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13. ABSTRACT *(Maximum 200 words)*

This final report covers a concept study conducted for the Defense Advanced Research Projects Agency (DARPA) Sensor Technology Office to develop a low cost weapon system concept to counter a proliferated cruise missile threat. The low cost and high accuracy of cruise missiles may make them the enemy weapon of choice in future conflicts. Our study focused on three main areas: 1) System Architecture Definition, 2) Interceptor (kill mechanism) Development, and 3) Performance / Cost Analysis, to define a weapon system concept and quantify its cost per kill relative to existing systems.

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06 October 1998

Lt. Col. Edward Gjermundsen, U.S. Air Force
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SUBJECT: Data Item Submittal

REFERENCE: (a) Contract No. MDA972-97-C-0008, MALD - Like Interceptor for Low Cost Cruise Missile Defense (LCCMD), CLIN 0002, CDRL A003, Final Technical Report

ENCLOSURE: (1) MALD-Like Interceptor for Low Cost Cruise Missile Defense (LCCMD) Final Technical Report, Revision A, Dated 05 October 1998 (1 copy)
(2) Raytheon TI Systems, Inc. DD Form 250 Number 735550 (1 copy)
(3) Raytheon TI Systems, Inc. DD Form 250 Number 735755 (1 copy)

Gentlemen:

Raytheon TI Systems, Inc. (RTIS) is pleased to submit enclosure (1) per the reference (a) requirements of the contract. The enclosure (1) submittal supersedes the Final Report dated 02 October 1998, and adds the DD Form 250 enclosures (2) and (3).

Enclosure (2) contains DD Form 250 Number 735550 for the LCCMD Final report, CLIN 002 of the reference (a) contract. Enclosure (3) contains DD Form 250 Number 735755 for CLIN 001 of the reference (a) contract. Please sign Block 21b of the DD Form 250s and return to RTIS.

The submission of this report and your acceptance of the DD Form 250s signify the completion of this contract's requirements.

Questions concerning contractual matters may be directed to Herman M. Flores at (972) 575-4414. Please direct technical or program related questions to Bill Daniels at (972) 575-5903.

Sincerely,

David Quinn

David Quinn
Data Manager

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Enclosure (1)
232-207-4094

MALD-Like Interceptor for Low Cost Cruise Missile Defense (LCCMD) Final Technical Report Revision A, Dated 05 October 1998

Contract MDA972-97-C-0008

CDRL A003

Sponsored by
Defense Advanced Research Projects Agency
Sensor Technology Office
MALD-Like Interceptor for
Low Cost Cruise Missile Defense

Issued by DARPA/CMO under Contract MDA972-97-C-0008

Prepared by:

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ABT	Air Breathing Threat
ACS	Actuator Control System
ADTOC	Air Defense Tactical Operations Center
AGL	Above Ground Level
BAA	Broad Agency Announcement
BLD	Blue Laydown
C.G.	Center of Gravity
CAP	Combat Air Patrol
CEC	Cooperative Engagement Capability
CEP	Circular Error Probability
CFCR	Centralized Fire Control Radar
CM	Cruise Missile
CMD	Cruise Missile Defense
COTS	Commercial Off The Shelf
CPI	Coherent Processing Interval
CpK	Cost Per Kill
DARPA	Defense Advanced Research Projects Agency
dBW	Decibel Watts
DF	Direction Finding
DMA	Defense Mapping Agency
DOF	Degrees of Freedom
DSP	Digital Signal Processors
EADSIM	Extended Air Defense Simulation
ECS	Engagement Control Station
EOD	Explodable Ordnance Disposal
ERIM	Environmental Research Institute of Michigan
ERP	Effective Radiated Power
ESA	Electronically Scanned Array
FCS	Fire Control System
FEZ	Fighter Engagement Zone
FOV	Field of View
FU	Fire Unit
G&C	Guidance & Control
GaAs	Gallium Arsenide
GEU	Guidance Electronic Unit
GPS	Global Positioning System
HFCR	Hypothetical Fire Control Radar
I&Q	In Phase & Quadrature
ICC	Information Coordination Center
IF	Intermediate Frequency
IMU	Inertial Measurement Unit
JFACC	Joint Forces Air Combat Commander
JLENS	Joint Land Elevated Netted Sensor
JSEM	Joint Services Endgame Model
LAR	Launch Acceptable Region
LCCM	Low Cost Cruise Missile
LCCMD	Low Cost Cruise Missile Defense
LMDS	Local Multipoint Distribution System
LNA	Low Noise Amplifier
LO	Local Oscillator
LR	Leak Rate
MALD	Miniature Air Launched Decoy
MB	Main Beam
MEMS	Microelectro Mechanical Systems
MER	Multiple Ejection Rack
MEZ	Missile Engagement Zone
MLI	MALD Like Interceptor
MMIC	Monolithic Microwave Integrated Circuit
NEA	Northeast Asia
O&S	Operation and System
Pk	Probability of Kill
Pmlc	Power in the Main Lobe Clutter
RCS	Radar Cross Section
RF	Radio Frequency
RMS	Root Mean Squared
S&A	Safe & Arm
S/N	Signal/Noise
SATCOM	Satellite Communications
SAW	Surface Acoustic Wave
SENGAP	Small Engine Advanced Program
SHORAD	Short Range Air Defense
SSPK	Single Shot Probability of Kill
STALO	Stable Local Oscillator
STO	Sensor Technology Office
SWA	Southwest Asia
TBE	Teledyne Brown Engineering
TBM	Tactical Ballistic Missile
TBMD	Tactical Ballistic Missile Defense
TP	Turn Point
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
WMD	Weapons of Mass Destruction

Final Report For Low Cost Cruise Missile Defense (LCCMD)

1.0 INTRODUCTION

This final report covers a concept study conducted for the Defense Advanced Research Projects Agency (DARPA) Sensor Technology Office to develop a low cost weapon system concept to counter a proliferated cruise missile threat. The low cost and high accuracy of cruise missiles may make them the enemy weapon of choice in future conflicts. Our study focused on three main areas: (1) System Architecture Definition, (2) Interceptor (kill mechanism) Development, and (3) Performance/Cost Analysis, to define a weapon system concept and quantify its cost per kill relative to existing systems.

2.0 EXECUTIVE OVERVIEW

Today, the worldwide total of cruise missile (CM) systems is in the tens of thousands, with rapid proliferation of technologically modest low cost cruise missiles (LCCMs). The threat can be widely distributed in time and space or concentrated into relatively small breakthrough raids. A defense concept must therefore be cost effective for a wide range of threat types, theaters, and scenarios.

This proliferated threat is assumed to have moderately small radar cross section (RCS), no countermeasures, or reactive maneuvers, and to fly as low as 100 meters over land and 30 meters over water such as the Chinese C-802 shown in Figure 1.

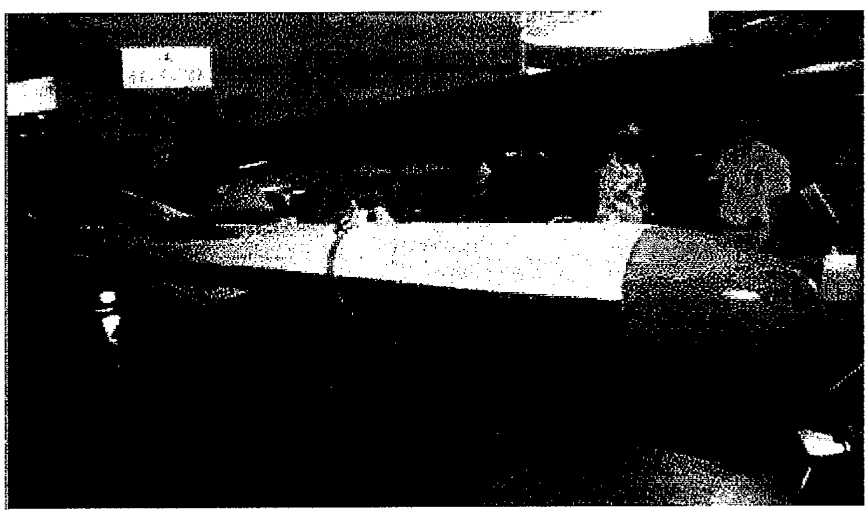


Figure 1. Chinese C-802

The challenge for this study was to conceptualize and quantify a low cost but effective defense concept against a wide range of raids of proliferated LCCMs. Defense system costs quantified in our study included not only expended cost but applied Operation and System (O&S) and allocated architecture asset cost. Effectiveness implies primarily low leakage rate but also long effective keepout range and system robustness to threat, scenario, and architecture excursions.

An advanced, long range threat detection and tracking capability was specified by DARPA for the study which is a key enabler for a new solution. The starting point system concept was to augment existing defenses with a very low cost, long range weapon tailored to match the threat and to capitalize upon the near real time remote targeting capability of the specified fire control system. More specifically, the concept was a low cost, long range air directed surface-to-air missile. To evaluate the architecture and operational concepts, we utilized the Extended Air Defense Simulation (EADSIM) to model a series of LCCM raids that ranged in size from 36 to 300 over relatively short periods of time. These test cases were evaluated in two theaters: (1) Northeast Asia and (2) Southwest Asia. We traded off architecture and laydown concepts, e.g., launcher type and placement, number of missiles, number of launchers ... ,interceptor designs, e.g., speed, range, single shot probability of kill (SSPK), and concepts of operation including fire doctrine and targeting/ retargeting to establish a baseline architecture. This architecture was used in subsequent simulations to quantify cost per kill and effectiveness. Our results indicate that at least a factor of five decrease in cost per kill while maintaining equivalent system performance is possible using our LCCM defense (LCCMD) system.

System Architecture Definition — As indicated in Figure 2, the concept assumes a long range fire control platform, such as a Joint Land Elevated Netted Sensor (JLENS), with long range tracking and targeting through a Patriot Fire Unit to in-flight LCCMD interceptors. The interceptors are launched to a basket from PAC 3 launchers (or from airborne platforms) upon threat identification and preliminary track by the fire control sensor or other surveillance systems. In order to achieve long range stand-off but assure long keepout ranges from forward positioned critical assets, launch on threat identification and preliminary track of a number of interceptors appropriate to the raid size allows the fewest number of launchers and the lowest flyout speed demands on the interceptor and therefore the lowest cost architecture. The LCCMD system features are listed in Table 1.

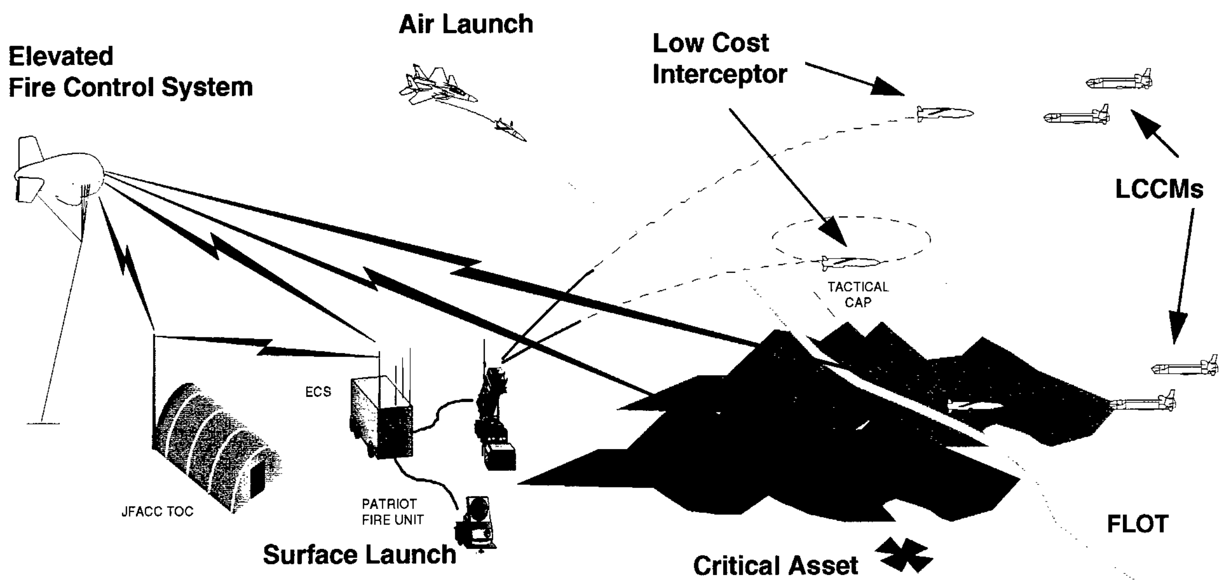


Figure 2. Long Range Fire Control Concept

The forward positioning of loitering interceptors at a location toward the predicted intercept point, like a tactical CAP, effectively provides, on command, the appropriate number and position of forward deployed launchers without the investment and support cost of actual ground deployment.

Table 1. LCCMD System Features

Approach	Advantage
Interceptor	
• Active Radar Seeker	• All Weather, Autonomous
• Jet Powered Vehicle	• Long Range, Low Cost
• GPS/Data Link Midcourse Guidance	• Minimum Burden on F/C Radar
• Warhead	• Lethality Enhancement
Architecture	
• Air Directed	• In Flight Targeting
• Integrated into Patriot AD	• Minimize O&S Costs
• Long Standoff Range, Layered Defense	• Flexible Deployment, Low leak rate, Minimize Cost per Kill

The primary question at the outset of the study was "how effectively could we define a low cost interceptor missile and concept of operation that provided sufficient performance and robustness to achieve the desired coverage, target acquisition, and kill capability?". To accomplish these objectives requires: (1) a significantly new interceptor seeker to meet the cost and performance objectives, (2) a new long range but very low cost delivery platform, (3) an innovative integrated interceptor design to achieve near hit-to-kill, and (4) a deployment concept that required minimal impact to existing air defense architectures yet achieved adequate coverage and redundancy in a wide variety of conditions.

The driving requirements for the problem as defined were the following:

- In order to achieve low leak rate for a low cost, moderate performance weapon, multiple shots per target must be provided for either by successive shots over an extended area, or very high speed fly-out, or by simultaneous engagements, i.e., salvo firings. This requires balancing launcher deployment, weapon speed, and costs of the interceptor and architecture.
- Long range keep-out emphasizes the need to achieve the required number of shots per target as early as possible in the incoming threat flight. This also affects the balancing among launcher deployment, weapon speed, and costs of the interceptor and architecture.
- Low system cost requires low expended cost, low delivery/launcher costs and low development, integration, and O&S costs. This requires minimizing the cost of modifications to the planned Air Defense infrastructure, minimizing the additional applied assets, while balancing the interceptor performance and cost.

The resulting most important trade-offs for the study evolved to the following:

- Interceptor performance versus cost (primarily seeker and platform costs)
- Leak rate and keep-out range versus architecture cost (primarily launcher cost).

The driving interceptor requirements are those that drive platform and seeker performance. To achieve low cost, we identified the requirements that typically drive cost (multi-mach missile speed, high transmitter power, gimbaled seeker, and complex analog receiver architecture) and selected the system architecture to reduce or eliminate these requirements. For example, a requirement for a small, light weight payload in an airframe with sub mach speed can be obtained with a minor modification to an existing low cost platform. Also, a moderate speed head-on engagement coupled with an accurate fire control handover cue allows a functionally simple seeker design. The iterative balancing of these requirements against cost was evaluated against the specific scenario and theater conditions to assess effectiveness and cost per kill.

Our LCCMD interceptor concept shown in Figure 3, is a low cost, air directed, all weather, missile that is based on a derivative of the miniature air launched decoy (MALD). The modified MALD like interceptor (MLI) has extended pitch and yaw maneuver capability so that it can engage air targets. A low cost 35 GHz radar was designed using micromechanical systems (MEMS) technology. The resultant strap down seeker uses an electronically steered array (ESA), commercial radio frequency (RF) components and digital signal processors (DSPs) to satisfy a $30 K design to cost goal.

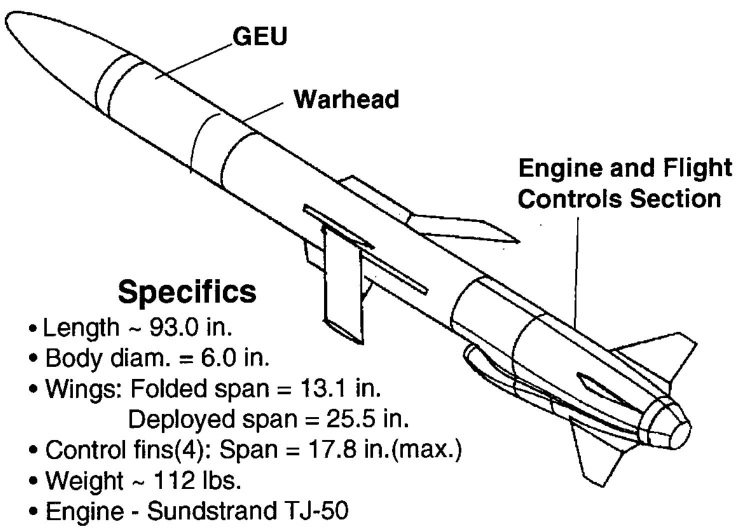


Figure 3. LCCMD Interceptor Concept

Interceptor Development — The block diagram in Figure 4 shows the key elements of our interceptor. The majority of the hardware (Airframe, engine group, warhead, battery, control system, RF, processor, comm-link, Global Positioning System/Inertial Measurement Unit (GPS/IMU)) could be assembled using today's off the shelf components. The aperture is based on emerging MEMS technology.

Airframe/Engine/Control System. The selected low cost airframe design that meets our baseline requirements uses conventional tail fin control with a mid-body wing. Folding wings mounted near the missile center of gravity (C.G.) provide near neutral pitch stability and minimize aerodynamic trim drag providing a high L/D ratio. This ensures long range interception capability or long loiter times, depending on the engagement scenario. Our MLI design also provides 8 to 10 "G" end game maneuverability which is needed for a 1 to 2 meter CEP. The MLI design is compatible with both air and surface launch. The MLI uses a SENGAP class jet engine, carries a 20 pound warhead, and can fly at mach 0.8 for over 20 minutes.

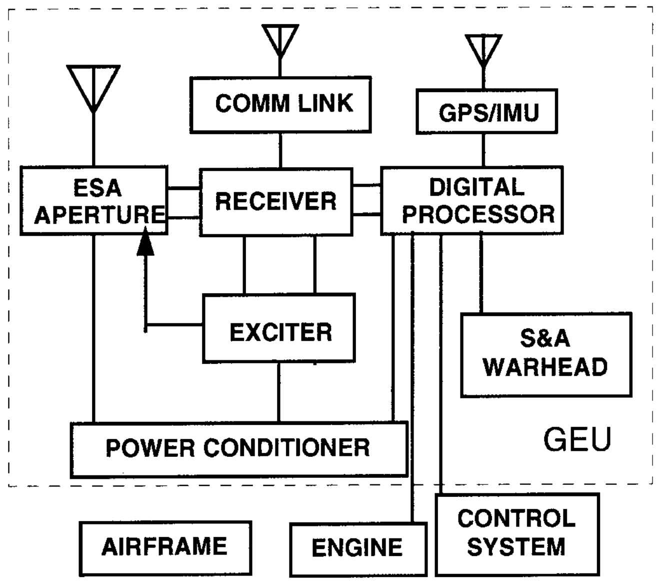


Figure 4. Interceptor Development Block Diagram

Guidance Electronic Unit (GEU). Based on the scenarios, target maneuvers, and expected CEP we designed a seeker architecture which uses a strap down active radar seeker operating at 35 GHz. The electronically scanned antenna (ESA) (illustrated in Figure 5) is comprised of linear subarrays that are stacked to produce a piecewise circular planar aperture. The Ka-Band seeker mockup is shown in Figure 6. Boresight directivity should exceed 33 dB and achieve more than 3.0 GHz operational bandwidth.

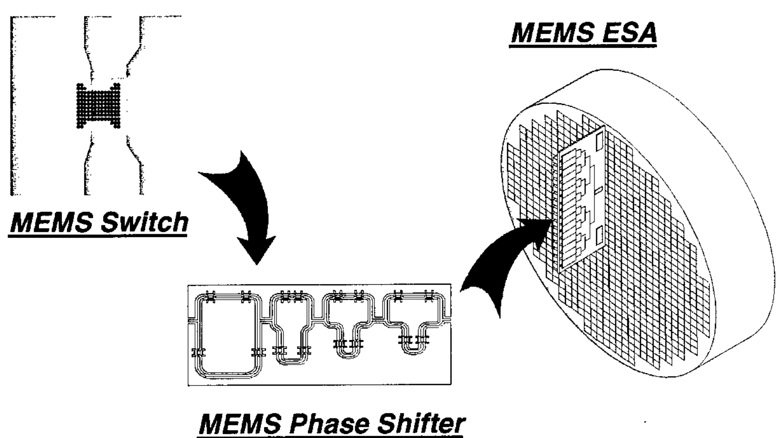


Figure 5. Electronically Scanned Antenna (ESA)

Low cost printed circuit antenna elements and commercial Monolithic Microwave Integrated Circuit (MMIC) power and low noise amplifiers are integrated with the MEMS phase shifters to complete the ESA. Based on our engagement model, 10 watts average power at 35 GHz satisfies detection and track requirements, even in adverse weather. This results in a requirement that each element must radiate 14 milliwatts.

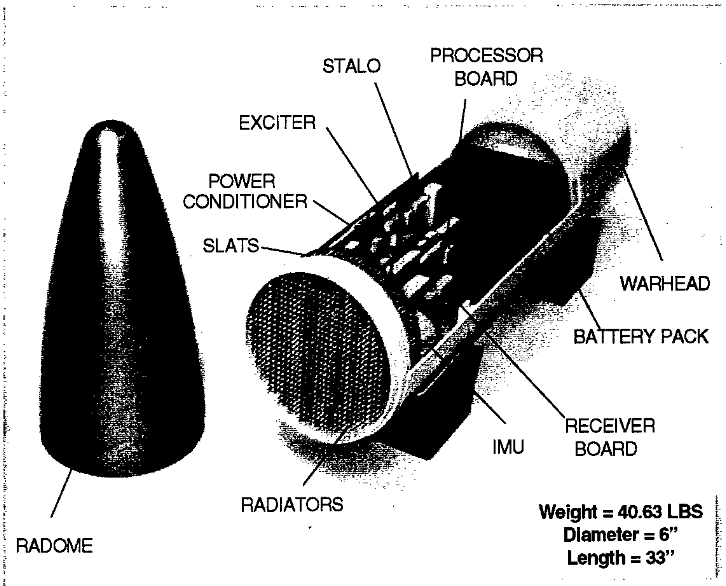


Figure 6. Ka-Band Seeker Mockup

Accounting for the insertion loss from the transmit amplifiers through the antenna and using a conservative 20 percent transmit amplifier efficiency, less than 200 watts of prime power will be used by the aperture. This includes the power needed by the low noise amplifiers (LNAs) and control electronics. The downconverter and frequency generators used in the receiver/exciter subassemblies also use commercial Gallium Arsenide (GaAs) MMICs.

Cost and Maturity. Several passes through a system design and technical feasibility process were made to baseline the lowest cost and risk interceptor. The most critical challenge is to build the seeker for under $30K. The main enabler is the use of a MEMS RF ESA that eliminates the skilled touch labor typically used to produce two axis mechanical scan antennas. After the MEMS ESA is demonstrated, this assures the potential to build a low cost, long range interceptor with an active terminal mode seeker for a "fly away " cost less than $80K. The major subsystem of the MLI and their relative maturity is shown in Table 2.

Table 2. MLI Major Subsystem with Relative Maturity

ELEMENT	MATURITY	COMMENTS
1) AIRFRAME	●	MODIFIED MALD
2) ENGINE GROUP	●	MALD
3) BOOSTER	●	HELLFIRE
4) WARHEAD	●	BLAST / FRAG
5) BATTERY	●	MALD
6) CONTROL SECTION	●	MODIFIED MALD
7) SEEKER		
APERTURE	○	KA-BAND MEMS ESA
RECEIVER / EXCITER	◐	DIGITAL RECEIVER
PROCESSOR	●	COTS DSP BASED
COMM	●	LOW DATA RATE
GPS / IMU	◐	XM982, ERGM
8) SYSTEM I&T	◐	AM^3 FACTORY

● PROVEN ◐ DEVELOPMENTAL ○ TECHNOLOGY

Performance/Cost Analysis — Two issues are key in determining the architecture effectiveness versus cost tradeoff. The first is "leak rate" which is the percent of incoming LCCMs in the raid that successfully penetrate defenses and arrive at the designated critical asset sites that were prescribed by representative geographical distributions in the test cases. Leak rate is statistically derived from the single shot probability of kill (SSPK)and the average total number of shots taken at each target. Historically, the interceptor design and engagement tactics versus expended cost trades converge to an SSPK within a fairly narrow range of 0.5 – 0.9. The second issue, is the number of shots per target. This is determined by the number of shot opportunities for each target and the fire doctrine regarding shots per opportunity. As a result, the key architecture tradeoff is the minimum cost laydown to achieve the number of shots per target required to achieve a desired leak rate.

In our study, we approximated a minimum cost solution for each theater by making minimal additions to the prescribed Blue Laydown for each case. Shown in Figure 7 is the general location of Patriot Fire Units and critical assets to be defended. The minimum cost additions were achieved by adding MLI launchers within the operational constraints of a Fire Unit. In some cases, for very low leak rate requirements it was required to add additional Fire Units. With the long flyout range of the MLI, we were able to effectively create layered defenses whereby outer rings were created on command by launching to outer waypoint positions upon threat identification, and then targeting each interceptor to a specific target whenever the threat entered the allowable engagement zone for that interceptor. Targets that "leaked" through the initial intercept attempt were reassigned to the next available interceptor within range. A second defense ring was defined, as required, by launching interceptors to intermediate waypoints to be in position to engage surviving leakers. Terminal point defense was utilized as the third layer where the critical assets were within range of the deployed Fire Units. By applying this minimum cost strategy, effectively any desired leak rate could be achieved. In all simulated cases a shoot-look-shoot tactic was used. However, in the case of a very low cost interceptor a shoot-shoot-look strategy would have small impact on the total system cost while allowing even lower achievable leak rates.

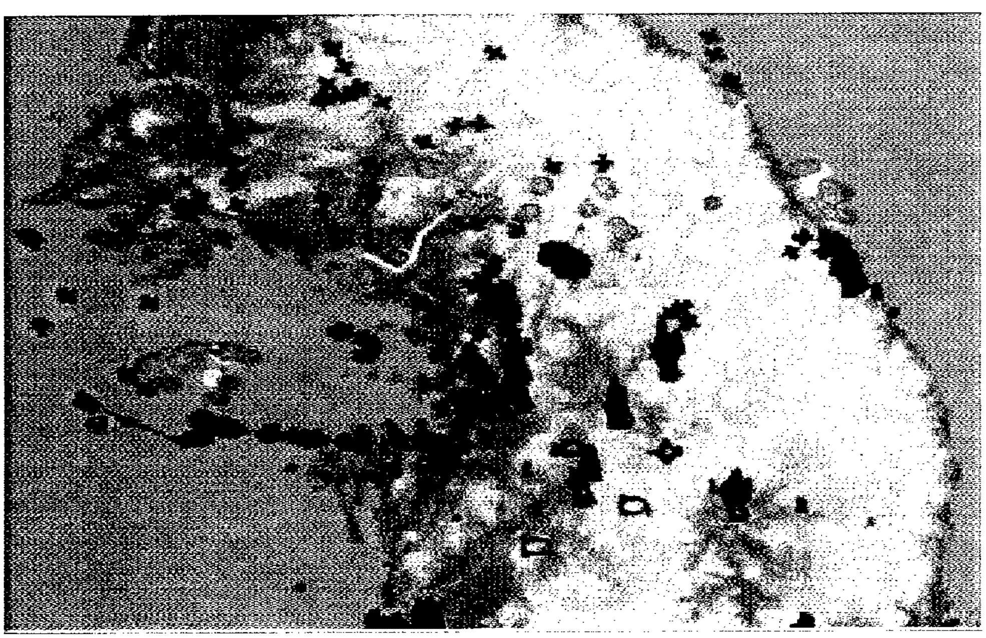


Figure 7. General Location of Patriot Fire Units and Critical Assets to be Defended

In the study, a large number of permutations of laydowns, leak rates, and interceptor design parameters were simulated for each of the theaters and raid sizes. We compared the leak rate and cost per kill with comparable cases where only proliferated Blue Laydown assets were applied. A representative sample of specific cases is shown in Table 3 where the statistical leak rate (LR) and the normalized cost per kill (CpK) are listed. As an example, for the Southwest Asia (SWA) theater, shown in the right column in Table 3, the 96 raid size case resulted in a 2 percent leak rate. From the simulation results, 144 Blue Laydown (BL) missiles were fired which for the cases in the table was the highest relative cost per kill (i.e. 100 percent). In contrast, the corresponding MLI plus 50 percent BL case had a 3 percent leak rate but at 22 percent of the cost. Also noteworthy are 300 raid size cases where for comparable leak rates the MLI plus 50 percent BL is a factor of 5.8 times lower cost than the BL case.

Table 3. Statistical Leak Rate and Normalized Cost Per Kill Representative Sample

Raid Size	NEA LR	NEA CpK	SWA LR	SWA CpK
	Blue Laydown Only			
96	2%	94%	2%	100%
200	5%	83%	8%	78%
300	11%	79%	12%	70%
	MLI + ≤ 50% Blue Laydown			
96	3%	22%	3%	22%
200	3%	20%	7%	16%
300	4%	23%	8%	12%

The results shown are representative only and do not present the optimized cost or leak rates achievable, however they do accurately depict the key relative comparisons, namely, that practically any desired leak rate can be achieved by providing the required number of shots per target for any of the architectures or laydowns. Cost, however, is a very strong dependent variable. The relative cost per kill shown in the table is a customer defined full cost, fair share parameter that is a complex function of the cost of applied, expended, and allocated assets as well as accounting for development, integration and O&S costs. By any accounting system the cost advantage of a low cost MLI LCCMD to counter the low cost cruise missile threat appears to be very substantial.

Conclusions — The remaining issues today are the risks of achieving the cost and performance potential of the innovative Ka-band seeker, and to a lesser extent, the performance and lethality of the integrated interceptor. We are currently pursuing risk reduction of the seeker implementation and look forward to the opportunity to prove the cost and performance of the integrated system. The concept is believed to be sufficiently robust to be scaleable to match the threat characteristics as they become better defined.

3.0 INTERCEPTOR TRADE STUDIES

Figure 8 shows the elements of the interceptor design trade process. The characteristics of the target and radar cue were provided by the Government and will not be repeated here. We defined the engagement geometries to optimize a tradeoff between cost and performance. The engagement geometry has been initially set for frontal intercepts only. This allows the use of a subsonic MALD like interceptor (MLI) and greatly simplifies the seeker design. In the last report, we showed the launch acceptable region (LAR) for the MLI and we used this in the many-on-many air war simulation (EADSIM). We used worst case (3σ) radar queues to test the limits of the MLI's ability to effectively neutralize the threat. This was accomplished through multiple runs of a six degree of freedom (6DOF) simulation.

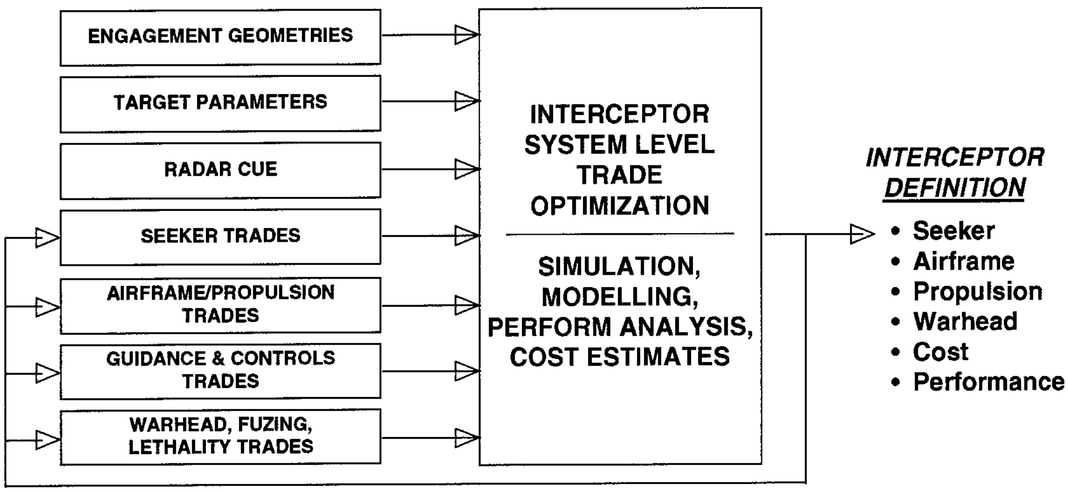


Figure 8. Interceptor Trade Space

The output of this iterative process will be detailed descriptions of the seeker, air vehicle, cost, and performance.

3.1 Seeker Trades

We have developed a look-down, shoot down radar model which was used to evaluate various seeker configurations. The two primary configurations are listed in Table 4. along with the defining parameters. Each configuration was designed to meet requirements flowed down from a parametric study of the guidance and control section and evaluated using the high fidelity 6DOF simulation. For the MALD like air vehicle maneuver capability, fire control radar cue error magnitude, and stated target characteristics, we determined that the seeker must have the target in autonomous track by 2 nmi to intercept and search an uncertainty cross range error of 1800 feet. Additionally, CEP predictions from the 6DOF simulations place a maximum standard deviation of 0.3 degree angle noise. As a starting point, we flowed down defining seeker requirements such as probability of acquisition, transmit peak power, noise figure, antenna patterns/gain, and carrier frequency. These preliminary flowed down requirements were iterated to optimize the hardware cost/performance tradeoff. The radar seeker simulation results are listed in Table 5. We used these parameters as input to a preliminary design for each of the major subassemblies (ESA, Receiver, exciter, etc.) to allow a sizing and costing effort. The radar simulation will model atmosphere attenuation, rain/ sea/land clutter, and multipath.

Table 4. Initial Input to the Radar Seeker Simulation

Parameter	X-Band	Ka-Band
Track Range (nmi)	>2	>2
Cross Range Error (feet)	1800	1800
Probability of Acquisition/Track	0.98	0.98
Angle Noise Floor (deg, 1σ)	0.3	0.3
Frequency (GHz)	10	35
Prelim Antenna Gain (dB)	21.5	33
Prelim Antenna Sidelobes	-13 dB	-16 dB
Prelim Transmit Peak Power (watts)	30	3
Prelim System Noise Figure (dB)	4.5	7.0
Maximum Rain Rate (mm/hr)	4	4

Table 5. Output Seeker Design Parameters from the Radar Simulation

Parameter	X-Band	Ka-Band
Required Detection Range (nmi)	2.7	2.7
Antenna Gain (dB)	21.5	33
Antenna Sidelobes	uniform	uniform
Transmit Peak Power (watts)	30	30
System Noise Figure (dB)	6	7
Dynamic Range	89	92
Number of Frequency Channels	9	9
Bandwidth (MHz)	200	200
Field of View (degrees)	50	50

3.2 Seeker Simulation

The air to air radar model used, had been adapted to simulate an active 6 inch diameter antenna ESA on a missile platform. The antenna has a uniform illumination pattern that results in approximately 17 dB peak sidelobes for the Ka-Band version and 14 dB for the X-Band antenna. The higher peak sidelobes in the X-Band version are primarily due to the limited number of elements (60) that are used to approximate the circular aperture. The sum and delta patterns are formed using a conventional monopulse comparator. During the simulations, both the target and the missile interceptor geometric fly outs are read from a data file which can be generated by a 6DOF simulation. This provides consistency in the engagements and although it does not provide a true end to end simulation, it provides a first order performance evaluation.

The clutter model is based on a normal land ERIM model. Other clutter models for sea and rough terrain are also being considered. Target radar cross section was modeled as a constant (exact value was provided by the Government) with Swerling 1 fluctuation statistics and a correlation time of 50 milliseconds. Glint was enabled for a target length of 5 meters, width of 3 meters, and diameter of 1 meter.

We used a high PRF waveform with a 33 percent duty factor. The processing loss of 2.9 dB includes straddle losses, threshold losses, quantization losses, and Doppler weight loss. We used a 5 millisecond coherent processing interval (CPI) that results in a 200 noise bandwidth. The model also included phase noise from the stable local oscillator (STALO), Doppler filter leakage and folding, and A/D timing jitter.

3.2.1 X-Band Seeker Simulations

The overall performance produced for a 30 watt peak power operating at 10 GHz and having a noise figure of 6 dB, produced overall performance illustrated in Figure 9. At approximately 2.5 nmi, the signal/noise (S/N) ratio was 10 dB. Target detects occurred before this range but this is used to illustrate the instantaneous dynamic range required by the digital receiver. The instantaneous dynamic range requirement can be assessed by measuring the power from main beam (MB) clutter present at the input to the receiver and also measuring the target power. As shown in Figure 9, the target power is 52 dB below the MB clutter. Since the target has undergone Doppler filtering with an associated 27 dB gain, the clutter to target ratio is 79 dB. Add an additional 10 dB for headroom and the requirement is 89 dB. This simulation also shows that STALO phase noise, jitter, and Doppler filter leakage do not compete with the target.

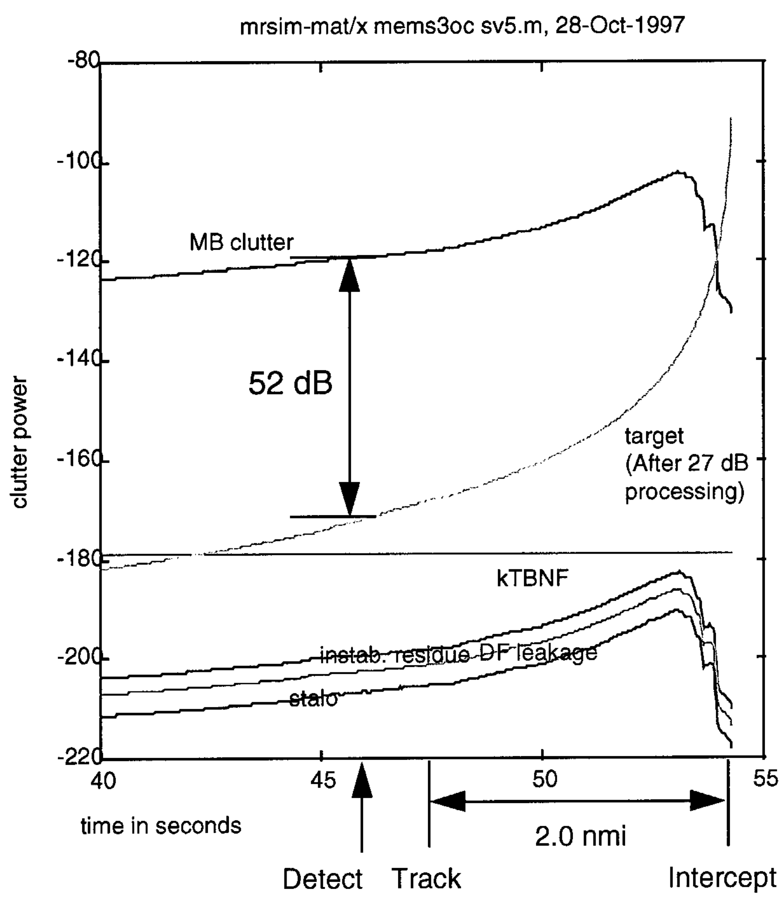


Figure 9. X-Band Seeker Performance

We performed extensive trade studies during the first half of this program using a 6DOF simulation. The objective of these studies was to determine the major contributors to miss distance from the guidance data output from the seeker. We found that the range dependent noise had less impact than the constant instrumentation noise that results from beam scanning, wave polarization errors, and channel tracking error. Figure 10 shows the elevation direction finding (DF) error versus time for the X-band seeker as the interceptor closes on the target. The 6DOF simulations indicate that if the RMS noise is less than 5 milliradians, the interceptor miss distance will be less than 1 meter. This level is achieved at 1 nmi to go. Without an end-to-end simulation, we have not proved that the X-band seeker angle noise is low enough to achieve a 1 meter circular error probability (CEP); however, the predictions shown in Figure 10 are very encouraging.

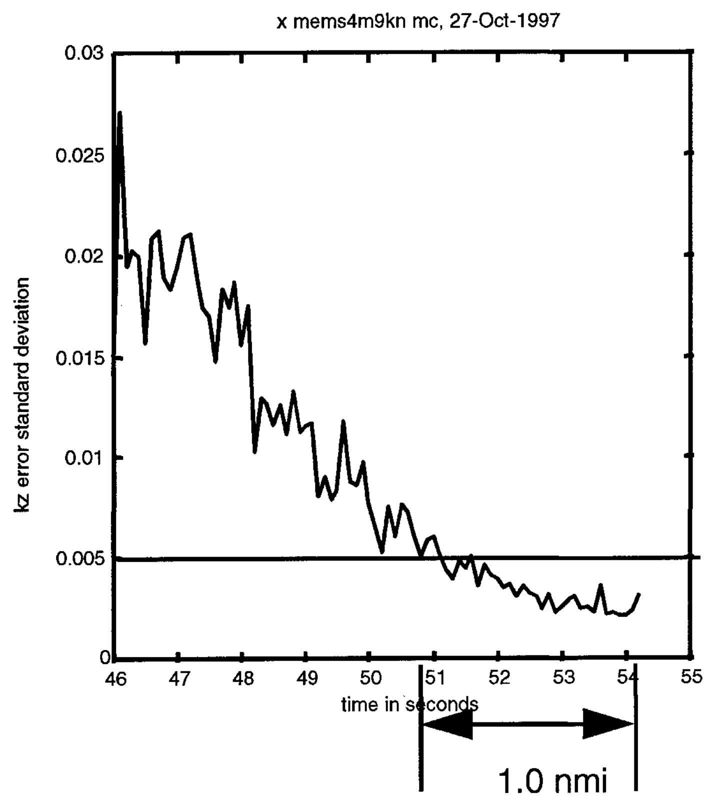


Figure 10. X-Band Elevation Angle Error vs. Mission Time

3.2.2 Ka-Band Seeker Simulations

A simulation for a 3 watt peak power operating at 35 GHz and having a noise figure of 7 dB, produced overall performance illustrated in Figure 11. At approximately 3.0 nmi, the S/N ratio was 10 dB. Target detects occurred before this range but this is used to illustrate the instantaneous dynamic range required by the digital receiver. The instantaneous dynamic range requirement can be assessed by measuring the power from MB clutter present at the input to the receiver and also measuring the target power. As shown in Figure 11, the target power is 50 dB below the MB clutter. Since the target has undergone Doppler filtering with an associated 30 dB gain, the clutter to target ratio is 80 dB. Add an additional 10 dB for headroom and the requirement is 90 dB. This simulation also shows that STALO phase noise, jitter, and Doppler filter leakage do not compete with the target.

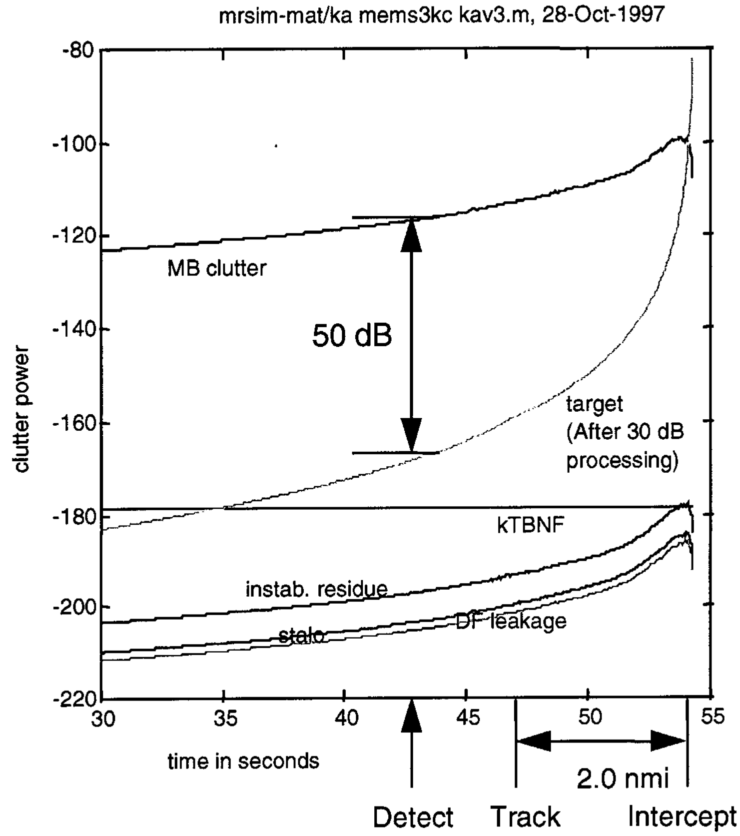


Figure 11. Ka-Band Seeker Performance vs. Mission Time

Using a 6DOF simulation we found the magnitude of angle noise that the guidance system could tolerate and achieve a CEP of less than 1 meter. Using the same source of error present in the X-Band seeker, with different values, Figure 11 shows the elevation DF error versus time for the Ka-Band seeker as the interceptor closes on the target. Since the 6DOF simulations indicate that an RMS noise level less than 5 milliradians provides an interceptor miss distance of less than 1 meter, we used this as a measure of acceptable performance. This level was achieved with 2 nmi to go. The predictions shown in Figure 12 are even better than the X-Band seeker and would have acceptable performance. An end-to-end simulation is required to prove that the Ka-Band seeker angle noise is low enough to achieve a 1 meter CEP.

3.2.2.1 Ka-Band Rain Clutter Effect on Seeker Dynamic Range

The RCS of rain is much larger at Ka-Band than at X-Band. At X-Band it is not a factor in determining dynamic range. At Ka-Band, depending on transmit power and antenna gain, it may be a factor. We used the closed form equation shown below to calculate the impact of 4 mm per hour of rain on the Ka-Band seeker. For this evaluation, we used a transmit power of 30 watts, since this level of power would be required at Ka-Band to overcome atmospheric attenuation. The power in the main lobe clutter (Pmlc) was -92.2 dBW and the noise is -174 dBW. This gives a clutter to noise ratio of 81.7 dB. If an additional 10 dB is added for headroom, the requirement is 92 dB. This is only slightly higher than the 90 dB requirement due to ground clutter.

$$Pt := 30 \qquad G := 2000 \qquad \lambda := \frac{3\cdot 10^{8}}{35\cdot 10^{9}} \qquad \eta := 1\cdot 10^{-5} \qquad RGW := 167$$

$$\theta b := \frac{\pi}{180}\cdot 3.4 \qquad Lbsc := .5 \qquad Lrad := .95 \qquad Rci := 267 \qquad Laci := .79\cdot .79$$

$$Pmlc := \frac{Pt\cdot G^{2}\cdot \lambda^{2}\cdot \eta\cdot (RGW)\cdot 2\cdot \pi\cdot\left(1-\cos\left(\frac{\theta b}{2}\right)\right)}{(4\cdot\pi)^{3}\cdot Lrad\cdot Lbsc}\cdot\frac{1}{Rci\cdot(Rci+RGW)\cdot Laci}$$

$$10\cdot\log(Pmlc) = -92.238$$

$$(10\cdot\log(200)-204+7)-10\cdot\log(Pmlc) = -81.752$$

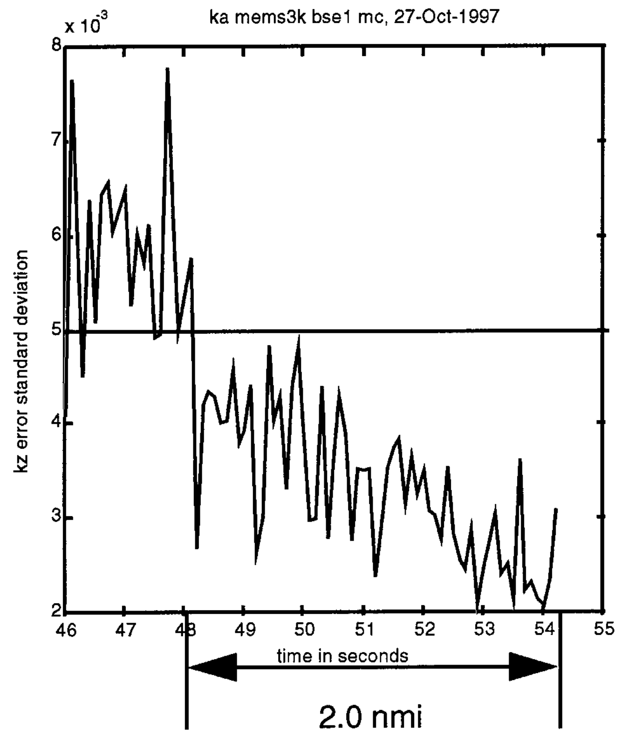


Figure 12. Ka-Band Elevation Angle Noise vs. Mission Time

3.3 Preliminary MLI Block Diagram

The system block diagram for the MALD Like Interceptor (MLI) is shown in Figure 13. The key subsystems in the radar seeker are the ESA Aperture, Receiver, Exciter, and Digital Processor. The additional subsystems in the guidance electronic unit (GEU) are the Comm Link, GPS/IMU, Power Conditioner, Battery, S&A, and Warhead will be discussed in the final report. The Control system, Actuators, Engine Group, Fins, and fuselage are adapted from MALD and have been discussed in prior reports. This report will focus on preliminary design work for the key radar seeker assemblies.

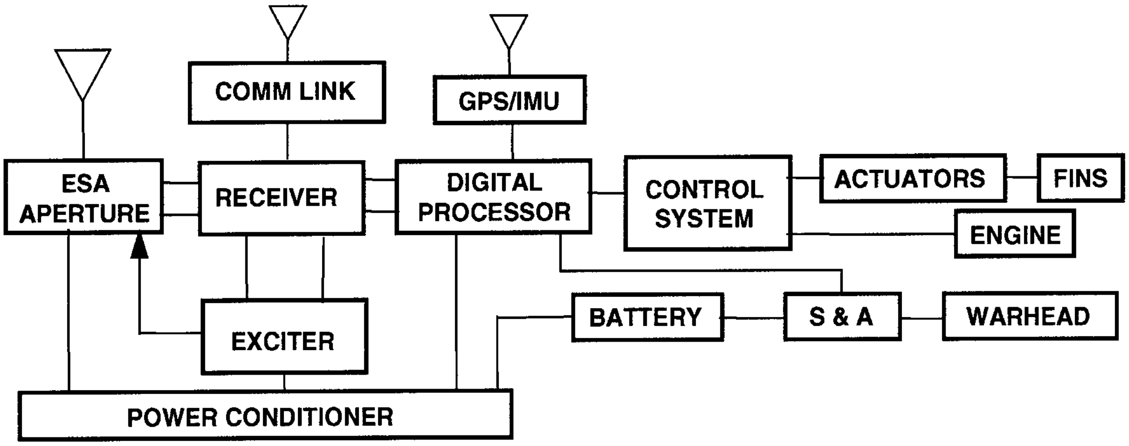


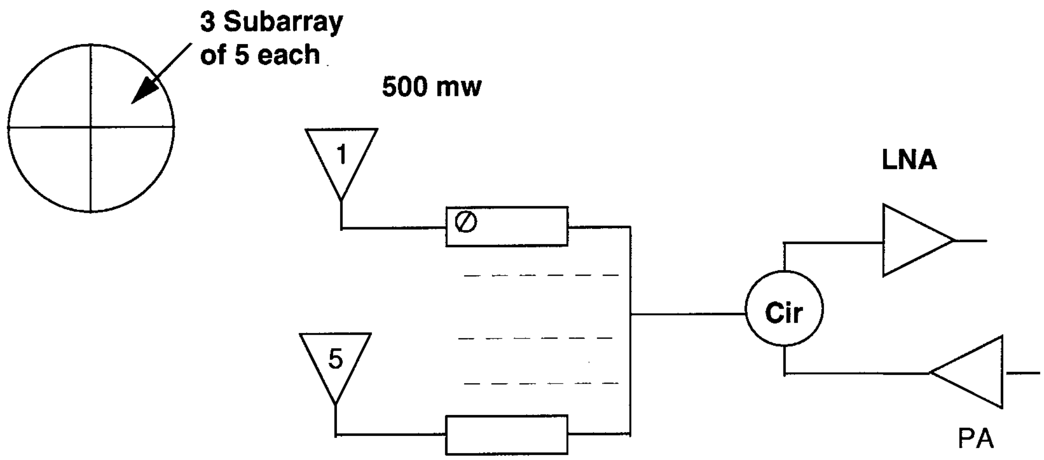
Figure 13. MLI System Block Diagram

3.3.1 X-Band Electronic Scanned Array (ESA) Preliminary Design

The X-Band ESA is comprised of 60 patch radiating elements spaced on a $\lambda/2$ rectangular grid and centered at 10 +/- 0.1 GHz . As shown in Figure 14, there will be four quadrants with three subarrays (4x3x5=60). The quadrants are used to form the monopulse beam (Sum, delta Az, delta El). Our seeker analysis (discussed in prior paragraphs) showed that no sidelobe reduction is needed beyond the patterns that result from using uniform illumination. Therefore, this aperture will have uniform illumination for both the transmit and receive modes. Since each element radiates 500 milliwatts of peak RF power, this ESA will radiate 30 watts. In conjunction with the element gain of 4.7 dB and the array gain of 16.8 dB, the ERP is 36.3 dBw. There will be approximately 2.9 dB of insertion loss between the output of the power amplifier and the radiator; therefore, the power amp should be capable of providing 5 watts peak RF power. There are several commercial off the shelf (COTS) MMIC chips that satisfy this requirement. The key element in the subarray is a MEMS 4 bit phase shifter. This phase shifter should have less than 2 dB insertion loss. For every dB of additional phase shifter loss, the power amp must deliver 2 dB of additional RF power to maintain the 2.7 nmi detection range on the target. A circulator is used to isolate the transmit and receive paths. The LNA should have less than a 2.1 dB noise figure. COTS GaAs MMIC chips are available that satisfy this requirement.

3.3.2 X-Band Receiver Preliminary Design

The receiver would have two channels using time division multiplex to share one channel with azimuth and elevation data. Each channel would use dual down conversion to translate the 10 GHz target return to an IF centered at 80 MHz. The 80 MHz would be directly sampled with a high speed A/D converter. We selected the first stage of downconversion to maintain a ratio of the local oscillator (LO) frequency to the RF frequency of 0.9. This ratio gives a spurious free bandwidth of 5 percent which is more than adequate for our 2 percent requirement. The majority of the components used in the receiver are COTS and adapted from the tremendous volume of microwave parts being supplied to the cellular telephone industry. Of the 89 dB dynamic range requirement at the seeker level, a 96 dB requirement has been allocated to the receiver. The components used in the design shown in Figure 15 are catalog items. We used the catalog performance specifications (gain, noise figure, compression point) and performed a cascaded component analysis to ensure the dynamic range requirement could be satisfied with these COTS components. Our analysis shows that the 96 dB can be achieved.



Loss Budet

Phase Shifter	2.0	db
5 way Ma	.4	
CIRt	.5	

	2.9	db

PA watts = (.500 x 5) + 2.9 db = ~ 5 watts

Figure 14. X-Band ESA Functional Block Diagram

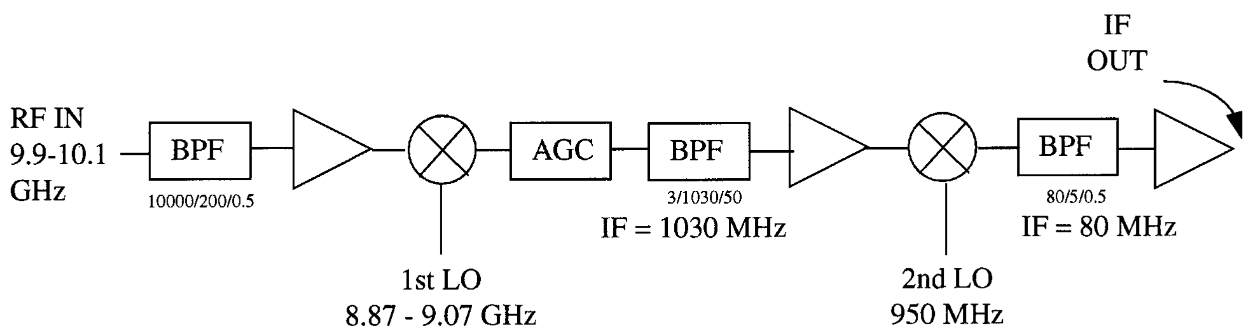


Figure 15. X-Band Receiver Functional Block Diagram

3.3.3 X-Band Exciter Preliminary Design

Our exciter design uses a UHF SAW oscillator as the primary frequency source. It is both multiplied, translated, and mixed with a 20 MHz crystal oscillator to produce nine different transmit frequencies in the 10 +/- 0.1 GHz frequency range. As in the X-Band receiver, we use a high percentage of catalog COTS components to realize the design. The SAW phase noise is extremely low. The plot of phase noise level as a function of frequency offset from the carrier was shown at the last review . After multiplication to 10 GHz, the contribution to system noise is negligible as shown in Figure 16. This SAW oscillator maintains low spurious even when subjected to mechanical vibration. These levels have not been quantified; however, preliminary analysis indicates suitability for our seeker application.

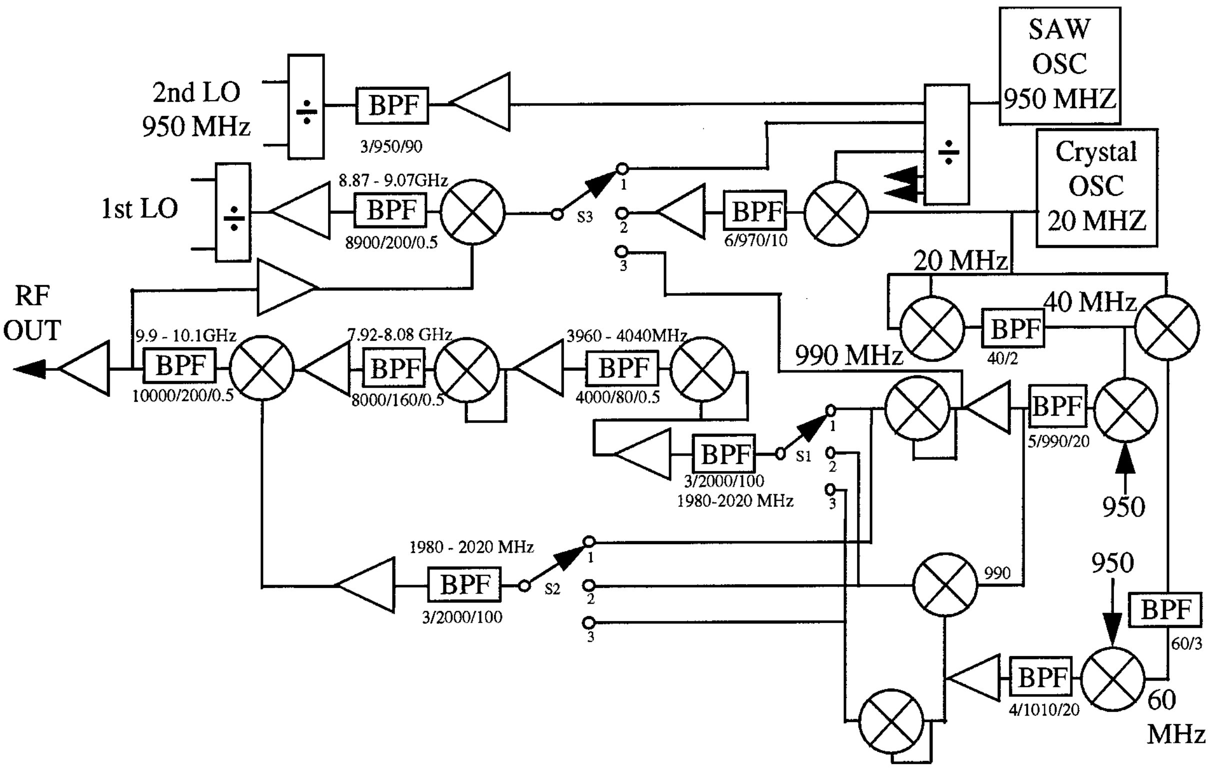


Figure 16. X-Band Exciter Functional Block Diagram

3.3.4 X-Band Digital Processor Preliminary Design

The digital processor is a departure from the conventional approach and makes use of the high throughput rate of emerging digital signal processor (DSP) technology. We developed a test bed digital receiver that employed IF sampling that digitizes an RF carrier. A 12 bit A/D operating at 20 MHz would effectively decimate the number of samples by a factor of four. A half band filter built by Harris converts the input 12 bit word to a 32 bit complex word. The in phase and quadrature (I&Q) components of the complex signal are generated by digital mixers in the half band filter. The digital data is then formatted to be compatible with a TMS 320C7x DSP. As a benchmark, this DSP can perform a 2048 point transform in 500 microseconds. There would be four C7x DSPs in the digital processor. They would perform all computations including windowing for the FFTs, FFTs, radome/receiver compensation, CFAR, Monopulse, clustering, tracking, auto pilot, receiver control, data link decode, and guidance integrated fuzing. A preliminary partitian of these functions is shown in Figure 17. Our processor would be software programmable and reconfigurable. This allows upgrades as improved algorithms become available and insertion or replacement of hardware as it becomes obsolete.

3.3.5 Ka-Band Electronic Steered Array (ESA) Preliminary Design

The Ka-Band ESA is comprised of 716 flared notch radiating elements spaced on a $\lambda/2$ rectangular grid and centered at 34 +/- 0.4 GHz. Figure 18 shows there will be four quadrants with 15 subarrays. The subarrays have between 8 and 15 elements each for a total in each quadrant of 179 elements. The quadrants are used to form the monopulse beam (Sum, delta Az, delta El). Our seeker analysis (discussed in prior paragraphs) showed that no sidelobe reduction is needed beyond the patterns that result from using uniform illumination. Therefore, this aperture will have uniform illumination for both the transmit and receive modes. Since each element radiates 43 milliwatts of peak RF power, this ESA will radiate 30 watts. In conjunction with the element gain of 4.7 dB and the array gain of 27.5 dB, the ERP is 47 dBW. There will be approximately 3.8 dB of insertion loss between the output of the power amplifier and the radiator; therefore, the power amp should be capable of providing 1.5 watts peak RF power. GaAs MMIC chips that satisfy this requirement have been demonstrated. The key element in the subarray is a MEMS 4 bit phase shifter. This phase shifter should have less than 2.5 dB insertion loss. For every dB of additional phase shifter loss, the power amp must deliver 2 dB of additional RF power to maintain the 2.7 nmi detection range on the target. A circulator is used to isolate the transmit and receive paths. The LNA should have less than a 2.3 dB noise figure. GaAs MMIC chips that satisfy this requirement should be available within the next year. Ka-Band amplifiers are rapidly being developed for the commercial digital communication market and this application will ultimately drive the price of these components down.

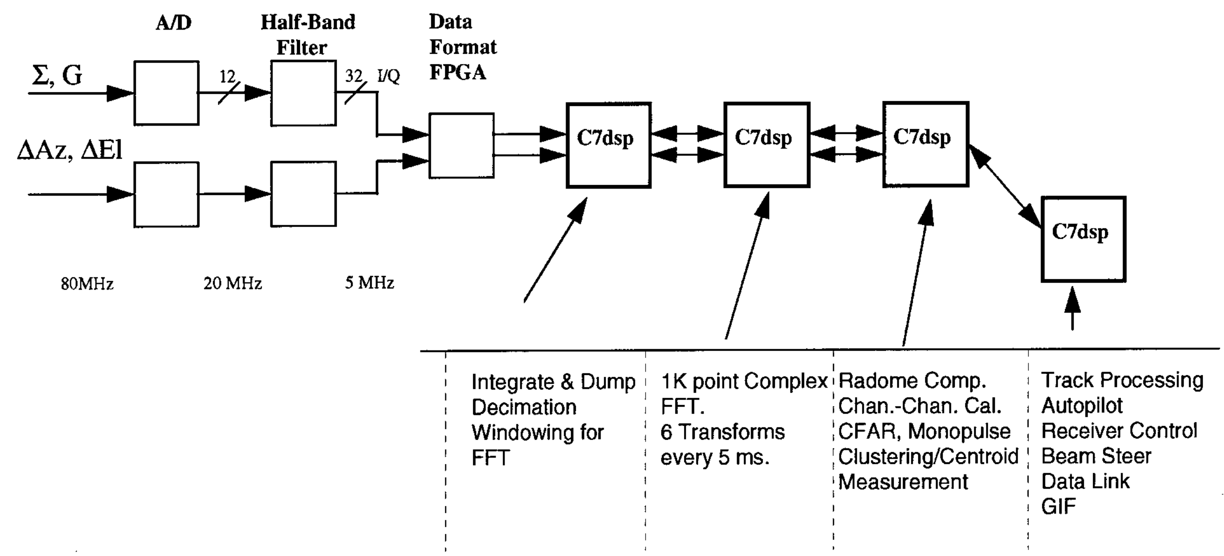


Figure 17. X-Band Digital Processor Functional Block Diagram

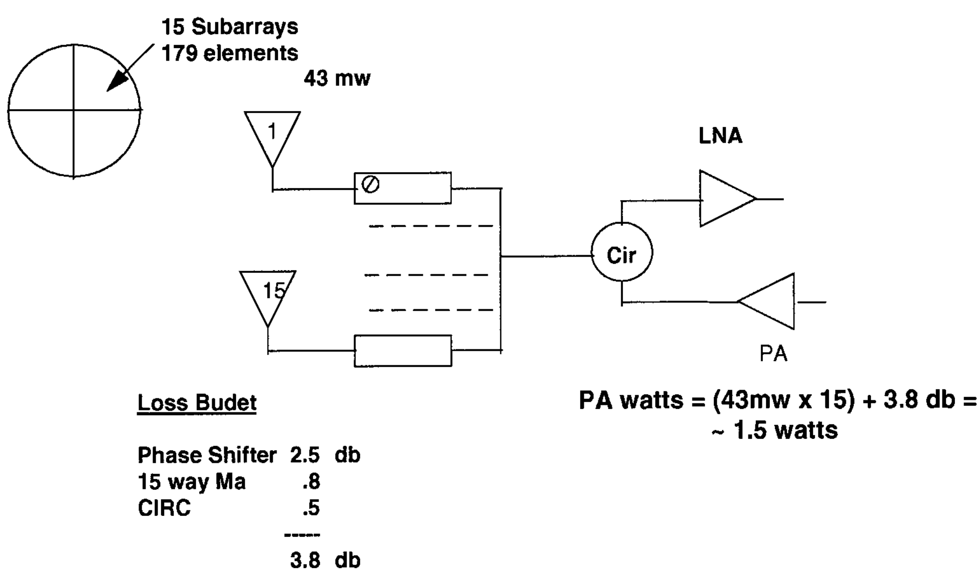


Figure 18. Ka-Band ESA Functional Block Diagram

3.3.6 Ka-Band Receiver Preliminary Design

This receiver would have two channels using time division multiplex to share one channel with azimuth and elevation data similar to the X-band design. As shown in Figure 19, each channel would use dual down conversion to translate the 34 GHz target return to an IF centered at 80 MHz. The 80 MHz would be directly sampled with a high speed A/D converter. We selected the first stage of downconversion to maintain a ratio of the local oscillator (LO) frequency to the RF frequency of 0.9. This ratio gives a spurious free bandwidth of 5 percent which is more than adequate for our 3 percent requirement. The majority of the components used in the receiver will be derived from COTS components currently in development for satellite communications (SATCOM) and LMDS applications. Of the 92 dB dynamic range requirement at the seeker level, a 93 dB requirement has been allocated to the receiver. We used flowed down performance specifications (gain, noise figure, compression point) and performed a cascaded component analysis to ensure the dynamic range requirement could be satisfied. Our analysis shows that the 93 dB can be achieved.

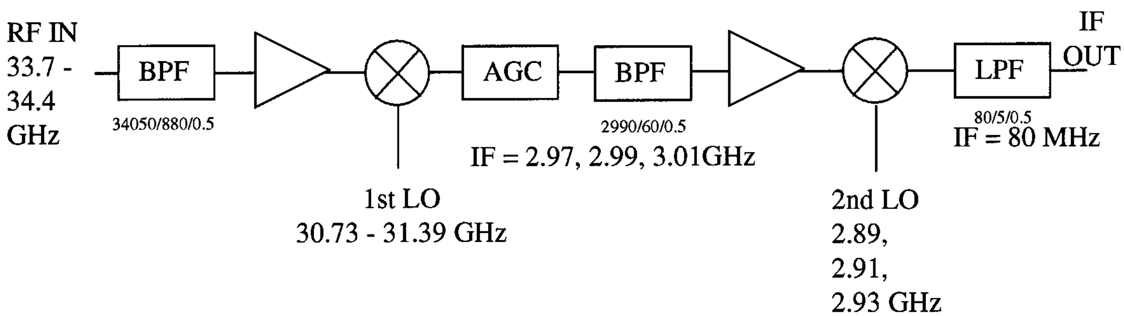


Figure 19. Ka-Band Receiver Functional Block Diagram

3.3.7 Ka-Band Exciter Preliminary Design

This exciter design uses the same UHF SAW oscillator we proposed for the X-Band exciter. It is both multiplied, translated, and mixed with a 20 MHz crystal oscillator to produce nine different transmit frequencies in the 34 +/- 0.4 GHz frequency range. As in the X-Band exciter, we use a high percentage of catalog COTS components to realize the design. The SAW phase noise is extremely low and when multiplied by an effective factor of 36, the contribution to system noise is negligible as shown in Figure 20. This SAW oscillator maintains low spurious even when subjected to mechanical vibration. These levels have not been quantified; however, preliminary analysis indicates suitability for our seeker application. Further analysis is being performed to determine improved Ka-Band synthesizer architectures.

3.4 Airframe/Propulsion Trades

We obtained engine thrust and fuel flow tables from Sundstrand for their TJ-50 engine. This data was used to determine flight speed and range for various flight altitudes and temperatures. The trade parameters are listed in Table 6. CEP has been used as the dependent variable in the majority of G&C trade studies. When the 6DOF simulations are performed, the maneuverability of the MLI in some cases sets the limit on the lowest CEP. Maneuverability is determined to a large extent by the responsiveness of the actuator control system (ACS) and the aerodynamic properties of the airframe. After performing a trade study on the ACS, shown in Table 6, we determined the bandwidth and slew rate requirements that keep the CEP low. The settings on the ACS provide a nominal air vehicle maneuverability (7.5 Gees Yaw and 12 Gees pitch plane) which was used on all the subsequent 6DOF simulations. A trade study was conducted to determine the pitch and yaw Gee requirements to determine if they can be relaxed from the baseline 12 Gee pitch plane and 7.5 Gee yaw plane requirements. The analysis was based on "time to go" when the target pulls a 2 Gee maneuver. If the target pulls a maneuver with less than 1.5 seconds to go, our analysis indicates that a 4 Gee pitch and yaw maneuver limit will produce a CEP less than 1 meter. If the target pulls a maneuver with 3 seconds to go, we need at least 6 Gees in each plane but a more robust requirement is 7.5 Gees in each plane. This is illustrated in Figure 21 for a parametric study of five different time to go simulations.

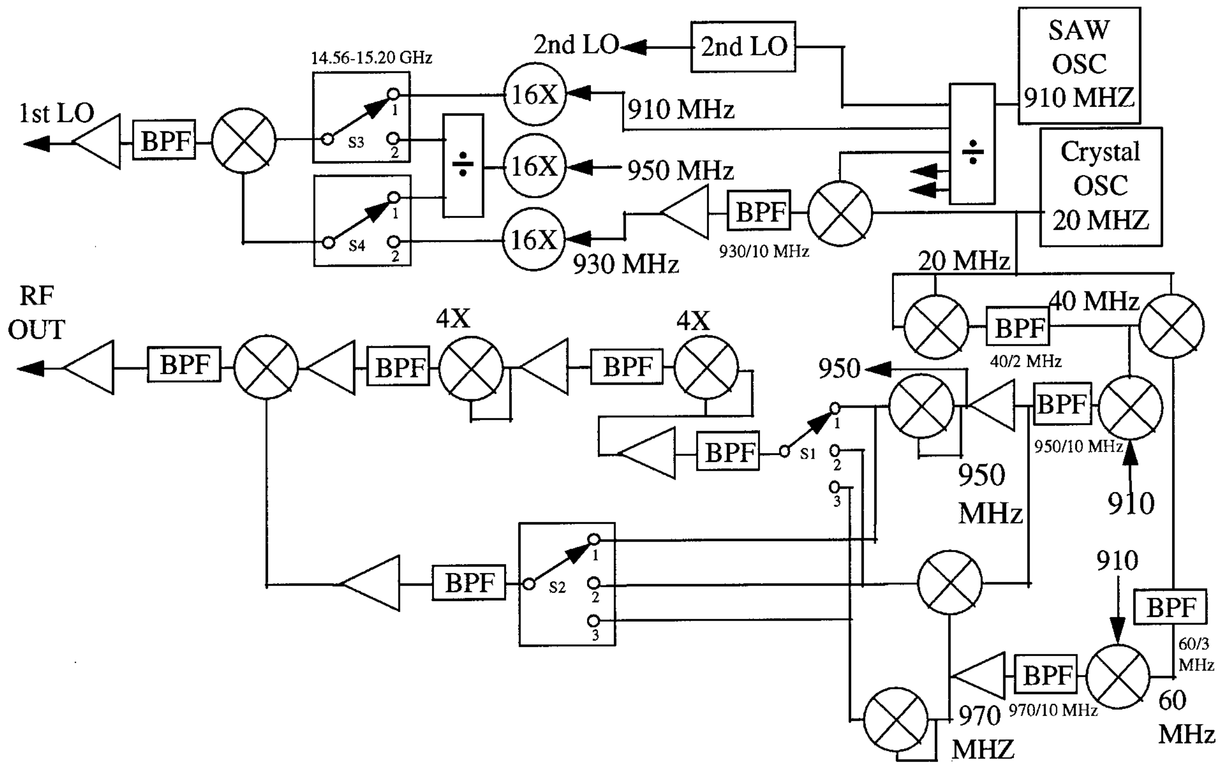


Figure 20. Ka-Band Exciter Functional Block Diagram

Table 6. Actuator Control System Trade Space

Factor	Minimum	Nominal	Maximum
Bandwidth (Hz)	5	20	40
Slew Rate (deg/sec)	200	200	900
Deflection (+/- deg)		20	
Hinge Moment (inch- lb)		25	
Position Accuracy (deg)		0.25	
LSB (deg)		0.1	
Linearity (%)		5	
Power (watts)		18	

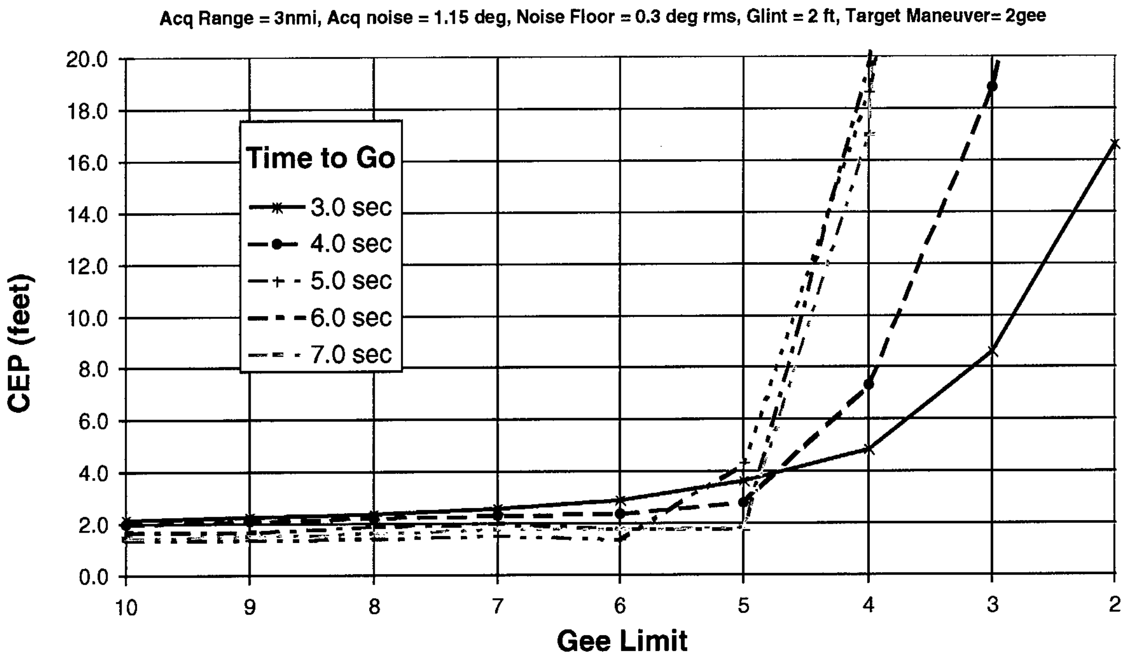


Figure 21. Airframe Gee Requirement Parametric Study

Table 7 has been modified to reflect our performance requirements for the airframe.

Table 7. Airframe/Propulsion Trade Space

Parameter	Minimum	Nominal	Maximum
Engine Thrust (lbs)	50	50	90
Pitch Gee Capability	4	7.5	12
Yaw Gee Capability	4	7.5	7.5
Air Temperature	Cold Day	Normal Day	Hot Day
Dive Angle	0	30 deg	30 deg
Cruise Altitude (ft)	90	20,000	30,000
Payload Weight (GEU + Warhead) (lbs)		41	
Diameter (in)		6.0	7.0

We determined that the TJ-50 engine and a cruise altitude of 20,000 feet meet our speed and range requirement of mach 0.75 and 100 nmi respectively.

3.5 Guidance & Control Trades

Prior to conducting this study, we upgraded the 6DOF model to generate the trajectory shaping used in the "dive to kill" intercepts. This was accomplished on previous simulations using a MATLAB routine to generate target and interceptor flight profiles and then inputting this data file to the 6DOF simulation.

Table 8 shows the list of parameters evaluated in the study. This study was conducted primarily to determine the major contributors to miss distance (CEP). The suspect error sources were range dependent and independent angle noise. We found that the range dependent angle noise has a small contribution to CEP and that the range independent angle noise has the dominant effect. An example of a parametric study for three interceptor configurations is shown in Figure 22. This shows that the 50 pound thrust engine with a 30 degree dive from a 20,000 foot cruise is as effective as a 90 pound thrust engine at maximum throttle in a co-altitude engagement of the target. This figure also shows that the 50 pound thrust engine is not adequate in the co-altitude engagement. Additionally, we found that 0.3 degrees of angle noise will create less than 4 feet of miss distance 50 percent of the engagements. We used this study to flow down the angle noise requirement to the seeker.

Table 8. Initial Input to the 6 Degree of Freedom (6DOF) Simulation

Parameter	Min	Nominal	Maximum
Acquisition Range (nmi)	1.0	2.0	3.0
Cross Range Cue Error (ft)	0	1200	2400
Noise Floor (1 σ)	0.0	0.1	1.0
Acquisition Noise (1 σ)	0.0	1.15	2.0
Glint (ft)	0.0	2.0	2.0
Gyro Errors (Bias, scale factor, noise)		0.4 mr/sec, 0.6%, 1.2 mr/sec	
Accel Errors (Bias, scale factor, noise)		0.66 ft/sec^2, 0.6%, 1.3 ft/sec^2	
Seeker Update Rate (Hz)		40	
Target Maneuver (Gees)	0.0	2.0	4.0

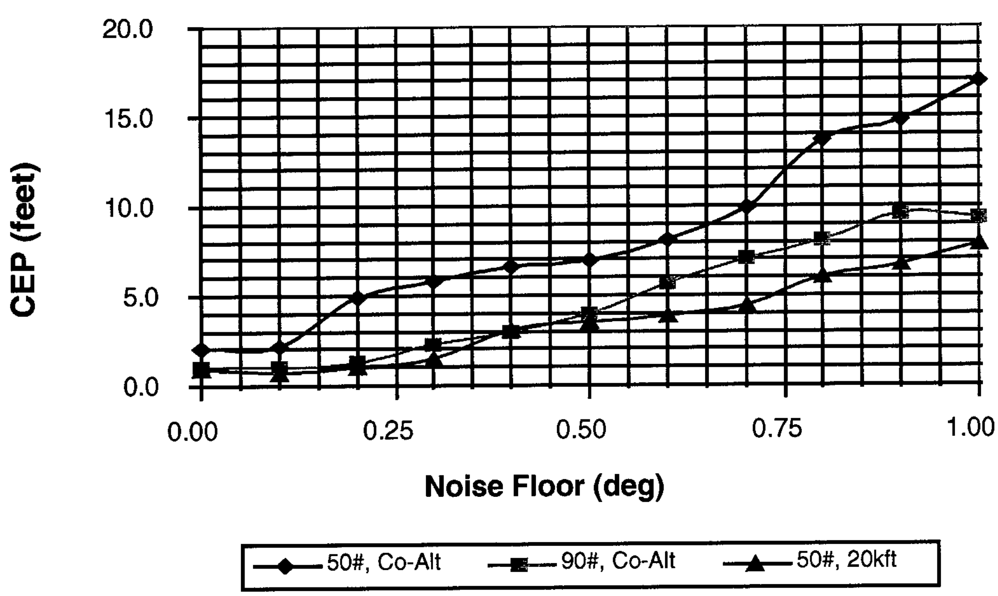


Figure 22. 6DOF CEP Predictions versus Range Independent Angle Noise with Engine Thrust and Engagement Geometry as a Parameter

3.6 Warhead, Fuzing, Lethality Trades

We used the Joint Services Endgame Model (JSEM) to evaluate several kill mechanisms. We investigated three different warhead designs that can produce the required effects. The first two rely on fragments as the damage mechanisms and the third warhead employs a shaped charge jet that is implemented in a novel manner and is highly lethal against an LCCM.

The LCCM consists of both types of components, but the majority of the presented area consists of relatively hard components (e.g., warhead, fuel, engine) along with the "softer" navigation and guidance components in the forward section. In the absence of adequate detailed target descriptive information about the LCCM, we reviewed the fragment damage functions currently being used for U.S. Air Force analyses of a modern air-to-air missile against an aircraft target. From this review we concluded that fragments of less than 60 grains would not realistically result in reasonably high kill probabilities for most of the LCCM components. Consequently, we used 60 grains as our baseline warhead design guide. We used this size for all fragmenting warheads to maintain a consistent basis for comparing the designs. It should be noted, however, that when better target information is available, modifications to our warhead concepts can be readily accomplished, if necessary.

3.6.1 Cylindrical Warheads

By using an energy density analysis for a warhead detonating on or near the CEP plane, we designed six warheads, three that can meet the performance requirements for a threshold of 25,000 ft-lbs/sq.ft. across a linear foot. Next, using the number of fragments and the required velocities, warheads were designed to produce these effects. The energy densities for these cylindrical warhead concepts are shown in Figure 23 and the general characteristics of these warheads are presented in Table 9.

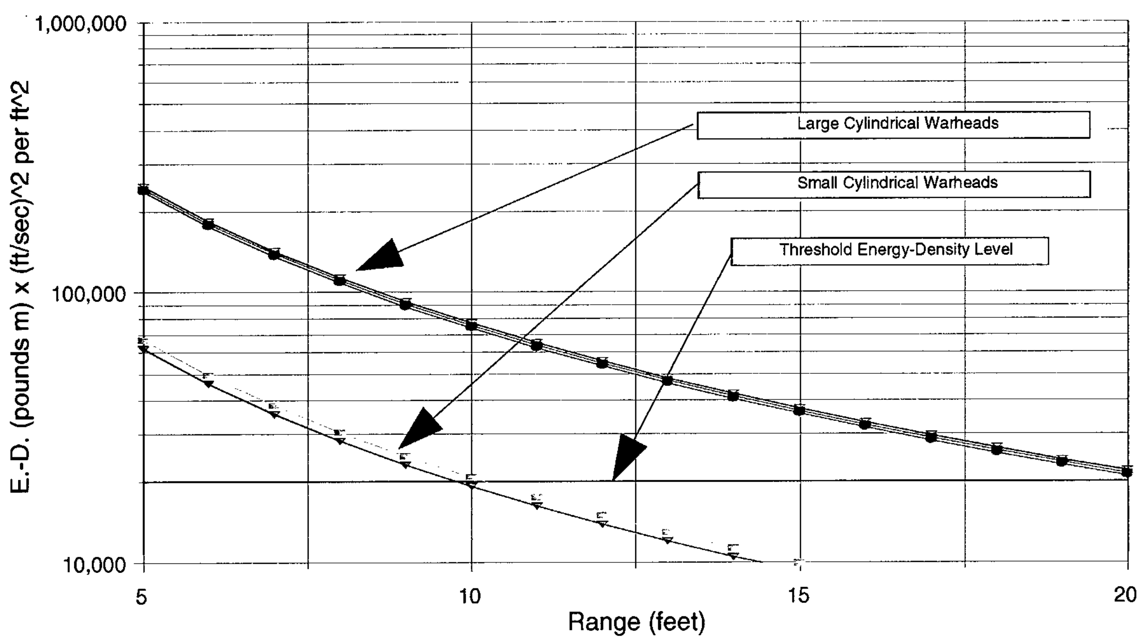


Figure 23. Energy Density vs Range for Cylindrical Warheads

Table 9. Cylindrical Warhead Trade Space

Design	Number of Fragments	Frag Vel (ft/sec)	Warhead length (inches)	Warhead diameter (inches)	Warhead weight (pounds)
1	2200	8000	14.0	6.0	41
2	3000	7000	21.8	4.8	46
3	4000	6000	38.3	3.6	52
4	525	8000	3.4	6.0	10
5	750	7000	5.4	4.8	11
6	1100	6000	10.5	3.6	14

As shown in Figure 23, the large cylindrical warheads produce the required energy density levels beyond 17 feet, and the smaller ones produce these effects beyond 8.5 feet.

3.7 Interceptor Cost Analysis

For the LCCMD study, we used parametric cost estimating tools to build cost models for the recurring and nonrecurring program elements. The primary computer model used was the PRICE Systems Computer Aided Parametric Estimating tool. We use the PRICE parametric cost models for estimating costs for proposals and to set design to cost benchmarks on-going contracts. This modeling capability allows design trade studies, risk and sensitivity analysis, manufacturing process capability benchmarking, and a tops down versus bottoms up cost stack up analysis.

The PRICE tool set has been used on other DARPA programs (Rapid Specific Signal Processors). The toolkit contains thousands of interactive equations providing the ability to model the full range of products: simple hardware, very complex hybrid microcircuits, and software. Our modeling included the complete product life cycle which takes into variables such as: manufactured items, purchased items, customer furnished items, NRE, multi-lot breaks, loss of learning, lot-to-lot learning, schedule, (compression, stretch, overlap, etc.), reliability/MTBF yields, degree of automation, programmer productivity, software languages, multilevel integration, financial factors (inflation, overhead, administrative, etc.), and technology improvement projections. Additionally, Raytheon was the first defense contractor to receive and implement single-process initiative approval from the government. This was a block change to convert missile manufacturing to all-commercial processes.

The major interceptor subassemblies that comprise the interceptor are shown in Figure 24. The guidance section is the largest cost element and for the configurations considered in this study typically accounted for 75 percent of the interceptor cost.

For the Ka Band MEMS ESA configuration, the cost of the guidance section was not driven by one subassembly as shown in Figure 25. Our cost projections indicate that for a 3000 quantity build, the seeker unit cost should be less than $30,000.

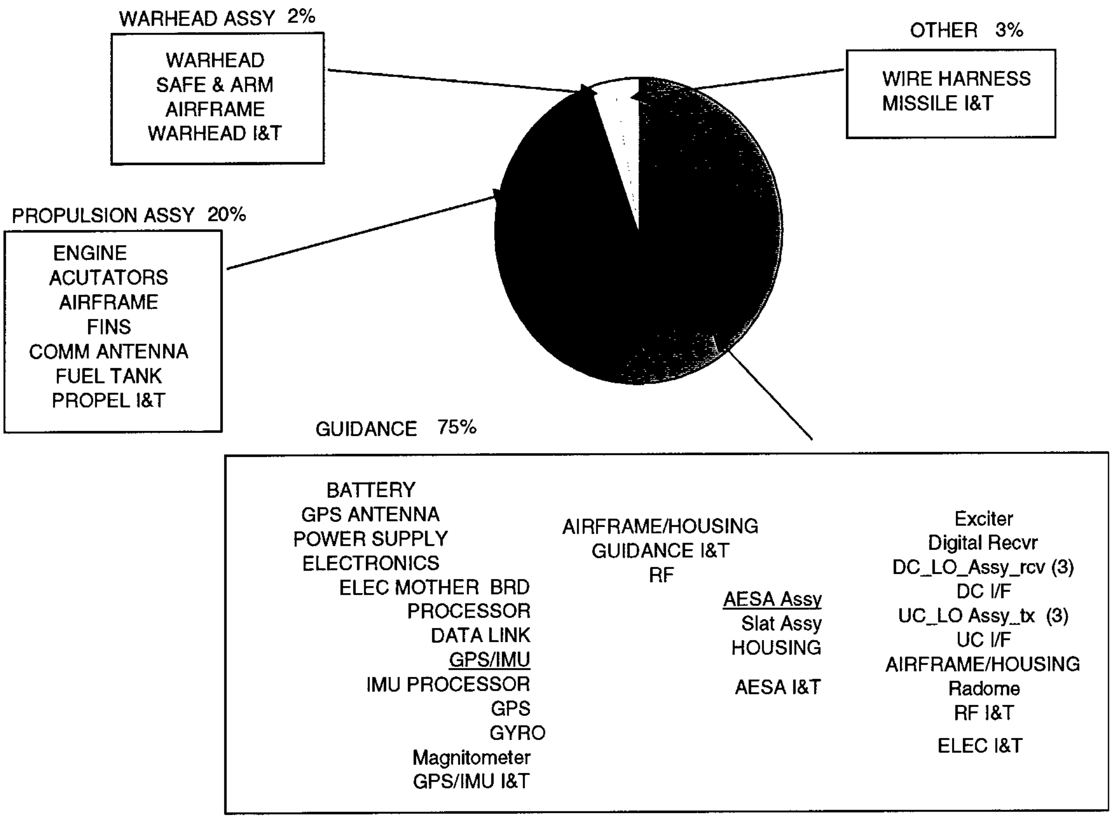
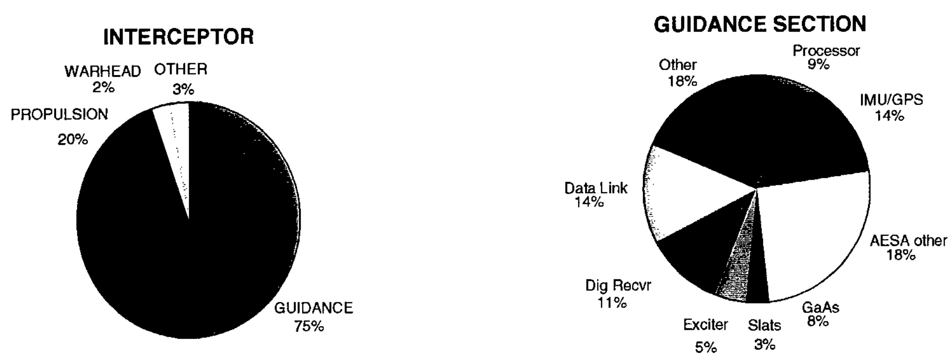


Figure 24. Interceptor Cost Breakout as a percentage of Total Cost



INTERCEPTOR CONFIGURATION

50 # THRUST ENGINE (SENGAP TYPE)
10 WATT Ka BAND SEEKER (MEMS)
C/A & P/Y CODE GPS
MICRO-OPTIC GYRO's

Ka BAND AESA
-64 SLATS
-716 MEMS PHASE SHIFTERS
-60 POWER AMPS
-60 LNA's

DIGITAL Rx
- 3 CHANNEL RADAR PROCESSOR
- FFT ASIC & 3 C7x DSP'S
- 1 CHANNEL COMM
- FPGA INTERFACE TO CAS, GPS

Figure 25. Guidance Section Unit Cost Breakout as a percentage of Total Cost

4.0 ARCHITECTURE EFFECTIVENESS AND COSTING ANALYSIS

4.1 Architecture Trade Studies

The system analysis implementation we pursued was a two step process: first, refine the modeling methods within EADSIM to better simulate the MLI engagement process and refine the employment processes necessary to integrate MLI seamlessly into the ground-based air and missile defense architectures using the NEA and SWA Scenarios; and then, conduct monte-carlo analysis for both scenarios to examine military utility, cost-per-kill, and system sensitivities to variations in MLI performance parameters.

4.2 Modeling Refinements

We developed front attack only constraints within the engagement planner necessitated by the MLI LAR. We added a multiple layered command structure within the Flexible Commander rule set to enable use of fighter rule sets to simulate MLI launch-to-CAP employment capability while enabling centralized engagement deconfliction. The ground launched MLI is characterized by an aircraft which flies a constant speed both for initial launch and flyout to intercept. The Pk is set as a nominal Pk over the entire region. The aircraft has a single air launched missile which it launches within 1-2 km of the threat. The MLI (aircraft) maneuvers to a point that allows a head-on engagement to occur. It approaches at altitude and commences a dive. Once the threat is engaged, the aircraft (MLI) returns to base since it has no more kill capability. These refinements provide a close representation of the centralized architecture engagements.

4.3 Architecture Considerations

Area coverage by an aerostat mounted fire control system operating from 3 km – 5 km above ground level (AGL) is roughly a 200-250 km radius. This covers a land area that might possibly be defended by up to 12 or more Patriot fire units. Thus, capitalizing on the existing C2 inherent in the Patriot air defense architecture makes sense. This argues for maximum use of the Patriot radar and ECS in conduct of the engagement while using the Aerostat mounted centralized fire control radar (CFCR) as a contributing sensor and relay platform.

The method of detecting, tracking, processing engagement information, and controlling the missile in-flight can be accomplished in a number of different architectures. The architecture described herein attempts to minimize overall costs and to take advantage of existing systems while maintaining the greatest combat effectiveness.

4.3.1 Ground Application

The MLI missile is resident on Patriot modified launchers. Engagement calculations are made by the firing battery Engagement Control Station (ECS). Track information on the threat is provided by the organic battery radar, MPQ-53, and the remote sensors such as the AWACs and the Aerostat acquisition and tracking radar. Patriot currently only calculates firing solutions for tracks provided by its own radar. With incorporation of the Cooperative Engagement Capability (CEC), Patriot will be able to calculate engagements based upon remote sensor track information. This will allow the Patriot launched missiles to engage targets beyond radar line-of-sight and allow Patriot to provide guidance commands to missiles outside the organic radar coverage through use of an airborne relay. This modification, if it occurs, will probably not be available before 2003.

Currently, operations with the PAC-3 missile require that the missile be within the Patriot radar field of view until the PAC-3 missile sensor acquires the target for final engagement. Remaining within the (FOV) of the radar allows it to provide guidance commands to the PAC-3 until acquisition is made by the active seeker on the missile.

To take advantage of an aerial platform radar assisting in engagements beyond the Patriot radar field of view, modifications to Patriot and the Aerial platform must be made. Patriot modifications include: the capability to calculate engagement solutions using an outside radar source, and the ability to derive solutions outside the radar FOV (Engage on Remote and Forward Pass). These should not be difficult to achieve, but do require extensive coordination with Patriot and scheduling the upgrades in their software builds. The Aerostat must have a capability to transmit to the MLI in-flight guidance information calculated by Patriot. This could be done using a C-band communications relay unit compatible with the C-band radar of Patriot. Information calculated by the ECS would be sent via CEC to the Aerostat (probably to a ground station processor and then via a fiber optic cable to the C-band relay). This would allow centralized (Aerostat) and de-centralized employment commonality.

The Aerostat C-band relay would have to be developed so it could follow the instructions from multiple Patriot Fire units. This requires a centralized control of the long range engagements to prevent multiple FUs from engaging targets within the overlapping coverages of units. (Remember that we have now given Patriot a 360 degree capability for engagement). ECS would only use MLI assigned to it or emanating from its launchers in considering engageability of targets. The central controller for battalion (up to 6 FUs) would be the existing battalion Information Coordination Center (ICC). The ADTOC would be the central controller for multiple battalions. The ADTOC may require new software development.

A system implication of this concept includes scheduling Aerostat radar beams to perform the initial missile capture immediately after launch, during midcourse, and during target handover to the missile seeker. The C-band relay transmitter would emulate the appropriate messages both to and from the missile. Maintaining missile track requires slightly more radar energy to complete the engagement, but serves to reduce the radar bias errors, thus improving the track accuracy for target handover.

4.3.2 Air Application

MLI can be air launched from most aircraft capable of employing the AIM-120 AMRAAM. Standard fighter loadout in an LCCMD configuration is two MERs, one loaded with a communications pod and five MLIs, and the other with six MLIs, four AMRAAMs or Sparrows, and four Sidewinders for F-15s and two MLI loaded MERs and two Sidewinders for F-16s. The communication pod connects to a 1550 MUX bus which is standard on both aircraft. The MER mounted pod converts fighter fire control system (FCS) data and commands to Patriot message formats and excites the pod transmitter accordingly.

4.4 Tactics

The study simultaneously pursued two interrelated thrusts in devising appropriate tactics for deploying and engaging MLIs. First the new capability provided by a long range fire control system and a long range weapon system requires new tactics to fully capitalize on these advantages. Second, to modify the existing simulation tools to approximate the new tactics within the constraints of time and money available. The final results are, we believe, approximations yet the relation comparisons are very significant.

4.4.1 Ground Launched MLI Employment Tactics

MLI will be ground launched from a Patriot Launcher System using a PAC-3 canister set loaded with 16 MLIs per launcher. Once clear of the launcher with the engine started, the MLI can initiate a turn to any azimuth with little loss in airspeed or range. This results in a nearly circular cardioid-shaped footprint oriented with the launcher. Using a cruise altitude of 6 km, MLI has an available flight time of over 20 minutes. This flight time can be translated into either range or airborne delay time awaiting engagement at a combat air patrol (CAP) orbit point.

4.4.1.1 Sensor Impacts

As a slow missile with a potentially very long range, MLI utility is driven by both the surveillance and acquisition sensors as well as the fire control sensor. Early threat detection, classification, and identification provides for early launch and a long flyout time to enable engagement at the outer limits of fire control coverage. While many surveillance systems (e.g., AWACS, Hawkeye, and JSTARS) do not provide fire control quality data, they are capable of performing the threat warning and classification functions sufficient to commit interceptors, particularly in the cases of massed raids. The MLI employs an active seeker. The probability of MLI target acquisition is directly proportional to target positional accuracy at handover. For surface based sensors, acquisition ranges are generally short, which results in small positional errors at handover. At the extended ranges provided by the elevated sensors, the handover accuracy errors are usually somewhat greater. This causes difficulty for the missile seeker, particularly in the case where seeker performance is constrained to reduce the cost of the interceptor. In order to exploit the extended range capability of MLI, either very long range, very accurate sensors, or a netted, distributed BMC4I architecture is required.

4.4.1.2 Launch-to-Intercept Employment

In the launch-to-intercept mode which in general is the third and final layer of defense, MLI is paired with a target at launch. The ECS computes an intercept geometry to determine if the front intercept logic is satisfied and that the intercept will occur prior to the cruise missile reaching the nearest defended asset, and then it selects the appropriate MLI launcher. If either check fails, a higher performance interceptor (e.g., PAC-2) is selected. MLI flight profile is a constant velocity climb at 0.6M to target altitude plus 100 meters or the highest altitude less than 6 km altitude that will permit two minutes of level flight at 0.7 M, before intersecting a 15° angle dive to intercept. Intercept navigation is to a turn point which places the MLI wings-level, 10 km in front of the target along its projected line of flight. After the turn point or if paired inside of the turn point, the navigation employed is lead collision to target position. MLI seeker turn-on and warhead arming are accomplished following 10 seconds of engine thrust and initiation of post-turn point maneuver command.

4.4.1.3 Launch to CAP Tactics

The unique capability of MLI to loiter following launch and prior to engagement provides for innovative employment tactics which can be readily tailored to varying tactical situations. The basis of all variations is the ability to launch to one or more CAP patterns and commit to intercepts from them. This is essentially a limited duration forward basing capability which tends to overcome the rather lengthy flyout times resulting from centralized launcher basing and the modest interceptor velocity. By staggering CAP locations, shoot-look-shoot firing doctrines can be employed with very short second shot intercept intervals, if needed, and the second interceptor committed to a different target if the first engagement was successful. This tiering of CAP orbits provides for multiple intercept opportunities and uses the concept of converging lines of defense for efficiency. Clearly, the concept of launch to CAP is most effective and efficient when wide area surveillance and fire control sensor support are available and supported with flexible BMC4I capability and tactics.

4.4.1.4 Firing Doctrine

When sufficient battlespace is available, a shoot-evaluate-shoot firing doctrine is preferable. As discussed above, flexible MLI engagement tactics will permit this in most cases. The low cost of MLI versus other interceptor missiles suggests that the last MLI shot opportunity should be a two-shot ripple before higher performance interceptors are expended. This concept provides for a reduced cost-per-kill and reserves the higher performance weapons for use against higher performance threats.

4.4.1.5 MLI Flight Termination

If the launch to CAP option is exercised, there is a high likelihood of MLIs nearing the end of their flight time with no targets available.

These can be disposed of by vectoring them to pre-determined disposal locations and commanding a descent to below terrain altitude. Since the command is not to a turn point to intercept, the seeker will not activate nor the warhead arm. If suitable explodable ordnance disposal (EOD) areas are not available and vectoring to crash in hostile territory is not an option, the launch to CAP option must be weighed against alternatives and consequences.

4.4.2 Air Launched MLI Employment Tactics

The air launched MLI option is carried by fighter aircraft stationed on 5 minute alert at selected air defense bases. Each fighter can carry up to 11 MLIs for LCCMD, in addition to at least 2 AMRAAM or Sidewinder load-out for high-performance threat engagement. Fighters are committed in elements of two. The fighters fly to a head-on intercept geometry with the intended target and fire from about 6 nm range. The MLI is guided from the fighter until the MLI comes within acquisition range of its seeker. These tactics are consistent with standard air-to-air tactics and do not place the fighters in a position of disadvantage in the case of incorrect target identification. LCCMD tactics include a vector to a turn point (TP) 10 nm ahead of the lead target along the projected flight path of the threat cluster at maneuverable cruise speed (Vmc) or higher. At the TP, flight lead will turn to the engagement vector and transition to a combat speed of 350 KIAS. The wingman will fly in 6 nm "Snake" formation (radar trail formation which allows both target and flight lead to be tracked simultaneously). If the leader misses the intercept, the wingman is in position to follow-on attack without excessive maneuvering or can engage targets assigned by flight lead. Normally, the leader will fire a single MLI and, if that misses, the wingman will ripple two. Fighters must engage targets sequentially except during very dense raids due to the tracking requirements and slow interceptor velocity which results in intercepts with short F-poles. However, track-while-scan capability permits next-engagement planning in a target-rich environment. The front attack requirement leads to a tactic of driving up the attack stream at the modest combat speed required by the slow missile and then accelerating and running at high speed to get in front of the raid for a second sweep. In the cases where a reattack is required due to missed intercepts by both aircraft, consideration will be given toward using a higher performance weapon from a stern aspect to reduce target travel.

4.4.3 Joint Force Employment

Joint force LCCMD operations are a subset of the air and missile defense mission normally assigned to the Joint Forces Air Combat Commander (JFACC). Air and ground based air and missile defense forces will be deployed and tasked from a total force perspective based on intelligence data, military judgment, and political realities. Ideally, optimal use of ground based defense assets will release air assets for other missions, which will ultimately reduce the air and missile threat to friendly forces and assets. Where ground based elevated sensors are not available, Patriot will likely be deployed to support the tactical ballistic missile defense (TBMD mission at the expense of the aircraft and CM defense mission. This mission will receive primary support from aircraft resources. Where ground based elevated sensors are available and missiles are available that can exploit them, primary responsibility for air and missile defense rests with the ground based elements supplemented by aircraft elements when and where needed.

4.4.4 Patriot Basing

As the only land-based TBMD system capable of protecting the rear corps assets currently operational, Patriot radars, engagement control stations (ECSs), and PAC-3 launchers will likely be deployed to defend against this threat set. As seen in the scenarios used for this study, this laydown will have serious drawbacks for the role of Patriot in the aircraft and CM defense missions in terms of both area coverage and mutual support if elevated sensor platforms to support these missions are not available. With elevated sensor support available and missiles capable of exploiting this asset, placement of the Patriot radars and ECSs to support the TBMD mission has little adverse impact on aircraft and CM defense capability.

4.4.5 Fighter Basing

Largely due to the quantities and types of ordnance carried and expended, counter-air fighters do not have the extensive logistics tail that air-to-ground roled fighters do. For this reason, air defense fighters can be deployed in small detachments to a large number of airfields. This dispersal also tends to reduce the flyout time required when scrambled from ground alert. Where sufficient numbers of fighter-capable airfields are located sufficiently close to the air defense zones and adequate surveillance and warning assets are available, ground basing of fighters is preferable to airborne alert, since it requires far less infrastructure to support.

In the centralized mode (elevated fire control sensors available) the fighters are based at mid-theater locations since their function is to provide mobile firepower where Patriot launchers are being reloaded or all rounds have been expended. In both cases, sufficient planning time is available to permit scramble of fighters and cruise to the threatened corridor.

In the decentralized mode (no or insufficient elevated fire control sensors available) the fighters are dispersed since they represent the area coverage forces. In this role the fighters are used where ground based coverage is not available and to prevent raid massing against critical nodes even if defended by Patriot.

5.0 MLI EFFECTIVENESS ANALYSIS

5.1 Overview

MLI, as a low cost cruise missile defense weapon, has the capability to provide wide area defense against lower performance threats. Its military utility is therefore a function of how well it can support this mission, without significantly adding to the infrastructure or logistics burden of the air and missile defense systems, and potentially free up joint force assets which would normally be tasked at greater cost. In order to assure a rigorous assessment, the Government has provided a family of scenarios for each of two theaters. These consist of 96, 200, and 300 cruise missile raids in the Northeast Asia (NEA) and Southwest Asia (SWA) theaters against a theoretical target set defended by baseline defensive laydowns. The Blue Laydowns (BLDs) include only Patriot fire units (FUs), Aegis ships, F-15 fighters, and a hypothetical elevated sensor concept. The desired system performance standard to be achieved is 10 percent or less leakage. Architectures to be evaluated include:

- Use 100 percent of the BLD, excluding the hypothetical elevated sensor concept, for LCCMD. BLD system inventories may be increased in order to meet the leakage requirement.
- Use 50 percent of the BLD, excluding the hypothetical elevated sensor concept, for LCCMD. BLD system inventories may be increased in order to meet the leakage requirement.
- Use 50 percent of the BLD, excluding the hypothetical elevated sensor concept, for LCCMD as required. MLI is introduced into the architecture. BLD system inventories may be increased in order to meet the leakage requirement.
- Use 100 percent of the BLD, including the hypothetical elevated sensor concept,for LCCMD. BLD system inventories may be increased in order to meet the leakage requirement.
- Use 50 percent of the BLD, including the hypothetical elevated sensor concept, for LCCMD. BLD system inventories may be increased in order to meet the leakage requirement.
- Use 50 percent of the BLD, including the hypothetical elevated sensor concept, for LCCMD as required. MLI is introduced into the architecture. BLD system inventories may be increased in order to meet the leakage requirement.

5.1.1 Target Modeling

The low cost cruise missile described in the LCCMD BAA flew at subsonic speeds at 30 meters over water and 300 meters over land, with only turns for navigational purposes (no evasive action). Terrain elevation was not to be modeled. However, the target set provided by the Government varied the flight altitudes, which in effect, provided some *de facto* terrain masking. Target maneuver in the larger raids included evasive maneuver in that cloverleaf patterns and starbursts were flown to confuse the battle manager. Reactive (to interceptor sensor detection) evasive maneuvers were not employed.

5.1.2 Sensor Modeling

The hypothetical elevated sensor concept was employed in the forward pass mode for all interceptor concepts. This employment is consistent with the Corps SAM/MEADS vision and offers significant extension of the Patriot PAC-3 missile engagement footprint. Hypothetical elevated sensor concept resources were modeled implicitly with the following constraints applied:

- Maximum of four concurrent intercepts using semi-active missiles (SM-2).
- Maximum of 20 concurrent active missiles in the target handover phase.
- Target identification range is 125 percent maximum target handover range.

5.1.3 Missile Modeling

Patriot PAC-3 and AEGIS SM-2 missiles were launched without considering launcher orientation constraints. This practice reduced the launcher and missile inventories required for the defense, which would significantly raise BLD cost per kill computations. The clutter rejection problems associated with low altitude intercepts were assumed to have been resolved for both of the missiles and a constant probability of kill (P_k) was used. MLI can maneuver immediately after launch which relieves the launcher orientation problems. The MLI was only committed on front intercepts (within 60 degrees of head-on intercepts) to ensure a high P_k was maintained.

5.1.4 BLD Siting

BLD assets were sited based upon efforts in a related study, and appear to be sited for TBMD, rather than CMD. This severely impacted the BLD performance when the hypothetical elevated sensor concept was not available. The hypothetical elevated sensor concepts (Aerostats) were based quite far to the rear, which created significant shortfall in utility coverage available. Forward area air defense systems were not played which left several forward assets uncovered in this study and tended to drive the cost per kill of the BLD systems upward since BLD systems, which are generally more expensive than SHORAD systems, have to be purchased to cover these assets. The number of kills by the blue systems would not change, we would have had to add the cost of the SHORAD systems which also would have had a Pk of 0.7.)

5.1.5 Rules of Engagement

Threats were required to be tracked by a fire control sensor prior to interceptor missile commit, regardless of the operational concept and safety features of the missile. This had minimal effect on faster, more expensive missiles, but significantly impacted the battlespace of the slower MLI.

5.1.6 Use of the Combat Air Patrol (CAP)

MLI was launched to a combat air patrol (CAP) position on launch if a direct intercept flyout was not achievable or if another interceptor was engaging the MLI's initial target. This essentially forward basing of the MLI provided for extended intercepts in areas where surface based launchers were unable to be placed. In one particular case, an Aegis cruiser was replaced in its entirety by an MLI CAP which proved equally as effective as the cruiser.

5.1.7 Models

The Extended Air Defense Simulation (EADSIM) was used as the Raytheon TI Team theater level effectiveness evaluation tool. EADSIM has over 200 registered users world wide and is accredited by numerous government agencies for use in operational effectiveness analyses. EADSIM models each player (weapon, sensor, engagement control station, aircraft, missile, etc.) and the interaction among players independently. It models the command and control decision processes and the communications among platforms on a message-by-message basis. It features a spherical, rotating earth and models terrain features using DMA data. In order to evaluate MLI effectiveness using the tactics described in Section 2, modifications to the EADSIM run models were required. Since TBE is the EADSIM developer, code modifications were developed for these limited applications however robust changes were not developed which would implement the flexibility MLI affords both air and ground based users. EADSIM is flexible enough that analyst manipulation can approximate many of the MLI features. However, many of these were not implemented in order to preclude "gaming" the scenario.

5.2 Analysis Run Matrix

In order to conduct a robust assessment of the military utility and cost per kill of the MLI concept, numerous deployments, operating concepts and employment strategies were modeled and evaluated. Analytic results of those which indicated promise in addition to the required set described in Section 5.1 are shown in Table 10.

Table 10. System Architecture Effectiveness Trade Space

Architecture		NEA						SWA					
		100%			50%			100%			50%		
		96	200	300	96	200	300	96	200	300	96	200	300
Baseline Blue Laydown	with AFC	2	10	34	5	17	51	2	16	35	4	23	68
	no AFC	11	29	82	19	50	104	32	98	109			
10% Leakage with "Plussed Up" 100% OR 50% Blue Laydown (NO MLI)	with AFC	2	10	34	5	18	39	2	16	35	4	23	
	no AFC	11	23	41	12	24	38	7	9	20	6	13	47
10% Leakage with Gnd-based MLI or F15MLI and 50% Blue Laydown Mixed Architecture	Gnd-based MLI with AFC				3	9	11	yellow-shaded = plussed up			2	17	23
	F15MLI no AFC * RUN WITH PLUSSED UP PAC UNITS				9	18	46				4	*12	*41
10% Leakage with Small Aerostat, Gnd-based MLI and 50% AEGIS, 50% F15 Mixed Architecture	with AFC				9	13					5	18	

5.3 Analysis

The 100 percent BLD (without the hypothetical fire control radar (HFCR)) cases generally limited the number of leakers to about 10 percent. This was achieved at a fairly high cost per kill ranging from $6.5M to $7.7M using the expended asset computation method prescribed by DARPA. In the 50 percent BLD case (without the hypothetical fire control radar) a significant number of additional assets were required which drove the cost per kill substantially higher. Intercepts occur on an average of 13 km from the launch point. The limitation on acquisition and track by organic sensors imposed by terrain severely reduces the effectiveness of the weapon systems and imposes a requirement for more weapons systems to cover the defended areas if leakage rates are to be kept low.

The contribution of the HFCR is significant in reducing the overall cost per kill. The HFCR is able to detect, identify, and track the cruise missile at significantly longer range. It is assumed that in addition to the HFCR providing support to the architecture, that the command and control systems are supported by the Cooperative Engagement Capability (CEC). The CEC allows for firing solutions to be calculated at each weapon system command and control node based on input from contributing sensors other than their own organic radar. Given this information, the weapon systems are able to launch well before their organic sensors acquire the target. With the assistance of the HFCR the intercepts occur at twice the distance (31 km) from the launcher than is the case where they rely upon their organic sensors. This capability also results in a three fold decrease or more in the number of leakers.

Evaluation of the MLI results clearly shows that the low cost, long range interceptor is a viable candidate as a moderate performance cruise missile defensive system. In the scenarios examined, the firing doctrine imposed allowed the MLI the first opportunity for engagement over the other weapon systems. This allowed a lower cost solution and reduced cost per kill. The keep out ranges, or the distance from the launcher to point of intercept (32 km) are similar to the results of the BLD with use of the HFCR. The ability of the MLI to fly to a Combat Air Patrol (CAP) enhances the effectiveness of the MLI weapon. On review of runs where MLI could either fly directly to intercept or go to CAP, we found that 85-90 percent of the kills took place with MLI from the CAP. Because the cost of the MLI is so low, the number of MLI left on CAP, and hence subject to destruction, does not adversely impact the cost per kill. The MLI is by far the least expensive solution.

Insights gained during the evaluation:

- MLI fired from ground platforms is the least expensive means of defeating the threat. Placement of the HFCR as far forward as possible is important to killing CM early in flight and ensuring that weapons of mass destruction (WMD) do not impact over friendly territory. Early launch of MLI with control passing to or through the HFCR imposes a most cost effective umbrella over the battlefield. The MLI on CAP provides a real alternative to placing weapon systems such as Aegis and Patriot in defensive positions. The MLI CAP can be placed on station when there is firm indication of an attack. Its effectiveness in the EADSIM runs has been demonstrated to be equal to that of emplaced surface based weapon systems.

- The least expensive means of employment of MLI is from the ground based mode. However, the fighter based platform provides significant flexibility in that fighters can be vectored directly to routes of threat ingress and can return to base without launching a missile if the situation dictates. The fighter basing also provides a means of getting MLI into long range positions faster than flyout from some remote ground based launcher. Hence the value of a multi-platform MLI is clearly evident.

Further exploration of MLI effectiveness in a mixed (TBM, ABT, CM, UAV) environment is called for. The MLI employment against modest threats may enhance the overall force effectiveness by allowing the more expensive and capable systems to go after the more difficult targets. Helicopters and UAVs are among the potential targets for MLI.

It is abundantly clear from the simulations and analysis that MLI is a significantly cost effective solution to a growing threat.

6.0 COST PER KILL ANALYSIS

Cost-per-kill estimates are based on the results of EADSIM architecture laydown and effectiveness analyses. The model is based on the defined DARPA asset cost matrix and cost basis. The cost per kill analysis were continually iterated throughout the study to refine laydown tradeoffs and engagement tactics. The results do not represent the optimum but are a good basis for comparing relative costs.

6.1 Approach

The cost per kill analysis is closely coupled with architecture sizing and effectiveness analysis and the interceptor design trades. Analysis of architecture cost and cost per kill (cpk) are employed as metrics to develop and optimize architecture laydowns (number and location of platforms ...), engagement tactics (FEZs, MEZs, CAP locations, rules of engagement , ...) and weapon design tradeoffs (LAR, speed, Pk, ...). The MLI architecture laydowns have evolved through iterations of effectiveness and cost analyses against number and location of additional Patriot Fire Units, number and location of launchers, number and location of CAPs, definition of launcher engagement zones, MLI scramble tactics, and in-flight targeting rules. The iterations in the MLI architecture configurations resulted in approximately an order of magnitude improvement in estimated leak rate and cpk. While these results do not reflect optimum solutions, they are considered to be representative for relative sizing and costing comparisons.

6.2 Costing

DARPA defined costing guidelines and element data were applied in the cost analysis for the run matrix. A summary of leak rate, assets expended costs, allocated platform cost, and cost per kill is shown for the completed cases in Table 11.

A standardized basis for comparing the case results by fixing leak rate at 10 percent was not completed; however, several conclusions can be interpreted from the case comparisons. First, the leak rates are less than or of the order of 10 percent for all cases except the decentralized cases (300 for NEA and all for SWA). In order to reduce the leak rate to 10 percent, additional Blue platforms and weapons can be added which will substantially increase the architecture investment and kill cost. Second, the expended asset cost for the BLD cases is large, compared with the mixed architectures for comparable cases. For comparison note the NEA centralized, 200 raid cases where expended costs are $1040M vs. $179M. Third, the allocated platform cost for the mixed MLI architectures is a large fraction of total architecture cost and, therefore, the cost per kill. For example, note the MLI, SWA, centralized cases where the allocated platform cost represents 47 - 77 percent of the cost per kill. Fourth, the cost per kill comparison between proliferated BLD architecture solutions and mixed MLI architecture solutions is very significant ($6.8M vs. $1.8M for the NEA, centralized, 200 raid cases).

A summary of the expended asset cost for each weapon is shown in Table 12 for the cases analyzed for the engagement rules applied. Little effort has been expended in minimizing the expended asset cost through tailoring the expended round mix or through engagement rules. This would likely result in a substantial reduction in the mixed architecture cost by more restrictive utilization of more expensive weapons. For example, in the NEA centralized, 200 raid case, 70 percent of the total expended asset cost was PAC3 which accounted for only 4 percent of total kills. Modest rule set changes would have substantially lowered the total architecture cost while retaining the low (2.5 percent) leak rate.

Table 11. Summary Leak Rate, Costs, and Cost per Kill

Case / Run	Leak Rate %	Assets Expended $M	Platform Allocation $M	Cost per Kill $M
BL,NEA Centralized - 100%				
96	2.1	470.8	249.0	7.7
200	5.0	1040.3	249.0	6.8
300	11.3	1489.8	249.0	6.5
BL,SWA Centralized - 100%				
96	2.1	525.4	249.0	8.2
200	8.0	937.4	249.0	6.4
300	11.7	1251.4	249.0	5.7
BL,NEA Decentralized - 100%				
96	11.5	200.9	249.0	5.3
200	19.0	400.5	249.0	4.0
300	27.3	621.2	249.0	4.0
BL,SWA Decentralized - 100%				
96	33.3	194.8	249.0	7.0
200	35.5	424.5	249.0	5.3
300	36.3	596.2	249.0	4.5
MLI,NEA,Centralized - 50%				
96	3.1	33.5	124.5	1.8
200	2.5	178.7	124.5	1.6
300	4.0	426.7	124.5	1.9
MLI,SWA,Centralized - 50%				
96	3.1	36.6	124.5	1.8
200	7.0	107.8	124.5	1.3
300	8.0	137.9	124.5	1.0

Table 12. Summary of Expended Cost by Weapon

Run / Case	SM 2 III	SM 2 IV	AMRAAM	PAC 2	PAC 3	MLI	Total
BL,NEA,96,Cent-100	20.6	80.2	31.2	0	338.9	0	470.8
BL, NEA,200,Cent-100	61.7	130.0	92.1	0	756.6	0	1040.3
BL,NEA,300,Cent-100	65.8	182.5	141.1	37.5	1063.0	0	1489.8
BLSWA,96,Cent-100	1.4	66.4	44.6	0	413.1	0	525.4
BLSWA,200,Cent-100	20.6	190.8	124.7	2.5	598.8	0	937.4
BLSWA,300,Cent-100	83.6	240.6	78.7	3.7	844.8	0	1251.4
BL,NEA,96,Decent-100	13.7	33.2	124.7	20.0	9.3	0	200.9
BL,NEA,200,Decent-100	21.9	91.2	142.6	93.7	51.1	0	400.5
BL,NEA,300,Decent-100	37.0	107.8	142.6	157.4	176.4	0	621.2
BL,SWA,96,Decent-100	0.0	38.7	71.3	33.7	51.1	0	194.8
BL,SWA,200,Decent-100	11.0	116.1	89.1	73.7	134.6	0	424.5
BL,SWA,300,Decent-100	41.1	168.7	89.1	102.4	195.0	0	596.2
MLI,NEA,96,Cent-50	0	0	0	0	0	33.5	33.5
MLI,NEA,200,Cent-50	0	0	0	0	125.3	53.3	178.7
MLI,NEA,300,Cent-50	0	0	0	0	362.1	64.6	426.7
MLI,SWA,96,Cent-50	2.7	0	0	0	0	33.9	36.6
MLI,SWA,200,Cent-50	17.8	41.5	0	0	0	48.5	107.8
MLI,SWA,300,Cent-50	19.2	41.5	0	0	0	77.2	137.9

7.0 CONCLUSIONS

We concluded the following from our Interceptor Study:

- Either the X- or Ka-Band seeker can provide adequate detection, track, and end game performance against the defined LCCM threat.
- Both X-and Ka-Band designs can be built using low cost COTS and NDI components.
- There is a minor cost penalty for the Ka-Band seeker relative to the X-Band seeker but the end game accuracy of the Ka-Band seeker is potentially superior.
- The 50 pound thrust SENGAP engine meets our look-down, shoot-down engagement tactic. A 90 pound thrust SENGAP type engine can, however, provide the required maneuverability capability for end game over a wider engagement envelop although at higher cost.

We concluded the following from our Architecture studies:

- Low leak rate (<5 percent) is achievable for the 96 and 200 NEA scenarios for all centralized architectures through assurance of multiple (> 4) shot opportunities against all targets.
- Cost per kill is driven by expended round cost except for allocated unused BLD assets.
- For the 96 and 200 raid NEA cases, MLI based architectures are significantly lower cost per kill than proliferated conventional architectures.
- Details of asset laydown and engagement tactics dominate leak rate and cost per kill compared with modest MLI design trades.
- The EADSIM MLI simulation results are considerably more conservative than an ideal MLI architecture.

8.0 RECOMMENDATIONS

The study has provided a strong case for a new low cost weapon system to counter the projected asymmetric LCCM threat. This capability would be of significant value both to assure a greatly reduced expended cost in moderate to large raids and also to provide a substantially lower investment cost to counter the threat of concentrated breakthrough raids. Two major technology issues remain in order to validate the cost and operational utility of an air directed MLI interceptor: (1) the low cost potential of a moderate performance MEMs based ESA, and (2) the adequacy of performance of an integrated interceptor that is based principally on low cost COTS and NDI parts. A sequential issue resolution plan is recommended first to validate that the innovative Ka-band seeker can be developed to meet the performance and cost goals, and second to demonstrate the operational effectiveness of the low cost interceptor design against the defined threats.

Enclosure (2)
232-207-4094

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15. ITEM NO.	16. STOCK/PART NO. DESCRIPTION *(Indicate number of shipping containers-type of container-container number.)*	17. QUANTITY SHIP/REC'D*	18. UNIT	19. UNIT PRICE	20. AMOUNT
0002 A003	SCIENTIFIC AND TECHNICAL REPORT (FINAL)	1	LO	NSP	NSP

Sign, Date, and Check BLK 21-B
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McKinney, Texas 75070

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ATTN: KRISTEN NUMRYCH
CONTRACTING OFFICER, DARPA

15. ITEM NO.	16. STOCK/PART NO. DESCRIPTION (Indicate number of shipping containers-type of container-container number.)	17. QUANTITY SHIP/REC'D*	18. UNIT	19. UNIT PRICE	20. AMOUNT
0001	MINATURE AIR LAUNCHED DECOY-LIKE (MALD-LIKE) INTERCEPTOR	1	LO	NSP	NSP

Sign, Date, and Check BLK 21-B
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Raytheon TI Systems Incorporated
2501 W. University Drive M/S 8012
McKinney, Texas 75070

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