2}} \right]^{M-1} \quad (46)$$

and

$$H^{(M,N)}(\rho) = \left( 1 - P_{TR} + P_{TR} e^{-\frac{\rho^2}{2\sigma_T^2}} \right)^N \left[ P_{FTR} + (1 - P_{FTR}) e^{-\frac{\rho^2}{2\sigma_{FT}^2}} \right]^M \quad (47)$$

### **III. MultiUAV Simulation Environment**

Wide area search scenarios presented in chapter II were employed in this research for the express purpose of validating the operation of MultiUAV Version 1.3, an existing USAF Wide Area Search Munitions simulation. MultiUAV is a Simulink[19] based simulation environment developed by the Control Sciences Division, Air Vehicles Directorate, Air Force Research Laboratory (AFRL/VACA). This simulation is currently used in ongoing research in industry, government, and academia to develop, modify, and improve the performance of decentralized cooperative control algorithms. This section discusses the simulation obtained from AFRL/VACA and changes that were made to facilitate this research.

#### **3.1 Original Simulation**

**3.1.1 Simulation Operation** The simulation operates on the general characteristics of wide area search munitions. Therefore, searching WASMs perform actions based on rules that control the event flow of the mission, as seen in Figure 3-1 MultiUAV State Engine.

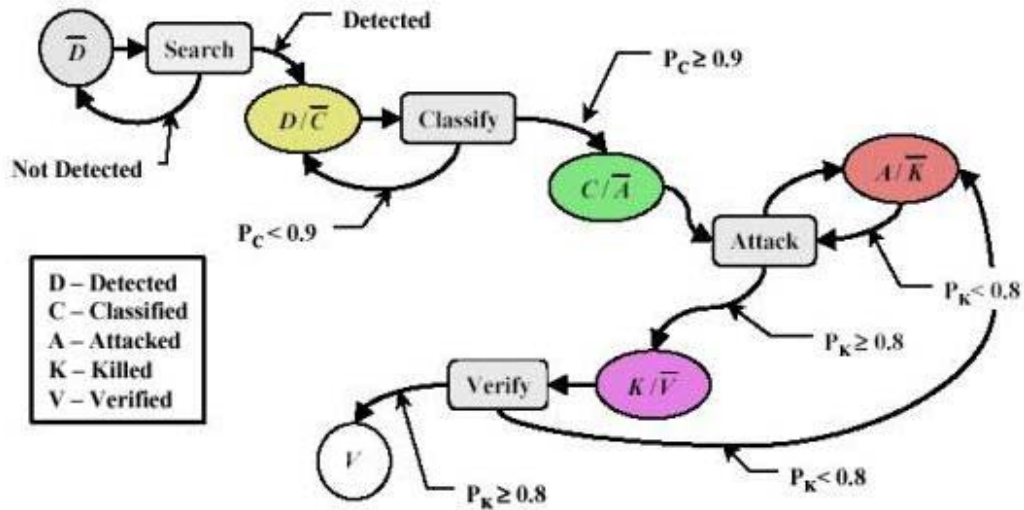


Figure 3-1 MultiUAV State Engine

The orders of operation for the rules that govern the chain of events, or ‘Kill Chain’, are as follows;

- *Detected*
- *Classified*
- *Attacked*
- *Killed*
- *Verified Destroyed*

The MultiUAV environment performs all operations based on the flow of these events.

A typical simulation begins with the vehicles starting from pre-determined positions and flying prescribed search patterns. When an object enters a vehicle’s field of regard, the vehicle classifies the object as a target or non-target and assigns a probability of correct classification based on the angle from which the vehicle viewed the object.

Several looks at a target are required to exceed the probability of target identification confidence,  $P_c$ . Upon meeting the required looks to meet or exceed the value of  $P_c$  a target type declaration is made. This information is passed to each vehicle, which then calculate the benefits of performing certain tasks. Possible tasks are:

- *Continue searching,*
- *Re-classify a previously classified target*
- *Perform target attack*
- *Perform battle damage assessment on an attacked target*

Vehicle tasks are assigned such that the overall benefit is maximized. This task allocation occurs each time the state of a target changes until the maximum simulation time is reached.

While the MultiUAV environment relies on several functions to perform the entire kill chain, Target Classification and Task Assignment have the greatest effect on the results of the simulation and thus will be explained in further detail.

## **3.2 Simulation Functions**

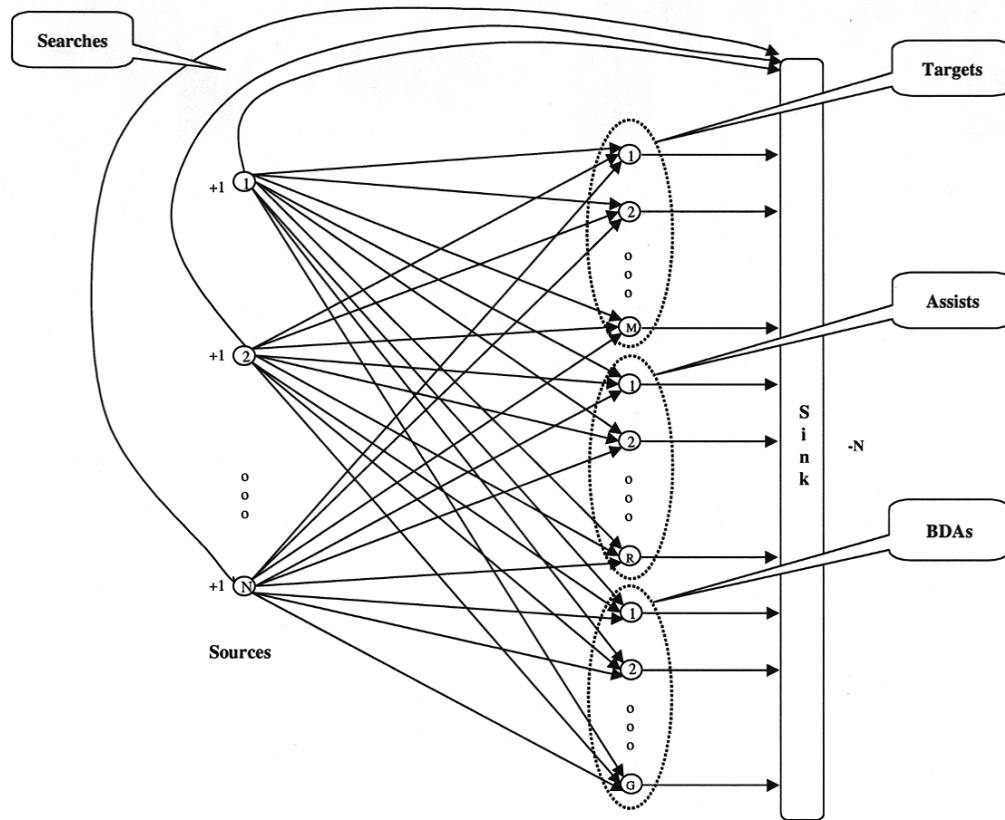
This section will cover the core functions of MultiUAV, know as the Embedded Flight Software (9). Highlighted are the modifications necessary to the simulation during this research effort.

### **3.2.1 Task Assignment**

The capacitated transshipment problem, as outlined in [14], provides the method for task allocation generation for the WASMs modeled in the MultiUAV environment. A



graphical representation of the network is shown in Figure 3-2 Capacitated Transshipment Network.



**Figure 3-2 Capacitated Transshipment Network**

The capacitated transshipment network is a modified linear programming problem that results in an integer solution. Capacitated transshipment is based on optimal routing of resources to meet demand in a network of defined capacity. At the sink of the network is a demand of  $N$ , where  $N$  is the number of WASMs. The targets are transshipment nodes with supplies and demands of zero.  $N$  WASMs must travel through the network to satisfy the end demand. The vehicles travel through the network along arcs that represent specific tasks and have certain value, or benefits, associated with them. The flow through the network is determined by the benefits associated with the various arcs. The values of these benefits are crucial to solving the network flow problem. By analyzing all arcs, the

optimal task allocation provides the greatest overall benefit to the system. MultiUAV employs a probabilistic approach [13] for task assignment, wherein emphasis is placed on killing high value targets over performing other tasks such as reclassification or battle damage assessment.

This research focused on a single WASM, and therefore the cooperative aspects of task allocation were not considered. Due to this consideration, very few modifications were made to the task allocation methods and therefore do not warrant discussion here.

**3.2.2 Target Classification and Confidence.** When a WASM classifies an object, the ATR function calculates a confidence level for that classification based on the angle from which the vehicle viewed the object. If the confidence is below a user-defined threshold, a second look at the target will be assigned to assist in classifying the object if the user specifies cooperation. Upon the second look, the individual confidences are then combined into a single confidence level that is compared to the threshold value. Once the confidence of correct classification is greater than the threshold, the object is deemed classified. This process assumes perfect identification of a target [10], and therefore a process to introduce error was introduced in order to provide realistic modeling of the ATR function. The *confusion matrix*, as described in section 2.2.1. is used to model the error associated with target misidentification.

The confusion matrix provides misidentification by allowing for a false target to be declared as real, and vice versa. This method implemented in the simulation is as follows:

- Upon encounter of either a true or false target, a random sample between 0 and 1 from a uniform distribution is performed

- The value of the random sample is compared to the diagonal and off diagonal terms of the corresponding column of confusion matrix.
- The target type is declared based on the above comparison

For example, assume a WASM has encountered a true target. If  $P_{TR}$  for the WASM is 95%, and the random sample from the uniform distribution is .85, the target would be declared as real. However, if the sample had exceeded .95, then according to the confusion matrix of Figure 3-3 Confusion Matrix of  $P_{TR} = .95$ , a false target would then be declared. The identical process occurs when a false target is encountered by a WASM. For a matter of convenience,  $P_{TR}$  and  $P_{FTR}$  were declared identical. This research looked at the results of two different ATR's, one having a  $P_{TR}$  of 95%, and one of 85%. Varying the capabilities of the two ATR's provided insight into the effect of false target declaration on the overall number of real vs. false target attacks. As a note, the simulation used truth information to identify what target type the WASM is *actually* seeing, while the output from the confusion matrix provides *perceived* information.

Declared Object	Encountered Object	
	Target	Non-Target
Target	.95	$1 - P_{FTR}$
Non-Target	.05	$P_{FTR}$

**Figure 3-3 Confusion Matrix of  $P_{TR} = .95$**

**3.2.3 Communications.** The simulation entails perfect global communication of perceived information. Currently MultiUAV provides error free, instantaneous dissemination of information to all vehicles operating in the simulation. It is important to note that a realistic depiction of communications would be range, bandwidth, and latency limited and information may be miscommunicated or not communicated at all. In a multi WASM simulation employing cooperation, Mitchell [16]

has noted different vehicles would calculate benefits based on different information, and the network flow problem may become unstable. This research focused on a single WASM and did not take into account these considerations, so inter vehicle communications was not applicable.

The communications architecture of MultiUAV was developed to separate *truth* information, or what the simulation *knows* to be true, from *perceived* information, or what the individual WASM would know based on its notion of the world around it. As a note, perceived information can vary from the truth as WASMs can misidentify targets via the confusion matrix. Dunkel [13] and Gozaydin [15] had made initial modifications to MultiUAV to allow WASMs to retrieve and store perceived information. This method was modified by creating a more efficient means of separating the perceived information from truth information by each vehicle in the simulation. This research did not focus on multiple WASMs cooperating, so the implications of perceived information were not as pronounced as they would be from multiple, cooperating vehicles relying on perceived information to make tasking decisions. This modification, however, did force a change in how the ATR confidence calculations were performed. Due to the possibility that multiple looks may be required on a single target, many different perceived type targets may be stored in memory by the WASM. To prevent this from occurring, the maximum confidence value was assigned to each target upon detection, thus preventing multiple looks at a single target. This however would have no effect on misidentification of a target.

**3.2.4 Lethality.** When a WASM attacks a target in MultiUAV, a simulated kill radius is considered that effects any target that lies within the area covered by the blast

radius. The MultiUAV simulation environment provides for the ability to model successful and unsuccessful attacks on a target, thus allowing more realistic kill scenarios to be considered. The kill event occurring within the warhead blast radius is modeled by comparing a random draw from a uniform distribution between 0 and 1 to a user-defined probability of kill ( $P_k$ ). For example, when a vehicle attacks a target, a random draw is made and compared to the value of  $P_k$ . If the random draw and  $P_k$  value are such that a successful hit occurs, then the target is considered killed.

This research used two values of  $P_k$ , 50% and 80%, to represent a small and large warhead, respectively. Thus, every scenario was evaluated for a small and large warhead. The number of successful and unsuccessful attacks for each scenario was collected for post processing.

**3.2.5 Battle Damage Assessment.** In a multiple cooperative WASM scenario, the final task in the kill chain is battle damage assessment (BDA). After a target has been attacked, another vehicle may be assigned to assess the damage done to that target. Due to this research's focus on a single WASM, the BDA state was never achieved, and thus no modifications were made to the BDA functionality of MultiUAV.

### ***3.3 Simulated Target Distributions***

The distribution of both real and false targets in the MultiUAV simulation is made possible by the use of three independent distribution methods; uniform, normal, and Poisson. The use of multiple distribution methods is necessary to model different target encounter scenarios. The following section describes the motivation and methodology employed with these three methods.

### **3.3.1 Battlespace Configuration**

The battlespace for scenarios 1-4 considers search strip 600 meter wide by 270,000 meters in length. This provides a search area with equal width of the WASM's primary target acquisition sensor, and with length that can be traversed by the WASM in a 30-minute time of flight. This search area was selected as it modeled as closely as possible the battlespace considered in scenarios 1-4.

Scenarios 5 and 6 require special attention in the construction of their respective search areas. The analytic models depicted in chapter II are constructed based on a circular search area. The search area used in the simulation, however, was of identical configurations as those of scenarios 1-4, with the exception of the overall length of the search area. This was necessary due to modeling limitations in the simulation. As a note, the analytic models for scenarios 5,6 were modified to reflect the change from a circular to linear search area.

### **3.3.2 Uniform Target Distribution**

A target distributed at random via sampling from a uniform distribution is the most direct method to place an expected number of targets over a battlespace of known area. This method is used when it is desired to distribute a fixed number of targets over a specified area. Such an example would be if battlefield intelligence has reported the known number of targets,  $N_{tgt}$ , within a specified battlespace but were unable to ascertain their locations. A random distribution of the known number of targets over the specified area is then performed within the simulation to match the expected battlefield conditions.

The uniform distribution is implemented by using a random number generator based upon a uniform distribution of  $N_{tgt}$ . This requires the user to provide the known

number of target to be encountered. Since MultiUAV is Matlab based, the uniform random number generator is easily implemented by using the built in command  $RAND(N_{tgt})$ . The  $RAND(N_{tgt})$  function generates an array of random numbers whose elements are uniformly distributed in the interval (0,1). Thus,  $RAND(N_{tgt})$  returns an  $N_{tgt}$ -by-1 matrix of random entries. The elements of the random vector are then multiplied by a scaling factor to convert them to a representative distance between 0 and the maximum length of the battlespace. The  $RAND$  function allows the user to seed the random number generator, and thus the simulation reseeds the random number generator as to prevent identical target distributions as the previous simulation run.

### 3.3.3 Normal Target Distribution

Distributing targets using a normal distribution allows for a concentration of targets about a specified mean,  $\mu_{loc}$ , with standard deviation  $\sigma_{loc}$ . For example, assume an intelligence report just arrived that specified the location of a target 10 minutes ago. If the mean and standard deviation of the sensor used to collect the location of the target is known, then a target location can be created in the simulation by using a the same mean ,  $\mu_{loc}$ , and standard deviation  $\sigma_{loc}$ . This assumes stationary targets. Modeling target locations via Normal distributions has the added benefit of allowing the possibility of not encountering  $N_{tgt}$ . This is made possible by selecting  $\sigma_{loc}$  to generate an expected percentage of total  $N_{tgt}$  encountered over the total battlespace.

The normal distribution is implemented in nearly the same way as the uniform distribution, with the addition of supplying the mean ,  $\mu_{loc}$ , and standard deviation  $\sigma_{loc}$ . In this case, the vehicle is assumed to begin searching at the location  $x=0$ , thus  $\mu_{loc} = 0$ . Next,  $\sigma_{loc}$  was chosen such that 80.64% of all targets would fall within the battlespace.

This was identified simply by referring to a normal distribution area chart [17] to identify the Z score, where

$$Z = \frac{X_{Max} - \mu_{loc}}{\sigma_{loc}}, \quad (48)$$

and  $X_{Max}$  is the length of the battlespace. Because it is assumed that  $\mu_{loc}$  is 0, and the normal distribution area chart refers to 80.64% as  $Z=1.3$ , or 1.3 standard deviations above the mean. Thus, by substitution,  $\sigma_{loc}$  is computed to be 98.46.

The computed standard deviation and zero mean value are used in the *RANDN(N<sub>tgt</sub>)* MATLAB command to produce a vector of  $N_{tgt}$  random normal target locations centered about the mean. As a note, it is possible to generate both positive and negative random values. Therefore, to simulate searching from the center of a distribution outward, all values are interpreted as the absolute value, and thus the WASM need only to fly in one direction to cover the entire target distribution.

### 3.3.4 Poisson Target Distribution

The Poisson distribution provides for target encounters to be modeled as an expected number of events,  $N_{tgt}$ , that will occur over a the specified battlespace. Thus, the expectation of many samples from a Poisson distribution will result in  $N_{tgt}$ , however each random sample may be above or below  $N_{tgt}$ . This allows for the modeling of non-constant  $N_{tgt}$  values for each simulation run, but still maintain a mean value of  $N_{tgt}$  over the total number of simulation runs.

The Poisson process was implemented in MultiUAV by using a Poisson distribution based random number generator (18). The random number generator requires  $\lambda$ , the Poisson Probability Law Parameter, for the target type. Thus



$$\lambda = \alpha A \quad (49)$$

where  $A$  is the area of the battlespace and  $\alpha$  is the target density  $\frac{1}{Km^2}$ . For example, if an average of  $N_{tgt}$  targets are distributed at random over a region  $A_s$ , and a vehicle can search at a rate of  $Q \frac{Km}{hr}$ , then the number of vehicles sighted by the WASM over a time

$T$  obeys the Poisson Probability law with parameter defined a

$$\lambda = \left( \frac{N_{tgt}}{A_s} \right) QT \quad (50)$$

where in this case

$$Q = WV, QT = A_s \quad (51)$$

and  $W$  is 600 meters and  $V$  is  $142.4 \frac{m}{s}$ . Thus  $Q = 85,440 \frac{m^2}{s}$

Now, if  $N_{tgt}$  is 10 false targets, and the WASM can search for 1800s, or 30 min, then  $\lambda = 10$ .

MultiUAV requires the exact location of a target so that it knows exactly where it lies within the simulated battlespace. As a note, Equation 50 describes the Poisson parameter  $\lambda$  for the entire  $A_s$ . Thus when using the Poisson distribution for random target locations  $A_s$  must be divided into many segments as to sample if there is a target present at that location. This affects Equation 50 by modifying  $A_s$  a smaller sample area,  $\Delta A$ .  $\Delta A$  was selected to be 14.24 meters long by 600 meters wide. Therefore, the battlespace was divided in 18000 segments, as the total length of the battlefield is 256,320 m and the individual segment length is 14.24 m.

**3.4 Additional Modifications.** In order to facilitate this research, several other modifications were made to the original simulation. These modifications allow summary

and output to a file of specified statistics and allow the activation or de-activation of various features such as distribution types. While these changes were important for this research effort, they did not affect how the actual simulation ran and are not described in detail here.

## IV. Results and Analysis

### 4.1 Simulation Considerations

In order to validate the MultiUAV simulation, the analytical results of the six scenarios developed in Section II were compared to empirical results from Monte Carlo simulations. Each scenario was configured in the simulation to match the false and true target density, the distribution type,. Additionally, the WASM lethality and the ability of the ATR algorithm to correctly classify the target type were set to match those values used in the scenario analytical formulation. These parameters can be sorted into two categories.

- WASM Parameters:
  - ATR capabilities modeled in the confusion matrix (Figure 2-2) as  $P_{TR}$  and  $P_{FTR}$ .
  - Warhead lethality,  $P_k$
- Battlespace Characteristics
  - Uniform number of Targets,  $N$
  - Uniform number of False Targets,  $M$
  - Real Target Poisson Probability Law Parameter,  $\lambda_T$
  - False Target Poisson Probability Law Parameter,  $\lambda_{FT}$
  - Standard Deviation of Target location,  $\sigma_{loc}$
  - Standard Deviation of False Target location,  $\sigma_{locFT}$

Park [11] has noted these values can be interpreted as both environmental factors relating to the conditions of the battlespace and design parameters of the WASM. These parameters would normally be emphasized in greater detail, as in the case of performing a trade study. However, the focus of this effort is to merely validate the performance of the MultiUAV environment, and thus arbitrary values for the above parameters were selected to make the analysis simple.

The output data derived from the simulations are provided in the form of quantitative values for each battlefield scenario. Thus, the analysis of output data focuses on the numbers of targets and false targets attacked and killed while the values describing the battlespace and WASM parameters are varied.

## 4.2 Validity Investigation Methodology

Scenarios 1-6, as outlined in chapter II were each implemented by varying the WASM Parameters and Battlespace Characteristics to create a range of realistic mission conditions. Table 4-1 Simulation Parameter Variations outlines the test values used to vary these parameters for scenarios 1-6.

Parameter	Value
$P_{TR}, P_{FTR}$	.85, .95
$P_k$	.5, .8

**Table 4-1 Simulation Parameter Variations**

As noted in chapter II,  $P_{TR}$ , and  $P_{FTA/E}$  are assumed identical for all scenarios. This table does not include the variations to the distributions of the targets, as this pertains to the individual scenarios. Each scenario evaluation was performed by following an identical test matrix, as outlined in Table 4-2 Test Matrix.

Test Case	$P_{TR}, P_{FTR}$	$P_k$
1	.85	.5
2	.85	.8
3	.95	.5
4	.95	.8

**Table 4-2 Test Matrix**

The configuration of the test matrix provided identical WASM parameters during the Monte Carlo runs for each scenario. For the purpose of validity investigation, the results of the simulation were compared to the calculated values of mission success predictions outlined in chapter II.

### **4.3 Validity Investigation**

The results derived from the simulation focused on five primary metrics outlined in section 2.1.3. They are

- Probability of real target attack,  $P_{AT}$
- Probability of false target attack,  $P_{AFT}$
- Probability of successful target kill,  $P_{Tk}$
- Probability of successful false target kill,  $P_{FTk}$
- Longevity of WASM given attack occurs,  $\frac{\bar{s}}{T_s}$ , where  $s$  is time of attack

Where  $P_{Tk}$  and  $P_{FTk}$  are calculated by

$$P_{Tk} = P_{AT} \cdot P_k \quad (52)$$

These five metrics represent the expectations that both real and false targets are attacked, destroyed, and on average how long the WASM searched the battlespace before engaging either a T or FT.

The following six sections represent the comparative results of the simulation vs. analytical formulations. The results are presented in tabular form, with the analytical solution to the expected probabilities in the *Analytical Calculation* column, and the mean of the total simulation results in the *Simulation Result* column. Each Monte Carlo simulation of a scenario was run 400 times, 100 per variation of  $P_{TR}$  and  $P_k$ . This number of runs was performed to yield high statistical confidence for the given model.

#### **4.3.1 Scenario I Results**

The simulation model for the validity investigation of scenario 1 was set up using a single uniformly distributed T, and Poisson distribution of FTs. Hence,  $\lambda_{FT} = 10$ , for the expectation of 10 false targets over the battlespace, and  $T = 1$ . The results are tabulated below.

<i>P<sub>tr</sub></i>	<i>P<sub>k</sub></i>	<i>Metric</i>	<i>Simulation Value</i>	<i>Analytical Value</i>	<i>PercentDiff</i>
0.85	0.50	PAT	46.0	44.0	2.0
		PAFT	48.0	45.1	2.9
		PTk	22.0	22.0	0.0
		PFTk	24.0	24.0	0.0
		s/T	0.3	0.3	1.0
	0.80	PAT	46.0	44.0	2.0
		PAFT	48.0	52.6	4.6
		PTk	37.0	35.2	1.8
		PFTk	41.0	42.1	1.1
		s/T	0.3	0.3	1.0
0.95	0.50	PAT	74.0	74.8	0.8
		PAFT	20.0	22.2	2.2
		PTk	37.0	37.4	0.4
		PFTk	11.0	11.1	0.1
		s/T	0.4	0.4	1.8
	0.80	PAT	74.0	74.8	0.8
		PAFT	20.0	22.2	2.2
		PTk	61.0	59.8	1.2
		PFTk	19.0	17.7	1.3
		s/T	0.4	0.4	1.8

**Table 4-3 Scenario 1 Results**

### **4.3.2 Scenario 2 Results**

The simulation model for the validity investigation of scenario 2 was set up using a Poisson distribution of  $T_s$ , and Poisson distribution of  $FT_s$ . Hence,  $\lambda_{FT} = 10$ , for the expectation of 10 false targets over the battlespace, and  $\lambda_T = 1$ . This setup resembles that of Scenario 1, with the exception that the targets are all modeled via Poisson distributions. The results are tabulated below.

<i>P</i> <sub>tr</sub>	<i>P</i> <sub>k</sub>	Metric	Simulation Value	Analytical Value	Difference
0.85	0.50	PAT	31.0	32.7	1.7
		PAFT	59.0	57.7	1.3
		PTk	15.0	16.4	1.4
		PFTk	30.0	28.9	1.1
		s/T	29.4	32.0	2.6
	0.80	PAT	31.0	32.7	1.7
		PAFT	59.0	57.7	1.3
		PTk	24.0	26.2	2.2
		PFTk	48.0	46.2	1.8
		s/T	29.4	32.0	2.6
0.95	0.50	PAT	50.0	50.1	0.1
		PAFT	27.0	26.4	0.6
		PTk	25.0	25.1	0.1
		PFTk	12.0	13.2	1.2
		s/T	33.2	38.3	5.1
	0.80	PAT	50.0	50.1	0.1
		PAFT	27.0	26.4	0.6
		PTk	37.0	40.1	3.1
		PFTk	22.0	21.1	0.9
		s/T	33.2	38.3	5.1

Table 4-4 Scenario 2 Results

### 4.3.3 Scenario 3 Results

The simulation model for the validity investigation of scenario 3 was set up using  $N$  uniformly distributed  $T$ s, and Poisson distribution of  $FT$ s. Hence,  $\lambda_{FT} = 10$ , for the expectation of 10 false targets over the battlespace, and  $N = 5$  for  $T$ s. The results are tabulated below.



<i>Ptr</i>	<i>Pk</i>	<i>Metric</i>	<i>Simulation Value</i>	<i>Analytical Value</i>	<i>Difference</i>
0.85	0.50	PAT	77.0	77.0	0.0
		PAFT	22.0	26.5	4.5
		PTk	39.0	38.5	0.5
		PFTk	8.0	13.3	5.3
		s/T	16.1	15.6	0.5
	0.80	PAT	77.0	77.0	0.0
		PAFT	22.0	26.5	4.5
		PTk	64.0	61.6	2.4
		PFTk	20.0	21.2	1.2
		s/T	16.1	15.6	0.5
0.95	0.50	PAT	92.0	91.2	0.8
		PAFT	8.0	11.2	3.2
		PTk	46.0	45.6	0.4
		PFTk	3.0	5.6	2.6
		s/T	17.2	16.3	0.9
	0.80	PAT	92.0	91.2	0.8
		PAFT	8.0	11.2	3.2
		PTk	77.0	73.0	4.0
		PFTk	8.0	8.9	0.9
		s/T	17.2	16.3	0.9

**Table 4-5 Scenario 3 Results**

#### **4.3.4 Scenario 4 Results**

The simulation model for the validity investigation of scenario 4 was set up using a N uniformly distributed T, and M uniformly distributed FTs. Hence, M = 10, for the expectation of 10 false targets over the battlespace, and N=1 for Ts. The results are tabulated below.

<i>Ptr</i>	<i>Pk</i>	<i>Metric</i>	<i>Simulation Value</i>	<i>Analytical Value</i>	<i>Difference</i>
0.85	0.50	PAT	41.0	42.9	1.9
		PAFT	57.0	54.1	2.9
		PTk	22.0	21.5	0.6
		PFTk	35.0	27.1	8.0
		s/T	35.6	34.5	1.1
	0.80	PAT	41.0	42.9	1.9
		PAFT	57.0	54.1	2.9
		PTk	35.0	34.3	0.7
		PFTk	49.0	43.3	5.7
		s/T	35.6	34.5	1.1
0.95	0.50	PAT	72.0	74.5	2.5
		PAFT	24.0	22.5	1.5
		PTk	37.0	37.3	0.3
		PFTk	18.0	11.3	6.8
		s/T	45.4	44.3	1.0
	0.80	PAT	72.0	74.5	2.5
		PAFT	24.0	22.5	1.5
		PTk	59.0	59.6	0.6
		PFTk	23.0	18.0	5.0
		s/T	45.4	44.3	1.0

Table 4-6 Scenario 4 Results

#### 4.3.5 Scenario 5 Results

The simulation model for the validity investigation of scenario 5 was set up using a  $N=1$  Normally distributed  $T$  having  $\sigma_T$  of 98.46 and Poisson distributed FTs. This was realized using  $\lambda_{FT} = 10$ , for the expectation of 10 false targets over the battlespace, and  $N = 1$  for Ts. The results are tabulated below.

<i>Ptr</i>	<i>Pk</i>	<i>Metric</i>	<i>Simulation Value</i>	<i>Analytical Value</i>	<i>Difference</i>
0.85	0.5	PAT	43.0	40.0	3.0
		PAFT	32.0	32.0	0.0
		PTk	21.0	20.4	0.6
		PFTk	16.0	15.8	0.2
		s/T	27.1	24.2	2.9
	0.8	PAT	43.0	40.0	0.5
		PAFT	39.0	32.0	7.0
		PTk	36.0	34.3	1.7
		PFTk	26.0	25.4	0.6

		s/T	29.3	24.2	5.1
0.95	0.5	PAT	67.0	64.4	2.6
		PAFT	10.0	10.5	0.5
		PTk	31.0	32.2	1.2
		PFTk	6.0	5.2	1.2
		s/T	35.6	33.0	2.6
	0.8	PAT	67.0	64.4	2.6
		PAFT	15.0	10.5	4.5
		PTk	55.0	51.5	3.5
		PFTk	9.0	8.4	0.6
		s/T	35.3	33.0	2.3

Table 4-7 Scenario 5 Results

#### 4.3.6 Scenario 6 Results

The simulation model for the validity investigation of scenario 6 was set up using a N Normally distributed T having  $\sigma_T$  of 98.46 and M Normally distributed FT having  $\sigma_T$  of 98.46. This was realized using M = 10, for the expectation of 10 false targets over the battlespace, and N = 1 for Ts. The results are tabulated below.

<i>Ptr</i>	<i>Pk</i>	<i>Metric</i>	<i>Simulation Value</i>	<i>Analytical Value</i>	<i>Difference</i>
0.85	0.5	PAT	37.0	30.2	6.8
		PAFT	54.0	43.0	11.0
		PTk	18.0	15.0	3.0
		PFTk	30.0	21.1	8.9
		s/T	26.1	25.0	0.1
	0.8	PAT	32.0	30.2	1.8
		PAFT	52.0	43.0	9.0
		PTk	29.0	24.0	5.0
		PFTk	44.0	34.4	9.6
		s/T	24.5	25.0	0.5
0.95	0.5	PAT	70.0	71.6	1.6
		PAFT	20.0	16.1	3.9
		PTk	36.0	35.8	0.2
		PFTk	11.0	8.0	3.0
		s/T	38.3	29.0	9.3
	0.8	PAT	69.0	71.6	2.6
		PAFT	16.0	16.1	0.1
		PTk	56.0	57.2	1.2
		PFTk	14.0	12.8	1.2
		s/T	32.1	29.0	3.1

Table 4-8 Scenario 6 Results

#### **4.4 Validation Results**

Tables 4-3 through 4-8 present the comparative results of scenarios 1 through 6. In review one can see the analytical predictions for all scenarios closely align with the simulation results. This is evident as the percent differences between the analytical and empirical data fall well within a 9.6% error bound defined by the confidence interval based on 100 samples per simulation run [22]. This is true for all cases except scenario 6 where  $P_{FTA}$  and  $P_{FTk}$  for  $P_{TR} = .85$  exceed the error bound by 2%. This is the result of data generated from several machines that have dissimilar random number generators.

The results indicate strong correlation between the analytical models for all scenarios, as the errors in all cases have fallen within the statistical confidence interval calculated for 100 simulation runs per scenario configuration.

## **VI. Conclusions and Recommendations**

An evaluation methodology to provide a baseline performance validation of the MultiUAV simulation tool has been proposed. This evaluation compares the simulation vs. analytical results for scenarios comprised of both real and false target attacks, in addition to the lifetime of a single WASM over a range of vehicle performance parameters. Six analytical scenarios provide the necessary variations in the type of multi-target distributions in order to evaluate the simulation performance parameters for varying battlespace conditions.

Comparative results presented in the previous section indicate the use of the MultiUAV simulation can provide valid target classification and kill information. The validation methodology presented here is crucial for further research involving MultiUAV for use in the study of cooperative WASMs. This allows future decentralized cooperative control research to focus on control algorithms, as the results of each target attack and kill are now deemed valid.

The following sections will discuss the limitations of the current research and propose future research topics to address these concerns.

### ***5.1 Limitations of the Validation Model***

In order to reproduce an environment described by the six analytic scenarios several simplifications in the simulation were necessary. First, a generic WASM was used in all cases to provide results representing broad applicability to future research applications. This was done by not allowing the WASM to perform any non-conventional search or attack capabilities that would limit the results to only certain vehicle types

possessing a similar capability. Lost search time due to a blind turn and/or redundancy was not covered. Second, the analytic solutions do not associate target classifications with the aspect angle in which it was seen by the WASM. Therefore, while MultiUAV is capable of performing this action it was disabled for this research. Finally, the analytical solutions were formulated based on static targets. Therefore the simulation was configured to present stationary targets

## **5.2 Recommended Further Research**

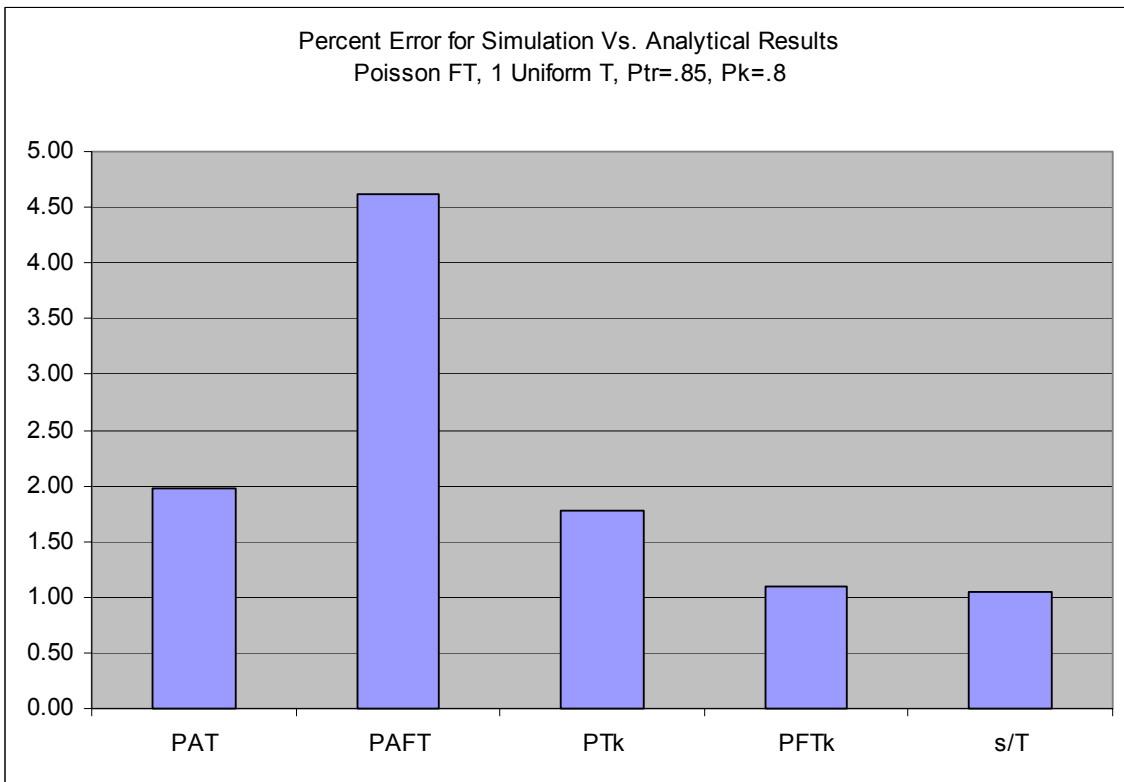
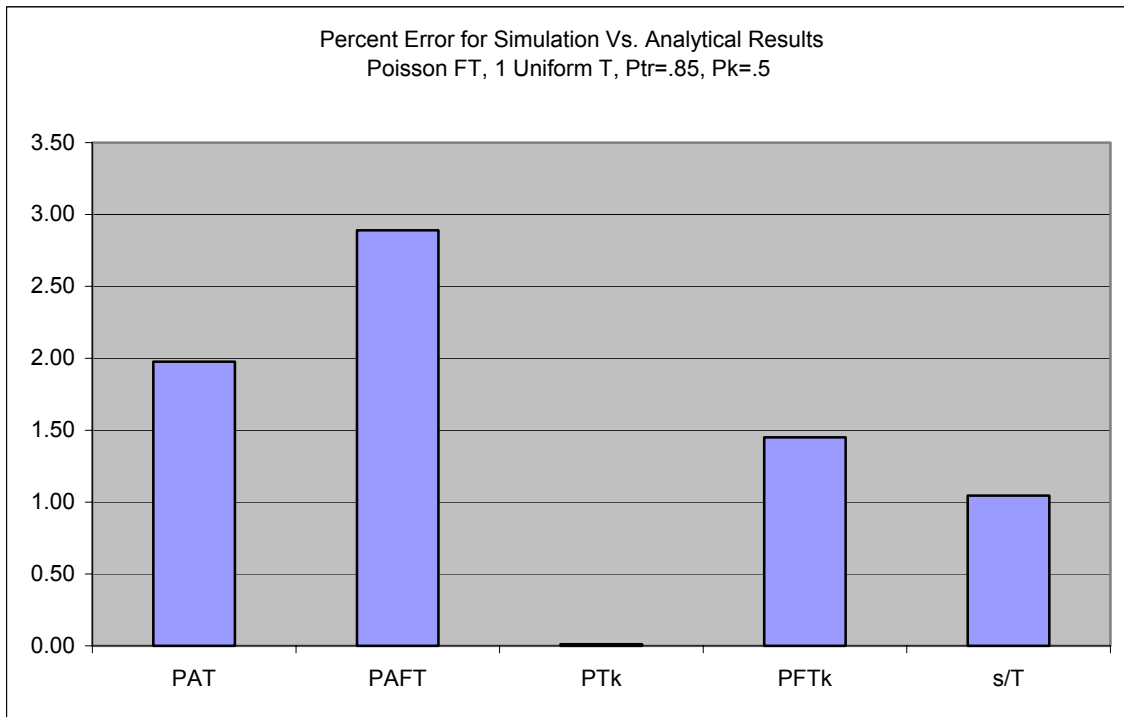
The validation methods presented here are valid for a single searching munition capable of attacking a single target in a static environment of real and false targets. There is a need, however, to expand this research to provide for the evaluation of more complex SEAD type scenarios employing cooperative WASMs or multi warhead capable UAVs. Multiple warhead capability analysis has already been performed for scenarios 1,2, however work to resolve the multi-warhead cases for the remaining scenarios is ongoing at this time.

Future work to expand the analytical methods presented in this research should incorporate mission success probabilities for multiple, cooperative WASMs. This, as mentioned earlier, will provide a method to validate the empirical results generated by a simulation using cooperative control algorithms. This includes formulating basic rules of engagement based on cooperative attack and/or target classification. Additionally, efforts should be made to incorporate various types of Ts, and allow for variations in FTs. This would allow for more than a simple binary confusion matrix, as was employed in this research. Finally, the statistical models should incorporate a the probability of a munition

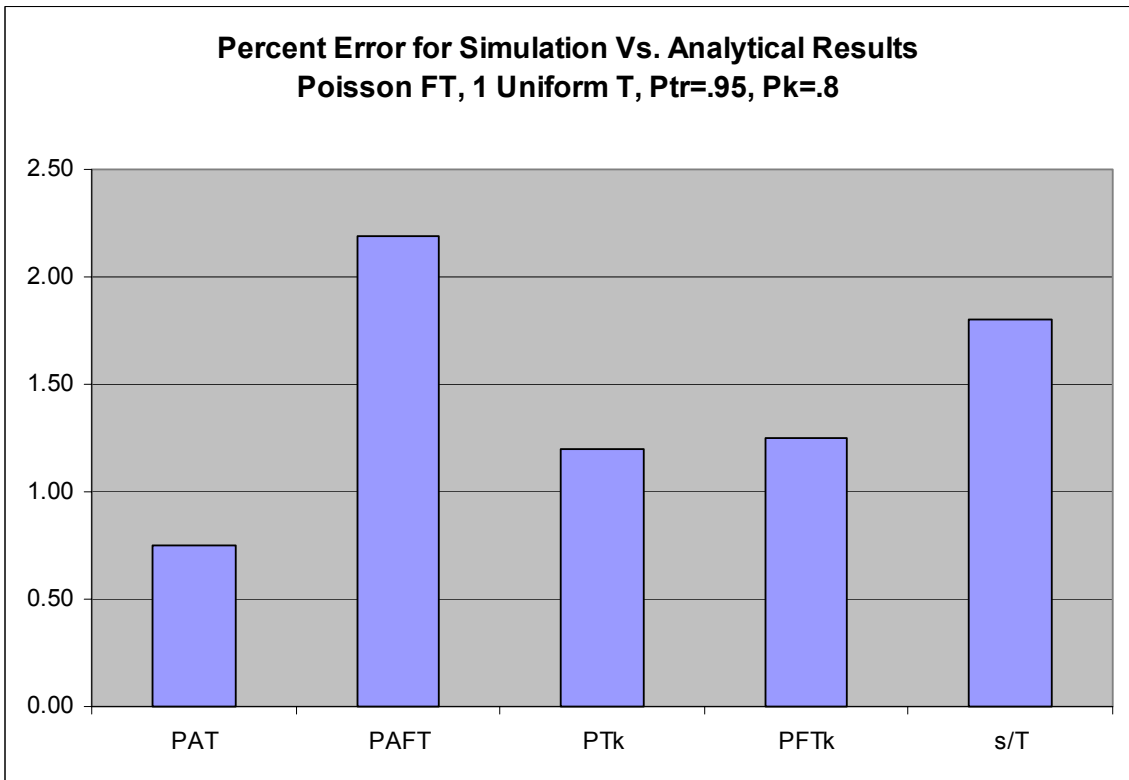
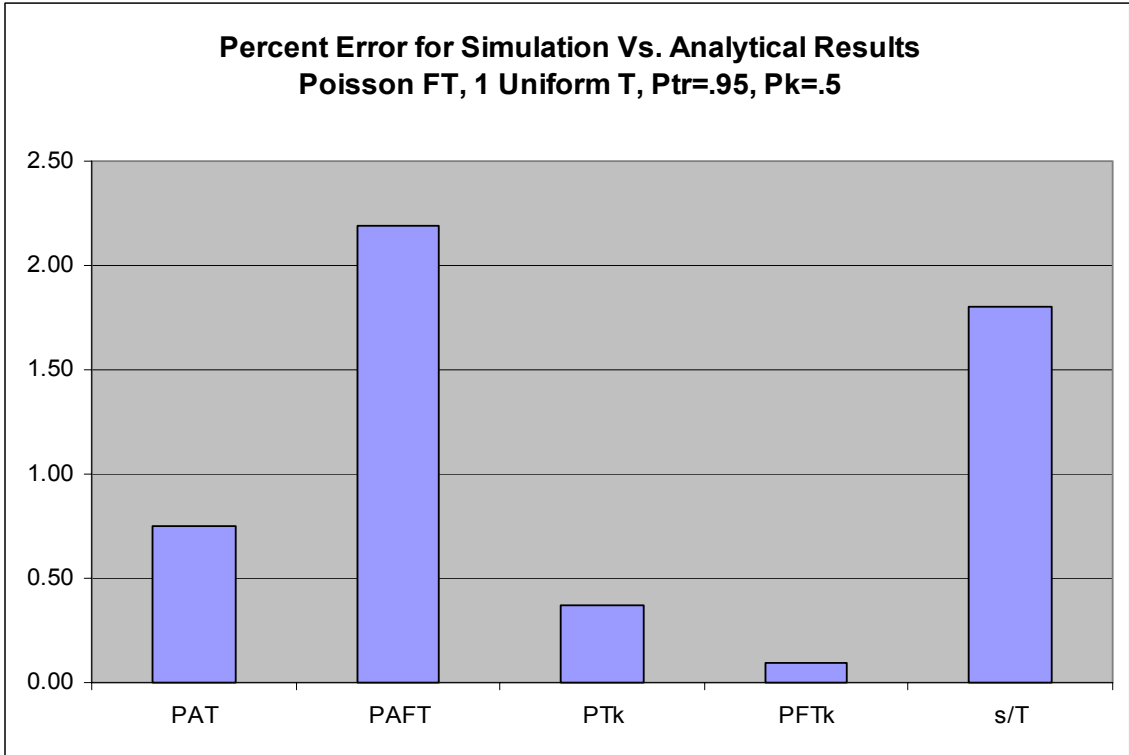
correctly identifying an object dependant on view angle in which it encounters the target. This will allow for more realistic target classifications.

Modifications are necessary to the MultiUAV simulation for future research in cooperative control of WASMs. The area of greatest improvement is to incorporate more realistic communications inter vehicle communications system. Currently the simulation environment assumes perfect communications between vehicles. While this is convenient for baseline comparisons a flawed communications system incorporating delays, latencies, and signal loss would present a more realistic scenario for cooperative control scenarios.

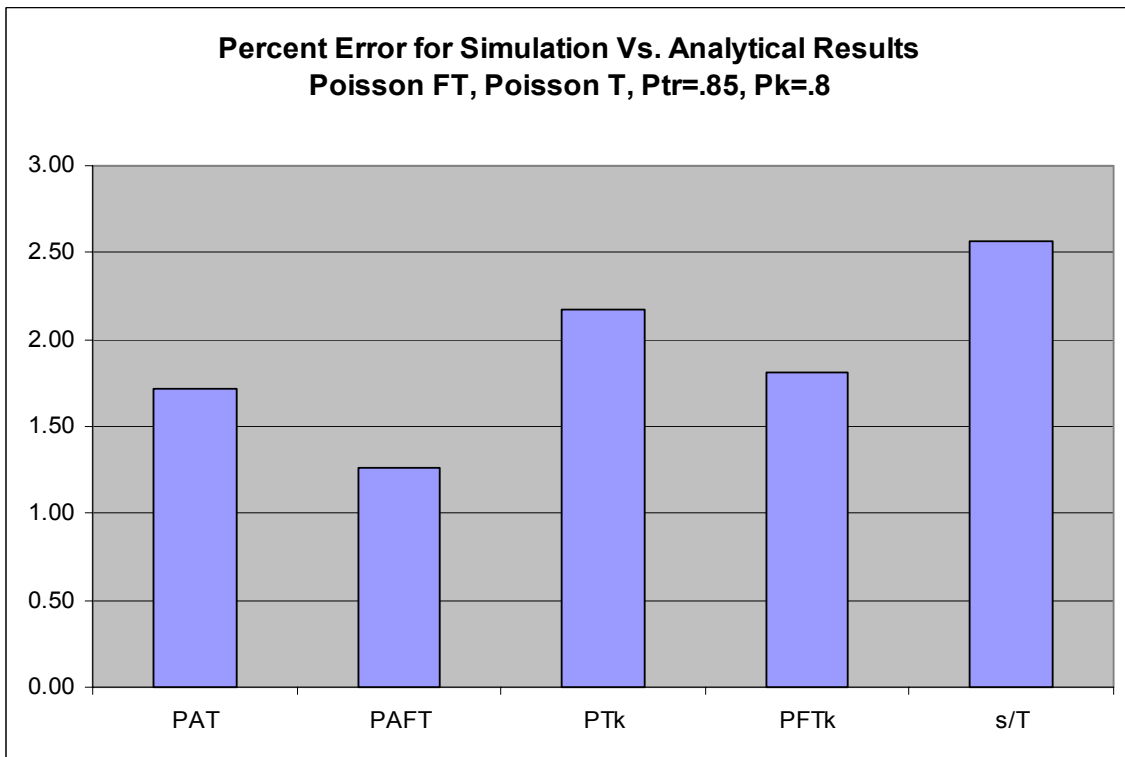
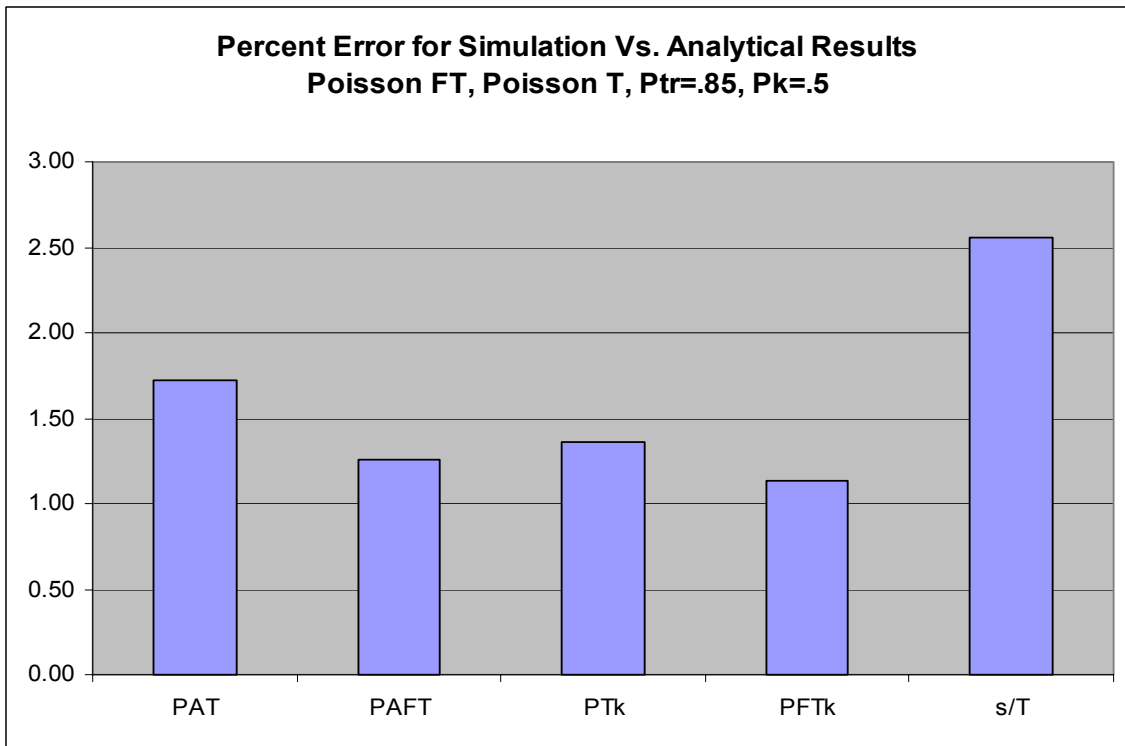
## Appendix A: Scenario 1 Data



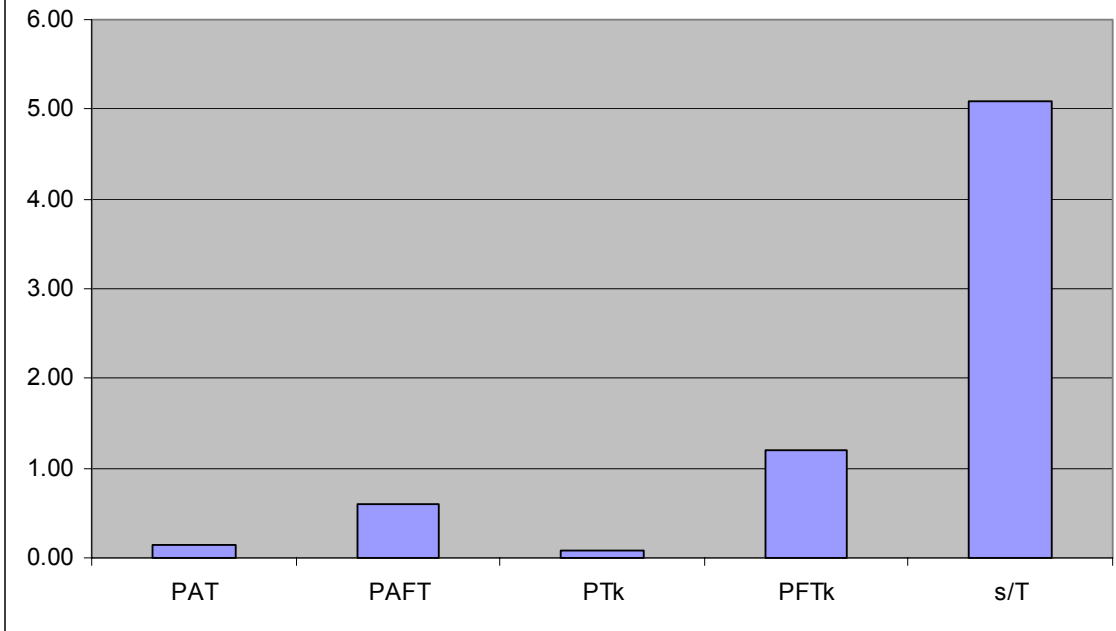




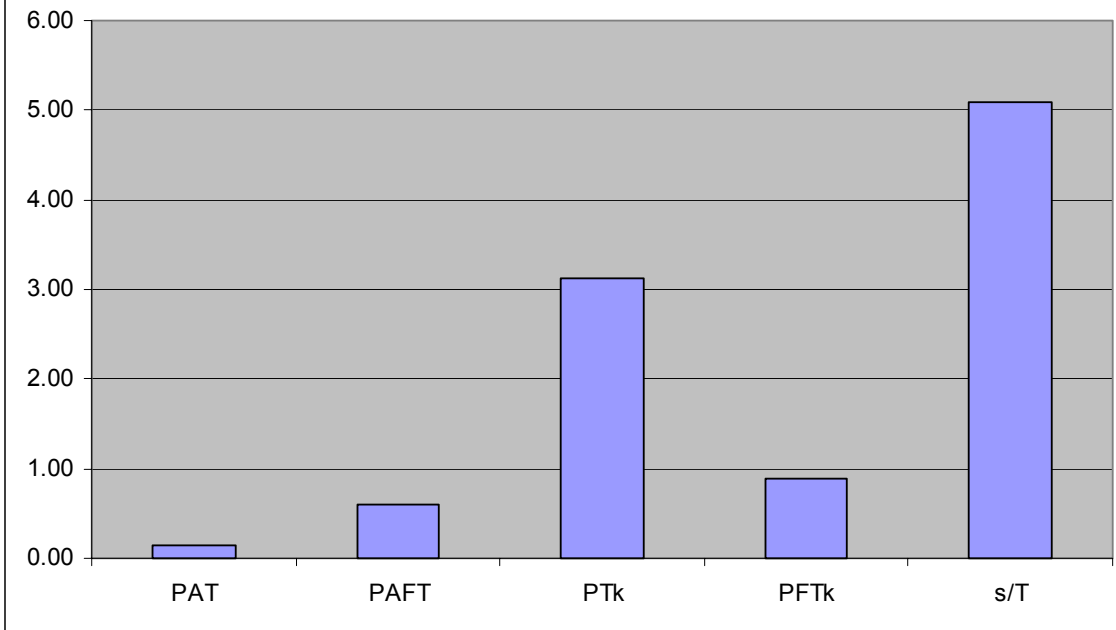
## Appendix B: Scenario 2 Data



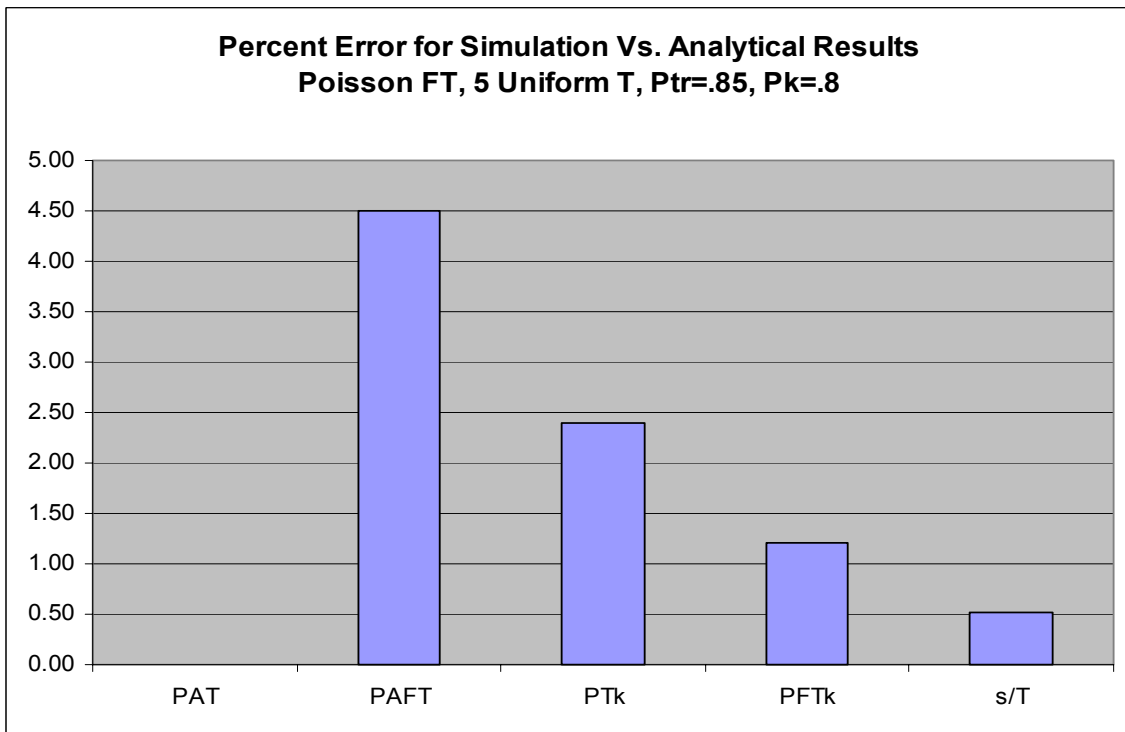
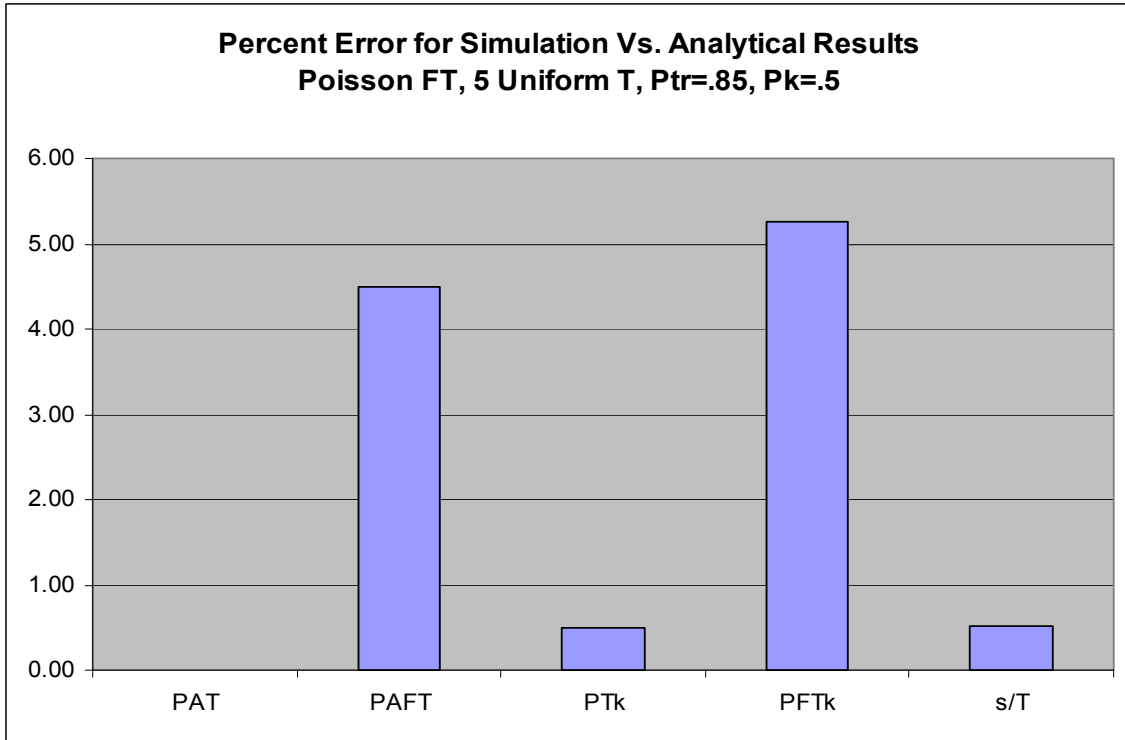
**Percent Error for Simulation Vs. Analytical Results Poisson FT,  
Poisson T, Ptr=.95, Pk=.5**

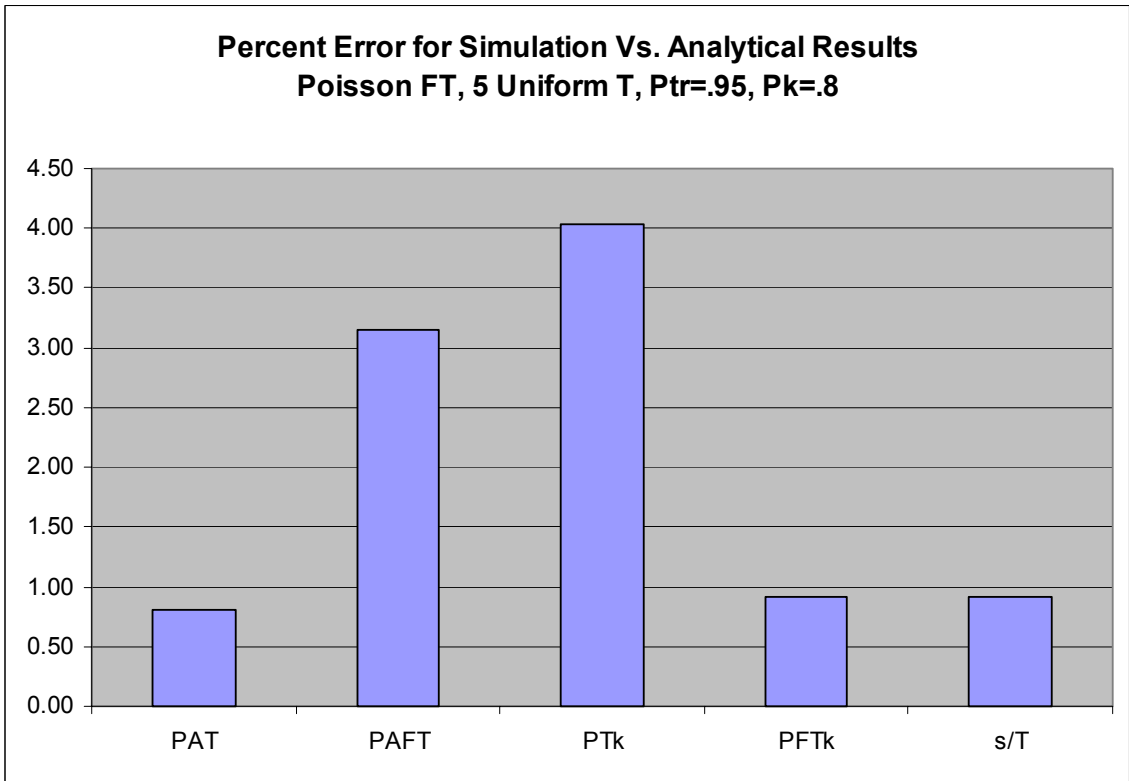
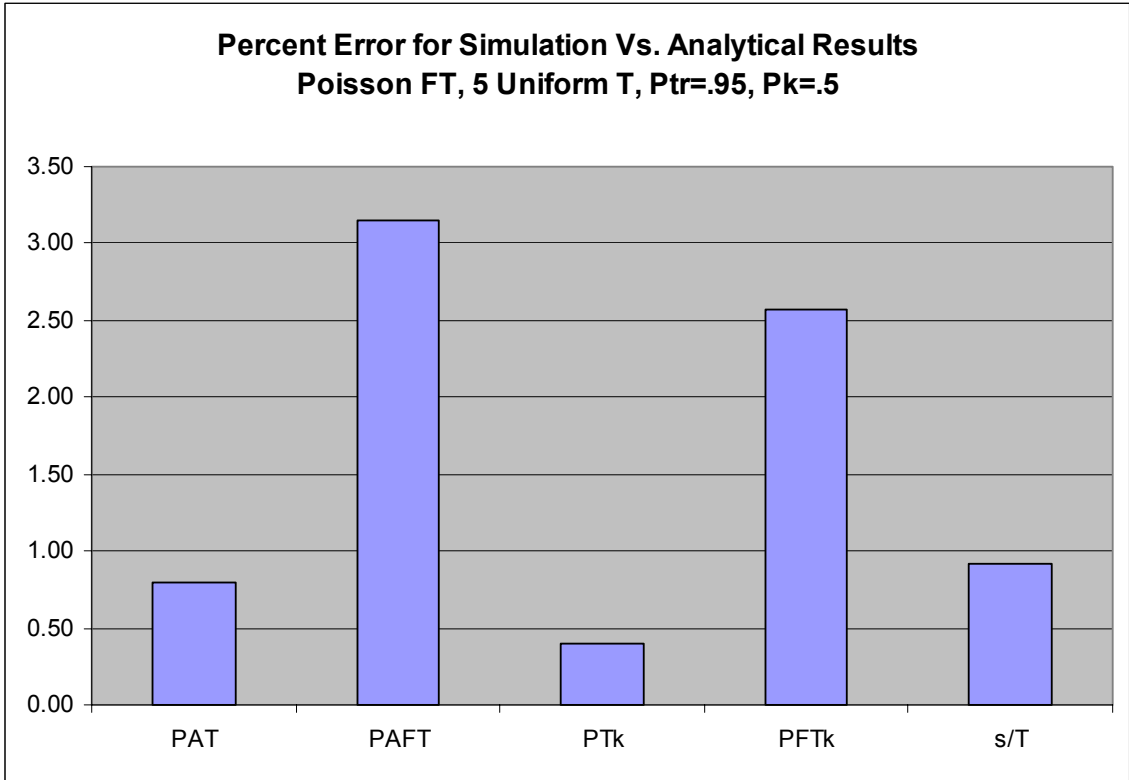


**Percent Error for Simulation Vs. Analytical Results Poisson FT,  
Poisson T, Ptr=.95, Pk=.8**

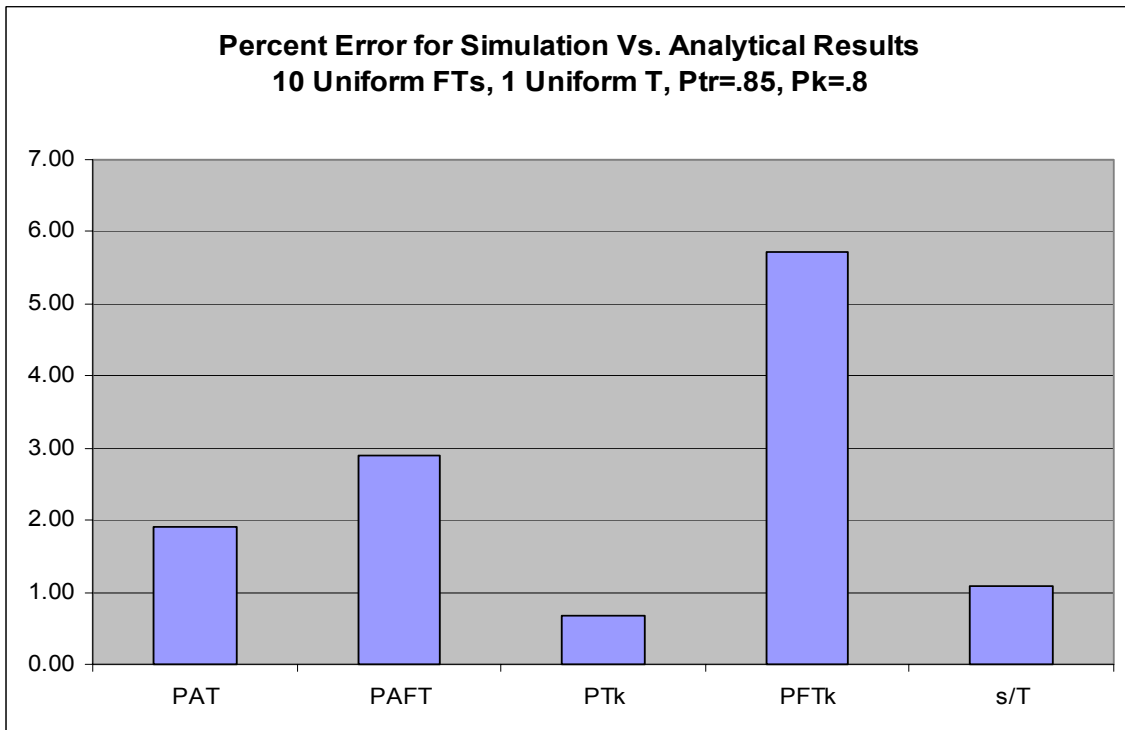
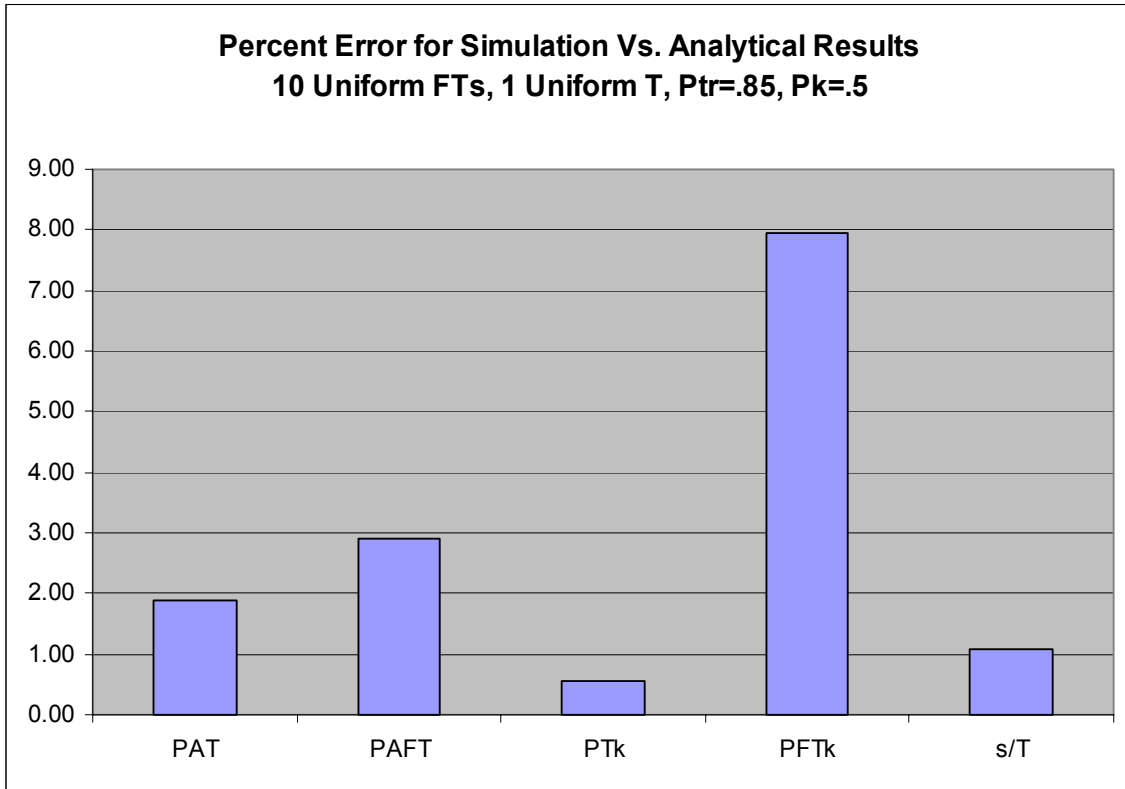


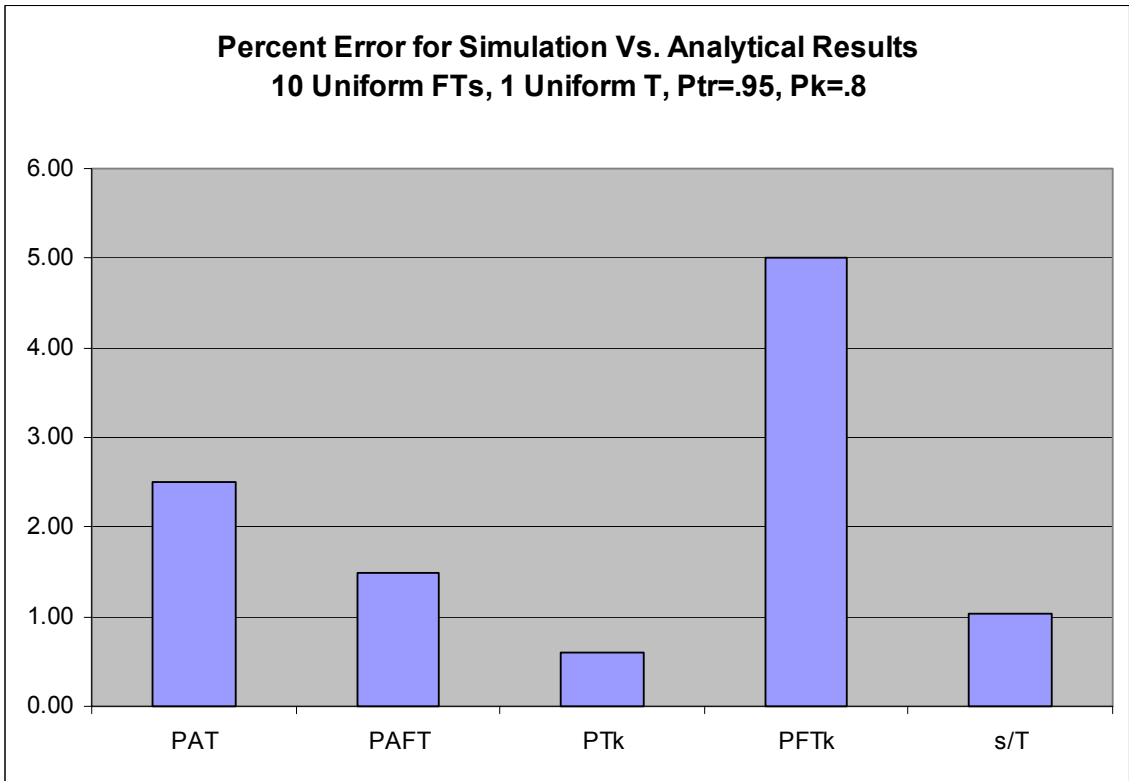
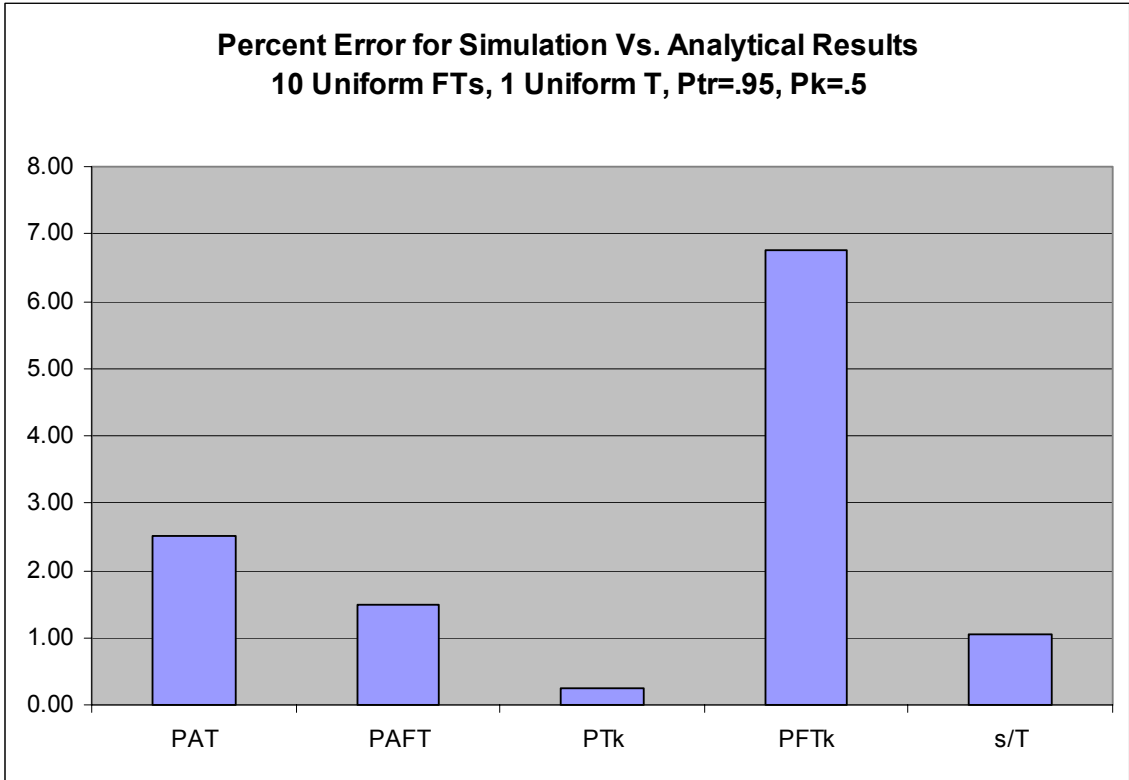
## Appendix C: Scenario 3 Data



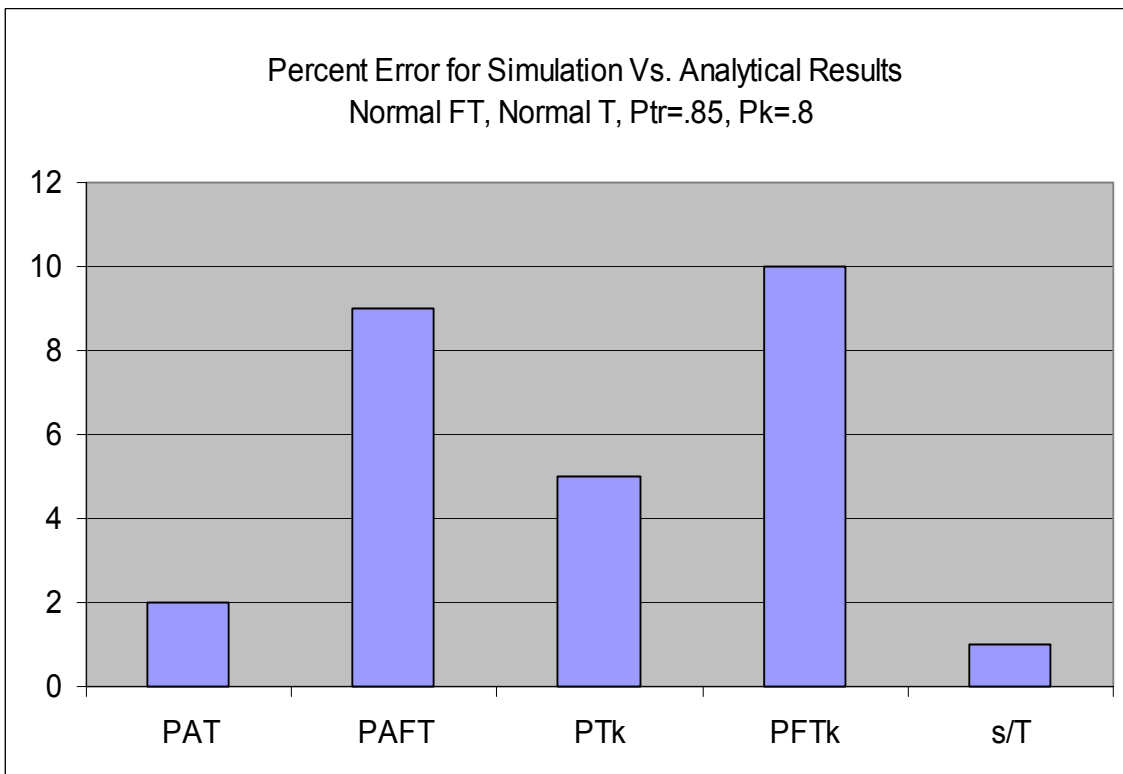
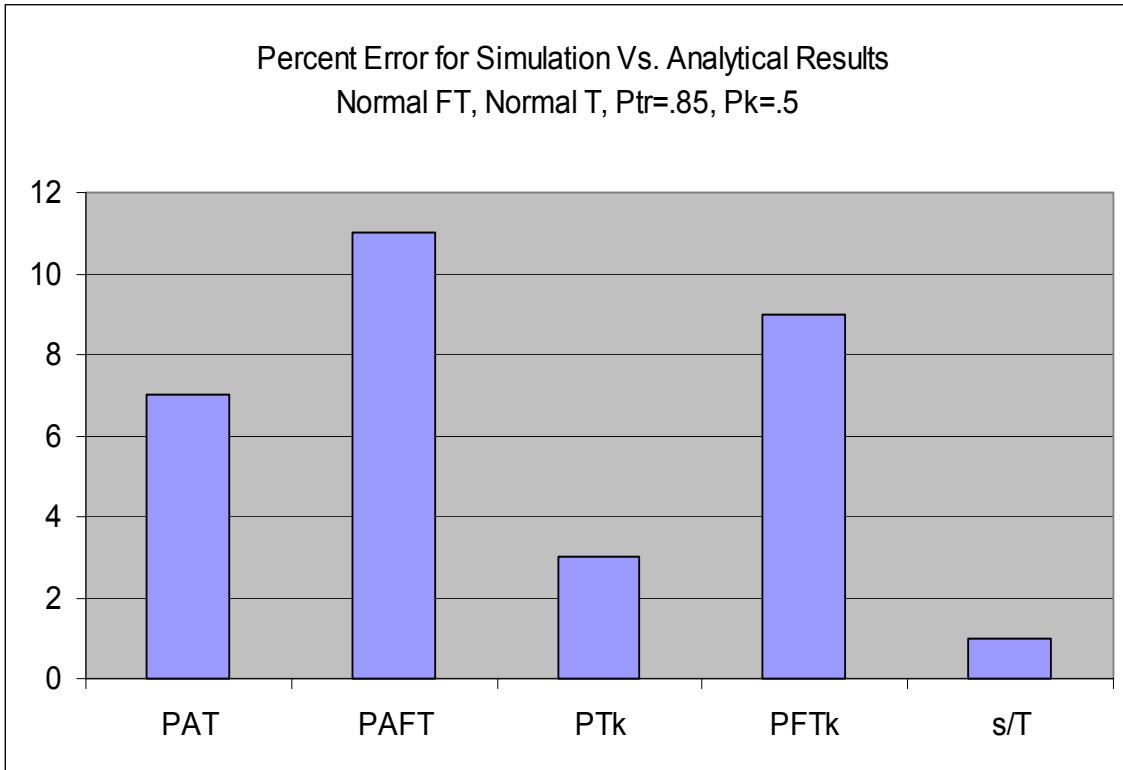


## Appendix D: Scenario 4 Data

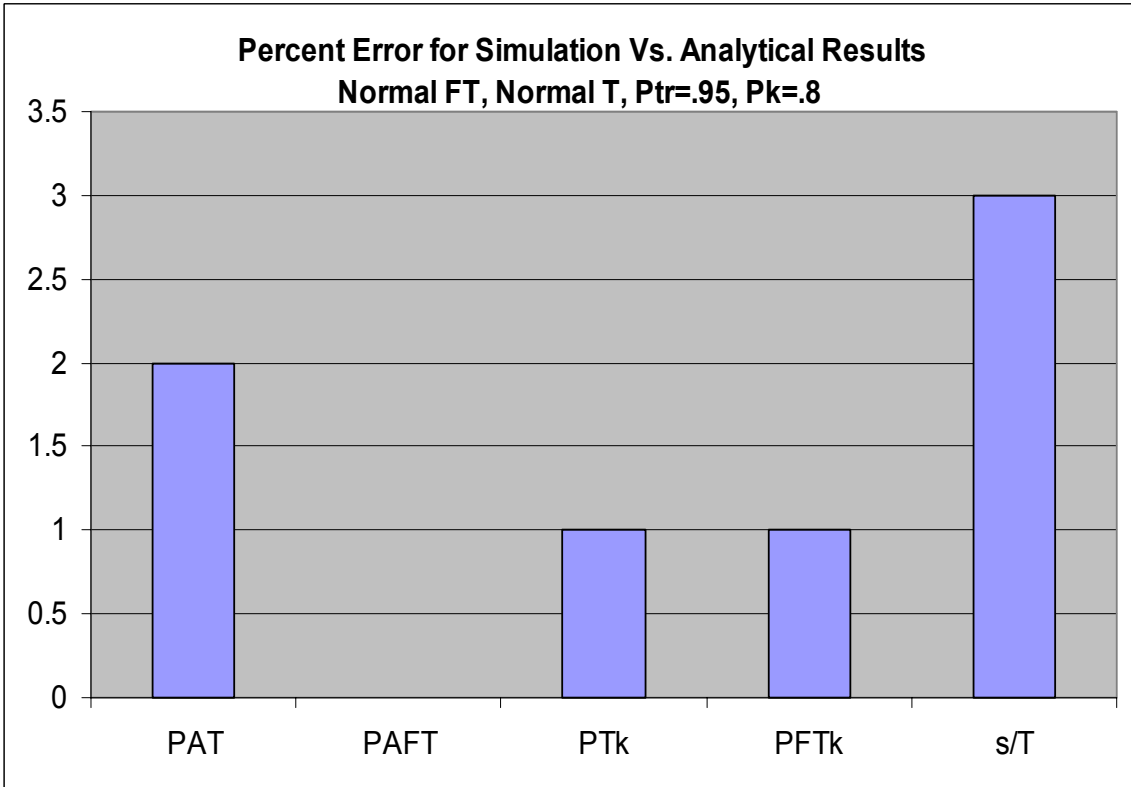
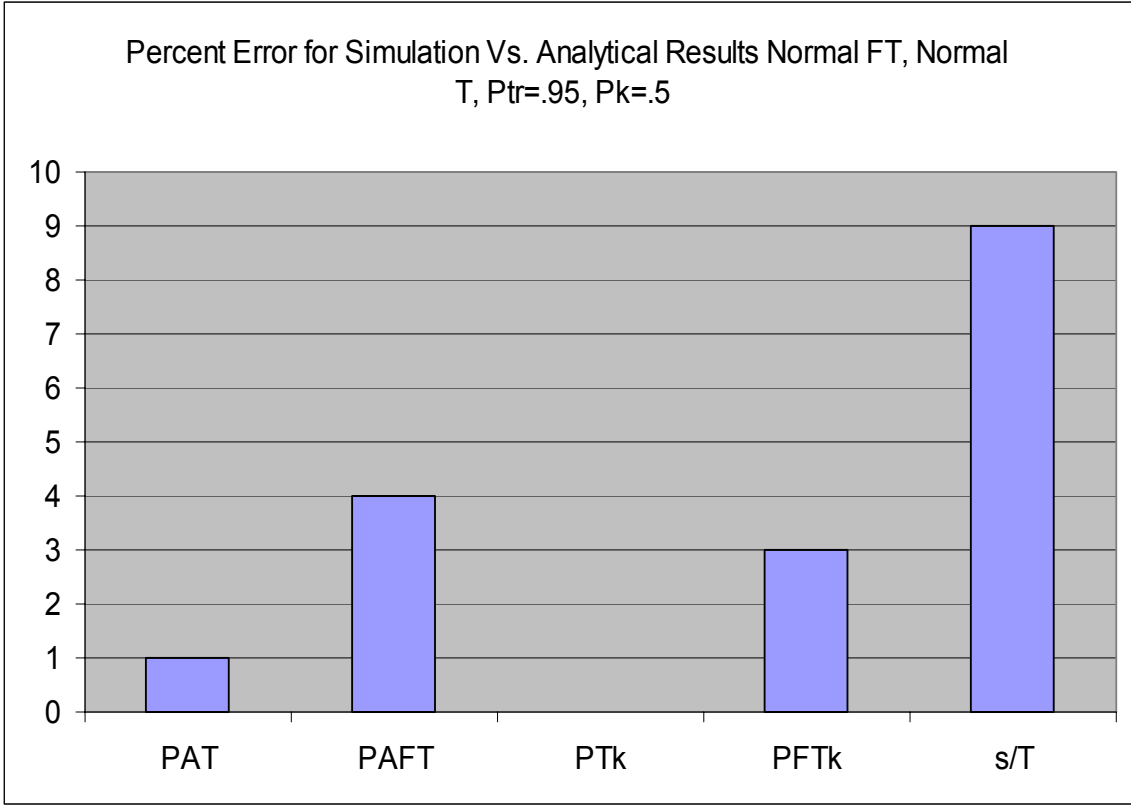




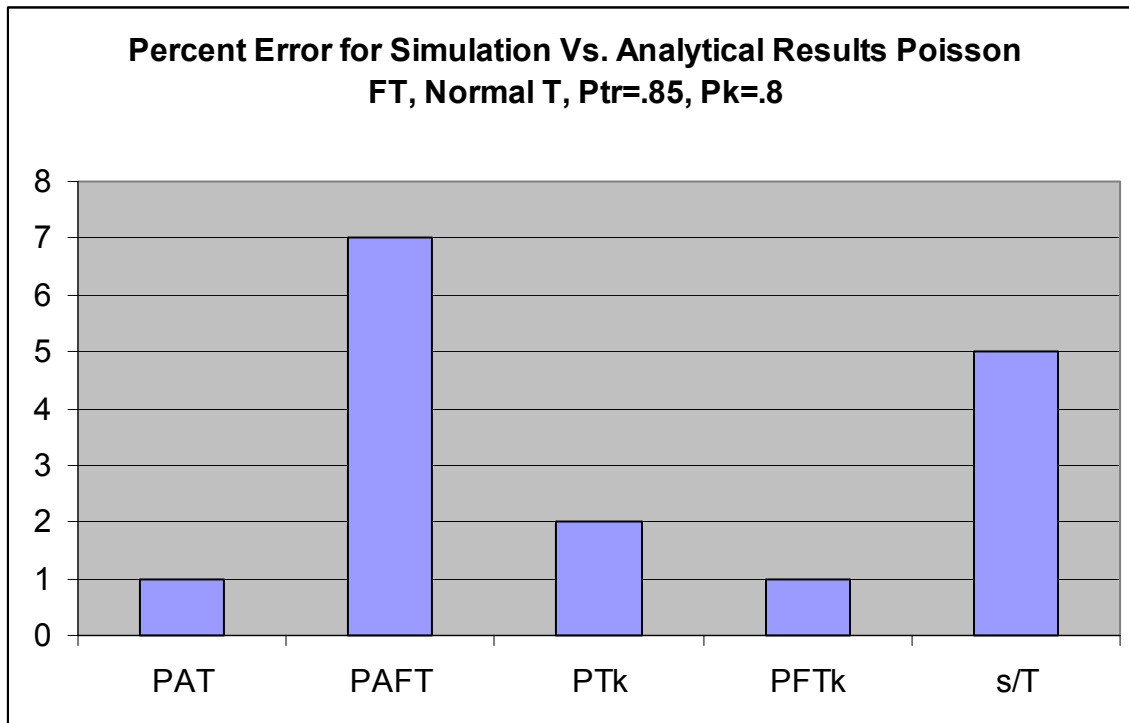
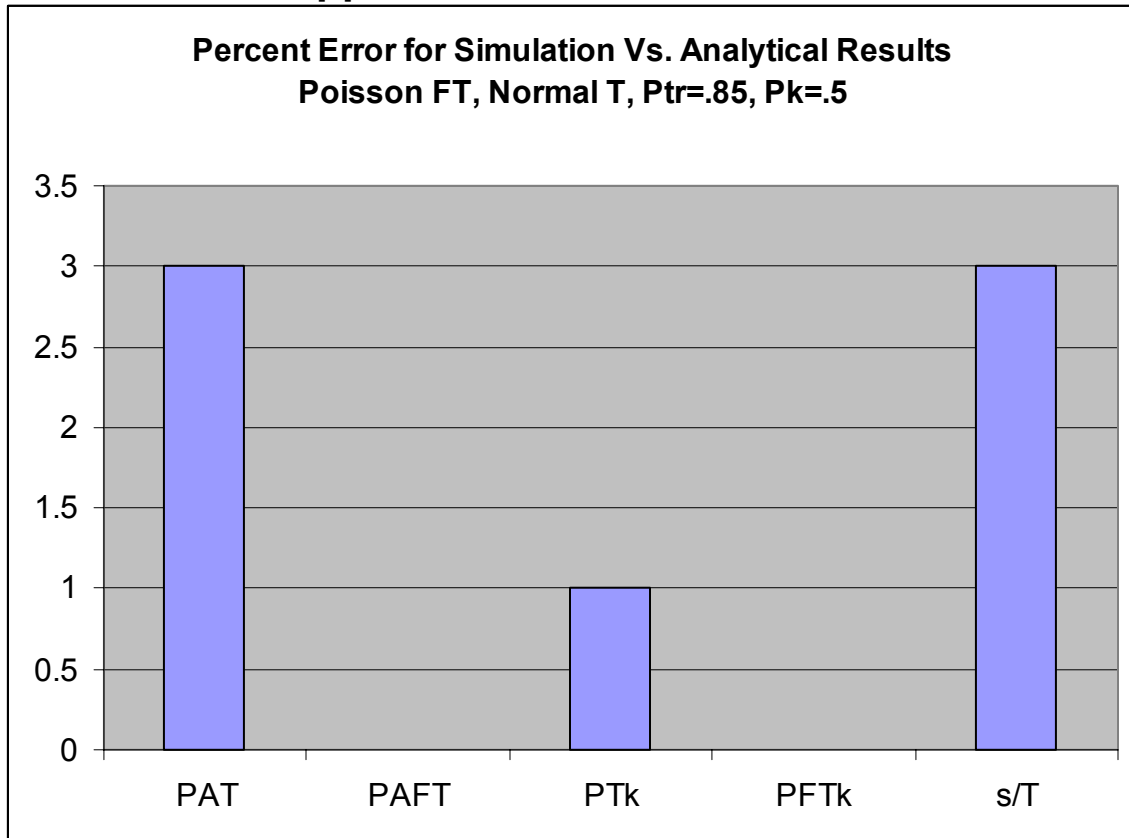
## Appendix E: Scenario 5 Data

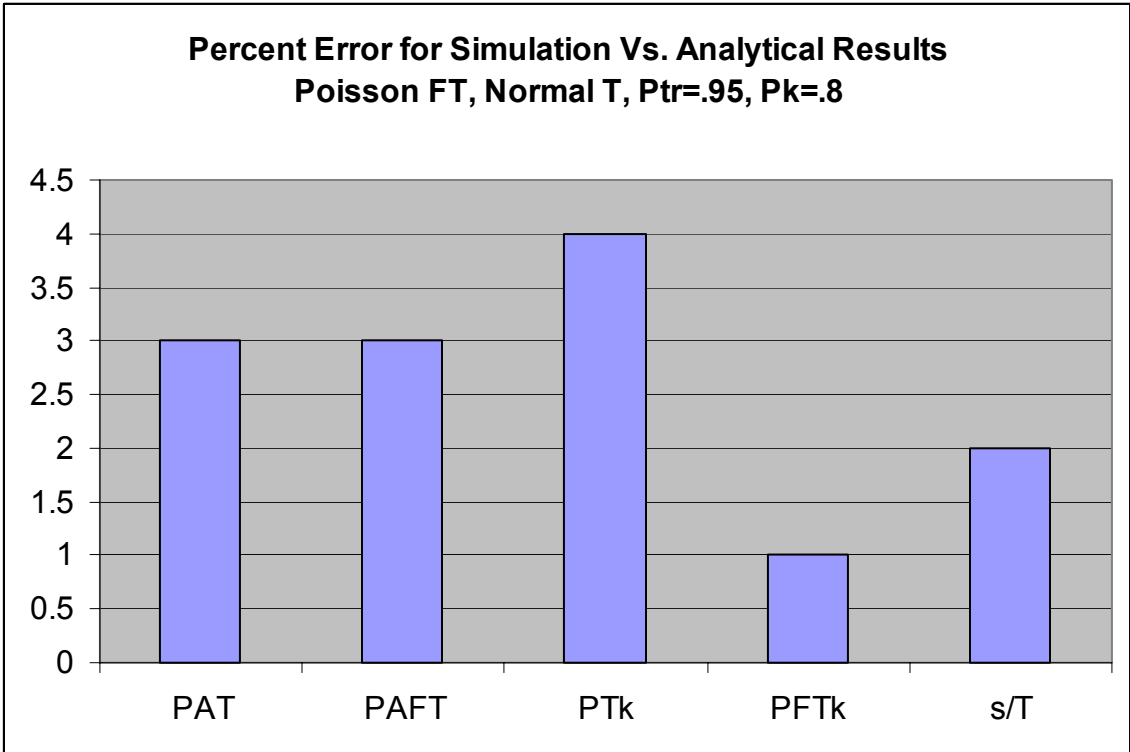
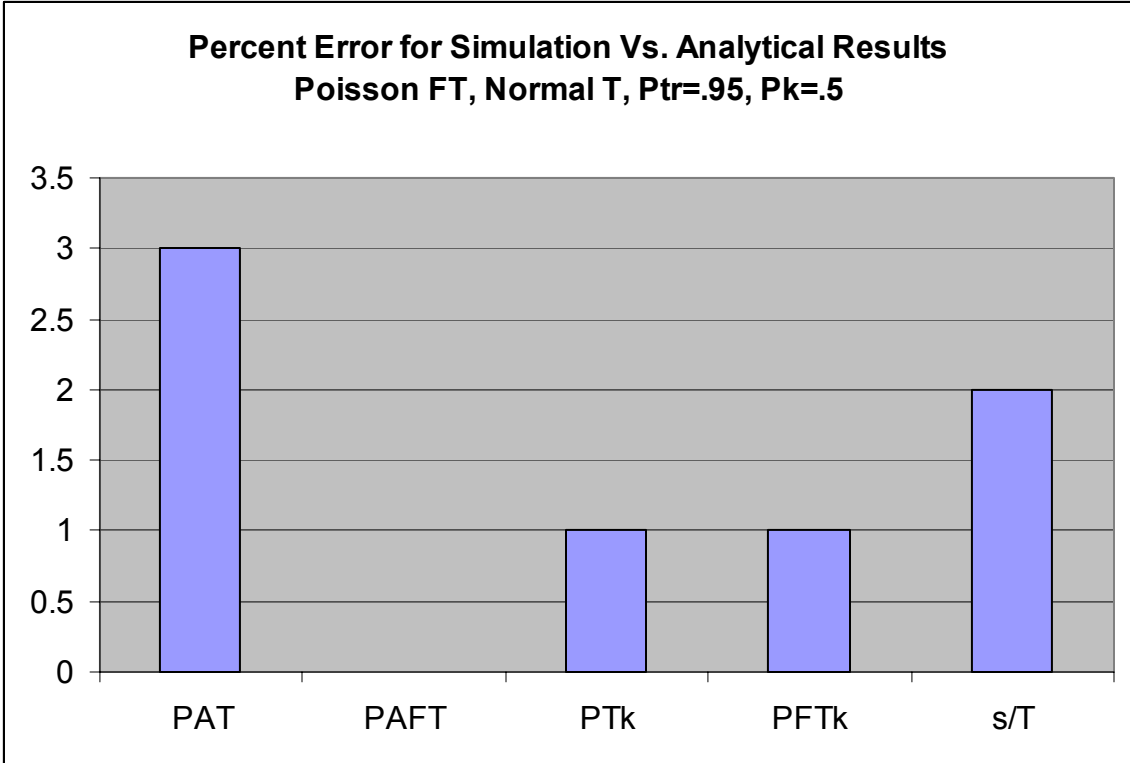






## Appendix F: Scenario 6 Data





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<b>14. ABSTRACT</b> Several research simulations have been created to support development and refinement of teamed autonomous agents using decentralized cooperative control algorithms. Simulation is the necessary tool to evaluate the performance of decentralized cooperative control algorithms, however these simulations lack a method to validate their output. This research presents a method to validate the performance of a decentralized cooperative control simulation environment for an autonomous Wide Area Search Munition (WASM). Rigorous analytical methods for six wide area search and engagement scenarios involving Uniform, Normal, and Poisson distributions of N real targets and M false target objects are formulated to generate expected numbers of target attacks and kills for a searching WASM. The mean value based on the number of target attack and kills from Monte Carlo simulations representative of the individual scenarios are compared to the analytically derived expected values. Emphasis is placed on Wide Area Search Munitions (WASMs) operating in a multiple target environment where a percentage of the total targets are either false targets or may be misconstrued as false by varying the capability of the WASM's Automatic Target Recognition (ATR) capability.					
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