AIR DEFENSE INITIATIVE
AIR-TO-AIR ENGAGEMENT ANALYSIS

VOLUME 1: PROBLEM DEFINITION, SOLUTION FORMATION, ILLUSTRATIVE RESULTS AND RECOMMENDATIONS

8 March 1991

Synetics

Synetics

TR-535-1

AIR DEFENSE INITIATIVE
AIR-TO-AIR ENGAGEMENT ANALYSIS

VOLUME 1: PROBLEM DEFINITION, SOLUTION FORMATION, ILLUSTRATIVE RESULTS AND RECOMMENDATIONS

8 March 1991

Accession For	
NTIS GRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

Covering the period:

31 January 1990 - 8 March 1991

Prepared under Contract No. DCA100-90-C-0031 for the Defense Communications Agency

Prepared by:

Richard D. Healy
Joseph M. Covino
Barry E. Griffiths

540 Edgewater Drive • Wakefield, MA 01880 • (617) 245-9090 • Fax (617) 245-6311

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
8 March 1991

3. REPORT TYPE AND DATES COVERED
Final 31 Jan 90 - 8 March 91

4. TITLE AND SUBTITLE
Air Defense Initiative Air-to-Air Engagement Analysis
Volume 1: Problem Definition, Solution Formulation, Illustrative Results and Recommendations

5. FUNDING NUMBERS
(C) DCA100-90-C-0031

6. AUTHOR(S)
Richard D. Healy, Joseph M. Covino and Barry E. Griffiths

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SYNETICS Corporation
540 Edgewater Drive
Wakefield, MA 01880

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-535-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
JDSSC/JNSV
Defense Communications Agency
Washington, DC 20305-2000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
This is volume one of a three volume final report

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified/Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This document presents the final results of an analysis of the effectiveness of a U.S. interceptor long-range defense force to defend against the cruise missile threat in the 2005 time frame. Contract effort focused on two related issues: formulation of the problem to permit examination of advanced surveillance and communication technology potentially defining a "cooperative engagement" concept, and a top-down approach to architecture modeling of the current and emerging generation air-to-air missiles. Preliminary results using unclassified data validate the approach.

14. SUBJECT TERMS
Cooperative Engagement
Air-to-Air Missile
Cruise Missile
Air Defense

15. NUMBER OF PAGES
70

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Synetics

17 June 1991

DTIC
Attn: Acquisition Section/Lachance
Cameron Station, Building 5
Alexandria, VA 22304

Dear Mr. Lachance,

As per your request, two unbound copies of each of three volumes of our report entitled "Air Defense Initiative Air-to-Air Engagement Analysis" is enclosed. The Report Documentation Page is provided with each volume.

If you could provide me with the AD numbers of these reports I would greatly appreciate it.

Thank you for your assistance in this matter.

Sincerely yours,

Joseph M. Covino
Manager
Strategic Systems Division

JMC/jf

Enc.

540 Edgewater Drive • Wakefield, MA 01880 • (617) 245-9090 • Fax (617) 245-6311

ACKNOWLEDGEMENT

This report was prepared under the direction of the Deputy Director, NMCS ADP by *SYNETICS* Corporation under Contract Number DCA100-90-C-0031 to the Defense Communications Agency.

(This page is intentionally left blank)

ABSTRACT

This document is the final report of an analysis of the effectiveness of a U.S. interceptor long-range defense force to defend against the cruise missile threat in the 2005 time frame, conducted by ***SYNETICS*** Corporation, and its subcontractors, Vitro Corporation and Veda Inc., under contract DCA100-90-C-0031 with the Defense Communications Agency. Contract effort focused on two related issues: formulation of the problem to permit examination of advanced surveillance and communication technology potentially defining a "cooperative engagement" concept, and a top-down approach to architecture modeling of the current and emerging generation of air-to-air missiles. Preliminary results using unclassified data validate the approach.

The other volumes of this report include:

Volume 1	Problem Definition, Solution Formulation, Illustrative Results and Recommendations
Volume 2	Detailed Error Models and Simulation Formulation for Case I: Pre-Launch Coordination without Post-Launch Updates
Volume 3	Simulation Tools: Current Status and Recommendations for Future Development

(This page is intentionally left blank)

EXECUTIVE SUMMARY

Problem Statement

Current air defense systems are not limited by physical inability to achieve a reasonable probability of kill against Low Slow Cruise Missile (LSCM) threats. Rather, the current low rate of information transfer from surveillance platforms to fighters, coupled with the relatively small search volumes of fighter fire control radars, leads to a relatively long time required to engage each threat cruise missile. Since the time available to each Long Range Defense Force (LRDF) to destroy the threat missiles is measured in minutes, it is the time line that controls the effectiveness of air-to-air cruise missile defense. In the case of High Fast Cruise Missile (HFCM) threats, physical reachability and time line considerations both represents serious constraints.

As defined, the problem is not one of individual platform capability but rather one of total force effectiveness potentially realizable by using the cooperative engagement concept. The intent of the cooperative engagement concept is to remove the engagement time limitation by making it possible to use sensor data other than the launch platform fire control radar to target threat missiles. In essence the targeting capability of a surveillance platform is used to hand the engagement to a launch platform which has not yet acquired the target. This may require improvements to surveillance sensor systems, navigation systems, fire control systems (FCS) and interceptor missiles; changes to the data contents of communications links; and automated communciations interfaces to the system components.

The air intercept missile (AIM) must be capable of acquiring the target based on pre-launch or in-flight targeting information and onboard sensor processing. This essentially eliminates AIM-7 and AIM-9 and requires a certain evolution for the AIM-120 AMRAAM. These considerations forced this study to concentrate on "notional" missile systems using a top-down rather than a bottoms-up modelling approach.

The scenario depicted in Fig. A represents one possibility for a cooperative engagement architecture designed for the cruise missile defense role. An E-3 surveillance aircraft, or successor, would automatically maintain target tracks internally. A digital communication link such as JTIDS Class 2 would supplement the current voice channel, providing target data to the defense fighters with minimal data latency or loss of precision. An upgraded fire control system on the fighters would track multiple targets simultaneously, on the basis of both own-platform data and all available data. The fighter pilot would select the fire control data set (own-platform or all-data), and would fire the interceptor missiles. When AMRAAMs are used, the current fighter-to-missile data link would be used to periodically update the targeting data. As in current AMRAAM intercepts, the onboard seeker would control the AMRAAM after seeker turn-on.

This architecture, if feasible, would have several advantages. First, it allows a simultaneous multi-target tracking and targeting capability (the E-3 already tracks a large number of targets). Second, it preserves a reasonable allocation of responsibilities: tracking and ground control

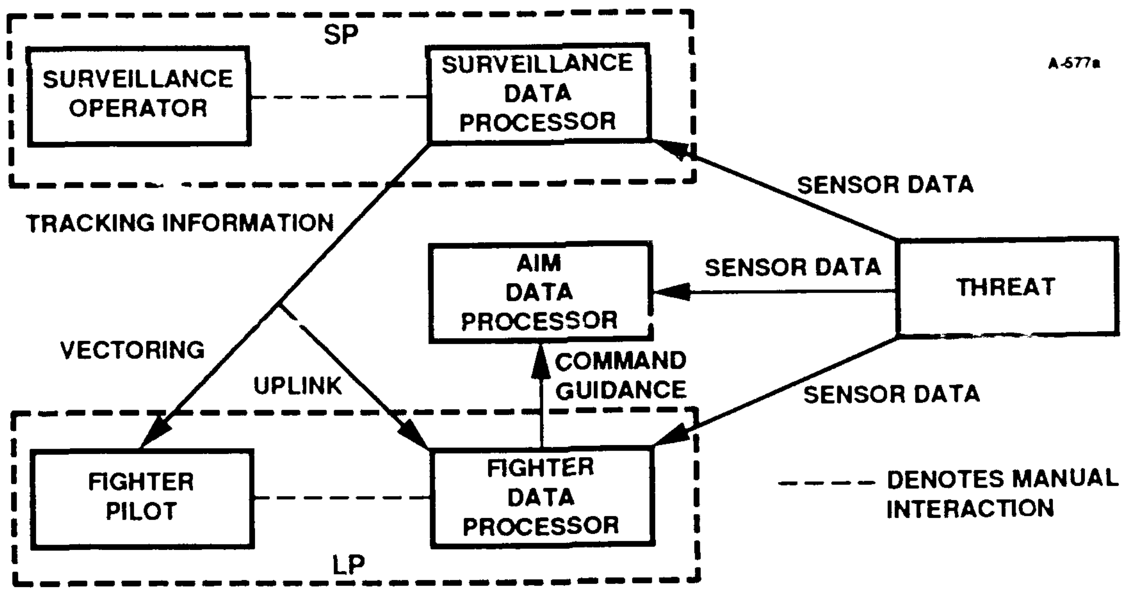

Figure A Possible Cooperative Engagement Architecture

functions are on the surveillance platform, while firing decisions are on the fighter. Third, potentially dangerous mode-control changes and coordination issues are avoided; the E-3 does not need to know which cruise missile a fighter is targeting, or when an interceptor is launched. Fourth, this architecture allows the fusion of all available data, rather than locking out the fighter's fire control radar. Fifth, the architecture offers the possibility of launch-and-leave operation, since AMRAAM updates could be made from E-3 data even if launch-time targeting included FCS data. Sixth, relatively few major new systems are required.

It should be emphasized this architecture was developed for illustrative purposes. While it may eventually prove to be a useful approach, significantly more analysis will be necessary to determine whether it is technically feasible, and whether it significantly improves operational effectiveness.

Problem Partitioning

We have made significant progress in developing a methodology to assess the operational effectiveness of cooperative engagement technologies. The methodology requires substantial use of sensitivity analysis to determine the combinations of critical parameters that will enable significant improvements in effectiveness. In order to apply available resources most effectively, the methodology also calls for partitioning the problem into three sub-problems: tracking/flyout, endgame, and few-on-few engagement. The results of the endgame analysis can be combined with the results of the tracking/flyout analysis using the Chapman-Kolmogorov equation; the results of this combined single-shot performance analysis can be inserted into the few-on-few effectiveness analysis as a parameter subset.

The tracking/flyout analysis can be performed as a direct covariance analysis, and some of the necessary models are described in this report. The endgame analysis can be performed either as a direct Monte Carlo simulation or through semi-analytic methods. Although we originally proposed to use high-fidelity Monte Carlo simulations, our work to date has shown that this approach is both too constrained, because they represent current point designs, and too expensive for use in identifying enabling technologies. It now appears that the most effective approach to endgame analysis for this study is to modify existing semi-analytic methods to our requirements, and to use high-fidelity Monte Carlo simulations only for limited benchmarking. Existing Government AMRAAM simulations would appear to be good candidates for such high-fidelity benchmarks.

Technology Insights

Standard tracking algorithms coupled with nominal SP surveillance platform (SP) accuracy was inadequate to localize target altitude sufficiently to produce an acceptable engagement for the scenarios considered. This led to a modification in the evaluated tracking algorithm to incorporate intelligence information about likely flight profiles which dramatically improved performance. Such modifications may have significant payoff against cruise missiles. They are well within the current state-of-the-art and involve only minor software changes to the tracking algorithms, but they are likely beyond the state of current practice.

For cases in which error parameters are roughly comparable, there appears to be an interesting interaction between SP orientation and launch platform (LP) firing direction. This suggests that the fire control solution, target selection, and engagement planning function can benefit significantly from the use of information about track quality. Since such data are too voluminous for voice transfer, a data channel is required to the LP. Moreover, these interactions demonstrate that there is value in examining how the various players (e.g., SP and LPs) are arranged on the battlefield. Finally, rapid solution of potential engagement values may require use of parallel or multi-processors in the FCS, and presentation of results to the flight crew may require enhancements in data presentation.

The data suggest that it is frequently the case that a longer intercept missile time-of-flight resulting in an end-game approach from a preferred direction results in higher effectiveness than a shorter direct path from a poorer direction. Such a trajectory shaping implementation would probably require changing the FCS software, but it should not require significant hardware changes for AMRAAM and beyond.

TABLE OF CONTENTS

PAGE NO.

TABLE OF CONTENTS (Continued)

PAGE NO.

LIST OF FIGURES

(This page is intentionally left blank)

LIST OF TABLES

(This page is intentionally left blank)

1. INTRODUCTION

This report is Volume 1 of the final report for Contract No. DCA100-90-C-0031 delivered in fulfillment of CDRL item TBD. The contract requires a methodical analysis of the capabilities of a US air battle group to protect CONUS against the current and projected cruise missile threat in the 2005 time frame. It provides for a series of analyses:

- Detailed endgame modeling for air-to-air missile defense against cruise missiles
- Examination of the potential for improving operational effectiveness through a potentially revolutionary concept known as "cooperative engagement"
- Evaluation of further interceptor missile and control system improvements suggested either by study team members or by Government personnel.

The contract provides detailed taskings for the base year and first option year, but it is written as a task ordering contract with provisions for modifying activity in response to study findings and external events.

The contract was awarded to a team headed by ***SYNETICS*** with subcontracts to Vitro Corp. and Veda, Inc. after detailed technical discussions and a formal proposal in accordance with the provisions for contracting with minority, subchapter 8(a) small businesses. Initial discussions began in May 1989. The effective date of the contract is 23 Jan 90.

1.1 OVERVIEW OF CONTRACT ACTIVITY

In accordance with the Statement of Work and the evaluated technical proposal, ***SYNETICS*** began working with Vitro and Veda to determine exactly how all of the proposed analyses fit together to meet the study objective. At the same time, Vitro began to develop a detailed endgame model of the AIM-7 Sparrow missile, and ***SYNETICS*** began to develop models for guidance and tracking errors. The parallel development was a result of schedule pressure identified both in the detailed technical briefings and in the technical proposal to achieve an air-to-air missile modeling capability for several US air interceptors in the base year.

As the work progressed, our understanding of the Government's underlying concern has grown. In particular, we have gained an appreciation of what is already known, what is suspected but not verified, and what yet needs to be determined.

As a result of significant earlier studies, it is apparently generally understood that current-generation air-to-air missile systems defending against cruise missiles permit unacceptably high numbers of leakers in the saturation environment which the potential adversary can generate. It is suspected that improved integration between the surveillance systems and engagement systems -- the "cooperative engagement" concept noted above -- may be the key to increased effectiveness (i.e., reducing leakers) by cutting the time needed for each shot. What has not been determined is the set of technologies and parameters that would lead to significant improvements through such a concept, and what apparent benefits would accrue in realistic operational scenarios.

We began this effort using a bottom-up approach beginning with detailed modeling of current and emerging generation air-to-air missiles. As the study evolved, it became clear that a top-down requirements-definition analysis was needed. The detailed modeling effort was suspended in July 1990. Instead, ***SYNETICS*** undertook to develop an architecture evaluation model capable of providing "lower bound" estimates of performance (i.e., for a given set of components and communications links, what is the best that can be achieved) as a tool to identify pacing technical issues within the cooperative engagement framework.

In early December, ***SYNETICS*** was notified by DCA personnel that funding would not be available for the second year of the contract due to budget constraints. As a result, it was much more desirable that the methodology and tool set be documented than that preliminary results be obtained for current systems. As an aid in the documentation and to prohibit unnecessary restriction of the report, no classified data were used in any of the evaluation scenarios. Instead, all parameters were obtained from strictly unclassified data sources.

1.2 ORGANIZATION

Section 2 contains a brief review of the relevant threat and defense systems. Defense systems are broken out as surveillance platforms (Section 2.1), the F-16 air defense fighter (Section 2.2), and the various air intercept missiles (Section 2.3).

Section 3 introduces the notion of cooperative engagement. This concept, broadly construed, has some base in experience; this is reviewed in Section 3.1. A discussion of the utility of the concept to cruise missile defense is contained in Section 3.2, and the consequences for the usefulness of current defense system components in that framework are discussed in Section 3.3. A candidate cooperative engagement architecture, making significant use of current technology, is presented in Section 3.4 as an example of the kind of integrated system that might be useful in cruise missile air defense. The analytic issues involved in evaluating such a cooperative engagement architecture are defined in Section 3.5.

Section 4 addresses the question of evaluation methodology. The fundamental measures of effectiveness are reviewed in Section 4.1, and the notion of partitioning the whole problem into connected sub-problems is explored in Section 4.2. The top-level structure of the tracking/flyout and endgame sub-problems in the context of cooperative engagement is discussed in Section 4.3. In Section 4.4, the idea of a top-down analysis driven by successively tighter lower bounds is suggested.

In Section 5, we discuss the planned study. Section 5.1 contains the principle Cooperative engagement cases to be analyzed over the course of the full study. Section 5.2 discusses our implementation of Case I during this study year, and Section 5.3 contains initial results.

Section 6 presents findings and conclusions from the first year effort. Section 6.1 addresses the air defense problem, and Section 6.2 addresses specific technology issues.

Section 7 contains recommendations for future work. It is subdivided into recommendations in the ADI problem arena and in related areas, Section 7.1 and 7.2, respectively.

(This page is intentionally left blank)

2. BACKGROUND: THREAT AND DEFENSE SYSTEMS

2.1 THREAT MISSILES

The threat missiles under consideration are those that have been previously called out by the Government as being of interest in the air-to-air cruise missile defense problem. This section presents the design parameters of these threat missiles that are of interest in the defense problem. Note that the cited parameters are those available from some elements of the open literature; other estimates may differ. On the basis of available information, the threats appear to be classifiable as either Low Slow Cruise Missiles (LSCMs) or High Fast Cruise Missiles (HFCMs). Within each class, current-generation, low-observable (LO), and very-low-observable (VLO) threats can be accommodated by considering radar cross-section (RCS) as a parameter to be varied.

AS-15 Kent

The Kent is an air-breathing, turbofan powered, low altitude air launched CM equivalent to the US Tomahawk. Launch is expected from the Tu-95Bear-H bomber and Tupolev Blackjack supersonic bomber. Depending on the source the missile may have a range of 648 nm or 1620 nm. A 200 kton warhead has been quoted. Terrain matching guidance similar to TERCOM is employed with a CEP of 150 ft. The missile has a length between 23 ft and 26.5 ft, a diameter of 1.7 ft and weight 3818 lbs. (Refs. 1,2,3,5)

AS-X-19

This missile is an air launched long range CM currently in development. It may be 40 ft in length and launched from the Bear H bomber.

ERALCM

The Extended Range Air Launched Cruise Missile is closely related to the SS-N-21.

SS-NX-21

This is a submarine launched CM that is similar to the U.S. Tomahawk. The 'X' in the designator signifies this system is still in the developmental stage. The Akula, Sierra and Victor III classes are expected launch platforms. It is expected that this missile is being designed for launch from standard submarine tubes in which case a diameter of 1.7 ft. It may be 23 ft long. An air-breathing turbojet power plant with a solid propellant rocket is expected yielding a range of 1620 nm and speeds of Mach 0.7. Inertial guidance is also anticipated. The Akula, Sierra, Mike and Victor III classes are expected launch platforms. This missile is the sea launches variant of the AS-15 Kent. (Refs. 1,2,3,5)

SS-NX-24

This is a submarine launched long range CM which may already be operational. A Yankee class submarine has been converted into a test platform. The missile may be 39 to 43 ft long. (Ref. 3)

ERSLCM

The Extended Range for Launched Cruise Missile is closely related to the AS-15.

2.2 CRUISE MISSILE DEFENSE SYSTEMS

Under current thinking, the basic unit of air-to-air cruise missile defense is to be the Long Range Deployment Force. Such a unit will consist of a surveillance platform plus two to six fighters, each armed with a mix of weapons. The surveillance platform might be an E-3 Airborne Warning And Control System (AWACS) aircraft or some E-3 successor. The fighters will be the Air Defense Fighter variant of the F-16. Weapons on the fighters will include some combination of the AIM-9 Sidewinder, the AIM-7 Sparrow, the AIM-120 Advanced Medium-Range Air-to-Air Missile (AMRAAM), and the Advanced Air-to-Air Missile (AAAM), in addition to cannon.

2.2.1 Surveillance Platforms

The primary current airborne surveillance platform for the USAF is the E-3 AWACS aircraft, which became operational in 1978. It is based on the KC-135 (Boeing 707) airframe. The E-3 employs a radar that is housed in a rotodome to allow mechanical scanning in azimuth. The scan rate is 6 rpm, allowing the E-3 to update its tracks every 10 sec. Operators on board the E-3 interpret the data on their consoles, and advise operational units (primarily by voice) over some 20 radio links. (Ref. 3)

Upgrades to the E-3, including the Block 30/35 upgrade now in progress, have added improved radar signal processing, improved computer capacity, and various Electronic Support Measures (ESM) capabilities. A Global Positioning System (GPS) receiver and a Joint Tactical Information Distribution System (JTIDS) Class 2 terminal are to be added as part of Block 30/35, significantly improving the E-3's navigation and communications capacities. One analysis indicates that use of JTIDS Class 2 would allow the E-3 to communicate up to 1500 track updates per 10 sec cycle. (Ref. 7)

The Navy E-2 aircraft is a smaller, carrier-based AWACS intended for fleet operations. It also employs a rotodome. Due to its different mission and smaller airframe, it is generally somewhat less capable than the E-3 of tracking small targets at long distance. (Ref. 3)

Various alternatives to the E-3 and E-2 have been suggested in the open literature. These alternatives include:

- An E-3 successor based on a conventional fixed-wing airframe possibly including the Swedish Erieye aircraft (Ref. 8)
- The Airborne Endurance Vehicle (AEV), an autonomous, unmanned fixed-wing aircraft with two-week time aloft, carrying several conformally-mounted sensors (Ref. 9)
- Several aerostat and blimp concepts, either carrying a conventional radar or with a phased-array radar mounted on the gas bag.

None of these systems has yet reached full-scale development.

2.2.2 F-16 Air Defense Fighter

The F-16 has been selected as the air defense fighter for the air-to-air cruise missile defense role. Therefore, no other fighters will be considered in this analysis unless the Government so desires.

The F-16 was designed as an agile, lightweight single-seat fighter with limited active radar capabilities. While active radar has been upgraded since the F-16 entered service, it is somewhat limited in capability compared to the F-15. In addition, the F-16 is somewhat limited in the amount of external ordnance it can carry, due to its relatively small size. (Ref. 10)

Some proposed F-16 successors would increase the ordnance capacity. For example, the Falcon 21 could accommodate up to four semi-submerged AMRAAMs plus two Sidewinders. This design might still be ordnance-constrained in the cruise missile defense mission.

General Dynamics has suggested the so-called "Pomona pod" as a way of allowing the F-16 to carry more ordnance into combat. Each pod could accommodate up to 10 AMRAAMs, with one pod under each wing. While this would presumably have negative consequences with respect to speed, agility, and observability, the payoff of the increased ordnance load may outweigh these factors for the cruise missile defense mission. Quantification of benefits must account for the number of threat missiles, the duration of the engagement, the time taken to engage each threat missile, and the probability of kill for each missile.

2.2.3 Interceptor Missiles

This section describes the characteristics of United States interceptor missiles.

AIM-9 Sidewinder

The AIM-9 Sidewinder relies on infrared homing. It travels at about Mach 2.5 at all aircraft altitudes and has a maximum range of 4.1 nm. It is powered by a single solid propellant rocket. The Sidewinder uses active optical proximity fuzing and 20 lbs of high explosive annular blast fragmentation warhead. The missile's length ranges from 9.5 to 10.2 ft, its wingspan varies between

1.9 and 2.1 ft, and weighs between 170 and 191 lbs depending on the variant. All variants have a diameter of 0.4 ft. (Refs. 1,2,3)

AIM-7 Sparrow

The AIM-7 Sparrow relies on semi-active radar homing of the launch aircrafts radar reflected from targets up to 100 km away. It travels at Mach 4 at all aircraft altitudes and has a range of 52 nm. It is powered by a single Mk 58 mod 3 solid propellant rocket. Fuzing includes both proximity and direct fuzes. An 88 lb continuous rod warhead packs the punch. The missile is 12.1 ft long, 0.7 ft in diameter with a wingspan of 3.3 ft. It weighs just over 500 lbs. (Refs. 1,2,3)

AIM-120 AMRAAM

The AIM-120 AMRAAM is a fire-and-forget missile that can engage up to eight targets when linked to the launching aircrafts track while scan (TWS) radar The launching platform provides inertial reference data on the target and itself to initialize the guidance system. Additional target updates can be sent during flyout, modifying the inertial command guidance. Terminal flight homing is based on a small active radar. This missile travels at speeds in excess of Mach 4 at an altitude up to 65 kft for a maximum range of 35 nm. It is powered by a single solid propellant rocket. Both proximity and contact fuzing are used. It contains 50.6 lbs of high explosive prefragmented warhead. The missile is 12.0 ft long, 0.6 ft in diameter with a wingspan of 2.1 ft. It weighs about 340 lbs. (Refs. 1,2,3)

AAAM

The AAAM is currently in the demonstration and validation test phase. Two teams are competing: General Dynamics/Westinghouse and Hughes/Raytheon. The GD team proposes semi-active guidance with a single solid propellant rocket; H/R proposes a ramjet powered missile with active radar guidance. The missile is expected to have a diameter of 0.75 ft, to weigh about 674 lbs, to obtain speeds of Mach 3 and to have a range in excess of 81 nm. (Refs. 2,3,4)

2.3 ABILITY OF DEFENSE SYSTEMS TO ENGAGE THREAT MISSILES

The defense systems outlined in Section 2.2 have varying abilities to engage the threat missiles considered in Section 2.1. For a missile-based air-to-air defense to work at all, interceptor missiles must be capable of reaching the threat cruise missiles. This reachability criterion will be addressed in Section 2.3.1. However, while reachability is a necessary condition for a successful engagement, it is not sufficient. In Section 2.3.2, other factors in a successful engagement are discussed.

2.3.1 Interceptor Missile/Threat Missile Reachability

The ability of the interceptor missiles described in Section 2.2.3 to reach the cruise missiles described in Section 2.1 is summarized in Table 2.3-1. It can be seen from an examination of Sections 2.1 and 2.2 that current-generation interceptor missiles are capable of reaching Low, Slow Cruise Missiles (LSCMs), once the fighter has acquired the threat missile and developed a good fire control solution.

TABLE 2.3-1

ONE-ON-ONE EFFECTIVENESS AGAINST CRUISE MISSILES

INTERCEPTOR	CURRENT TARGET		ENHANCED THREAT (LO/VLO)	
	LOW SLOW	HIGH FAST	LOW SLOW	HIGH FAST
AIM-7	EFFECTIVE; LIMITED BY SEEKER ACQUISITION	AERO/PROPULSION LIMITED	POSSIBLY EFFECTIVE; SEEKER ACQUISITION LIMITATIONS MORE SEVERE	AERO/PROPULSION LIMITED
AIM-9	EFFECTIVE; LIMITED BY SEEKER ACQUISITION	AERO/PROPULSION LIMITED	POSSIBLY EFFECTIVE; SEEKER ACQUISITION LIMITATIONS MORE SEVERE	AERO/PROPULSION LIMITED
AIM-120	EFFECTIVE; LIMITED BY FIGHTER FCS ACQUISITION	AERO/PROPULSION LIMITED	PROBABLY EFFECTIVE; FCS ACQUISITION LIMITATIONS MORE SEVERE	AERO/PROPULSION LIMITED
AAAM	EFFECTIVE; LIMITED BY FIGHTER FCS ACQUISITION	EFFECTIVE; LIMITED BY FIGHTER FCS ACQUISITION	PROBABLY EFFECTIVE; LIMITED BY FCS ACQUISITION	PROBABLY EFFECTIVE; FCS ACQUISITION LIMITATIONS MORE SEVERE

On the other hand, it can be seen that current-generation interceptor missiles cannot reliably engage High, Fast Cruise Missiles (HFCMs). The limitations of the interceptor missiles that prevent them from reaching HFCMs are basically those of airframe and propulsion system. Thus, the AIM-7, AIM-9, and AIM-120 cannot be expected to reach HFCMs even with upgrades.

The next-generation air intercept missile, AAAM, should be capable of reaching HFCMs in addition to LSCMs.

2.3.2 Relationship to Operational Effectiveness

We have seen in the preceding section that current-generation AIMs have the physical ability to engage LSCMs, and that the AAAM should have the physical ability to engage HFCMs, on a single-shot basis.

However, in order to take that shot, the fighter pilot must be vectored toward the threat missile, acquire the threat missile with his onboard sensors, launch the missile, and remain to update the missile (with the fighter's illuminator, in the case of the AIM-7; with uplinked commands, in the case of the AIM-120). Reachability says nothing about the time that this procedure consumes.

Operational effectiveness can be seen to encompass two areas, namely per-shot effectiveness and preparation time. A system that leads to a large number of threat missiles destroyed must have good performance in both areas. Some improved subsystems, such as improved communications, may make possible simultaneous improvements in both areas. Still, tradeoffs of single-shot performance for speed of preparation may be advisable.

Consider the example of a case where there are a large number of threat missiles, and a large number of available interceptor missiles. It may be possible to create shots with P_k of 0.9 in 5 min, or shots with P_k of 0.8 in 3 minutes. In a 30 min engagement, the former choice would lead to an expected result of 5.4 destroyed threats, while the latter would lead to an expected result of 8.0 destroyed threats.

It can be seen, then, that operational effectiveness does not depend solely on per-shot effectiveness, but also on:

- Threat scenario
- Available defensive ordnance
- Surveillance and communications assets
- Defensive tactics.

All of these issues require further definition in order to complete an assessment of operational effectiveness.

3. CONCEPT FORMULATION FOR COOPERATIVE ENGAGEMENT

3.1 CURRENT APPLICATIONS

The operational concept of today's air-to-air intercept engagements generally assumes that launch platforms act independently in engaging threats. That is, while they may be guided toward threats by Ground Control Intercept (GCI) operators, actual targeting data are derived solely from own-platform resources (for purposes of this report, "GCI" includes such resources as intercept capabilities based on the E-3 or E-2 aircraft). One reason for this is that the available methods for transferring data from a surveillance system to an engagement system have serious limitations with regard to information capacity and data latency. On the E-3 aircraft, for example, several different operators must read out information from their separate subsystems, coordinate a response, and direct fighters via a voice channel. This approach clearly limits the amount of surveillance platform data used in targeting.

There are certain systems today, demonstrated or under development, that envision the use of improved methods for multi-platform coordination that might allow the use of one platform's surveillance resources in targeting another platform's weapons. A demonstrated system is the Navy's "Forward Pass." Using this system, a Navy Standard Missile with semi-active homing is launched from one ship, and seeks its target using an illumination source located on a second platform. Forward Pass requires a high degree of interplatform coordination: Launch time and flyout trajectory must be coordinated with illumination scheduling and missile control logic. The advantage of this system is that platforms that cannot launch Standard Missiles (or have run out of reloads) can be used to designate targets for platforms with Standard Missiles, thereby improving engagement range and increasing the number of engageable threats.

A similar system is reportedly under consideration for the Advanced Air-to-Air Missile (AAAM). In this scheme, a semi-active AAAM could target a threat illuminated by another platform.

A significantly different approach is reportedly under consideration as an F-15 retrofit capability. In this scheme, digital data received via the JTIDS Class 2 (TADIL-J) communications system would be used to cue sensors and generate targeting solutions on an F-15. (The F-15 requirement for JTIDS is currently under review by Tactical Air Command.) Launches of interceptor missiles (such as AMRAAM) could be based in whole or in part on this remote data. The effectiveness of such a system would depend largely on the quality of the remote-based targeting solution, the effectiveness with which the data can be incorporated into the launch platform's fire control solutions, and threat actions during the interval between the time of validity of the surveillance data and the time the interceptor missile begins endgame. (Ref. 11)

3.2 UTILITY IN CRUISE MISSILE DEFENSE

This cruise missile defense application differs in several important respects from the standard air-to-air defense problem. These differences may mean that somewhat different considerations apply in determining the utility of cooperative engagement concepts.

First, the cruise missile threats under consideration have low radar cross sections. Even with current-generation threats, the range at which a fighter fire control radar can detect the threat is a more significant consideration than the flyout range of the interceptor missile. Future low-observable (LO) and very-low-observable (VLO) cruise missiles will make this issue more pronounced.

Second, current information suggests that the cruise missile threats do not have significant ECM or evasion capabilities. Thus, the problem in cruise missile defense simply involves finding the threats and attacking them; self-defense on the part of the defenders is not a major issue.

Third, current concepts call for a relatively small number of fighters (two to six) and a single surveillance platform to cover a relatively large area, containing a potentially large number of threats. Thus, large separations between defender aircraft are likely.

Fourth, the air-to-air cruise missile defense problem is time-constrained. Cruise missiles that have not been shot down do not turn to engage the interceptors; they proceed toward their targets. Thus, the primary role for air-to-air cruise missile defense is in destroying as many cruise missiles as possible offshore, before ground-based interceptors can be brought to bear and before the cruise missiles' targets are reached. If the defenders start to engage the cruise missiles 100 nm to sea, and the cruise missiles approach the coast at 0.8 Mach, then the useful period of the engagement is only 12.5 min.

Several conclusions are called for. First, current defensive systems cannot target cruise missiles at long range. Second, the major limitation on defense system effectiveness is not that cruise missiles escape interceptors that have been targeted on them, but that the fighters take too long to acquire and engage each cruise missile. Third, improved targeting systems tor this application must stress range and multiple-target capacity. Fourth, effective air-to-air cruise missile defense should be achievable with lower-rate, lower-quality targeting data then is required for defense against modern fighter aircraft.

Consider a system that would allow an illuminator on one platform to direct one home-all-the-way semi-active interceptor missile in a 4.0 Mach pursuit of an 0.8 Mach cruise missile from an initial range of 25 nm. This illuminator would be fully occupied with this one threat for approximately 50 sec, and could be expected to provide very high-quality targeting information and a very high probability of kill. In a 12.5 minute engagement, such a system could engage and kill up to 15 threats. This is useful, but not revolutionary.

Consider, instead, a system that would allow a tracking system on a surveillance platform to update or illuminate one target track per second, with a ten-second scan period. Thus, ten tracks could be maintained on an interleaved time-sharing basis. Clearly such a system would be inadequate to attack highly maneuverable fighters, but might very well provide sufficient data quality to attack non-jamming, non-evasive, low-dynamics cruise missiles. In a 12.5 minute engagement, such a system could engage and kill up to 150 targets, if sufficient interceptor rounds are available. Such a capability would be revolutionary.

3.3 APPLICABILITY OF CURRENT CRUISE MISSILE DEFENSE SYSTEMS

It can be seen that the various defense systems discussed in Section 2 have varying degrees of applicability to the cooperative engagement concepts described in Section 3.2.

There is no obvious means whereby an AIM-9 (Sidewinder) could be used in cooperative engagement situations. This heat-seeking, home-all-the-way missile needs to acquire its target before launch, and acquisition does not depend on any resources that can be loaded onto a second platform.

There appears to be relatively little advantage to be obtained for cruise missile defense by creating a means for an AIM-7 (Sparrow) launched by one fighter to home on a target illuminated by another fighter. Acquisition range would not be significantly improved, and neither would the number of targets simultaneously engaged. In a target-rich environment with no danger from the cruise missiles to the fighters, there is also no significant advantage to redirecting interceptor missiles after one fighter runs out of missiles.

The AIM-120, on the other hand, is a good candidate for cooperative engagement methods in intercepting Low, Slow Cruise Missiles (LSCMs). It already possesses inertial guidance and a targeting uplink capability. A complementary surveillance platform would be one that can track multiple cruise missiles simultaneously, at significantly longer range than the F-16 fire control radar, with an adequate combination of data quality and data rate to place the AMRAAM close enough to the cruise missile at local seeker turn-on to give a high probability of kill. The E-3, or a successor platform, may be able to fill this requirement. Note again that it may not be necessary for the surveillance platform to give the same quality tracking data as the F-16 fire control radar. As noted above, the cruise missile is an easier target to kill than a fighter once its low observability is overcome, and it may be acceptable to trade some single-shot probability of kill for an improved timeline.

The AAAM may be a good candidate for engaging High, Fast Cruise Missiles (HFCMs). A fully-active AAAM could be used for cooperative engagement of an HFCM in much the same manner as AMRAAM could engage LSCMs. A semi-active AAAM would require a long-range illuminator to be useful in a cooperative engagement approach to cruise missile defense. An AAAM illuminator on another fighter would have limited benefits, for the same reasons noted above in the discussion of the AIM-7. A long-range illuminator mounted on another (surveillance-type) platform could be a component of an E-3 successor, but is an unlikely retrofit to current-generation surveillance systems.

3.4 AN ILLUSTRATIVE COOPERATIVE ENGAGEMENT ARCHITECTURE

The system depicted in Fig. 3.4-1 represents one possibility for a cooperative engagement architecture designed for the cruise missile defense role. An E-3 surveillance aircraft, or successor, would automatically maintain target tracks internally. A digital communication link such as JTIDS Class 2 would supplement the current voice channel, providing target data to the defense fighters with minimal data latency or loss of precision. An upgraded fire control system on the fighters would track multiple targets simultaneously, on the basis of both own-platform data and all available data. The fighter pilot would select the fire control data set (own-platform or all-data), and would fire the interceptor missiles. When AMRAAMs are used, the current fighter-to-missile data link would be used to periodically update the targeting data. As in current AMRAAM intercepts, the onboard seeker would control the AMRAAM after seeker turn-on.

The hierarchical, decentralized filter structure suggested for this architecture is designed to ensure data integrity while ensuring that full use can be made of all available data. The filter should include error variables that account for misregistration between the surveillance platform and own-platform sensors. A strong candidate for implementation of this filter structure is the Net Information Approach (NIA), a decentralized Kalman filter developed by ***SYNETICS*** for Strategic Defense Initiative multi-platform sensor coordination problems (Fig. 3.4-2) (Ref. 12). Use of the NIA filter structure could result in significant data compression on the surveillance-to-fighter link with negligible loss of information content. Adoption of the NIA filter structure would also allow each fighter to share tracking data based on own-platform sensors with other platforms, if this should prove useful.

This architecture, if feasible, would have several advantages. First, it allows a simultaneous multi-target tracking and targeting capability (the E-3 already tracks a large number of targets). Second, it preserves a reasonable allocation of responsibilities: tracking and ground control functions are on the surveillance platform, while firing decisions are on the fighter. Third, potentially dangerous mode-control changes and coordination issues are avoided; the E-3 does not need to know which cruise missile a fighter is targeting, or when an interceptor is launched. Fourth, this architecture allows the fusion of all available data, rather than locking out the fighter's fire control radar. Fifth, the architecture offers the possibility of launch-and-leave operation, since

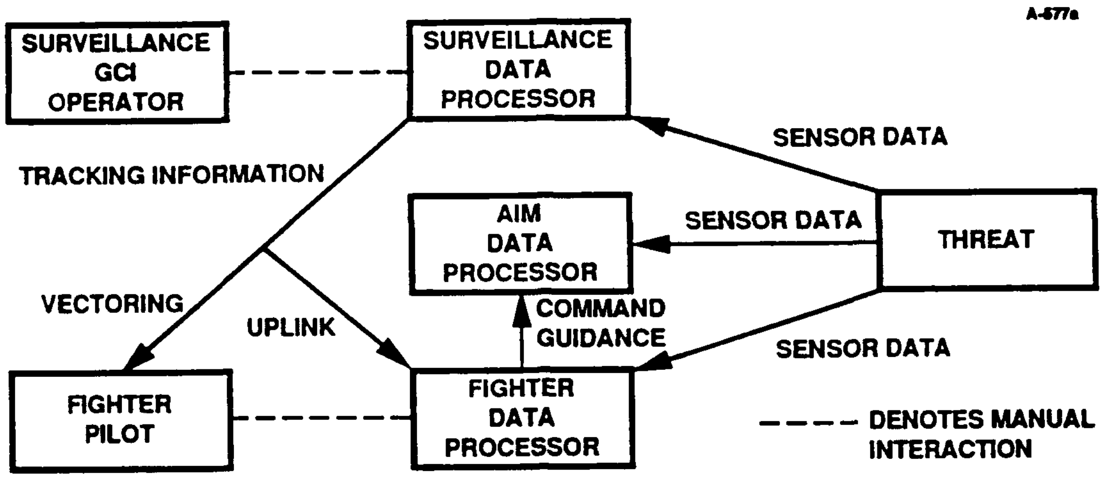

Figure 3.4-1 Possible Cooperative Engagement Architecture

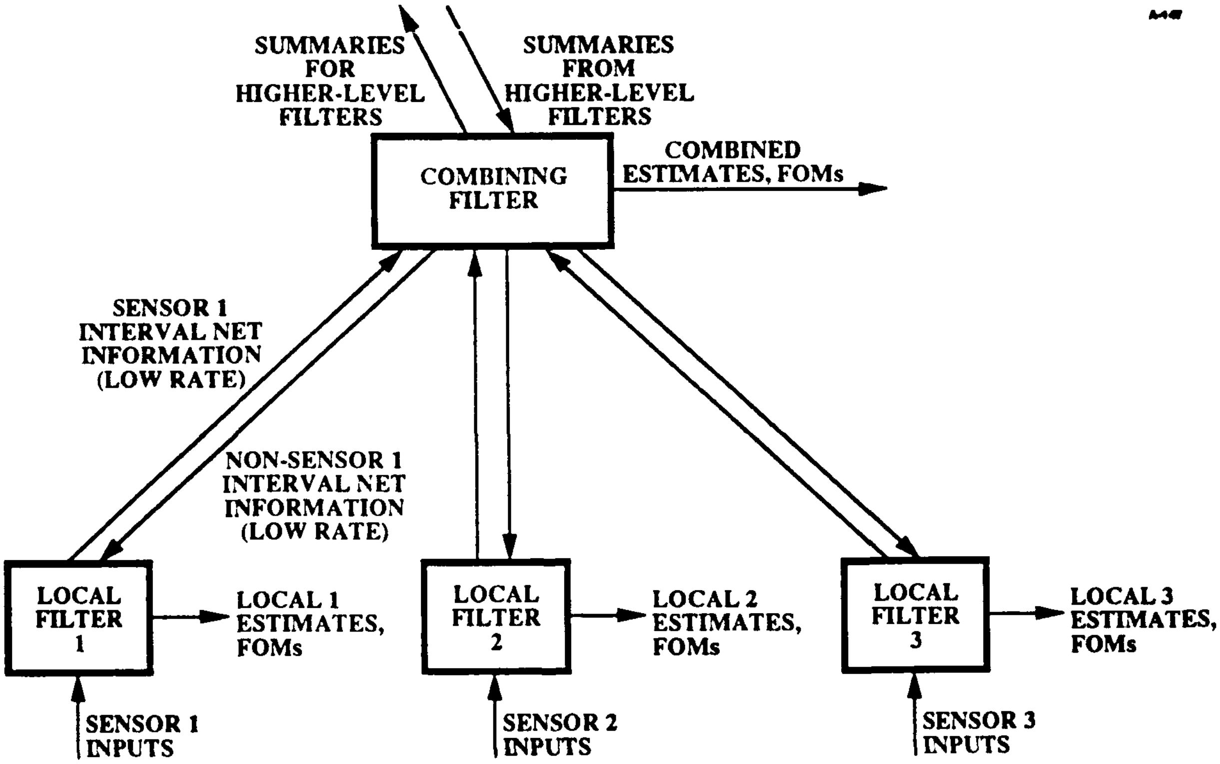

Figure 3.4-2 Distributed Estimation Architecture

AMRAAM updates could be made from E-3 data even if launch-time targeting included FCS data. Sixth, relatively few major new systems are required.

One of the issues concerning the feasibility of this architecture that requires further analysis is the selection of the fighter-to-interceptor missile data link. If launch-and-leave operation is necessary for effective cruise missile defense, then it may be necessary to ensure that fighter-to-interceptor missile data link be maintainable when the fighter is not headed toward the interceptor missile. The ability for one fighter to link with more than one missile may be necessary as well. Plessey has recently proposed the development of a lightweight, receive-only JTIDS Class 2 terminal suitable for tactical missiles, which would provide these features. Their impact on operational effectiveness will need to be assessed as part of this study.

It should be emphasized this architecture was developed for illustrative purposes. While it may eventually prove to be a useful approach, significantly more analysis will be necessary to determine whether it is technically feasible, and whether it significantly improves operational effectiveness.

3.5 ISSUES TO BE ADDRESSED IN EVALUATING A COOPERATIVE ENGAGEMENT ARCHITECTURE

As noted above, introduction of cooperative engagement methods into cruise missile defense results in some novel evaluation issues. Fundamentally, we wish to know whether such an introduction will increase the number of cruise missiles that can be shot down. In order to evaluate this with reasonable accuracy, we need to identify the specific engineering issues that are raised by cooperative engagement methods; evaluate those engineering impacts; and project the engineering impacts into operational effectiveness.

First, we need to evaluate single-shot effectiveness. Single-shot effectiveness depends in part on interceptor missile qualities (ability to fly out from launch to a commanded point; likelihood of killing the cruise missile given the engagement geometry at the start of endgame), and in part on the quality of the external targeting data of interest (accuracy, rate).

Second, we need to evaluate the multi-target capabilities of the system. This depends on the tracking characteristics of the surveillance platform (tracks maintained simultaneously), the nature of the surveillance/fighter logical data interface (bits per update, or equivalent), and surveillance/fighter communications capacity (bandwidth, allocation method).

Third, we need to combine all of these factors into an operational effectiveness analysis. Note that a radically redesigned targeting capacity will probably imply that tactics on the part of the defense forces will change from tactics using current systems; note also that the threat scenario may change as well, due to enemy knowledge of revised defense capabilities and tactics.

In Section 4, we shall discuss the means by which these issues can be evaluated.

4. EVALUATION METHODOLOGY

4.1 MEASURES OF EFFECTIVENESS

In evaluating the effectiveness of cooperative engagement concepts in the cruise missile air defense problem, it is important to distinguish between several possible objectives. One objective might be to determine the precise performance of a particular interceptor system design in a mission. A second, quite different objective, is to determine the enabling requirements for a technology that allow a mission to be accomplished with acceptable effectiveness.

An alternative approach to defining requirements is to determine bounds on achievable performance, rather than examining detailed point designs. This approach will be elaborated below.

The first step in determining the requirements for a new technology to enable a mission is to determine where, in the overall mission, the technology in question would have an impact on performance. Then, it can be determined how other portions of the mission depend on the effects of the technology in question.

Detailed models of the technology under consideration can then be constructed, emphasizing scenarios that stress the technology. These models only need to be sufficiently complete to work on the scenarios to be examined. Simplified models can be used for other aspects of the mission, provided that dependencies on the technology at issue are retained.

The models can then be exercised to examine mission performance as a function of feasible combinations of model parameters. In particular, the models should be exercised to identify sensitivities of mission effectiveness to critical subsystem parameters. Critical points on parameter tradeoff curves can then be identified, and requirements thus established.

Once critical points have been identified and requirements established, more detailed designs can then be constructed. Mission effectiveness can then be confirmed through high-fidelity simulation of one or a few such detailed designs.

4.2 PROBLEM PARTITIONING

Models for a problem of this magnitude can be developed and exercised in two basic ways. The obvious way is to build a single simulation that addresses every aspect of the engagement, from threat scenario and defense tactics down to the details of the tracking filters and fuzing. Modifications to any portion of such a model require that consistency be maintained throughout, and that the entire model must be exercised as a unit. The less obvious way is to build a set of sub-models whose inputs and outputs can be interconnected in mathematically rigorous ways, and yet can be modified and exercised independently.

The single-simulation approach has certain advantages. The principal one is this: It can always be made to work, regardless of linearity or nonlinearity, internal feedback structure, forms of probability distribution functions, or output measures. On the other hand, the single-simulation approach has certain drawbacks. Chief among these is its inflexibility. If one portion of a unified model needs to be analyzed using Monte Carlo methods due to (for example) nonlinearity, then the whole model must be analyzed using Monte Carlo methods -- even if the majority of the variables could otherwise be analyzed using the (much less expensive) direct covariance method.

The sub-model approach demands first that the total model be decomposed into several sub-models, and the sub-model interconnections defined. Then a means for integrating the outputs of the sub-models must be found. Once these preliminary steps are complete, model development and exercise for each component proceeds much as in the case of a single unified model (just smaller).

A powerful tool for integrating the outputs of two probabilistic sub-models is the Chapman-Kolmogorov equation. This equation is:

$$P_{\underline{x}}(a) = \int P_{\underline{x}/\underline{Y}}(a/b)\, dP_{\underline{Y}}(b)$$

where

$P_{\underline{x}}(a)$ is the unconditional probability that random variable $\underline{x}$ is less than a

$dP_{\underline{y}}(b)$	is the differential at b of the unconditional probability that random variable $\underline{y}$ is less than b
$P_{\underline{x}/\underline{y}}(a/b)$	is the conditional probability that random variable $\underline{x}$ is less than a if random variable $\underline{y}$ is less than b
$\int$	is the integral over all b, taken in the Riemann-Stieltjes sense

This equation expresses the way that the probability distribution of $\underline{x}$ can be computed if the form of the dependency of $\underline{x}$ on $\underline{y}$ is known, and the probability of $\underline{y}$ is also known. In such a case, the probability distribution of $\underline{x}$ can be computed indirectly via the Chapman-Kolmogorov equation, rather than directly (as through a unified simulation). No loss of precision is incurred due to using the Chapman-Kolmogorov equation instead of direct unified simulation, provided that the requisite interface variables are properly identified.

The required probability distribution data may be obtained in a number of ways. For certain classes of problems, the complete distribution depends on relatively few statistics that can be calculated directly (e.g., multi-dimensional gaussian distributions characterized by a vector mean and covariance matrix.) Many tracking problems are among these. For other cases, the probability distributions must be obtained by reducing data from a Monte Carlo ensemble. These cases include most nonlinear problems, such as occur in interceptor endgames. The means by which the distribution data are obtained for one sub-model has no bearing on the means for obtaining distribution data from another sub-model. Therefore, use of the Chapman-Kolmogorov equation, where possible, affords a high degree of flexibility in choosing the most efficient methods to conduct each part of the analysis.

It can be readily seen that the Chapman-Kolmogorov equation will be most useful in cases where there are relatively few elements of the interface vector $\underline{x}$ and where the variables of interest can be separated into a block-feedforward structure -- that is, where $\underline{x}$ depends on $\underline{y}$ but $\underline{y}$ does not depend on $\underline{x}$. Thus, the tracking and flyout components of an interceptor missile engagement can be integrated with the endgame component using Chapman-Kolmogorov, since there are relatively few variables of interest at seeker turn-on (threat range, bearing, relative speed, threat altitude, and interceptor altitude).

Chapman-Kolmogorov is not as useful in cases where there is an essential feedback structure in the variables of interest. In the operational effectiveness problem, subsequent launch decisions depend in part on the success of a prior launch (endgame outcome). While an interface vector could be defined that would eliminate the feedback structure, it would have large dimension, and therefore would be computationally infeasible.

Thus, we have partitioned the overall operational effectiveness problem into three components sub-models:

- Endgame
- Tracking/flyout
- Few-on-Few Mission simulation.

Endgame and tracking/flyout models will be developed and exercised separately, and results integrated using the Chapman-Kolmogorov equation. The integrated tracking/flyout/endgame results thus represent single-shot performance. These single-shot performance results will be supplied as an input to the few-on-few mission simulation.

4.3 SUB-PROBLEM MODELING

4.3.1 Tracking/Flyout Segment

Consider the problem of tracking and flyout for an interceptor missile. A high-level block diagram of the necessary functions is depicted in Fig. 4.3-1. The outputs of this system include threat and interceptor position and velocity at the start of the engagement endgame.

The "Threat Behavior" block for a cruise missile includes its intended flight path, as well as random deviations about that path. Deviations are due to such factors as navigation errors, autopilot and airframe response times, and so on.

The "Tracking and Guidance Subsystem" block includes all sensors used in tracking the threat, whether located on the surveillance platform or on the fighter. Tracking filters, data association algorithms, and interplatform communications are also included. The objective of the

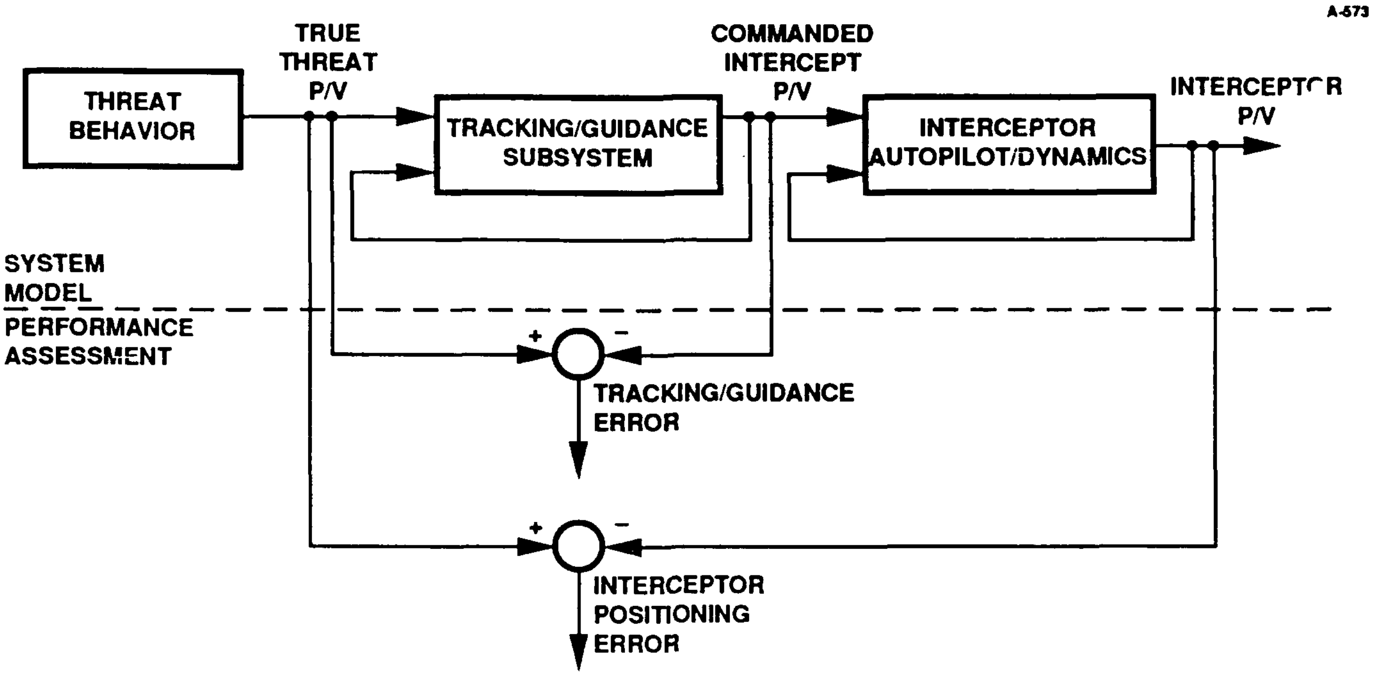

Figure 4.3-1 Tracking and Guidance Subsystem

tracking and guidance subsystem is to generate a commanded intercept position and velocity for the start of the endgame, that will result in a high probability of kill. A local metric for the performance of this subsystem is the deviation between the true threat position and velocity, and the commanded intercept position and velocity. This deviation (modulo the desired offset[1] at endgame initiation) is the tracking and guidance error -- the amount by which the tracking and guidance subsystem aimed the interceptor missile at a less-than-ideal spot.

The "Interceptor Autopilot/Dynamics" block includes the interceptor missile propulsion, autopilot, and aerodynamics. The autopilot tries to place the interceptor missile at the commanded intercept point, to within the physical limits of the missile. A local metric for actual missile positioning is the deviation between the true threat position and velocity, and the attained interceptor position and velocity.

Clearly this interceptor positioning error must be larger (in an ensemble sense) than the tracking/guidance error. The interceptor missile cannot, as a rule, come closer to the threat missile at the start of the endgame than the point at which it was aimed. The additional limitations of the

[1]As described in Section 4.3.3.3, a targeting offset is required to maximize effectiveness. It is normally supplied by the launch platform's FCS.

interceptor missile in actually reaching the commanded intercept point depend in part on threat characteristics -- modern fighters are probably harder to catch than LSCMs if you are equally well-informed as to their trajectories. These concerns are elaborated in the following discussion.

4.3.2 Endgame Segment

Consider now the endgame segment depicted in Figure 4.3-2. For a given launch condition (in the case depicted, a pursuit), we wish to command the interceptor missile to fly out to some ideal commanded intercept position and velocity prior to local seeker turn-on (Point B on figure) with respect to the actual threat missile position and velocity (Point A on figure) at the same time.

In fact, of course, the interceptor missile position and velocity with respect to the threat missile at local seeker turn-on is slightly different from the ideal (Point C on figure). This deviation is precisely the interceptor positioning error described in Section 4.3.1, and arises from threat missile maneuvering, imperfections in tracking, and physical limitations of the interceptor missile. At turn-on, the seeker on the interceptor missile will be able to detect and track the threat missile if it is within a certain field of view. This field of view depends on:

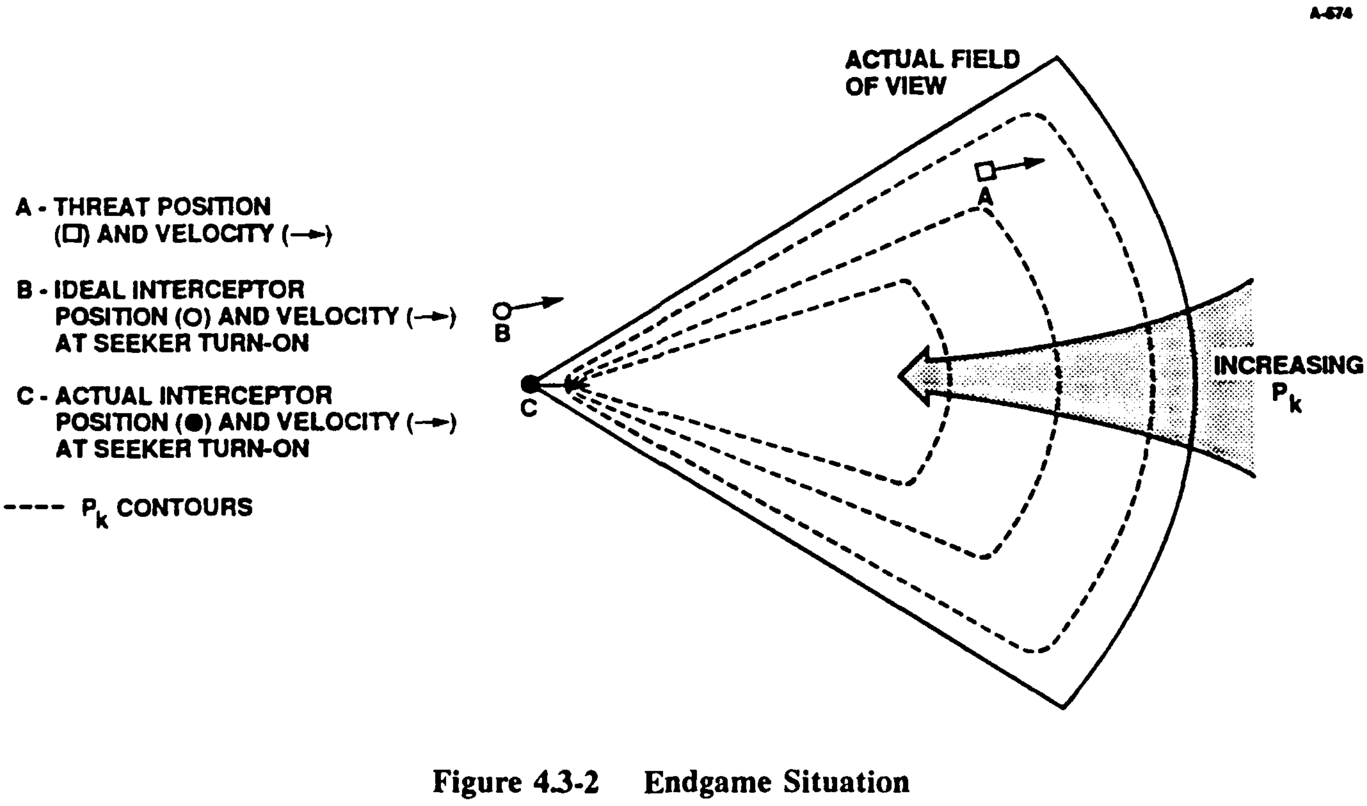

Figure 4.3-2 Endgame Situation

- The relative heading (with respect to the target track) of the interceptor at turn-on

- The width of the field of view at the sensor

- The effective detection range of the seeker against the particular threat missile (depends on radiated power and threat RCS).

Clearly the probability of the interceptor killing the threat is zero if the interceptor cannot see the threat at turn-on, or very shortly thereafter; thus, P_k is non-zero for (at most) this field of view.

Within the field of view, the interceptor missile can be thought to have P_k contours depending on the interceptor missile's ability to kill the threat missile given other aspects of the situation at turn-on. These other aspects include:

- Reachability (due to relative velocity vector at turn-on, as well as limitations of interceptor and threat missile dynamics)

- Threat visibility characteristics (glint, RCS as a function of aspect angle)

- Seeker characteristics

- Fuzing and warhead characteristics.

Thus, an "ideal endgame" would be one in which any threat within the field of view at turn-on could be killed with probability one. Any improvements in interceptor endgame performance, due to improved maneuverability, improved signal processing, improved fuzing, improved warheads, and so on, can be thought of as collectively modifying the actual P_k contours within the field of view in the direction of the "ideal endgame." Due to the difficulty of precisely modeling the aforementioned characteristics to obtain the P_k contours, simpler semi-analytic models will be employed initially.

This semi-analytic approach to endgame analysis has been developed further in work done for ballistic missile defense (BMD) (Ref. 13). The BMD problem as analyzed is much like the cruise missile defense problem in that the threat does not react to the interceptors. Considerations such as sensor field of view, tracking error, threat reachability by the interceptors, and fuzing/warhead effectiveness, are explicitly addressed in this work. In this study we have extended the connections between the probabilistic nature of tracking errors and the absolute limits of threat reachability based on cludes from the BMD literature. Detailed are provided in Volume 3.

4.3.3 Cooperative Engagement Scenario

4.3.3.1 *Tracking/Flyout Segment*

The cooperative engagement scenario analyzed for this report includes a surveillance platform which transmits the location and quality information about the target to the missile only once, just prior to launch. This is depicted in Figure 4.3-3. To characterize the tracking/flyout segment four quantities must be determined at handover time. These are:

- Mean position and velocity of the intercepting missile
- Position and velocity covariance of the intercepting missile
- Mean position and velocity of the target
- Position and velocity covariance of the target.

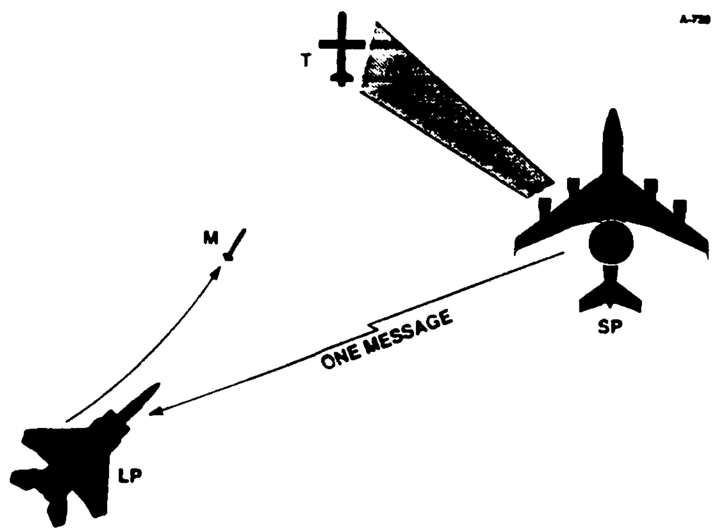

Figure 4.3-3 Cooperative Engagement Scenario

To compute these quantities the error covariances matrices of the missile and target at launch and handover times are required.

Use of this information is depicted in Fig. 4.3-4. The SP observes the target and forms an estimate of the current target location and velocity. A prediction is made, probably in the LP FCS, of the location and velocity of the target for some future intercept, and a predicted kill point is established. The LP FCS computes an intercept missile trajectory to achieve the kill using both the estimated location and velocity and information about the quality of those estimates. This trajectory is labeled as a Predicted Trajectory. The Resulting Trajectory is the approximation to the desired trajectory actually achieved by the interceptor. (The covariances of M and T location at handover are used in evaluating the scenario and are not available to the participants in the actual engagement.)

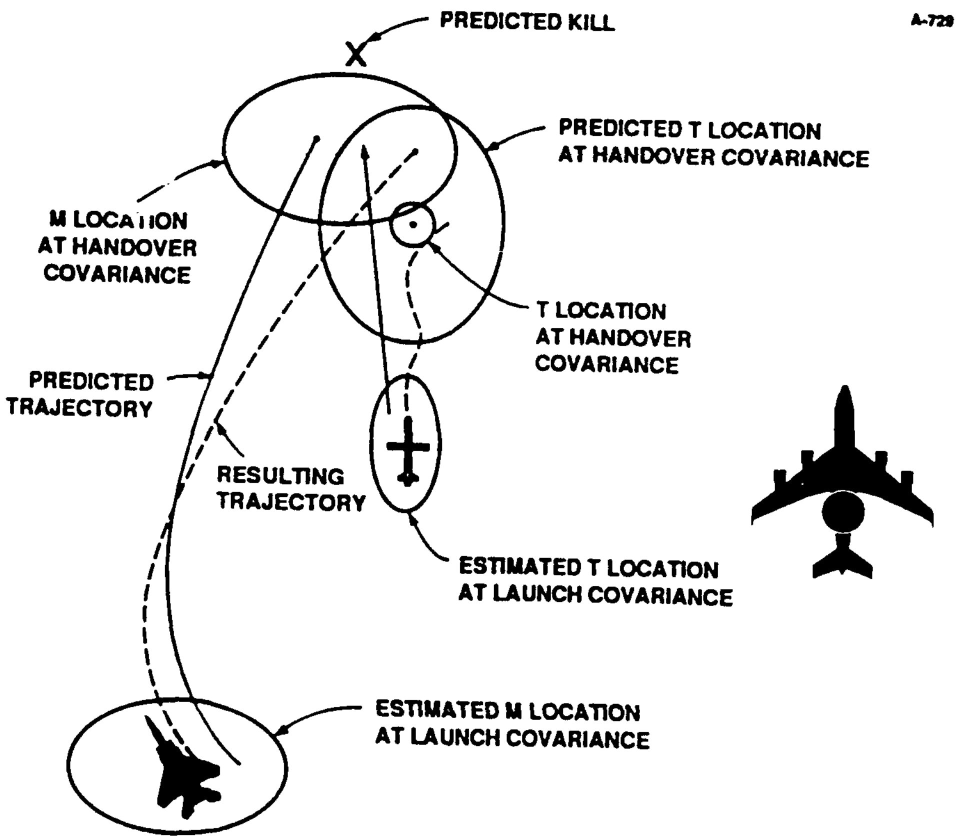

Figure 4.3-4 Cooperative Engagement Procedure Overview

4.3.3.2 *Endgame Segment*

The endgame situation modeled in Fig. 4.3-2 can be simplified significantly for notional missiles and warheads when the data describing effectiveness variation over the region are not available. In such cases, it is generally appropriate to remove reachability data from the contours, develop a representation of the intersection between the visible region and the reachable region, and represent warhead effectiveness more simply in this reduced region. Figure 4.3-5 depicts a plane section through a reachable and visible region which is described by a conical seeker field-of-view with isotropic visibility and lateral acceleration limits on the missile. The assymetry near the bottom of the picture is a result of a non-zero relative velocity angle between T and M at handover. The cut was taken in the plane defined by the velocity vectors. Additional details of the calculation are included in Volume 3.

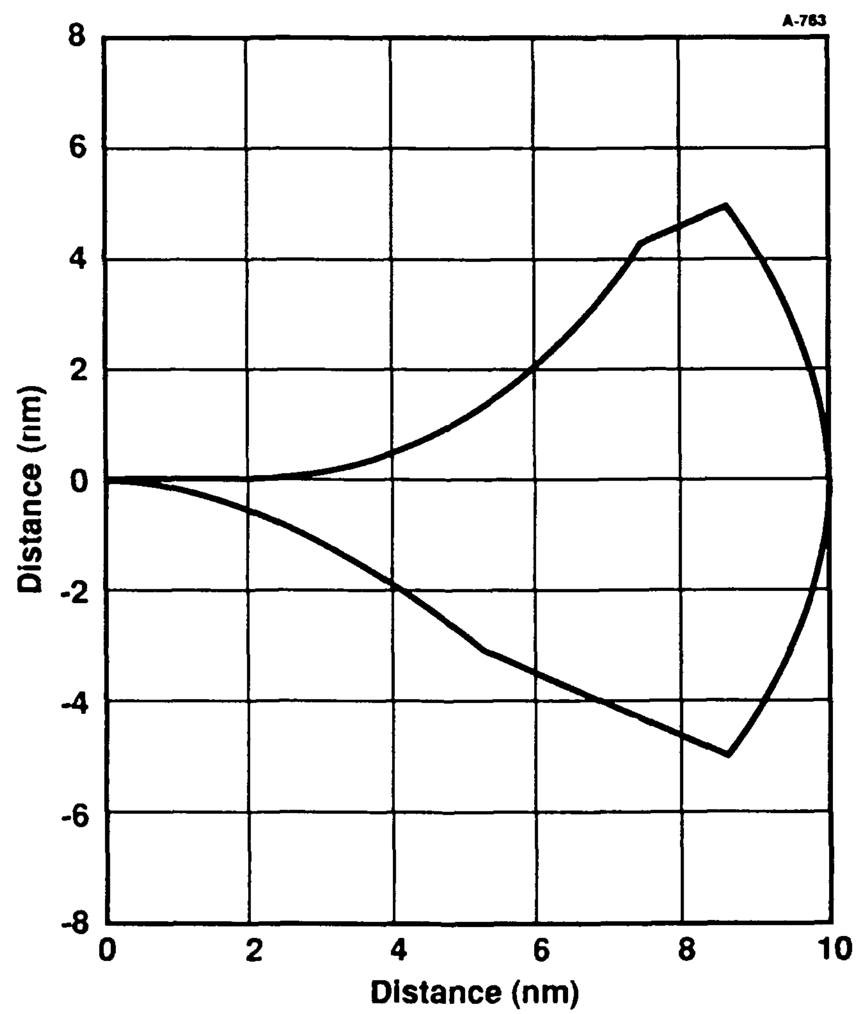

Figure 4.3-5 Planar Section of the Reachable and Visible Region

4.3.3.3 *Total Evaluation*

With the simplifications described in Section 4.3.3.2, the Chapman-Kolmogorov equation reduces to an integration of the probability density function described by a vector mean and covariance matrix over the region of the reachable/visible set and is easily visualized. (Note that a Monte Carlo solution is not necessary.) Figure 4.3-6 represents the process.

The ordinates represent the probability density function at points in the plane described by the reachable/visible set. Near the apex of the cone, the region is limited by the missile lateral acceleration. At the outer limit, the visibility radius (VRad) dominates. Along the outer edges, seeker field-of-view dominates.

The central point of the distribution in Fig. 4-3-6 is offset into the reachable/visible region in order to maximize overall effectiveness. This represents a targetting offset that must be inserted in the FCS solution.

The output of the evaluation is the probability that the target will be within the reachable/visible region at seeker turn-on (i.e., handover). A value of 1.0 means that it is always in the region while 0.0 means it is never there. We call this measure <u>relative effectiveness</u>. The large the value, the better the engagement outcome.

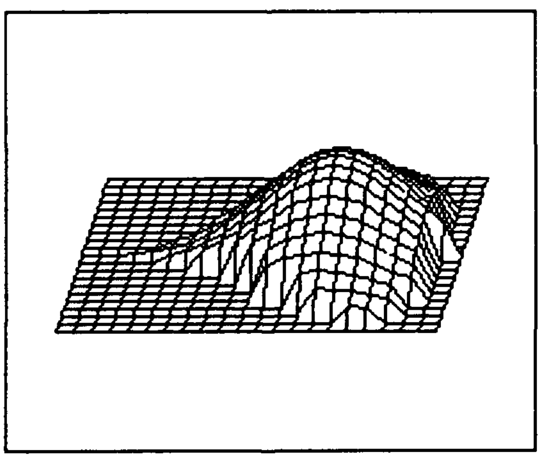

Figure 4.3-6 The Combined Evaluation Integral

4.4 EVALUATION APPROACH

4.4.1 Top-Down vs. Bottom-Up

We noted in Section 4.1 that the evaluation of a given detailed design is quite distinct from determining enabling requirements. In the former case, the precise details of the design are exactly what is at issue. In the latter case, details are often less important than aggregate effects, provided that the critical dependencies on the technology under examination are not destroyed.

We noted in Sections 4.2 and 4.3 that the single-missile analysis (track and launch through kill) breaks out into two major segments: Track/flyout and endgame. Cooperative engagement techniques are implemented in the track/flyout segment; the effects of cooperative engagement are seen in the relative situation at seeker turn-on, as discussed in Section 4.3.2.

In consequence, there are two basic approaches to performance evaluation, one of which is most appropriate for each of the two analysis objectives.

The bottoms-up approach is more appropriate to detailed design evaluation. In this approach, high-fidelity detailed models are constructed for each component of the fixed design. These components are integrated into a system model, which is then exercised for the conditions of interest.

The top-down approach is more suitable to determining enabling requirements. In this approach, detailed models are only constructed for components of direct interest. Related components are modeled on a lumped basis, taking care to preserve functional dependencies on models of direct interest. Extensive use is made of sensitivity analysis, whereby parameters are varied to determine their effect on system performance.

In using the top-down approach, the general method is to successively eliminate possibilities that will not provide desired levels of performance. Thus, it is useful to determine optimistic bounds on performance. The analysis process might start using optimal filters in the flyout segment and "ideal endgames" in the endgame segment; this would show the effect of cooperative tracking and guidance if everything else is "perfect," and would distinguish designs meriting further study from those that can be eliminated promptly. Later refinements might use mismatched filters in the flyout segment and "ideal-but-reachable" (i.e., constrained by maximum dynamics) endgames; and eventually (if desired) narrow down to a set of feasible designs.

For example, if a cooperative engagement system using 10 sec track updates does not provide adequate performance when the "ideal" endgame is used, then one can be assured that 10 sec updates will never provide adequate performance with realistic endgames, and no more effort need be spent on the 10 sec update case. It has not been determined that a 10 sec update will work; only that it has not yet been eliminated. Later refinements (as described above) might well rule out the 10 sec update in favor of an 8 sec maximum. Consider the limitations of the reverse process: If one uses a detailed, realistic 1990 endgame model and the 10 sec update does not yield adequate performance, it cannot be determined whether the performance limitation is due to the endgame or the guidance method. Repeated changes to the endgame model, representing hypothetical endgame improvements that might be possible by 2005, might eventually show that a 10 sec update could work under some circumstances, but the process is unnecessarily arbitrary, expensive, and slow.

4.4.2 Implications for Model Fidelity

The implications of the above discussion are not that either high or low fidelity is required to meet the objectives of this analysis, but rather that the fidelity must be properly placed. Since the objective of the study is to examine the utility of cooperative engagement techniques, a fairly high level of fidelity is required for the tracking/flyout segment. By contrast, the endgame model must show some bound on performance as a function of guidance position and velocity errors, field of view, and detection range, but the details of glint, RCS as a function of aspect angle, fuzing, and warhead can be left until a later stage.

At some stage in the analysis it will be useful to obtain a validated baseline performance reference for some relevant (i.e., potentially useful in cooperative engagement) interceptor missile. Since it appears that AIM-7 and AIM-9 are not likely candidates for cooperative engagement, due to their home-all-the-way guidance systems, and since no validated models will be available for either AAAM in the near term, an accepted model of the current AMRAAM design would make a useful benchmark. It appears that the Government has one or more such models, which might be useable for this project. Due to the problem partitioning discussed in Section 4.2, it is not expected that significant modifications to the model software would be needed to extract the necessary reference data.

5. MODEL OVERVIEW

Following the analysis of Sections 3 and 4, we have concentrated to date on developing the tracking and flyout models necessary to support a lower bound analysis of interceptor positioning error at the start of the endgame. A description of the model structure and error variables is found in Volume 2, Detailed Errors Models and Simulation for Case I: Pre-Launch Coordination without Post-Launch Updates. The software environment in which we developed and exercised the tracking/flyout models is found in Volume 3, Simulation Tools: Current Status and Recommendations for Future Development.

5.1 PRINCIPAL CASES FOR ANALYSIS

In order to investigate the benefits that cooperative engagement could bring to the air-to-air cruise missile defense problem, several cases are suggested. By analyzing these cases in the indicated order, it will be possible to determine exactly where in the engagement improvements to C^2 systems will have the most value.

Case I: Initialization Only

In this case, the surveillance platform provides a radar-derived estimate of the threat missile track before launch of the interceptor missile, but no further updates are provided. In order to emphasize the cooperative engagement aspects and to stress the guidance solution, the launch platform will be assumed to have no own-sensor data on the threat missile.

The interceptor missile guidance system is initialized with the launch platform's navigation solution. The interceptor missile then flies with inertial guidance to the local seeker turn-on point. Thus, error models must account for surveillance platform and lunch platform navigation errors, radar tracking errors, and interceptor missile guidance errors.

Subcases involve modifications to the launch platform and interceptor platform navigation suites. It is assumed that both platforms will have inertial navigation systems (INS); quality may be current-generation medium-accuracy (approximately 0.8 nm/hr drift for the USAF standard SNU-84) or next-generation precision-accuracy (approximately 0.1 nm/hr). In addition, either platform may or may not have a Global Positioning System (GPS) receiver. It will be assumed that the navigation suite on the surveillance platform will be at least as good as that on the launch platform.

Case II: Initialization Plus Updates

Case II resembles Case I, except that the surveillance platform will provide additional track updates periodically after launch of the interceptor missile. Update period is a major parameter for sensitivity analysis. Case II may have the same navigation-suite subcases as Case I.

Case III: Initialization Plus Updates With Feedback

It will be noted that, in Cases I and II, any residual coordinate-system misregistration at launch time will propagate through the entire flyout. That is, threat missile track updates will be given in the surveillance platform frame, while the interceptor missile will respond in the launch platform frame.

If the surveillance system can observe the track of the interceptor missile in surveillance platform coordinates, at the same time that the interceptor missile reports its own track in launch platform coordinates, this residual misregistration could be corrected. Thus, in Case III it will be assumed that the interceptor missile might have a transponder to permit this calibration function.

Once again, Case III may have the same navigation-suite subcases as Case I.

Other Cases

An additional class of cases, which would likely be examined after Cases I, II, and III above, would allow inputs from launch-platform sensors or from other surveillance platforms in the vicinity. The example architecture in Section 3.4, which uses the NIA distributed estimation architecture, is capable of integrating such multi-source data.

All of the above cases have concentrated on inertial command guidance for the flyout phase, since it appears to be most useful for cooperative engagement cruise missile defense in the near term (Section 3.3). If further analysis indicates that a multistatic configuration that does not use inertial command guidance is a viable option for the 2005 time frame, these cases could be adapted to such a configuration.

5.2 CASE I IMPLEMENTATION ASSUMPTIONS

5.2.1 Computer Implementation

During this effort, *SYNETICS* implemented a simplified version of the Case I model described in Volume 2 of this report using PC-hosted tools. Primary simplifications, which involved reducing the complexity of several phases of the mathematical models, included:

- Segmenting the kinematic trajectories into pieces in which either acceleration or turn rate was constant
- Precomputing trajectories based on desired end-game geometry rather than solving for intercept solutions
- Separating the problem into distinct pieces (SP and T, LP and M) each of which was handled independently and then combined
- Eliminating a transfer alignment maneuver and initializing M by "degrading" the LP covariance.

The first two simplifications are common practise for analyzing navigation systems; they are believed to have, at most, minor accuracy implications.

The structure of Case I is such that this implementation preserves all model features. This technique allowed us to obtain results in the PC environment without further simplifying the models.

The last simplification is as much a matter of data scarcity as it is a convenience. Detailed transfer alignment models must involve explicit handling of aircraft flexure, bending, and vibration as well as detailed descriptions of how the stores are loaded on the aircraft. (These data are not available for an F-16 with Pomona pod, and the F-16 is known to be quite "lively".) While it is common practise to "degrade" all error terms (except for position and velocity), it is necessary to evaluate the implications of these assumptions on study conclusions. For the cases considered, transfer alignment effects appear to be second order and a detailed error evaluation was not conducted.

The end-game evaluation also involved numerical simplifications. The transcendental equations involved in the reachability calculations were "gridded" and solved using a two-stage table look up; and the probability integration step size was fixed as a percentage of the end-game region. The approximations are considered to have little impact on results and can be easily adjusted. The second simplification requires manual intervention to ensure accuracy and should be replaced by a more autonomous algorithm in future work. Care was taken to adjust the integration mesh to the point at which it appeared to have negligible impact on results.

A more detailed description of the implementation is contained in Volume 3.

5.2.2 Specific Cases

Figure 5.2-1 depicts the three SP orientations (with respect to nominal T motion) considered. Orientation A aligns T motion with SP range measurements providing the most accurate information about T motion during the observations. Orientation C aligns T motion with angle measurements providing the least accurate information about T motion during the observations. Orientation B provides an intermediate accuracy evaluation of T motion. In all cases, T represents an LSCM.

Figure 5.2-2 depicts three LP firing positions (with respect to T motion). Direction 1 represents a pure "tail" shot, which is the best geometry for attacking a non-maneuvering target. Direction 2 represents a "side" shot, which may be the worst geometry. (A "head" shot trades increased closing velocity for greater maneuverability through the regions of highest error density, while the side shot pays less of a closing velocity penalty but is more restricted in its ability to reach the central region of the density function. Relative "value" is entirely dependent on specific details of the M sensor, relative velocity advantage, and target location errors; no "absolute" relationship exists.) Direction 3 represents an intermediate geometry with favorable orientation.

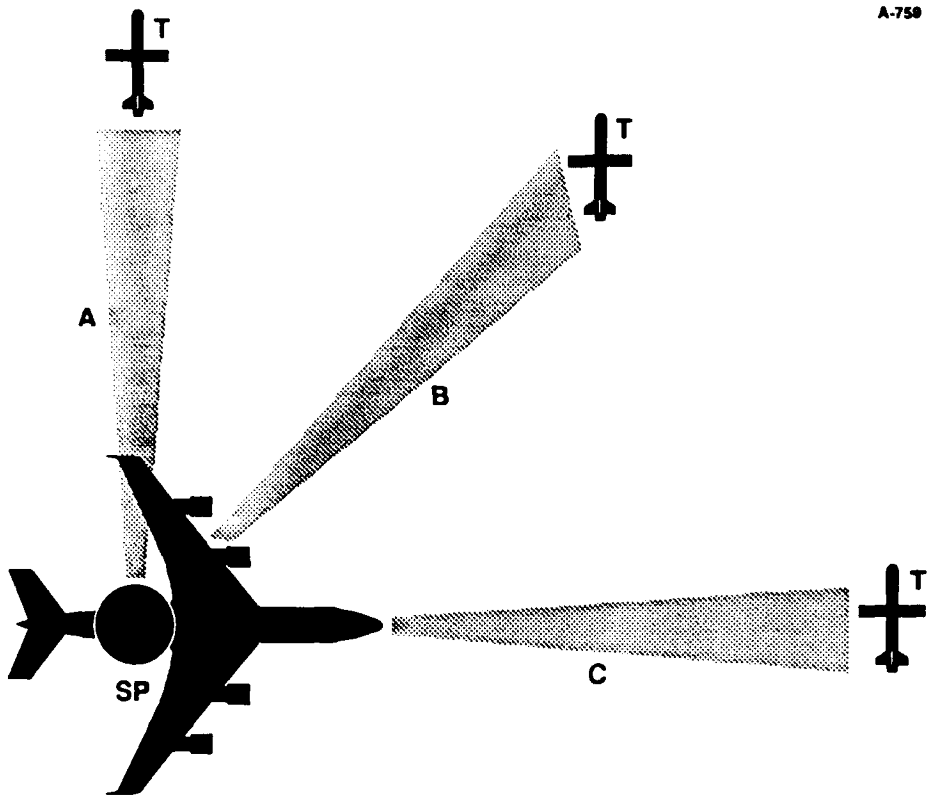

Figure 5.2-1 SP Orientation with Respect to Target Motion for Case I Results

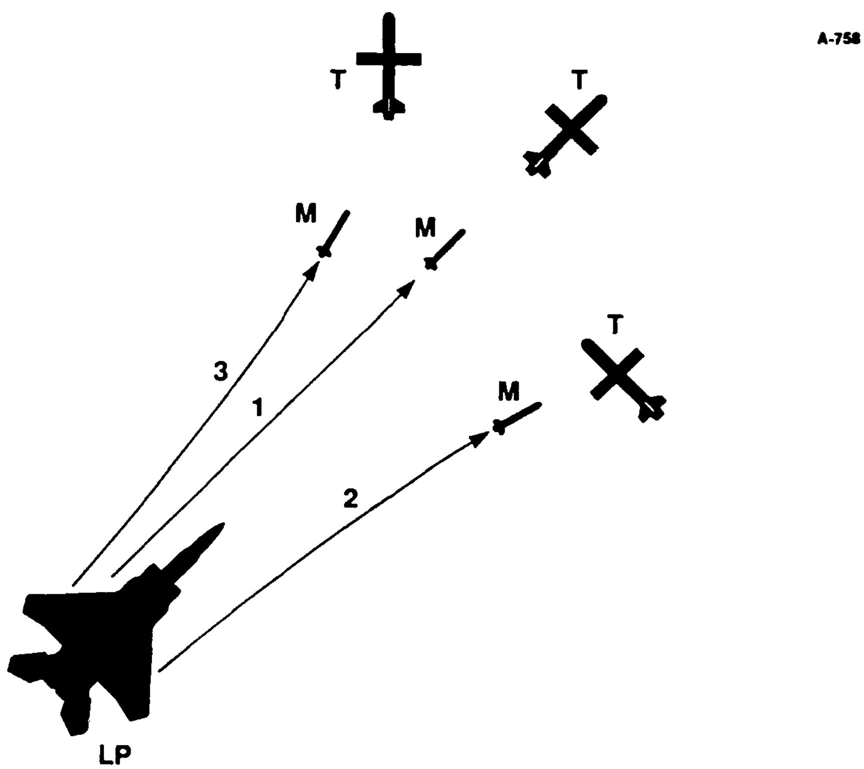

Figure 5.2-2 LP Firing Direction with Respect to Target Motion for Case I Results

For each candidate M (expressed in terms of seeker field-of-view, visibility radius and lateral acceleration limit) each of these 9 combinations was evaluated for 3 times of flight for each M. Transfer alignment was simulated as perfect, intermediate, and poor for a total of 81 cases. Results were obtained for several additional weapon system parameter variations for a total of several hundred total cases. A complete set of results is presented in Volume 3.

5.3 Initial Results

This section presents a selected subset of the results obtained during the study from which particular insights were obtained. The reader is invited to review the entire data set contained in Volume 3.

The first result is not documented in numerical tables in Volume 3. During simulation setup and debug, it became apparent that standard tracking algorithms coupled with nominal SP surveillance mode accuracy was inadequate to localize T altitude sufficiently to produce an acceptable engagement. The standard tracking algorithm is initialized using no a priori information about T location. (This is achieved numerically by assigning a large uncertainty, typically on the order of 100 km, in the tracking filter.) Although this is reasonable for horizontal position, it is unreasonable for the altitude of non-evading cruise missiles. We artificially limited the altitude uncertainty to several km for these simulations, corresponding to a modified tracking algorithm capable of using intelligence information about likely flight profiles. We believe this to be well within current state-of-the-art but recognize that it is likely to be beyond the state of current practise.

5.3.1 A Representative Data Set

Table 5-1 presents the relative effectiveness[2] of the nominal missile against a large target (nominal radar cross section of 1 m^2) as a function of SP orientation and LP firing direction. For simplicity, the firing direction access is ordered 1, 3, 2 since performance is expected to degrade in that order.

[2] The end-game model assumes constant lethality within the engagement region. To convert to probability of kill, multiply results by single shot P_k. To compute damage, use P_D, etc.

TABLE 5-1

VARIATION IN RELATIVE EFFECTIVENESS WITH SP ORIENTATION AND FIRING DIRECTION (Nominal VRad, Large Target)

SP Orientation	M TOF[sec]	LP Firing Direction		
		1	3	2
A	40	0.90	0.76	0.37
	70	0.85	0.72	0.34
B	40	0.86	0.81	0.50
	70	0.81	0.75	0.46
C	40	0.37	0.32	0.33
	70	0.26	0.22	0.21

In general, the results confirm expectations. Aligning the SP orientation with the principal axis of T motion provides the highest quality targeting information which results in the best performance. (There is a nearly a factor of 3 between SP orientation A and C in the "preferred" firing direction.) Using a tail shot or aft oblique shot produces much better results than side shots, although the degradation is not so large as to outweigh tactical considerations. Moreover, these data suggest that an improvement in the fire control algorithm that "curved" the intercept toward a tail shot might be better than a direct flight in even at the expense of increased time-of-flight when there is sufficient information available in the SP data. (Compare A-1-70 with A-3-40.) The comparison is slightly more convincing when an intermediate time-of-flight is used.

There are also some interesting and counter intuitive behaviour in the table. The best side shot occurs with an oblique SP orientation (B). This occurs because the orientation of the SP tracking errors happen to align better with the reachability region for this configuration even though the overall tracking error magnitude is slightly higher than in case A. Similar, but less dramatic, results are observed for the oblique shot, Direction 2, between orientations A and B. (Variations for case C are not considered significant. The effectiveness is poor in all firing directions.)

These variations do not change the implications for fire control solution at a single target: the best solution is always to try for a short range tail shot. They do have potentially significant implications for a few-on-many engagement if information about track quality is distributed by the SP, as indicated in the problem formulation of Section 4.3. As the defending force maneuvers to attack, pilots will have to decide which target to attack when and from what direction preserving their route to the next target. A decision to take a slightly lower probability shot at one target enroute to the next will probably yield higher overall payoff for many types of scenarios. This observation warrants further confirmation using m-on-n simulation.

5.3.2 **Target Observability Considerations**

One of the study objectives was to evaluate the impact of Low Observable (LO) and Very Low Observable (VLO) threats on the defending force. The reduced radar cross section (RCS) of LO targets affect the cooperative engagement scenario in two ways: it limits the observation accuracy of the SP and shortens the M visibility radius, VRad.

Table 5-2 presents simulation results for a number of conditions using a visibility radius of 10.0 nm as a baseline. It is fairly uninteresting, but will provide a basis for some comparisons. Results of changing VRad can be obtained immediately by comparing these data to Table 5-1 on an entry by entry basis.

Table 5-3 provides similar data for a small target (nominal RCS of 0.1 m^2). In addition to adjusting the SP radar, it was necessary to adjust the M visibility radius to correspond to the same detection threshold, in this case to 5.62 nm. (RCS and radiated power enter the radar equation in the numerator with the fourth power of radius in the denominator.)

The results show the same trends and slightly counter-intuitive behaviour as in Table 5-1. Note that firing direction 3 is essentially equivalent to firing direction 1 from SP orientation B. Again, error ellipse orientation is thought to explain the behavior.

TABLE 5-2

VARIATION IN RELATIVE EFFECTIVENESS WITH SP ORIENTATION AND FIRING DIRECTION (Large VRad, Large Target)

SP Orientation	M TOF[sec]	LP Firing Direction		
		1	3	2
A	40	1.0	1.0	0.98
	70	1.0	1.0	0.98
B	40	1.0	0.99	0.97
	70	1.0	0.99	0.95
C	40	0.85	0.66	0.67
	70	0.69	0.49	0.51

TABLE 5-3

VARIATION IN RELATIVE EFFECTIVENESS WITH SP ORIENTATION AND FIRING DIRECTION (Nominal VRad, Small Target)

SP Orientation	M TOF[sec]	LP Firing Direction		
		1	3	2
A	40	0.60	0.48	0.18
	70	0.53	0.43	0.17
B	40	0.52	0.55	0.29
	70	0.47	0.46	0.25
C	40	0.20	0.17	0.18
	70	0.14	0.12	0.11

5.3.3 Missile Performance Parameters

Please note that while it is tempting to compare Table 5-1 and 5-3, they are not really comparable because the target RCS has changed which affects both the SP and M parameters. This does, however, lead to an interesting comparison worth further consideration. Table 5-4 compares M performance against Large targets for a variety of effective seeker radiated power. The nominal case corresponds to Table 5-1 and the high power case corresponds to Table 5-2. An intermediate value for time-of-flight was added to the table.

Note the very significant value of increased seeker power to effectiveness in the range of our study. It is so dramatic that it may be desireable to trade engagement envelope (M energy expressed as time-of-flight but corresponding to launch weight) for additional power. Such a recommendation could be made only after evaluation in an m-on-n environment.

Parametric studies of the impact of transfer alignment quality on effectiveness are included in the data set in Volume 3, but they are not particularly interesting. For the range of degradation factors considered, there was negligible impact on performance.

Additional parametric studies involving M acceleration limits and seeker look angle were not conducted during this initial problem formulation portion of the study. (They properly belong in Option Years.)

TABLE 5-4

VARIATION IN RELATIVE EFFECTIVENESS WITH SEEKER POWER AND AND MISSILE TIME-OF-FLIGHT (SP Look A and LP Direction 1)

Seeker Power [VRad]	M Time-of-Flight [sec]		
	40	55	70
High	1.0	1.0	1.0
Nominal	0.90	0.87	0.85
Low	0.43	0.37	0.34

(This page is intentionally left blank)

6. FINDINGS AND CONCLUSIONS

6.1 THE AIR DEFENSE PROBLEM

In the course of this effort to date, we have significantly increased our understanding of current limitations of air-to-air engagement systems in intercepting cruise missiles. We have also made substantial progress toward analyzing the effectiveness of cooperative engagement techniques in removing these limitations.

It appears that the various threat cruise missiles identified in the Statement of Work can be organized into two classes, Low Slow Cruise Missiles (LSCMs) and High Fast Cruise Missiles (HFCMs). Within these classes, the level of observability can be readily accommodated by considering the Radar Cross-Section (RCS) to be a variable parameter.

Current defense systems are not limited by physical inability to achieve a reasonable probability of kill against LSCM threats. Rather, the current low rate of information transfer from surveillance platforms to fighters, coupled with the relatively small search volumes of fighter fire control radars, leads to a relatively long time required to engage each threat cruise missile. Since the time available to each Long Range Defense Force to destroy the threat missiles is measured in minutes, it is the time line that controls the effectiveness of air-to-air cruise missile defense. In the case of HFCM threats, physical reachability and time line considerations both represent serious constraints.

The intent of the cooperative engagement concept is to remove this engagement time limitation by making it possible to use sensor data other than the launch platform fire control radar to target threat missiles. This will require improvements to communication links and fire control systems at a minimum. It may also require improvements to surveillance sensor systems, navigation systems, and interceptor missiles. New subsystems currently under development, cited in this report, may have sufficient capabilities to support the cooperative engagement concept if they are integrated appropriately. One possible integration architecture is discussed in Section 3.4. Either the AIM-120 AMRAAM or the active-homing version of the AAAM appears to have the most promise as an interceptor of LSCM threats in a cooperative engagement architecture, while the active-homing version of the AAAM appears to be the most promising cooperative-engagement interceptor against HFCMs. Tracking and guidance modeling to date has largely concentrated on these interceptor missiles.

We have made significant progress in developing a methodology to assess the operational effectiveness of these technologies. The methodology requires substantial use of sensitivity analysis to determine the combinations of critical parameters that will enable significant improvements in effectiveness. In order to apply available resources most effectively, the methodology also calls for partitioning the problem into three sub-problems: endgame, tracking/flyout, and few-on-few engagement. The results of the endgame analysis can be combined with the results of the tracking/flyout analysis using the Chapman-Kolmogorov equation; <u>the results of this combined single-shot performance analysis can be inserted into the few-on-few effectiveness analysis as a parameter subset.</u>

The tracking/flyout analysis can be performed as a direct covariance analysis, and some of the necessary models are described in this report. The endgame analysis can be performed either as a direct Monte Carlo simulation or through semi-analytic methods. Although we originally proposed to use high-fidelity Monte Carlo simulations, our work to date has shown that this approach is both too constrained in representing current point designs, and too expensive for use in identifying enabling technologies. <u>It now appears that the most effective approach to endgame analysis for this study is to use our modified semi-analytic methods and to use high-fidelity Monte Carlo simulations only for limited benchmarking</u>. Existing Government AMRAAM simulations would appear to be good candidates for such high-fidelity benchmarks.

6.2 SPECIFIC TECHNOLOGY ISSUES

Standard tracking algorithms coupled with nominal SP surveillance mode accuracy was inadequate to localize T altitude sufficiently to produce an acceptable engagement for the scenarios considered. Instead, we assumed study conditions which correspond to a modification in the tracking algorithm to incorporate intelligence information about likely flight profiles. In the study case, only the altitude channel was modified. Such modifications are well within the current state-of-the-art and involve only minor software changes to the SP, but they are likely beyond the state of current practice.

For interesting cases (i.e., those for which error parameters are roughly comparable), there appears to be an interesting interaction between SP orientation and LP firing direction. This suggests that the fire control solution, target selection, and engagement planning function can benefit significantly from the use of information about track quality. Since such data are too voluminous for voice transfer, a data channel is required to the LP. (Data are inconclusive about the link to M identified in Section 3.4). Rapid solution of potential engagement values may require use of parallel or multi-processors in the FCS, and presentation of results to the flight crew may require enhancement to data presentation.

It appears that there is significant benefit to trajectory shaping against non-evasive cruise missiles. The data suggest that it is frequently the case that a longer M time-of-flight resulting in an end-game approach from a preferred direction results in higher effectiveness than a shorter direct path from a poorer direction. Such an implementation would probably require changing the FCS software, but it should not require significant hardware changes for AMRAAM and beyond.

Performance against LO and VLO targets degrades significantly, but not to the point at which the candidate architecture is totally ineffective. Moreover, it might be possible to enhance M performance (e.g., increased sensor power, incorporation of multiple sensors, or bistatic sensing) to improve performance significantly.

6.3 CONCLUSIONS

The analytic techniques and models developed during this initial year of the study can be used to provide top-level system evaluations of cooperative engagement concepts. The models preserve all of the features currently thought to relevant including:

- Target characteristics such as velocity, maneuverability, and apparent size (e.g., RCS)
- Search platform characteristics such as radar quality, tracking capability, navigation quality, and communications links to the force
- Launch platform characteristics such as navigation quality, communications links, maneuverability and range

- Intercept missile characteristics such as navigation quality, maneuverability and range, seeker characteristics and (potentially) fuzing characteristics

- Location and trajectory of all engagement participants.

Additionally, the techniques developed have a natural and straight forward interface to high quality m-on-n force evaluation tools such as the Veda SICM model, planned for use in option years. Such a tool can be used to determine the combat effectiveness payoff of specific technical trades identified in Section 6.2.

7. RECOMMENDATIONS

7.1 ADDITIONAL WORK IN THE ADI PROBLEM ARENA

SYNETICS recommends continuing the study through at least the next phase with particular emphasis on:

- Assessing the interactions of additional SP orientations and LP firing directions to determine the relative importance of coordinating the two within the LP fire control system
- Investigating variations in seeker field-of-view and missile maneuver limits to identify the interesting cases
- Building the interface to the SICM model and conducting at least a preliminary evaluation of the combat effectiveness of some of the concepts identified to date.

If the SP orientation/ LP firing direction interactions continue, there may be significant benefit to improving the computational capability LP fire control systems and their ability to present tactical information choices to the flight crew. Moreover, the presence of extensive interactions in realistic battle scenarios would be a convincing argument for distributing the surveillance data to all LRDF platforms and permitting decentralized battle execution.

The interesting endgame cases represent the regions with highest opportunity for incremental payoff in future weapon system engineering efforts. Comparing these regions with the parameters of particular weapon systems may help to focus future research efforts.

An m-on-n engagement model, such as SICM, is required to assess the potential combat payoff of the technological improvements identified so far in this study. The study is incomplete without an assessment of effectiveness using realistic engagement tactics.

We also recommend investigating the utility and feasibility of incorporating intelligence data within the SP tracking algorithms for use against the cruise missile class of targets. Such work in not specifically within the scope of the existing contract options, but it could be assigned as one of the undefined tasks in future years.

7.2 ADDITIONAL WORK IN RELATED AREAS

SYNETICS believes that two innovative features of this study should be evaluated for export to problems in related areas. In particular, we recommend:

- Evaluating the potential to use the information mixing concepts of Section 3.4 in other scenarios (e.g., bomber defense, relocatable targets, etc.)

- Investigating the utility of the improved endgame effectiveness analysis to other weapon system studies.

The hierarchical, decentralized approach to information mixing is relatively new and may be widely applicable on the modern battlefield when point-to-point communications links possess intermittent characteristics. The endgame formulation represents an improvement in its approach to handling the statistical quantities over published techniques.

REFERENCES

1. Aviation Week and Space Technology, 20 March 1990.

2. General Dynamics - Pomona, "The World's Missile Systems," 8th ed., August 1988.

3. "Jane's Weapons Systems, 1988-1989," Jane's Yearbooks, 1988.

4. "Navy Awarding $42M Contracts for Advanced Missile Demonstration," Aviation Week and Space Technology, 8 Feb 1988.

5. Forsberg, R., ed, "World Weapons Database, Vol I: Soviet Missiles," Institute for Defense and Disarmament Studies, 1986.

6. Gelb, A., ed., "Applied Optimal Estimation," MIT Press, 1974.

7. Golliday, C.L., "Data Link Communications in Tactical Air Command and Control Systems," IEEE Journal on Selected Areas in Communications, September 1985.

8. Nordwall, B., "Sweden Develops New Radar, Computer for Gripen and Airborne Early Warning," Aviation Week and Space Technology, 2 July 1990.

9. Galdos, J.I., J.M. Covino, and B.E. Griffiths, "Multi-Sensor Data Fusion Architecture for the Autonomous Endurance Vehicle (AEV)," *SYNETICS* Corporation, October 1989.

10. "Jane's All the World's Aircraft, 1986-87," Jane's Yearbooks, 1986.

11. Pollenz, R.S., and R.W. Keith, "Joint Tactical Information Distribution System (JTIDS) Operational Performance in the F-15 Theater Defensive Counterair Mission," Teledyne Brown Engineering, Report No. MD88-CECOM-0008, 10 November 1988.

12. Griffiths, B.E., and J.M. Covino, "Net Information Approach: Phase I Final Report," *SYNETICS* Corporation, May 1990.

13. Chang, C.B., "A Model of Sensor-Interceptor Trade-Off Analysis," Lincoln Laboratory, Technical Report 599, January 1982.

(This page is intentionally left blank)