FireSat Design Trade Study: Effectively Bridging MBSE and MBD

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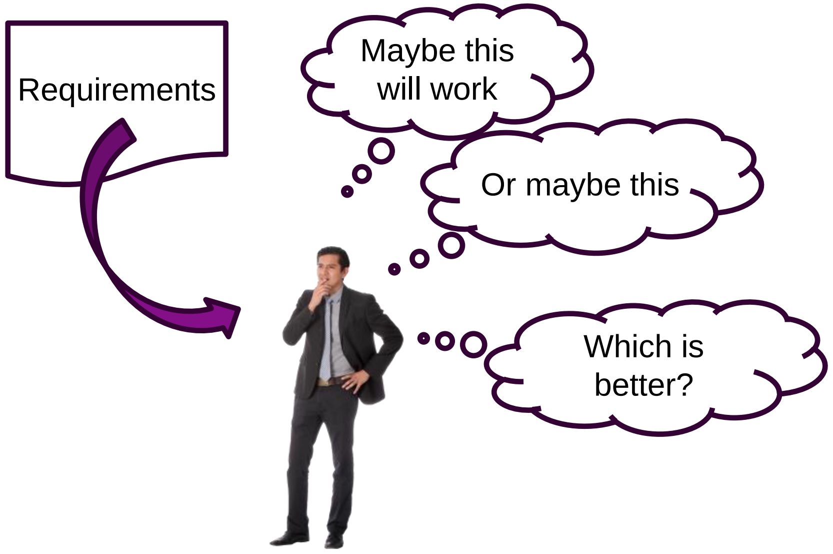
Outline

- Background
  - Barriers to DE trade studies
  - Approach
- Case Study
  - MBSE and MBD models
  - Model integration and data exchange
  - Solution methods
- Results
- Conclusions and Benefits

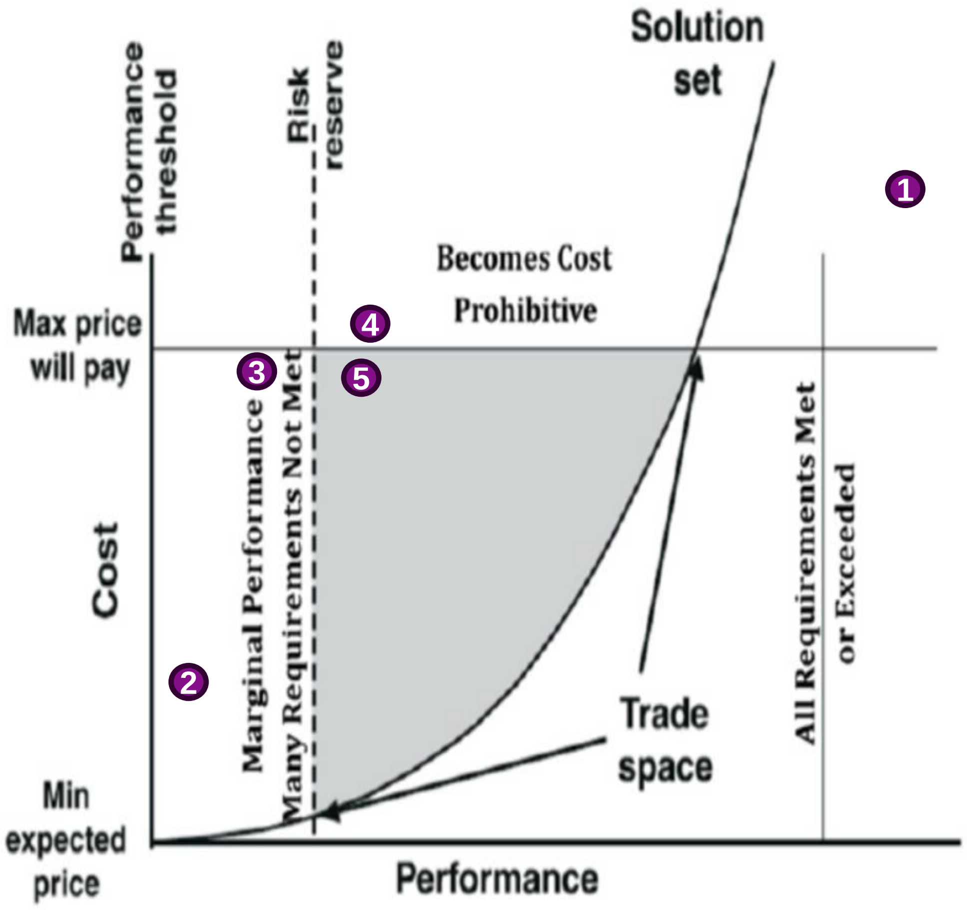
Background

- Trade studies are essential to informed design decisions
- Characteristics of trade studies
  - Complexity of analyzing options
  - Multiple, multi-domain technical factors
  - Non-technical factors (CAIV)
  - Defining criteria for best
- Barriers to applying digital engineering
  - Formulation time & computational time
  - Identifying integration points between tools
  - Maintaining consistency between tools



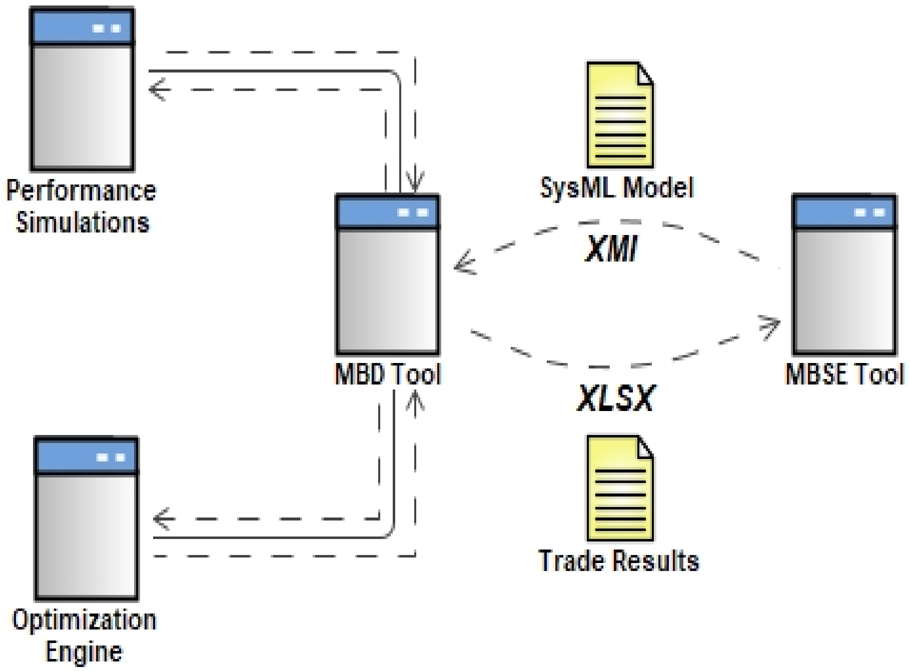
Obstacles to Effective CAIV Trades

- Success of CAIV rests on iterative trade that effectively explore large portions of the feasible design space
- Goal is continual, iterative cost/schedule/performance trades
- Impediments
  - Time to construct, run & integrate simulations
  - Cost estimation dependence on design detail
- CAIV reality is sequential approach
  - Design/simulate 1 aspect/refine design
  - Compare cost of two options/choose
  - Simulate another aspect / repeat
  - Evaluate total cost at end



Approach

- Modern M&S MBD tools provide rapid **creation and execution** of detailed physics-based models
- Orchestrating the workflow between these MBD tools and MBSE tools is essential to performing integrated trade studies
  - Maintain central common source of truth for design data
  - Define methods for exchanging both data and model constructs
  - Choose tool in which trade is done (solutions compared)



FireSat MBSE Model

Cameo Systems Modeler©

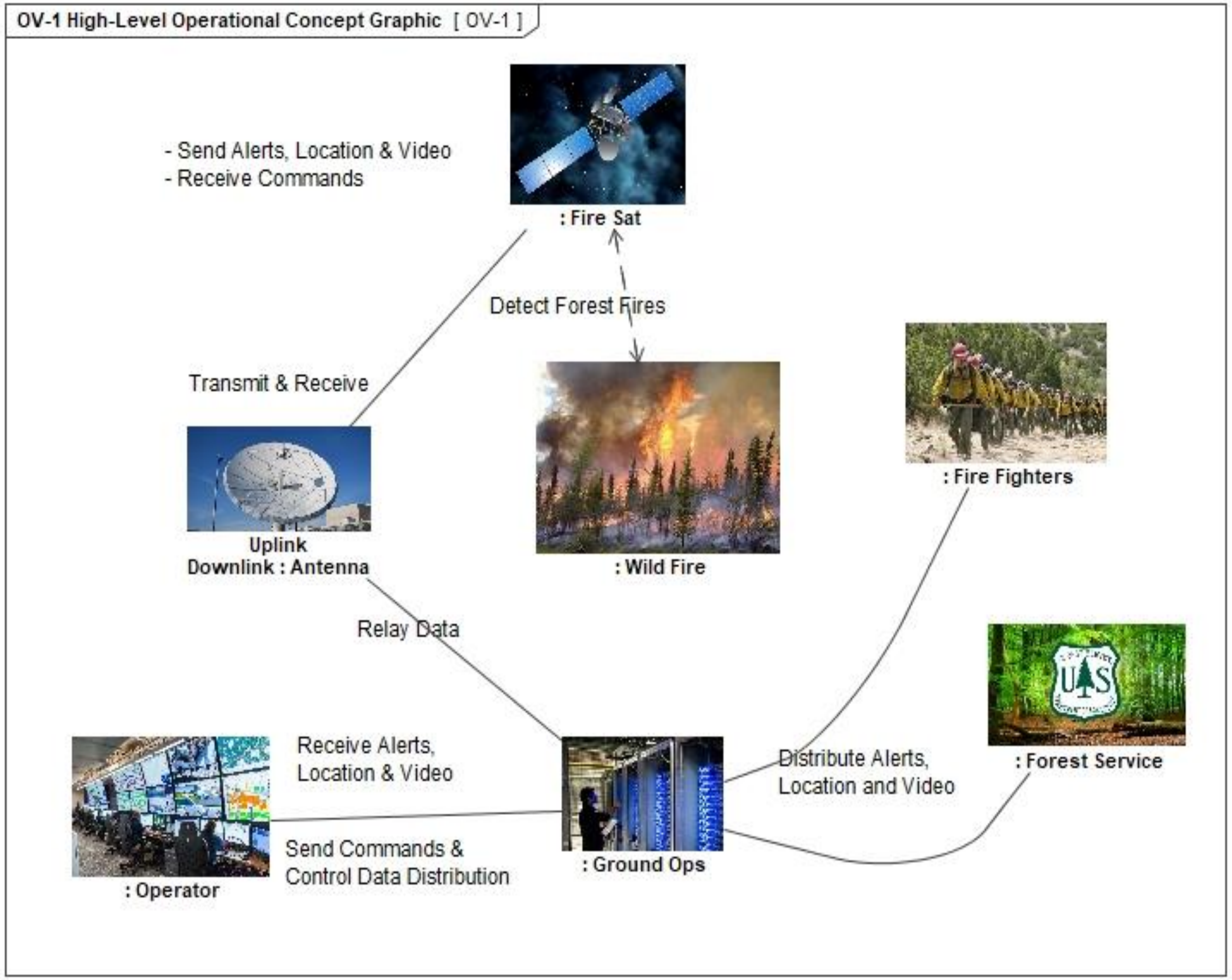
No Magic, Incorporated, a Dassault Systèmes company

Purpose of MBSE Tool / SysML Model

- Captures work products of concept development phase of traditional Systems Engineering process
  - Stakeholder requirements
  - Concept of operation
  - Architecture development
  - System requirements development
  - Interface definition
- Creates model elements embedded with design information
  - Structure
    - Compositional elements
    - Hierarchy
    - Interfaces / connectivity
    - Descriptive & quantitative parameters
  - Behavior
    - Functions
    - Flows across interfaces

> ➢ ***Does not perform detailed analyses, simulations, or trades***
> ➢ ***Can hold results and design truth resulting from trades***

FireSat Mission



- High Level Requirements
  - Develop satellite-based system to detect forest fires
  - Send alerts, real-time video, and geolocation data to ground
  - Distribute to fire fighters and jurisdictions
  - Minimal time to detect, down link and distribute
  - Location accuracy

Functional Analysis

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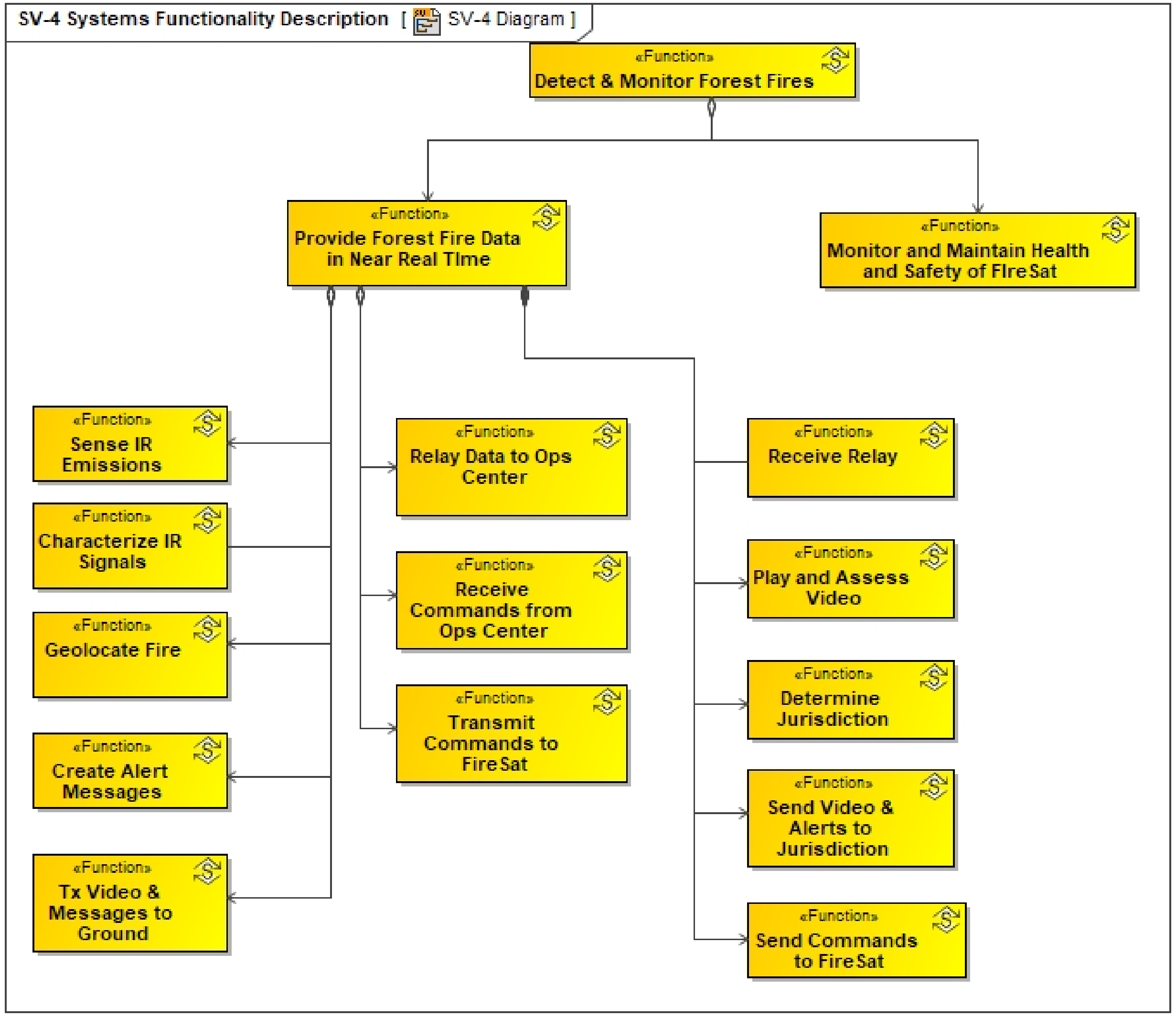
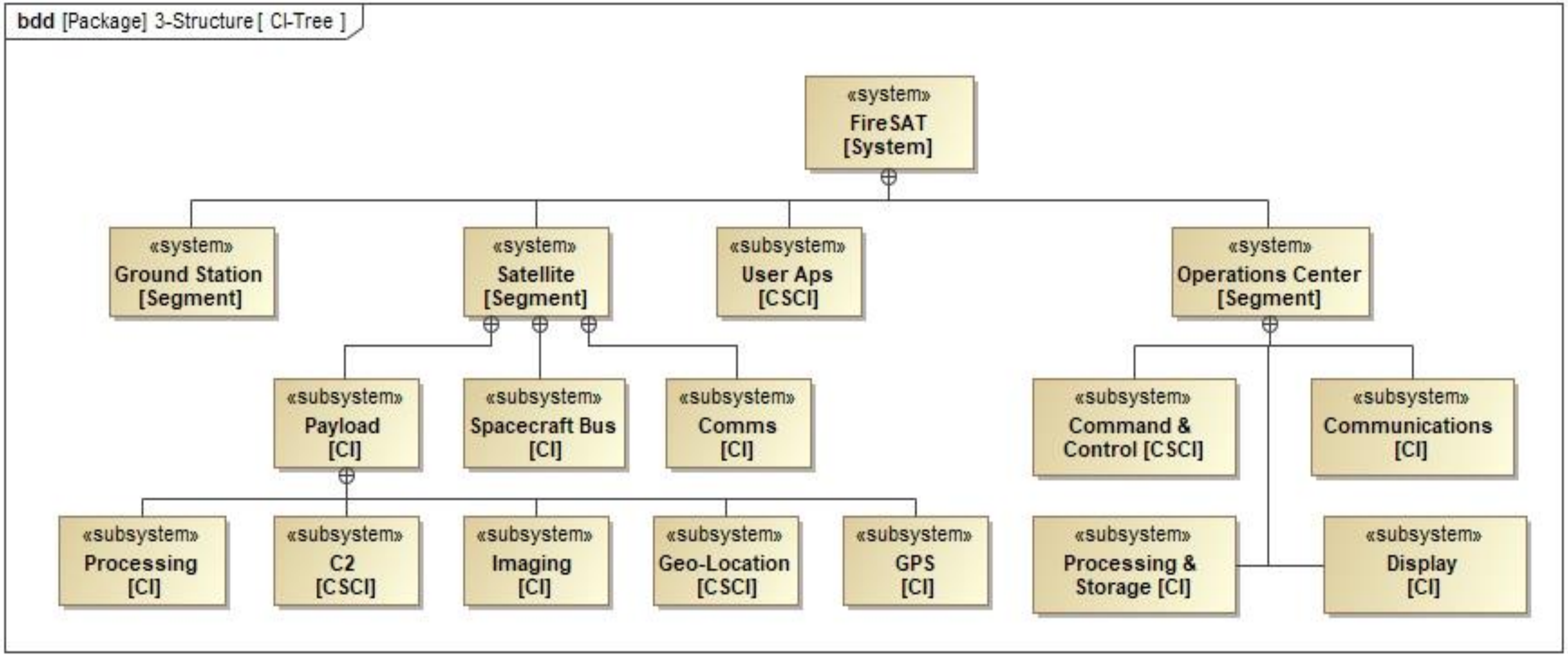


- Definition and decomposition of functions that provide required capability
- Iterative to level necessary to support development of architecture

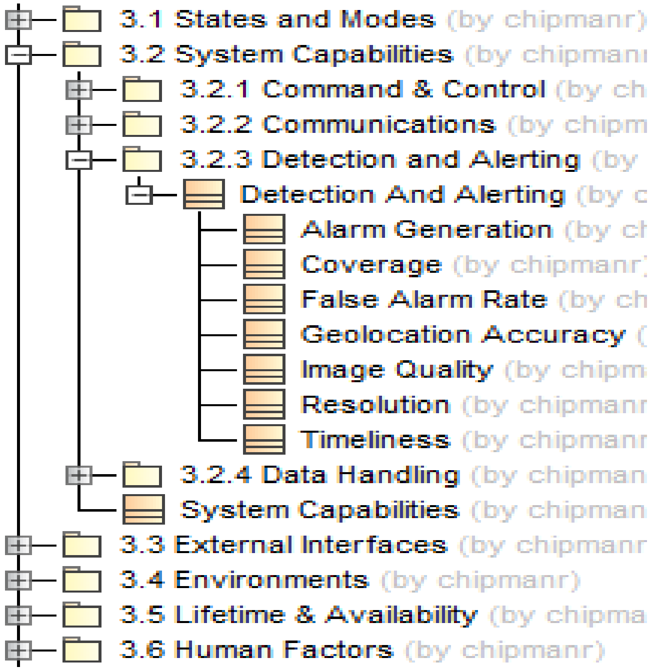
System Architecture

Hierarchical Definition and decomposition of architecture



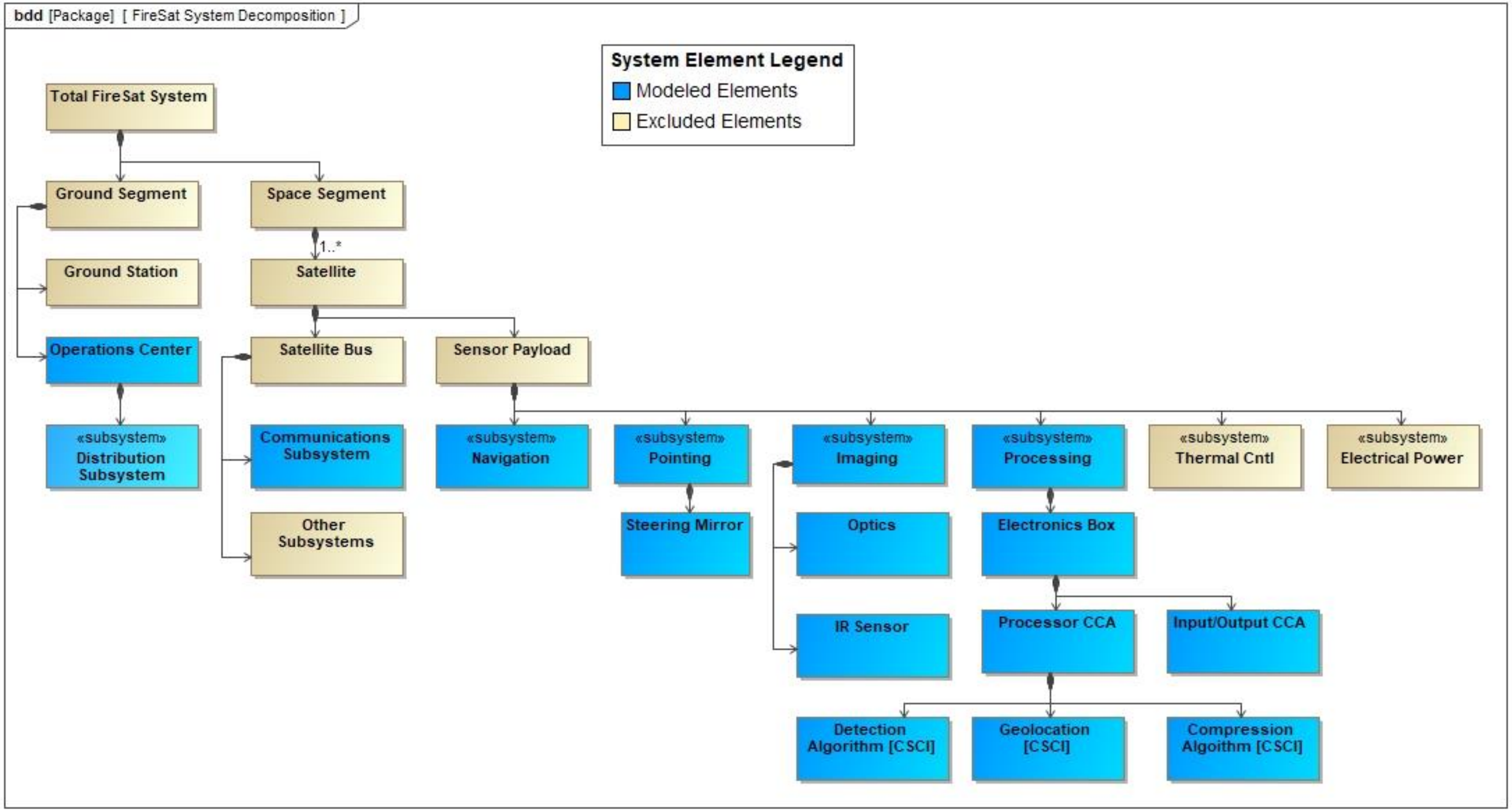
System Requirements

- Derived and decomposed system requirements
- Allocated to FireSat subsystems that must satisfy them

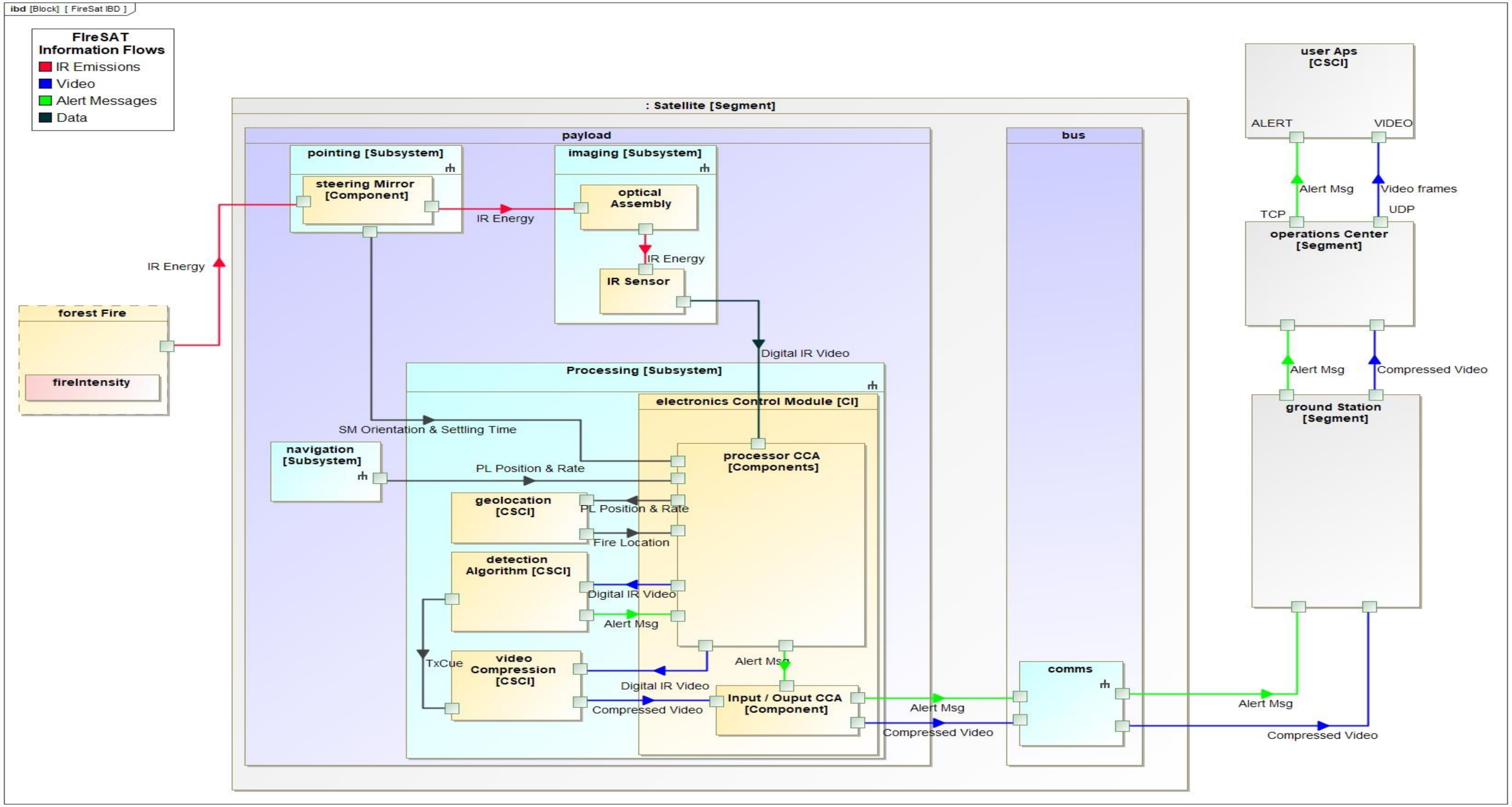


Name	Text	Satisfied By
System Requirements	SYSTEM REQUIREMENTS	
States and Modes	See Diagram	Ground Station [Segment] Satellite [Segment] User Aps [CSCI]
System Capabilities	SYSTEM CAPABILITIES	
Communications	COMMUNICATIONS	
Detection And Alerting	DETECTION & ALERTING	
Detection Time	System shall detect a fire within 90 minutes of its reaching the threshold set for IR Intensity	Imaging Navigation Pointing
Geolocation Accuracy	System shall locate a fire within 1 km of its epicenter	Navigation Pointing Imaging
Coverage	Coverage of specified forest areas within the US at least twice daily.	Bus Imaging
Probability of detection	The system shall detect 80% of fires that reach the threshold set for IR intensity	Imaging Processing Navigation
False Alarm Rate	The system shall identify forest fires with less than 20% within 8 hours with less than 10% false positives	Imaging Processing
Alarm Generation	Within 20 minutes of detecting a fire, the system shall generate and transmit alerts to end users	Processing
Image Quality	The sensor shall sense thermal emissions with a sensitivity less than 150W (TBD), and a resolution of less than 3 miliiradians.	Imaging Pointing
Data Handling	DATA HANDLING	
Command and Control		
Command & Control	Ops Center personnel shall be able to issue commands to the satellite to point the sensor to a chosen location on the earth's surface.	Command & Control [CSCI] Processing & Storage [CI] Processing

Elements Modeled in Trade



Model Signal Flow from Fire to Responder



FireSat MDA Model

MATLAB®, Simulink®, System Composer

MathWorks, Inc.

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Satellite Orbit and Pointing Simulation

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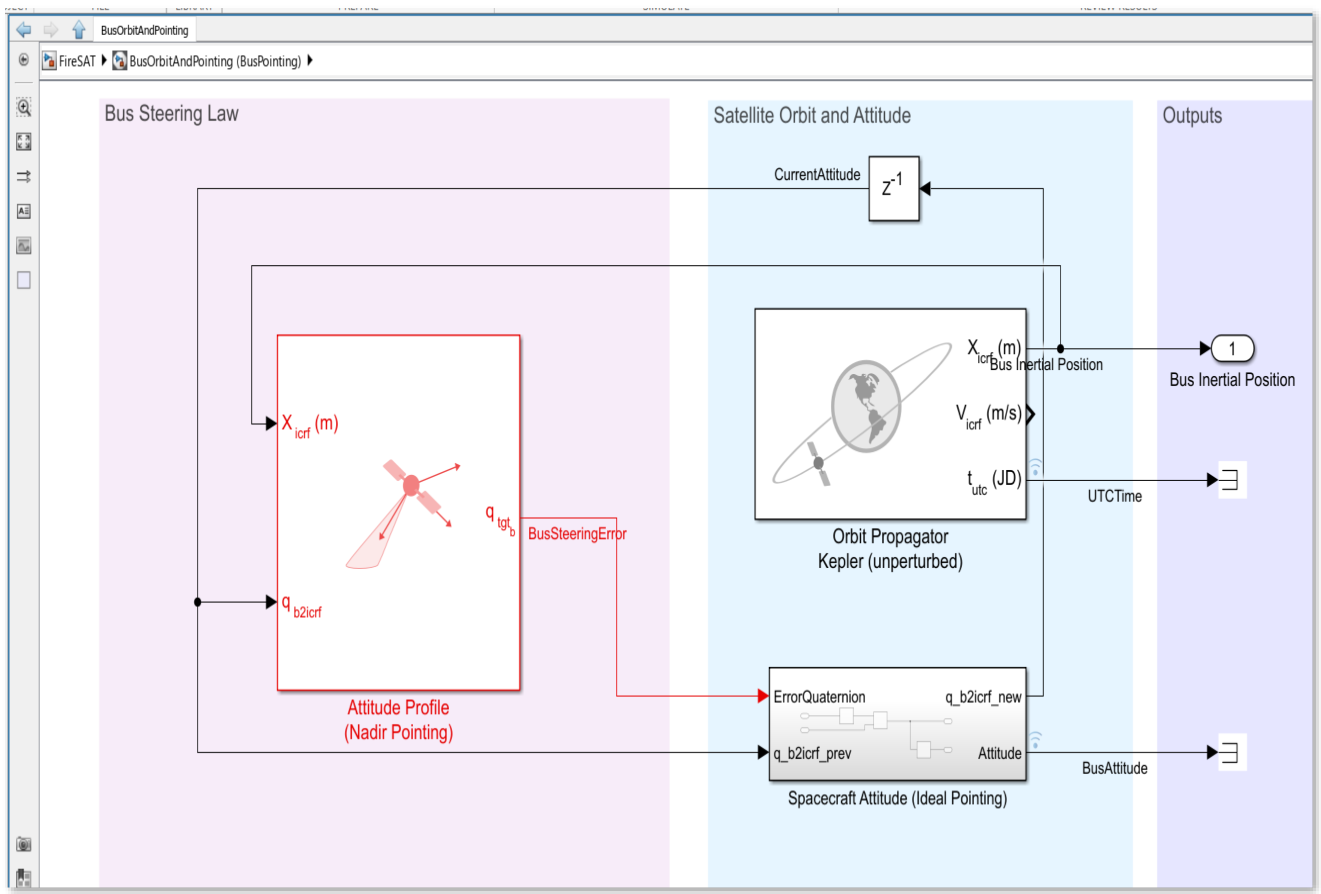
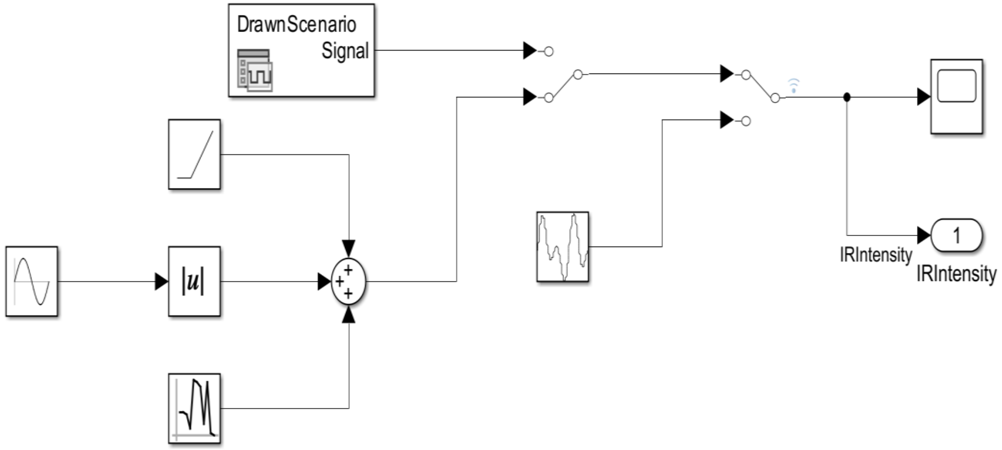
- Satellite Dynamics Options
  - Geostationary
  - Kepler Orbit*
- IR sensor with gimbaling mirror views earth surface
- Gimbal Options
  - Fixed
  - Continuous Sweep
  - Periodic Discrete Pivots*

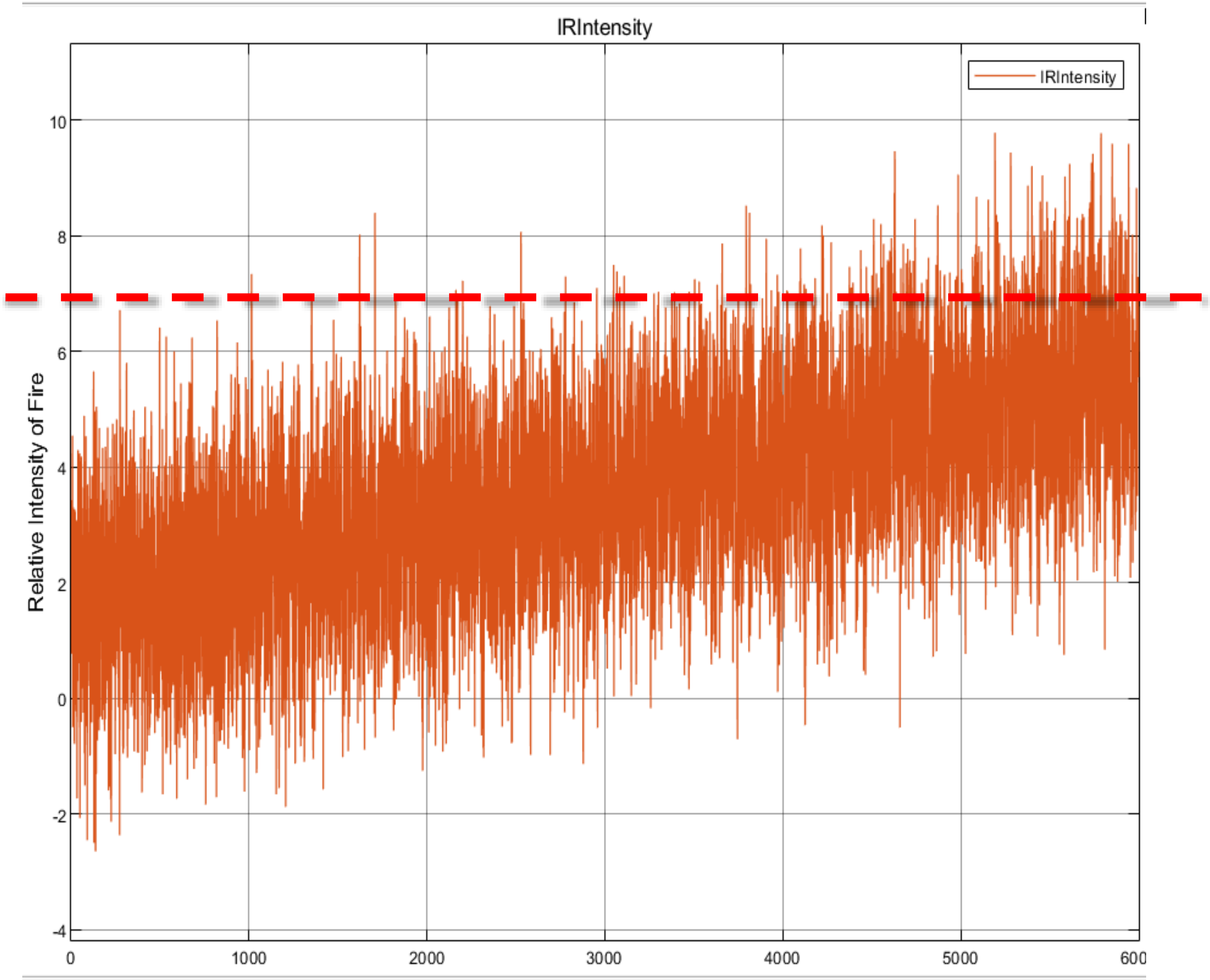
*Chosen for this study



Fire Simulation

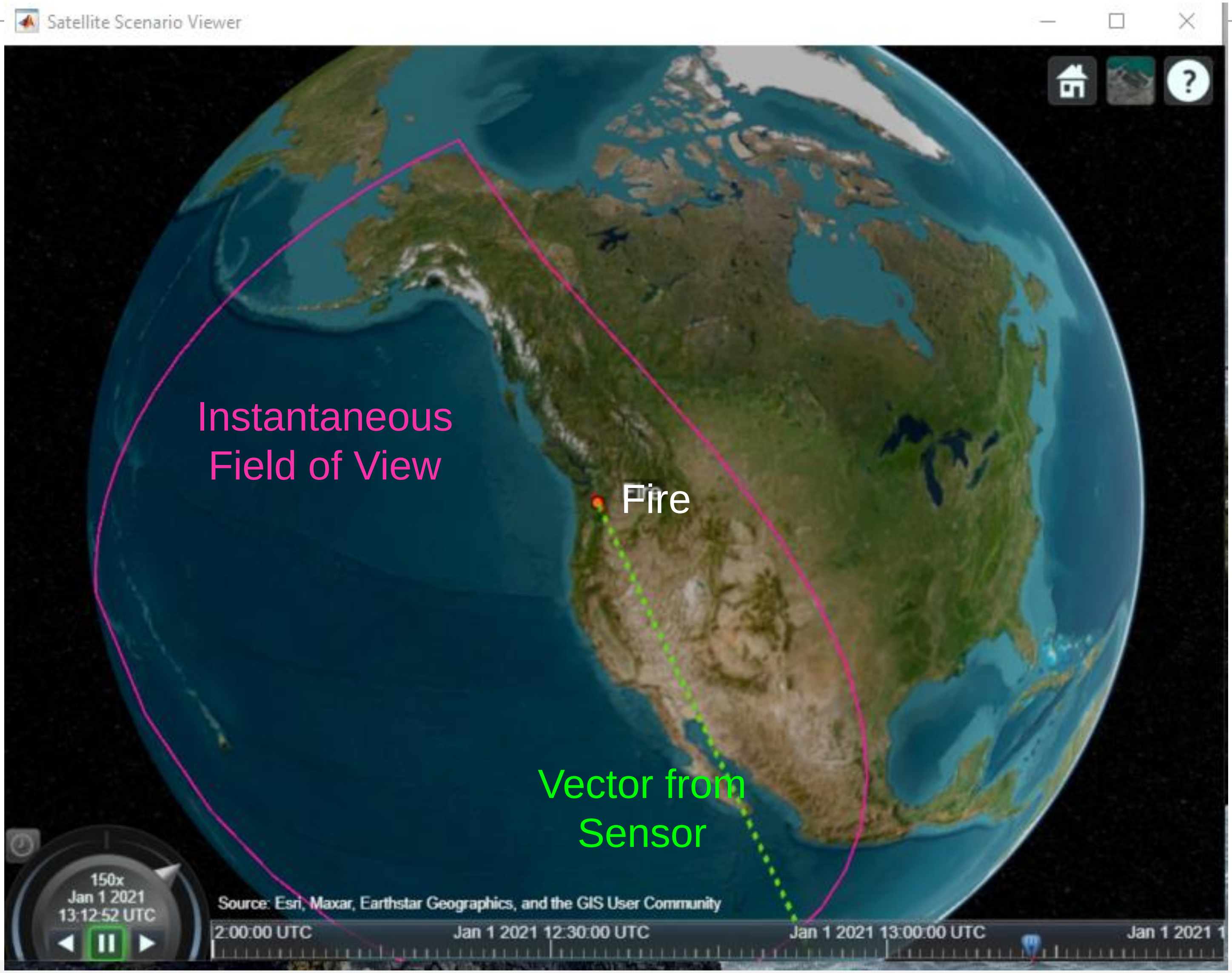
- Randomly Chosen Epicenter
- Growing Intensity with random noise fluctuations
- Detection threshold



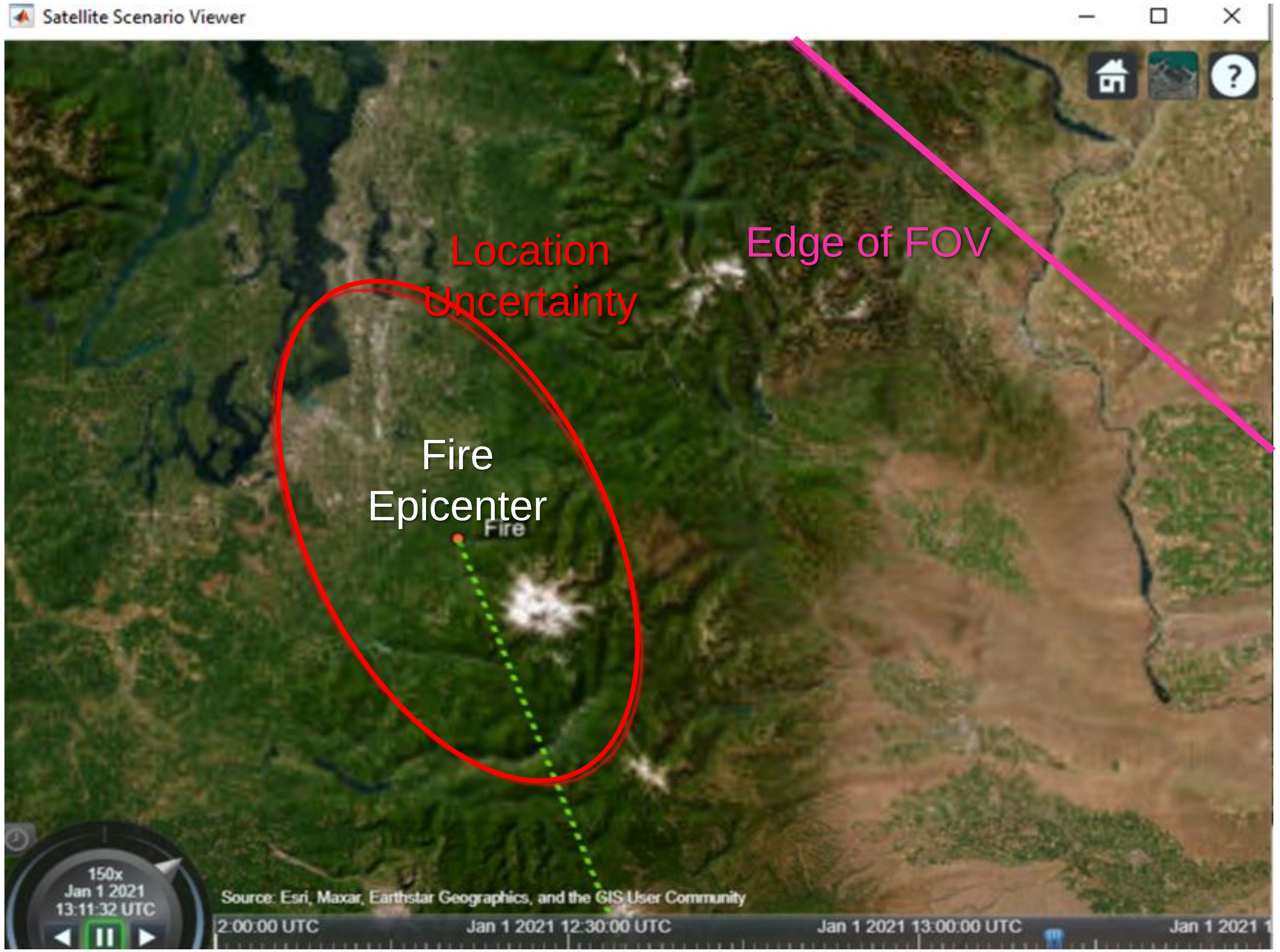


Coverage and Detection Computed in Simulation

- Sophisticated, complex, physics-based simulations and analyses are needed for meaningful trade studies



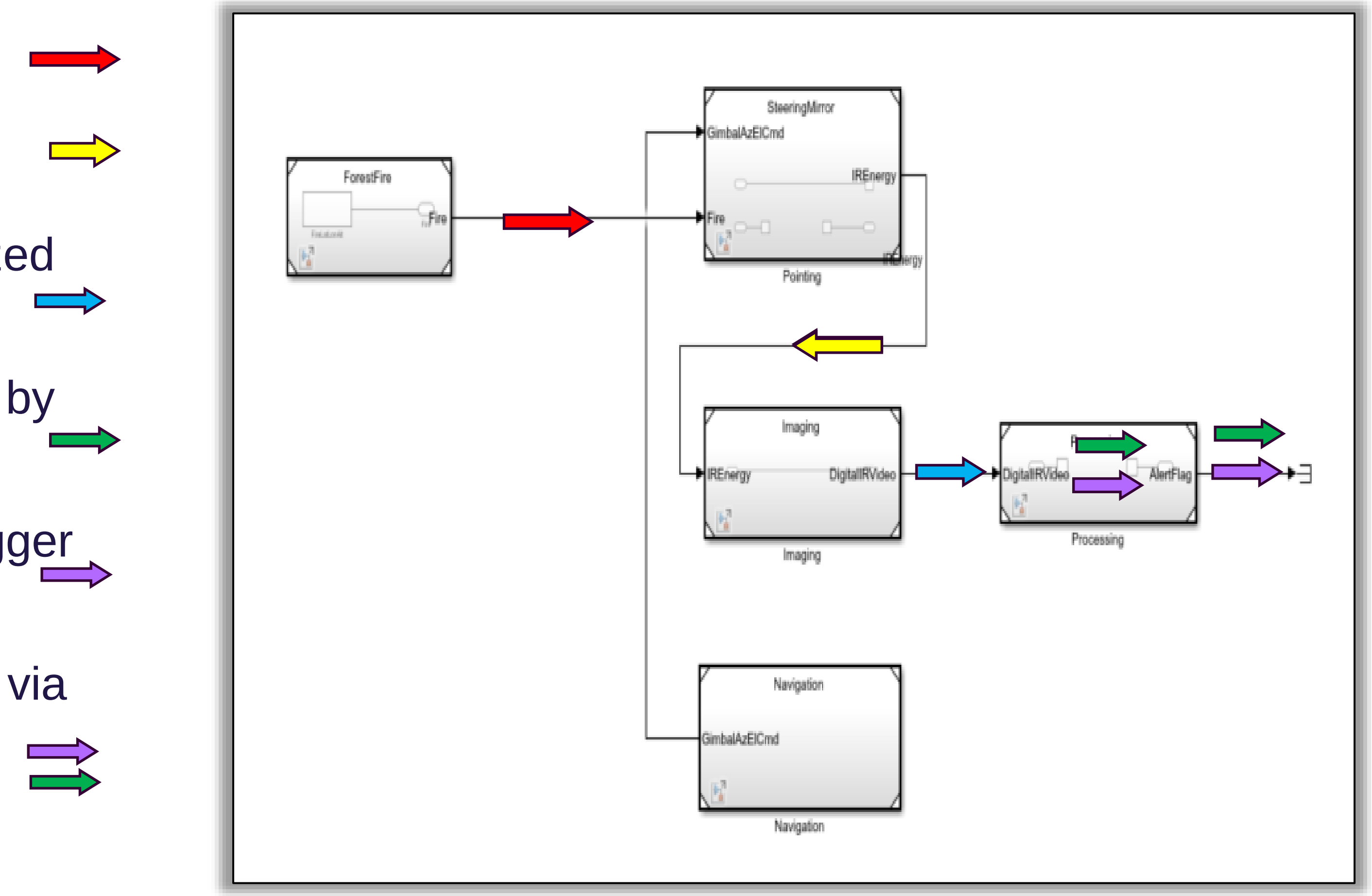
Details Matter



- Design parameters passed in SysML model feed the simulation
- Simulation results analyzed to compute KPPs
- Using same parameters, MATLAB computes costs of each design variant

Signal Flow Model

- Signal Paths
  - IR Radiation from Fire
  - Light Guided by Optics
  - Images Captured and Digitized by FPA
  - Digitized Images Processed by Algorithms
  - Threshold Exceedances Trigger Alerts
  - Alerts & Video Sent to Earth via Bus Comms
  - Routed to Fire Fighters



Model Integration and Data Exchange

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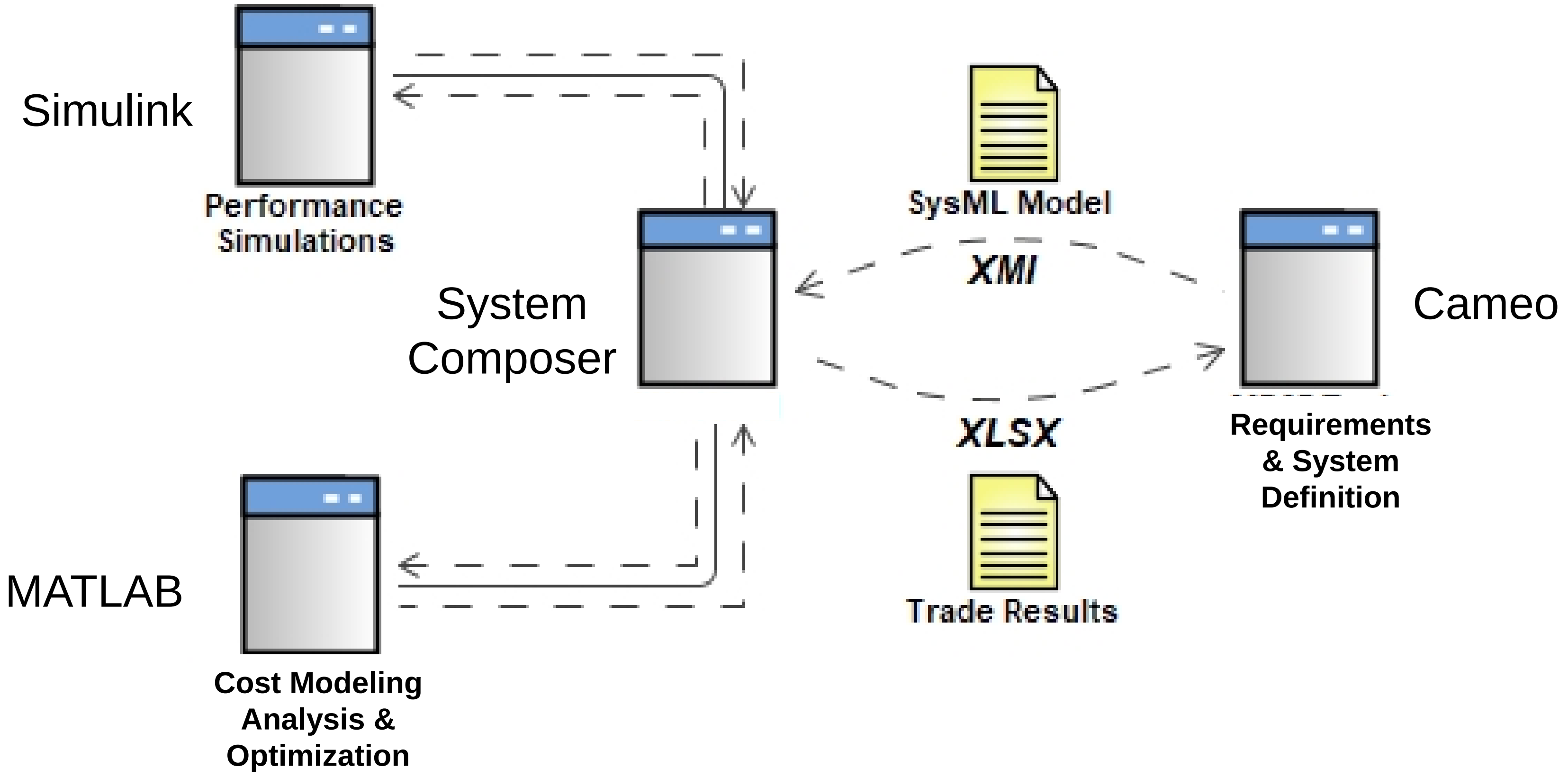
Analysis & Solution

System & Problem



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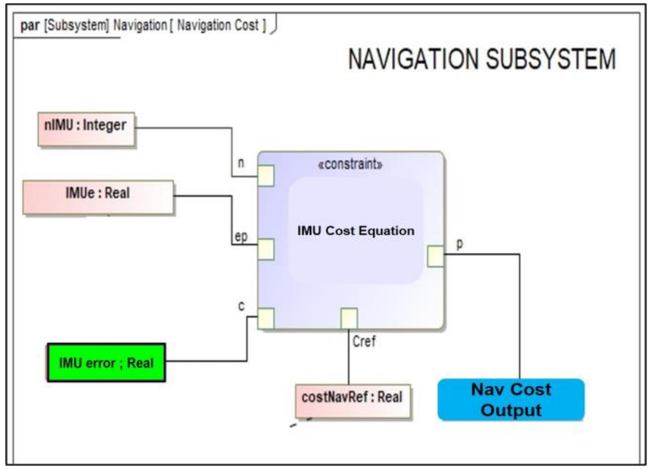
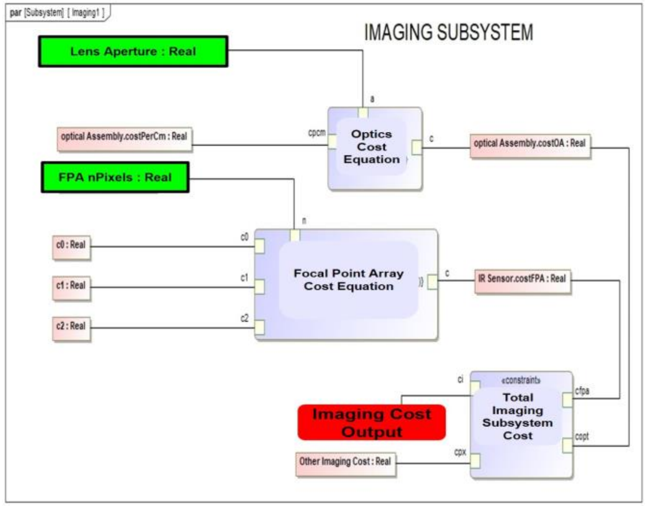
Cost Models

Subsystem Costs Modeling

Cost Models in SysML

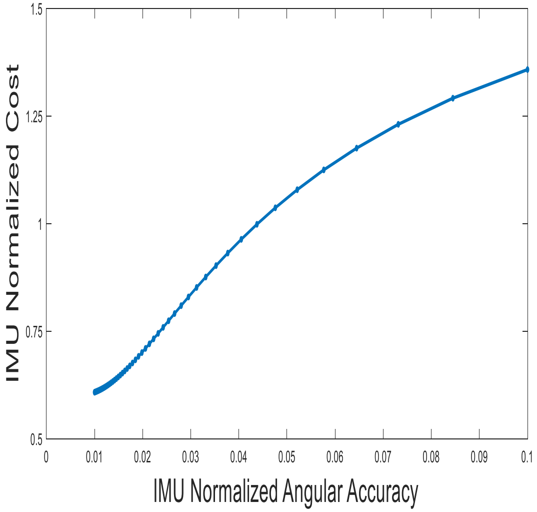


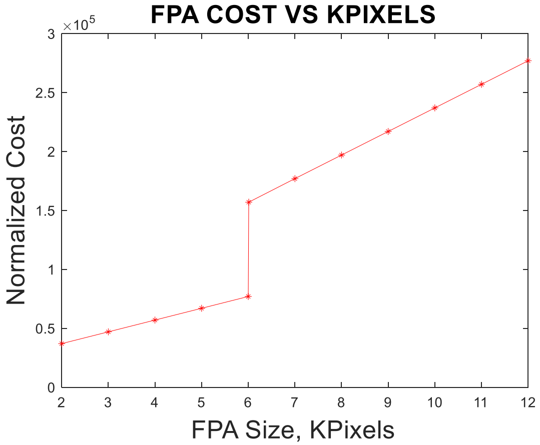


Cost Models in MATLAB:
Actual cost equations themselves

$$C1 = C0 + C1e^{-nx^2/m}$$
$$a^2 + b^2 = c^2$$
$$\ldots.$$

➢ *Straight-forward to model & solve same equations in MATLAB*





Trade Study Formulation and Solution Methods

Scope of Trade Study

- Key Performance Parameters (KPP)
  - Area Coverage
  - Accuracy in Determining Fire Location
  - Time to Detect Fire
  - Probability of Fire Detection
  - Probability of False Positives
  - Cost
- Subsystems Affecting Metrics
  - Navigation
  - Pointing
  - Optical
  - Imaging
  - Processing (not in scope)
- Contributing Factors
  - Orbital Parameters
  - Field of View
  - Pointing Error
  - Navigation Error
  - Focal Plane Array
- Design Parameters
  - IMU Angular Accuracy
  - Optics FOV and Aperture
  - FPA Number of Pixels

Mapping Design Parameters to Subsystems

	Pointing Subsystem	Navigation Subsystem	Imaging Subsystem		Processing HW	Processing SW
			Optics	FPA		
Design Elements	Gimbaled Mirror	IMU	Lens	FPA	Processors	Algorithms
Design Parameters	• Type • Speed	• Angular Error	• FOV • Aperture	• nPixels • Edge Effects	• Type • Number • Speed	• SLOC • Complexity
Coverage	✓		✓	✓		
Fire Location Accuracy	✓	✓	✓	✓		✓
Time to Detect	✓	✓	✓	✓	✓	✓
Detection Probability		✓	✓	✓		✓
Probability False Positives			✓	✓		✓
Cost	✓	✓	✓	✓	✓	✓

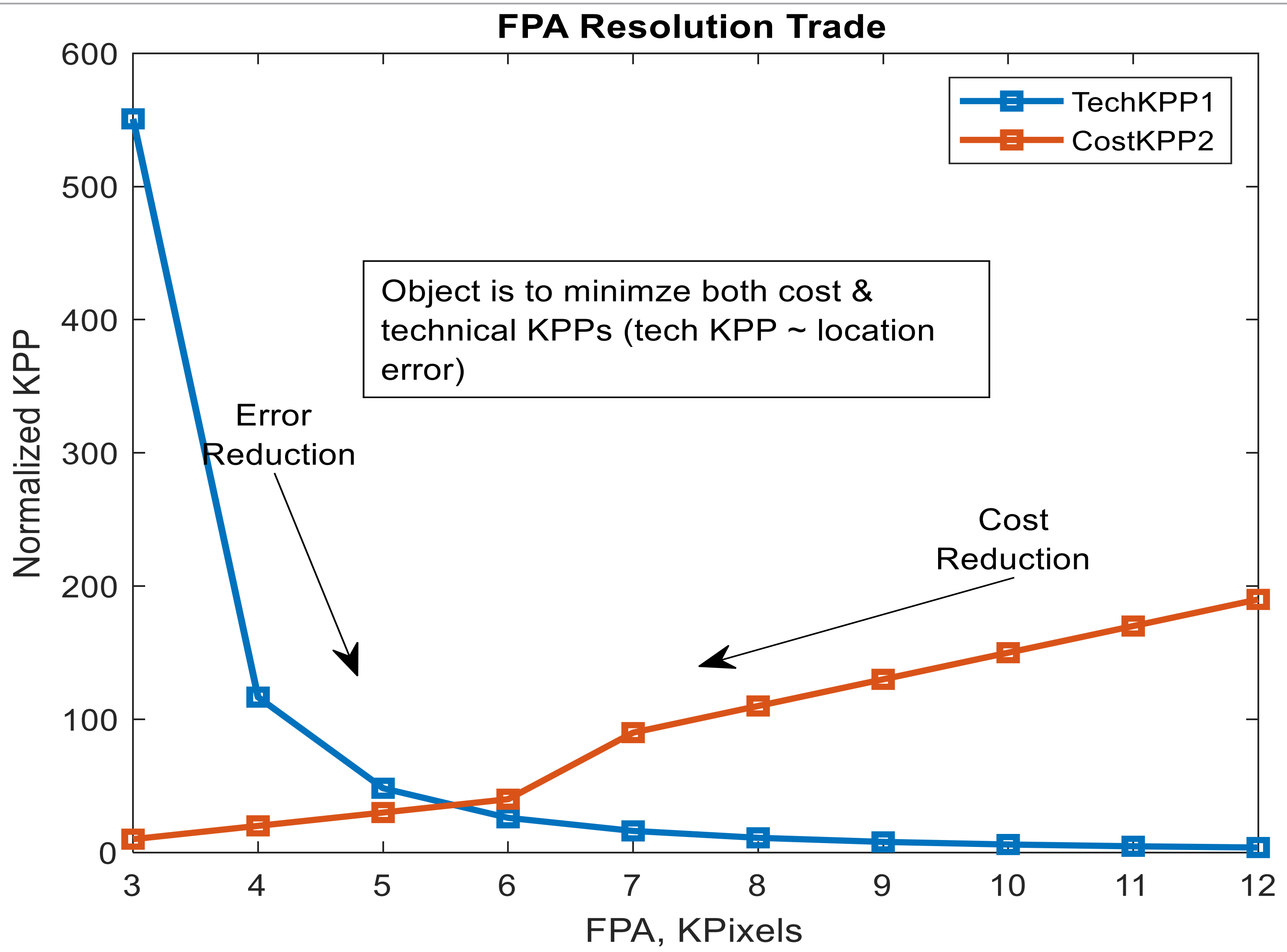
Multi-Objective, Multi-Variable Optimization

- Solution Space
  - Many feasible solutions
  - May have multiple optimal solutions
  - May be non-continuous
  - May have local maxima or minima
- Solution Methods
  - Many approaches and techniques:
  - Exhaustive search, non-linear programming
  - Bayesian optimization, ***Pareto optimization***, particle swarm optimization
  - AI, Machine learning, self-organizing mapping, and genetic algorithms
  - Choice influenced by available resources and time constraints

M&S Results

Optimal solutions

Trade on FPA Resolution



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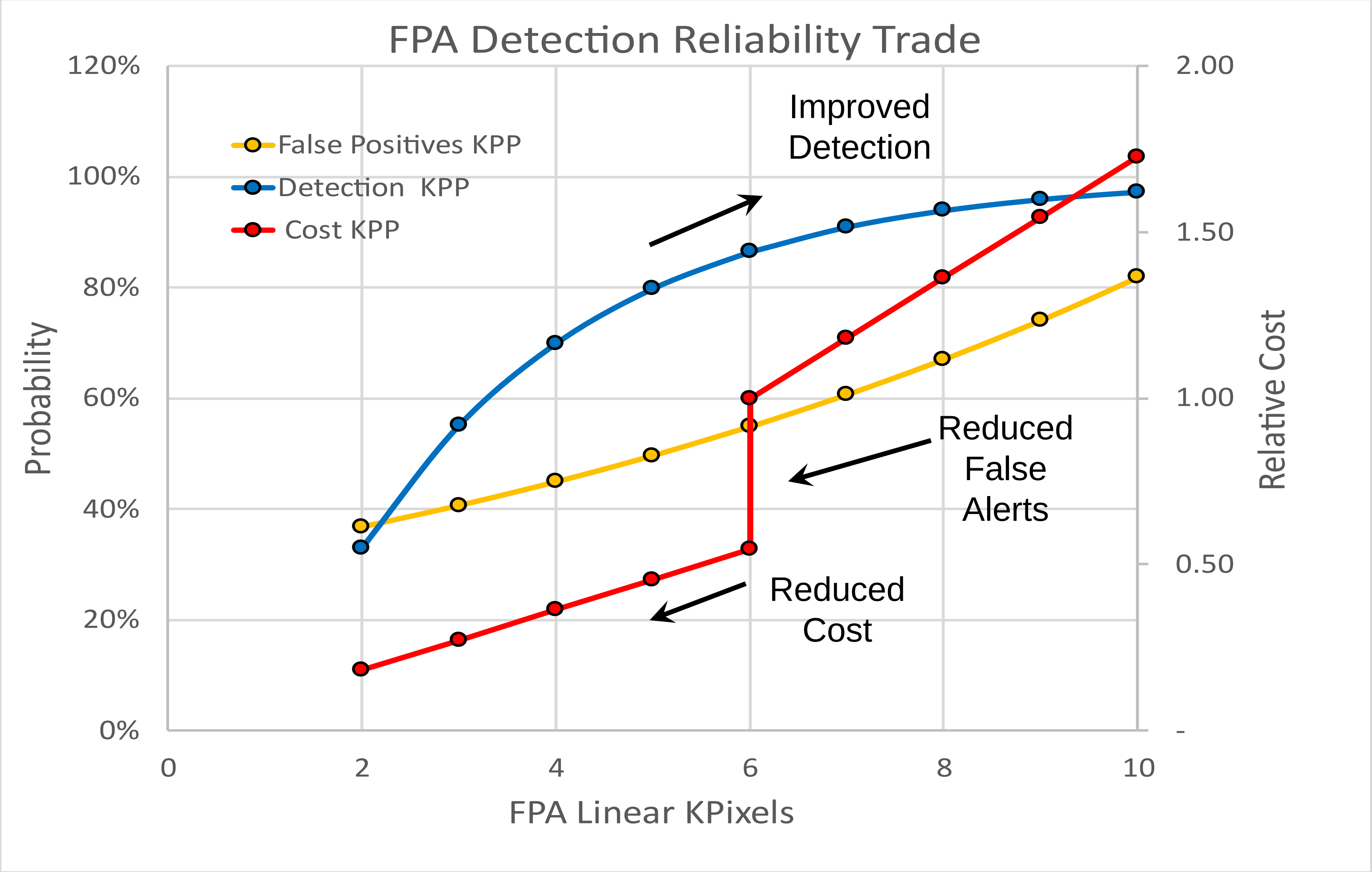
Multiple KPP Trade



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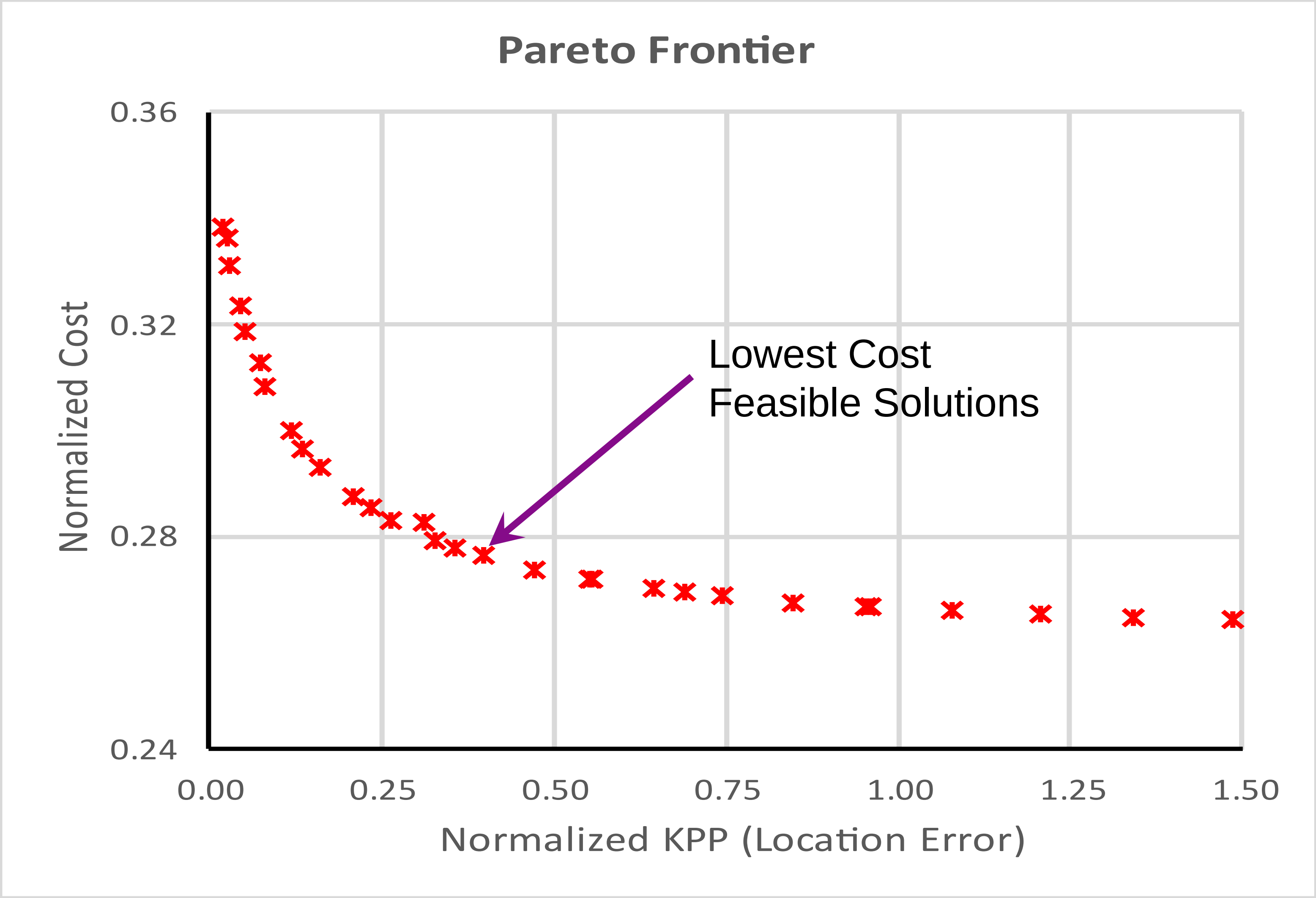
Pareto Front
Aperture and IMU Design Parameters



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Evaluation against Requirements

- System requirements included KPPs on
  - Detection Time (<90 min)
  - Location Accuracy (<1 km)
  - Probability of Detection (> 80%)
- Design target chosen for cost KPP
- KPP objectives set in MBSE tool
- Pareto front solutions from M&S
  - Exported to MBSE tool
  - Re-normalized to align with requirements
  - Evaluated against the KPPs

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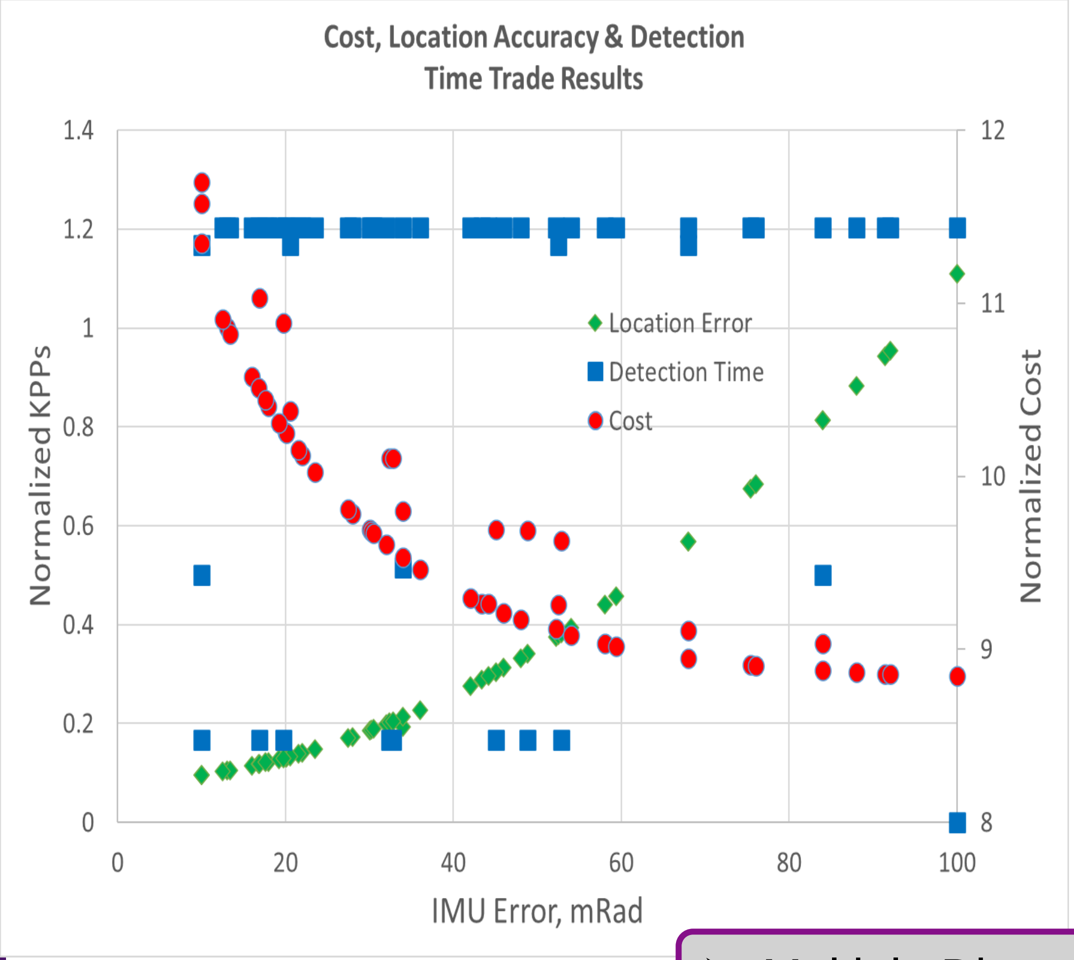
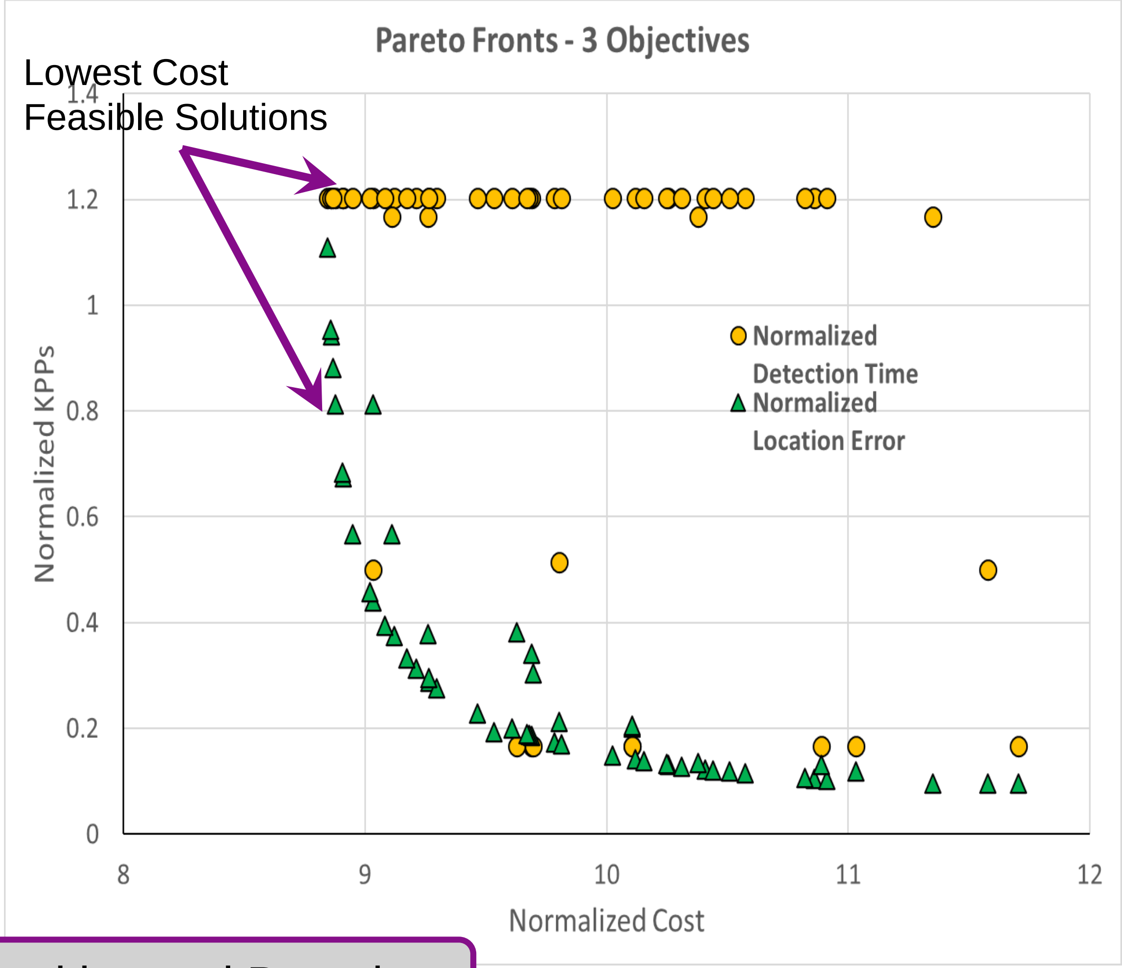
Results Returned to MBSE Model

- Results exported from MATLAB into Cameo using Excel format
- Parametric diagram used to compare predicted KPPs (cost and accuracy) with their required values
- Instance table flags pass/fail ratings of each solution

Name	aperture : Real	IMUe : Real	: CostObjective	: KPP1Objective	Cost : Real	Location Error : Real
01	6.69	24.19	fail	pass	0.301	0.1181
02	6.84	15.22	fail	pass	0.32	0.0467
03	6.69	32.19	pass	pass	0.29	0.2096
04	6.69	48.19	pass	pass	0.27	0.4731
05	6.69	56.19	pass	pass	0.27	0.6462
06	6.69	64.19	pass	pass	0.27	0.8481
07	6.69	40.19	pass	pass	0.28	0.3278
08	6.69	52.19	pass	pass	0.27	0.5561
09	6.69	72.19	pass	fail	0.27	1.0796
10	6.69	26	fail	pass	0.3	0.1365
11	6.69	42	pass	pass	0.28	0.3583
12	6.69	60.19	pass	pass	0.27	0.7435
13	6.69	76.19	pass	fail	0.27	1.207
14	6.69	28.19	pass	pass	0.29	0.1605
15	6.69	44.19	pass	pass	0.28	0.397
16	6.69	80.19	pass	fail	0.26	1.3422
17	6.69	34	pass	pass	0.29	0.234
18	6.69	36.19	pass	pass	0.28	0.2653
19	6.69	68.19	pass	pass	0.27	0.96
20	6.84	19.22	fail	pass	0.31	0.0745
21	6.69	92	pass	fail	0.27	1.7904
22	6.69	58	pass	pass	0.27	0.6894
23	6.84	11.22	fail	pass	0.34	0.0253
24	6.69	20.19	fail	pass	0.31	0.0822
25	6.72	16.22	fail	pass	0.32	0.053

Optimization with Three Objectives





➢ Multiple Discontinuities and Branches

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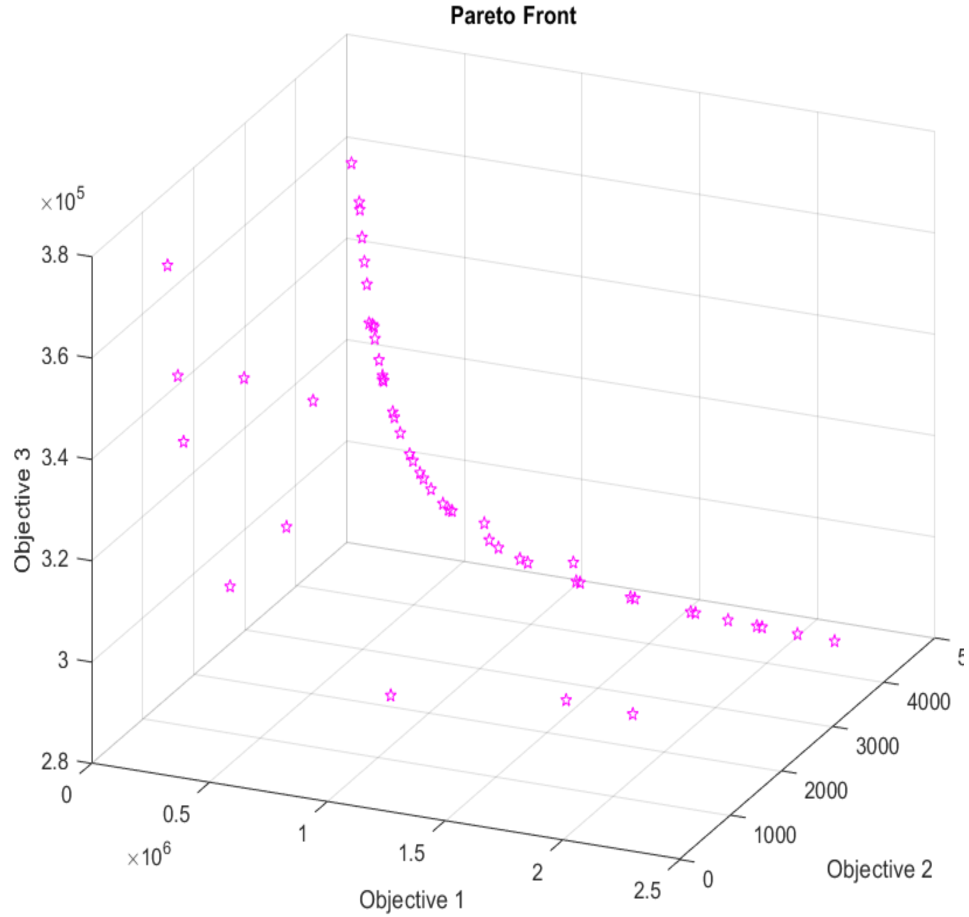
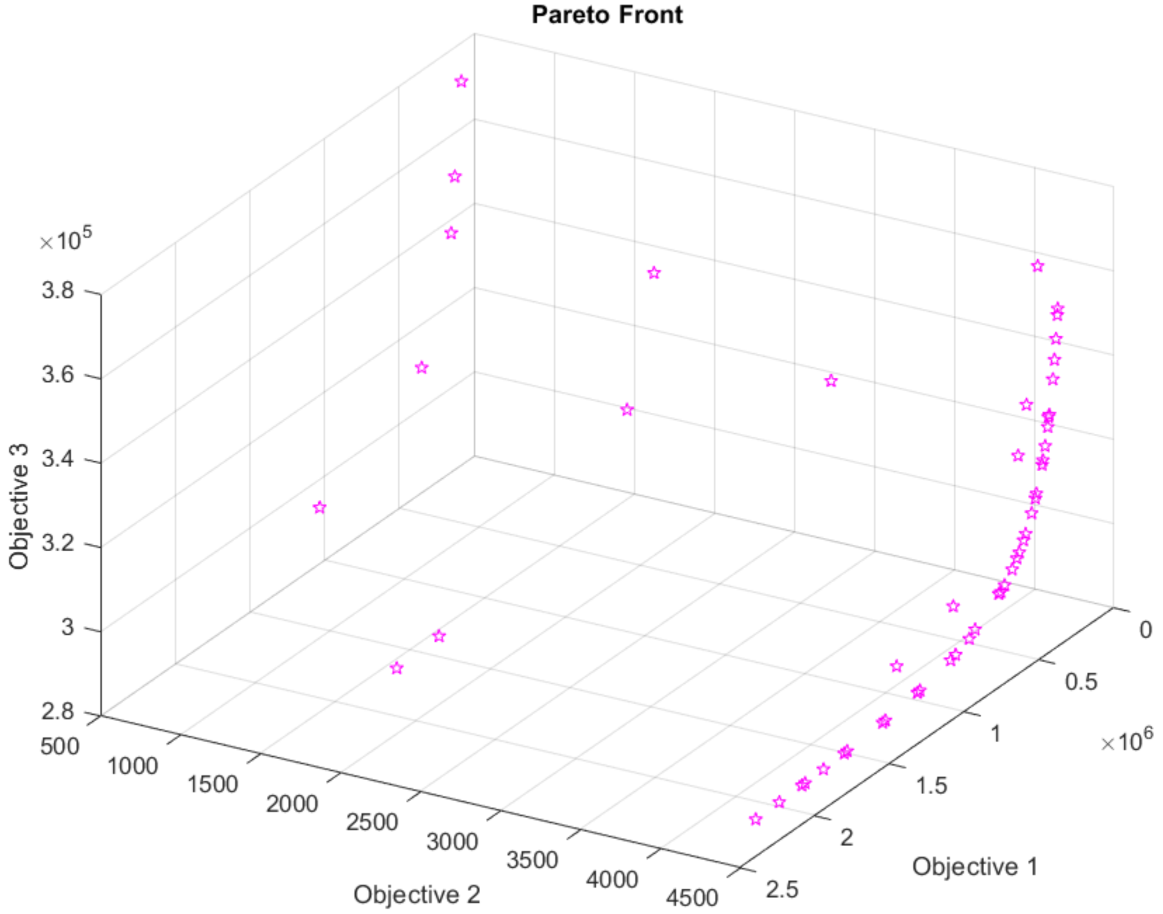
Pareto Frontier Plotted in Three Dimensions





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Results for Three Objectives

- Objectives
  - Accuracy locating fire
  - Time to detect fire
  - Cost
- Fewer optimal solutions

Name	aperture	IMUe	nKPix	Accuracy Objective	Detection Time Objective	Cost Objective	Location Error	Detection Time	Cost
11	6.6563	16	2	pass	fail	fail	0.1152	1.2034	10.5744
12	6.6563	16.75	2	pass	fail	fail	0.118	1.2034	10.5098
13	6.6563	32	2	pass	fail	pass	0.1992	1.2034	9.6078
14	6.6563	20.125	2	pass	fail	fail	0.1322	1.2034	10.2472
15	6.6563	18	2	pass	fail	fail	0.123	1.2034	10.4073
16	6.6563	13	2	pass	fail	fail	0.1049	1.2034	10.8584
17	6.6563	22	2	pass	fail	fail	0.141	1.2034	10.1195
18	7.0938	48.8438	3	pass	pass	pass	0.3405	0.1668	9.6886
19	6.6563	28	2	pass	fail	pass	0.1736	1.2034	9.7824
20	6.6563	21.5	2	pass	fail	fail	0.1385	1.2034	10.1524
22	6.6563	91.4063	2	fail	fail	pass	0.9436	1.2034	8.8596
23	6.6875	52.1875	2	pass	fail	pass	0.375	1.2034	9.1212
24	6.6563	36	2	pass	fail	pass	0.2279	1.2034	9.4649
25	6.6563	30	2	pass	fail	pass	0.186	1.2034	9.6908
26	6.9688	34	2.375	pass	pass	pass	0.2132	0.515	9.8023
27	6.9063	20.5313	2.125	pass	fail	fail	0.134	1.1673	10.3783
28	6.6563	13.375	2	pass	fail	fail	0.1061	1.2034	10.8205
29	6.6563	46	2	pass	fail	pass	0.3128	1.2034	9.2108
30	6.6563	54	2	pass	fail	pass	0.3947	1.2034	9.0817
31	7.0938	16.8438	3	pass	pass	fail	0.1184	0.1668	11.0316
32	6.6563	30.25	2	pass	fail	pass	0.1877	1.2034	9.6799
33	6.6563	76	2	pass	fail	pass	0.6842	1.2034	8.9066
34	7.2813	32.4063	2.625	pass	pass	fail	0.202	0.1668	10.1062
35	6.8125	45.0625	3.25	pass	pass	pass	0.304	0.1668	9.6946
36	6.6563	30.5	2	pass	fail	pass	0.1893	1.2034	9.6693

Conclusions / Benefits

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- MBSE/MDA simplifies and accelerates trade studies
  - Provides holistic representations of systems, extensible to SoS’s
  - Source of truth for design parameters; collection point for performance predictions from external high-fidelity M&S tools
- Advantages of Integration with high fidelity M&S tools
  - Ability to perform large numbers of trade studies rapidly
  - XMI standards-based interface to exchange models and design variables
  - Straight-forward implementation of cost modes
  - Optimization tools
  - Wider exploration of the design space leading to more optimal solutions