2006-06

Ship Anti Ballistic Missile Response (SABR)

Johnson, Allen P.; Breeden, Bryan; Duff, Willard Earl;
Fishcer, Paul F.; Hornback, Nathan; Leiker, David C.;
Carlisle, Parker; Diersing, Michael; Devlin, Ryan; Glenn, Christopher...

Monterey, California: Naval Postgraduate School

https://hdl.handle.net/10945/7268

SEA-9/TDSI
Future Surface Combatant Ballistic Missile Defense (BMD) Integrated Project
Final Presentation

07 June 2006

"It is the policy of the United States to deploy as soon as is technologically possible an effective National Missile Defense system capable of defending the territory of the United States against limited ballistic missile attack (whether accidental, unauthorized, or deliberate) with funding subject to the annual authorization of appropriations and the annual appropriation of funds for National Missile Defense."

--National Missile Defense Act of 1999 (Public Law 106-38)

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On December 16, 2002, the President announced he had directed the DoD to begin fielding initial missile defense capabilities in 2004-2005 to meet near-term ballistic missile threat to our homeland, deployed forces, friends, and allies. Responding to this direction, the Missile Defense Agency (MDA) is developing an integrated system called the Ballistic Missile Defense System (BMDS) to provide a "layered defense". That is, over time the BMDS will become capable of dealing with all three phases of a hostile ballistic missile's flight – boost, midcourse, and terminal, as well as defending against all ranges of ballistic missiles.

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These newer threats on the world stage see Weapons of Mass Destruction (WMD) as weapons of choice, not of last resort to exert political pressure or to evoke unpopular responses. In this case, ballistic missile WMDs are a lethal means to compensate for the conventional strength of the U.S., allowing these entities to pursue their objectives through force, coercion, and intimidation.

To deter such threats, the U.S. and its allies must devalue ballistic missiles as tools of extortion and aggression through an active presence and a formidable ballistic missile defense. Doing so would undermine the confidence of adversaries that threatening a missile attack would succeed in affecting the secure status of the target citizenry and way of life. In this way, although missile defenses are not a replacement for an offensive response capability, they are an added and critical dimension of contemporary deterrence.

George W. Bush, 2002

- 2006 CNO Guidance
  - "Secure at home and abroad"
  - "Deter Aggression by would-be foes"
  - "Interoperability and cooperation among services, government agencies, coalition partners, and NGO's"
- Sea Power 21
  - Sea Shield
  - Sea Base

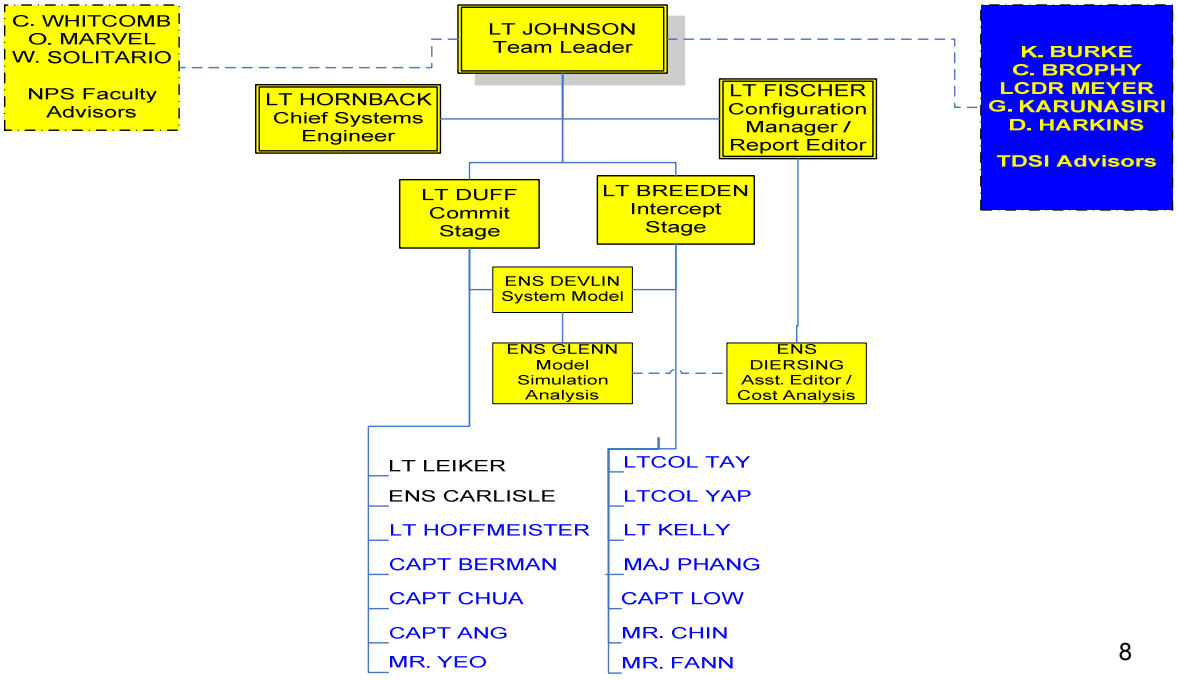
Tasking

"Use a top-down, system of systems approach to examine future surface combatant operations in terms of their conduct and support of current and emerging sea-based Theater Ballistic Missile Defense (TBMD) missions,"

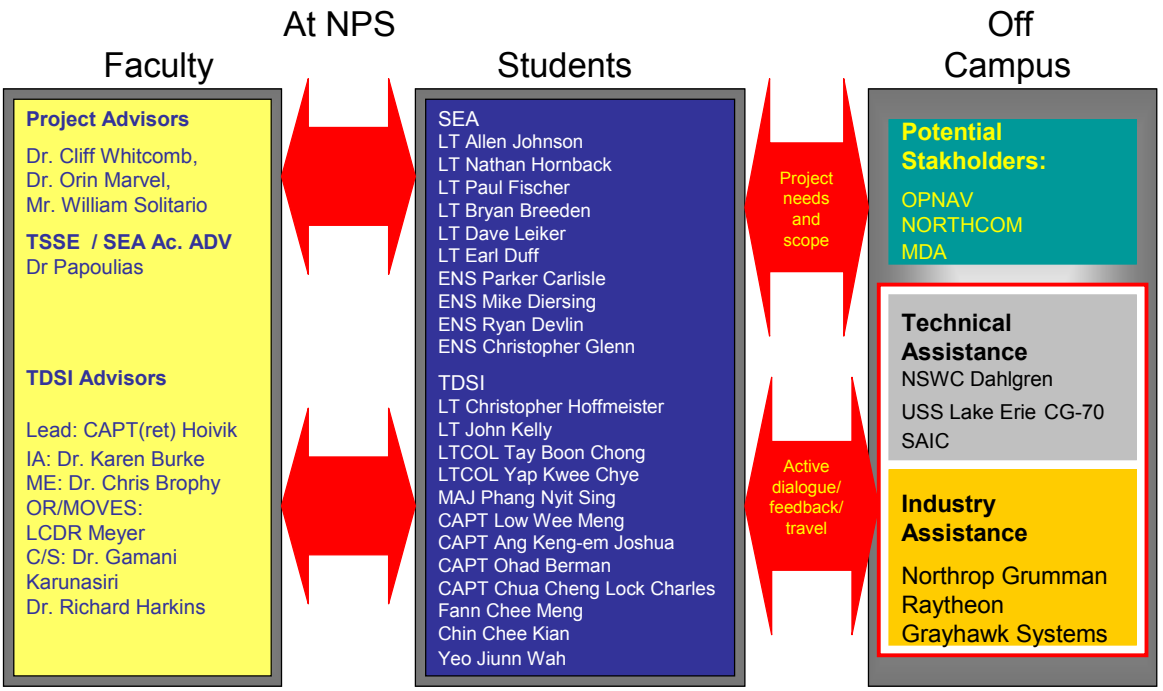
Agenda

- Introduction
- Systems Engineering Process
- Break
- DRM, Scenario Development, Functional Analysis, and Architecture Development
- Break
- Model Development, Analysis of Alternatives, 1st and 2nd Iteration Simulation Results, Simulative Analysis and Architecture Evaluation
- Break
- Final Architecture Selection, Cost Analysis, Conceptual System Design, Operational Scenarios, Model Refinements, 3rd Iteration Simulation Results, Simulative Analysis, and Conceptual System Design Evaluation
- Conclusions and Future Work

Team SABR



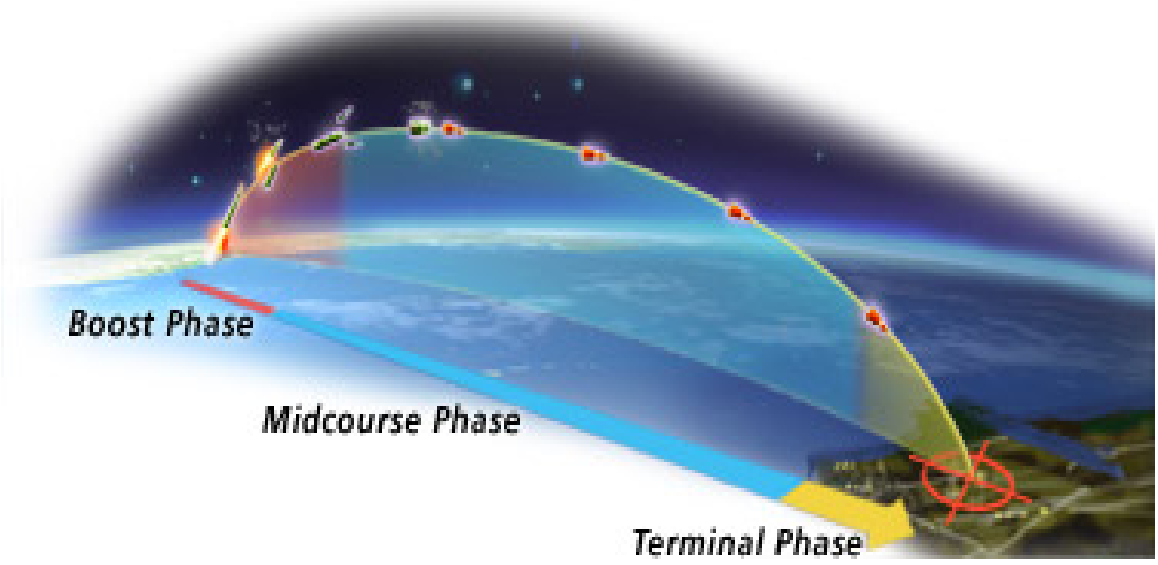
Project Interface



Characteristics of Ballistic Missile Flight

- Boost phase: The portion of flight immediately after launch, when the missile burns fuel (solid or liquid) to accelerate and lift its payload into the air. Duration is approximately 110 to 300 seconds.
- Midcourse: The portion of flight where the missile payload is separated from the booster rocket and is traveling without power on its trajectory toward a target.
- Terminal: The final portion of flight when the missile's warhead re-enters the earth's atmosphere (if exo-atmospheric) and falls towards its target, propelled only by its momentum and the force of gravity.

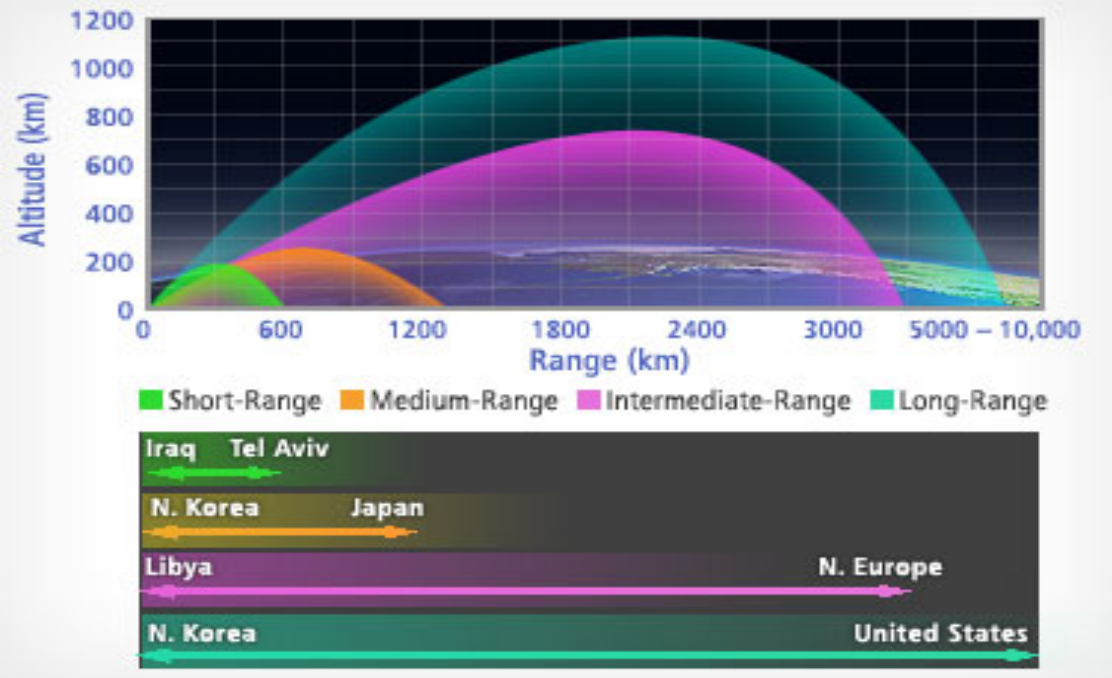
BM Trajectory



TBMD Definition

TBMD is the capability to defend forces, territories, and interests of the United States, its allies and friends against ballistic missile threats employed in a given geographical region. Specifically, it includes all classes of missiles that are employed against Short Range (SR), Medium Range (MR), and Intermediate Range (IR) targets (500-3500 km) within a given region.

BM Ranges



Problem Statement

"Develop and evaluate a conceptualized ship-based BMD system architecture to meet emerging short to intermediate range ballistic missile threat capability in the 2025-2030 time frame. The system must be able to integrate with prospective coalition BMD architectures and contribute to the whole of layered BMD."

Project Scope

In Scope

- Part of the overall layered IBMDS and coalition BMD effort (the sea-based portion of BMD effort)
- 2025-2030 timeframe
- Sea-based
- Must counter the perceived SR to IR ballistic missile threats
- Intercept warhead in the boost through midcourse phases (earliest engagement possible)

Out of Scope

- BMs that survive beyond midcourse will not be engaged by the sea-based system
- Post-intercept debris collateral damage and intercept over-flight issues
- Vulnerability of the ship due employment of sensors, FC radar, and employment of interceptor(s) (EW sig)
- Ability for ship self-defense while conducting active BMD (will be covered by ship self-defense system)
- Non-physical interceptors (cyber attack, etc)

System Bounding Assumptions

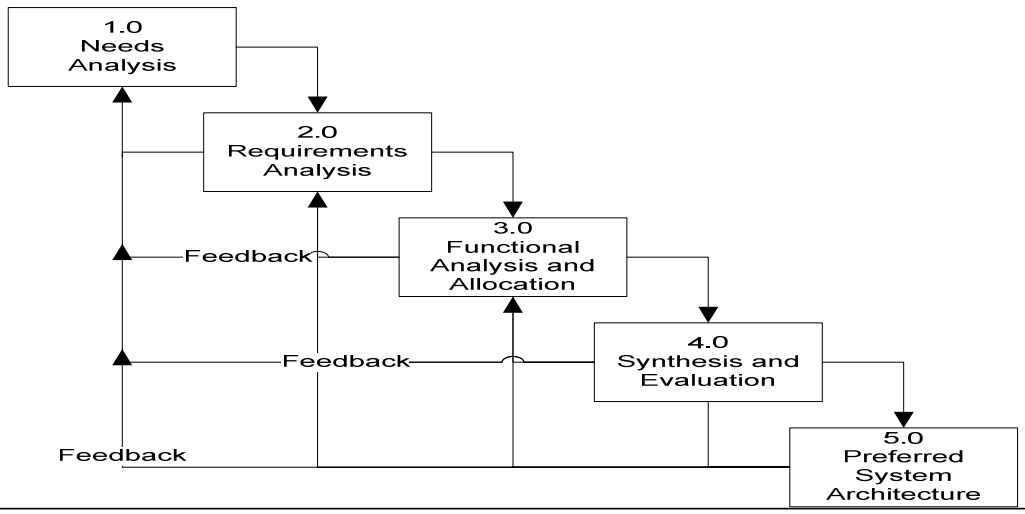
- Integrated external sensor network is deployed and operational for all Unified Commands
- Collaborative Information Exchange (CIX) exists between all participants in the IBMDS (Global)
- BMD System will be installed as part of a ship
- Physical interceptor(s) (i.e. missile, rail gun, DEW, etc.) will be employed if able
- Automated Battle Management System exists on ship

Projected Threat Ballistic Missile

- Highly proliferated ballistic missile easily acquired with the right amount of $$
- SR to IR (<3500 km)
- Exo-atmospheric capable
- Mobile launch capable
- Deployed decoys throughout trajectory
- Two-stage solid propellant (est. 140 s burn time)
- Can hit targets with a CEP of 3.5 km
- Can target land and sea targets

Brief Project Overview

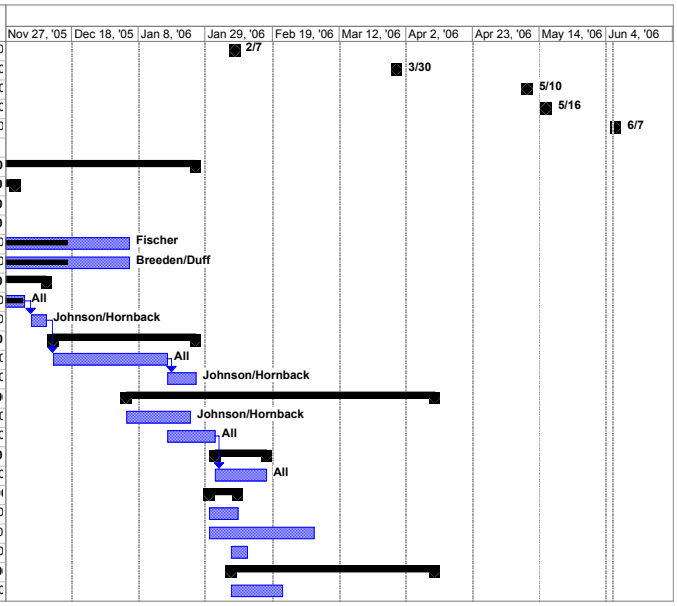
- Conducted extensive research
- Defined Problem Statement
- Chose SE approach



Brief Project Overview (con't)

- Developed SE Plans and Project Schedule

ID	Outline Numbe	Task Name	Duration	Start	Finish
1	1	Conduct IPR	0 days	Tue 2/7/0	Tue 2/7/0
2	2	Conduct PDR	0 days	Thu 3/30/0	Thu 3/30/0
3	3	Conduct CDR	0 days	Wed 5/10/0	Wed 5/10/0
4	4	Final Report	0 days	Tue 5/16/0	Tue 5/16/0
5	5	Final Presentation	0 days	Wed 6/7/0	Wed 6/7/0
6					
7	**6**	**Project Planning and Research**	**45 days**	**Tue 11/8/0**	**Wed 1/25/0**
8	**6.1**	**Formulate Tasking Statement**	**16 days**	**Tue 11/8/0**	**Tue 11/29/0**
12	**6.2**	**Develop Draft PMP**	**11 days**	**Tue 11/8/0**	**Tue 11/22/0**
15	**6.3**	**Develop Draft SEMP**	**11 days**	**Tue 11/8/0**	**Tue 11/22/0**
17	6.4	Identify Current and Future BM Threats	30 days	Tue 11/8/0	Wed 1/4/0
18	6.5	Identify Current and Future U.S. BMD Capabilit	30 days	Tue 11/8/0	Wed 1/4/0
19	**6.6**	**Needs Analysis**	**20 days**	**Mon 11/14/0**	**Fri 12/9/0**
20	6.6.1	Needs Identification	15 days	Mon 11/14/0	Fri 12/2/0
21	6.6.2	Needs Validation	5 days	Mon 12/5/0	Fri 12/9/0
22	**6.7**	**Develop Design Reference Mission**	**21 days**	**Mon 12/12/0**	**Wed 1/25/0**
23	6.7.1	Develop Nominal Scenarios	14 days	Mon 12/12/0	Mon 1/16/0
24	6.7.2	Develop Stressing Scenarios	7 days	Tue 1/17/0	Wed 1/25/0
25	**7**	**Prelimiaryl System Design**	**69 days**	**Wed 1/4/0**	**Mon 4/10/0**
26	7.1	Develop CONOP	14 days	Wed 1/4/0	Mon 1/23/0
27	7.2	Generate System Requirements	11 days	Tue 1/17/0	Tue 1/31/0
28	**7.3**	**Identify TPMs**	**12 days**	**Wed 2/1/0**	**Thu 2/16/0**
29	7.3.1	Develop primary MOEs/MOPs	12 days	Wed 2/1/0	Thu 2/16/0
30	**7.4**	**Conduct Functional Analysis**	**7 days**	**Mon 1/30/0**	**Tue 2/7/0**
31	7.4.1	Conduct Functional Allocation	7 days	Mon 1/30/0	Tue 2/7/0
32	7.5	Develop Design Architecture	25 days	Mon 1/30/0	Fri 3/3/0
33	7.6	Conduct Gap Analysis	5 days	Mon 2/6/0	Fri 2/10/0
34	**7.7**	**Preliminary System Synthesis**	**46 days**	**Mon 2/6/0**	**Mon 4/10/0**
35	7.7.1	Develop System Model	12 days	Mon 2/6/0	Tue 2/21/0



Brief Project Overview (con't)

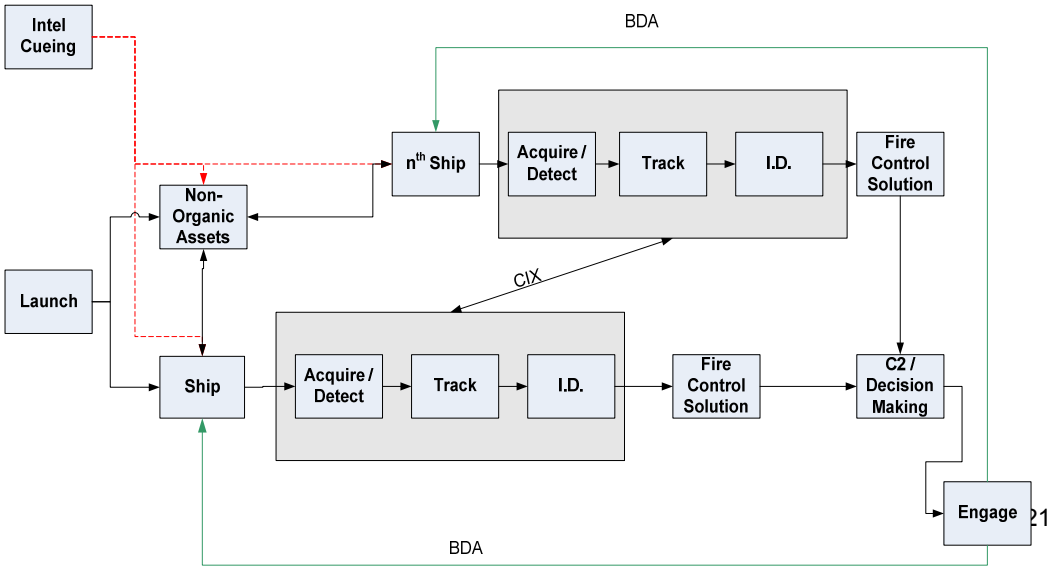
- Developed Design Reference Mission and Initial Scenarios

DRMP

Event	Required Equipment	Environmental Factors			
		Condition	Best	Expected	Worst
Commit Phase					
Missile Launch	Threat Launch	# of missiles	1	2	6
		# of locations	1	2	3
Missile Detection	Satellite Detection System	Sat time to detect	0		
		Ship time to Detect	0		
Missile Tracking	Organic & Non-Organic Radars	# of missiles	1000	1000	1000
Fire Control Solution	Organic & Non-Organic Radars, Fire Control Computers	Time to compute			
Analyze Fire Control Solutions	ABMS, Network	Operational	Yes	Yes	No
Choose Optimum Fire Control Solution(s)	ABMS, Fire Control Computer	Time to compute			
Transmit Kill Order		Time to transmit			
Missile Engagement	Participating Units (shooters)	Weapons available	All	Most	1
Missile Kill	BDA Capable System	Operational	Yes	Yes	No
Missile Re-Engagement	End State	Re-Engage, Handoff, End	End	End	Handoff

Brief Project Overview (con't)

- Developed needs, requirements, MOEs and MOPs
- Defined system functions

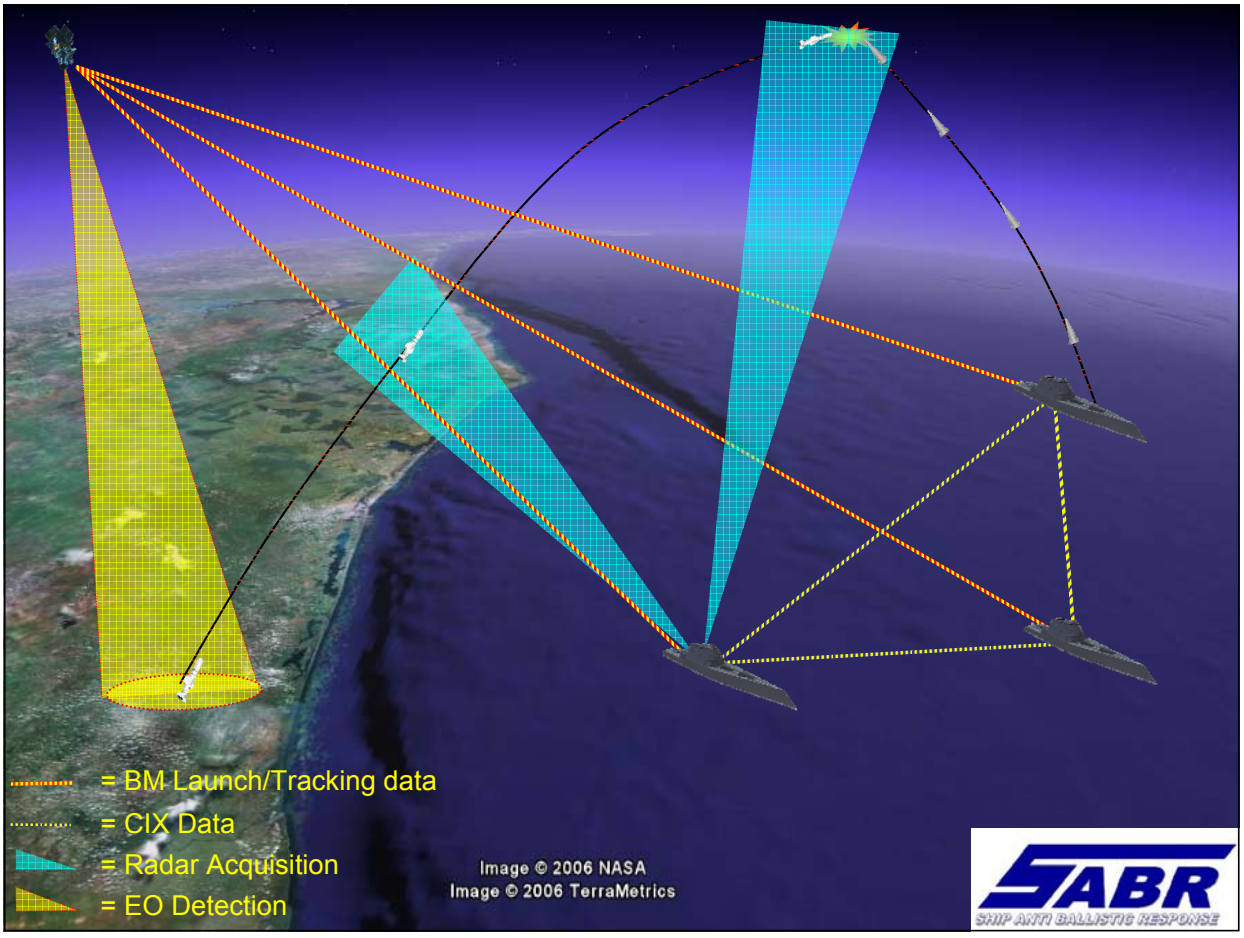


Brief Project Overview (con't)

- Developed alternatives
- Developed initial threat and system models
- Conducted analysis of alternatives using
  - Statistical analysis
  - Sensitivity analysis
  - Cost Analysis
  - Trade off studies
- Defined the preferred architecture
- Refined models
- Developed new operational scenarios

Brief Project Overview (con't)

- Tested the preferred architecture using new scenarios
- Conducted system analysis
- Evaluated findings
- CONCEPTUAL SYSTEM DESIGN



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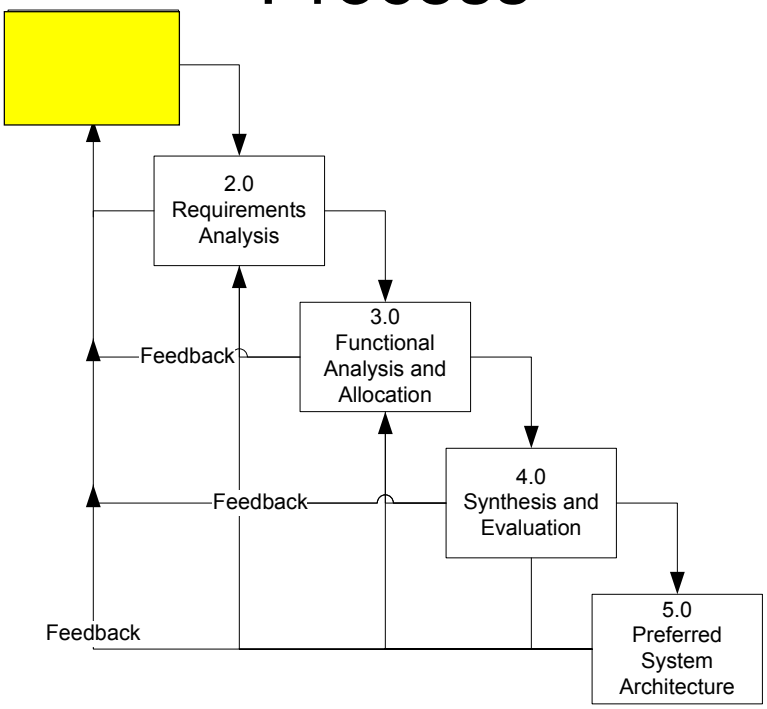
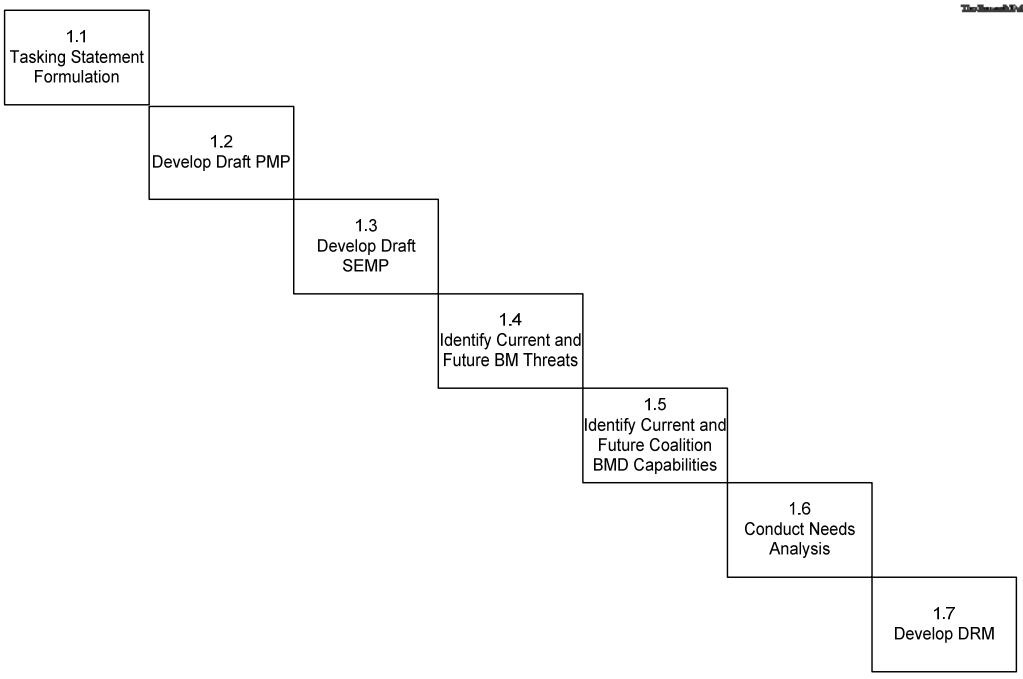
Systems Engineering Process

LT Hornback

Systems Engineering Process



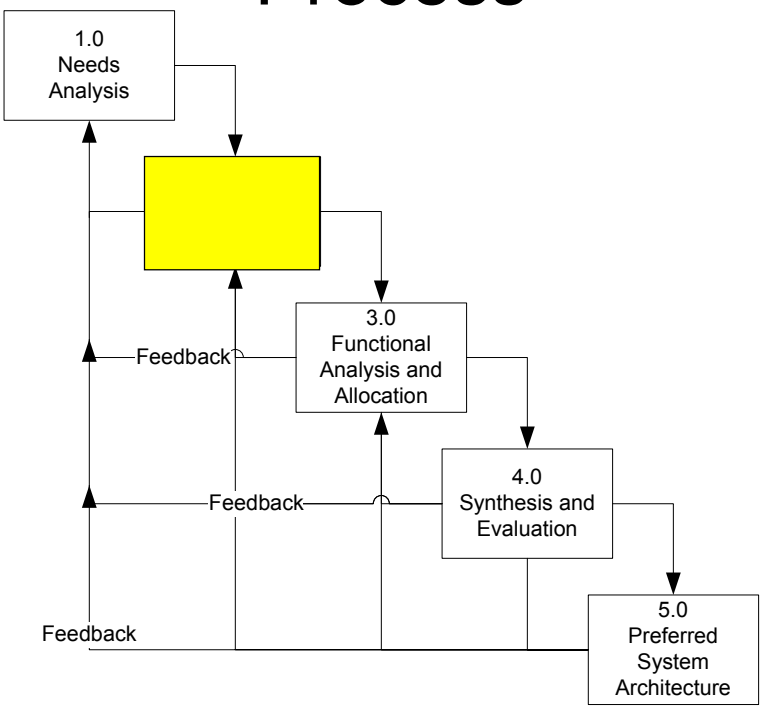
1.0 Needs Analysis Breakdown



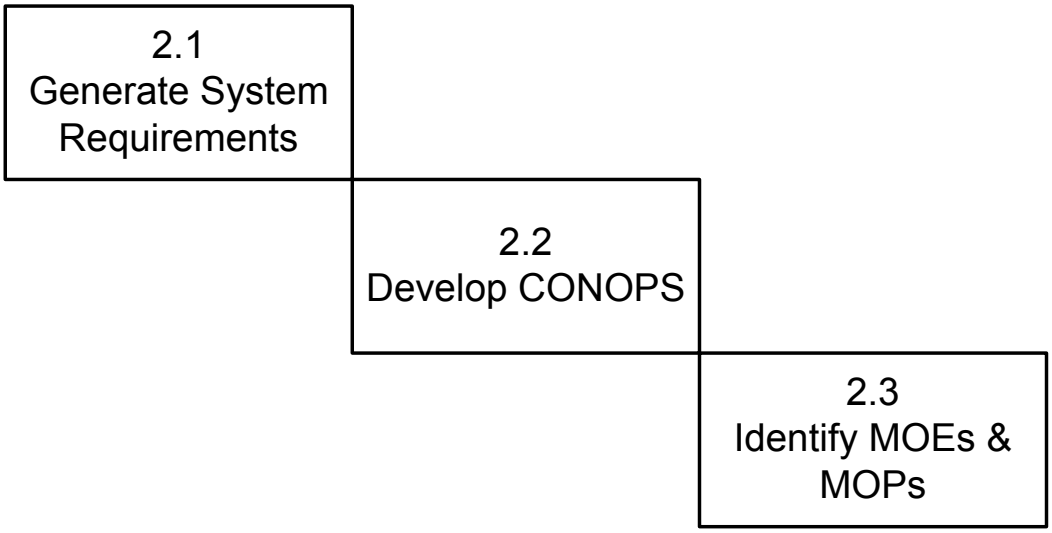
Needs

- Protect Coalition Partners from Ballistic Missile Threat.
- Operate Independent of Nation State Territorial Boundaries.
- Employ over a wide range of environmental conditions.
- Assimilate into the Integrated Layered BMD system.
- Interoperate with coalition partners.
- Destroy TBMS with a high probability of kill.

Systems Engineering Process



2.0 Requirements Analysis Breakdown



Requirements

- Rapidly deployable Sea Based Platform capable of prolonged operations.
- Stable platform capable of operations in heavy seas.
- Detect and track over the horizon ballistic missile launch and flight path.
- Share real-time sensor, weapon, fire control, and BDA data among coalition forces.
- Prioritize threats and optimally pair assets with highest probability of kill.
- Designate targets with a low probability of kill to other assets.

System MOE's

- Probability of Kill
- Probability of detection.
- Probability of false alarm.
- Probability of correct identification.
- Max number of targets effectively engaged per minute.
- Number of successful Battle Damage Assessments (BDA) (good or bad) gathered and processed per minute.
- Number of successful Command and Control decisions made per minute.

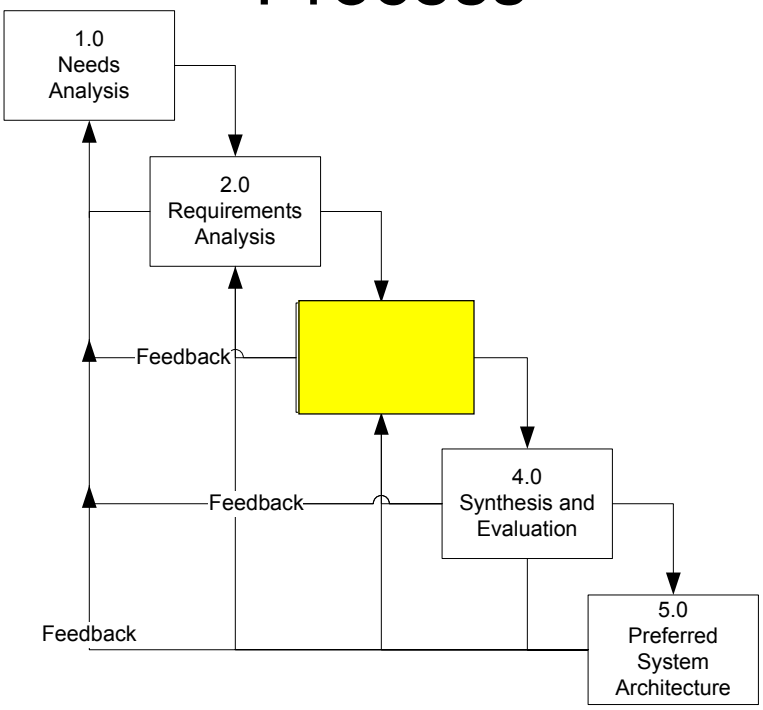
System MOE's cont.

- Max number of targets simultaneously tracked and identified per minute.
- Probability of worldwide sensor coverage.
- Probability of cooperative information exchange (CIX) function operational.
- Max number of designated target files passed to other assets per minute.
- Max number of sufficient power supply situations for mission accomplishment per minute.
- Max number of mission completed regardless of environmental conditions (wind, seas, and cloud cover) per minute.
- Number of days of sustained operations.

System MOP's

- Number of BM simulated
- Number of BM detected
- Number of non-detections
- Number of false alarms
- Number of handoffs
- Number of engagements
- Number of simultaneous engagements
- Number of failed engagements
- Mean non-organic detection time
- Mean time to relay detection
- Mean time to process detection
- Mean organic detect time
- Mean track formulation time
- Mean time to identify
- Mean threat prioritization time
- Mean weapons pairing time
- Mean engagement time
- Mean time to conduct BDA
- Mean time available for reengagement
- Mean time to end of midcourse

Systems Engineering Process



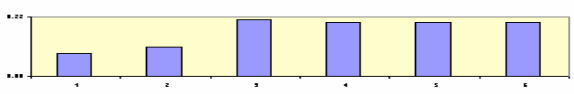
3.0 Functional Analysis and Allocation Breakdown

3.1
Conduct Functional Analysis

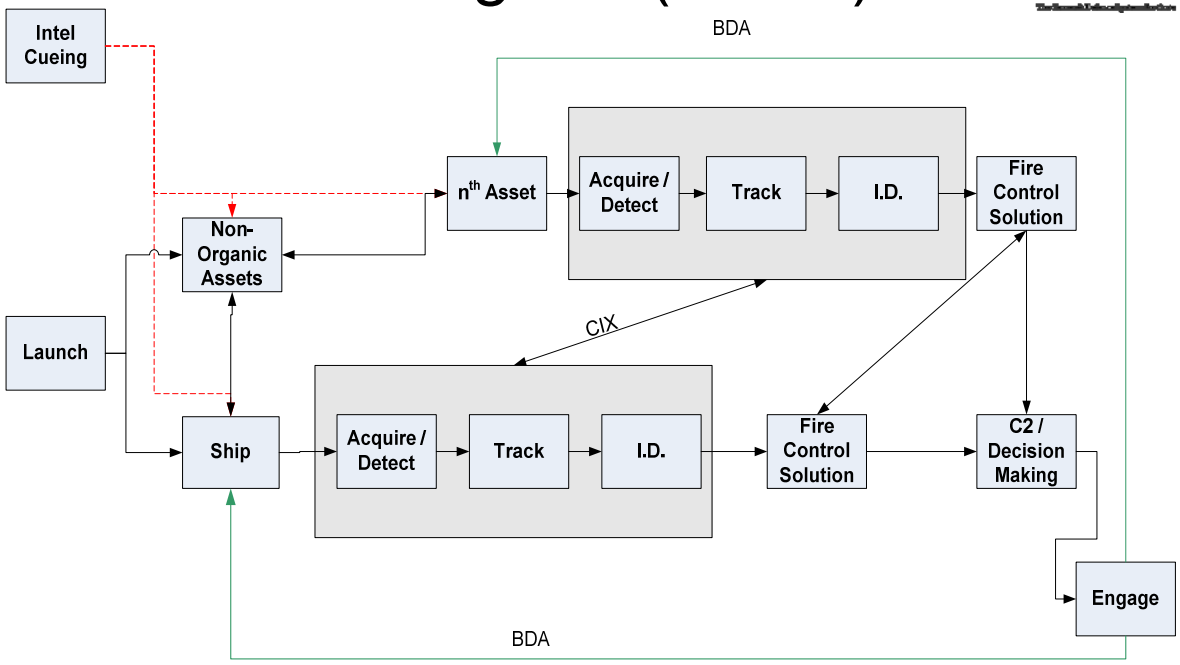
3.2
Functional Architecture Development

Functional Analysis

Needs (What's)	Weights		Requirements/Capabilities (How's)					
			Rapidly deployable sea based platform capable o prolonged operations	Stable platform capable of operations in heavy seas	Detect and track over the horizon ballistic missile launch and flight path	Share real-time sensor, weapon, fire control, and BDA data among coalition forces.	Prioritize threats and optimally pair assets with highest probability of kill	Designate targets with a low probability of kill to other assets
Protect coalition partners from ballistic missile threat	0.2727	0.273	3	1	9	9	9	9
Operate independent of Nation State territorial boundaries	0.0909	0.091	9	1	9	0	0	0
Employ over a wide range of environmental conditions	0.1364	0.136	9	9	9	3	3	3
Assimilate into the Integrated Layered BMD system	0.0909	0.091	0	0	9	9	9	9
Interoperate with coalition partners	0.1364	0.136	0	0	0	9	9	9
Destroy TBMS with a high probability of kill	0.2727	0.273	1	9	9	9	9	9
Check Sum		1.00						
Goal Value								
Threshold Value								
Weighted Performance			3.1	4.0	7.8	7.4	7.4	7.4	37.0
Percent Performance			0.085	0.109	0.210	0.199	0.199	0.199	



Functional Flow Block Diagram (FFBD)



Alternative Architectures

Commit	Intercept: A (MS)	Intercept: B (DE)	Intercept: C (RG)
X (Radar 1)	AX	BX	CX
Y (Radar 2)	AY	BY	CY

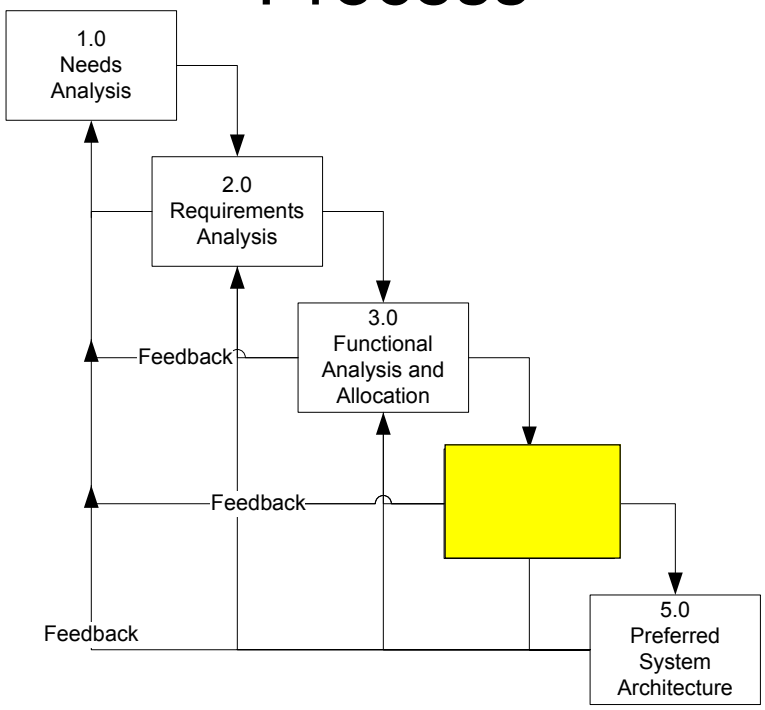
MS = Missile
DE = Directed Energy
RG = Rail Gun

Radar 1 = Phased Array Radar
Radar 2 = Skin-of-the-ship Radar

Functional Allocation

Functions	Components						
	Interceptor (RG, M, DEW)	CIX / DATA Voice	ABMs	Fire Control System	Radar (AEGIS/SOTS)	Nonorganic Asstes	Sea Frame
Receive intel cueing		X					
Acquire non-organic asset information		X				X	
Acquire / Detect target					X		
Track target					X		
Identify target			X		X		
Generate fire control solution(s)			X	X			
Make C2 / Decision			X				
Engage ballistic missile	X						
Exchange information		X					
Gather and process BDA		X					
Presence							X

Systems Engineering Process



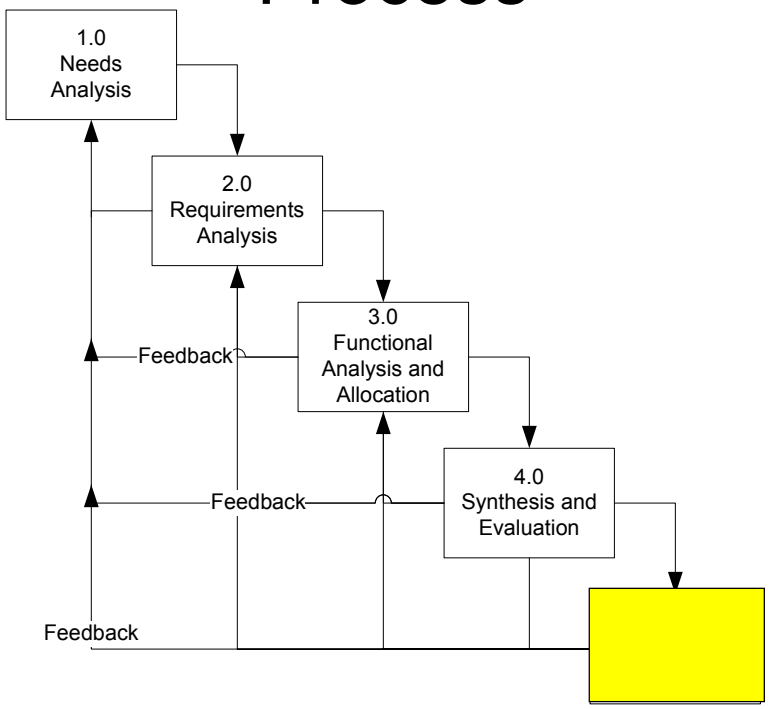
4.0 Synthesis and Evaluation Breakdown

- 4.1 System Synthesis
- 4.2 Conduct Simulative Analysis
- 4.3 Evaluate CONOP
- 4.4 Update and Refine Models
- 4.5 Conduct Cost Analysis

4.0 Synthesis and Evaluation Breakdown cont

- 4.6 Refine MOEs/ MOPs
- 4.7 Validate CONOP
- 4.8 Design Architecture
- 4.9 Refine System Synthesis
- 4.10 Conduct System Design Review / Validation
- 4.11 Perform Final System Adjustments

Systems Engineering Process



Design Reference Mission (DRM) and Scenarios

LT Earl Duff

DRM Definition

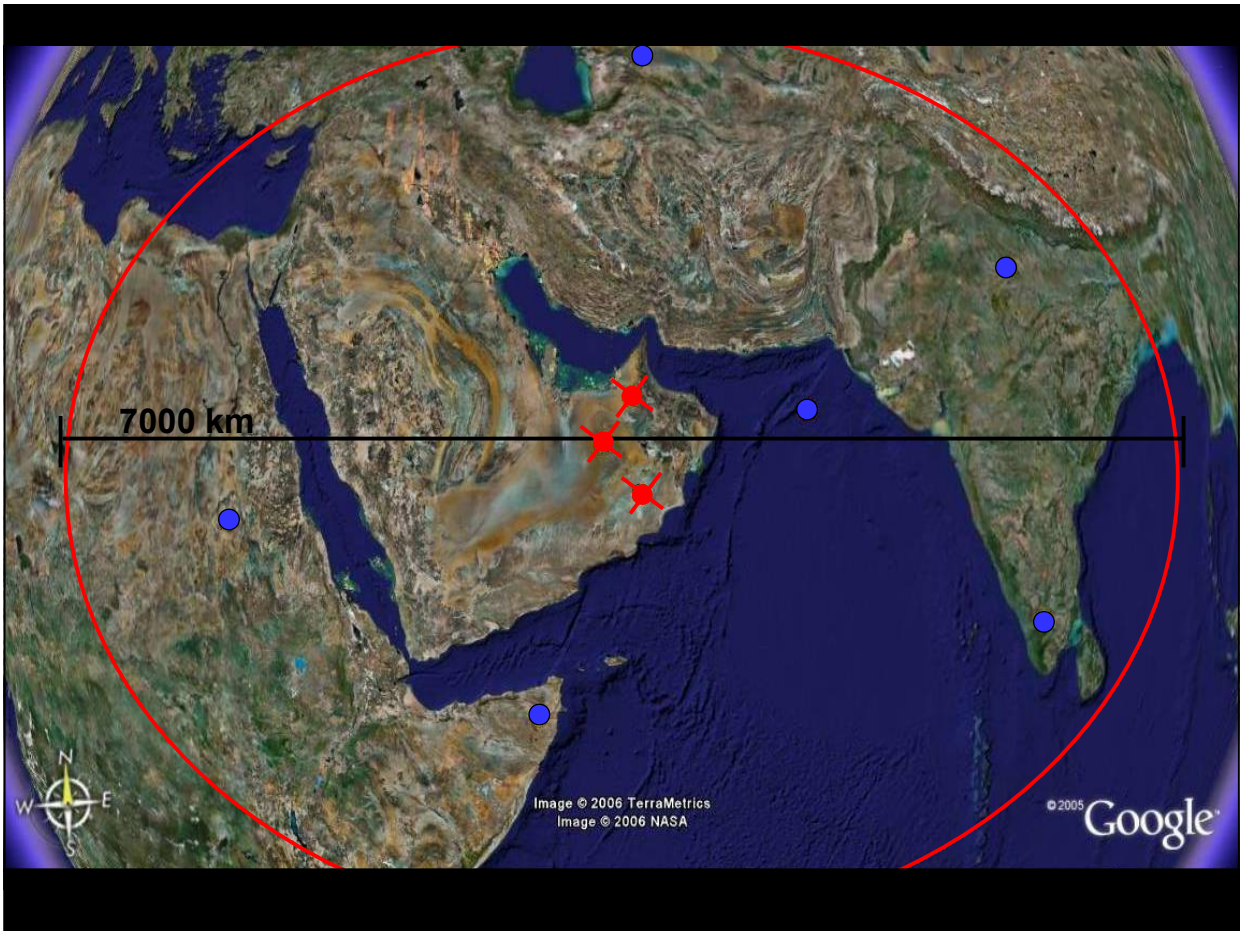
- Design Reference Mission: A systems engineering tool that states the problem not the solution
- Two parts: DRM Profile (DRMP) & Scenarios
  - Design reference mission profile is a matrix that places values and conditions to scenarios
  - Scenarios were ranked best, expected and worst

Design Reference Mission Profile

Event	Required Equipment	Environmental Factors			
		Condition	Best	Expected	Worst
Commit Phase					
Missile Launch	Threat Launch	# of missiles	1	2	6
		# of locations	1	2	3
Missile Detection	Satellite Detection System	Sat time to detect	0	10	None
		Ship time to Detect	0		
Missile Tracking	Organic & Non-Organic Radars	# of missiles	1000	1000	1000
Fire Control Solution	Organic & Non-Organic Radars, Fire Control Computers	Time to compute	0	3	10
Analyze Fire Control Solutions	ABMS, Network	Operational	Yes	Yes	No
Choose Optimum Fire Control Solution(s)	ABMS, Fire Control Computer	Time to compute	0	3	10
Transmit Kill Order		Time to transmit	0	3	10
Missile Engagement	Participating Units (shooters)	Weapons available	All	Most	1
Missile Kill	BDA Capable System	Operational	Yes	Yes	No
Missile Re-Engagement	End State	Re-Engage, Handoff, End	End	End	Handoff

Fictitious Area of Interest

- Expected scenario:
  - Launch sites are closer to coast
  - Low number of “tail chase” engagements
- Worst case scenario:
  - Launch sites are further from coast
  - Increased number of “tail chase” engagements



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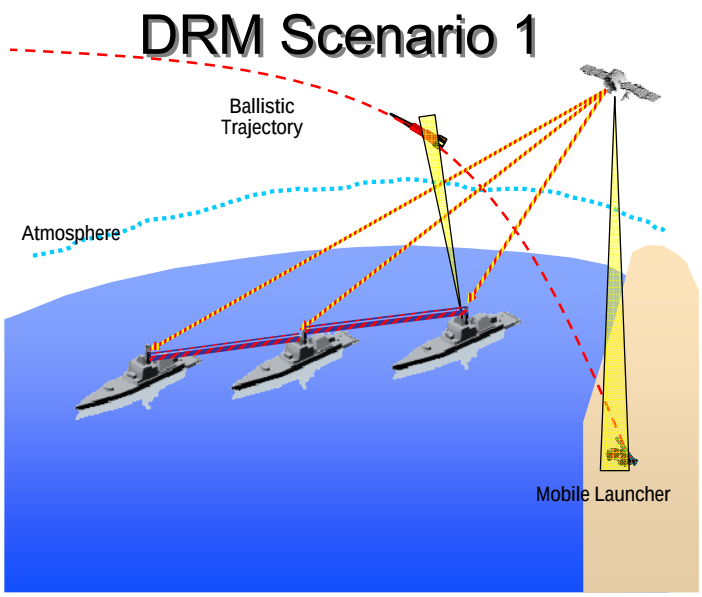
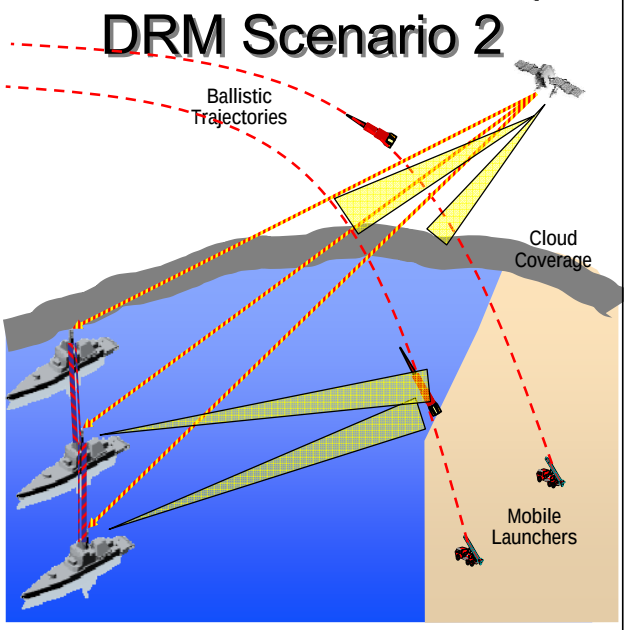
Scenarios- Best

- Basis for system verification
- All system functions are online and at optimal performance
- Environmental factors do not limit system performance



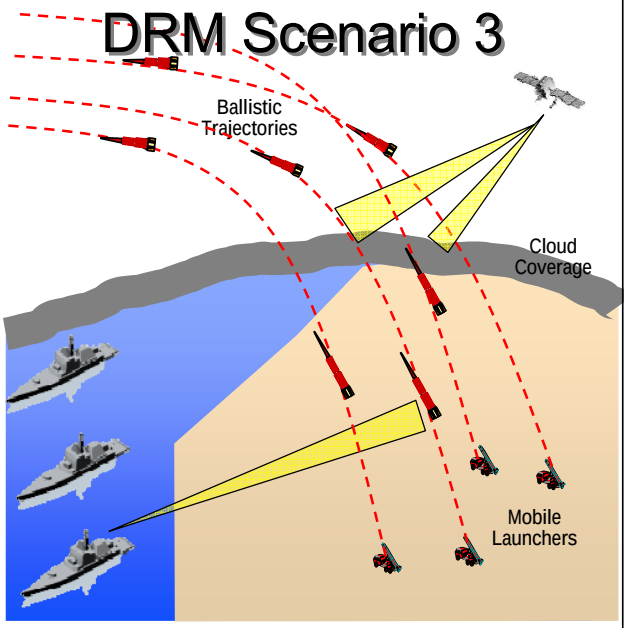
Scenarios- Expected

- Threats are further from the coast
- Weather degrades system performance
- More than one threat



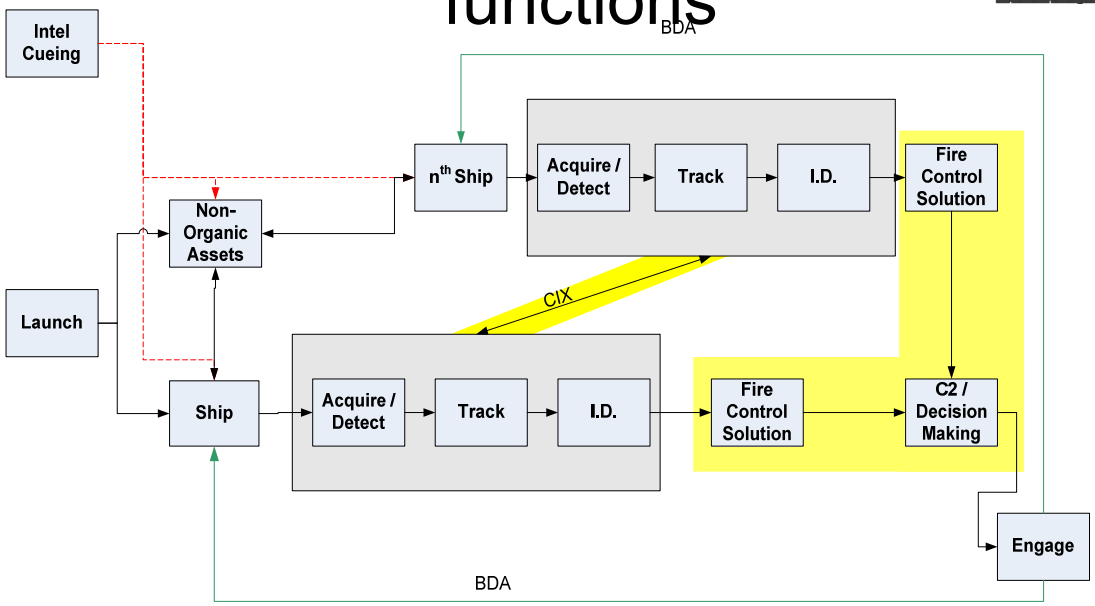
Scenarios- Worst Case

- Multiple threats from multiple launch sites
- Threats are much further from coast
- Weather degrades system performance
- CIX is not functional



Commit Component

Commit and Data Exchange Sub-functions



Commit Stage

- Defined: From threat missile launch to launch of interceptor.
- Requires integration of all system components
  - Sensors
  - CIX
  - ABMS
- Employ interceptor before end of missile boost phase

Commit Stage

- Develop a system that fuses coalition sensors, fire control computers and interceptors.
- Trade off between interceptor and fire control solution time.

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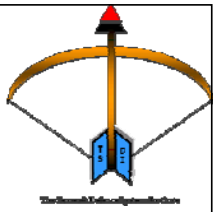
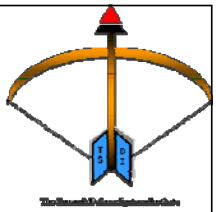
Needs



- **Detect missile launch**
- **Track & identify threat**
- **Prioritize Threats**
- **Pair with Interceptor**
- **Engage Threat w/ Interceptor**
- **BDA**
- **Exchange Data w/ Coalition Assets**

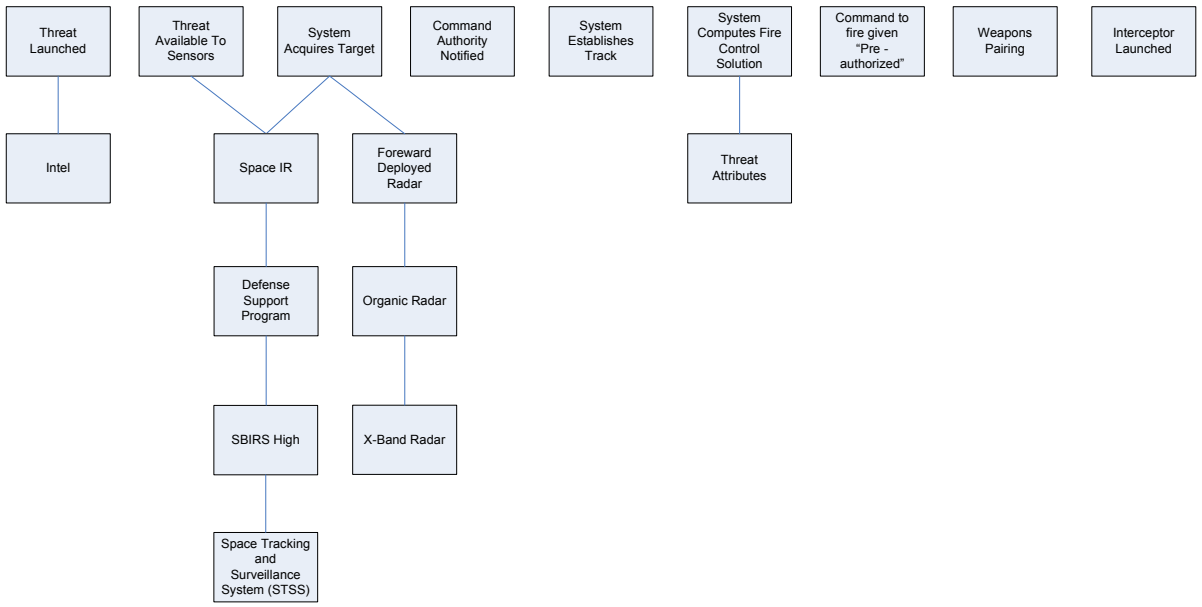
SABR
SHIP ANTI BALLISTIC RESPONSE

Requirements

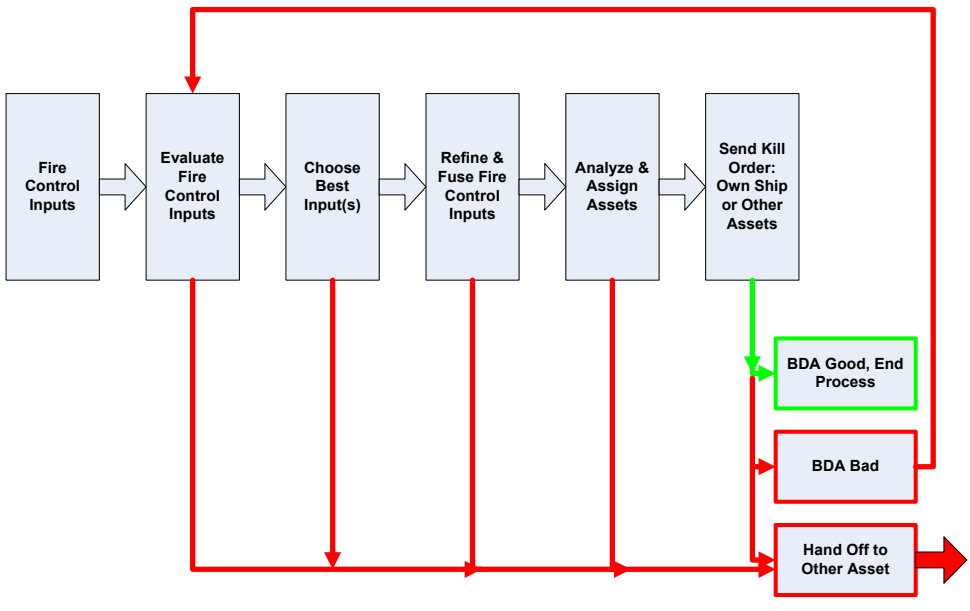


- Continuous worldwide satellite coverage
- P(d)≥0.99
- P(FA)≤0.01
- Produce fire control solution in order to intercept threat.
- Discriminate between threat & decoys
- Determine engagement order for all shooters

Commit Stage



Commit Stage Kill Chain



ABMS and CIX

LT Chris W. Hoffmeister

Talking Points

- ABMS
  - Mapping SE Generations to ABMS
  - Concepts and Architecture
  - Enablers
- CIX
  - Concepts and Architecture
  - Enablers

ABMS Definition

The system of facilities, equipment, communications, procedures, and personnel that perform functions in direct support of planning, directing, and controlling operations of forces pursuant to the missions assigned, specifically relating to the high degree of automation at the tactical and operational levels of action.

All encompassing Coalition Level command and control system.

ABMS Needs

- Operate independent of nation state territorial boundaries
- Employable over a wide range of environmental conditions
- Interoperate with Coalition Partners
- Share and correlate sensor and asset data
- Generate optimal engagement actions

ABMS Requirements

- Rapidly deployable and capable of prolonged operations
- Capable of operations in heavy seas
- Share and correlate sensor data
- Passing off of targets

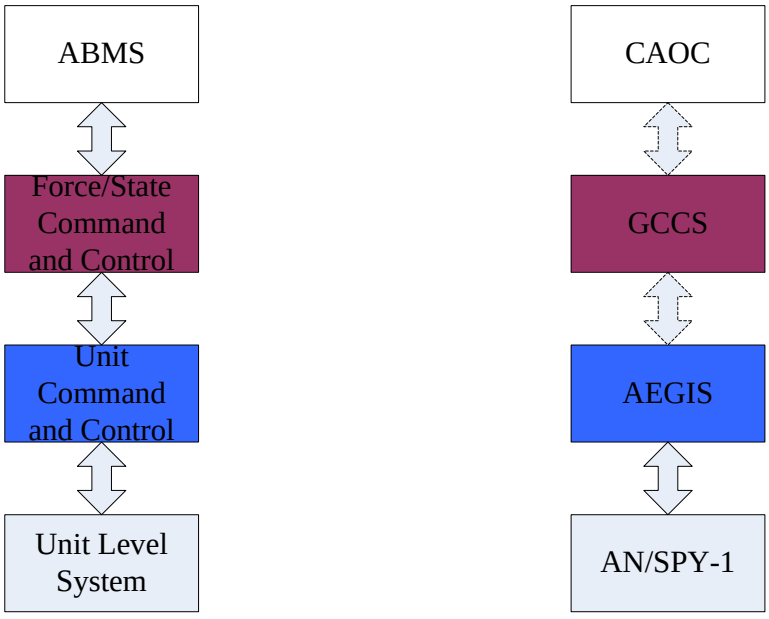
ABMS Functions

- Receive intelligence cueing
- Determine comprehensive BDA
- Share asset data

ABMS Concepts

- Layered
- Information Assurance
  - Availability
  - Confidentiality
  - Integrity
  - Authentication
  - Nonrepudiation
- Information Systems Security
  - Personnel Security
  - Physical Security
  - Communications Security
  - Computer Security
  - Emissions Security

ABMS Architecture



Concept **Example**

ABMS Enablers

- Operations Research to determine optimal engagement actions
- Symmetric and Asymmetric Cryptography
- Strong (2 and 3 factor) Authentication
- RAID Storage, Flash Storage
- Common Criteria

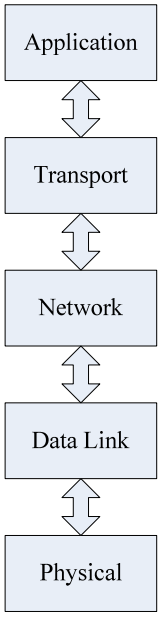
CIX Definition

The system of facilities, equipment, procedures, and personnel that perform functions in direct support of communications between interconnected nodes.

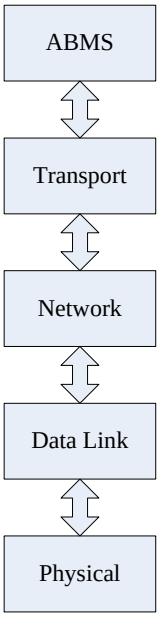
It's the private network.

CIX Concepts

- Modeled after TCP/IP (Layered)
- Wired and Wireless
- Encryption at individual layers



CIX Architecture



Concept

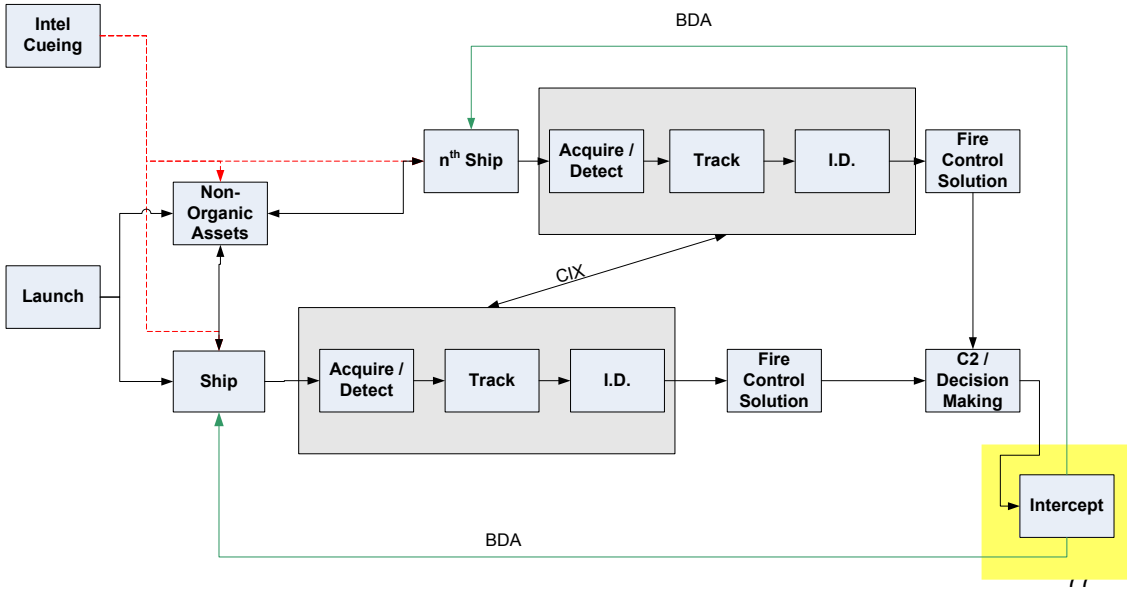
CIX Enablers

- Wired Communications
  - Fiber Optic
  - Shielded Metal
- Wireless Communications
  - Satellite
  - 802.11, 802.16
  - Spread Spectrum
- Symmetric and Asymmetric Cryptography

Intercept Component

LT Bryan Breeden

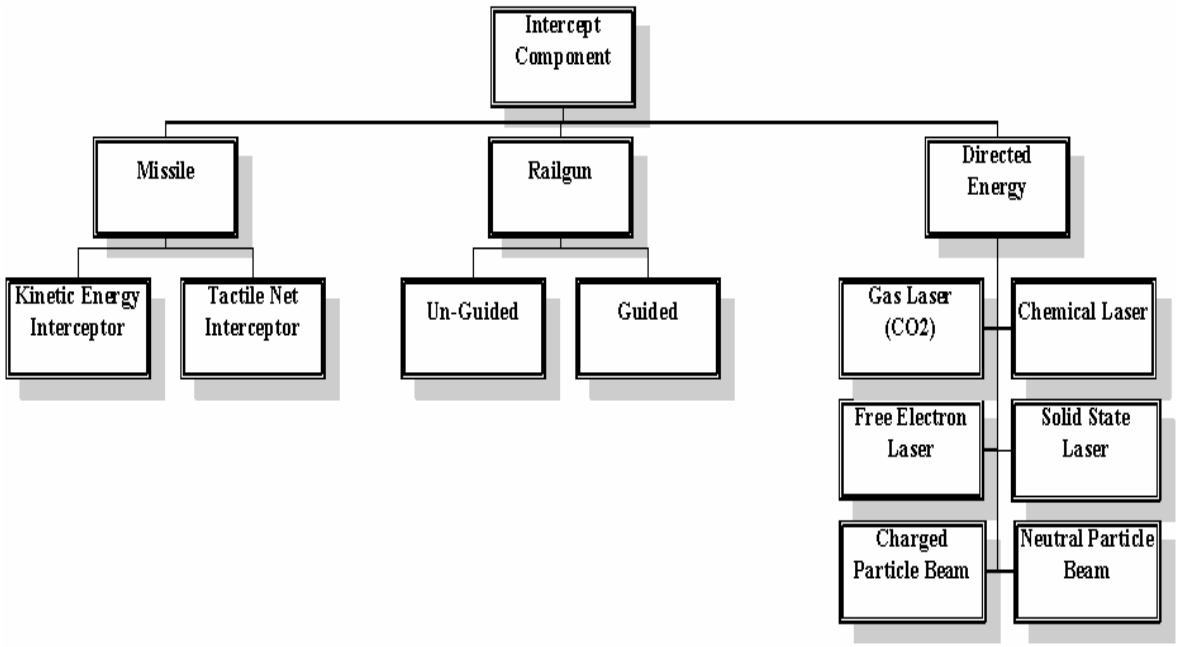
Intercept Component



Intercept Component

- Defined: The 'In-Flight Phase' of Engagement
  - Launch to Intercept
- Develop an interceptor capable of defeating SRBM to IRBM from the sea.
- Expected Alternatives:
  - Interceptor Missiles
  - Railgun
  - Directed Energy

Possible Interceptors



Intercept Considerations

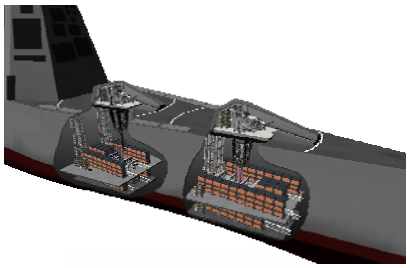
- Interceptor Missile:
  - Dimensions
  - Speed
  - Range
  - Maneuverability
  - Flight Profile
  - Data Rate for Guidance System
  - Terminal Guidance
  - 'Kill Mechanism'
  - Vulnerability

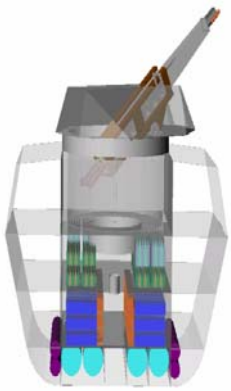
Intercept Considerations

- Directed Energy:
  - 'Turret'
    - Dimensions
    - Power Requirements
    - Energy Requirements
    - Firing/Re-Charge Rate
  - Lethal Range
  - 'Guidance'
    - 'Laser Illuminator'
  - Vulnerability

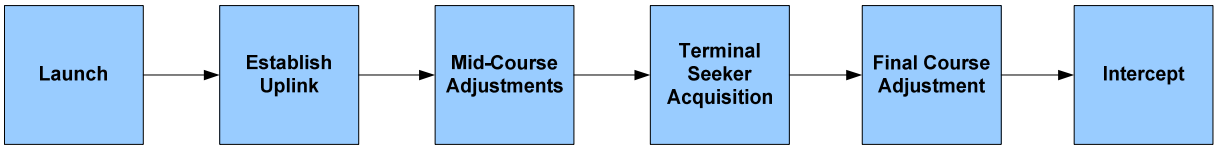
Intercept Considerations

- Rail Gun:
  - 'Turret'
    - Dimensions
    - Power Requirements
    - Energy Requirements
    - Firing/Re-Charge Rate
    - Barrel/Rail Life
  - Lethal Range
  - Guided or Ballistic
  - Vulnerability





Intercept Kill Chain



Overview of Architectures

Jiunn Wah Yeo
Chee Meng Fann

Sensor Architecture

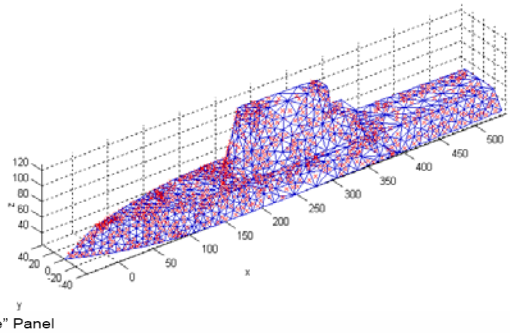
- Multi-layered Ballistic Missile Defense Sensor Systems
- Wide-range of multi-spectrum sensors to detect and track threat missiles through all phases of their trajectory
- Space and Satellites Tracking Surveillance Systems
- Land-and sea-based early warning and forward deployable radar systems.

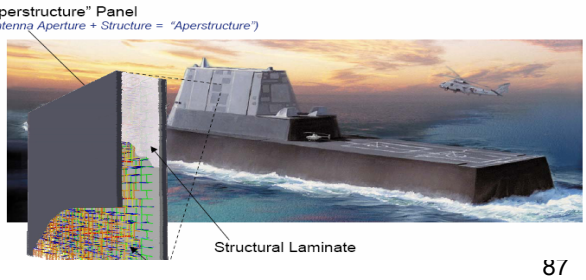
Stand-alone Configuration

- Considerations for stand-alone configuration using onboard ship-borne sensor systems:
  - Conformable aperstructure, skin of the ship (SOTS) radar, exploits the entire ship's structure as a radar aperture
  - Multifunction phased array radar (MFPAR), with dedicated Search, Track and Fire Control functions

Conformable Aperstructure SOTS Radar

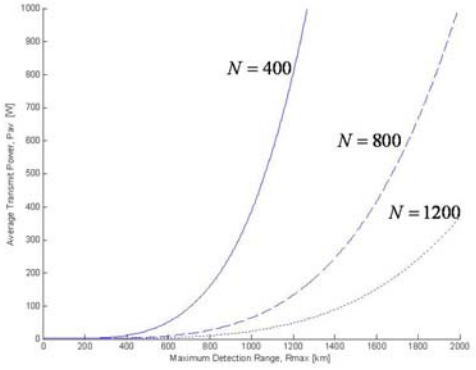
- Exploit the ship's structure as a radar aperture, individual antenna elements are conformal and integrated into the ship's structure
- Enhanced power-aperture product and angular resolution
  - Aperture size ≈ 200m
  - Beamwidth ≈ 1.3°
- Perform early warning and cueing of fire control radar





SOTS Radar Technical Aspects

- Analysis:
  - Maximum range of 1000 km achieved using 400 elements.
  - If 800 elements available, 1600 km possible.
  - If 1200 elements available, >2000 km possible.



Parameter	Specification
Operating frequency	300 MHz
Number of elements	1200
Detection range for 10 m² target	2000 km
Average power per element	500 W
Beamwidth	1.3°
Pulse width	16 ms
Duty cycle	0.25

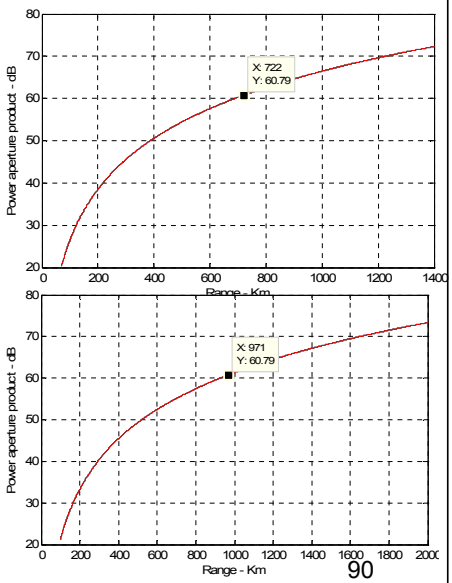
Multifunction Phased Array radar

- MFPAR providing dedicated search, track and fire control and missile guidance capabilities simultaneously
- Improved power-aperture product with high angular accuracy and resolution
  - PAP ≈ 60.8dB
  - Beamwidth ≈ 1.6°
- Extended detection range when operated in tandem with early warning radar

MFPAR Technical Aspects

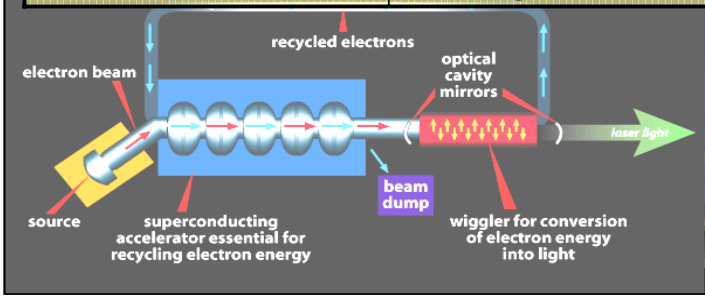
- Analysis:
  - Maximum detection range of 772 km in surveillance mode.
  - Maximum detection range of 971 km in tracking mode, when cued by early warning radar.

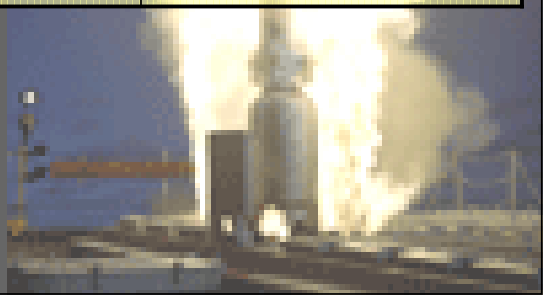
Radar Parameters	MFPA Radar
Operating Frequency (GHz)	3.3
Pulse repetition frequency (Hz)	17
Total average power (kW)	100
Effective aperture (m^2)	12.0
Power-aperture product (dB)	60.8
Receiving gain (with weighting) (dB)	42.6
Weighted azimuth beamwidth (deg)	1.6
Weighted elevation beamwidth (deg)	1.52
Detection range in surveillance mode (deg)	772
Detection range in tracking mode (deg)	971



Interceptor Variants

Type of Interceptor	Interceptor Variant	Max. Effective Range
Missile	SM-X blk 0 – 6 km/sec	1800 km
	SM-X blk 1 – 8 km/sec	2400 km
Rail Gun	RG-BMD blk 0 – 8 km/sec	2200 km
	RG-BMD blk 1 – 10 km/sec	4400 km
Directed Energy	Free-Electron Laser	500 km
	Charged Particle Beam	500 km





Missile Interceptor

- What is missile interceptor?
  - A defensive missile designed to counter other missiles
- Current missile interceptors
  - MIM-104 Patriot (US Army)
    - Solid fuel rocket motor, > Mach 5
  - Standard Missile SM-3 Block 1 (US Navy)
    - 3-stage solid fuel, up to 1200 km, 4 km/sec

Missile Interceptor Advantages & Disadvantages

- Mature technology
- High speed
- Long range
- Can be guided along trajectory

- Pin-point intercept
- Big & bulky
  - Propulsion
  - Sensor

Directed Energy Weapon

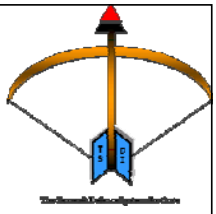
Definition

- Weapon that uses highly correlated, intensified and directional energy beam in the megawatts class as the kill mechanism.

Modern DE systems

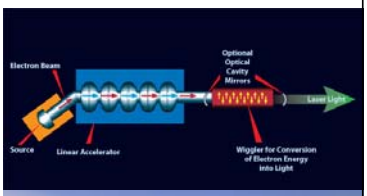
- Solid state laser
- Gas laser
- Chemical laser
- Free electron laser
- Particle beam

Advantages and Disadvantages of DEW

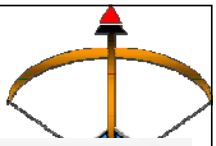


- Speed of light delivery of high power destruction beam onto desired target
- Energy required to propel laser is basically electrical power
- Multiple target engagements and rapid retargeting with electronic steering

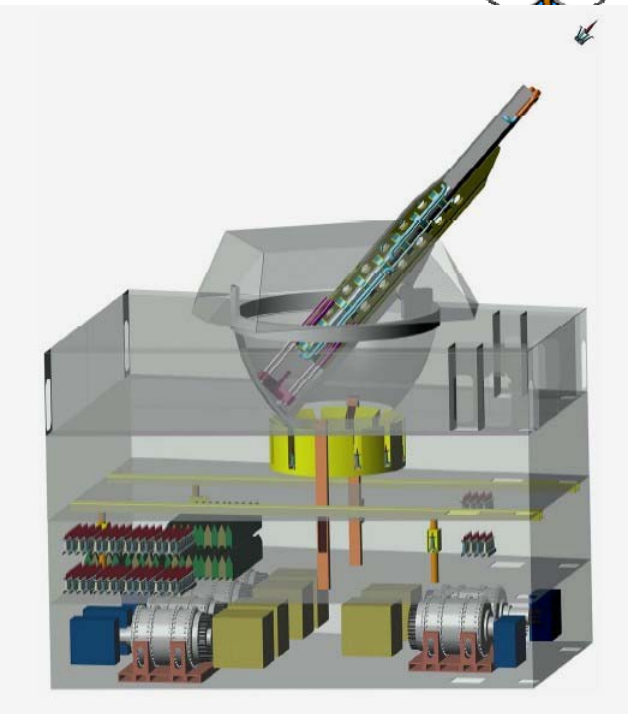
- Power supply source for high power energy beam generation. (megawatt output)
- LOS
- System cooling & Waste heat management
- Atmospheric attenuation (Absorption, Scattering, beam divergence, etc)
- On board ship beam delivery system (sea state affecting beam delivery)



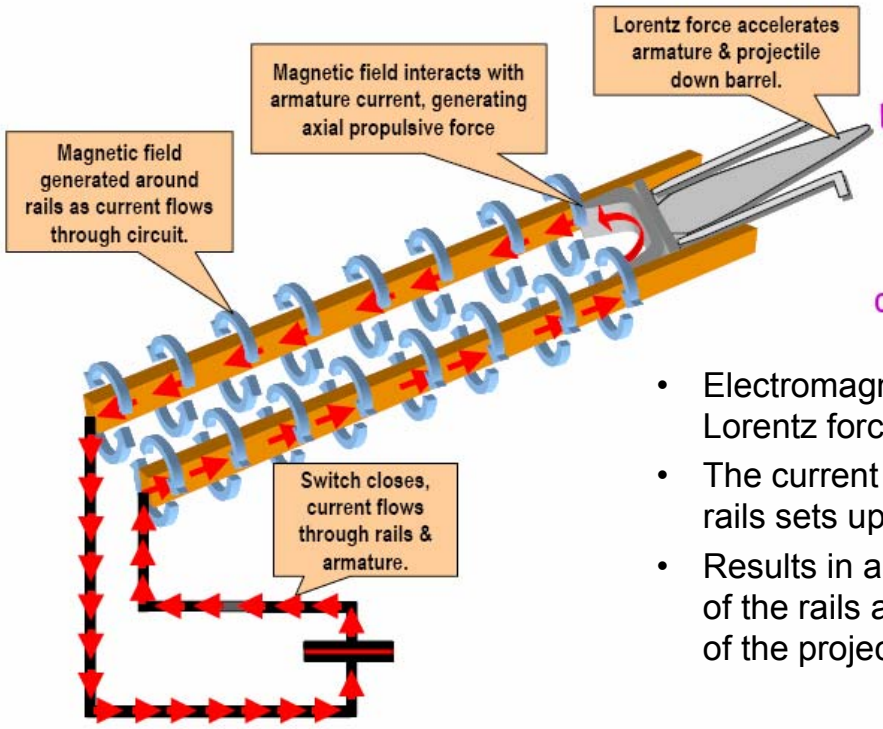
Railgun

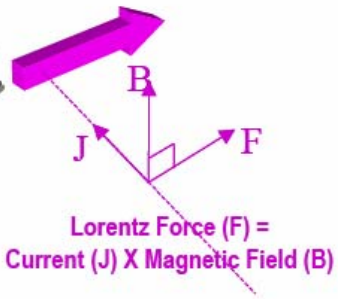


- Conventional launching method uses mechanical and chemical energy.
- Utilizes electromagnetic force for propelling projectile.
- High muzzle velocity.
- High kinetic energy.



Railgun Theory





- Electromagnetic force - Lorentz force
- The current flowing through the rails sets up a magnetic field.
- Results in a mutual repulsion of the rails and the accleration of the projectile along them.

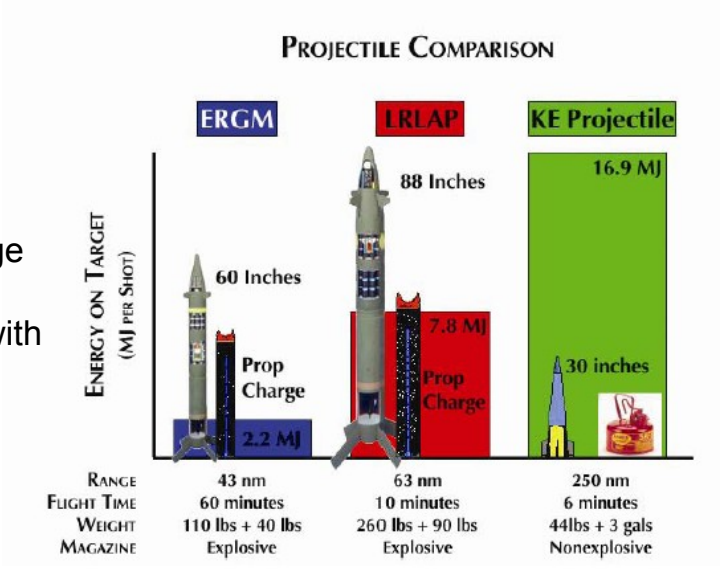
Adapted: Exploring the possibilities of a Naval Electromagnetic Railgun (38th Annual Gun and Ammunition Symposium

Current Railgun Capabilities

- **Sandia National Research Laboratories**
  - Launcher: 6 mm
  - Mass of object: 0.1 gram
  - Speed: 16 km/s
- **Maxwell Laboratories**
  - Mass of projectile: 1.6 kg
  - Speed: 3.3 km/s
  - Energy: 9 MJ
- **Electromagnetic Launcher - Kirkcudbright, Scotland**
  - Speed: 2.5 km/s
  - Range: Beyond 200 nautical miles / 370 km
  - Power requirement: 15 ~ 30 MW
- **University of Texas – Institute of Advanced Technology**
  - Flight mass: 15kg
  - Muzzle Velocity: 2.5 km/s
  - Range: Beyond 270 nautical miles / 500 km
  - Impact Velocity: 1.6 km/s

Railgun Advantages

- High Impact Energy
- Size / Weight / Space
- No explosives
- Extremely High Speed / Range
- Interaction of KE penetrator with the missile / High shock Transmission
- Adiabatic heating and ignition causing explosion and deflagration
- Scale up / down
- Less Recoil

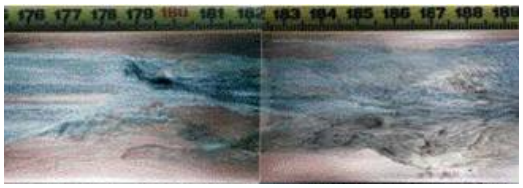


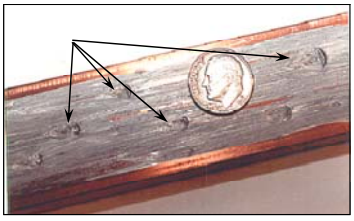
$$KE = \frac{1}{2}mv^2$$

Railgun Disadvantages

Rail Gun

- Rail erosion caused by high temperature
- Durability of rails
- Strong and conductive materials needed
- Electrical Drive

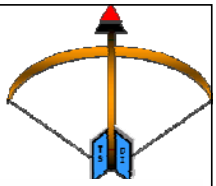




KE Penetrator

- Flight Performance in higher atmosphere, high moisture environment
- High Speed – high shock: Using air spike, multiple projectiles

Projected Capabilities



- **Flight Mass : 2 kg**
- **Launch Velocity: 10 km/sec**
- **Guided**
- **Range: beyond 4400 km**
- **Firing Rate: 16 to 20 RPM**
- **Cost: ~ $60k per round**

Notional Navy EM Gun:
- Flight Mass – 15 kg
- Launch Mass – 20 kg
- Launch Velocity – 2.5 km/s
- Muzzle Energy – 63 MJ
- Breech Energy – ~150 MJ
- Barrel Length – 10 m
- Peak Accel. – 45 kg's
- Firing Rate – 6 to 12 RPM
- Peak Power – 20 to 40 MW
- Peak Current ~ 6 MA
- In-Bore Time ~ 8 – 10 msec

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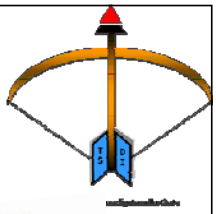
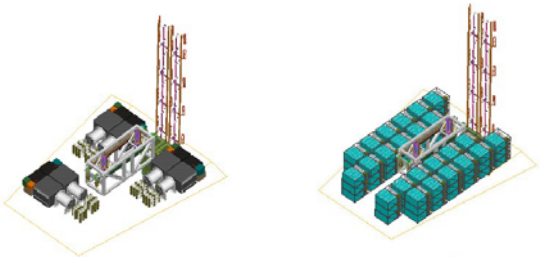
Adapted: Exploring the possibilities of a Naval Electromagnetic Railgun (38th Annual Gun and Ammunition Symposium

Future Development



- **Projectiles**
  - Launch Dynamics
  - GPS/INS
  - Drag
  - Terminal Effects
- **Power**
  - Capacitors
  - Pulsed Alternators
- **Railgun**
  - Material: Conductive, Temperature & wear resistance, strength
  - Cooling
  - Electromagnetic Interference / Compatibility



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Architecture Development

LT Bryan Breeden

Modeled Sensors

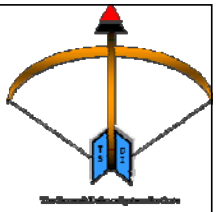
Type of Sensor	Sensor Variant	Maximum Detection Range
Inorganic	Sensor Network	n/a
MFPAR	MFPAR blk0	730 km
SOTSR+MFPAR	SOTSR/MFPAR blk0	1500 km
	SOTSR/MFPAR blk1	2000 km

Modeled Interceptors

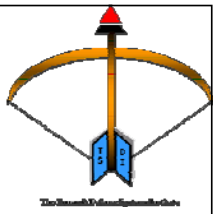
Type of Interceptor	Interceptor Variant	Interceptor Velocity	Maximum Effective Range
Missile	SM-X blk0	6 km/sec	1800 km
	SM-X blk1	8 km/sec	2400km
Railgun	RG-BMD blk0	8 km/sec	2200 km
	RG-BMD blk1	10 km/sec	4400 km
Directed Energy	Free-Electron Laser	$3x10^5$ km/sec	500 km
	Charged Particle Beam	$3x10^5$ km/sec	500 km

Architecture Matrix

Ballistic Missile Defense Alternative Architecture Matrix							
		Interceptor Variant					
		Missile		Railgun		Directed Energy	
		SM-X blk0	SM-X blk1	RG-BMD blk0	RG-BMD blk1	Free-Electron Laser	Charged Particle Beam
Sensor Variant	Inorganic Sensor Network	ISN - M	ISN - M+	ISN - R	ISN - R+	ISN - FEL	ISN - CPB
	MFPAR blk0	P - M	P - M+	P - R	P - R+	P - FEL	P - CPB
	SOTSR/MFPAR blk0	(S/P) - M	(S/P) - M+	(S/P) - R	(S/P) - R+	(S/P) - FEL	(S/P) - CPB
	SOTSR/MFPAR blk1				(S/P)+ - R+		

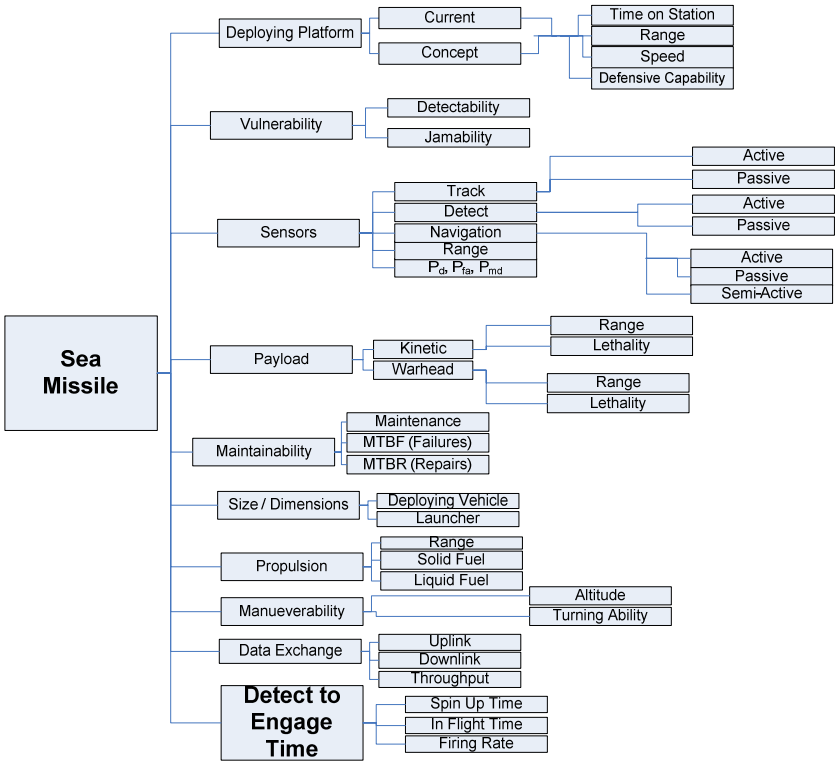


SABR
SHIP ANTI BALLISTIC RESPONSE

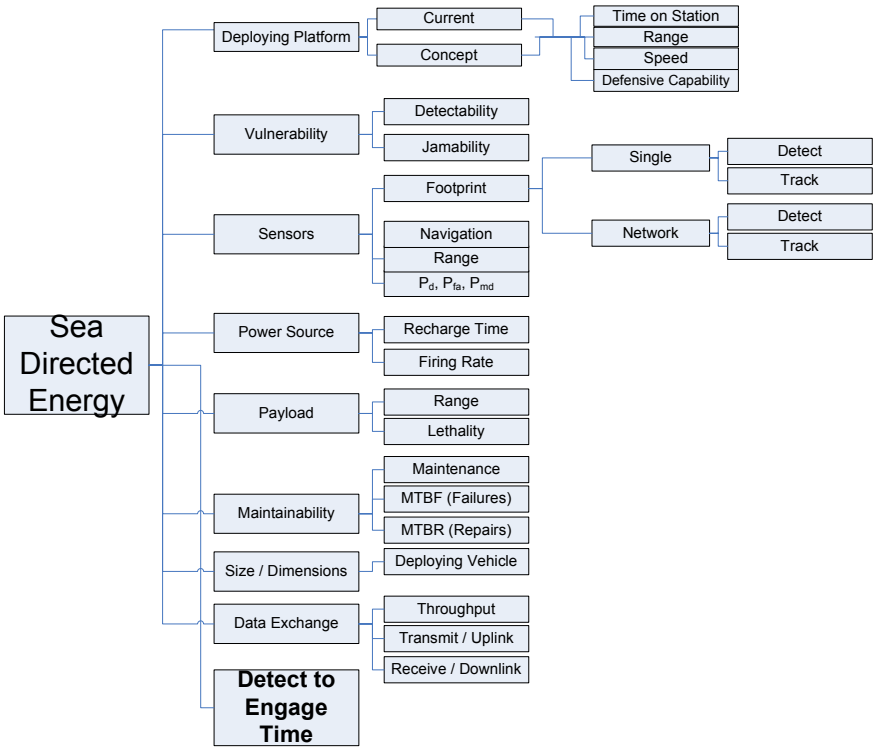


Back ups

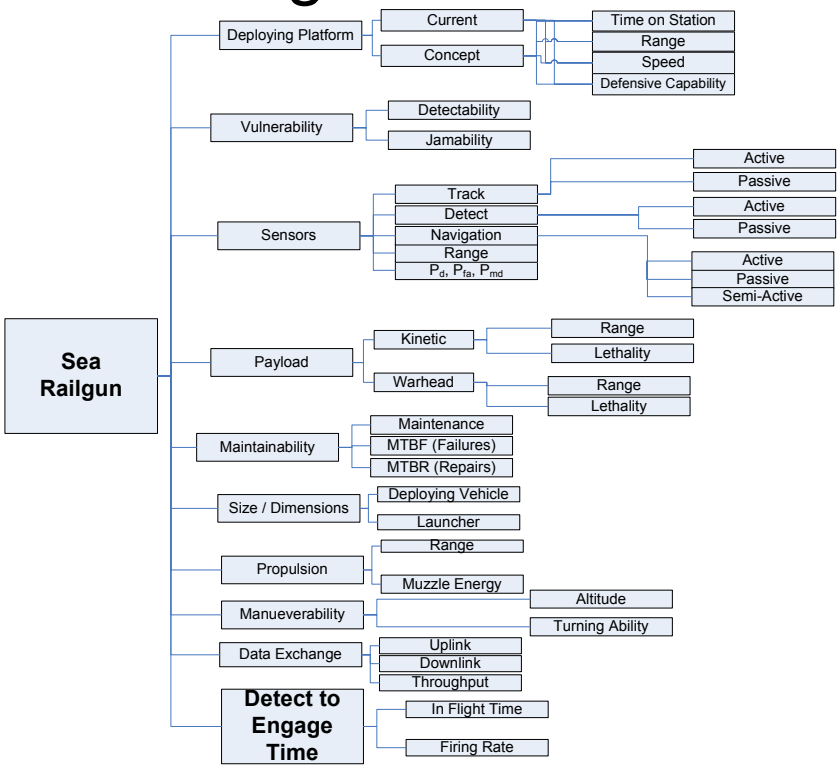
Missile Breakdown



DEW Breakdown



Railgun Breakdown



Physical Model

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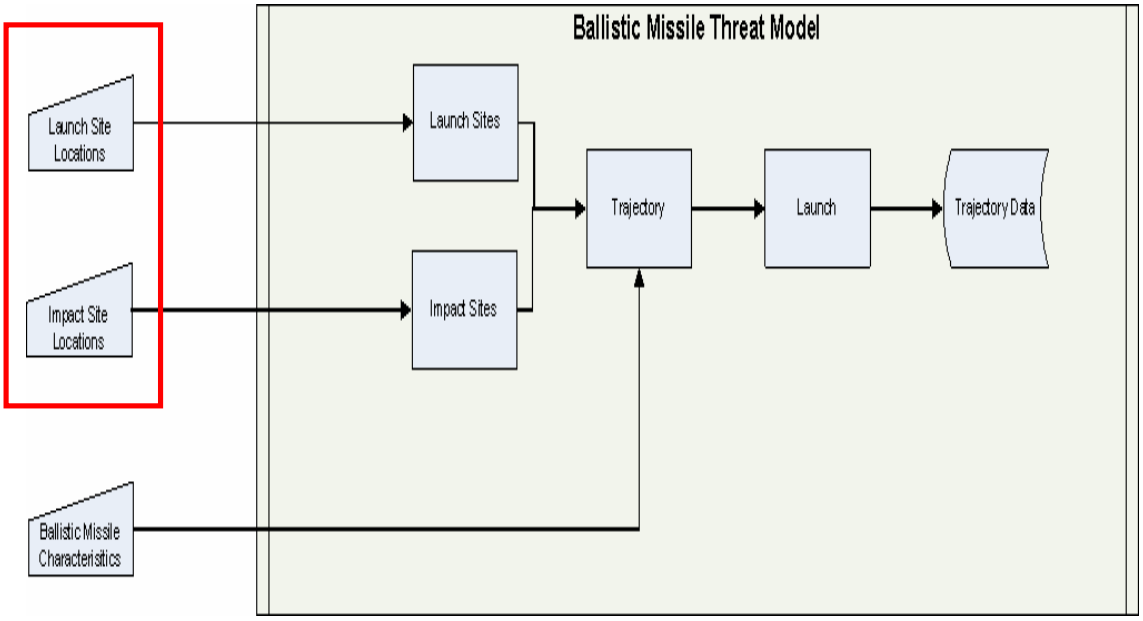
Lat/Long to XY Conversion
+
Ballistic Missile Parameters
+
Interceptor Parameters
+
Trajectory Models
=
Physical Model

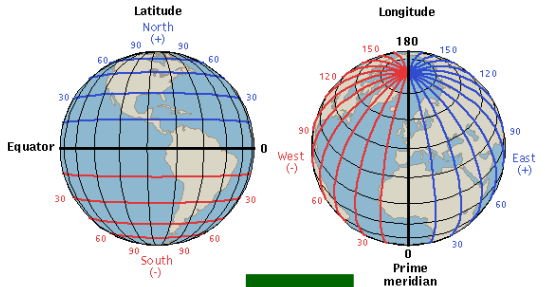
Modeling Process

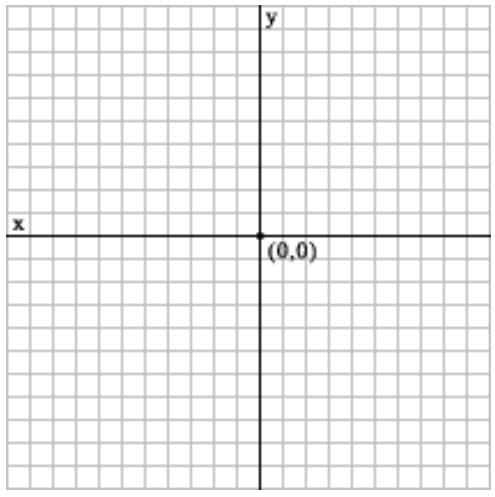
- **Where to Start ???**
  - Define Threat
  - Model 'Simple Boosted' Trajectory
  - Identify Launch Sites
  - Identify Target Sites
- **Adding Complexity…**
  - Account for:
    - Drag
    - Lift
    - Gravity
    - Curvature of the Earth
  - Eliminate manual entries to attain desired impact range and launch angle
- **Grid Assignment:**
  - Eliminate manual grid construction
  - Use latitude and longitude to input all positions

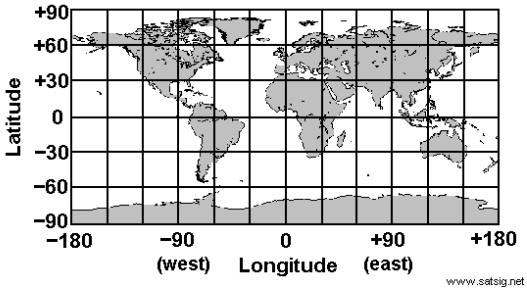
Ballistic Missile Threat Model- subcomponents



Latitude/Longitude→(X,Y)







Lat/Long →(X,Y) Conversion

- Degree/Minute/Second to Decimal Degree

$$DecimalDegree = Degree + \frac{Minute}{60} + \frac{Second}{3600}$$

- Great Circle Range

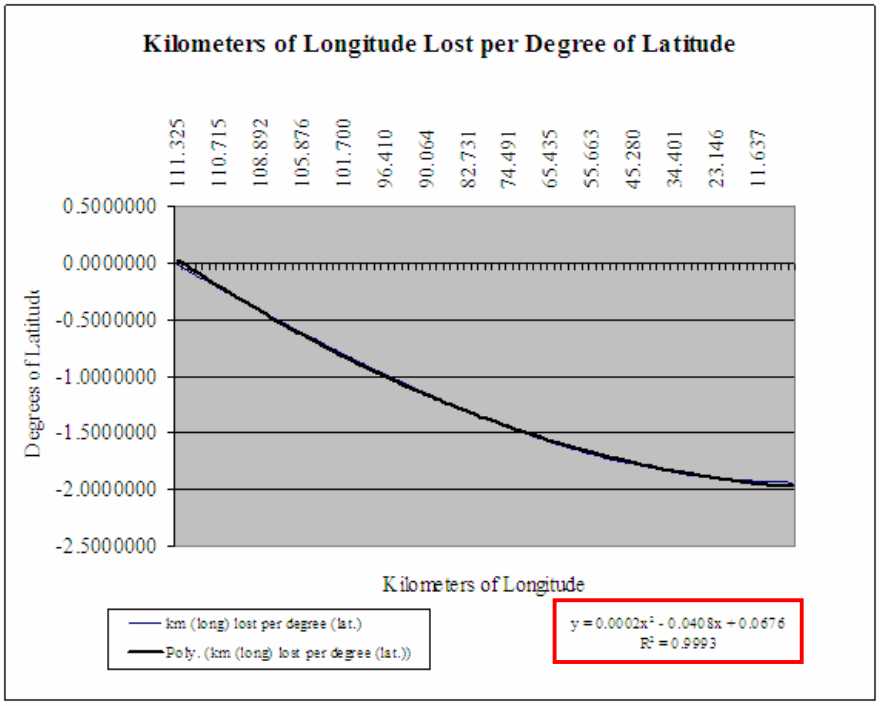
$$D = \cos^{-1}\left[(\sin(lat_1) * \sin(lat_2)) + (\cos(lat_1) * \cos(lat_2) * \cos(|long_1 - long_2|))\right] * 111.325$$

Lat/Long →(X,Y) Conversion

$$Latitude_{km/\deg ree} = 111.325 * (latitude_{\deg ree})$$

$$Longitude_{km/\deg ree} = 111.325 * [\cos(latitude_{\deg ree})]$$

Lat/Long →(X,Y) Conversion



Lat/Long →(X,Y) Conversion

$$Latitude(km) = °\Delta Lat * 111.325$$

$$Longitude(km) = °\Delta Long * \left[111.325 * \cos(°Lat_{decimal}) - 0.0002 * °\Delta Lat^2 - 0.0408 * °\Delta Lat + 0.0676\right]$$

Geographic Inputs

***Note: (+) = North or East ; (-) = South or West

Reference Site:								
	Latitude				Longitude			
Launch Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	21	51	5	21.851	53	9	9	53.152

Launch								
	Latitude				Longitude			
Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	21	51	5.02	21.851	53	9	8.97	53.152
2	23	50	37.83	23.844	55	20	13.06	55.337
3	20	5	8.98	20.086	55	54	32.12	55.909
4				0.000				0.000
5				0.000				0.000
6				0.000				0.000

Target								
	Latitude				Longitude			
Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	18	20	53.23	18.348	32	59	23.45	32.990
2	9	32	37.62	9.544	49	24	30.96	49.409
3	39	29	46.50	39.496	56	35	52.18	56.598
4	22	15	50.74	22.264	64	26	6.34	64.435
5	27	24	12.74	27.404	75	49	58.10	75.833
6	12	12	17.93	12.205	77	33	22.13	77.556
7				0.000				0.000
8				0.000				0.000
9				0.000				0.000
10				0.000				0.000
11				0.000				0.000
12				0.000				0.000

Surface Ship								
	Latitude				Longitude			
Ship #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1				0.000				0.000
2				0.000				0.000
3				0.000				0.000

XY-Cartesian Plane Output

Grid Assignment		
Site #	Lat (km)	Long (km)
LS1	0.000	0.000
LS2	221.809	222.458
LS3	-196.552	287.810
LS4		
LS5		
LS6		
TS1	-390.002	-2126.199
TS2	-1370.145	-408.774
TS3	1964.314	298.007
TS4	45.944	1161.822
TS5	618.092	2245.026
TS6	-1073.887	2643.623
TS7		
TS8		
TS9		
TS10		
TS11		
TS12		
Ship1		
Ship2		
Ship3		

Grid Reference Ranges

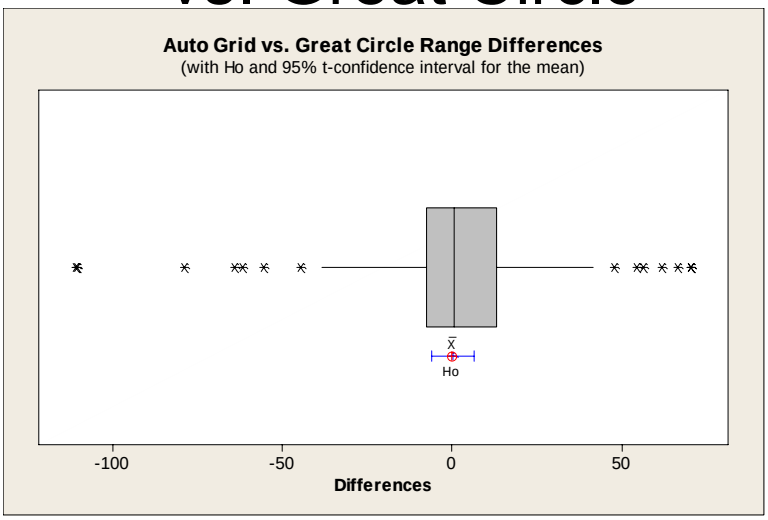
	LS1	LS2	LS3	LS4	LS5	LS6
TS1	2161.672	2427.037	2421.748			
TS2	1429.823	1712.534	1364.752			
TS3	1986.790	1744.141	2160.889			
TS4	1162.730	955.684	907.029			
TS5	2328.557	2061.024	2119.986			
TS6	2853.415	2746.064	2513.877			
TS7						
TS8						
TS9						
TS10						
TS11						
TS12						

Great Circle Ranges

	LS1	LS2	LS3	LS4	LS5	LS6
TS1	2141.945	2397.220	2415.164			
TS2	1427.418	1712.096	1365.666			
TS3	1991.373	1746.540	2161.870			
TS4	1164.738	948.215	917.530			
TS5	2373.016	2092.536	2184.021			
TS6	2805.627	2679.474	2472.357			
TS7						
TS8						
TS9						
TS10						
TS11						
TS12						

Mean Range Difference (all scenarios) = 0.20km

XY Planar Grid vs. Great Circle

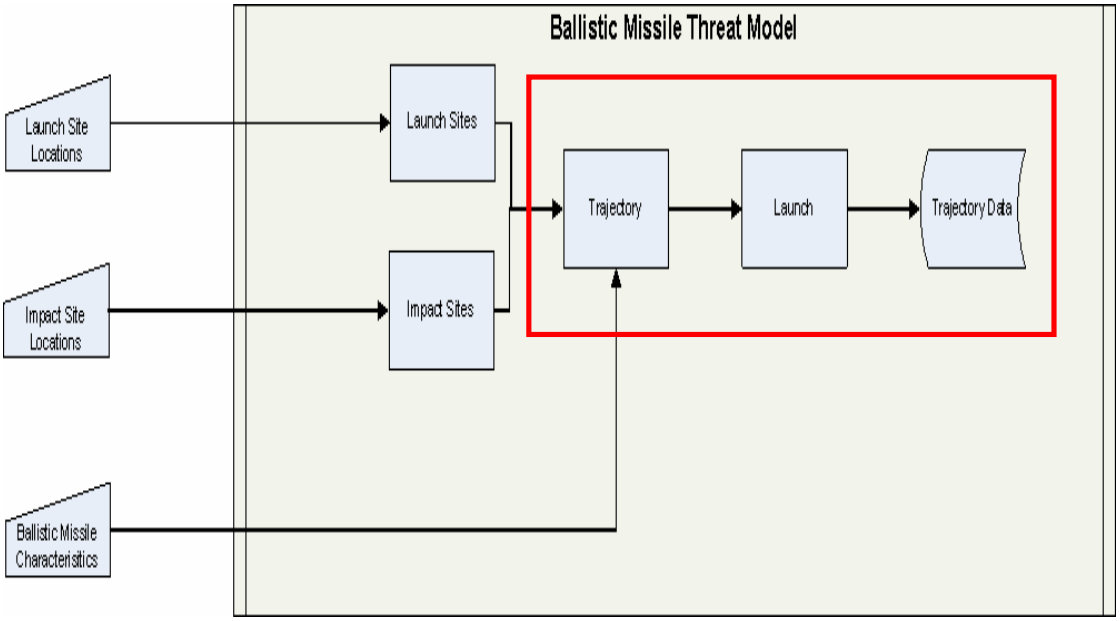


	N	Mean	StDev	SE Mean
Auto Grid	94	1580.40	762.89	78.69
Great Circle	94	1580.20	760.64	78.45
Difference	94	0.201266	31.006098	3.198035

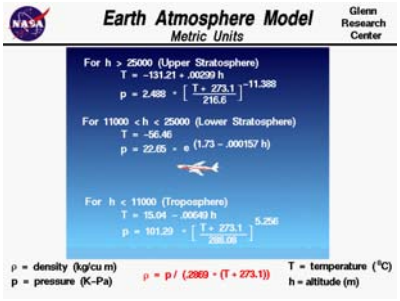
95% CI for mean difference: (-6.149397, 6.551929)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.06 P-Value = 0.950

No Significant Range Difference

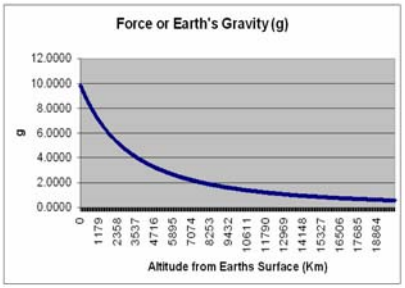
Ballistic Missile Threat Model- subcomponents



Physical Model: What went into it?



Ballistic Missile Threat Parameters	
Total Mass:	67000 Kg
Warhead Mass:	1500 Kg
Propellant Mass:	55944 Kg
Dry Booster Mass:	9556 Kg
Burn Time:	140 seconds
BM Frame Height:	15.50 m
BM Frame Diameter:	2.50 m
Warhead Height:	3.85 m
Warhead Diameter:	2.50 m
(theta):	90.00 degrees
(phi):	259.61 degrees
Divert Angle:	36.00 degrees
Divert Time:	60.00 seconds
Specific Impulse:	263 seconds
m-dot:	99.9 kg/sec
Number of Engines:	4



Conservation of Momentum

Conservation of Mass

Linear Motion

Drag

Rail Gun Parameters	
Total Mass:	2 Kg
Warhead Mass:	2 Kg
Warhead Height:	0.50 m
Warhead Diameter:	0.13 m
(theta):	149.575 degrees
(phi):	89.558 degrees
Muzzle Velocity	10.00 km/sec

Specific Impulse

Thrust Control

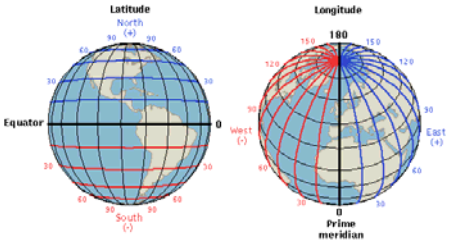
Thrust

m-dot

Mass

Velocity

Curve of the Earth



Subsonic Velocity		
1 km/sec=	2236.93629	mph
mph	km/sec	m/sec
0.0000	0.0000	0.0000
249.0000	0.1113	111.3130
Transonic Velocity		
mph	km/sec	m/sec
250.0000	0.1118	111.7600
759.0000	0.3393	339.3034
Supersonic Velocity		
mph	km/sec	m/sec
760.0000	0.3398	339.7504
1499.0000	0.6701	670.1130
High Supersonic Velocity		
mph	km/sec	m/sec
1500.0000	0.6706	670.5600
3499.0000	1.5642	1564.1930
Hypersonic Velocity		
mph	km/sec	m/sec
3500.0000	1.5646	1564.6400
7500.0000	3.3528	3352.8000
High Hypersonic Velocity		
mph	km/sec	m/sec
7501.0000	3.3532	3353.2470
17500.0000	7.8232	7823.2000

Physical Model Robustness

- Linear Motion Equations
- Gravity as a function of Altitude
- Curvature of the Earth
- Conservation of Momentum
- Conservation of Mass
- Specific Impulse
- Mass Flow Rate
- Thrust
- Thrust Control
- Drag
- Lift
- Air Density
- Atmospheric Temperature
- Atmospheric Pressure
- Hypersonic Theory
- Latitude/Longitude Inputs

Physical Model

- Primary Inputs
  - Geographic
  - Ballistic Missile
  - Railgun

***Note: (+) = North or East ; (-) = South or West

Reference Site:								
	Latitude				Longitude			
Launch Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	21	51	5	21.851	53	9	9	53.152

Launch								
	Latitude				Longitude			
Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	21	51	5.02	21.851	53	9	8.97	53.152
2	23	50	37.83	23.844	55	20	13.06	55.337
3	20	5	8.98	20.086	55	54	32.12	55.909
4				0.000				0.000
5				0.000				0.000
6				0.000				0.000

Target								
	Latitude				Longitude			
Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	18	20	53.23	18.348	32	59	23.45	32.990
2	9	32	37.62	9.544	49	24	30.96	49.409
3	39	29	46.50	39.496	56	35	52.18	56.598
4	22	15	50.74	22.264	64	26	6.34	64.435
5	27	24	12.74	27.404	75	49	58.10	75.833
6	12	12	17.93	12.205	77	33	22.13	77.556
7				0.000				0.000
8				0.000				0.000
9				0.000				0.000
10				0.000				0.000
11				0.000				0.000
12				0.000				0.000

Surface Ship								
	Latitude				Longitude			
Ship #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1				0.000				0.000
2				0.000				0.000
3				0.000				0.000

Ballistic Missile Threat Parameters	
Total Mass:	67000 Kg
Warhead Mass:	1500 Kg
Propellant Mass:	55944 Kg
Dry Booster Mass:	9556 Kg
Burn Time:	140 seconds
BM Frame Height:	15.50 m
BM Frame Diameter:	2.50 m
Warhead Height:	3.85 m
Warhead Diameter:	2.50 m
(theta):	90.00 degrees
(phi):	269.61 degrees
Divert Angle:	36.00 degrees
Divert Time:	60.00 seconds
Specific Impulse:	263 seconds
m-dot:	99.9 kg/sec
Number of Engines:	4

Rail Gun Parameters	
Total Mass:	2 Kg
Warhead Mass:	2 Kg
Warhead Height:	0.50 m
Warhead Diameter:	0.13 m
(theta):	149.575 degrees
(phi):	89.568 degrees
Muzzle Velocity	10.00 km/sec

Physical Model- Geographic

- **Inputs:**
  - Latitude
  - Longitude
  - Reference Position
- **Outputs:**
  - XY Cartesian Grid
    - Reference Position at the origin

***Note: (+) = North or East ; (-) = South or West

Reference Site:

	Latitude				Longitude			
Launch Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	21	51	5	21.851	53	9	9	53.152

Launch

	Latitude				Longitude			
Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	21	51	5.02	21.851	53	9	8.97	53.152
2	23	50	37.83	23.844	55	20	13.06	55.337
3	20	5	8.98	20.086	55	54	32.12	55.909
4				0.000				0.000
5				0.000				0.000
6				0.000				0.000

Target

	Latitude				Longitude			
Site #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1	18	20	53.23	18.348	32	59	23.45	32.990
2	9	32	37.62	9.544	49	24	30.96	49.409
3	39	29	46.50	39.496	56	35	52.18	56.598
4	22	15	50.74	22.264	64	26	6.34	64.435
5	27	24	12.74	27.404	75	49	58.10	75.833
6	12	12	17.93	12.205	77	33	22.13	77.556
7				0.000				0.000
8				0.000				0.000
9				0.000				0.000
10				0.000				0.000
11				0.000				0.000
12				0.000				0.000

Surface Ship

	Latitude				Longitude			
Ship #	degrees	minutes	sec	decimal Lat	degrees	minutes	seconds	decimal Long
1				0.000				0.000
2				0.000				0.000
3				0.000				0.000

Physical Model- Ballistic Missile

- **Inputs:**
  - Total BM Mass
  - Warhead Mass
  - BM Frame Height/Diameter
  - Warhead Height/Diameter
  - Number of Engines
  - Burn Time
  - Specific Impulse
  - Mass Flow Rate

- **Outputs:**
  - Trajectory
    - Per Time Step:
      - Velocity
      - X-Coordinate
      - Y-Coordinate
      - Z-Coordinate
      - Range from Launch Site
    - Time and Position of:
      - Launch
      - End of Boost
      - Apex
      - End of Midcourse (Terminal)
      - Impact

Ballistic Missile Threat Parameters	
Total Mass:	67000 Kg
Warhead Mass:	1500 Kg
Propellant Mass:	55944 Kg
Dry Booster Mass:	9556 Kg
Burn Time:	140 seconds
BM Frame Height:	15.50 m
BM Frame Diameter:	2.50 m
Warhead Height:	3.85 m
Warhead Diameter:	2.50 m
(theta):	90.00 degrees
(phi):	259.61 degrees
Divert Angle:	36.00 degrees
Divert Time:	60.00 seconds
Specific Impulse:	263 seconds
m-dot:	99.9 kg/sec
Number of Engines:	4

Physical Model- Railgun

- **Inputs:**
  - Total RG-round Mass
  - RG-projectile Mass
  - Muzzle Velocity

- **Outputs:**
  - Trajectory
    - Per Time Step:
      - Velocity
      - X-Coordinate
      - Y-Coordinate
      - Z-Coordinate
      - Range from Launch Site
    - Time and Position of:
      - Launch
      - Apex
      - Impact

Rail Gun Parameters	
Total Mass:	2 Kg
Warhead Mass:	2 Kg
Warhead Height:	0.50 m
Warhead Diameter:	0.13 m
(theta):	149.575 degrees
(phi):	89.558 degrees
Muzzle Velocity	10.00 km/sec

Launch-to-Target Selection

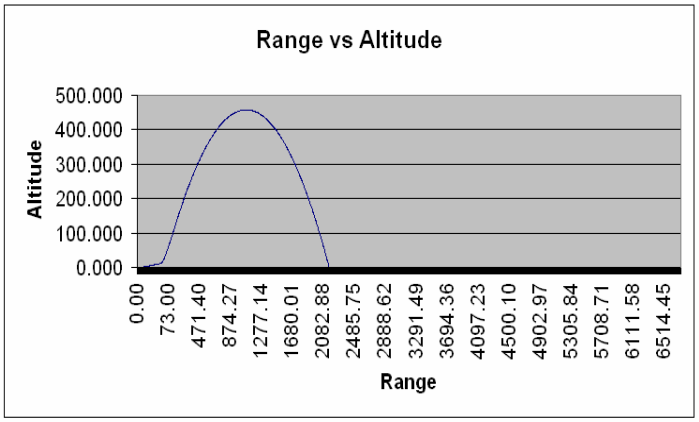
Ballistic Missile Threat Parameters	
Total Mass:	67000 Kg
Warhead Mass:	1500 Kg
Propellant Mass:	55944 Kg
Dry Booster Mass:	9556 Kg
Burn Time:	140 seconds
BM Frame Height:	15.50 m
BM Frame Diameter:	2.50 m
Warhead Height:	3.85 m
Warhead Diameter:	2.50 m
(theta):	90 degrees
(phi):	259.6060 degrees
Divert Angle:	36 degrees
Divert Time:	60 seconds
Specific Impulse:	263 seconds
m-dot:	99.9 kg/sec
Number of Engines:	4
Thrust:	1130038 N
Thrust Control:	91.1411%
Rollover Rate:	0.00E+00 radians
Acceleration:	16.9 m/sec^2
Acceleration (g's):	1.7 g's
g:	9.8 m/sec^2
G:	6.67E-11 Nm^2/Kg^2
Mass-Earth:	5.98E+24 Kg
Radius-Earth:	6.37E+06 m
Curve of Earth:	7.82E-08 per m
Time Step:	1.00 seconds

User Inputs
Calculation Result

Minimum Range: 501.423 km
Maximum Range: 3504.470 km

Minimum Throttle Reduction: 4.6620% Max Efficiency
Maximum Throttle Reduction: 18.2873%

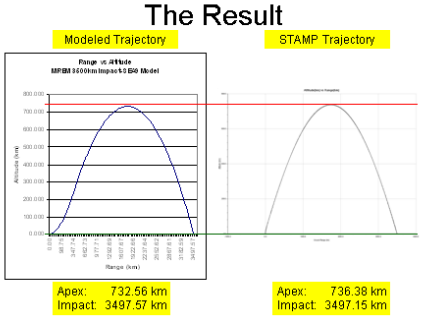
Event	Time (sec)	Velocity (m/s)	Latitude(km)	Longitude (km)	Altitude (km)	Range (km)
Select Launch Site:	1		0.000	0.000	0.000	
Launch:	0.00	7.03	0.000	0.000	0.000	0.000
End of Boost:	140.00	2567.57	-28.940	-157.776	124.022	202.762
Midcourse:	141.00	2557.73	-29.578	-161.252	126.580	207.122
Apex:	401.00	1.09	-195.350	-1065.001	457.943	1175.628
Terminal:	585.00	-1808.19	-312.665	-1704.578	290.787	1757.243
Impact:	706.00	-2998.08	-389.175	-2121.693	0.000	2157.090
Select Target Site:	1		-390.002	-2126.199	1.000	2161.672

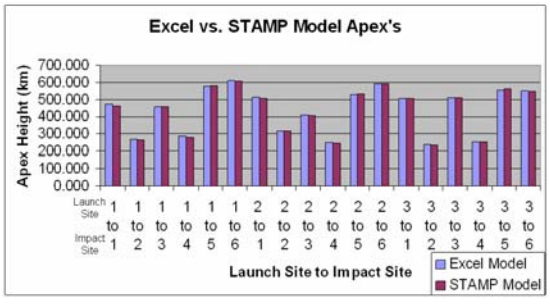


Threat Ballistic Missile Model- validation

- Each Launch Site to Impact Site was run in STAMP and the trajectories compared
  - Apex: 0.13%
  - Range: 0.05%
  - Ratio: 0.15%
- Railgun Model is based on similar Trajectory Model
  - Boost Aspects removed and Muzzle Velocity added

The Result





Lat/Long to XY Conversion

+

Ballistic Missile Parameters

+

Interceptor Parameters

+

Trajectory Models

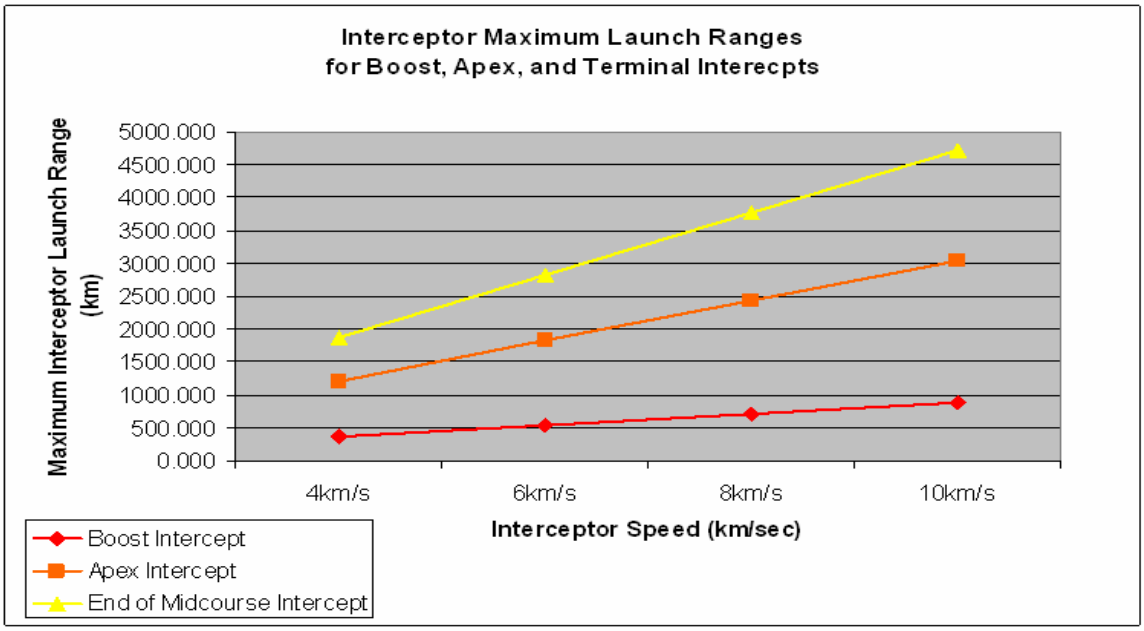
=

Physical Model

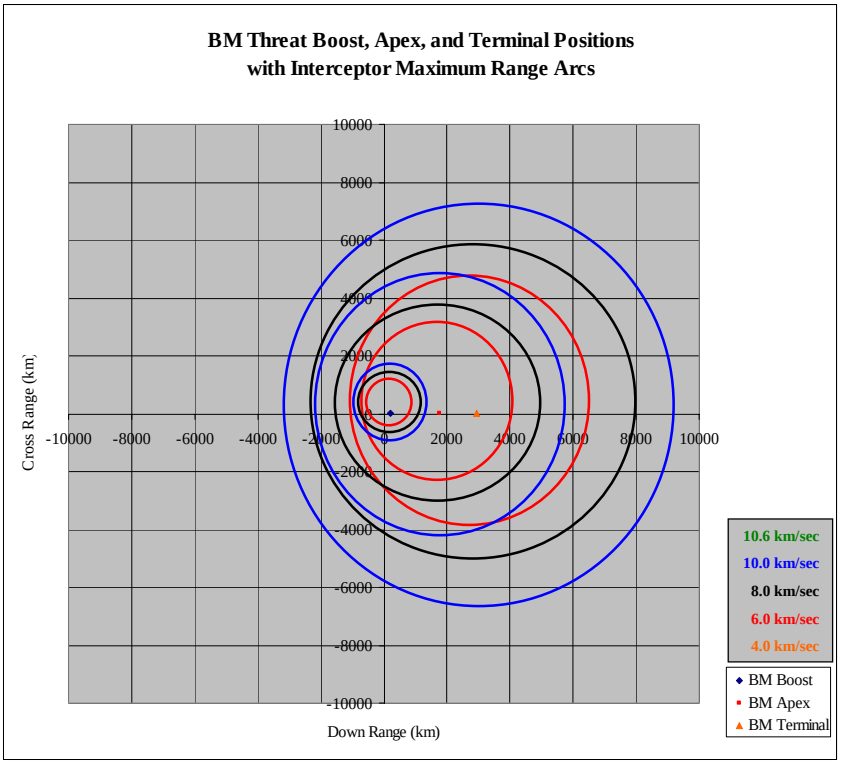
What else does the Model say about the Railgun?

- Explicit:
  - Launch Data
  - Flight Trajectory
    - Position
    - Time
  - Impact Data
- Implicit:
  - Effective Range of Railgun Round
  - Coverage Area
    - Allowable Area of Operations
  - Interceptor Effectiveness and Salvo Size trade space

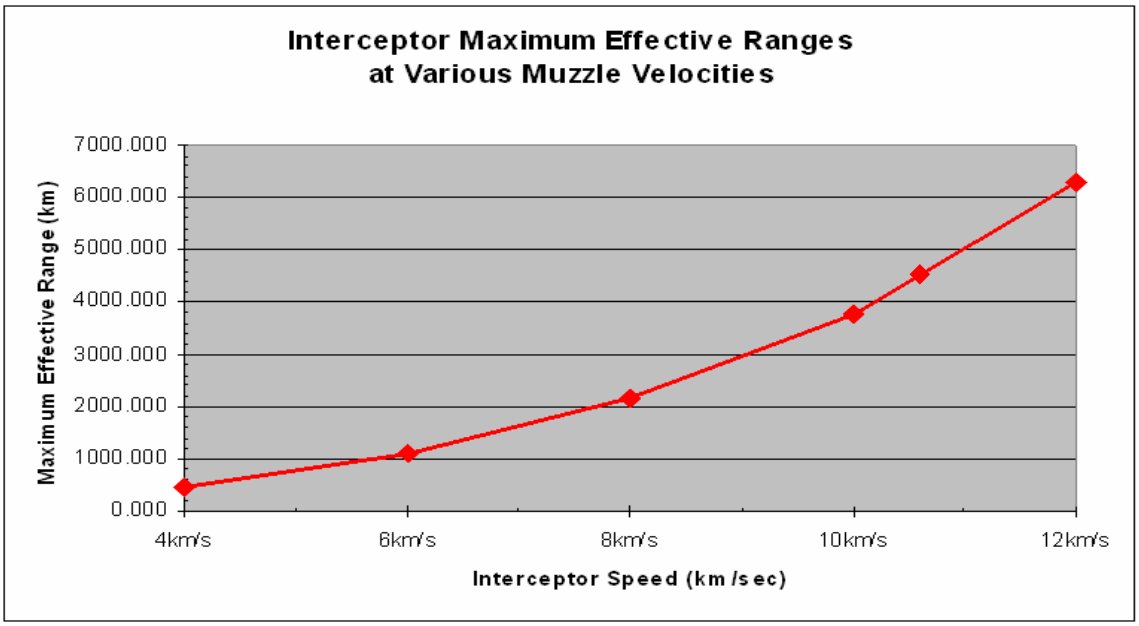
Maximum Allowable Operating Area



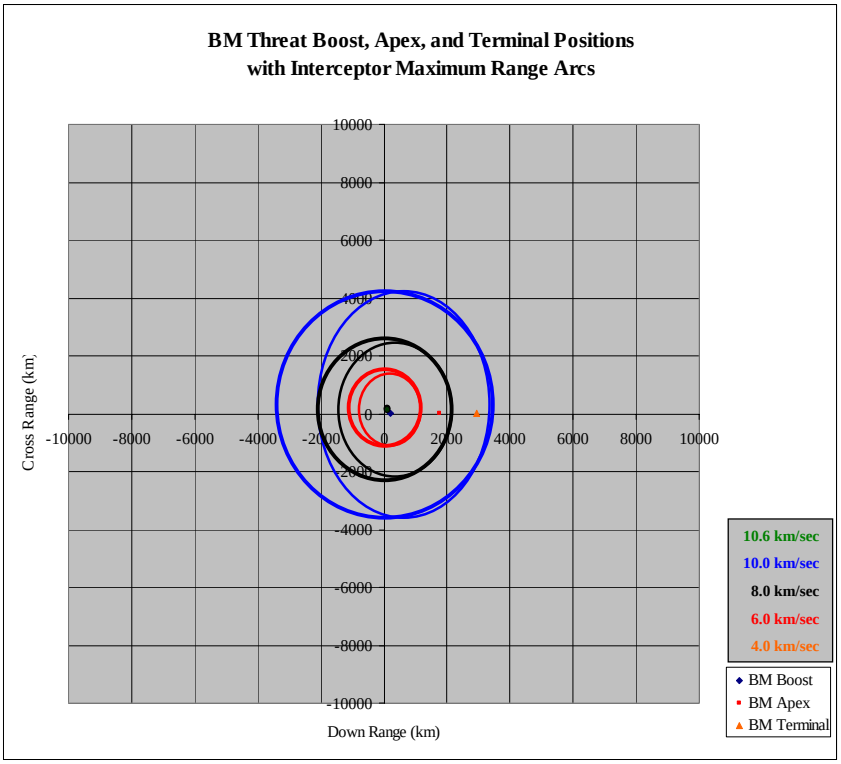
Maximum Allowable Operating Area



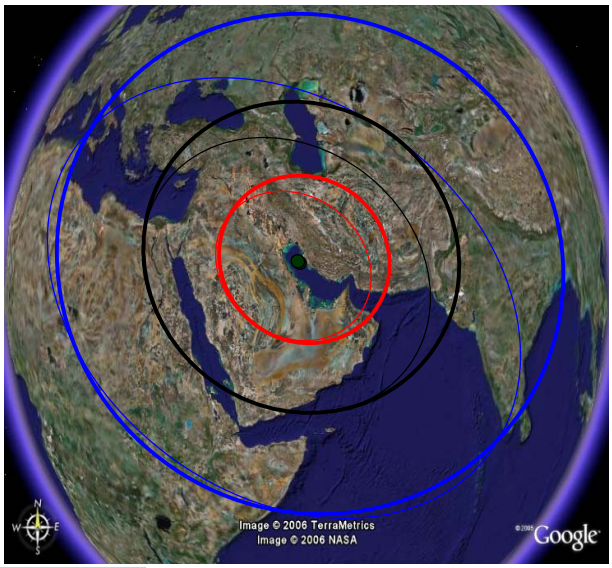
Max. Effective Range

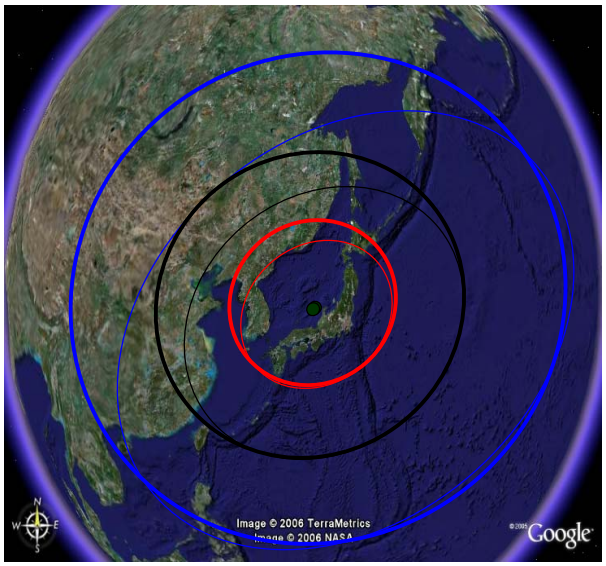


Max. Effective Range



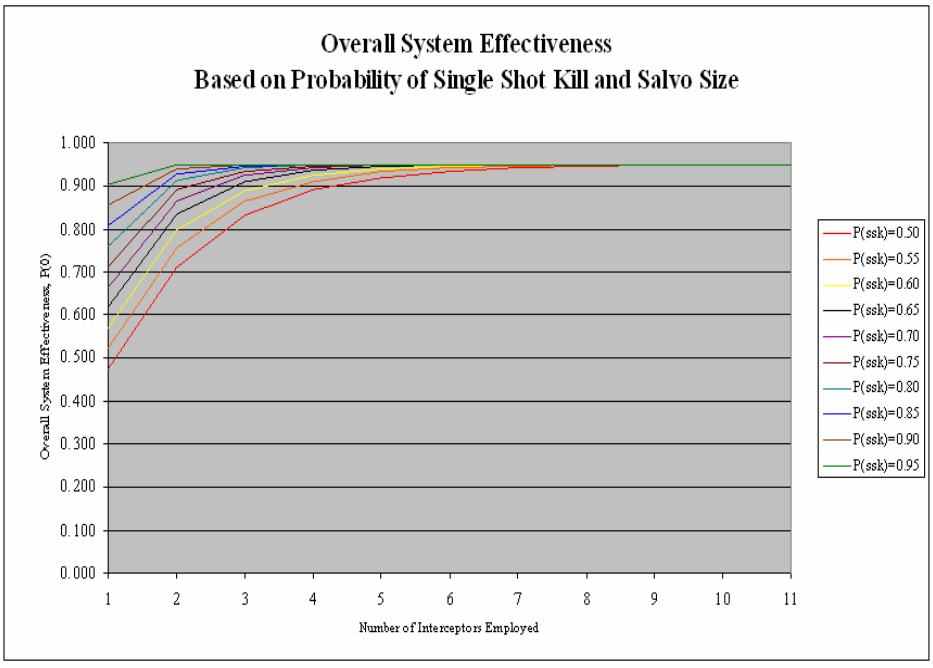
Effective Range vs. Tail Chase



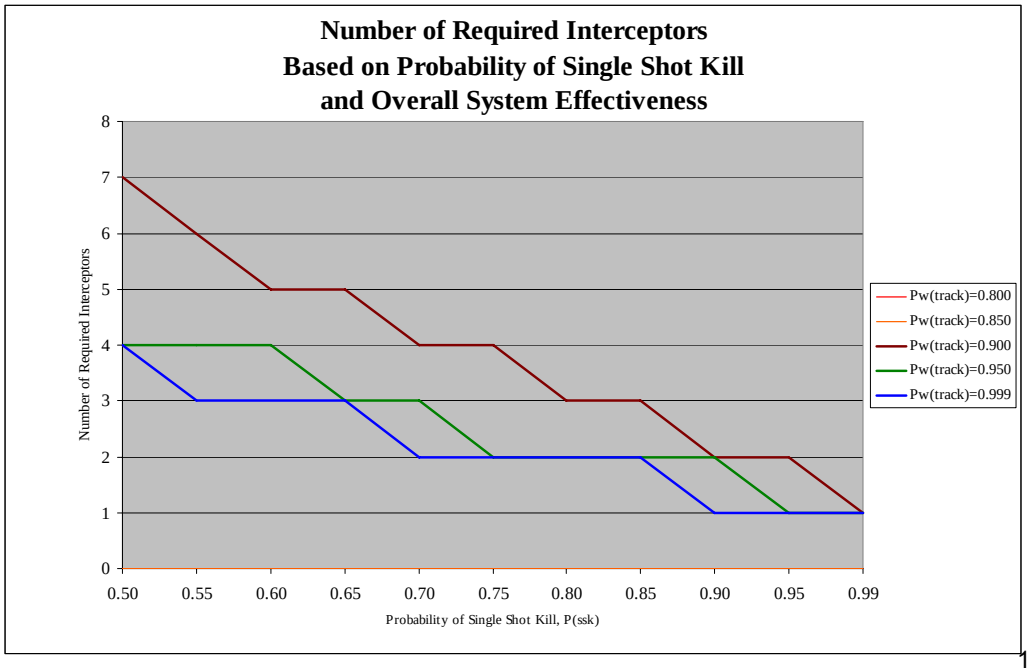


10.0 km/sec
8.0 km/sec
6.0 km/sec

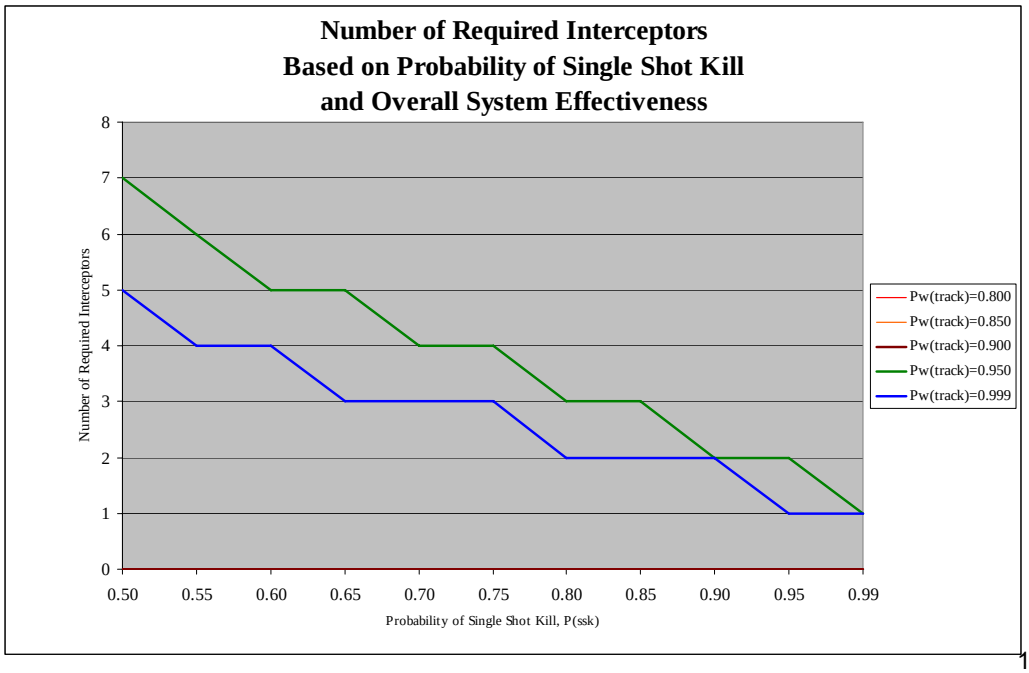
P(0) at P_w(track)=0.95, W=1



Required Interceptors: P(0)=0.90, W=1



Required Interceptors: P(0)=0.95, W=1



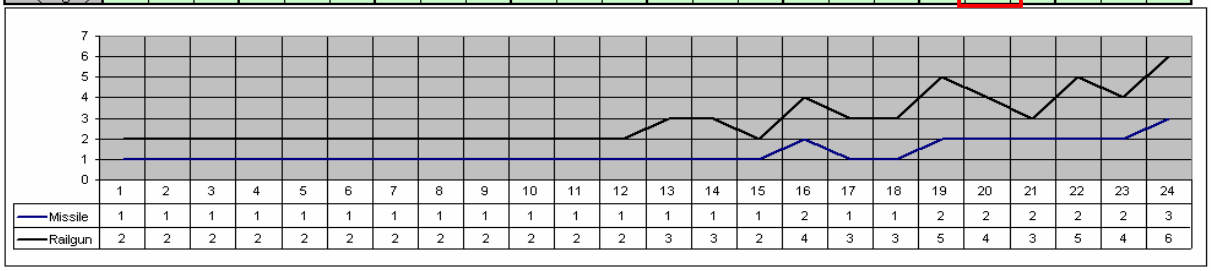
Salvo Size Calculation

$$n = \frac{\ln\left(1 - \frac{P(0)^{1/W}}{P_w(track)}\right)}{\ln(1 - k_w)}$$

P(0)=Overall System Capability
Pw(track)=Probability of Tracking the Warhead
kw=Probability of Killing the Warhead
W=number of Warheads
n=number of Interceptors Needed

W=	1.00
kw(missile)=	0.90
kw(railgun)=	0.60

P(0)=	0.600	0.600	0.600	0.650	0.650	0.650	0.700	0.700	0.700	0.750	0.750	0.750	0.800	0.800	0.800	0.850	0.850	0.850	0.900	0.900	0.900	0.950	0.950	0.990
Pw(track)=	0.900	0.950	0.990	0.900	0.950	0.990	0.900	0.950	0.990	0.900	0.950	0.990	0.900	0.950	0.990	0.900	0.950	0.990	0.910	0.950	0.990	0.960	0.990	0.999
n(missile)=	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	2	2	2	2	3
n(railgun)=	2	2	2	2	2	2	2	2	2	2	2	2	3	3	2	4	3	3	5	4	3	5	4	6



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Missile	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	2	2	2	2	3
Railgun	2	2	2	2	2	2	2	2	2	2	2	2	3	3	2	4	3	3	5	4	3	5	4	6

*Wilkening, Dean A., A Simple Model for Calculating Ballistic Missile Defense Effectiveness, p 205.

Salvo Size Calculation

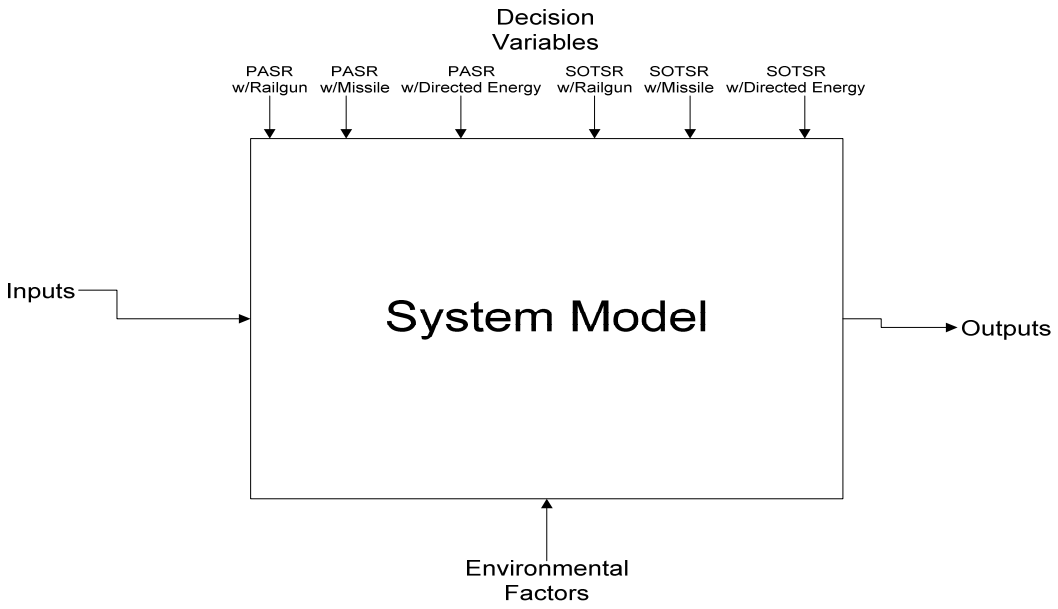
Weapon Load:	
80	Missiles
1200	Railgun Rounds (600 per mount)
Total Engagements @ 90% Effective)	
40	Missile Engagements
300	Railgun Engagements
7.50 : 1	Railgun:Missile Engagements
Total Number of Engagements/Ship	
0.60	P(kill)
20	rounds per minute
4	rounds per engagments @ 90% Effective
5	engagements per mount per min
2	number of mounts
10	engagements per min per ship
8.48	minutes average time to terminal
1699.00	km average range of BM flight
84	Estimated BM's simultaneously in flight
336	Railgun Rounds needed
216	Number of Engagements Remaining Onbd

Expected System Capability vs. Number of Simultaneous In-Flight Ballistic Missile							
	st. dev.			Mean	st. dev.		
	-3	-2	-1		1	2	3
time (min)	3.41	5.10	6.79	8.48	10.16	11.85	13.54
# of Ships	Ballistic Missile's In-Flight						
1	34.15	51.02	67.90	84.77	101.64	118.52	135.39
2	68.30	102.05	135.79	169.54	203.29	237.03	270.78
3	102.45	153.07	203.69	254.31	304.93	355.55	406.17

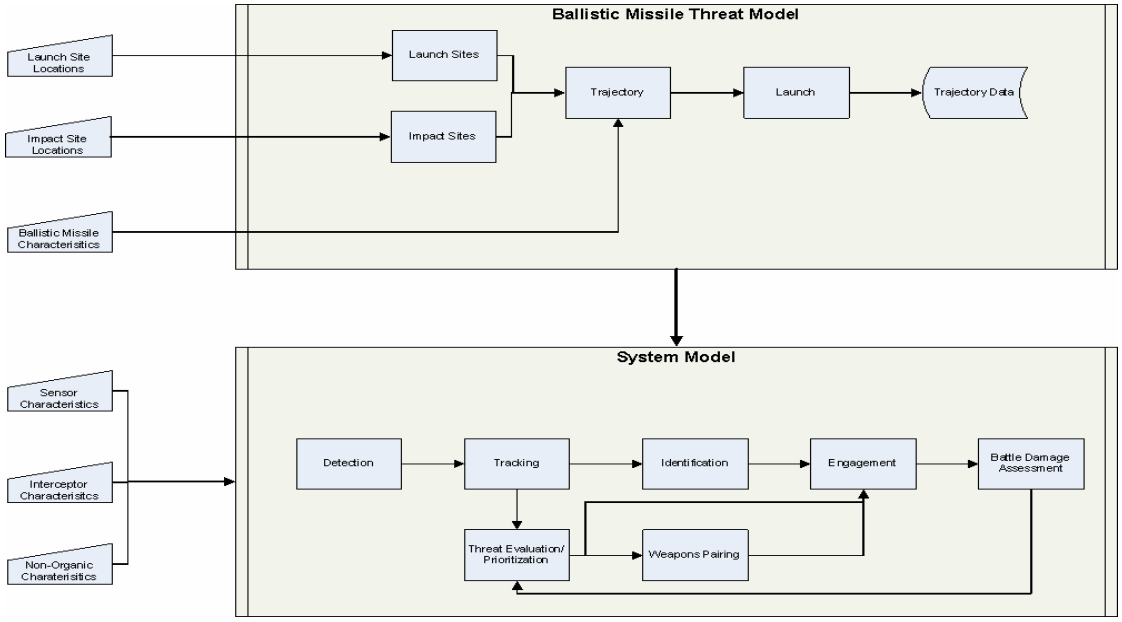
Functional Model

ENS Ryan Devlin

Preliminary Model Overview



System Model Subcomponents



* Modeled in: Extend Version 6.0 and Microsoft Excel 2003

Goals

- Evaluate the various system architectures in order to determine which are significantly better or worse than the others
- Integrate various Radar System Parameters into an overall System Model

Assumptions

- Sufficient Ship Power is available to perform all necessary tasks
- Radar Detection Ranges follow the Radar Range Equation
- Time is the dominating factor
- Ship's Position is fixed during BM Threat Time of Flight

System Model Robustness

- Detection height determined based on radar range equation
- Phased Array detection ranges based on forecasting capabilities based the Aegis system
- Skin of the ship radar ranges based on Dr. David Jenn's conformal radar research
- Interceptor capabilities based on forecasting of current capabilities and research initiatives
- Ballistic trajectories validated by STAMP

System Model Inputs (commit stage)

- Primary Inputs:
  - Probability of Non-Organic Detection
  - Satellite Sweep Rate
  - Non-Organic Time to Detect
  - Ship Detection Range/Height
  - Probability of Ship Detection
  - Time for Ship to Detect
  - Time to Establish a Track
  - Probability of Keeping Track
  - Time to Identify
  - Time to Evaluate Threats
  - Time for Weapons Pairing
  - Time to Conduct BDA
  - Probability of Good BDA

System Model Inputs (Interceptor)

- Interceptor Velocity
- Time Correction Factor (accounts for laser time on target and ballistic trajectory of rail gun round)
- Max Engagement Range
- Max Engagement Height
- Probability of Kill
- Maximum Number of Targets Engaged Simultaneously

System Model Inputs (threat model)

- Launch Site Position
- Missile Position (X, Y, Z)
- Time of Flight
- End of Midcourse

System Model Outputs

- # of BM threats simulated
- # of detections
- # of non-detections
- # of false alarms
- # of hand-offs
- # of engagements
- # of failed engagements
- Mean non-organic time to detect
- Mean time delay in detection relay
- Mean time to process detection
- Mean organic detection time
- Mean track formulation time
- Mean time to ID
- Mean Threat Prioritization time
- Mean weapons pairing time
- Mean engagement time
- Mean weapons pairing time
- Mean time to conduct BDA
- Mean time to end of BM midcourse
- Launch site and Target

Measures of Effectiveness

- **Mean time available for reengagement**
- **Mean engagement time**
- **Probability of engagement**
- **Probability of kill given an engagement**
- **Probability of detection**
- **Probability of false alarm**
- **Probability of missed detection**
- **Probability of hand-off**

Preliminary Data Analysis

ENS Chris Glenn

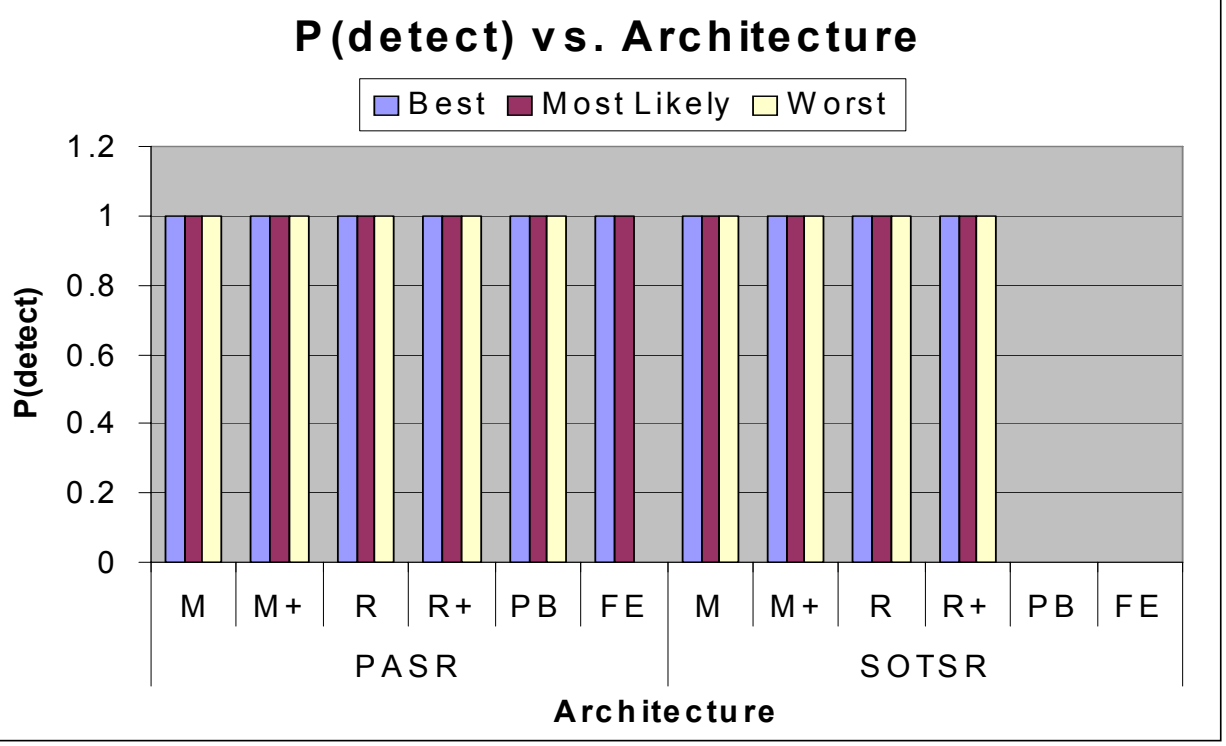
Simulation Procedure

- Some inputs are held constant for all architectures and scenarios; others varied depending on scenario and architecture
- 36 total architecture/scenario combinations
- 500 runs per architecture/scenario combination
- Best and Most Likely Scenarios took from approximately 1 hour to 3 hours for the various architectures
- Worst case scenario took several hours to run for each architecture (9 hours for DEW)

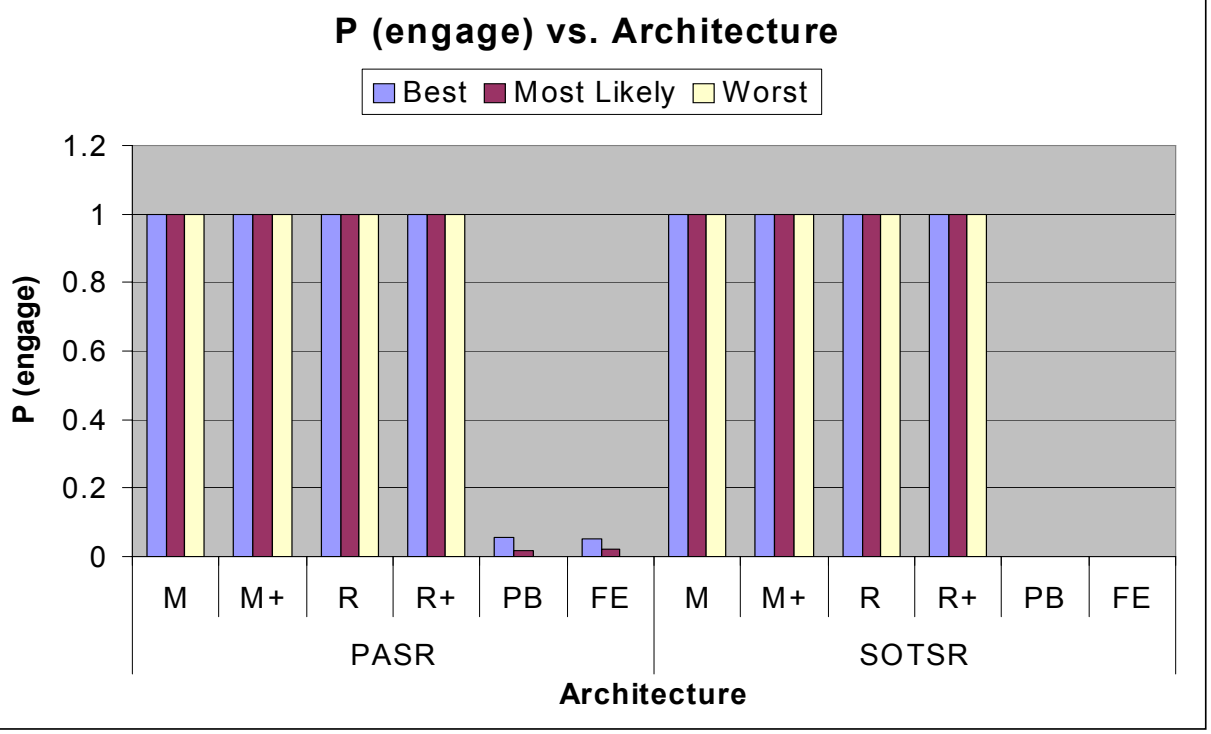
Measures of Effectiveness

- P (engage)
- P (Hand-off)
- P (false alarm)
- P (detect)
- P (kill)
- Detect to BDA Time
- Time left to reengage

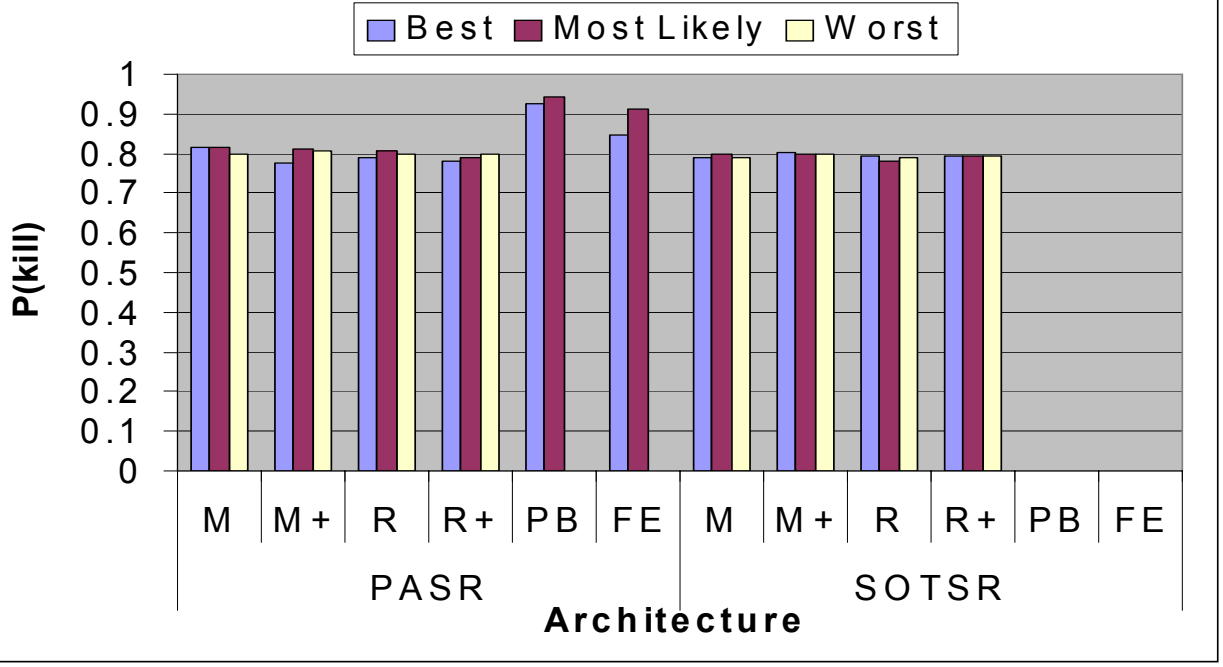
P (Detect)



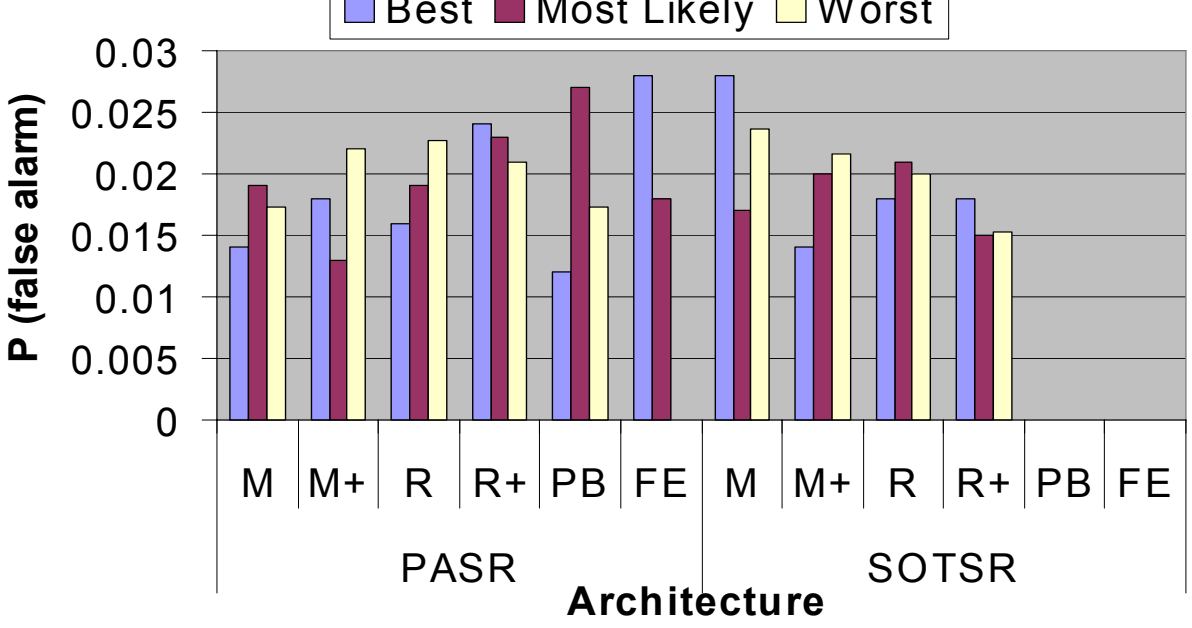
P (Engage)



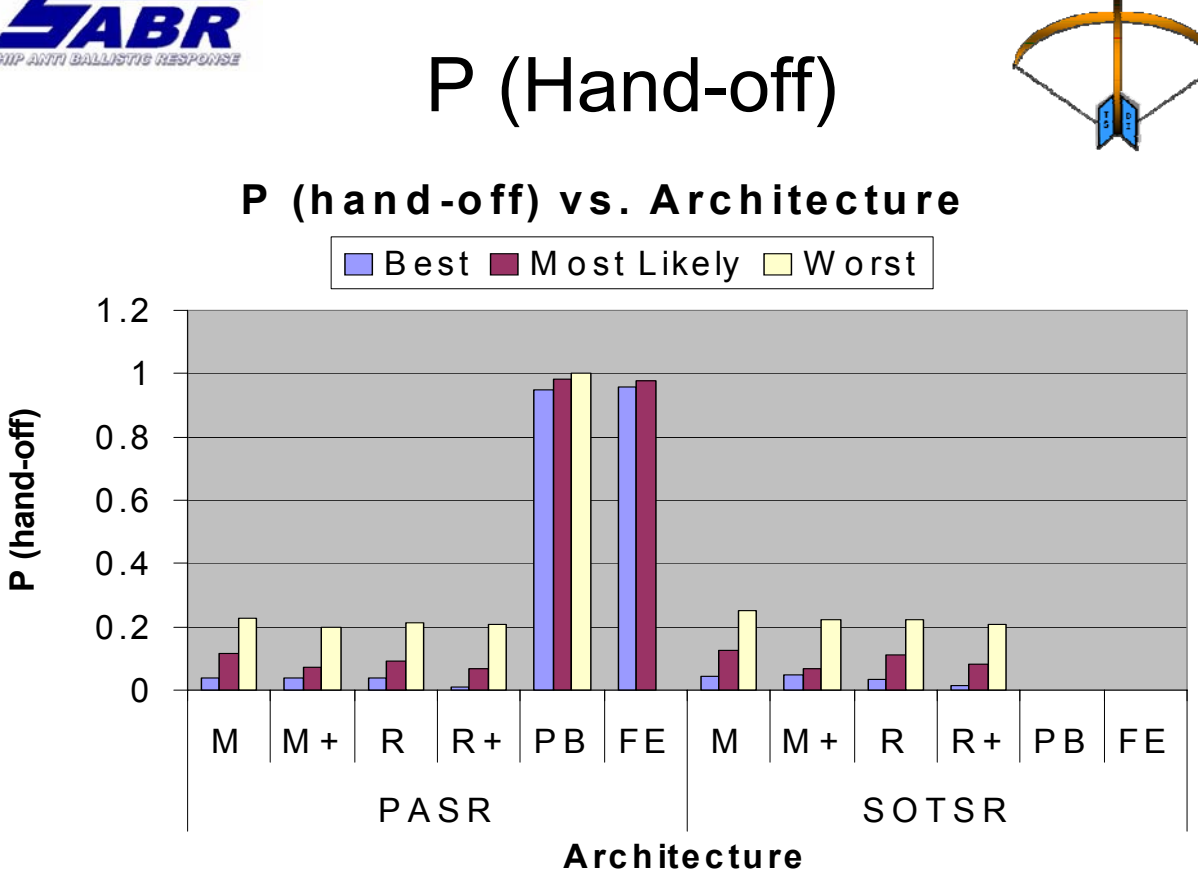
P (Kill)



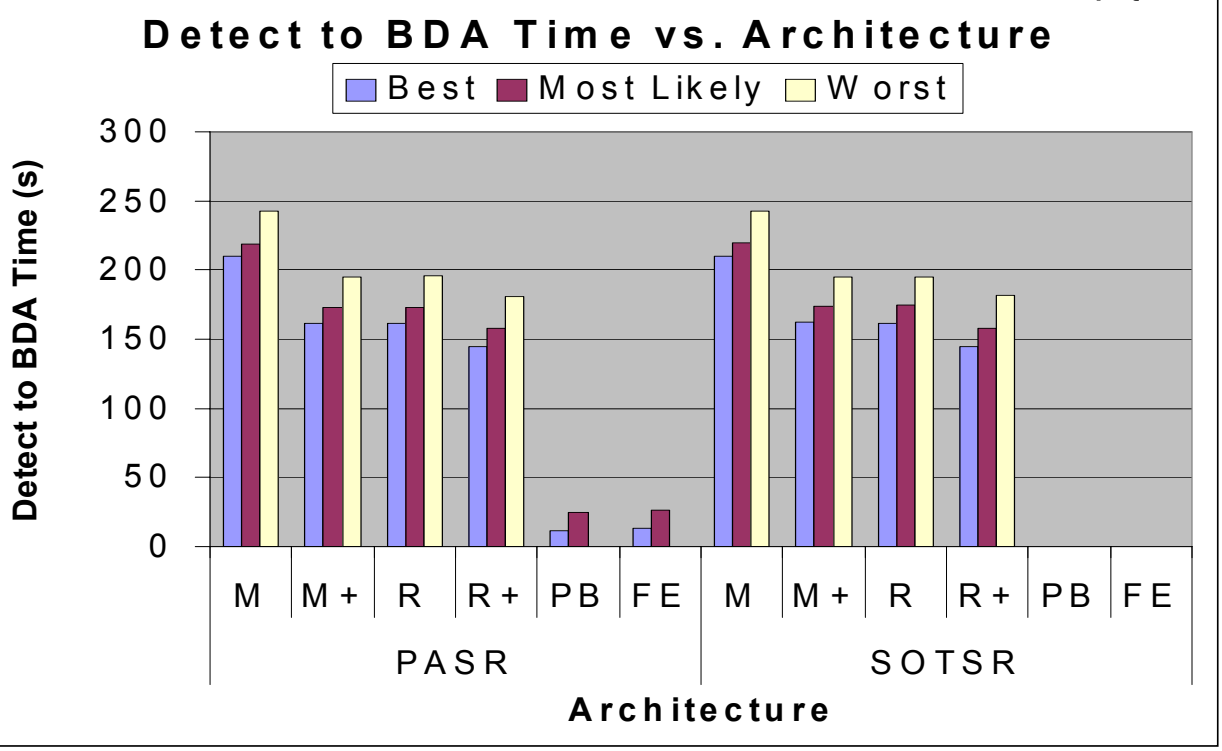
P (False Alarm)



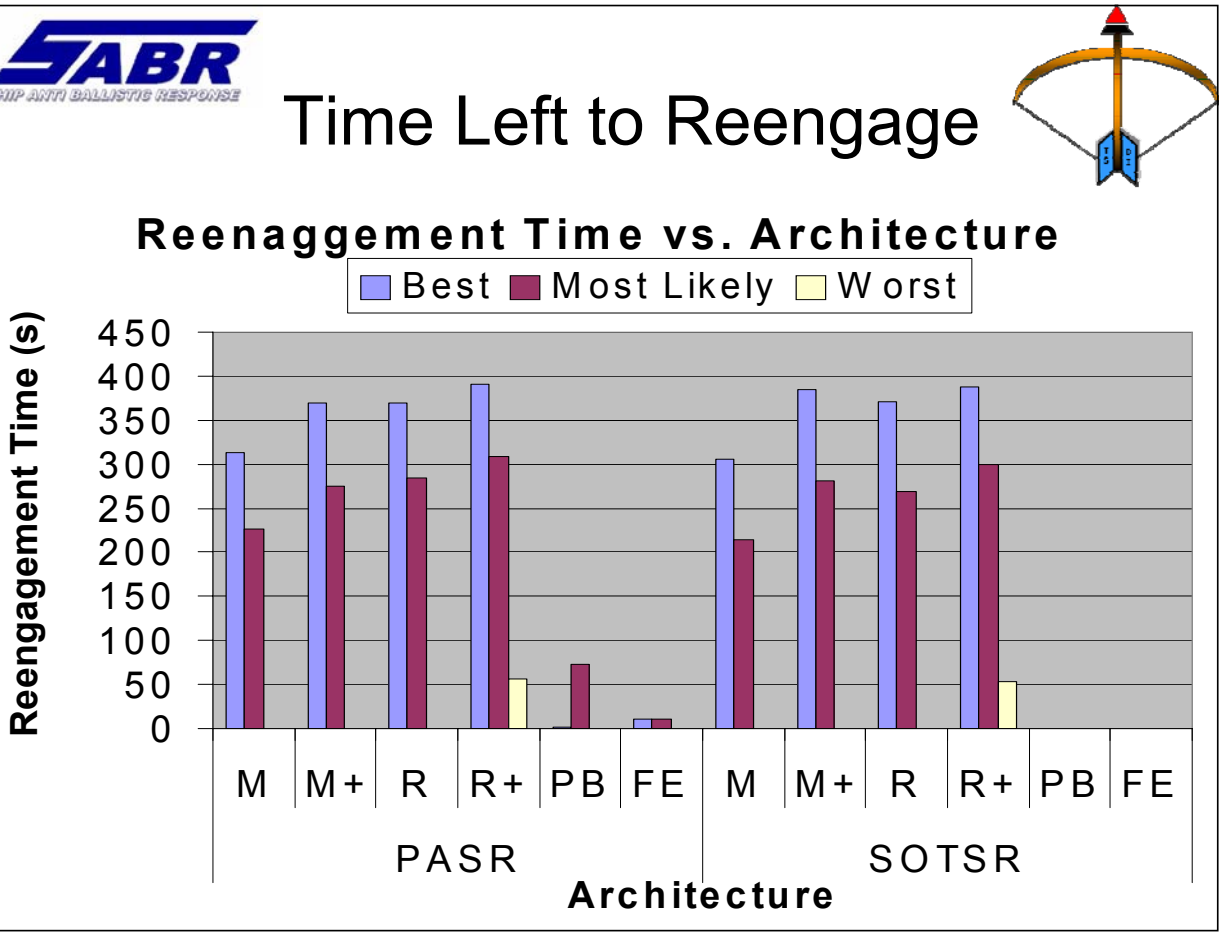
P (Hand-off)



Detect to BDA Time



Time Left to Reengage



1st Iteration Simulation Summary

- Directed Energy Weapon eliminated due to its limited range
- Rail Gun and Missile had nearly equal performance
- 4 of initial 12 architectures eliminated
- Radars had no impact on the results because inorganic assets detected all missile launches
- Determined areas of improvement

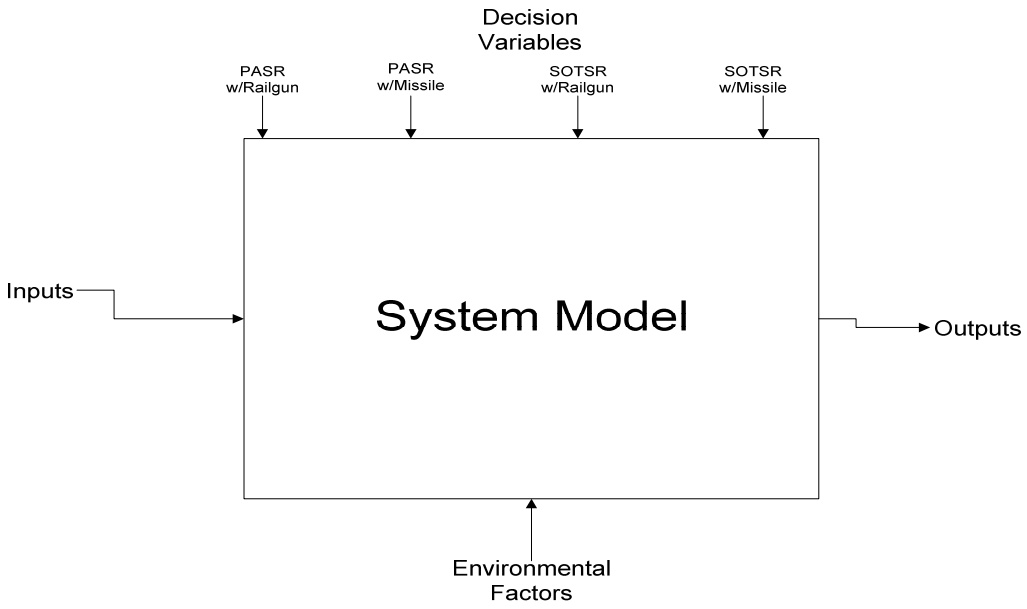
Refined Model

ENS Ryan Devlin

Why Change the System Model?

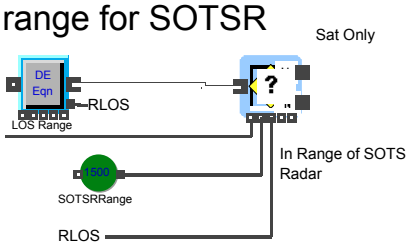
- Detection height calculated solely based on max detection range
- SOTS Radar model not set up properly to model cueing of the PASR
- All missiles detected by satellite so no preferred radar has been identified

Refined Model Overview

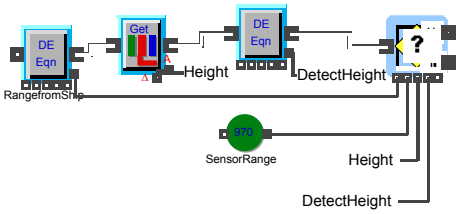


System Model

- Satellites eliminated by making P(d) = 0
- 'DE Equation' block added to calculate LOS Detection range for SOTSR



- Separate Detection delays and blocks for SOTSR Radar
- Detection Height Calculated using the Radar Range Equation



- P(k) fixed for interceptors
  - Rail gun Pssk = .6
    - Salvo size = 4
  - Missile Pssk = .8
    - Salvo size = 2

Improvements

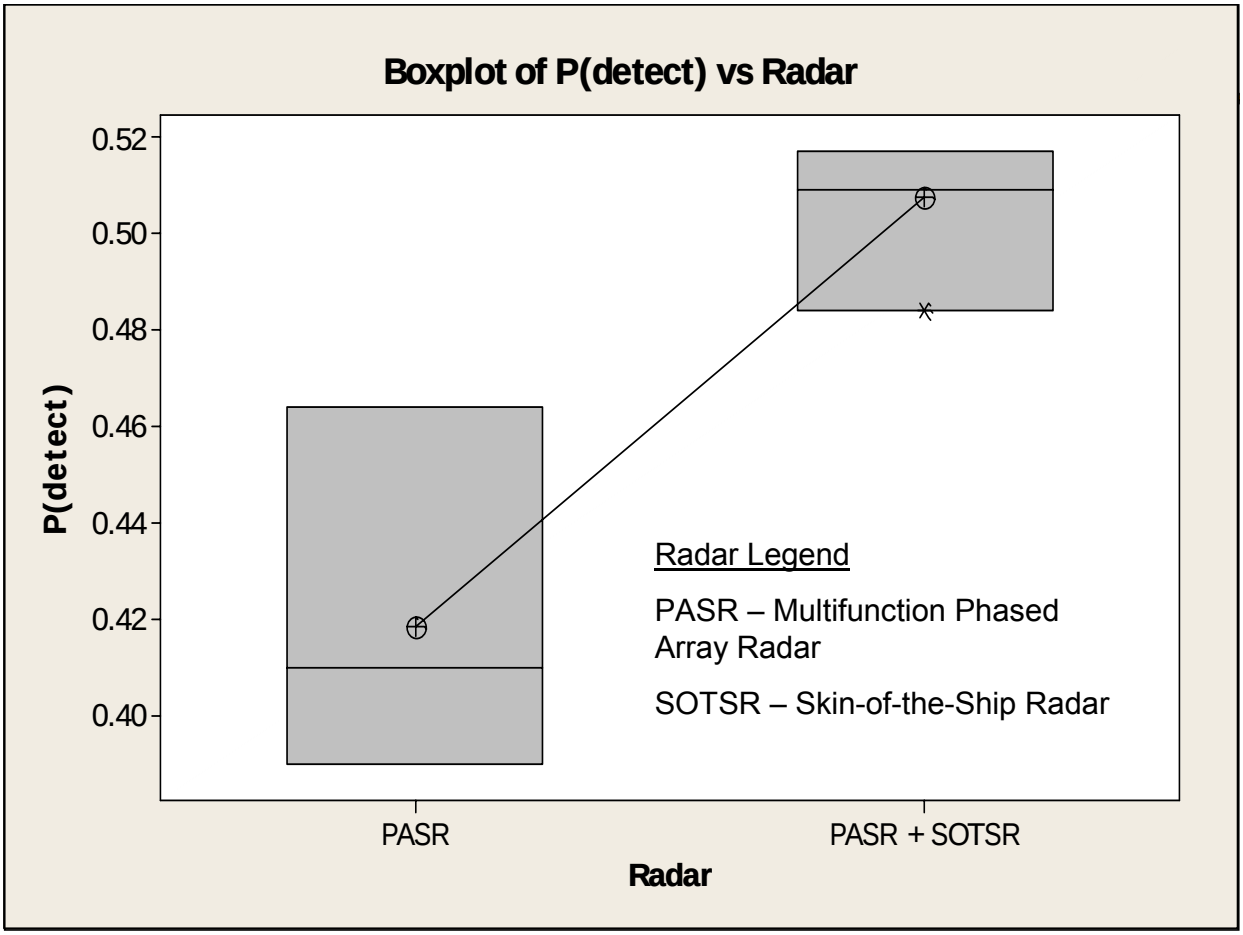
- Radar range calculation improved ship detection
- SOTSR line of sight calculation based on AREPS
- SOTSR cueing PASR added to model
- Weapon terminal performance assessed
- No satellite detections

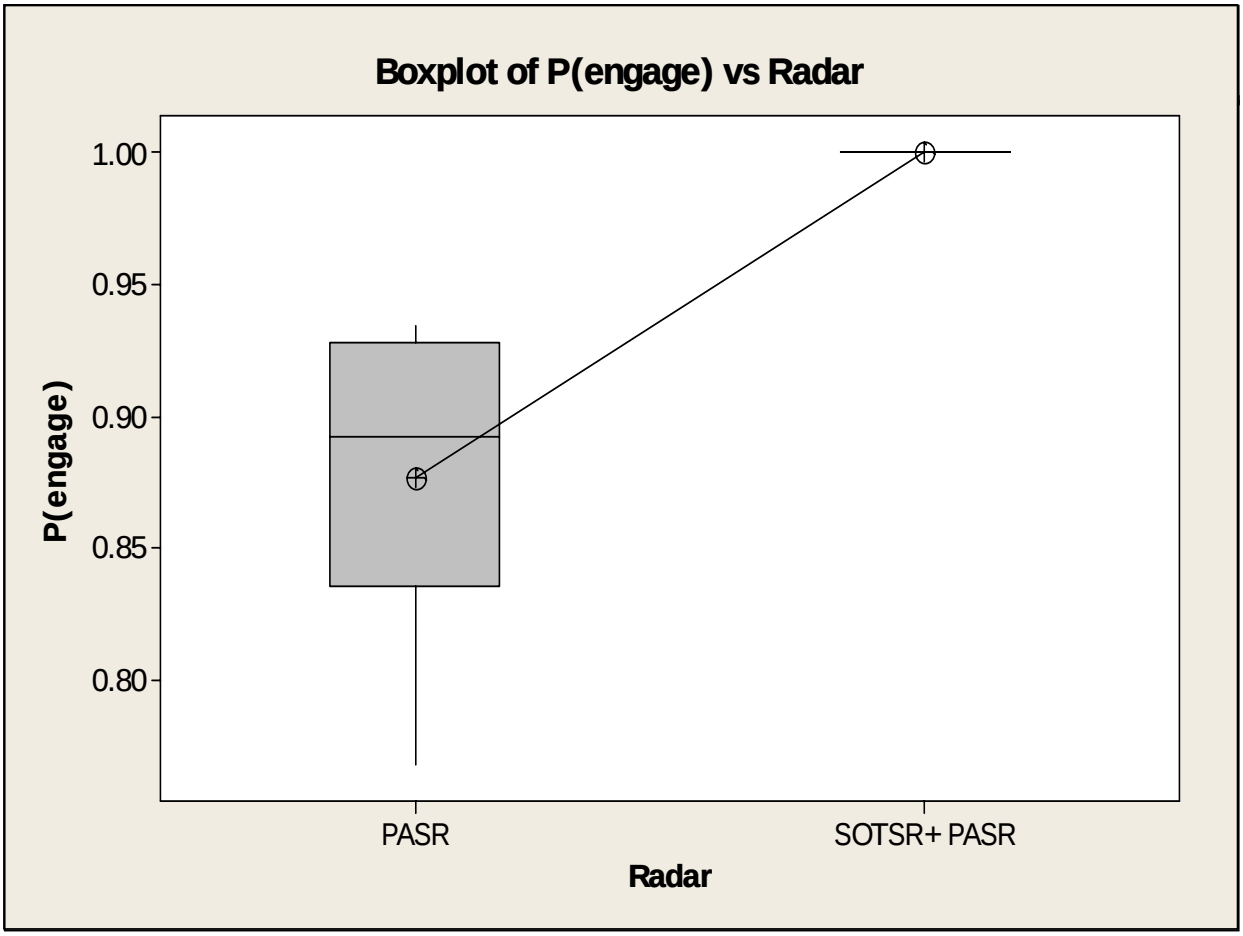
Refined Data Analysis

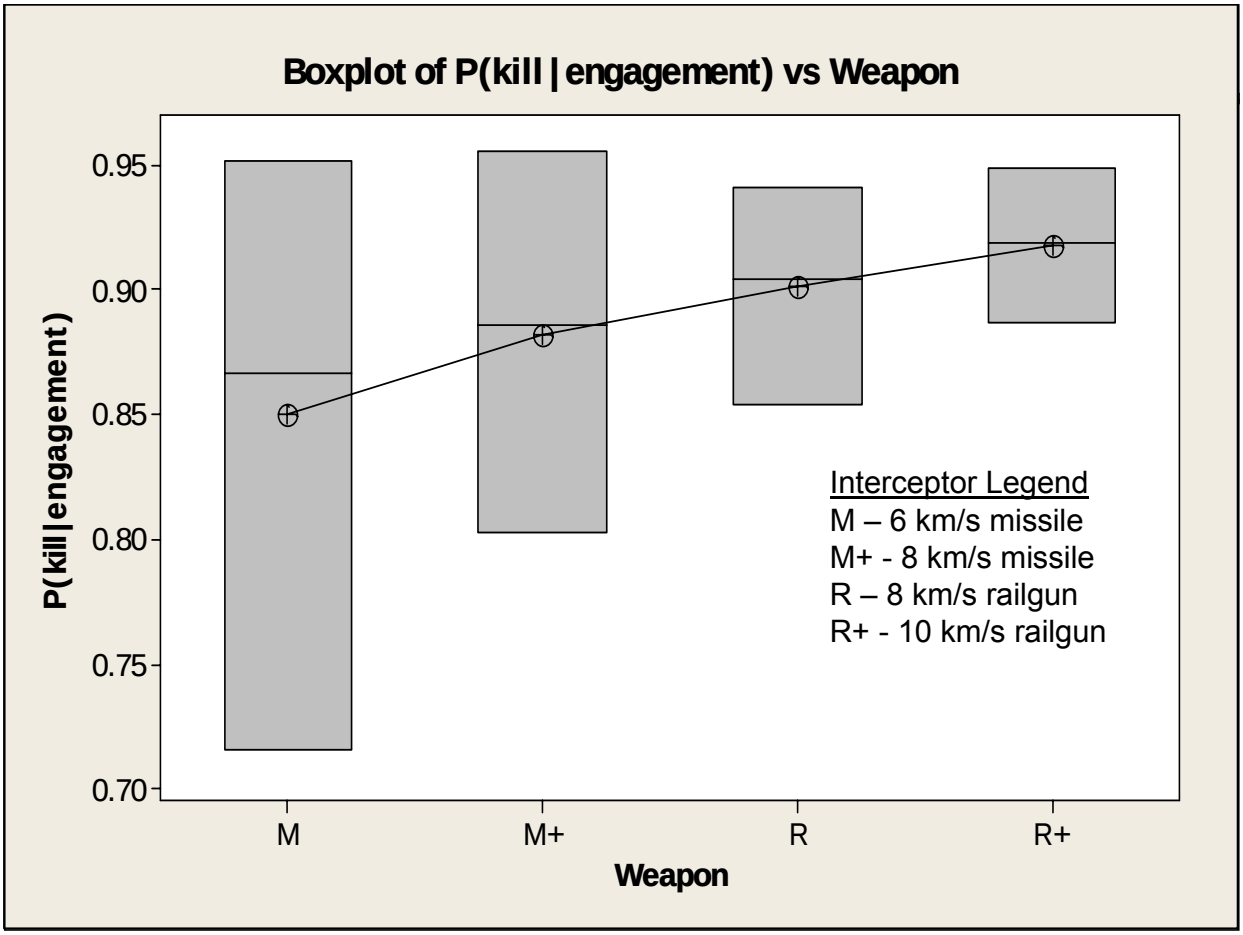
ENS Chris Glenn

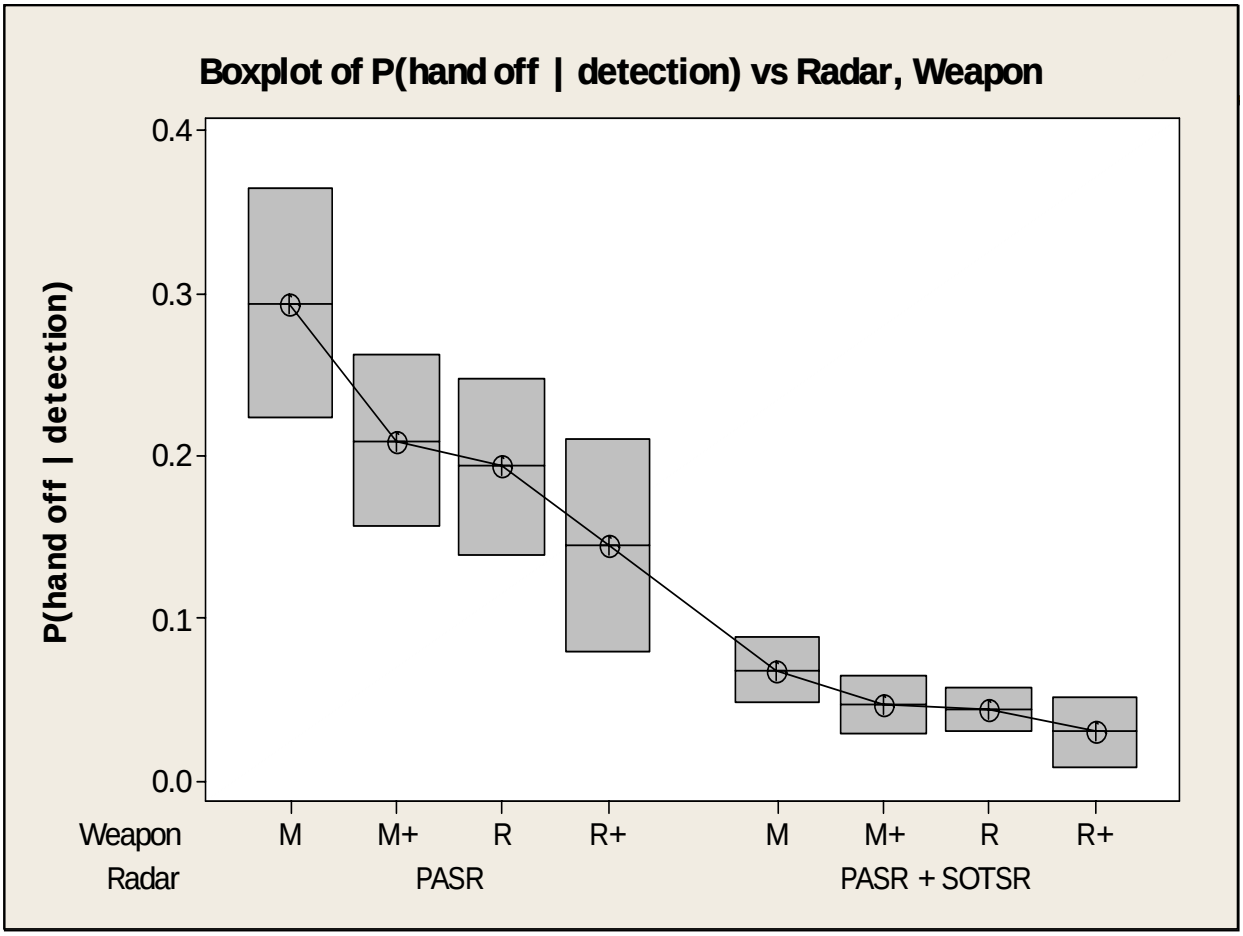
2nd Iteration of Simulations

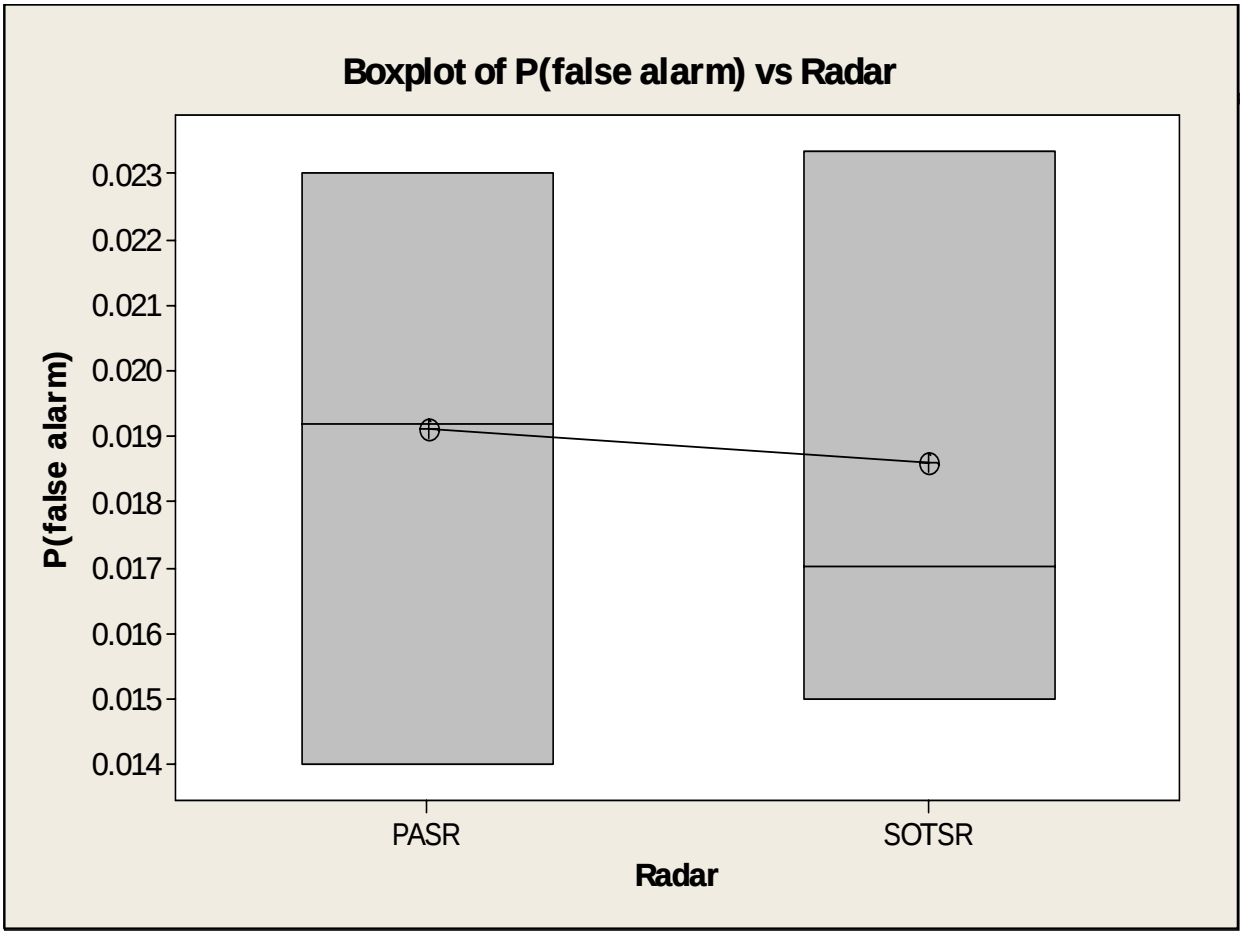
- Focus on determining a breakout between weapons and radars
- Minitab used to generate ANOVA, confidence intervals, interactions, and statistical significance.

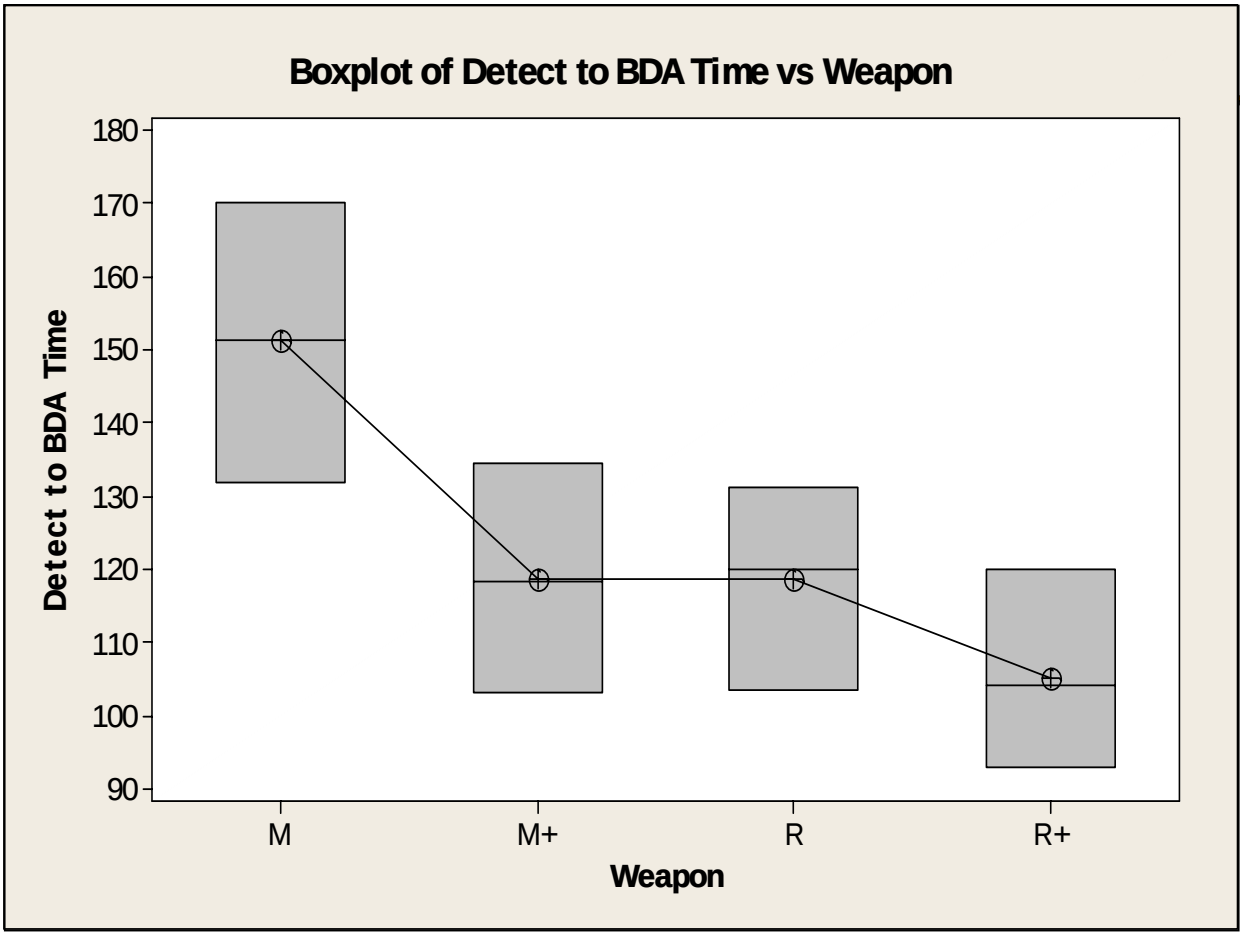

Boxplot of P(detect) vs Radar
0.52
0.50
0.48
0.46
0.44
0.42
0.40
P(detect)
Radar Legend
PASR – Multifunction Phased Array Radar
SOTSR – Skin-of-the-Ship Radar
PASR
PASR + SOTSR
Radar

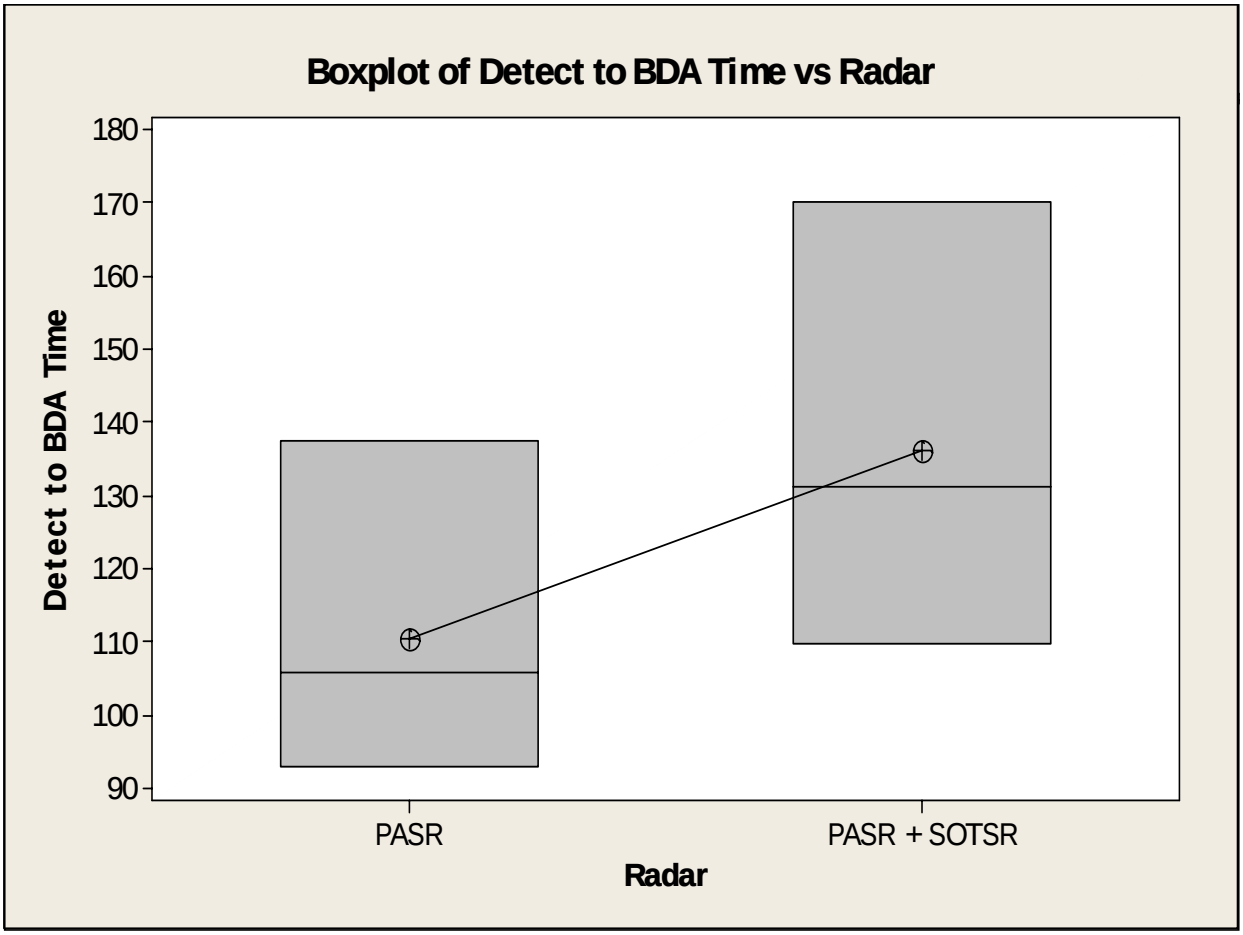

Boxplot of P(engage) vs Radar
1.00
0.95
0.90
0.85
0.80
P(engage)
PASR
SOTSR+ PASR
Radar


Boxplot of P(kill | engagement) vs Weapon
P(kill|engagement)
0.95
0.90
0.85
0.80
0.75
0.70
M
M+
R
R+
Weapon
Interceptor Legend
M – 6 km/s missile
M+ - 8 km/s missile
R – 8 km/s railgun
R+ - 10 km/s railgun

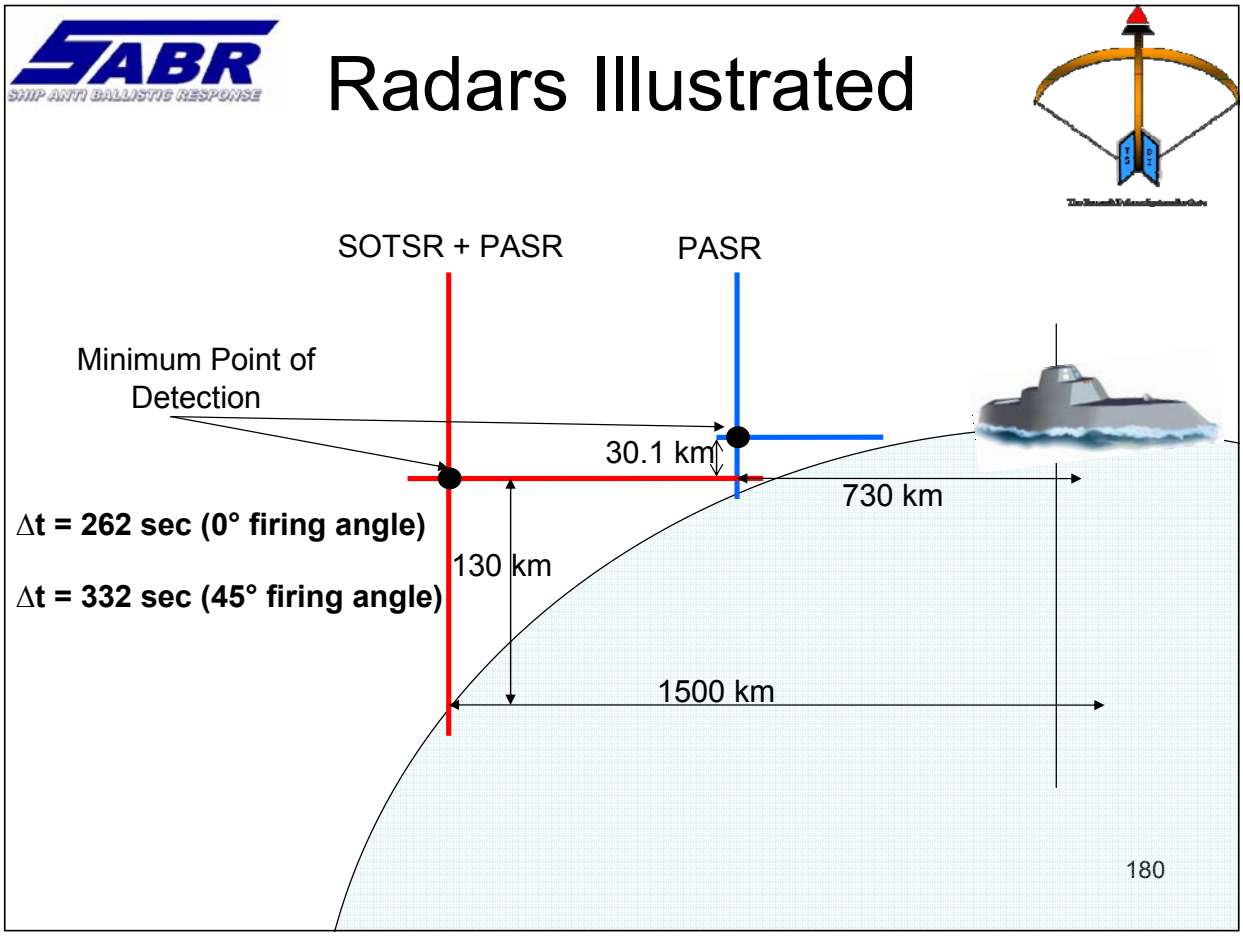

Boxplot of P(hand off | detection) vs Radar, Weapon
P(hand off | detection)
0.4
0.3
0.2
0.1
0.0
Weapon
M
M+
R
R+
M
M+
R
R+
Radar
PASR
PASR + SOTSR


Boxplot of P(false alarm) vs Radar
P(false alarm)
0.023
0.022
0.021
0.020
0.019
0.018
0.017
0.016
0.015
0.014
PASR
SOTSR
Radar


Boxplot of Detect to BDA Time vs Weapon
Detect to BDA Time
180
170
160
150
140
130
120
110
100
90
M
M+
R
R+
Weapon



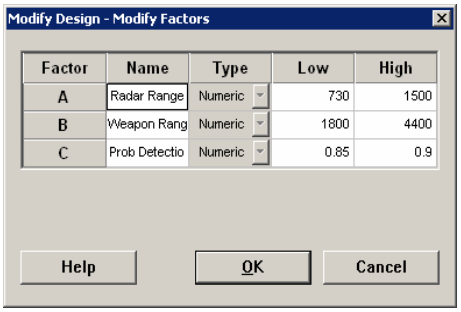
Radars Illustrated



Factorial Analysis

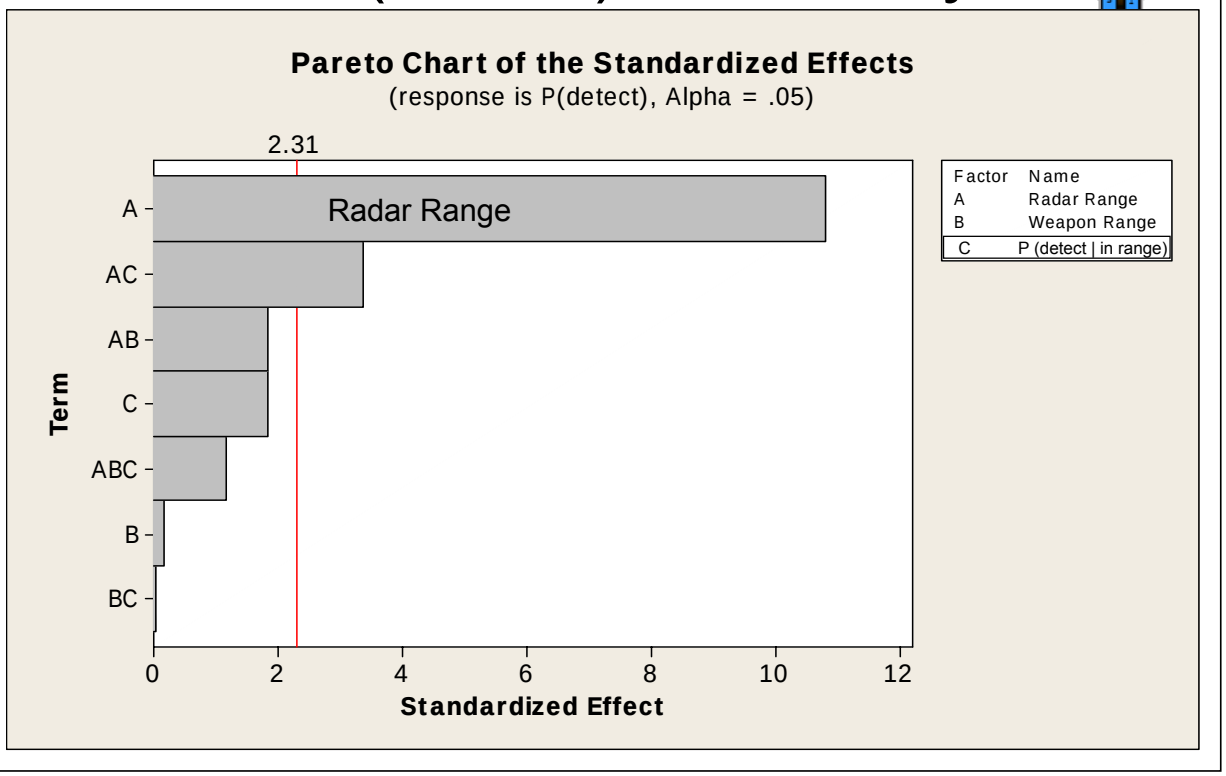
Factorial Analysis Setup

- 18 factors with 2-3 levels = 2^{18} to 3^{18} possible combinations
- Factor Reduction left 3 factors with 2 levels = 8 combinations
  - Weapon Range
  - Radar Range
  - Probability of detection

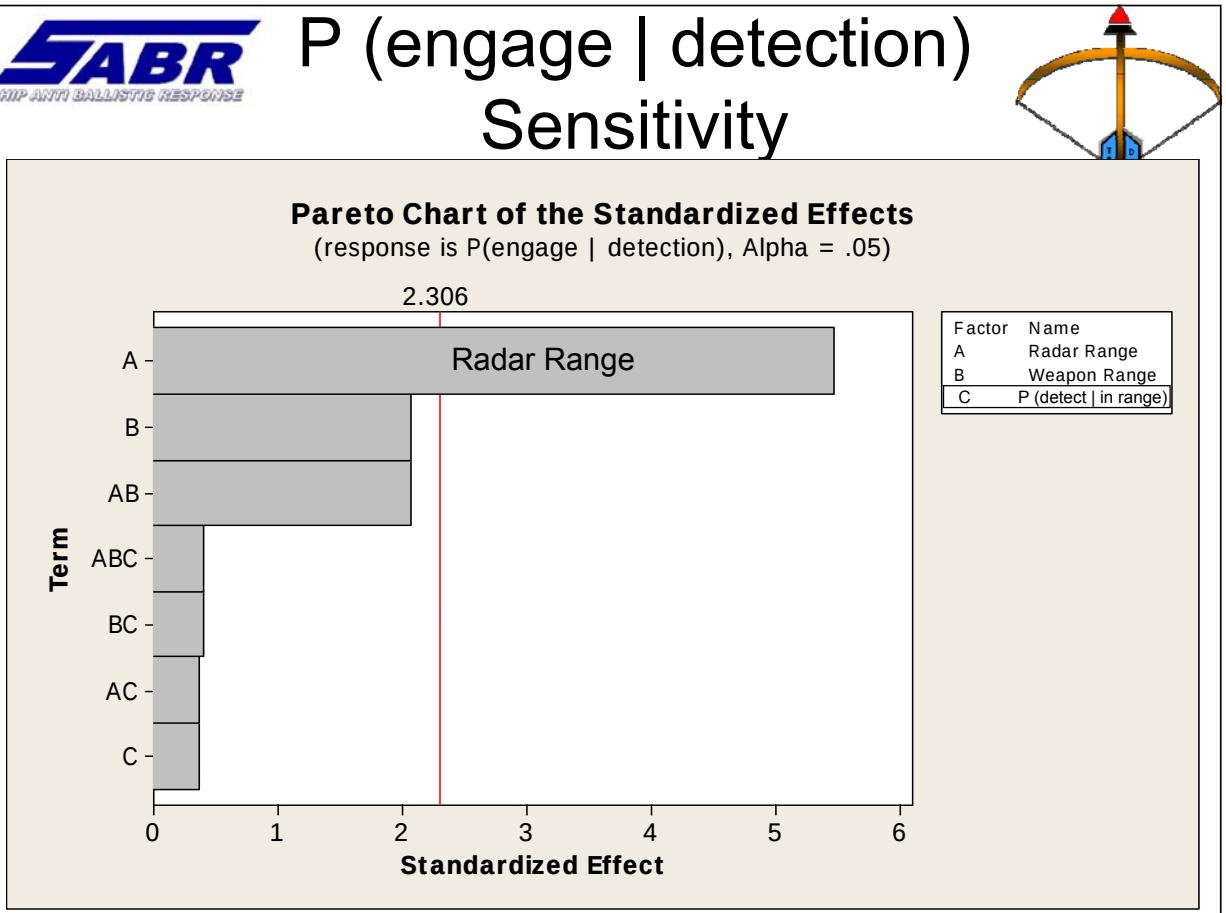


- Analyze factors' effects on 5 MOE's
- Sensitivity, Tradeoff, and Cost Analysis conducted

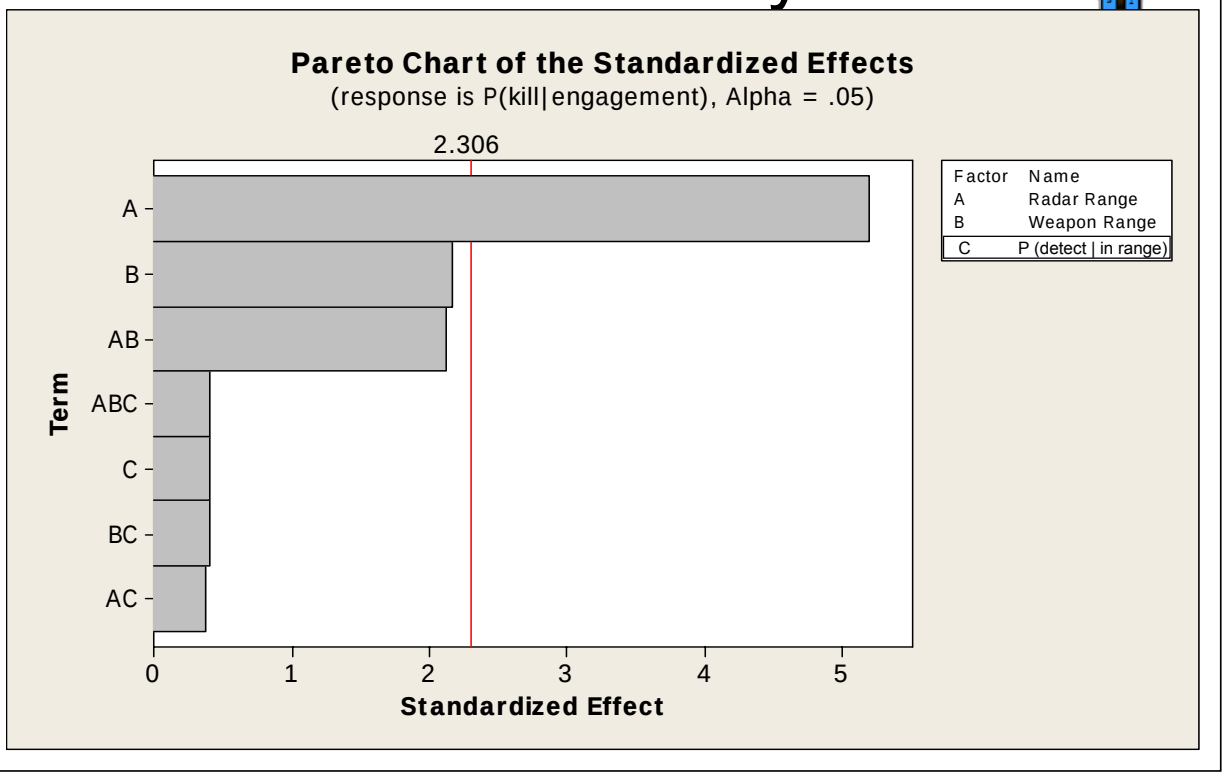
P (detect) Sensitivity



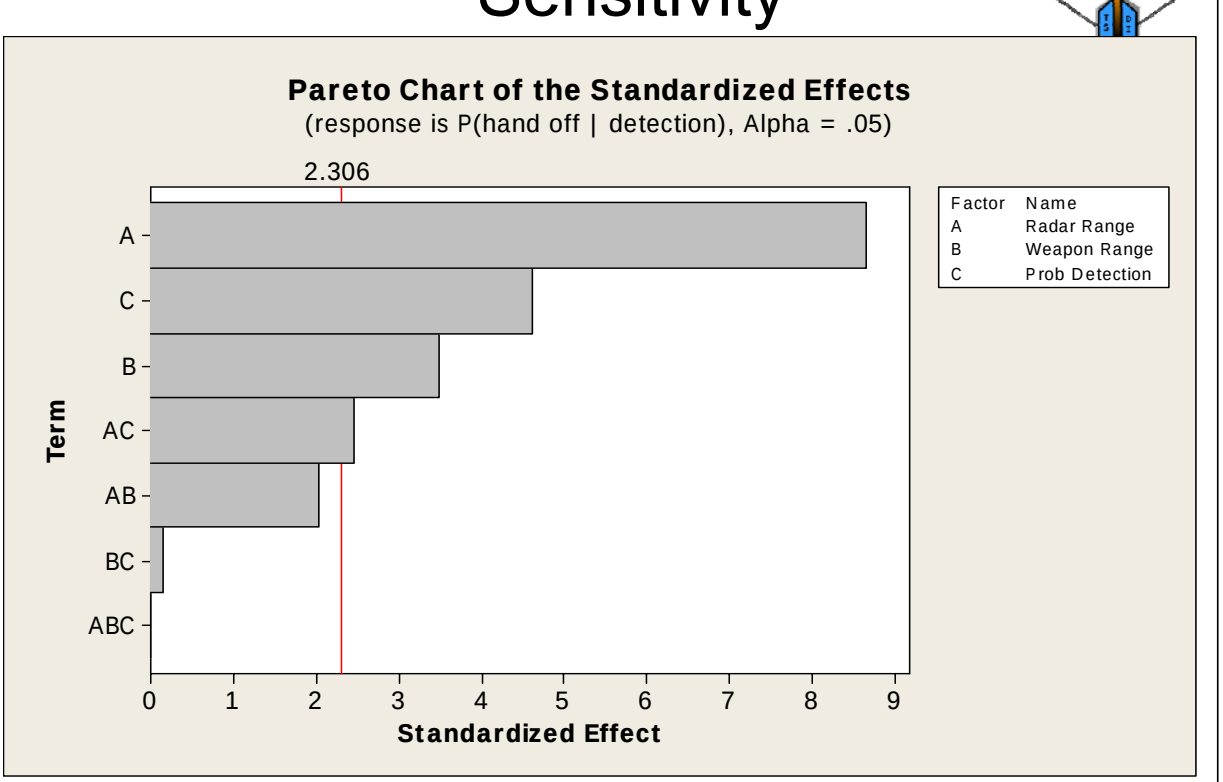
P (engage | detection) Sensitivity



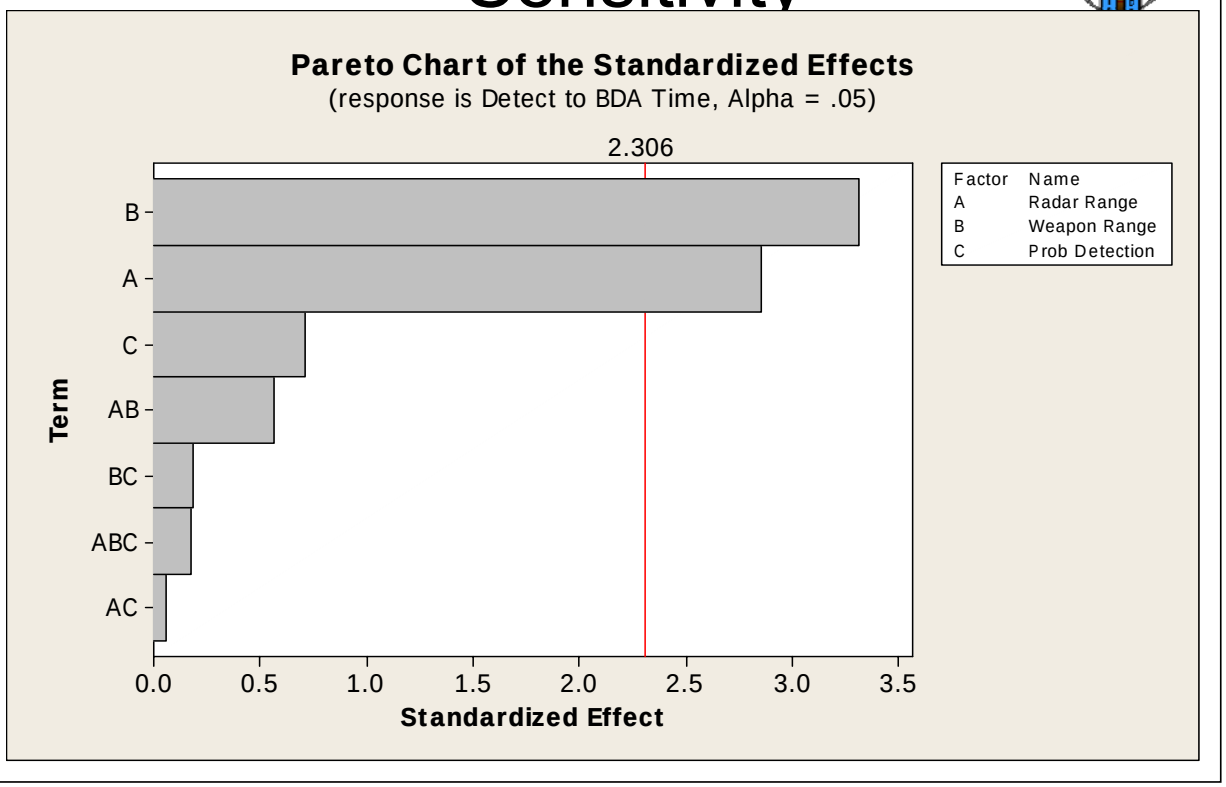
P (kill | engagement) Sensitivity



P (hand-off | detection) Sensitivity



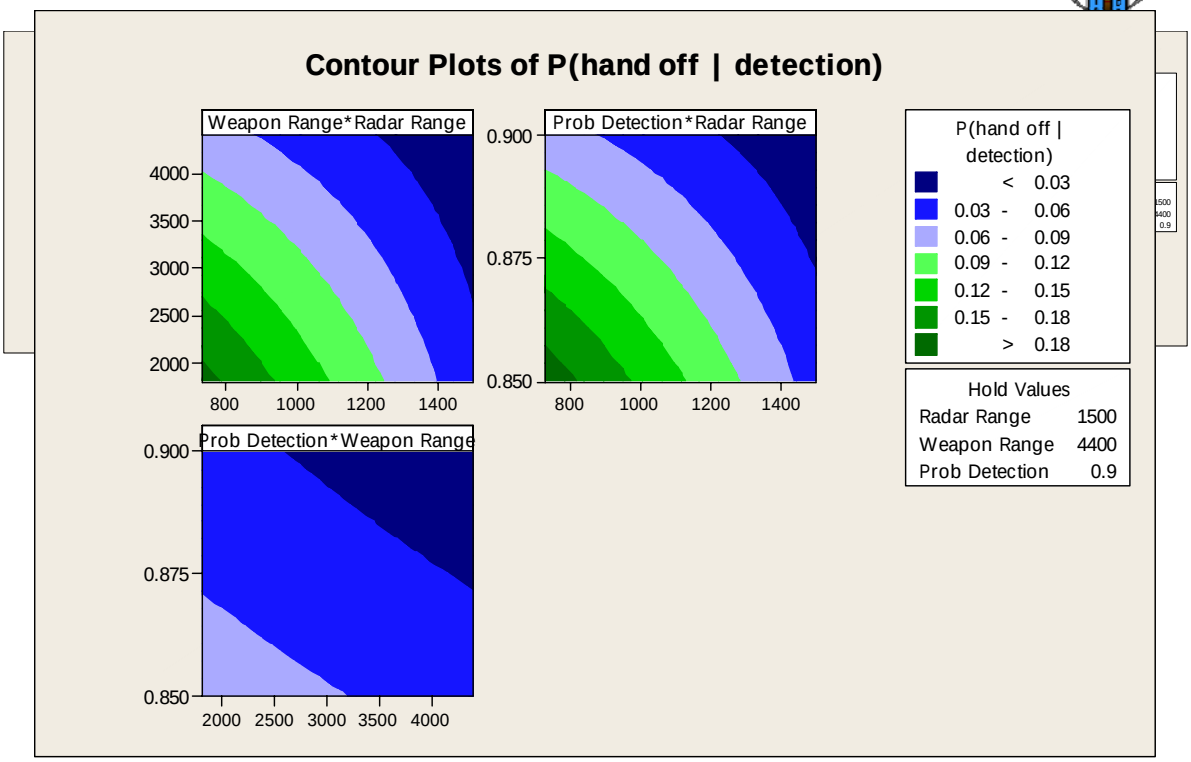
Detect → BDA Time Sensitivity



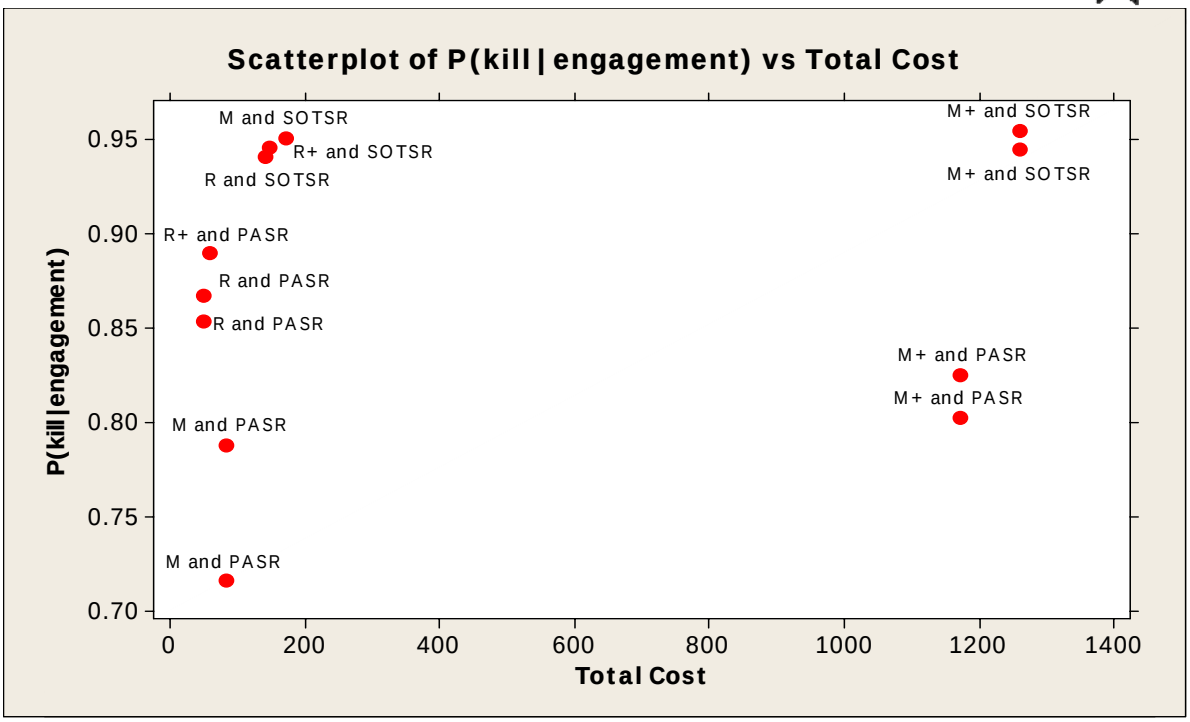
Sensitivity Analysis Summary

- **For BMD mission, inorganic sensor networks yield greater effects than organic sensors.**
- **System is most sensitive to and limited by radar range not weapon capability.**
- **10+ km/s still needed to engage threat missile before end of midcourse.**

Trade-off Studies



Cost Trade-off Analysis



Weapon and Radar Trade-offs

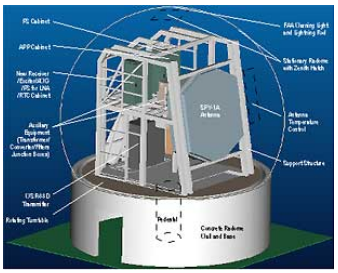
- If organic cueing data is required radar range is single most important factor
- If inorganic sensor is capable of sending track data, than weapons will be single most important factor to systems ability to engage and negate the threat missile

Additional Analysis

- Very few significant interactions among Scenario, Radar, and Weapon variables.
- There was a significant statistical difference between the independent Radar and Weapon Architectures.

2nd Iteration Summary

- SOTSR performed better in conjunction with the MFPAR.
- 10 km/s Railgun projectile performed better against all metrics due to longer range and high velocity.



Final Architecture

MFPAR assisted by SOTSR and Railgun

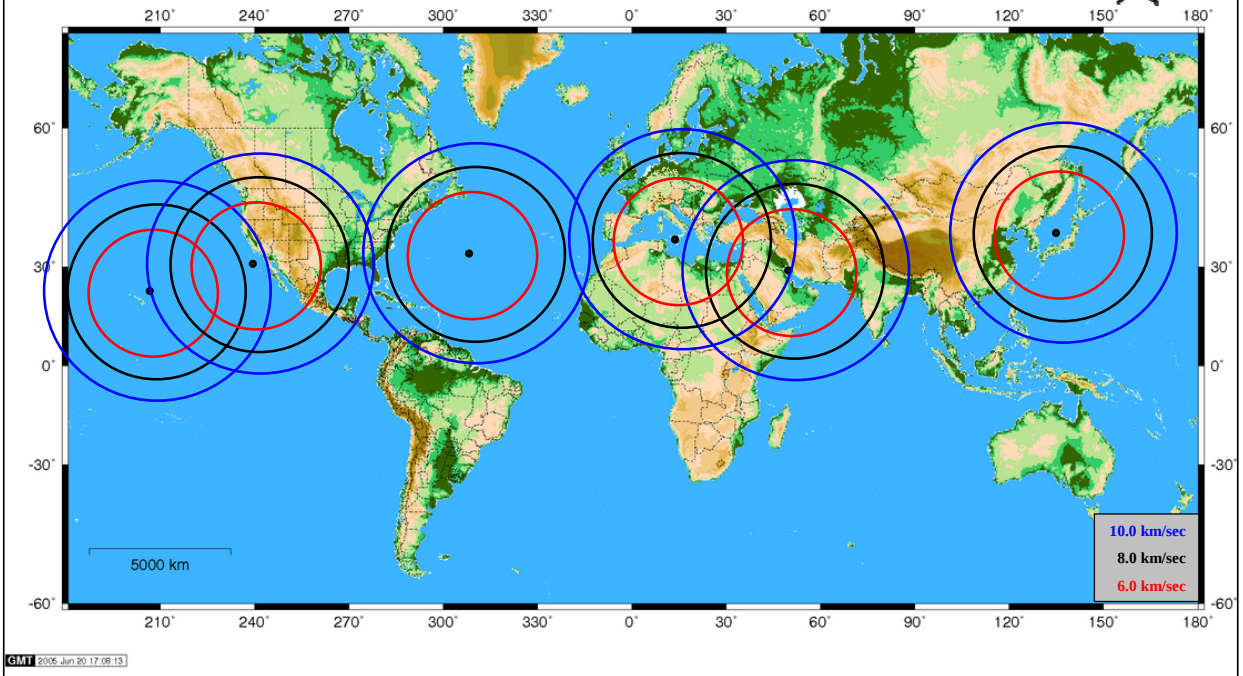
SHIP ANTI BALLISTIC RESPONSE

Physical Modeling Backups

Future Model Work

- Areas for further model refinement
  - Improve Grid Assignments to further reduce range errors
  - Account for **all** Drag and Lift (not just Hypersonic Values)
  - Account for Coriolis Effect
  - Better incorporate control surfaces in missile flight (roll-over rate)
  - Develop BM Database for use in Threat Selection
  - Integrate Railgun Trajectory as Fire Control Solutions within System Model

Global Capability



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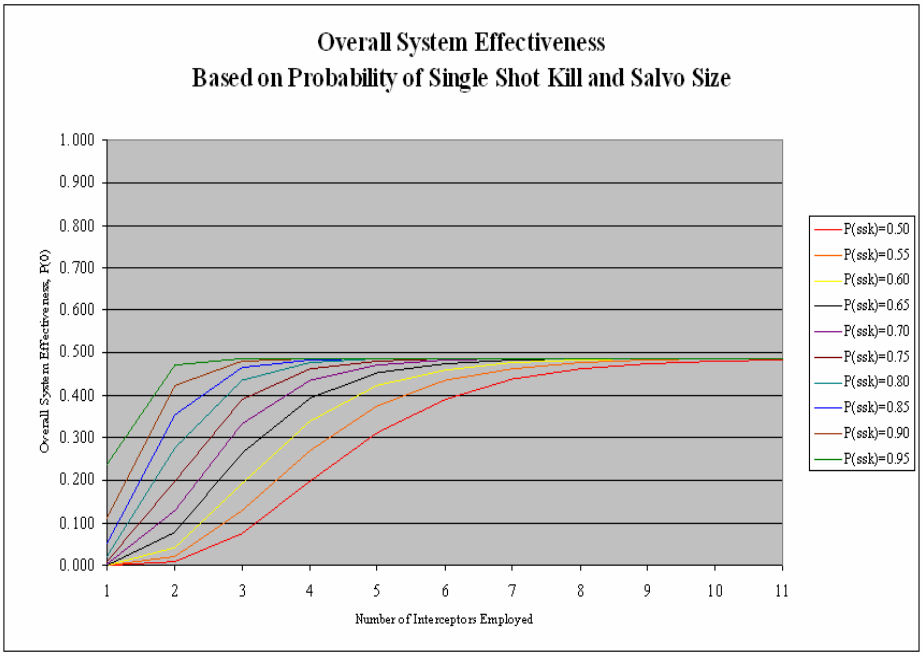
Map from www.42.org

P(0) at P_w(track)=0.95, W=14



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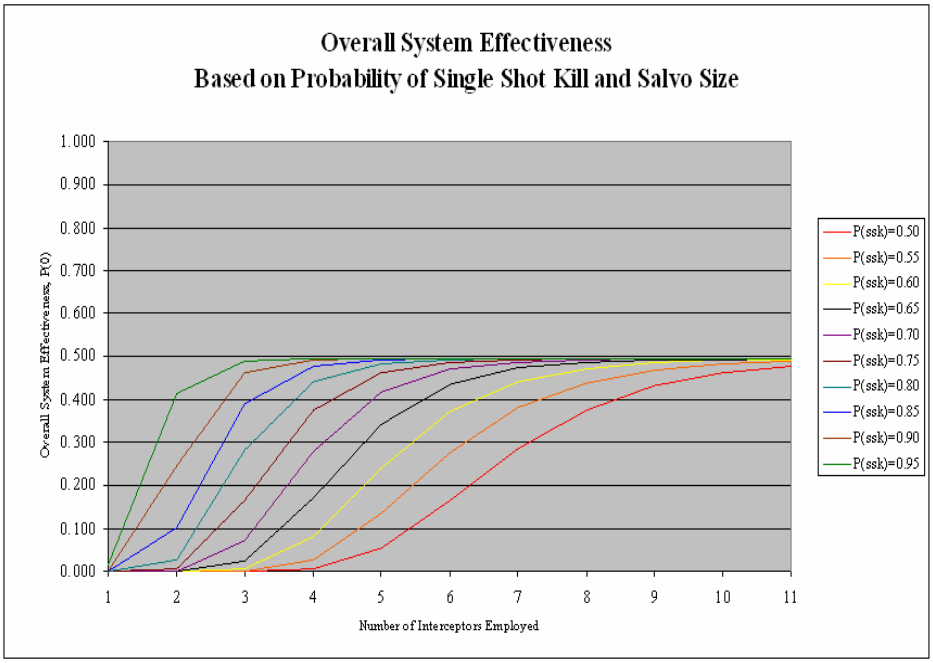
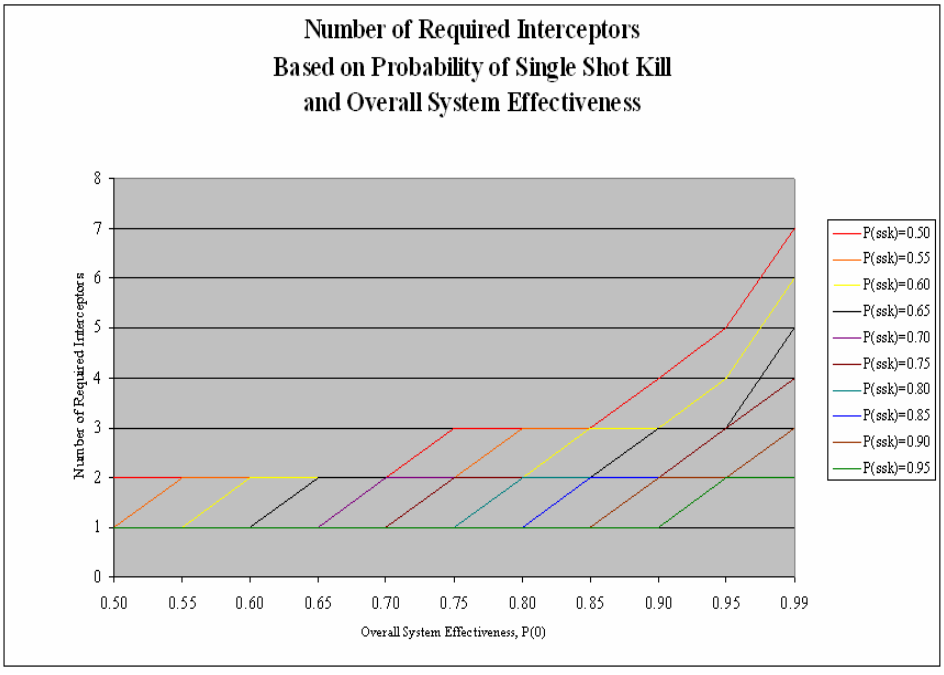
P(0) at P_w(track)=0.99, W=70



Required Interceptors: P_w(track)=0.99, W=1



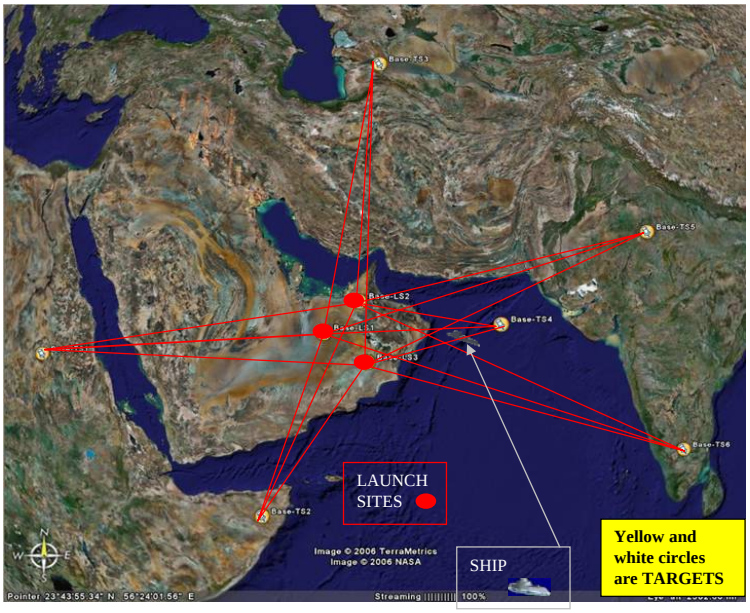
Operational Scenarios

LT Fischer

Final Scenario Refinement

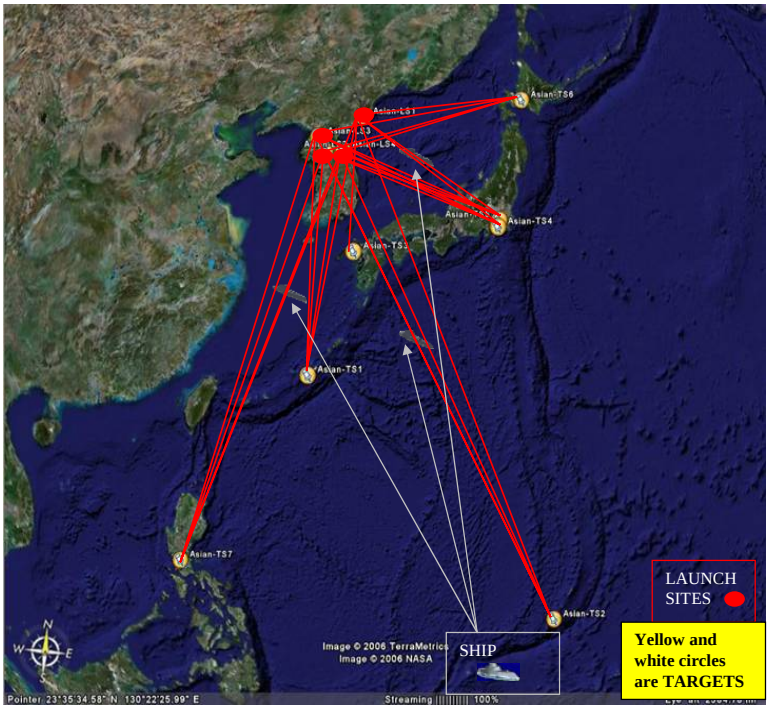
- Unclassified approximation to the Major Combat Operations (MCO's)
- Test capabilities to geographical and tactical scenarios:
  - Functional
  - East Asian
  - Middle East
  - Sea Base

Functional Model



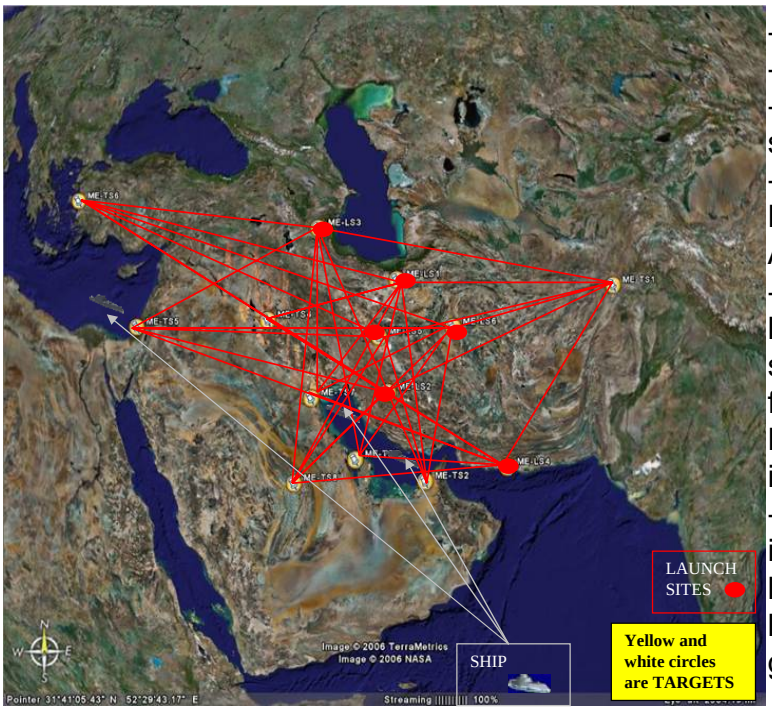
-Purely a Test Scenario; not applicable to any particular geographic region.
-1 ship vs 3 Launch sites - 5 dispersed land targets, and 1 sea target, provided data on all possible engagement geometries.

East Asia Defense



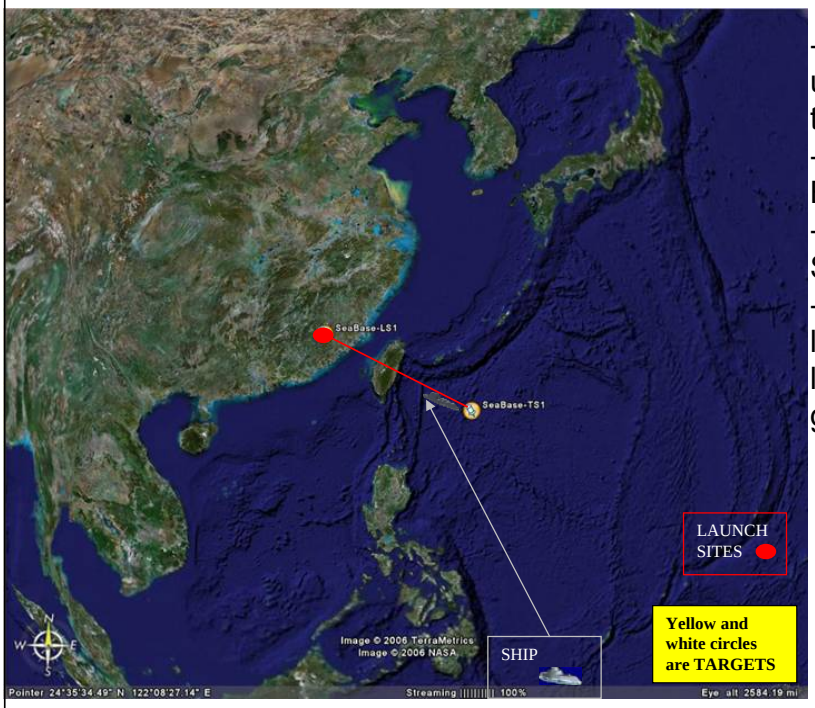
-Large waterspace area.
-3 ships vs. 4 known launch sites, defending 7 targets
-Ships located in Sea of Japan, East China Sea, and Philippine Sea, providing coverage to all anticipated missile flight routes.
-Stresses defense against large, simultaneous threat salvoes, with the potential for several max-range intercepts.
-Up to 260 enemy missiles in flight at any time, up to 65 launched from any launch site. This is randomly generated by the model.

Middle East Defense



-Most demanding scenario.
-Small waterspace area
-3 ships vs 6 known launch sites defending 8 land targets.
-Ships located in eastern Med, Northern and Southern Arabian Gulf.
-Stresses defense against large, simultaneous threat salvoes, with the potential for several Medium- and Minimum-Effective Range intercepts.
-Up to 300 enemy missiles in flight at any time, up to 50 launched from any launch site. This is randomly generated by the model.

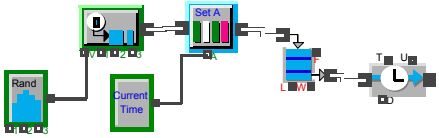
Sea Base Defense



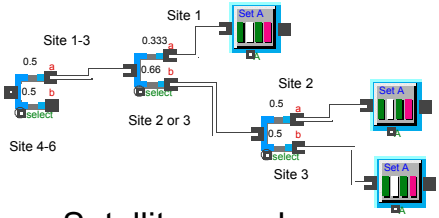
-Evaluates a direct attack upon an underway naval task force(a CSG or ESG).
-Used to validate self-defense BMD capability
-1 ship vs 1 known launch Site, defending the Sea Base.
-Up to 50 missiles can be launched from the launch site. This is randomly generated by the model

Final System Model

- Number of missiles variable for each scenario

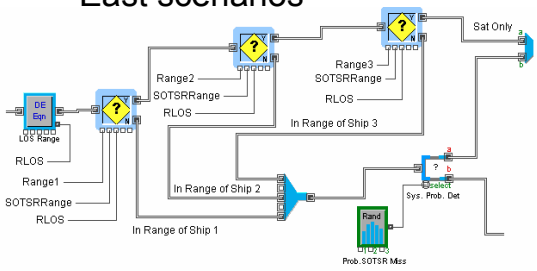


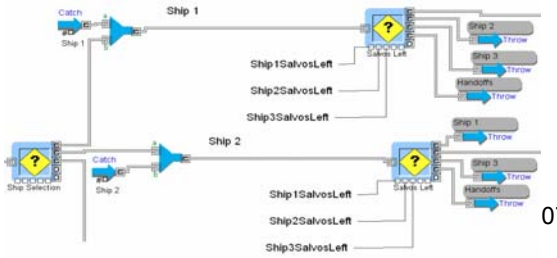
- Both launch site and target chosen randomly



- Satellites used

- Three ships used for Southeast Asia and Middle East scenarios





Cost Analysis

ENS Diersing

Conceptual System Attributes

- Extended Range Detections
- Deep magazines
- No competition for magazine space
- Lower cost per engagement
- Highest projectile velocities

Sensor

- Stand Alone Multifunction Phased-Array Radar eliminated through simulation results
- Skin of the ship radar (SOTSR), with phased array assist preferred sensor
- Dr. David Jenn (NPS), design lead
- Cost per SOTSR unit: $~131 million
- Cost per Spy-1B radar: $30 million
- TOTAL COST: ~$161 Million

Interceptor

- SM-3 vs Railgun
- SM-3 cost: $11.3 million per missile (Block 1)
- Railgun cost per round: $30,000-45,000 (20 kg guided projectile)
- For 2 kg round, miniaturization factor of 2X cost

Platform

- Current CG-47 cost per ship: $1 billion
- Additions of electric drive, stronger hull design, new technologies
- 20 years from present
- CG(X) cost estimate per ship: $3.2 billion

(Congressional Budget Office, 2003)

Platform Operating Cost

- CG(X) estimated annual operating cost: $27 million (Congressional Budget Office, 2003)
- Interceptor (Railgun) cost per salvo: approx. $240,000
- Total Annual Operating Cost (assuming 10 engagements): $29.4 million

Total System Cost Comparison

	SM-3	Railgun
Platform	$3,439,360,000	$3,439,360,000
Railgun mounts	$0	$140,000,000
10 salvos	$226,000,000	$2,400,000
1 year ops	$29,019,600	$29,019,600
SOTSR	$130,858,950	$130,858,950
Total (FY$2006)	$3,825,238,550	$3,741,638,550
Inflation Index	1.5076	1.5076
Total (FY$2025)	**$5,766,929,638**	**$5,640,894,278**

Total System Cost Comparison with One Year of Operations (Base Year 2006)

Tradeoffs

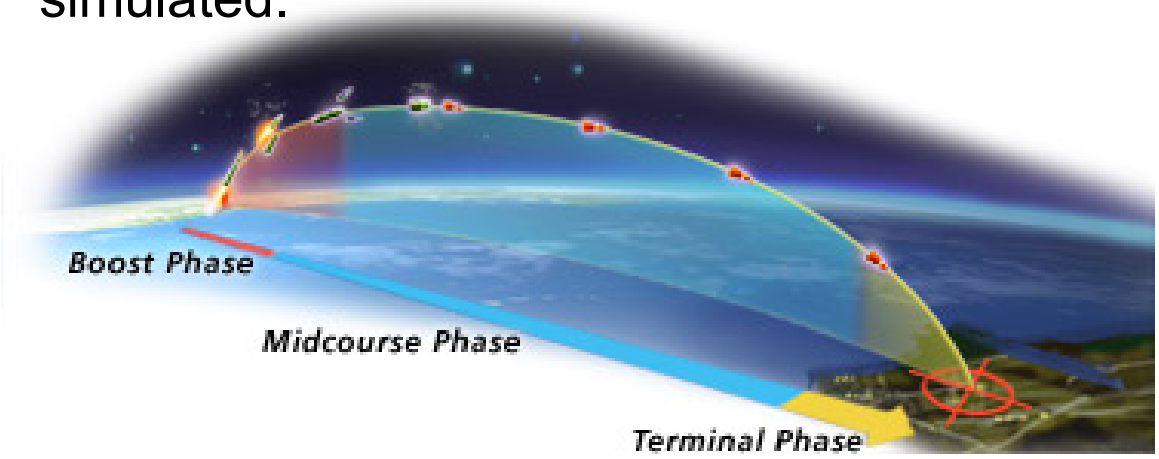
- Increased performance did not dictate higher costs
- Interceptor cost per salvo: SM-3: $22.6 million (2 missiles), Railgun: $240,000 (4 shots)
- Approx. 94 Railgun salvos for cost of one SM-3 salvo
- Railgun better performance in simulations
- Drawback-SM-3 is being tested; Railgun still in development

Conceptual System Analysis

ENS Glenn

Final Iteration of Simulations

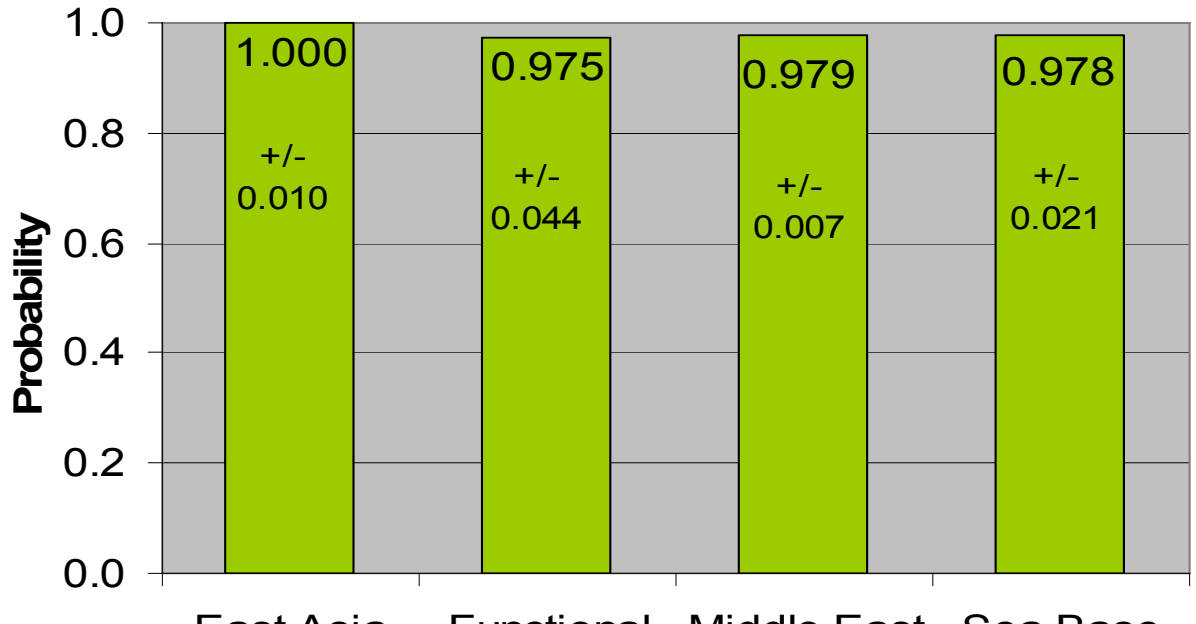
- Only 10 km/s Railgun Round paired with SOTSR in conjunction to the MFPAR was simulated.



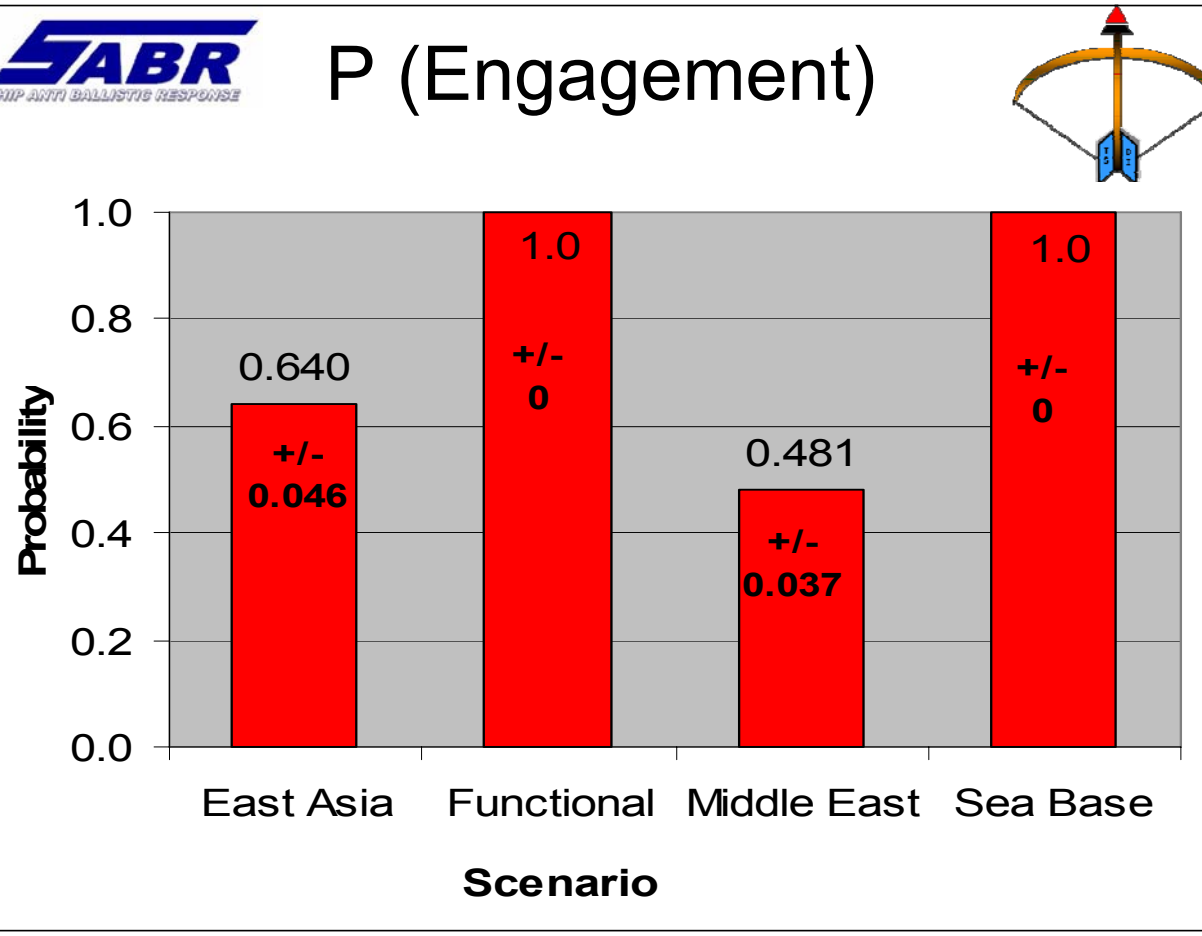
Measures of Effectiveness

- P (engage)
- P (kill)
- P (detect)
- P (false alarm)
- P (hand-off)
- Ave. time left to reengage
- Ave. Detect to BDA time

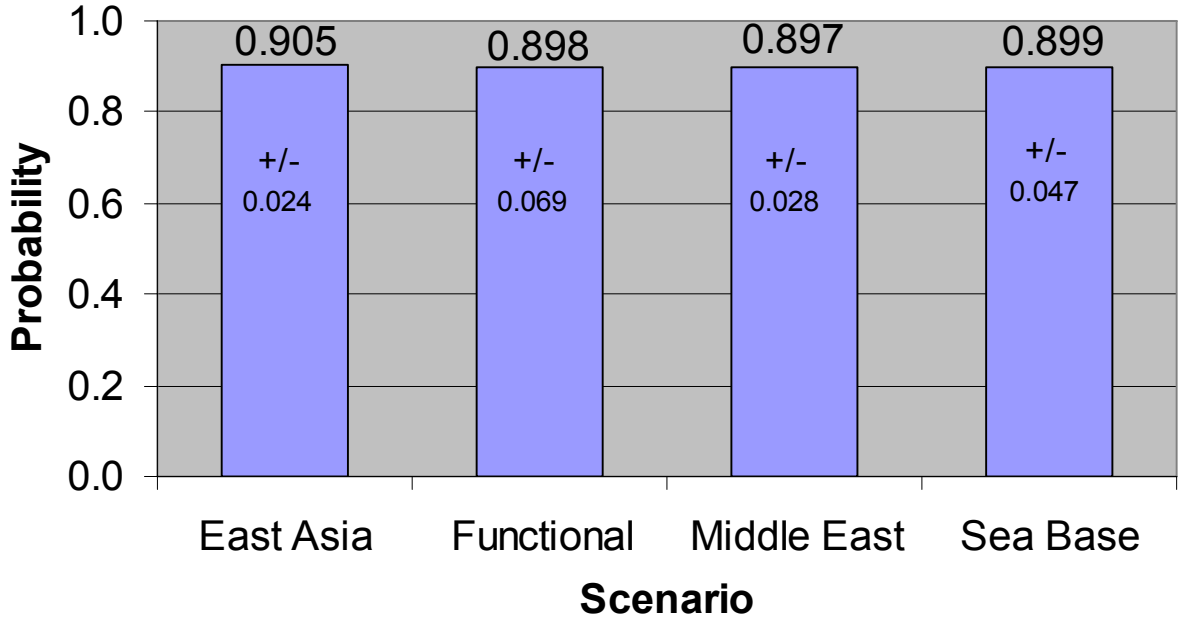
P (Detect)



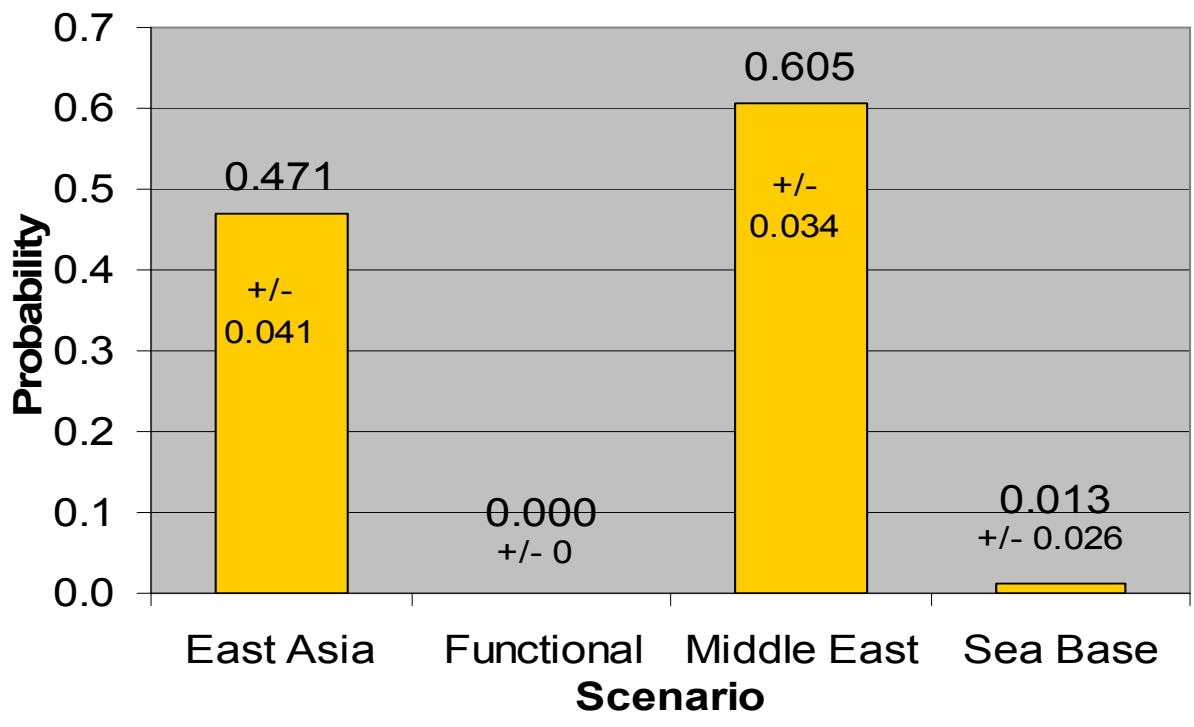
P (Engagement)



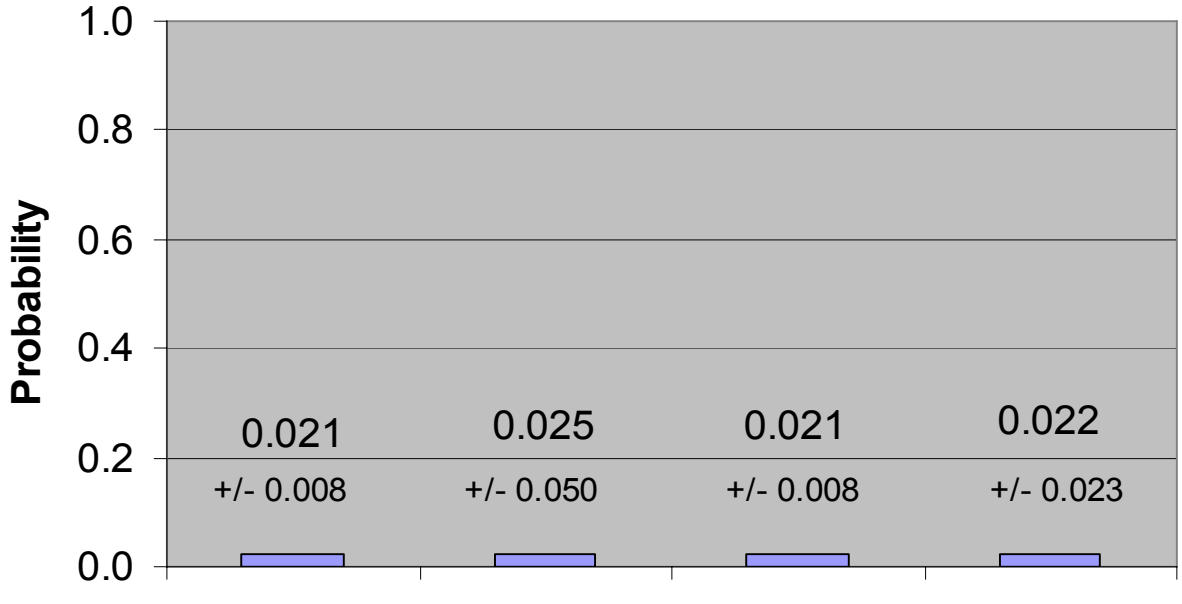
P (kill | engagement)



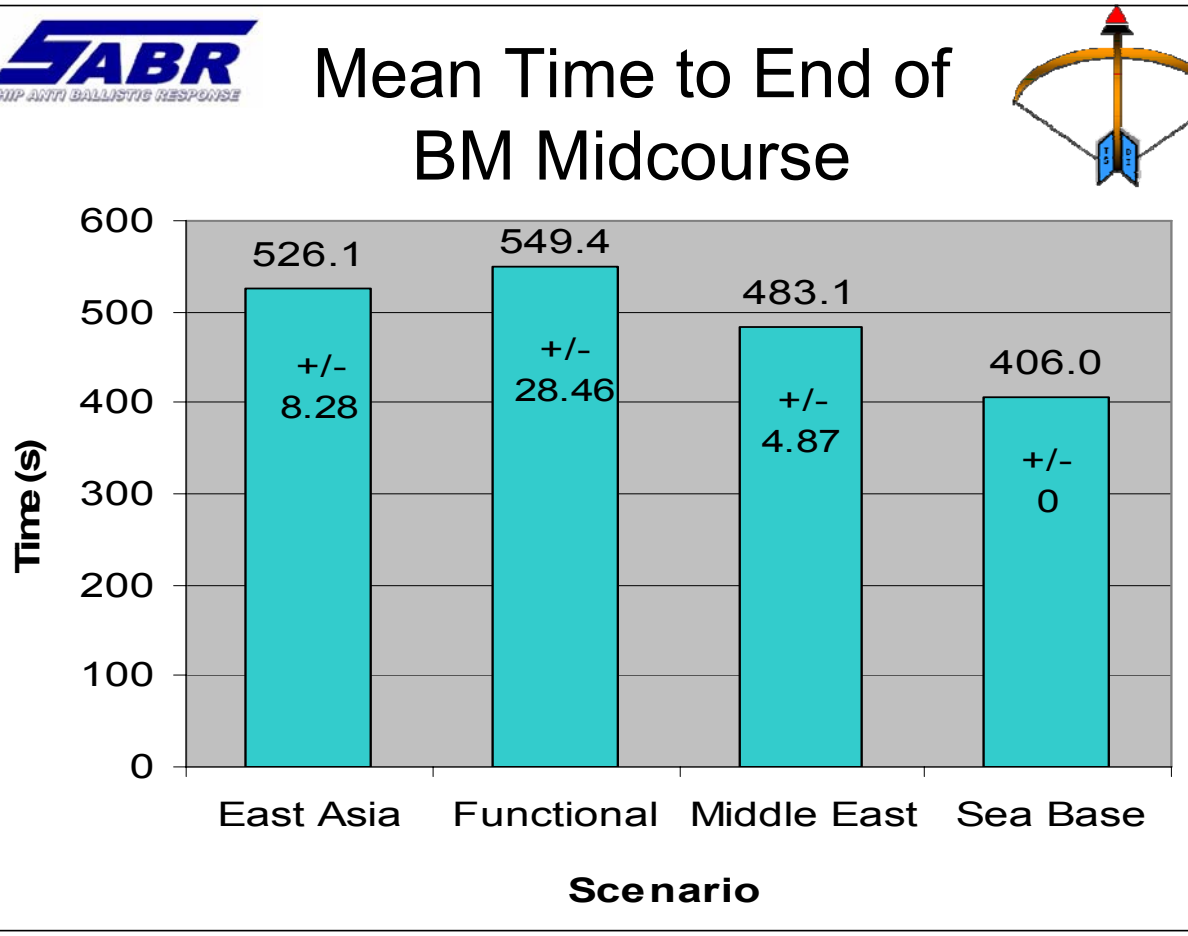
P (Hand-off | Detection)



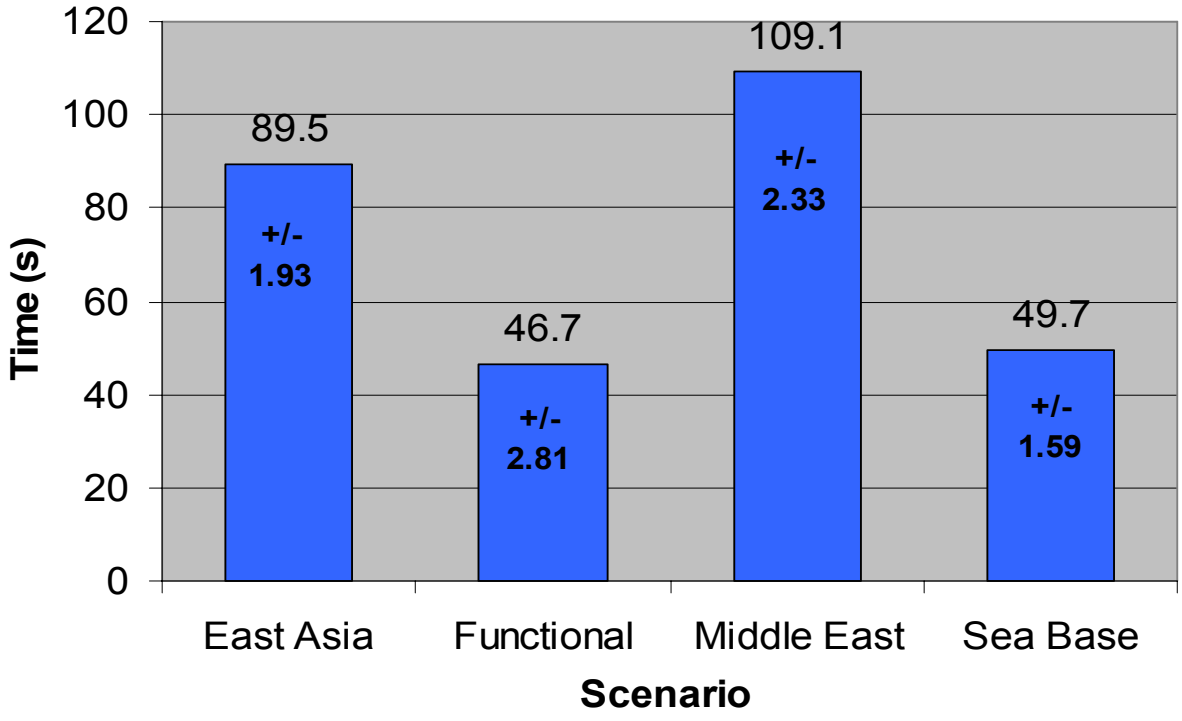
P (False Alarm)



Mean Time to End of BM Midcourse



Mean Detect to BDA Time



Final Iteration conclusions

- System saturates at ~150 simultaneous airborne threat missiles.
- System will need assistance of coalition and non-organic assets in Middle East and Asian scenarios.

Conclusion

LT Johnson

Purpose

- Parallel current efforts by DoD in BMD
- Seek a feasible solutions for future sea-based BMD challenges using systems engineering methodology, examining:
  - Entire detect-to-engage sequence from detection to post-engagement assessment
  - Feasible architecture alternatives
- Simulation and analysis of architecture alternatives
- Recommendation for a path for future BMD system development

Sensor Take-Aways

- Organic sensors (even state-of-the-art sensors such the conformable Skin-of-the-Ship (SOTS) early warning radar) can only detect 50-60% of launched ballistic missiles at best.
- Non-organic sensors are essential to the detection and tracking of threat ballistic missiles. Combined with the organic sensors of the seaframe, ballistic missiles are detected nearly 100% of the time, regardless if there are 1 or 300 simultaneously launched.

Detection Take-Aways

- In the absence of non-organic sensors, a combination of radars and sensor systems performs better than any individual sensor alone. The combination of the conformable SOTS early warning radar and the multi-functional phased-array radar (MFPAR) out performed the MFPAR on its own by detecting an average of 10-12% more of the total ballistic missiles in a threat salvo

Time Take-Aways

- The most critical aspect of ballistic missile defense (BMD) is time. The faster a threat ballistic missile is detected, the faster that information travels to all players in the coordinated ballistic missile defense, the faster engagement (C2) decisions can be made, then the faster an interceptor can be employed (and re-employed if required). Improvements in any or all of these aspects, and the time it takes to conduct battle damage assessment (BDA) can only improve the probability of kill.

Network Take-Aways

- A collaborative information exchange (CIX) is critical to share all detection, identification, tracking, fire control (FC), and C2 information between all players in the BMD network. Inability to provide this critical information denies each player in the BMD network a common operating picture and ability to perform an intercept if they are determined to be the optimal asset for the engagement.

C^2 Take-Aways

- An automated battle management system (ABMS) is key to ensuring the best player in the BMD network takes the “optimal shot” based on engageability, weapon system readiness and availability, and location of player. This type of decision-making aid reduces the amount of critical thinking required by BMD commanders (if “in the loop”) and reduces the time table between detection and interceptor employment.

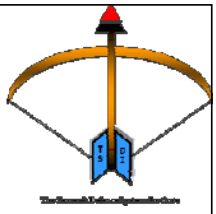
Speed Take-Aways

- Speed of the interceptor is critical aspect of BMD. Increased speed has direct correlation to probability of kill given an engagement and also to the probability of reengagement if required. Speed is also a critical enabler for engagement of ballistic missile threat that are not closing the general position of the BMD player. High speed projectiles expand the engageability window against crossing and tail-chase ballistic missile threats.

Cost Take-Aways

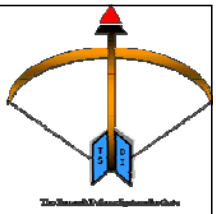
- A multiple-rail gun system placement on the seaframe is the best configuration that combines the highest performance deepest magazines, with the lowest cost of operation (cost of four projectile salvo of an estimated $240,000 vice the cost of a two interceptor-missile salvo of $22.6 million).

Mobility Take-Aways



- A SABR-enabled ship can be quickly moved into theatre, operate in international waters, and provide a credible defense against short to intermediate range ballistic missiles.
- Mobility via the waterspace translates to the first line of BMD for 80% in the world.

Negation Take-Aways



- Sea based BMD would alleviate the burden on land and air based interceptors by providing a first-response ballistic missile negation percentage (% of ballistic missiles destroyed of the total threat salvo) of 43-58% for a salvo up to *300 short to intermediate range ballistic missiles simultaneously*. Though this percentage appears small, the reality is that there are only a handful of nations that could coordinate a simultaneous ballistic missile salvo of this magnitude.

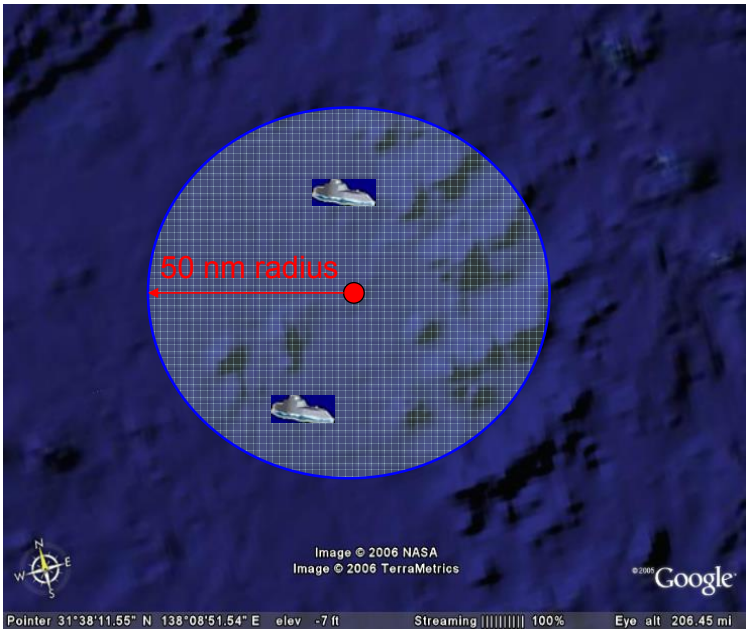
Negation Take-Aways (con't)

- It is far more likely that the missile launches would be staggered and use less numbers per salvo. Smaller threat salvos and/or ballistic missiles launched in succession only improve these percentages.
- Using the original three ship operational employment, a simultaneous threat salvo of approximately 150 ballistic missiles or less provides a negation percentage of approximately 90%.

Negation Take-Aways (con't)

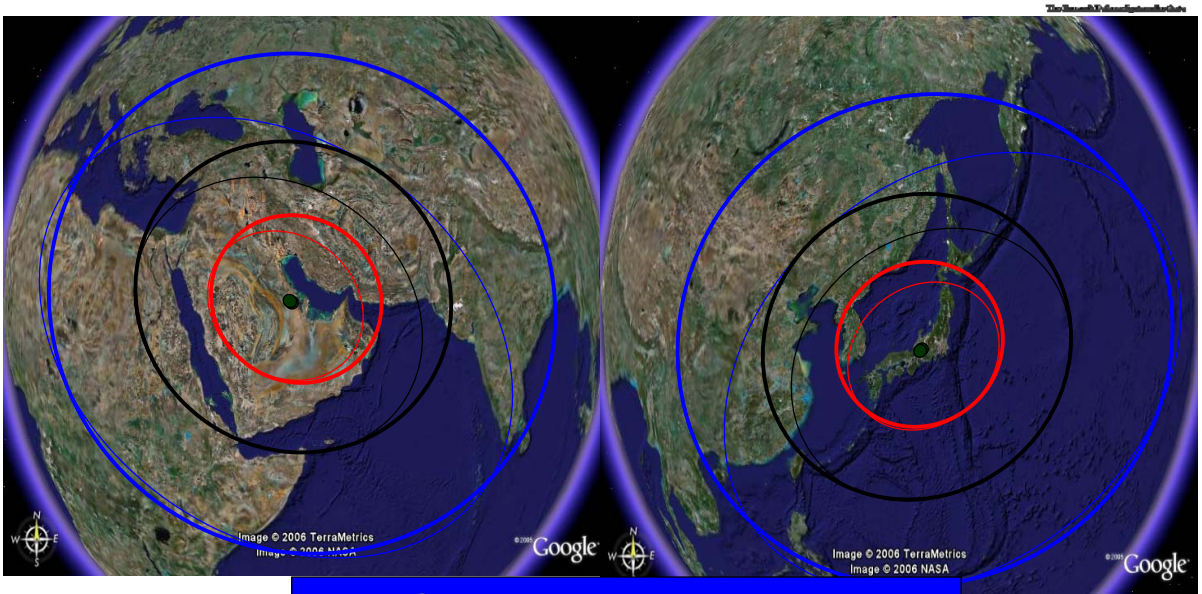
- In the remote chance that a simultaneous 300 ballistic missile salvo can be launched, the negation percentage can be increased to approximately 90% by adding an additional SABR system ship to the 50 nm radius operating area of each ship originally on station.

Saturation Level Improvement



- 2 more rail gun mounts
- 1200 additional rounds

Single Ship Capability



10.0 km/sec
8.0 km/sec
6.0 km/sec

Single ship saturation is approximately 50 simultaneous launched BMs

Outside the Conceptual Design Selection

- Flexible system design model
  - Threat modifications
  - Sensor modifications
  - Network modifications
  - Interceptor modifications
- Foundation for follow-on studies

Follow-on Studies

- TSSE Ship Design
- Railgun Theses
- ABMS Architecture
- CIX
- Conformable SOTS Radar


SABR
SHIP ANTI BALLISTIC RESPONSE