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Kulac, Oray.

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THESIS

A COMPARATIVE ANALYSIS OF ACTIVE AND PASSIVE SENSORS IN ANTI-AIR WARFARE AREA DEFENSE USING DISCRETE EVENT SIMULATION COMPONENTS

by

Oray Kulac

March 1999

Thesis Advisor: Thomas H. Hoivik
Thesis Co-Advisor: Thomas W. Lucas
Second Reader: Arnold H. Buss

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Anti-air warfare (AAW) has been a top priority for the world's navies in developing tactics and choosing the most effective ship defense systems. Analyses of such extremely complex system behaviors require the utilization of innovative tools that are flexible, scalable and reusable. This thesis develops a model as an analysis tool to measure the effectiveness of radar and IR sensors in AAW area defense. The model is designed to support reuse, provide easy model configuration, flexibility and scale changes. A component-based simulation approach was adopted for this model using the JAVA™ programming language to provide the necessary scalability and flexibility. The MODKIT approach was used as the architecture of component designs and SIMKIT, was used for discrete event simulation purposes. In addition, a small combat component library was constructed for future research. To demonstrate the analysis capability of the model a comparative analysis was conducted for radar and IR sensors in AAW area defense.

The results of the simulation runs indicate that the model provides a good capability for aiding decision making, including effectiveness analysis, parameter sensitivity analysis, and exploratory analysis.

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A COMPARATIVE ANALYSIS OF ACTIVE AND PASSIVE SENSORS IN ANTI-AIR WARFARE AREA DEFENSE USING DISCRETE EVENT SIMULATION COMPONENTS

Oray Kulac
Lieutenant J.G., Turkish Navy
B.S., Turkish Naval Academy, 1993

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Author: [redacted]
Oray Kulac

Approved by: [redacted]
Thomas H. Hoivik, Thesis Advisor

[redacted]
Thomas W. Lucas, Thesis Co-Advisor

[redacted]
Arnold H. Buss, Second Reader

[redacted]

Richard E. Rosenthal, Chairman
Department of Operations Research

ABSTRACT

Anti-air warfare (AAW) has been a top priority for the world's navies in developing tactics and choosing the most effective ship defense systems. Analyses of such extremely complex system behaviors require the utilization of innovative tools that are flexible, scalable and reusable. This thesis develops a model as an analysis tool to measure the effectiveness of radar and IR sensors in AAW area defense. The model is designed to support reuse, provide easy model configuration, flexibility and scale changes. A component-based simulation approach was adopted for this model using the JAVA™ programming language to provide the necessary scalability and flexibility. The MODKIT approach was used as the architecture of component designs and the SIMKIT was used for discrete event simulation purposes. In addition, a small combat component library was constructed for future research. To demonstrate the analysis capability of the model a comparative analysis was conducted for radar and IR sensors in AAW area defense.

The results of the simulation runs indicate that the model provides a good capability for aiding decision making, including effectiveness analysis, parameter sensitivity analysis, and exploratory analysis.

THESIS DISCLAIMER

The reader is cautioned that the computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The defense of ships from air threats is one of the important concerns of the world's navies. Currently, over 70 nations can pose an air threat to seaborne units. This threat is posed by missile attacks from ships, land-based sites or aircraft. Sensors are the primary component of AAW systems. However, propagation conditions at low altitudes cause difficulties for surveillance systems, such as radar. Therefore, the infrared search and track (IRST) sensor has been a welcome addition to ship defense systems. The effective use of infrared (IR) sensors will also increase the stealth of Naval Task Forces, which is an important aspect of modern naval warfare. One method of deciding which sensor to use in AAW is to determine how active and passive sensor effectiveness differs in multiple AAW scenarios. An analysis should be conducted to measure the effectiveness of active and passive sensors in AAW through actual testing. However, the growing cost of operational trials makes extensive live tests of military systems nearly impossible. Therefore, analyses of such extremely complex system behaviors necessitate the utilization of innovative tools that are both flexible and reusable.

Computer modeling can be a good tool for AAW decision analysis. First of all, it is less expensive and safer than real life trials. However, computer-modeling efforts are subject to some problems. In traditional modeling, it is difficult to design a model to efficiently and effectively support the appropriate analyses. Also, models are generally built in closed architectures, and therefore are difficult to adapt to the specifics of different analysis efforts, as a result they

tend to become very large. To have to develop new models for solving each new specific problem without the benefit of tested software is time consuming and expensive, due to developmental complexity and test requirements.

Due to these existing model problems, the analyst is often forced to build his own model as an analysis tool. The operations analyst needs a model to be flexible, modular and scalable. A good method for meeting these requirements is to use a component-based discrete event simulation written in the Java™ programming language. Therefore, this thesis incorporated a component-based discrete event simulation approach and the Java™ programming language to build and use a library of air defense models. The MODKIT approach, developed by MAJ. Arent Arntzen, Norwegian Air Force, is used as the architecture of component designs and SIMKIT, developed by Prof. Arnold Buss and Kirk Stork, is used for discrete event simulation purposes in this thesis. The model developed, supports reuse, easy model configuration, flexibility, and scale changes in successive stages of analysis.

To demonstrate the model's analysis capability, an exploratory analysis is conducted to measure the effectiveness of radar and infrared sensors in an AAW area defense environment with respect to several MOE's. The results of the simulation runs indicate that the model can provide a good capability for aiding decision making, through conducting effectiveness analysis, parameter sensitivity analysis and exploratory analysis.

Approximately 10,000 simulation runs were conducted for analysis and model test purposes. Two different scenarios were used to investigate the effectiveness of the radar and the IR. Scenario-I represents the case where the convoy is detected but not identified. Therefore, every single ship is attacked by one ASM. Scenario-II represents the case where the convoy is both detected and identified. Accordingly, a raid of three ASMs is fired on the AAW ship, to saturate its AAW defense system, and one single ASM is fired at the high value unit (convoy ship three). Initially, a close formation is used in both scenarios to increase the number of ASMs that the AAW ship can successfully engage. This follows from the fact that the number of possible shots increases as the closest point approach (CPA) between the SAM ship and target decreases.

It was observed from the simulation results that the earth's curvature effect was the limiting effect for the sensor detection range, especially for the radar. A sensor height value of 65 feet was used for the trials. For an ASM flying at an altitude of eight meters, the radar horizon range is approximately 16 NM. The maximum detection range of radar is 21 NM and in this case it can only see a range of 16 NM.

A suitable distance between ships value was investigated for the SAM kill probability value of 0.5. The distance between the ship's can be extended to four NM for the IR and five NM for the radar without degrading the AAW system effectiveness.

Simulation results showed that, with the given data, the IR sensor provided the same effectiveness as the radar for the non-stressing scenario and stressing scenario with high SAM kill probabilities, like 0.85. For low SAM kill probabilities like 0.6 and 0.5 the radar had higher effectiveness than the IR. This difference was more significant in the stressing scenario (scenario-II).

ACKNOWLEDGMENTS

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I. INTRODUCTION

A. PURPOSE

Anti-Air Warfare (AAW) has been and still is a top priority for many of the world's navies in developing tactics and choosing the most effective ship defense systems. Moving naval operations near land, as was done during the siege in the Bosnia crisis and the proliferation of anti-ship missiles (ASMs) has increased the number of nations that are capable of attacking ships. This has increased the importance of AAW. The first step in conducting this warfare is to use shipborne sensors, both passive and active, efficiently. The effective use of sensors also will improve the stealth of Naval Task Forces, which is an important aspect of modern naval warfare. For this reason, regulating the usage of sensors is a very important operational decision for naval tactical commanders. For the Turkish Navy, this decision is also very important because it has to decide which ship sensor configurations can be used most effectively in tactical areas.

One method to estimate and compare the effectiveness of active and passive sensors in multiple AAW scenarios is through simulation. The purpose of this thesis is to develop a tool that facilitates this type of analysis through the development of simulation components and to conduct an initial comparative analysis demonstration for active and passive sensors. The model provides the necessary means to conduct a first stage evaluation of sensor effectiveness in multiple scenarios.

B. BACKGROUND

The growing cost of operational trials makes extensive live tests of military systems nearly impossible. Analyses of such extremely complex system behaviors necessitate the utilization of innovative tools that are both flexible and reusable.

Computer modeling is a good tool for AAW decision analysis. First of all, it is cheaper and safer than real life trials. It does not require the availability of actual systems. For example, with a flight simulator, an actual F-16 is not needed to conduct tactical training. It also provides the capability to repeat some segments of the mission. However, computer-modeling efforts are subject to some problems. It is difficult to design a model to efficiently and effectively support the appropriate analyses. Also, models are generally built in closed architectures, are difficult to adapt to the specifics of different analysis efforts, and tend to become very large. It is also extremely difficult to know the exact sensitivity of model outputs due to the inevitable uncertainties in the inputs. As a result, modelers often tend to underestimate the uncertainties of the inputs and, consequently, outputs. Additionally, since most models have not been officially verified and validated, many decision-makers do not have confidence in the model results.

Due to these problems of the existing models, the analyst is often forced to build his own model as the analysis tool and to develop flexible methods to conduct analyses. The operations analyst knows that effective analysis requires the model to be flexible, modular and scalable. The model should be flexible enough to adjust itself to fast changing and improving environments. For example, the military operations analyst should be able to easily incorporate new technological developments in weapon systems in their model. The model should be modular to support fast adjustments, new additions and removals. To have to develop new models for solving each new specific problem without the benefit of tested software is time consuming and expensive, due to the development complexity and test requirements. The model should be scalable to support analysis of different force sizes and mixes. The model should therefore provide the necessary properties to analyze one frigate or a destroyer squadron with a little effort. Another helpful feature is that the model should be platform-independent.

A good method for meeting these requirements is to use a component-based discrete event simulation written in the Java™ programming language. Therefore, this thesis will incorporate a component-based discrete event simulation approach and the Java™ programming language to build and use a library of air defense models. The environment that is developed will facilitate the exploration of multiple scenarios and architectures without relying on the veracity of a single run. The MODKIT approach, developed by MAJ. Arent Arntzen, Norwegian Air Force, is used as the architecture of component designs and SIMKIT, developed by Prof. Arnold Buss and Kirk Stork, graduate of NPS, is used for discrete event simulation purposes in this thesis. More detailed descriptions will be given about these two tools in the following chapters.

Due to uncertainties in the inputs to the model, such as probabilities of kill for guided missiles (G/M), the "Exploratory Analysis" approach is used as the analysis method. The analysis concentrates on how the model is used, not the model itself. "The space of scenarios, decisions, and measures of effectiveness will be searched in search of robustness" [Ref.1] This approach reduces the risk of uncertainties in the input data.

C. THESIS OBJECTIVES

This thesis is designed to build a flexible and scalable tool that can be used to provide information for anti-air ship defense decisions and to demonstrate the utilities of the model with a proof of concept analysis. As a proof of concept demonstration of the model and analysis approach, this thesis compares the effectiveness of active and passive sensors in an AAW environment. The objectives are:

- To build a flexible, modular and expandable ship area defense simulation using MODKIT and SIMKIT.
- To study the effectiveness of active and passive sensors in an AAW environment and to provide this information to the appropriate decision-makers. A great strength of Operations Research (OR) is that it helps the decision-maker to achieve a better solution and to do so with greater confidence. [Ref. 2:p. 4]. Because of the vast uncertainty in AAW environments the exploratory analysis approach is used.
- To conduct the initial phase of the construction of a library of loosely coupled OR components for the Turkish Navy.

- To provide a base for follow-on OR thesis researchers.

D. RESEARCH QUESTIONS

1. Primary Research Questions

- What should be the primary discrete event simulation components required to construct an AAW Ship defense model for analyzing AAW sensors?
- What analysis can be conducted to demonstrate the utility of the model?

2. Secondary Research Questions

- What should be an appropriate resolution for the AAW ship defense model?
- What are the important characteristics of active sensors to model AAW ship defense?
- What are the important characteristics of passive sensors to model AAW ship defense?
- What are the most important battle scenarios for conducting sensor analysis for TURKEY area AAW defense, and how should the model be constructed to run these scenarios?
- What are the Measures of Effectiveness for this analysis?
- Which variable inputs should be fixed for analysis purposes?

E. METHODOLOGY

Models are only approximations of actual systems, and, their reliability depends on the quality of the input data. In this study it has been very difficult to obtain accurate input data, such as the probability of kill for guided missiles (G/M), detection probabilities of sensors, etc., because of their high-level security clearance needs. Thus, the model was run many times with many different input levels, requiring a large number of computational experiments. For exploratory modeling, "a large space in the domain of interest (and all the solutions in it) will be examined, then a solution will be selected." [Ref. 1] In traditional analyses, the solution is found and the area around it is examined. Exploratory analysis not only provides the necessary decision flexibility, but it also reduces the risks associated with imperfect input data; an important consideration of this thesis.

A selective resolution approach was used to decide the resolution level of the model, i.e.; initial modeling was carried out with a relatively aggregate model. The results of the first analysis were then used to select the next higher resolution. A high-resolution approach was not selected since the objectives of this thesis did not require this amount of detail. Therefore, some simplifications and assumptions were made for the ship self defense (SSD) model; these will be explained in the following chapters.

The specific methodology used in this thesis research consists of the following steps:

1. Conduct a literature search of books, magazine and newspaper articles, web sites, and library information resources.

2. Determine simulation model input, output requirements, events and event details.

3. Conduct a thorough review of existing discrete event simulations, SIMKIT and MODKIT. Identify the components needed to model and specify the simulation events for these components.

4. Write the code for the components that are needed for the model.

5. Test and crosscheck the model for single ship applicability.

6. Choose appropriate scenario(s) to do the exploratory analysis.

7. Conduct the exploratory analyses.

8. Analyze the results for relative efficiencies of active and passive sensors.

9. Determine conclusions and make recommendations.

F. SCOPE OF THE THESIS

Since this thesis is the initial phase in the development of a library of AAW models, the scope of the thesis is limited to the following:

1. A collective usage of SIMKIT and MODKIT to create simulation models for a variety of combat situations.

2. An initial analysis of the effectiveness of active and passive sensors for naval area air defense by using the SSD model.

3. The conclusions will be based on the results of analysis using these models and simulations only.

G. ORGANIZATION

This thesis consists of six chapters. The first chapter introduces the problem statement and the tool, or the component-based discrete event simulation, and the method or exploratory analysis that is chosen to solve the problem.

The second chapter includes a brief history of AAW, defines modern ship anti-air-warfare defense systems and provides information about active and passive sensors that are commonly used in today's AAW.

The third chapter provides definitions about the modular discrete event simulation and documents the structure and the components of the ship-self-defense model that is developed for this research.

The fourth chapter defines the scenarios and the measures of effectiveness (MOE) that are used in analysis.

In Chapter five the analysis is conducted and the results of the analysis are evaluated.

The sixth chapter contains the final conclusions and recommendations about the results and possible future research areas.

II. SENSORS IN ANTI-AIR-WARFARE(AAW)

A. A BRIEF HISTORY OF ANTI-AIR-WARFARE

The objective of air defense at sea is to conduct assigned missions effectively in the face of airborne attacks. The history of the development of this warfare area is similar to the development of aircraft and anti-ship missiles (ASM's). Technology always had a big impact on the AAW mission effectiveness.

The first attack from air on warships was conducted on Christmas Day of 1914 by a motley collection of British seaplanes which took off to attack the German Zeppelin sheds and units of the High Seas Fleet in Cuxhaven [Ref. 3:p.8]. This was an unsuccessful raid but a remarkable achievement, since it happened only 11 years after the first powered flight. In those days the use of air weaponry and air defenses at sea was not efficient. In the early years of World War II, those navies possessing aircraft carriers considered the carrier-borne fighters as the first and strongest element of the air defense; anti-aircraft guns were supplementary weapons. As airborne attack capability improved, the need for a good ship AAW defense became apparent. In May 1941, the German battleship Bismarck, the most powerful ship afloat, was severely wounded by an air attack that left her mobility destroyed, making her prey to British surface ships. Also, in the Mediterranean, the British fleet suffered some serious damage by German air attacks. These events taught both sides some lessons, and towards the end of the war ship gun systems for self-defense against air attack were developed and proliferated.

Today, air defense of ships is one of the important concerns of the world's navies, since over 70 nations can pose an air threat to sea-borne units. This threat is posed by missile attacks from ships, land-based sites or aircraft. Since the diversity of the attacking systems has increased, the development of effective air defenses has become increasingly complicated and sophisticated.

B. COMPONENTS OF THE AAW SHIP SELF DEFENSE ORGANIZATION

Today, a general air defense organization of a ship consists of the following systems and components.

1. Surveillance Sensors
    a. Human Eye
    b. Radar
    c. Laser
    d. Infrared
    e. Electronic Support Measures(ESM)
2. Fire Control Radar
3. Hard-kill Weapon Systems
    a. Passive Missiles
    b. Semi-active Missiles
    c. Active Missiles
    d. Guns

4. Soft-kill Systems

   a. Electronic (Jammers)

   b. Physical (Decoy, Chaff)

Since radar and infrared sensors are the most used sensors for ship surveillance, this thesis will concentrate on evaluating the mission efficiency of the radars and infrared sensors in the AAW role.

C. SENSORS IN AAW

AAW and all other naval operations depend on the ability of the units to obtain and maintain location information on the enemy. For this reason, sensors are the primary component of AAW systems. This warfare mission cannot be conducted without the detection of a target. Detection of low altitude anti-ship missiles in a maritime environment is of vital importance to surface ships. However, propagation conditions at low altitudes cause difficulties for surveillance systems such as radar. Therefore, the infrared search and track (IRST) sensor has been a welcome addition to ship defense systems. The following is a brief history and general structure of these two sensor types.

1. Radar

The term RADAR is derived from the description of its primary role as a RAdio Detection And Ranging system. Detecting many small, fast targets at long ranges day or night, through clouds or dust are its key properties. However, it is an active system and its resolution is poor when compared to an electro-optical system. This thesis will consider a conventional pulse scanning system, which is illustrated in Figure 1. This system has been designed to translate electronical data into information. It basically emits a signal and waits for it to return. When the signal returns, it is processed by the system to generate information.

The *timer in* Figure 1 begins the cycle of radar operation by sending a pulse to the *modulator* and to the *indicator.* The indicator records the departure time of the *transmitted radio frequency* (RF) energy. The modulator provides a high voltage direct current pulse to the *transmitter.* Then, the transmitter generates the RF energy in the form of a short powerful pulse. The high-energy pulse travels from transmitter to the *antenna* through a switching mechanism called a *duplexer.* To permit the use of a single antenna for transmission and reception, the duplexer connects the transmitter to the antenna during transmission and isolates the *receiver* to protect its sensitive parts. For the receive process, the duplexer does the opposite of this process. Thus, the antenna both transmits the RF energy and receives echoes. When there is an incoming echo signal, the receiver amplifies this signal. The amplified signal goes to the indicator which displays the radar information.

The technical history of the radar starts as early as 1873 when Maxwell described in mathematical form how electromagnetic waves could propagate through the atmosphere. In 1887, Hertz demonstrated it practically. This was the beginning of the radar era. The first observation of the radar effect was made in 1922 at the U.S. Naval Research Laboratory (NRL) in Washington, D.C.

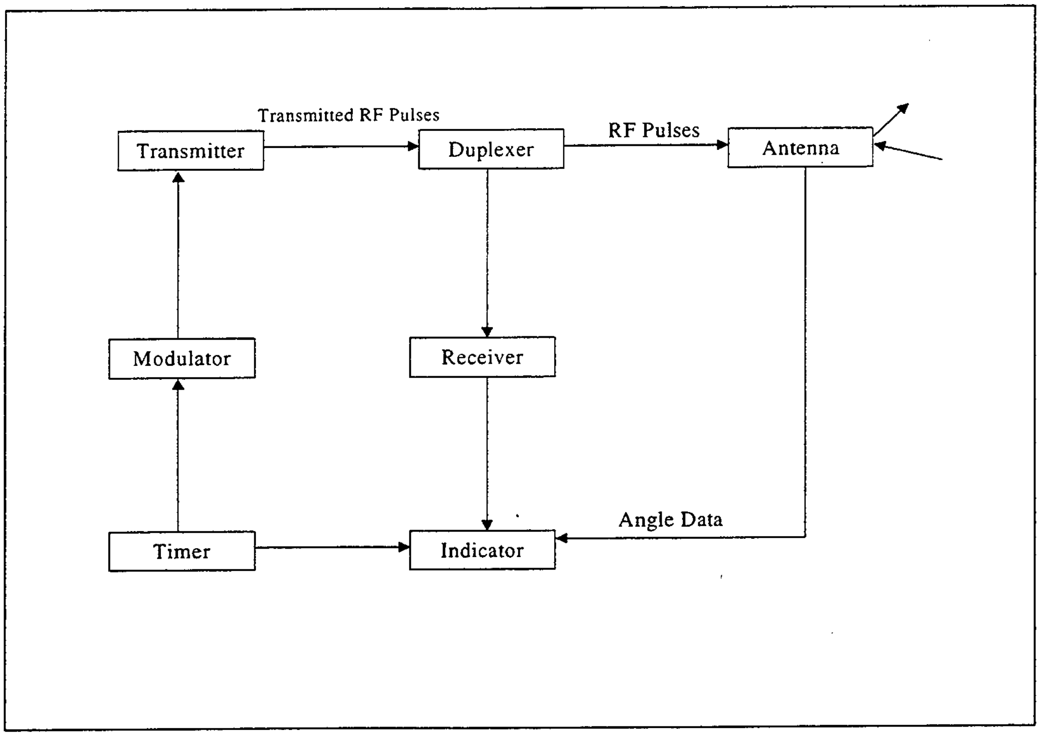

Figure 1. Block Diagram of a Conventional, Pulsed Scanning Radar System. [Ref. 4:p. 77].

World War II caused a huge surge in the development of radar technology. New and better radar systems emerged during the 1950s. Two of these were the monopulse tracking radar and MTI radar. Monopulse tracking radar is a type of tracking radar that permits the extracting of tracking error information from each received pulse and offers a reduction in tracking errors as compared to conventional radar systems. MTI (Moving Target Indicator) radar shows only targets that are in motion. Signals from stationary targets are subtracted from the return signal in this system [Ref 5].

Later in the 1960s the first large electronically steered phased-array radars were put into operation. This radar uses many antenna elements which are combined into a controlled phase relationships. The antenna remains stationary while the radar beam is electronically scanned. The use of many antenna elements allows for a very rapid and high directivity of the radar beams [Ref. 5]. Over the next two decades, radar technology evolved to a point where radars were able to distinguish one type of target from another. Serial production of phased-array radars for air-defense (Aegis System) also became feasible during this time. Today radar is used in a wide range of applications from weather predictions to sophisticated space research.

2. Infrared (IR) sensors

IR sensors use a target's naturally generated exhaust or temperature gradient for detection in the 3-14 μm wavelength. They can be used during the day or at night. IR sensors are passive devices that do not transmit any energy, and thereby prevent enemy detection and advance warning. However, they are greatly affected by bad weather.

IR sensors are basically electro-optical (EO) sensors. The main difference between them is that EO sensors are used to map ground areas or locate targets in the presence of ground reflection. IR sensors are used to locate targets in a clear background such as sea surface or air. An IR sensor consists of optics, a device that collects and transmits a light beam, a detector, which converts optical radiation to an electrical signal, and a series of signal processing electronics. Figure 2 is a block diagram of an IR system.

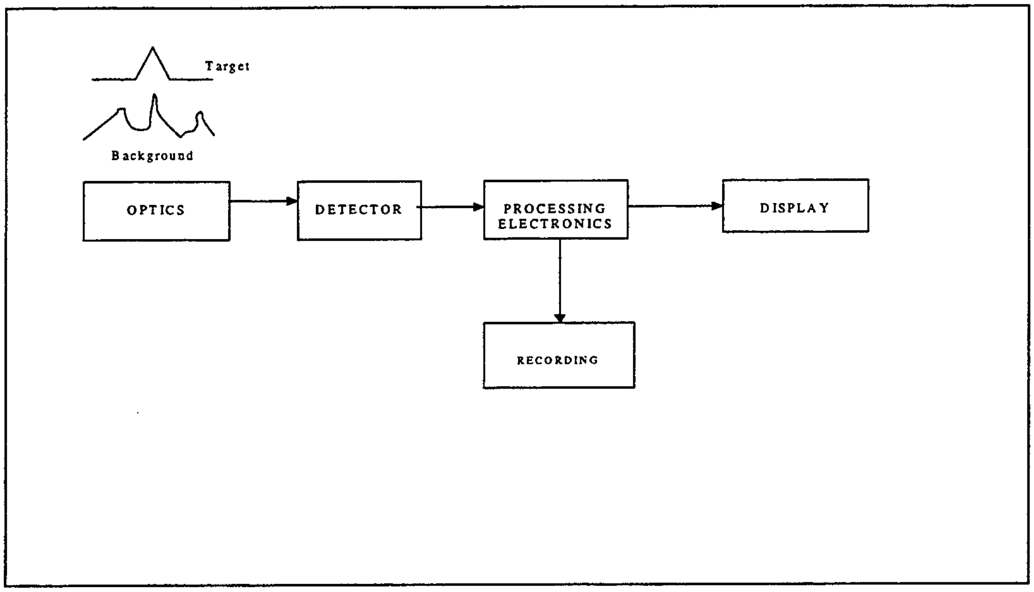

Figure 2. Typical Block Diagram of an IR Sensor. [Ref. 6]

Leonardo da Vinci was the first scientist to state that light might be a kind of wave. This statement is known to be the starting point of EO research. The invention of the telescope, microscope and photography are among the most significant contributions of optics. The period from 1900 to 1980 was witness to the union and evolution of optics and electronics and thus the creation of the complex field of electro-optics. The first optical detector was developed in 1935 and was used for missile quittance during World War II. IR sensor usage in the navy started in the 1960s. Today, IR sensors and IRST systems are being used on modern warships. Hollandse Signaalapparaten's, a major sensor and command control systems producer in Europe, sensor products Sirius and Irscan, Lockheed Martin's advanced air defense electro-optical sensor (AADES), and SAGEM's Vampir are some examples of today's IR sensors. It has been claimed that "all these passive sensors can be integrated with any active sensor system to comprise a complete combat system." [Ref.7]

III. SOFTWARE COMPONENTS AND SHIP SELF DEFENSE MODEL (SSD)

A. DEFINITION OF A SOFTWARE COMPONENT

The definition and structure of software components in modeling and computer literature has varied widely. From a modeling stand point, it is generally agreed that a component should have the following properties. A component should be a stand-alone entity. It should communicate, that is, pass messages or provide data, with other components in a standardized way. It should be easy for users to connect and disconnect a component from a system. Additionally, a component should be well documented. [Ref.8]. A good example of a component system is the personal computer (PC). A PC has many parts (components) that communicate with each other. It is very easy to connect/disconnect or change components depending on need and use. Most importantly, all of these components work together to form a complex system. A good software program will do likewise.

As mentioned before, modularity, scalability and flexibility should be the main properties of a simulation model. An AAW analyst should easily adapt a newly developed sensor in the simulation model and conduct the analysis for a single ship or for a task group without spending much time on model adjustments. After experimenting with different combat simulation models, software components have been proven to be the best tool that contains all these properties. The purpose of Operations Research (OR) type of combat components is to provide a library of reusable software to speed development of

OR applications and make them more reliable. To have to develop new models for solving each new specific problem without the benefit of tested software is time consuming and expensive due to developmental complexity and test requirements. Reusing proven components will help developers build OR applications more efficiently.

The object-oriented JAVA™ programming language was selected to implement these components because it is computer platform independent and provides a rich environment for application development. Using JAVA™ will make efficient components more widely available and easier to use for follow on researches.

As mentioned before, software components are needed to simulate complex systems. For example, a warship can be divided into detailed parts and these parts modeled with software components. A motion software component will simulate its motion, a sensor software component simulates its sensing, a fire control software component simulates its fire control system etc. When combined, a solid warship model with its main systems is created. If another sensor type is needed, it will be very easy to remove the existing one and add a different one. If these components come from a software component library which has validated software components, analysts can conduct a detailed analysis on a given problem without spending much time with building tools.

This thesis develops software components for analysis and for addition to the software component library. It is a continuation of Maj. Arent Arntzen's (Norwegian Air Force) thesis study in air defense modeling. [Ref. 8]. A component-based modeling approach called MODKIT and developed by Arent Arntzen, is used in this thesis. MODKIT is basically comparable to the Sun Microsystems Comp. Java™ Beans. [Ref. 9]. However, Java™ Beans are generally used for creating graphical user interfaces which limits its applicability for analysis. MODKIT satisfies the needs of Operations Analysis at many levels of robustness by providing flexible model configuration and reusable components for future analyses.

B. MODKIT COMPONENTS

A MODKIT component (M*odComponent*) is designed to have the necessary requirements for the duties defined in the previous sections. It has a standardized way of sending or receiving messages from other components and processing these messages. This send/receive process is conducted by four connectors (pins). Two of these pins deal with incoming/outgoing events and the other two deal with incoming/outgoing properties. The following is the list of these pins and their duties:

- *Property user.* The *property user* is the part of the component that deals with incoming properties
- *Property source.* The *property source* is the part of the component that deals with outgoing properties
- *ModEvent listener.* The *modevent listener* is the part of the component that deals with incoming events
- *ModEvent source.* The *modevent source* is the part of the component that deals with outgoing events

Figure 3 shows the general structure of a M*odComponent* and its interfaces.

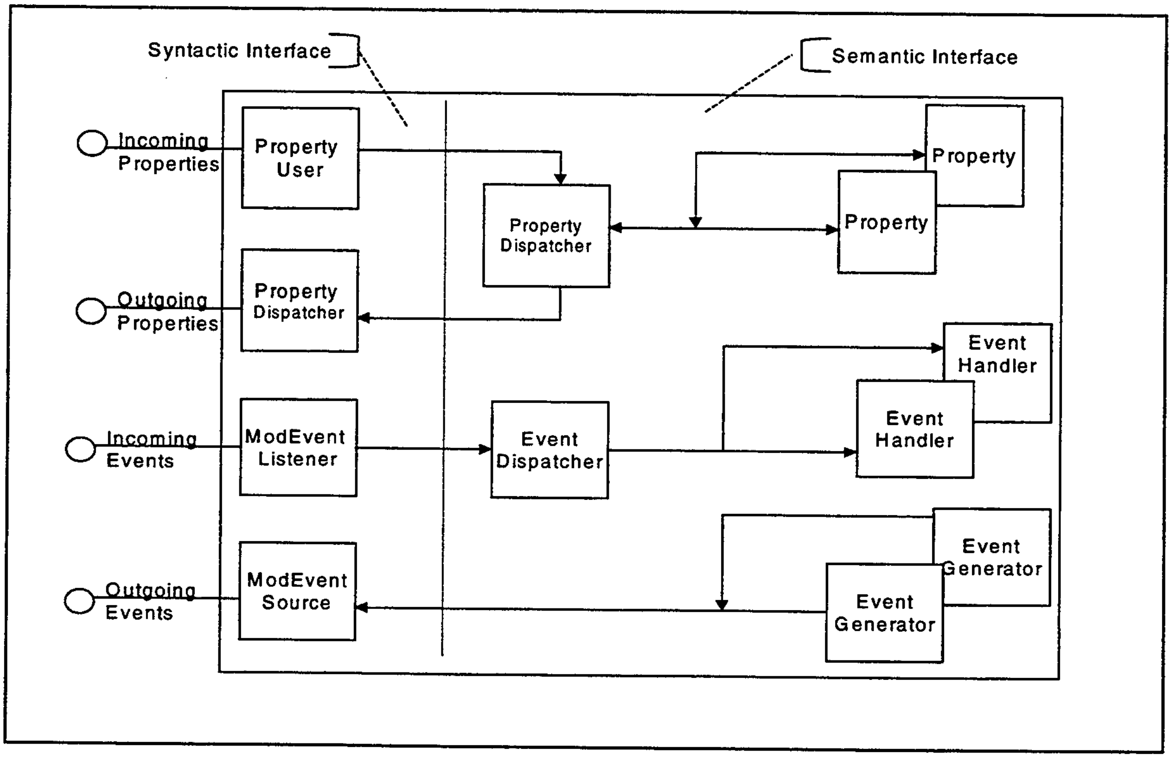

Figure 3. Structure of ModComponent. [Ref. 8]

If a *ModComponent* wants to inform other components about a new change in its status, it will generate (fire) a message to all listener components without caring how the listeners react to that message. The content of this message is defined in the *event object* transmitted. This object is called a M*odEvent*. A M*odComponent* can generate and listen to M*odEvents*. A M*odComponent* is limited in what it can do. Sometimes another component may tell a M*odComponent* what action to take or it may obtain some information from it. This action is implemented by using properties. A *property* is a piece of data that a component has, uses or can provide. [Ref. 8]. For example, a motion component obtains its destination from another component (e.g. ship fire control system component) and starts to head towards the destination. This process can be done by setting *the* destination property of the motion component to a coordinate value.

The *property user* and *property source* parts are connected with the *property dispatcher* part of the ModComponent. The p*roperty dispatcher* determines whether a component has the requested property or not. Any component can obtain a property from another component by using the '*getProperty*' method or set its property by using the '*setProperty*' method. For example, by using *getProperty,* it is possible learn the ship's location (usage *getProperty*("CurrentLocation")) or by using the *setProperty* method, its movement can be stopped (usage *setProperty* ("Moving" ,false)). When a component uses the *getProperty* method to obtain a property from another component, this request will go to a *property user* connector (pin) and then this pin will inform the *property dispatcher.* The *property dispatcher* will find the requested property in the component, and send the property to the requesting component by way of a *property source* pin.

When a M*odComponent* generates a M*odEvent,* the *ModEvent source* pin will broadcast this event to the listener components. When a M*odComponent* receives a generated M*odEvent* by any other component by way of an *event listener*, the event will be passed to the *event dispatcher.* The e*vent dispatcher* will process the event and send it to a *related event handler.* For example, a sensor component generates a detection event when it detects a target. The fire control component, which listens to the sensor component, hears the detection event generation, and then reacts or handles that event in a certain manner.

A M*odComponent* has two kinds of interfaces, which are called *syntactic* and *semantic,* to provide its compatibility with other components. The s*yntactic* interface is the same for all M*odComponents* and consists of the p*roperty user,* the p*roperty source,* the M*odEvent listener, the ModEvent source* and the M*odEvent.* It has four standard pins and a standard message structure for these pins.

The *Semantic interface* consists of generated events, provided properties, handled events and used properties. It can change from one component to another. The semantic interface gives a standard structure for get and set property methods and for event handler or event generator methods.

Any interactions between components are controlled by another component called the *mediator.* For example, a *sensor-target mediator* determines a detection interaction between sensor and target.

These are the basic properties of MODKIT. Interested readers can find more detailed definitions about components in Arntzen's thesis [Ref.8].

C. SHIP SELF-DEFENSE (SSD) MODEL

An area ship self-defense model was developed using the JAVA™ programming language to conduct the necessary analysis for this thesis research. An event step simulation was used. A full-scale simulation of sensors and weapon systems in air defense was not possible within the scope of this thesis. However, a first stage exploratory analysis was conducted by using this model.

The Ship Self Defense Model (SSD) is designed to provide a simulation of one ship with its complement of weapons and sensors. The ship's mission is to defend itself and escorted ships against an attack of anti-ship missiles (ASMs).

The purpose of the model is to assess the performance of active and passive sensors in different anti-air-warfare area defense scenarios. Since the detection time of the sensor is only a surrogate measure of effectiveness for ship survival, the fire control system of the ship is also modeled.

The SSD is composed of the following warfare simulation components.

- Surveillance sensor
- Fire Control System
- Launcher
- Tracker
- Surface to air missile (SAM)
- Anti-surface missiles (ASM)
- Contact (Detected ASM)
- Sensor-ASM Mediator
- ASM-SAM Mediator
- Linear Motion Component
- Organizer

Also, to help with the analysis, two auxiliary components, called *StatsHelper* and *Test*, were incorporated. Figure 4 is the general structure of the SSD model.

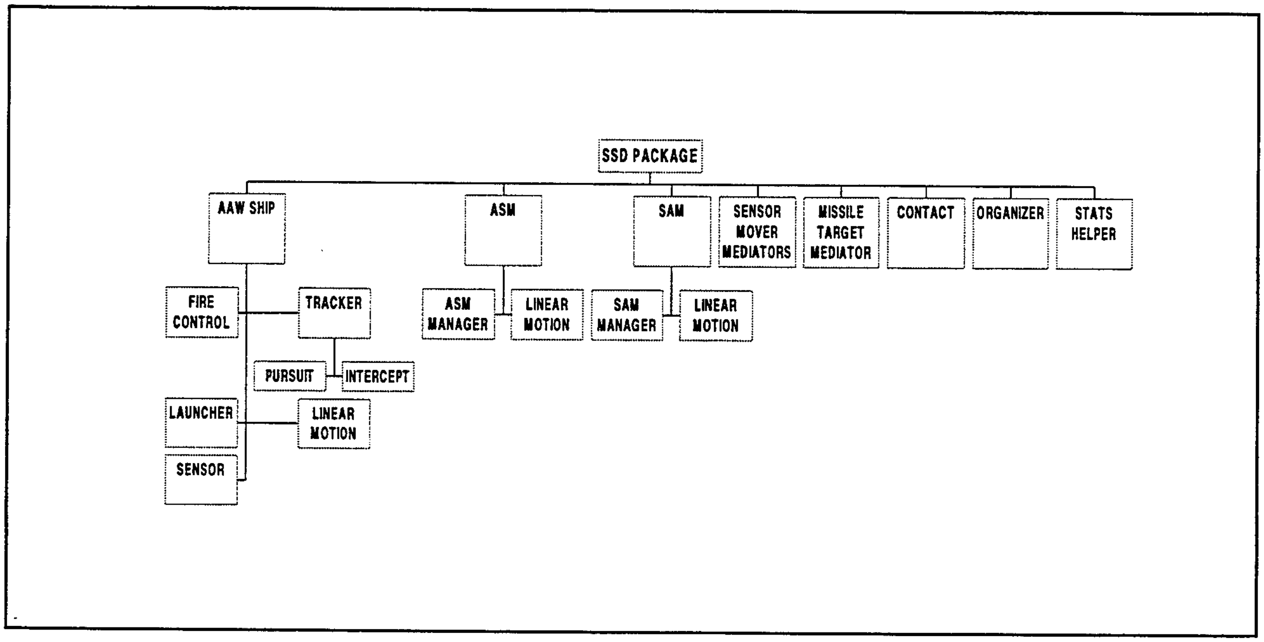

Figure 4. General Structure of the SSD Model.

The work structure of the SSD model is shown in Figure 5. In the graph, blocks represent the simulation components. One-head arrows represent an event generation or a property set action and two head arrows represent a getproperty action. When an ASM component (1) starts to move towards a surveillance sensor component, an organizer component (2) creates a *sensor-ASM* mediator (3) between them. The *sensor-ASM* mediator decides the detection time and notifies the surveillance sensor (4). The *sensor-ASM* mediator also keeps track of the no detection situation. The surveillance sensor component informs the fire control system (5) when it has a detection. The fire control system does the necessary calculations for a fire decision and then gives the track target order to the tracker (6) and the launch missile order to the launcher (7). When the launcher launches a SAM (8), the organizer component creates an ASM-SAM mediator (9) between SAM and ASM. The SAM-ASM mediator is the referee that decides the engagement/disengagement events for this interaction.

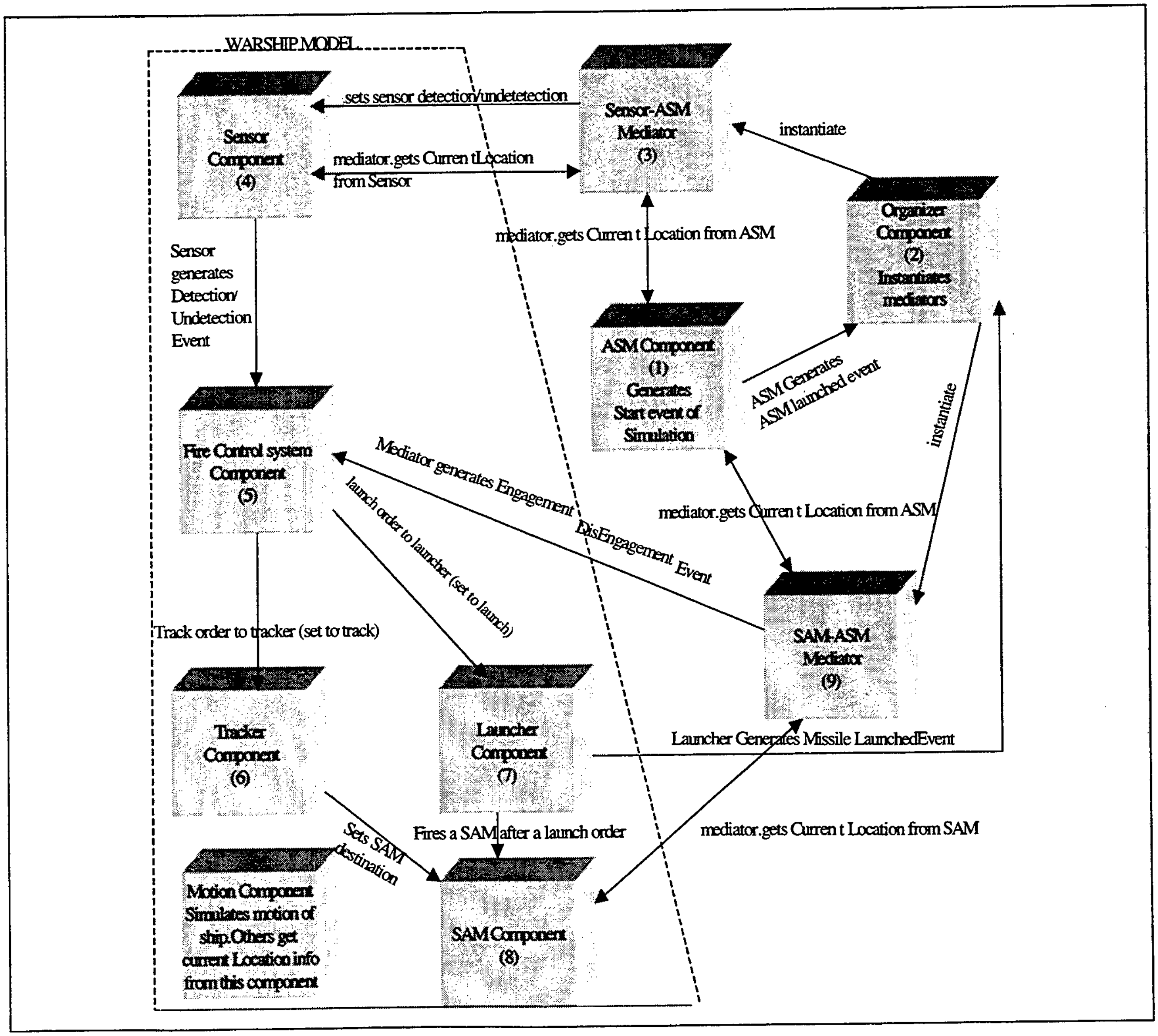

Figure 5. General Work Structure of the SSD Model.

The following components comprise the SSD model. To aid in the understanding of the components an event graph is sometimes used. [Refs. 10 and 11]. However, event generation, event handling, property setting and getting are not defined in conventional event graphs. As a result, rectangular boxes are introduced to define these in this research.

1. Linear Motion Component (Basic Mover)

This component simulates the basic linear motion of an object. By using this component it is possible to give a three dimensional (x,y,z) or four dimensional (x,y,z,time) destination coordinate to an object, to start its motion, to stop it, and to learn its current location or velocity at any time. It may be visualized as the engine of any moving object. It should have a starting point and a maximum speed value when this component is created. This component also is used to simulate the convoy ships. Figure 6 is the event graph of this component.

The linear motion component generates a *moverStopped event* when it stops, an *arrivalAtLocation event* when it arrives a given destination, and a *movingViolation event* when it cannot comply with the move order.

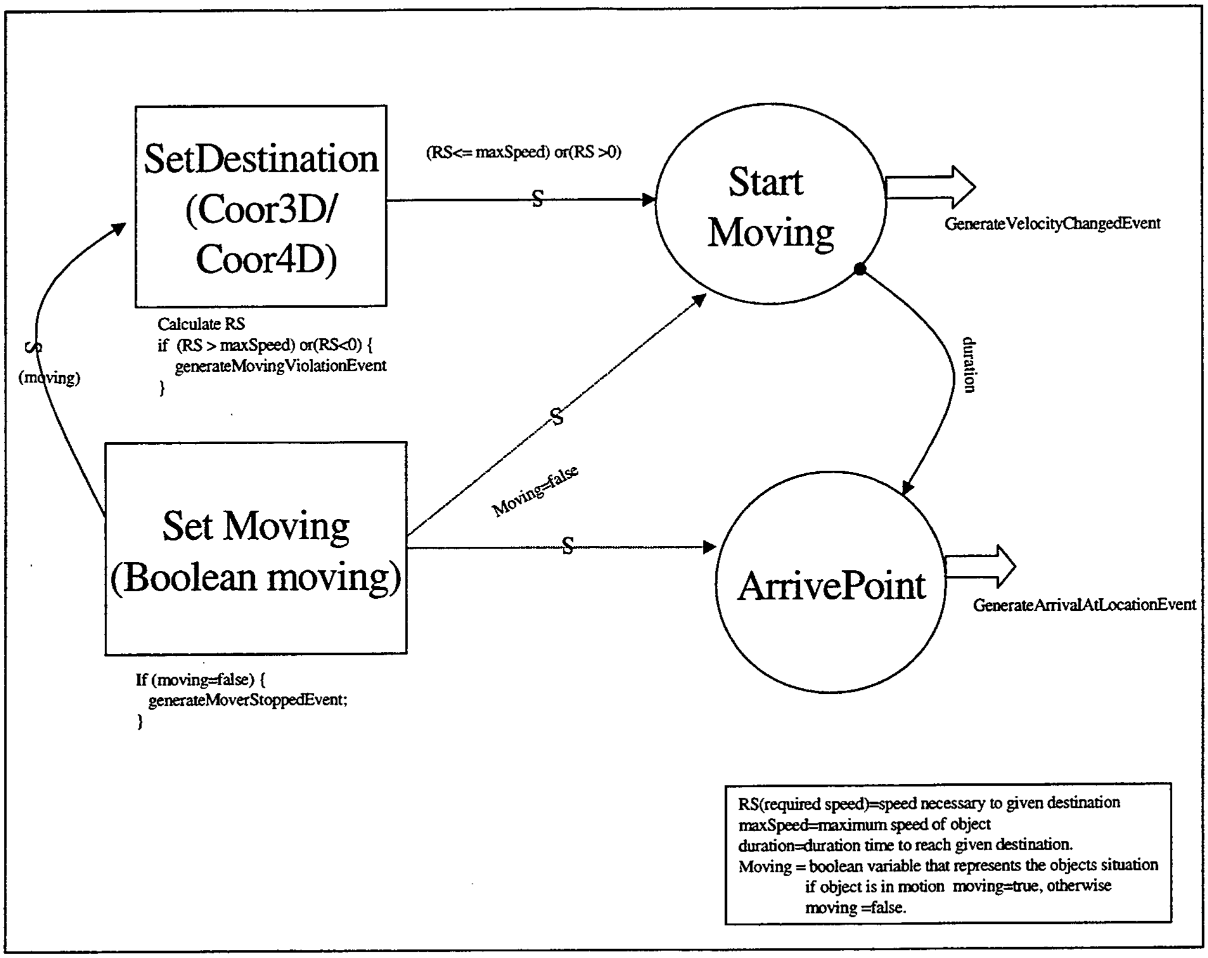

Figure 6. Event Graph of Linear Motion Component

2. Anti-Surface-Missile (ASM) Component

This component represents an anti-surface-missile. It has a kill probability variable which represents its target hit probability. The ASM component uses the linear motion component for its motion. To start a move it must be aimed at a ship. When it starts to move it will generate an *asmLaunched* event to inform the organizer component. The ASM component stops when it hits its target or when a SAM component hits it.

3. Surface-to-Air-Missile (SAM) Component

The Surface to air missile (SAM) component represents a general surface to air missile. The SAM component uses the linear motion component for its motion. Its properties are max/min range, maximum flight time of missile, maximum speed, kill radius, which represents the necessary distance that a SAM should travel to a target to destroy it, and a kill probability which is the SAM's hit probability.

4. Sensor-ASM Mediator

Mediators are the referees of the model. They make detection and engagement decisions. The sensor-ASM mediator checks the interaction between the sensor and any ASM. If there is an interaction, it decides the times for detection and lost contact for any target, in this research an ASM. Also, it verifies the no detection situation and records the number of ASM's that are not detected by the sensor. The sensor-ASM mediator uses the following algorithms to conduct this process. For the continuous looking model, which was developed by Prof. Arnold Buss, seen in Appendix A, the mediator first calculates the ASM's entrance times to the sensor's maximum range. When an ASM enters the sensor's maximum range, the mediator determines the detection time according to a continuous looking algorithm. For the discrete model, the target and sensor positions are checked every scan period according to the sensor scan rate and the distance between the sensor and target calculated. The mediator looks at the sensor's probability of detection and compares this probability with the generated random number. After this, the comparison decides whether the target is detected or not. Figure 7 is the event graph of the sensor-ASM mediator.

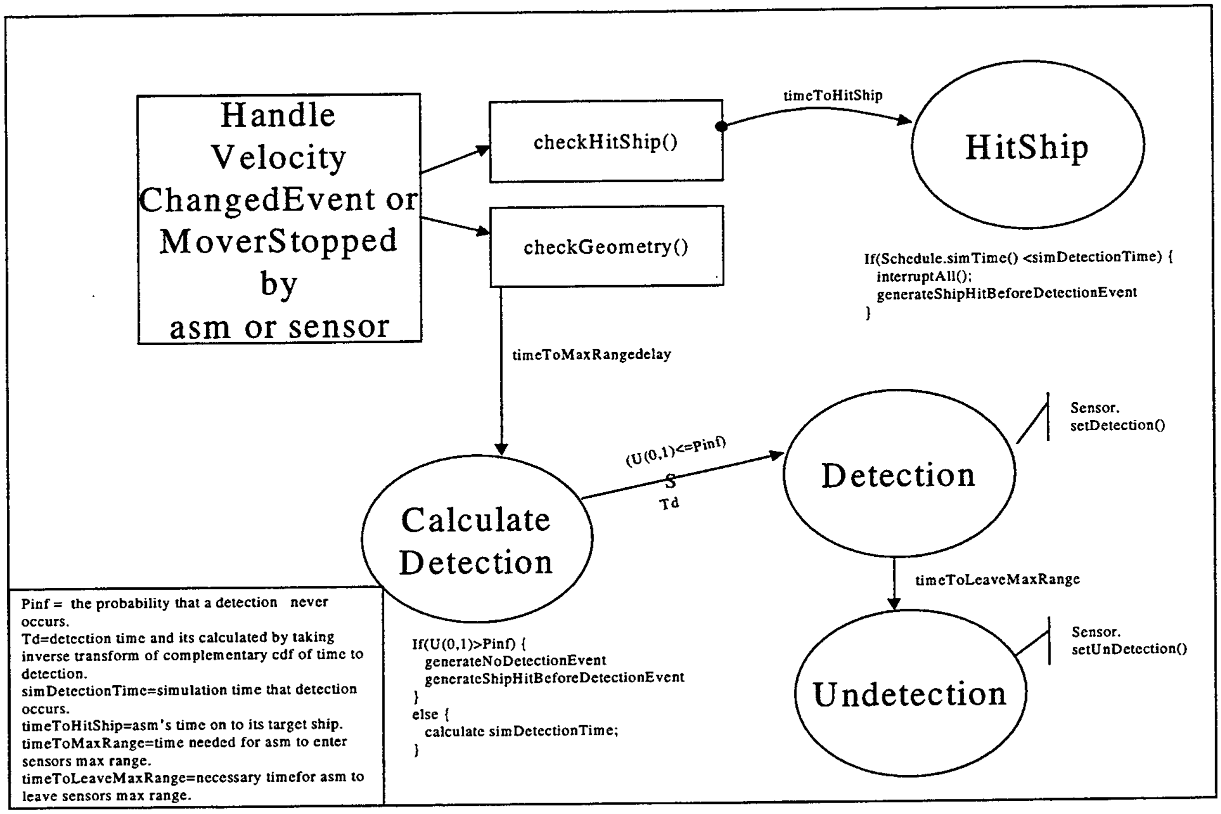

Figure 7. Event Graph for the Sensor-ASM Mediator

5. Surveillance Sensor Component

Two different surveillance sensor types are used in this thesis. The radar represents an active sensor and the IRST represents a passive sensor. In the initial modeling efforts, the author first tried to model the electronic structure of the sensors. However, this experiment showed that the sensor structure had electronic behaviors that were too complex to model and were not needed to meet initial combat simulation requirements. The sensor physics approach could be useful for a sensor design, but is not needed for combat mission analysis. Therefore, the sensors are modeled according to their given detection probabilities for a unique environment. This data can be obtained from more detailed models and field data.

The surveillance sensor is modeled in two ways. One model is the continuous look model developed by Prof. Arnold Buss presented in Appendix A. Two important assumptions were made for this model.

- Uniform linear motion was used for the ASM and the sensor.
- The instantaneous detection probability of the ASM was modeled to be inversely proportional to the square of the distance between the sensor and the ASM.

The other sensor model is the discrete model which needs a sensor scan rate and detection probabilities versus range as a function of scan rate.

The surveillance sensor needs max/min range, maximum track capacity, and alpha (proportion constant between detection probability and inverse of distance square) variables to define it. All detection time and lost contact time calculations are made in the sensor-ASM mediator, as mentioned before. After these calculations are made, the sensor-ASM mediator notifies the sensor at the time of detection and time of lost contact. The sensor then generates detection and lost-detection events at these times.

6. Organizer Component

The organizer component is built to create the mediators when they are needed. It listens to the ASM and the launcher components to manage this goal. When there is a generation of the *asmLaunchedEvent* from an ASM component, the organizer will check which target is in the ASM's direction, and will create a sensor-ASM mediator between the sensor and the ASM. Figure 8 diagrams the relationships between all these components.

When there is a *missileLaunchedEvent* generation from the launcher, the organizer will create a SAM-ASM mediator between fired SAM and incoming ASM. This interaction will be discussed in later sections.

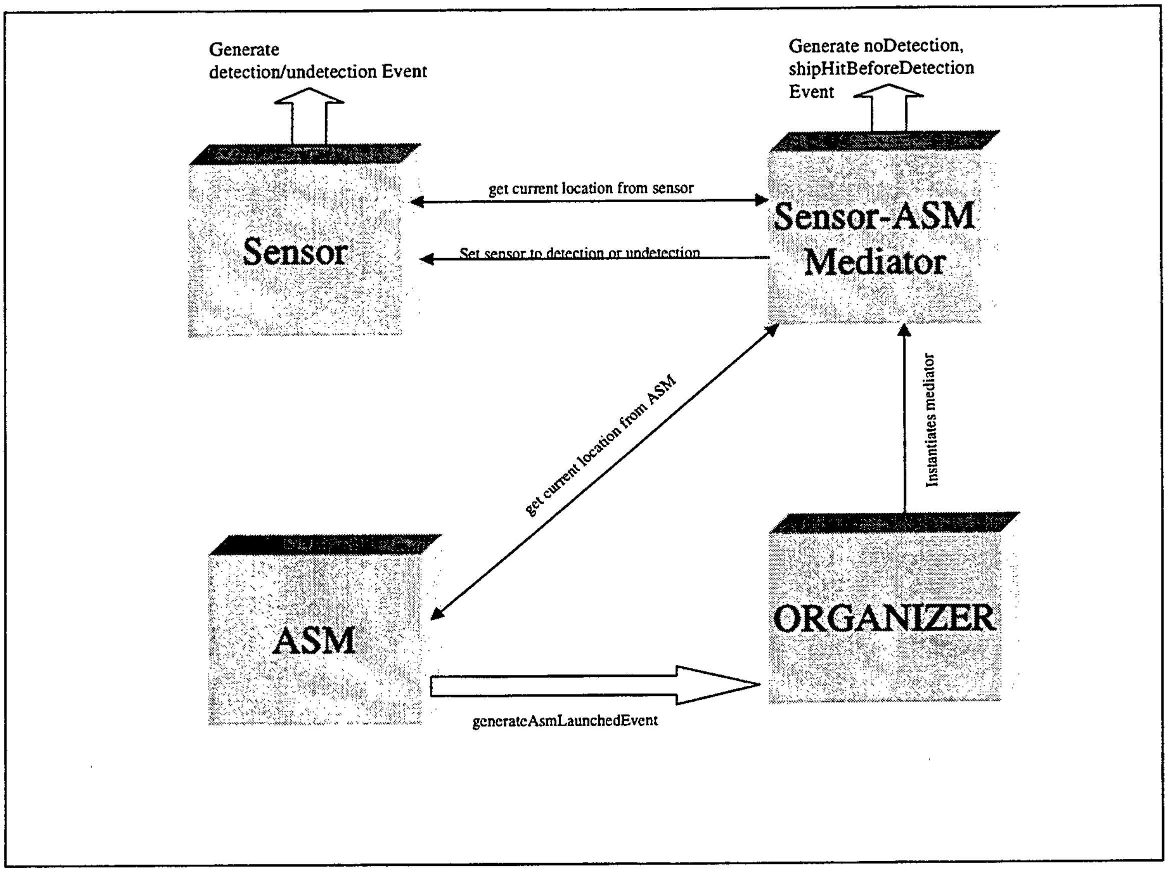

Figure 8. The Interaction between the Components for the Detection Evaluation Process

7. Tracker Component

If the SSD is viewed as a queuing model, trackers can be defined as the servers of the target queue. When tracking a target they will be busy until the interception of the ASM and SAM, that is, homing all the way. This continuous tracking requirement is a very important constraint in the air defense mission of a ship, which is why trackers are explicitly modeled in this thesis.

The tracker guides the SAM until it intercepts the ASM. It can perform this task in two different ways. One is the pursuit course approach. In this approach, the tracker looks at the ASM's position at given intervals and resets the SAM interception point at each interval. The time interval defines the track resolution of the tracker. The second method is the intercept course approach. In this method the tracker sets the SAM destination directly to the intercept point for the SAM and the ASM. The intercept course method was used in this research to reduce the errors in track correlation which require a more detailed model and to decrease model run time.

The tracker has a max/min range and slew delay properties. The slew delay is the necessary time delay used to simulate the tracker's search for the target. The tracker generates a *targetTrackedEvent* when it tracks a target. Figure 9 is the event graph of the tracker component that uses the intercept course approach.

8. Launcher Component

The launcher contains the surface-to-air missile (SAM) components. Every launcher can have only one type of missile and a fixed number of missiles. The Launcher has a launch delay which represents the time delay for launching a SAM after the fire order. Especially for horizontal launchers, this delay turns out to be important, since, these launchers must look at the target's direction before the firing of the SAM. When there is a missile launch, the launcher component generates a *missileLaunchedEvent.* The organizer listens for the launcher and creates an ASM-SAM mediator when it hears a missile launched event. Figure 10 is the event graph of the launcher component.

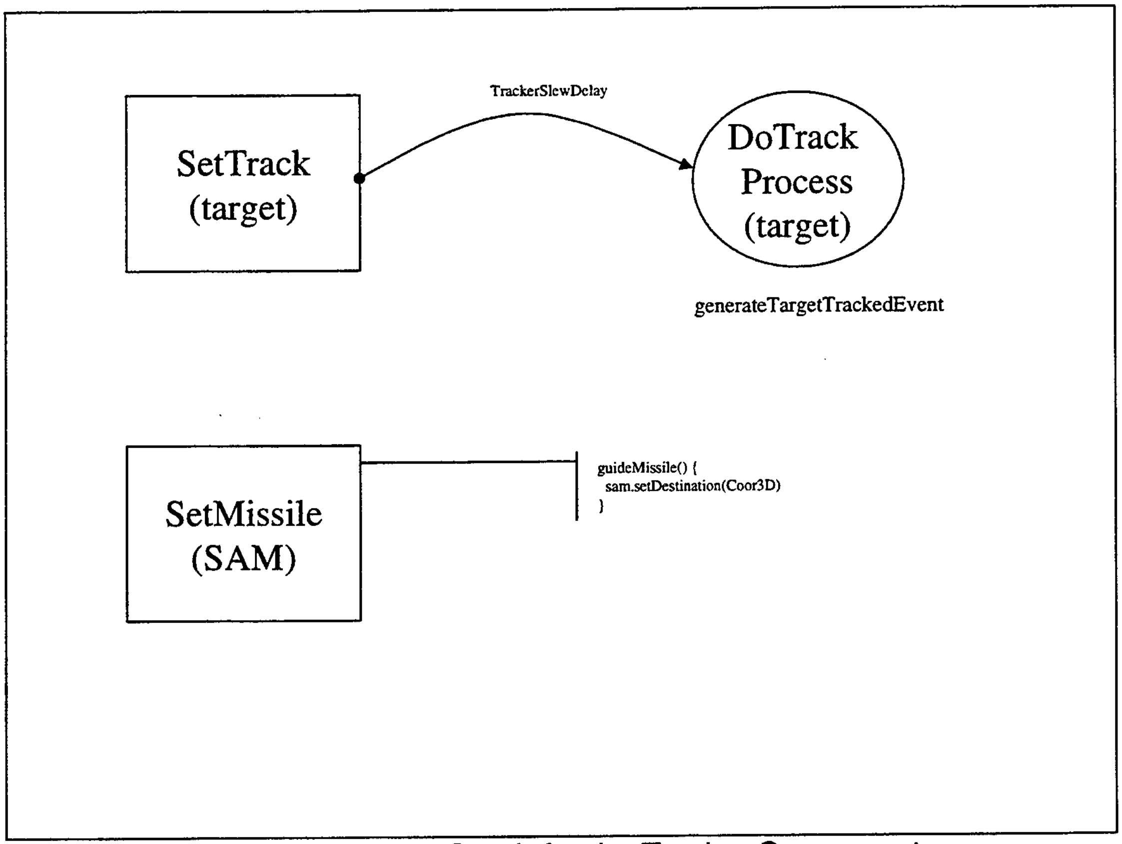

Figure 9. Event Graph for the Tracker Component

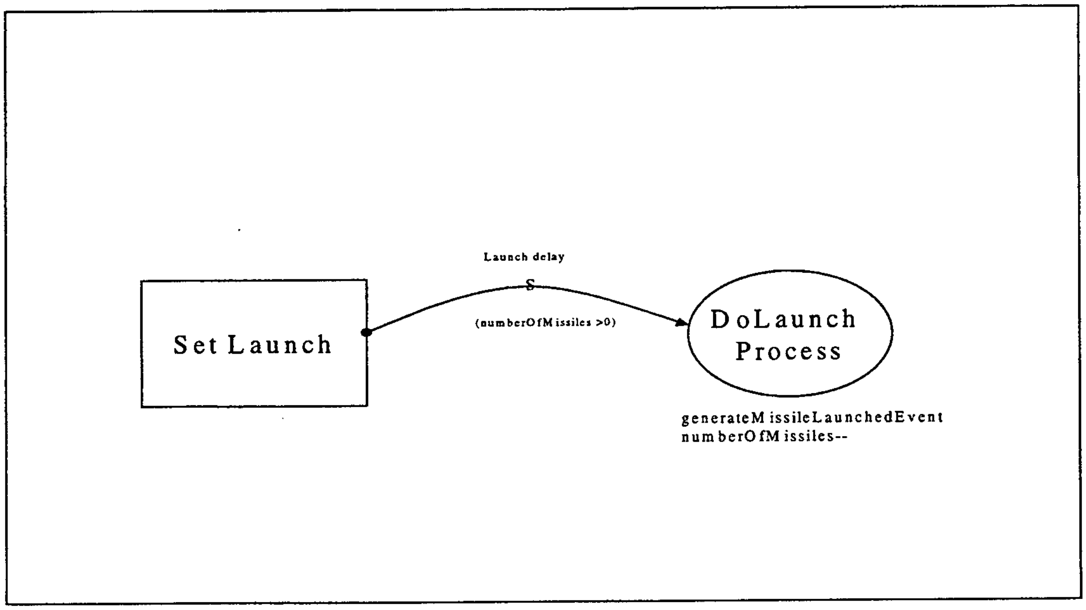

Figure 10. Event Graph for the Launcher Component

9. ASM-SAM Mediator

The ASM-SAM mediator does the necessary calculations for the engagement/disengagement of the ASM and SAM, and broadcasts this result to the concerned components. It uses a general cookie-cutter approach. First, it calculates the ASM's entrance time into the SAM's kill radius. When this happens it generates a random number and compares this with the missile's kill probability, and according to this comparison it generates a hit (engagement) or a miss (non-engagement) event. Figure 11 shows the interaction between components for engagement evaluation.

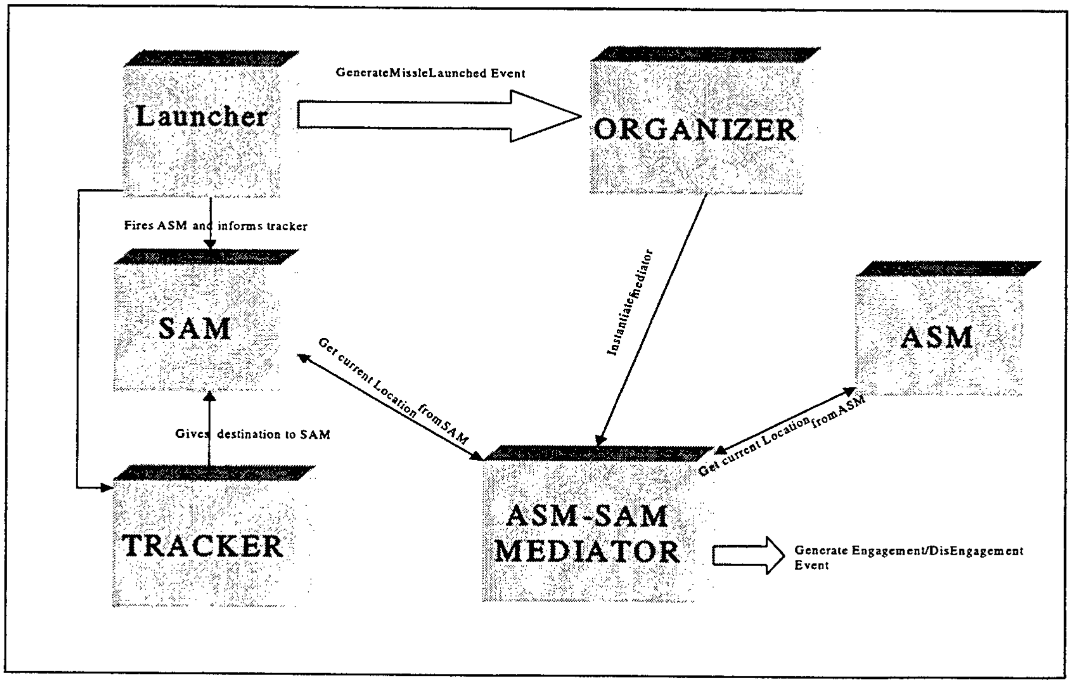

Figure 11. The Interaction Between Components for Engagement

10. Fire Control System Component

The fire control system is the brain of the SSD model. When it hears a detection event generation by a sensor, it makes the necessary calculations for a launch decision and gives the track and launch orders to the tracker and the launcher. The fire policy used in the model is a Shoot-Look-Shoot policy. This policy is a good choice if the main ship has a limited amount of missiles, which is the case for most of the world's navies, and the SAMs have a high probability of kill. This component is designed for an area defense mission. It accomplishes this mission by using the following algorithm:

a. When there is a detection, it first verifies the detection, adds a time delay, then checks if there are any ships within a tolerance bearing of ASM's approach direction.

b. If there are no ships in a given bearing of the ASM's approach direction, then nothing is scheduled. Otherwise, it calculates the ASM's expected arrival time to these ships, takes the minimum of these times and places the ASM in a priority queue according to this time. In an equality case, it looks at the ASM's target ship's priority and places the ASM in a queue according to this priority.

c. The fire control system then calculates the SAM and ASM's interception time, adds the launch and track delays to this time, and compares this total fire time with the ASM's time to ship impact.

d. If the total fire time is less than or equal to the ASM's time to ship impact, then it gives a launch order, otherwise it checks the ASM again at its predicted time of ship impact. Because of track errors the fire control system can make a mistake and the ASM's target might be another ship. In this case, if the ASM is still flying, it will repeat the same evaluations as in c and d.

e. If a fire order is given and the SAM cannot hit the incoming threat, it does the same calculations as in c and d, but in this case there is not any track delay.

Figures 12 and Figure 13 are the event graphs of the fire control system that show the general work structure of the system.

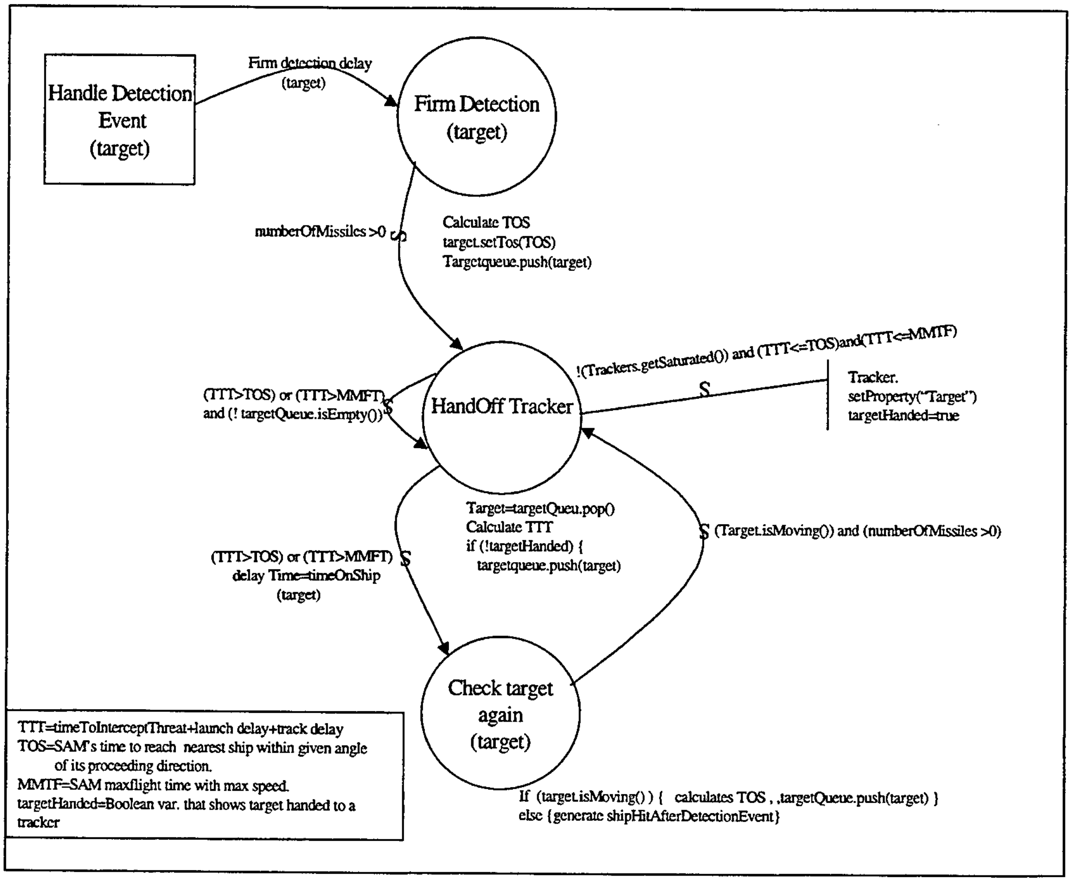

Figure 12. Event Graph of the Fire Control Component for the Handle Detection Event

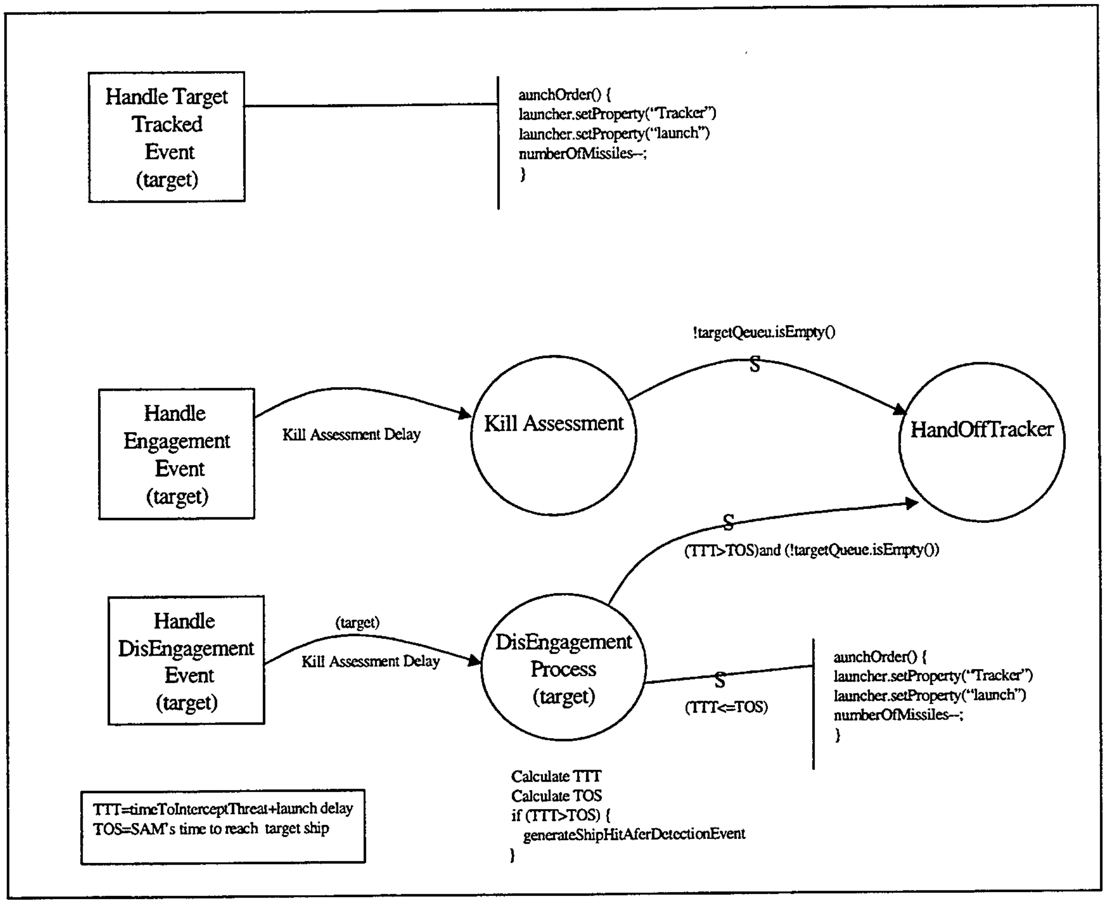

Figure 13. Event Graph of the Fire Control Component for the Engagement the Disengagement and the Target Tracked Events

Figure 14 shows the interaction between the fire control component and other components.

11. Contact Component

The contact component is designed to prevent illegal access to the ASM's properties. When the sensor-ASM-mediator decides to initiate a detection event it will not pass the exact ASM data to the sensor, although it will pass the contact to the sensor. A target's position error is added by a contact component to

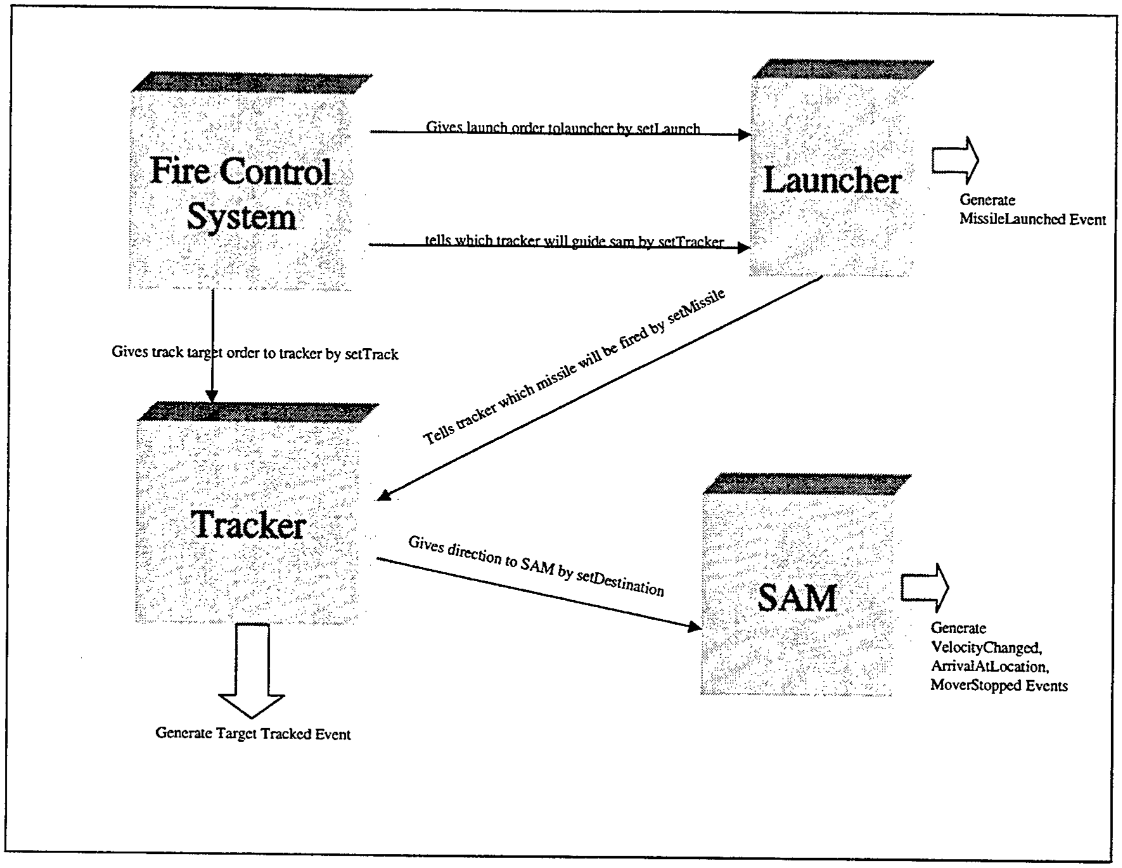

Figure 14. The Interaction between the Fire Control Component and the Launcher, the Tracker, the SAM Components

simulate the sensor's detection error. The sensor does not know anything about the identity of the target. Modeling of the identification process may be an area for future studies.

IV. MODEL RESOLUTION AND ANALYSIS SCENARIOS

This chapter uses SSD components to conduct an exploratory analysis to measure the effectiveness of sensors in AAW missions. The parameters used to model the weapon systems are from open sources. Hence, the analysis should be considered as an illustration of how this tool can be used in forming decisions.

The first section of this chapter presents the model resolution and modeling assumptions. The second section introduces the actual systems that are modeled with SSD components. In the third section, measures of effectiveness are defined for use in the analysis. The last section describes the scenario that is used in the analysis.

A. MODEL RESOLUTION AND MODELING ASSUMPTIONS

The following assumptions are made in modeling the SSD components.

- The motion of the objects is modeled by uniform linear motion. That is, incoming ASM's and outgoing SAM's fly at constant velocity.
- Ship motion is modeled, but not used in this research.
- Ship superstructure is not modeled.
- ASM's are assumed to be sea-skimmers and stay at their constant sea-skimming altitude.
- The ASM's probability of hit value for ships is assumed to be one.
- The ASM's seeker and radar cross section are not modeled.

- SAM's are modeled as semi-active missiles. The homing type for SAM's is modeled as home-all-the-way.

- Detailed tracker characteristics are not modeled. The Tracker tracks every ASM passed on by the surveillance sensor with a probability of one.

- Soft-kill methods are not modeled.

B. ACTUAL SYSTEMS MODELED IN SIMULATION

To conduct the analysis, the following actual systems are modeled with SSD components.

1. Exocet Anti-Ship-Missile

The exocet is a medium-range anti-ship missile produced by the AeroSpatiale Company. The first firing of an exocet was on 10 June 1971. Operational trials began in October 1972 and were completed by the summer of 1974. Development was completed in September 1984 and the missile was pressed into service with the French Navy in April 1985. It was used by Argentina in the South Atlantic Conflict of 1982, and by Iraq in the Iran-Iraq war. There are two different models of the exocet: the MM38 and MM40. Production of the MM38 was completed in June 1993, while production of the MM40 continues with Block-1 and Block-2 versions. It is one of the more famous ASM's and more than 30 countries own this missile. For this reason, this missile was chosen for this research. Table 1 presents the physical properties of an exocet missile. [Ref. 12]

	MM38	MM40 Block-1
Length	5.21 m	5.78 m
Diameter	0.35 m	0.35 m
Weight	735 kg	855 kg
Speed	0.9 mach	0.9 mach
Range	2-22.5 nmiles (4-42 km)	2-38 nmiles (4-70 km)
Sea-Skimming Height	8 m (2-5 m in calm sea)	8 m (2-5 m in calm sea)

Table 1. Physical Properties of an Exocet Missile.[Ref.12]

2. Evolved Sea Sparrow Surface to Air Missile

The Evolved Sea Sparrow (ESSM) is a point defense surface to-air missile. Its history begins in the mid-1950's. The growing threat from the ASM's underlined a need for the development of a point defense missile system. The US Navy used the RIM-7E missile, which was the precursor to the sea sparrow, to satisfy this need. After 1968, a joint development effort was conducted by NATO countries and the system was renamed the NATO sea sparrow missile system (NSSMS). In the late 1980's, the ESSM project was proposed to these countries and by the summer of 1992, the ESSM became the only practical solution to meet NATO's needs for an improved ship missile defense system. [Ref. 12] Today, the ESSM is being used by 11 countries and destined to become NATO's next generation ship AAW defense weapon. [Ref. 13]

Table 2 presents the physical properties of the ESSM.

Length	3.7 m
Launch Weight	282 kg
Speed	3.0 mach
Range	30 km
Max. Altitude	50,000 ft
Estimated Single-Shot Probability of Kill	Subsonic : 0.85 Supersonic : 0.75

Table 2. Physical Properties of The Evolved Sea Sparrow Missile. [Ref.13]

3. IRSCAN Infrared Sensor

The IRSCAN is a fast-reaction surveillance system which has been under development by the Signaal company since the mid-1980's. It is designed to detect both air and surface targets. After extensive trials between 1991 and 1992, it was pressed into service by the Royal Netherlands Navy. In late 1993, Signaal began to develop a long-range infrared search and track system, SIRIUS, based upon IRSCAN technology. A preproduction model of this system was scheduled to be built in 1998 with trials continuing in 1999[Ref. 12]. In this research, the detection probabilities for the IRSCAN were obtained from test data of the infrared search sensor trials. Table 3 contains the physical properties of IRSCAN.

Wavelength	8-12 μm (3-5μm,8-12μm)
Detection Capability	Aircraft and supersonic Missiles : Typically 20 km Subsonic Missiles : 12 km
Target Designation Accuracy	< 1 mrad
Internal Track Capacity	> 500 tracks real time
Scanning Speed	78 rpm
Elevation	14.6 °
False Alert Rate	<1 false alert/h

Table 3. Specifications of IRSCAN.[Ref.12]

4. AN/Sps-40 Air Surveillance Radar

The AN/SPS-40 is a two dimensional naval air search and surveillance radar for the detection of targets at long and medium ranges. It was pressed into service in the US Navy during the early 1960's. Since its introduction, it has been upgraded on a number of occasions[Ref.12]. Detection probabilities used in this research are taken from development test trials and do not necessarily represent the actual values for the AN/SPS-40 radar. Table 4 presents the air surveillance operational capabilities of the AN/SPS-40.

Frequency	UHF Band	
Detection Capabilities :	Short-Range	Long-Range
Min range	500m	3.7 km
Max Range	--	370 km
Scan Period	4-8 sec.	
Track number	511	

Table 4. Specifications of The AN/SPS-40 Radar.[Ref.12]

5. Mk-29 Horizontal Launcher

The Mk-29 is a lightweight horizontal launcher. This launcher is usually associated with the sea sparrow missile. It contains eight sea sparrow missiles. The launcher must turn toward the incoming ASM before a launch proceeds. A nominal launch delay and a salvo delay were used in simulation runs to model the slew time.

6. Signaal Tactical Tracking And Illumination Radar

The Signaal tactical illumination radar (STIR) performs automatic and simultaneous control of missiles against high-speed sea-skimmers and divers for medium to long-range performance. The sea sparrow and standard missiles can be controlled by the STIR. It has a design range of more than 60 km [Ref.12]. A nominal track delay was used to model the track process in simulation runs.

7. SEWACO Command And Weapon Control System

The SEWACO is a modular collection of integrated sensor, weapon and command subsystems built around a common command control system (C2 system). Its brain is the STACOS (Signaal Tactical Command System) which is designed to present raw and/or processed sensor data from search and fire control radars together with IFF, electronic warfare and other sources [Ref.12]. In this research the basic fire control decision process of such a system was modeled. Nominal delay times were used to model the detection process and kill assessment process.

C. MEASURES OF EVALUATION USED IN THE ANALYSIS

To analyze the effectiveness of sensors in the AAW mission, the following measures of effectiveness (MOE's) are used:

- **MOE 1.** Probability of no leakers. A leaker represents a target that successfully penetrates the area AAW defense layer. This MOE is the probability of having no ships hit. All ASM kills, without considering the range of kill, are included in this probability value.
- **MOE 2.** Probability of kill out of the risk range. This MOE is the probability that targets are killed outside of a given range around a ship. This MOE is introduced since, some ASMs have the capability to explode and damage their target before they hit it, e.g., proximity fuse missiles.

- **MOE 3.** Number of SAMs expended. The average number of SAMs launched during the ASM attack.
- **MOE 4.** Engagement period. This MOE represents the mean of the total tracking time spent on an incoming ASM. This time period starts from the initial track time of the ASM and ends when the ASM is destroyed or hits one of our ships.
- **MOE 5.** Time To Detect. This MOE represents the mean of the time difference between the ASM's entrance time into the sensor's maximum range and ASM's detection time.
- **MOE 6.** Number of Killed ASMs. Average number of ASMs that are destroyed.

D. SCENARIOS

Two scenarios were used as an example to demonstrate the model capability for evaluating the effectiveness of the sensors in the AAW mission. The threat axis was assumed to be known and the AAW formation was aligned according to the threat axis.

1. Scenario-I

For scenario-I, every ship is attacked by one ASM in each run. A time delay is used between ASM firings. A close formation is used to increase the number of ASMs that the SAM ship can successfully engage. This follows from the fact that the number of possible shots increases as the closest point of approach (CPA) between the SAM ship and target decreases. Figure 15 shows the ship formation for the scenario.

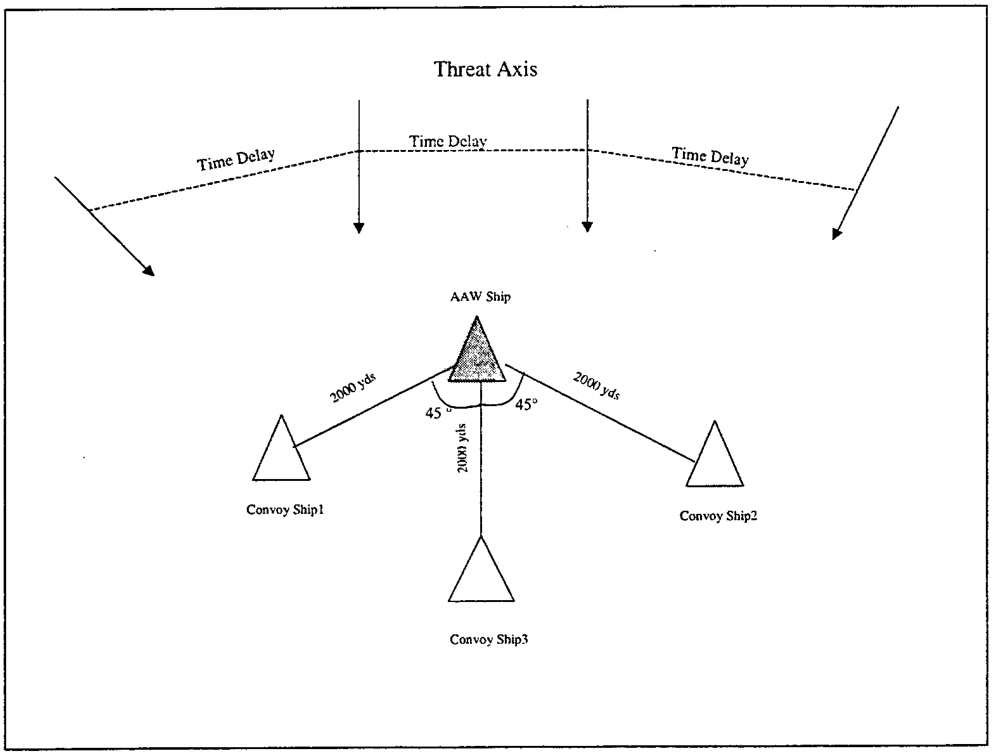

Figure 15. Scenario-I AAW Defense Formation. One AAW frigate defending three convoy ships. Every ship is attacked by one ASM in each run with a time delay.

2. Scenario-II

The same formation is kept in the second scenario. It is designed to illustrate a situation when the convoy is detected and identified by an enemy force. To saturate the AAW ship's defense system a raid of three ASMs are fired at the AAW ship with a time delay per firing. A fourth ASM is fired at the high value unit (Convoy ship3) at the same time with the second missile in the raid. Figure 16 describes scenario-II.

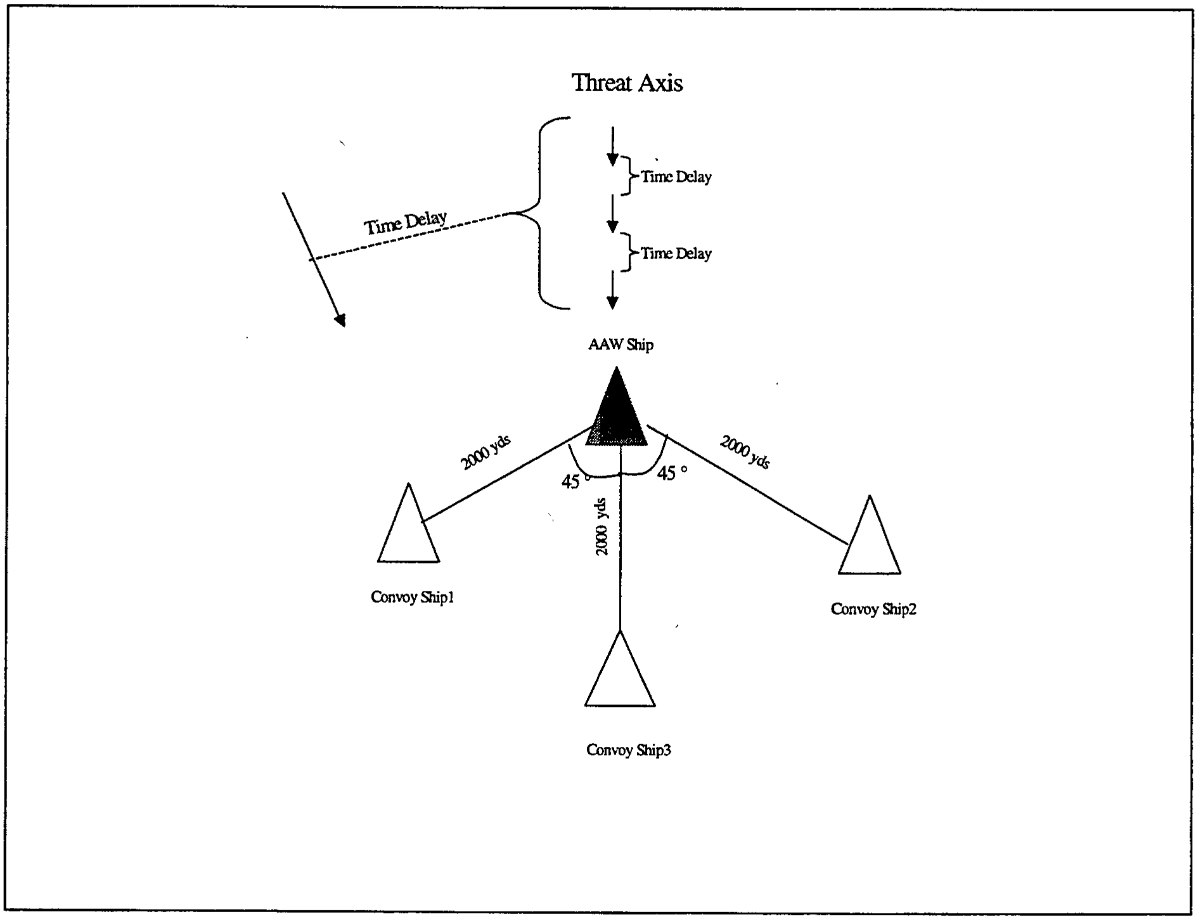

Figure 16. Scenario-II AAW Defense Formation. One AAW frigate defending three convoy ships. The AAW frigate is attacked by three ASM, the high value unit (convoy ship three) is attacked by one ASM.

V. ANTI AIR WARFARE AREA DEFENSE ANALYSIS

A. INTRODUCTION

This section discusses the results of the simulation runs that were conducted to demonstrate the model's exploratory analysis capability. All of the parameters used in the simulation runs are from open sources and should be considered rough estimates. The results of the runs should not be considered exact answers to the research questions. However, this analysis demonstrates the model's potential as an analysis tool.

In this analysis, measures of effectiveness were used to evaluate the capability of the AAW systems. Data collection from the model was handled with the help of *ModComponents* and *ModEvents*. For this purpose, a *listener* component recorded all of the events in a run and displayed them when required.

During the model development exploratory runs were made to evaluate alternative model enhancements. As mentioned in Chapter III, sensors can be modeled by using two different approaches: 1) continuous approximation to a discrete looking model, and 2) the discrete looking model itself. Initially, the continuous approximation to the discrete looking model was chosen to conduct the runs because of its discrete event behavior. However, preliminary sensor detection test data did not comply with the assumptions that were made in the continuous approximation model. A least squares method was used to fit the data. However, exploratory runs showed that fitted data did not give the necessary accuracy. Fortunately, due to the power and flexibility of component-based modeling, a change to a discrete looking sensor model was readily made.

For our demonstration analysis it was assumed that the IR search and track system had a laser range finder. For the IR range error, the laser finder's range error of 5 meters was used. An error of 450 meters was used for the radar range error. [Ref. 12]

The following section discusses the results of the simulation runs. There was only one set of detection probability data available for each sensor type: radar and IR. Thus, in this analysis, sensors could not be compared in different environments (that is, good or bad weather conditions). Therefore, an exploratory analysis was conducted by changing the other parameters, such as SAM's probability of kill, maximum launch range values, etc., of the AAW system for each of the two sensor types. A more complete analysis would also vary environments. The detection versus range values of the IR are for good weather conditions. There were no available data for bad weather conditions, such as heavy rain or fog, in which the IR is known to perform poorly.

Scenario-I was run for two sensor types: radar and IR. Then, the effects of the SAM's kill probability and maximum launch range on AAW defense effectiveness were investigated for each sensor. A suitable distance between ships was also investigated for both sensors. Scenario-II was run with the initial parameters and then the SAM's kill probability of 0.85 was incrementally changed to 0.5 for a comparative analysis.

B. EXPLORATORY ANALYSIS

This thesis investigates the effectiveness of the two types of sensors in two scenarios. Scenario-I represents the case where the convoy is detected but not identified. Therefore, every single ship is attacked by one ASM. Scenario-II represents the case where the convoy is detected and identified. Accordingly, a raid of three ASMs is fired on the AAW ship to saturate its AAW defense system and one single ASM is fired at the high value unit (convoy ship three).

The sample size in each run was 300. This provided a 95% confidence interval length of no more than 0.11 for population proportions.

1. Scenario-I

In scenario-I three convoy ships are defended by an AAW ship, as shown previously in Figure 15. One ASM attacks each ship in the AAW formation with a time difference of 4 seconds between ASM launches. It is assumed that the threat axis is known (a common situation for Mediterranean navies). Thus, the formation is shaped according to the threat axis. The distance between the AAW ship and the convoy ships is 2000 yds. (1 nautical mile (NM)). The AAW ship has two trackers and eight evolved sea sparrow missiles (SAM's) with a single-shot kill probability of 0.85 and a maximum range of 16 NM. The risk range is 1 NM for each ship. The risk range is defined as the farthest range at which the ASM can damage the ship. Other model assumptions are as described in Chapter IV. The parameters varied to conduct a comparative analysis on sensors are the maximum launch range capability of the SAM, the SAM single-shot kill probability, and the distance between ships. The following MOE's, which were explained in detail in Chapter IV, were used in the evaluation.

- MOE 1: Probability of No Leakers.
- MOE 2: Probability of Kill Outside of the Risk Range.
- MOE 3: Number of SAM's expended.
- MOE 4: Mean Engagement Period (Mean track time of a target in minutes).
- MOE 5: Mean Time to Detect (in minutes).
- MOE 6: Mean Number of Killed ASM's.

The results of the simulation runs are presented in Tables 5a and 5b.

		P(No Leakers)	**P(Kill Out of Risk Range)**	**Mean Number of SAM's expended**
Scenario-I	Radar	0.99 std 0.032	0.99 std0.032	4.69 std 0.84
	IR	0.99 std 0.01	0.99 std 0.01	4.64 std 0.8

Table 5a. Simulation Results for MOE1-3 of Scenario-I. This scenario produced virtually identical AAW performances for the radar and the IR sensor.

		Mean Engagement Period	**Mean Time To Detect**	**Number of Killed ASM's**
Scenario-I	Radar	0.438 std0.1556	0.01 std 0.026	3.99 std 0.12
	IR	0.2557 std 0.1	0.19 std 0.094	3.98 std 0.05

Table 5b. Simulation Results for MOE4-6 of Scenario-I. This scenario produced virtually identical AAW performances for the radar and the IR sensor for the mean number of killed ASM's only.

As seen in Tables 5a and 5b, the radar and the IR sensors showed the same results for the probability of no leakers, the probability of kill outside the risk range, the mean number of expended SAMs and the mean number of killed ASMs. However, the IR sensor had longer mean time to detect value and lower mean engagement period. The results showed that the AAW system provided good protection (P(No leaker)=0.99) for the convoy with both sensors.

The probability of no leakers values were exactly the same as the probability of kill out of risk range, for both sensor systems. This shows that all of the engagements were conducted outside the risk range.

The radar showed a mean time to detect values of 0.01 minutes and the IR showed a value of 0.19 minutes. This difference can be explained by the earth's curvature effect. A sensor height value of 65 feet was used for the trials. For an ASM flying at an altitude of eight meters, the radar horizon range is approximately 16 NM. The maximum range of the radar is 21 NM. However, it can only see an eight meter high target at a range of 16 NM. For 16 NM and lower ranges, the radar has high detection probabilities. This explains the small mean time to detect value of the radar.

Since the radar detects targets at longer ranges than the IR, the AAW defense system can spend more time on engagements and has a longer mean engagement times than the IR. As a result, in scenario-I both sensor types provided a similar AAW defense capability for the convoy.

a. Effects of SAM Launch Range

SAM launch range capability was varied by using ranges of 16, 12 and 9 NM. 16 NM is the maximum launch range of the evolved sea sparrow missile and nine NM is the maximum launch range of the NATO standard sea sparrow missile. The MOE values remained the same at each range. Since, the mean detection ranges for the radar and the IR were 15 NM and 9 NM respectively. The changes in the SAM's maximum range did not significantly affect simulation outputs.

b. Effects of SAM Probability of Kill

Today's ASMs have high maneuver and speed capabilities which theoretically reduce the SAM's kill capabilities. To see the effects of SAMs probability of kill on AAW defense effectiveness, the probability of kill values of 0.85, 0.6 and 0.5 were used. The theoretical probability of kill value is 0.85 for the evolved sea sparrow missile. The SAM kill probability values of 0.6 and 0.5 were used as the worst case values in the simulation runs.

(1) Simulation Run Results for MOE1-MOE3.

Table 6a and Figure 17 display the results of the simulation runs for MOE1-MOE3 for the radar and the IR sensor for the SAM single-shot probability of kill values of 0.85, 0.6 and 0.5.

Single-Shot Kill Prob.		P(No Leakers)	P(Kill Out of Risk Range)	Mean Number of SAM's expended
0.85	Radar	0.993 std 0.032	0.997 std0.032	4.69 std 0.84
	IR	0.99 std 0.02	0.996 std 0.01	4.64 std 0.8
0.6	Radar	0.88 std 0.32	0.95 std0.029	6.09 std 1.35
	IR	0.78 std 0.4	0.93 std 0.148	6.06 std 1.4
0.5	Radar	0.66 std 0.47	0.87 std0.19	6.88 std 1.31
	IR	0.58 std 0.46	0.85 std 0.2	6.67 std 1.3

Table 6a. Simulation Results for MOE1-3 of Scenario-I for Different SAM Kill Probabilities.

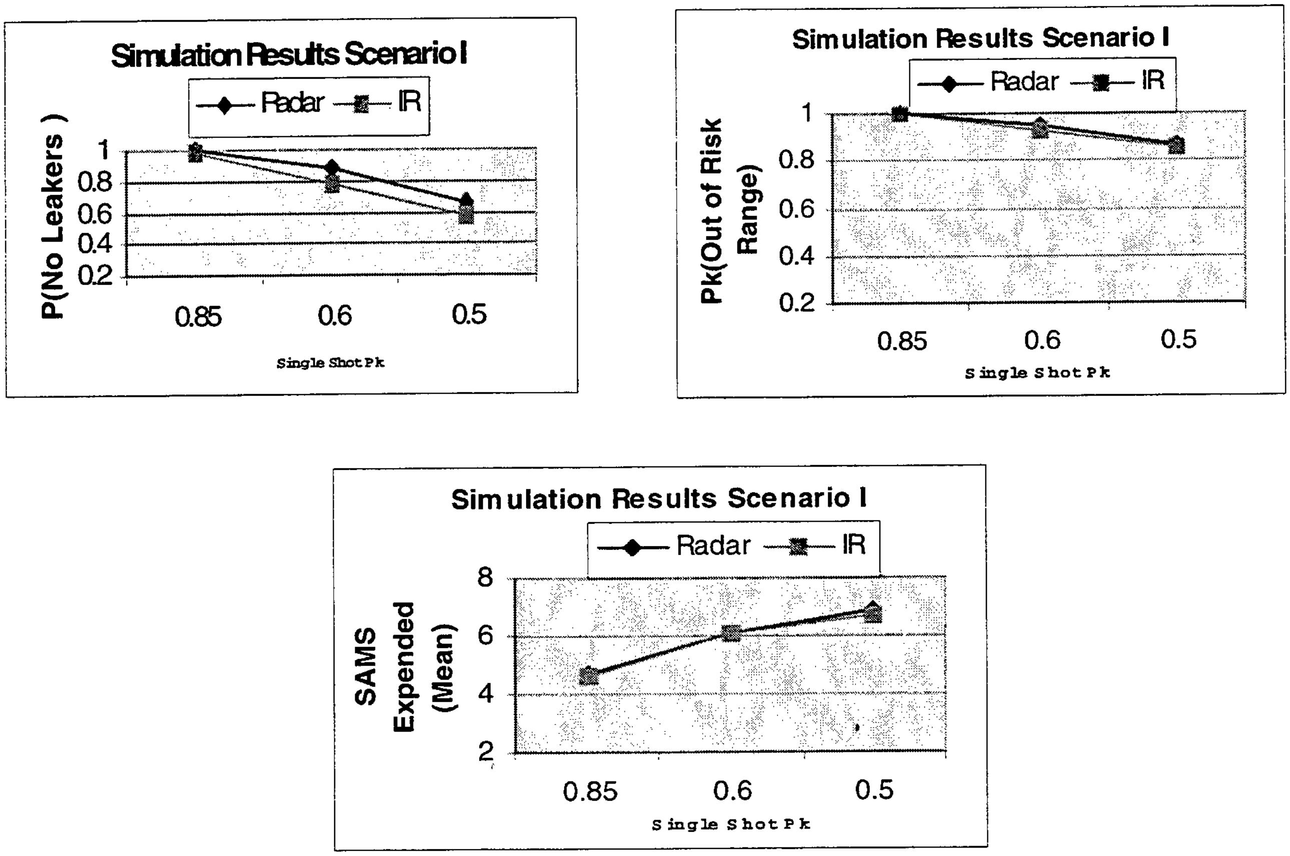

Figure 17. Plots of MOE1-3 for the Radar and the IR Sensor for the SAM Single-shot Kill Probabilities of 0.85, 0.6 and 0.5.

As can be seen, this scenario produced nearly identical values for the radar and the IR sensor except for the probability of no leakers values and the radar had better values for low kill probabilities. The probability of no leakers values showed a decrease as the SAM single-shot kill probability decreased for both sensors. As the SAM kill probability decreased to 0.5 from 0.85, the probability of no leakers decreased by 0.33 for the radar and by 0.41 for the IR. At a 5% level of significance, the radar had higher probability of no leaker values than the IR for SAM kill probability values of 0.6 and 0.5 (p-values are 0.012 and 0.04 for SAM kill probability values of 0.6 and 0.5 respectively.) This is assuming good weather, where the IR sensor is at its best. In bad weather, a greater disparity between the systems may be expected.

The probability of kill out of risk range values showed a decrease as the SAM single-shot kill probability decreased. The probability of kill outside the risk range value decreased by 0.12 for the radar and by 0.14 for the IR. The radar had higher probability of kill out of risk range value than the IR sensor for the SAM single-shot kill probability of 0.6 (p-value = 0.019). The significant difference for the SAM single-shot kill probability of 0.5 was less (p-value = 0.08).

The mean number of expended SAMs increased as the SAM's kill probability decreased for both sensors. The radar expended slightly more SAMs than the IR sensor. However, the difference is only statistically significant at 5% level of significance for the SAM kill probability of 0.5 (p-values are 0.22, 0.39, 0.024 for the SAM kill probability values of 0.85, 0.6 and

0.5 respectively).

(2) Simulation Run Results for MOE4-MOE6.

Table 6b and Figure 18 display the results of the simulation runs for MOE4-MOE6 for the radar and the IR for the SAM single-shot probability of kill values of 0.85, 0.6, 0.5.

Single-Shot Kill Prob.		Mean Engagement Period	Mean Time To Detect	Number of Killed ASM's
0.85	Radar	0.438 std 0.1556	0.01 std 0.026	3.99 std 0.12
	IR	0.2557 std 0.1	0.19 std 0.094	3.99 std 0.05
0.6	Radar	0.55 std 0.29	0.01 std 0.026	3.83 std 0.51
	IR	0.33 std 0.1	0.19 std 0.094	3.79 std 0.5
0.5	Radar	0.65 std 0.3	0.01 std 0.026	3.57 std 0.7
	IR	0.37 std 0.22	0.19 std 0.094	3.56 std 0.78

Table 6b. Simulation Results for the MOE4-6 of Scenario-I for Different SAM Kill Probabilities.

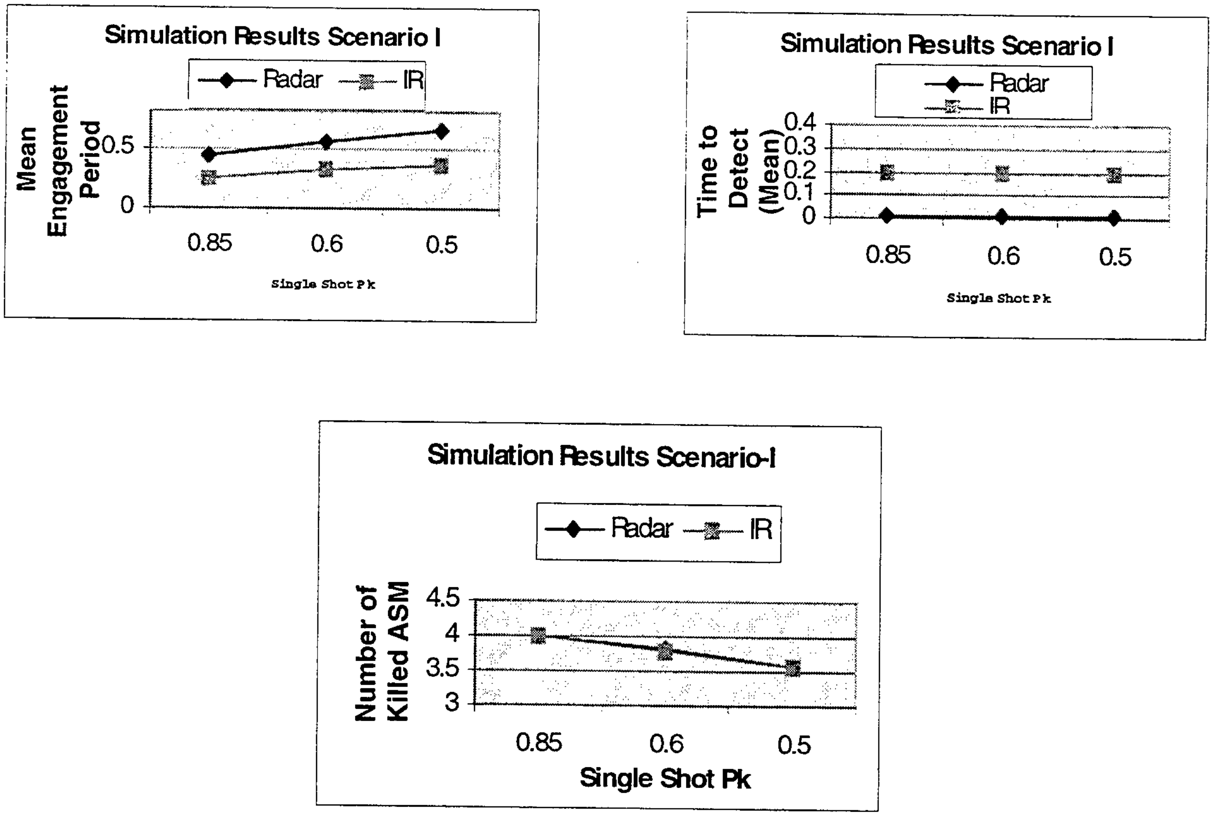

Figure 18. Plots of MOE4-6 for the Radar and the IR Sensor for the SAM Single-shot Kill Probabilities of 0.85, 0.6 and 0.5.

As can be seen, the mean engagement period increased and the mean number of killed ASMs decreased as the single-shot kill probability value decreased. The mean engagement period for the radar showed an increase from 0.43 to 0.65 minutes as the probability kill value and maximum range value for SAM were decreased. For the IR sensor, the change was from 0.25 to 0.37 minutes. The mean time to detect values were the same with the previous trials since the same seed was used for the random numbers. The mean number of killed SAMs decreased as the SAM single-shot kill probability decreased for both sensor types. For the SAM single-shot kill probability of 0.6

and 0.5 the radar killed slightly more SAMs than the IR. However, this is not statistically significant at a 5 % level of significance (p-values are 0.16 and 0.4 for the SAM single-shot kill probability of 0.6 and 0.5 respectively).

c. Effects of the Distance Between Ships

The distance between the ships was one nautical mile (NM) in the initial runs. However, this distance may not always be a good tactical choice. A close formation provides a better target for the enemy, and reduces the stealth characteristics of the force. Consequently, distance values of four and five NM were investigated with the SAM's the worst case probability of kill value of 0.5.

(1) Simulation Run Results for MOE1-MOE3.

Table 7a and Figure 19 display the simulation results with respect to MOE1-3 for the radar and the IR for the distance between ships values of one, four and five NM.

Distance Between Ships		P(No Leakers)	P(Kill Out of Risk Range)	Mean Number of SAM's expended
1 NM	Radar	0.66 std 0.47	0.87 std 0.19	6.88 std 1.31
	IR	0.58 std 0.46	0.85 std 0.2	6.67 std 1.3
4 NM	Radar	0.66 std 0.47	0.86 std 0.2	6.88 std 1.29
	IR	0.55 std 0.49	0.77 std 0.21	6.41 std 1.35
5 NM	Radar	0.63 std 0.4	0.82 std 0.21	6.78 std 1.33
	IR	0.48 std 0.5	0.75 std 0.23	6.25 std 1.49

Table 7a. The Simulation Results for Different Distances between Ship's Values for SAM Kill Probability Value of 0.5.

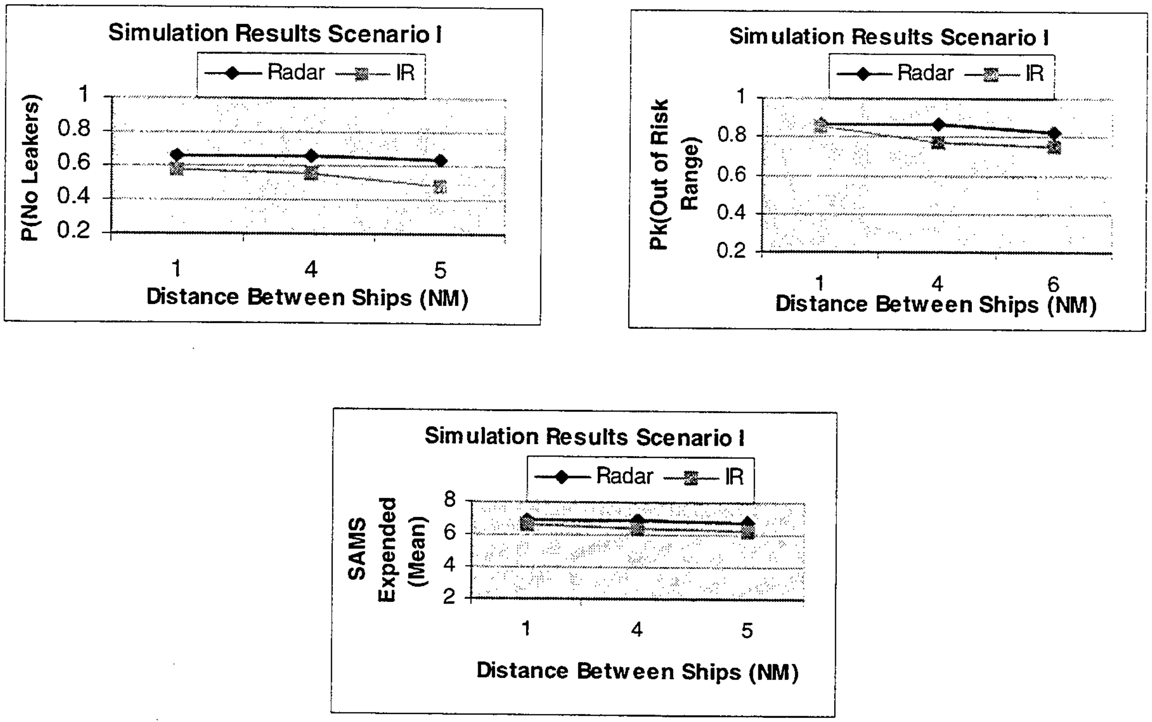

Figure 19. Plots of MOE1-3 for the Radar and the IR Sensor for Different Ship Distance Values.

As can be seen, the IR showed a decrease for the MOE1-3 for ship distance values of four and five NM. For the radar a decrease was observed for five NM. The radar simulation results for the distance value of four NM were the same as the values for the previous one NM trials. However, the IR's probability of kill outside the risk range, the probability of no leakers, and the mean number of SAMs expended values started to decrease when the distance between ships increased to four NM. At 1% level of significance, the IR's probability of kill out of risk range for ship distance of one NM was higher than the IR's probability of kill out of risk range for ship distance of four NM (p-value $\cong 0$). The IR significantly expended fewer SAMs when the distance between ships increased to four NM (p-value=0.008). Although, the mean number of SAMs expended is statistically significant, the small difference in means may not be tactically significant.

For the radar, five NM was the distance where the probability of kill out of risk range, the probability of no leakers, and the mean number of expended SAMs started to change. However, the only significant change occurred in probability of kill out of safe range, at a significance level of 1% (p-value = 0.0004).

(2) Simulation Run Results for MOE4-MOE6.

Table 7b and Figure 20 display the simulation results with respect to MOE4-6 for the two sensors for the distance between ships values of one, four and five NM.

Distance Between Ships		Mean Engagement Period	Mean Time To Detect	Number of Killed ASM's
1NM	Radar	0.65 std 0.3	0.01 std 0.026	3.56 std 0.7
	IR	0.37 std 0.22	0.19 std 0.094	3.5 std 0.7
4 NM	Radar	0.61 std 0.35	0.01 std 0.026	3.51 std 0.79
	IR	0.39 std 0.25	0.19 std 0.094	3.4 std 0.7
5 NM	Radar	0.63 std 0.37	0.01 std 0.026	3.45 std 0.82
	IR	0.42 std 0.27	0.19 std 0.094	3.32 std 0.47

Table 7b. The Simulation Results for the MOE4-6 for Different Distance between Ships Values for the SAM Kill Probability Value of 0.5.

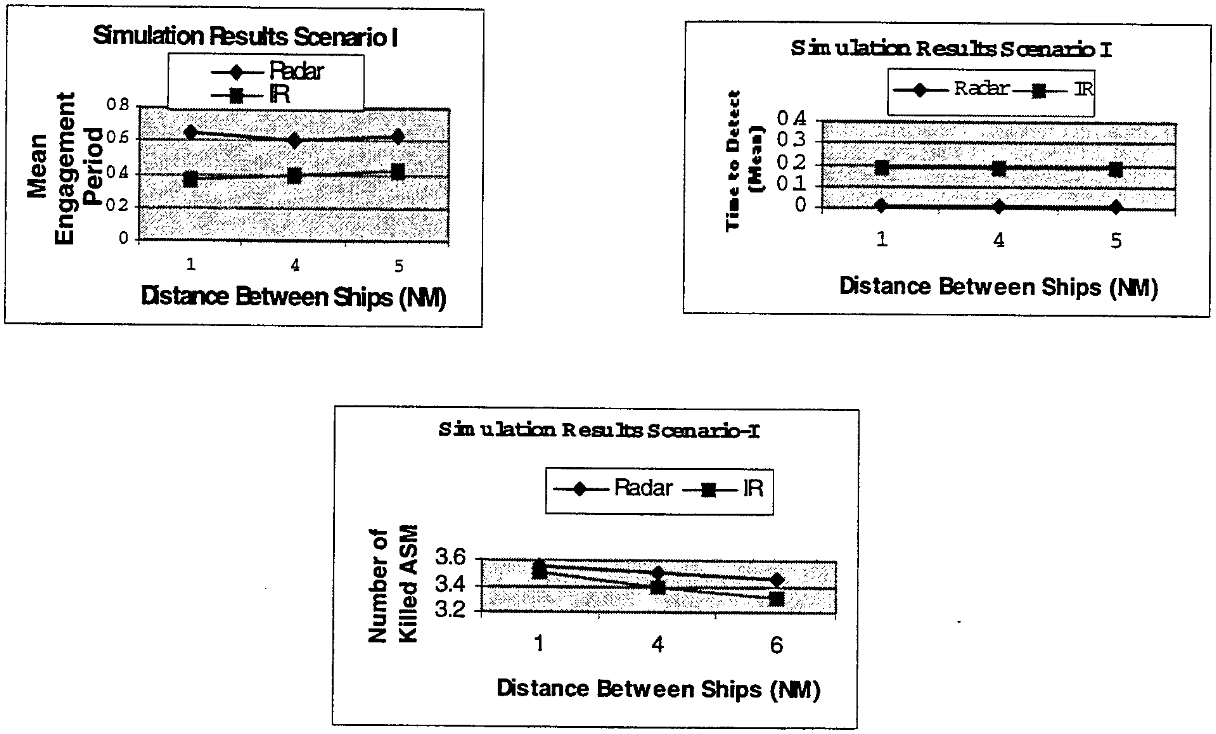

Figure 20. Plots of MOE4-6 for the Radar and the IR Sensor for Different Ship Distance Values.

As shown above, the mean engagement period increased and the number of killed ASMs decreased as the distance between ships increased for both sensors. The mean time to detect values were the same with the previous trials since the same seed was used for the random numbers. The mean engagement period of the IR increased to 0.42 from 0.37 as the distance between ships increased. The radar mean engagement period decreased to 0.61 when the distance between ships increased to four NM. Then, it increased to 0.63 as the distance between ships increased to five NM. It is suggested that this small anomaly was due to random variation. The mean number of killed ASMs showed a decrease for both sensors as the ship distance decreased. For the radar the difference is significant (p-value=0.03) for the ship distances of one NM and five NM. For the IR sensor a significant difference was observed between one NM and four NM (p-value=0.04). As a result, distances between ships can be extended to four NM for the IR and five NM for the radar without measurably decreasing the AAW defense effectiveness.

2. Scenario-II

In scenario-II, three convoy ships are defended by an AAW ship as previously shown in Figure 16. This scenario is designed to illustrate the situation where the convoy is detected and identified by enemy forces. To saturate the AAW ship's defense system a raid of three ASMs are fired at the AAW ship with a time difference of three seconds per firing. A fourth ASM is fired at the high value unit (Convoy ship3) at the same time with the second missile in the raid. It is assumed that the threat axis is known and the formation is formed according to the threat axis. The distance between the AAW ship and the convoy ships is 2000 yd. (1 NM). The AAW ship has two trackers and eight evolved sea sparrow missiles (SAM's) with a kill probability of 0.85 and a maximum range of 16 NM. The risk range is 2000 yds (1NM) for each ship. The model assumptions are as described in Chapter IV. The results of the simulation runs are presented in Tables 8a and 8b. For scenario-II, the AAW performances for the radar and the IR sensor were virtually the same as scenario-I and therefore no overall change in AAW system effectiveness was noted. However, a decrease was observed in the mean engagement period for both sensors.

		P (No Leakers)	P(Kill Out of Risk Range)	Mean Number of SAM's expended	Mean Engagement Period	Mean Time To Detect	Number of Killed ASM's
Radar	Scenario I	0.993 std 0.032	0.997 std 0.32	4.69 std 0.84	0.438 std 0.15	0.01 std0.02	3.99 std 0.12
	Scenario II	0.993 std 0.085	0.994 std 0.06	4.68 std 0.89	0.39 std 0.15	0.01 std 0.02	3.98 std 0.26
IR	Scenario I	0.99 std 0.02	0.996 std 0.01	4.64 std 0.8	0.2575 std 0.102	0.19 std 0.09	3.97 std 0.05
	Scenario II	0.98 std 0.1	0.98 std 0.05	4.63 std 0.78	0.235 std 0.102	0.19 std 0.09	3.97 std 0.11

Table 8. Simulation Results for Scenario-I and Scenario-II. Both sensor types had virtually identical AAW performances for the two scenarios.

a. Effects of SAM's Probability of Kill

To see the effects of SAM's probability of kill values on the AAW system defense effectiveness, the SAM's probability of kill value was changed to 0.5 for scenario-II and compared with scenario-I. The results of the simulation runs are presented in Table 9.

		P(No Leakers)	P(Kill Out of Risk Range)	Mean Number of SAM's expended	Mean Engagement Period	Mean Time To Detect	Number of Killed ASM's
Radar	Scenario I	0.66 std 0.47	0.87 std0.19	6.88 std 1.31	0.65 std 0.3	0.01 std 0.02	3.57 std 0.7
	Scenario II	0.58 std 0.4	0.87 std 0.19	6.88 std 1.31	0.56 std 0.32	0.01 std 0.02	3.51 std 0.2
IR	Scenario I	0.58 std 0.46	0.85 std 0.2	6.67 std 1.3	0.37 std 0.22	0.19 std 0.09	3.56 std 0.78
	Scenario II	0.50 std 0.49	0.77 std 0.22	6.45 std 1.3	0.32 std 0.2	0.19 std 0.09	3.43 std 0.7

Table 9. Simulation Results of Scenario-I and Scenario-II for SAM Kill Probability of 0.5. Scenario-II showed a decrease in AAW defense effectiveness for both sensors.

Almost all of the MOE's showed a decrease in scenario-II, the more stressing one, for both sensors. The mean time to detect values were the same with the previous trials since the same seed was used for the random numbers. Figure 21 displays the plots of the MOE's for two different scenarios.

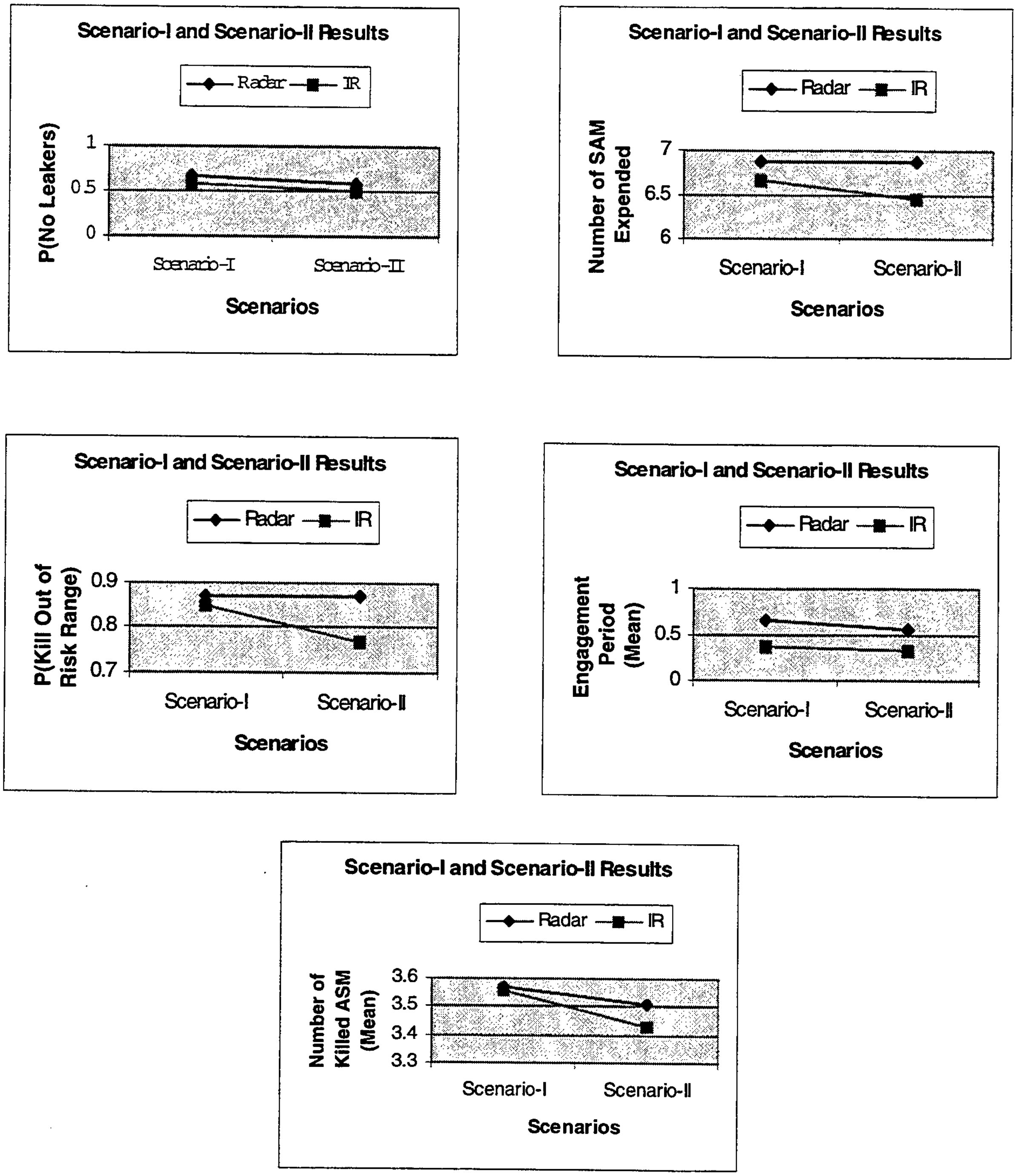

Figure 21. Plots of MOE's for the Radar and the IR Sensor for Scenario-I and Scenario-II.

The probability of no leakers value showed a decrease for the radar and the IR sensor in scenario-II. For the radar and the IR sensor, the probability of no leakers value in scenario-I is significantly higher than the probability of no leakers value in scenario-II (the radar p-value = 0.022, the IR p-value = 0.025). The radar had a significantly higher probability of no leakers value than the IR in scenario-II (p-value = 0.025).

The probability of kill out of risk range value of the radar did not show a change in scenario-II. However, the probability of kill out of risk range for the IR showed a significant decrease (p-value $\cong$ 0). The radar had a significantly higher probability of kill out of risk range value than the IR in scenario-II (p-value $\cong$ 0). This result could indicate that for scenarios that saturate the AAW system, the radar may be tactically preferred to the IR sensor due to its higher probability of kill out of risk range value.

The radar expended the same number of SAMs as in scenario-I. However, the IR sensor expended significantly fewer SAMs in scenario-II than the scenario-I (p-value = 0.019). In scenario-II the radar expended significantly more SAMs than the IR (p-value $\cong$ 0). Although, the mean number of SAMs expended is statistically significant, the small difference in means may not be tactically significant.

The mean engagement period showed a decrease for both sensor types in scenario-II. The radar had a higher mean engagement period than the IR because of its longer detection range. The radar's mean engagement period decreased to 0.56 from 0.65 and the IR sensor's mean engagement period decreased to 0.32 from 0.37.

The mean number of killed ASMs showed a decrease for both sensors. The change in mean number of killed ASMs between the scenarios for the radar was not statistically significant (p-value=0.077). However, the IR sensor killed significantly less ASMs in scenario-II than in scenario-I (p-value=0.0162). As shown, the radar killed significantly more ASMs than the IR in scenario-II (p-value=0.028). However, the mean difference of 0.08 ASM killed may not be tactically significant.

VI. CONCLUSIONS AND FUTURE RESEARCH AREAS

A. GENERAL

Today's high-speed technological changes and their impact on AAW provide a challenge to AAW acquisition planners who are already under tight budgetary constraints. The need for innovative analysis tools that are both flexible and reusable is crucial. Simulation is one of the most employed tools for AAW analyses. However, building simulation models in traditional ways is still costly, especially for countries with small budgets.

This thesis develops a model as an analysis tool to measure the effectiveness of radar and IR sensors in AAW area defense. The model is designed to support reuse, provide easy model configuration, flexibility and scale changes. A component-based simulation approach was adopted for this model using the JAVA™ programming language to provide the necessary scalability and flexibility. In addition, a small combat component library was constructed for future research. The source code of the model can be obtained from the following web-site: "http://diana.or.nps.navy.mil/~ahbuss/kulac/". To demonstrate the analysis capability of the model a comparative analysis was conducted for radar and IR sensor in the AAW area defense.

The results of the simulation runs indicate that the model provides a good capability for aiding decision making, including effectiveness analysis, parameter sensitivity analysis, and exploratory analysis.

B. SUMMARY OF COMPARATIVE ANALYSIS

Detecting low-altitude missiles is a great concern for all navies in the world. Radar is the primary surveillance asset onboard warships. However, radar has difficulty in detecting low-altitude anti-ship missiles due to the small radar cross-section of the ASM, clutter, electronic countermeasures and poor reception at low elevations over the water [Ref. 14]. Moreover, radar reduces the stealth of the Naval task force because of its active nature. Conversely, IR sensors improve the stealth of the naval task force because of their passive behavior. Using the SSD package, a demonstrative comparative analysis was conducted to measure the effectiveness of radar and IR in two AAW area defense scenarios. Approximately 10,000 simulation runs were conducted for analysis and test purposes. The following results were obtained from this research.

1. Scenario-I

In scenario-I (non-stressing), both sensor types provided basically the same AAW defense capability for the convoy. The following specific conclusions were derived from the comparative analysis:

- The probability of the no leakers was 0.99 for both sensors.
- All the missile engagements were conducted outside the risk range.
- The earth's curvature effect was the limiting effect for the sensor detection range especially for the radar. Since, a sensor

height of 65 feet was used for the trials the radar horizon range is approximately 16 NM for an ASM flying at an altitude of eight meters. Although the maximum detection range of radar is 21 NM its capability can not be fully utilized in either scenario.

2. Parameter Sensitivity Analysis

Since both systems provided a good protection to the convoy (P(No Leakers)=0.99), the number of trackers and the number of convoy ships parameters were not changed. However, to see the effects of SAM's probability of kill and launch range changes, another set of exploratory runs were conducted. In these runs, the number of convoy ships and the number of trackers were fixed at two and the probability of kill values of 0.85, 0.6,0.5 and the range values of 16, 12, 9 NM were used for each sensor type. Additionally, a suitable distance between ships value was investigated for the SAM kill probability value of 0.5 Following results were obtained from the exploratory runs:

- The SAM's maximum launch range had either minimal or no effect on the simulation results.
- The two systems showed similar results where the SAM's kill probability value is 0.85. However, for the SAM's kill probability values of 0.6 and 0.5, the radar provided better protection for the convoy.

- The distance between the ship's can be extended to four NM for the IR and five NM for the radar without degrading the AAW system effectiveness.

3. Scenario-II

In scenario-II, a more stressful situation was modeled, where the AAW system is saturated. Simulation runs were conducted for SAM kill probabilities of 0.85 and 0.5. Scenario-II simulation runs showed that the two sensor types again provided the same effectiveness. However, the radar and the IR's performance decreased as the SAM's probability of kill value decreased to 0.5. In this case the radar provided better protection for the convoy.

4. Scenario Comparison

The IR sensor has a mean detection distance of 10 NM and the radar has a mean detection distance of 15 NM. This difference does not cause significant change in AAW defense effectiveness for the scenarios with high SAM kill probabilities (0.85), since the SAM has a very high speed. However, for lower SAM kill probabilities (0.6 and 0.5), especially in dense scenarios, for example, scenario-II, the radar performs better than the IR.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

The SSD package is designed to conduct a variety of analyses in different naval warfare environments. It is one of the first steps of the combat simulation component library and provides a base structure for advanced combat analysis. The following modeling areas should be researched for improvement of the SSD package, including the additions of more components to the library.

- Currently, the motion of the objects is modeled by uniform linear motion in the SSD package. To obtain more realistic results, the motion of the objects should be modeled by non-linear motion.
- A detection algorithm that explicitly considers the radar cross-section of the targets should be developed. This will provide more sensitive results.
- Seekers of the missiles and different types of SAM's, e.g., active SAM's, should be modeled to improve the model capabilities. The ASM's and the SAM's were not modeled in detail in the SSD package.
- Algorithms for integration of different sensors, e.g., radar and IR sensor (sensor cueing) and for multiple targets tracking should be developed to increase the capability of the model.
- Models of different tracker components to analyze different missile guidance systems and tracker behaviors should be developed to enhance the capabilities of the model.
- Track correlation and weapons coordination algorithms for naval task forces that contain multiple AAW ships should be developed to increase the scale of the model.
- Modeling of close-in weapon systems and soft-kill methods to conduct a full scale AAW defense analysis should be developed to increase the resolution of the model.
- Research on the integration of the radar and IR sensors is a good area for model development and analytic exploration.

APPENDIX A. CONTINUOUS APPROXIMATION TO DISCRETE LOOKING MODEL

This appendix shows the derivation of time to detect by using inverse transform method [Ref. 15].

Assumptions:

1. Uniform linear motion of target.
2. Instantaneous detection rate is inversely proportional to the square of the distance from the sensor.

Objective:

1. Probability distribution of time to detect.
2. Inverse transform method to generate time to detect.

Distribution of Time to Detect:

Let $r_T(t)$ be the distance from the target to the sensor at time t and assume that at time t = 0 the target has just entered the sensor's range.

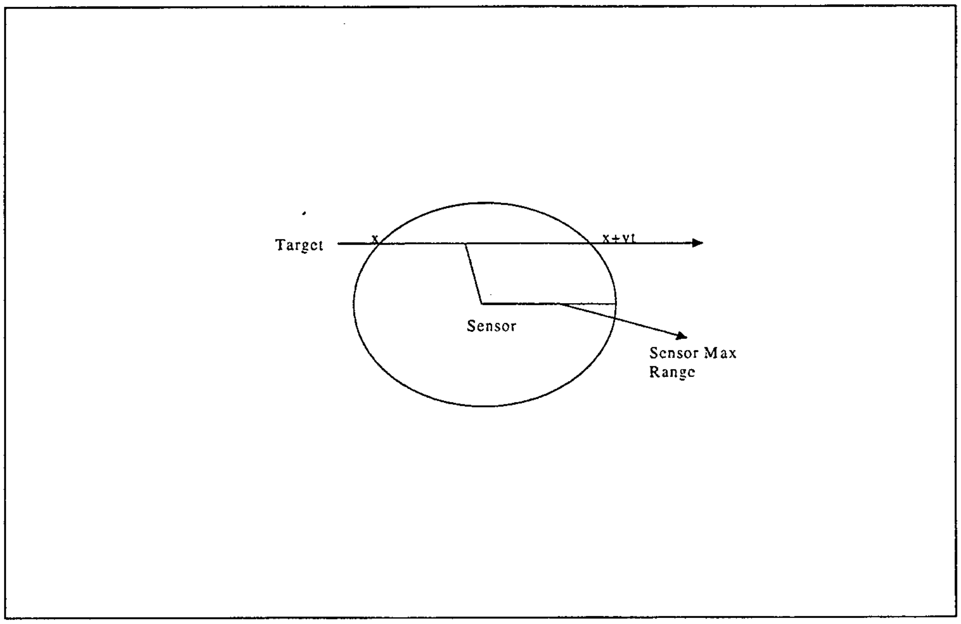

Figure A1. The Interaction between Sensor and Target.

Then, the complementary cdf of the time to detection T_D is:

$$\overline{F}_D(t) = \Pr\{T_D > t\} = \exp\left\{-\int_0^t \frac{\alpha}{r_T(x)^2}\right\} \tag{1}$$

Where α is the proportional constant for the instantaneous detection probability. Assuming uniform linear motion, target is at position x + tv, x is the position when the sensor enters the range and v is its velocity. In this case, we have

$$r_T(t)^2 = \|v\|^2 t^2 + 2(x.v)t + \|x\|^2, \tag{2}$$

so that

$$\int \frac{dq}{r_T(q)^2} = \frac{1}{\sqrt{\|x\|^2\|v\|^2 - (x.v)^2}} \tan^{-1}\left(\frac{t\|v\|^2 + x.v}{\sqrt{\|x\|^2.\|v\|^2 - (x.v)^2}}\right) \tag{3}$$

The ccdf $\overline{F}_D(t)$ is therefore,

$$\overline{F}_D(t) = \exp\left\{-\frac{\alpha}{\sqrt{\|x\|^2\|v\|^2 - (x.v)^2}}\left[\tan^{-1}\left(\frac{t\|v\|^2 + x.v}{\sqrt{\|x\|^2\|v\|^2 - (x.v)^2}}\right) - \tan^{-1}\left(\frac{x.v}{\sqrt{\|x\|^2.\|v\|^2 - (x.v)^2}}\right)\right]\right\} \tag{4}$$

Now, the ccdf in Equation (4) shows that T_D is a defective random variable that has $P_\infty = \Pr\{T_D = \infty\} = \lim_{t\to\infty} \overline{F}_D(t)$. Applying this to Equation (4)

$$P_\infty = \exp\left\{-\frac{\alpha}{\sqrt{\|x\|^2\|v\|^2 - (x.v)^2}}\left[\frac{\pi}{2} - \tan^{-1}\left(\frac{x.v}{\sqrt{\|x\|^2\|v\|^2 - (x.v)^2}}\right)\right]\right\} \tag{5}$$

We can interpret P_∞ as the probability that a detection never occurs even if the engagement has an infinite duration. Now we can generate T_D using time-honored inverse transform method as follows.

1. Generate U~Un (0,1)
2. If U < P_∞, return $T_D = \infty$
3. Else return $T_D = \overline{F}_D^{-1}(U)$

Here, P_∞ is given equation (5) and $\overline{F}_D^{-1}(U)$ is in Equation (6) below:

$$\overline{F}_D(u) = \frac{\sqrt{\|x\|^2\|v\|^2 - (x.v)^2}}{\|v\|^2}\tan\left[-\frac{\log u\sqrt{\|x\|^2\|v\|^2 - (x.v)^2}}{\alpha} - \frac{x.v}{\|v\|^2}\right] \tag{6}$$

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