Small Near-Earth Object Observing System (SNOOS)

A Modeling Approach for Architecture Effectiveness

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SEOR 798/680

Topics

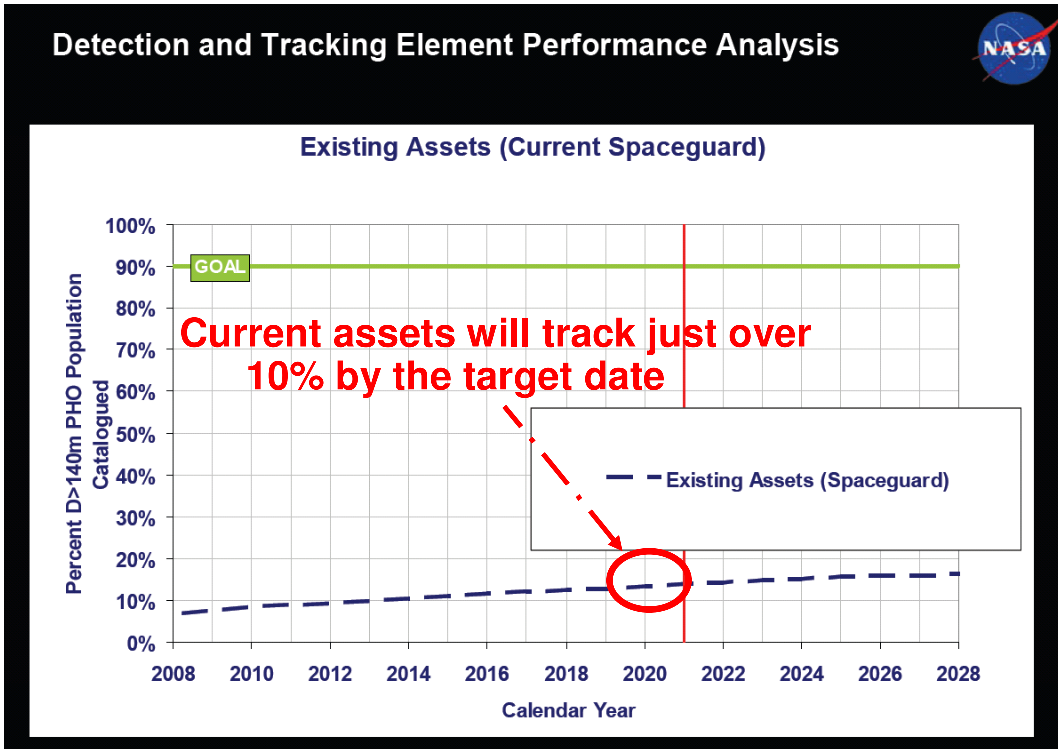
- Problem Background: Planetary Defense
- Team Role
- System Engineering
- Effectiveness Analysis
- Architecture Selection
- Cost Analysis

Terminology

- Astronomical Unit (AU)
  - Distance between Earth and sun
  - 1 AU = 149.6M kilometers
- Near Earth Object (NEO)
  - Comets and asteroids whose closest orbital approach is within 1.3 AU of the sun
- Absolute Magnitude, (H)
  - NEO visible signature at 1 AU

Problem Background [1]

- Near Earth Objects (NEOs) pose a threat to the existence of the human race
- In 2005 Congress directed NASA to detect, track, catalog, and characterize NEOs on a collision course with Earth
- Congressional goal calls for 90% catalog of large NEO (>140 meter diameter) estimated population by 2020
- Current NASA capability cannot meet the goal



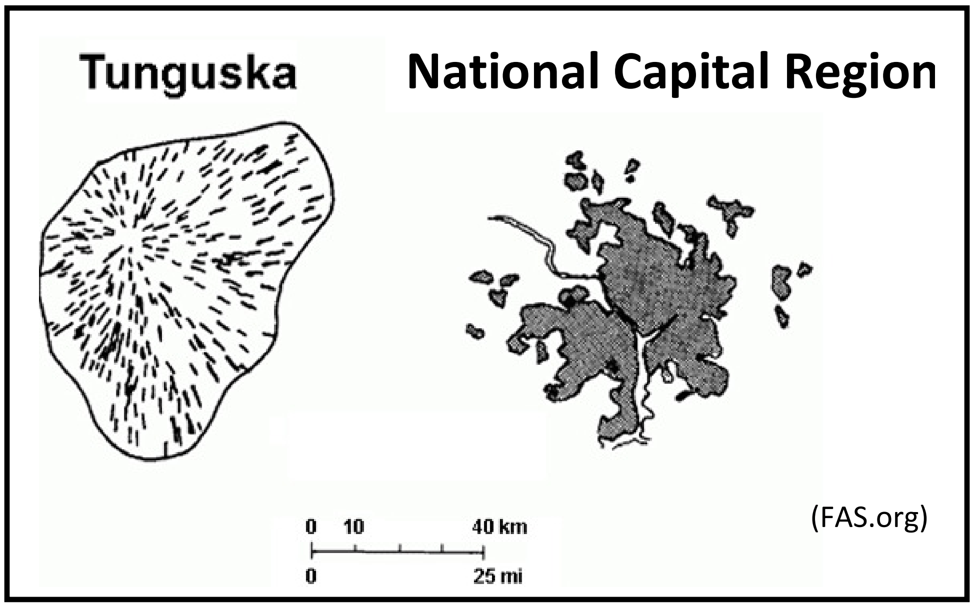
(NASA/JPL)

Problem Background [2]

- ***But what about smaller NEOs (30 - 140 meters), which can still destroy local populaces and cause economic devastation?***
- Small NEO to large NEO population = 36:1[(1)] – impact likelihood is higher
- Small NEOs possess enough kinetic energy to cause severe destruction
  - Tunguska, Russia 1908: ~ 50m NEO destroyed 830 mi^2
  - Small NEO impact can kill hundreds of thousands, and/or cause economic devastation (e.g. destruction of financial center or oil-producing area)

Size (meters)	Energy Yield (Megatons)	Prob(Earth-impact)*yr^{-1}
30	2	0.003
40	4	0.002
50	8	0.001
60	15	0.0006
80	30	0.0004
100	61	0.0002
120	122	0.0001
140	244	0.00007

(NASA)



(FAS.org)

Problem Statement

Small Near-Earth Objects pose a significant threat to life on Earth. No current or planned effort to observe them exists.

Small NEOs = 30 to 140 meters in diameter

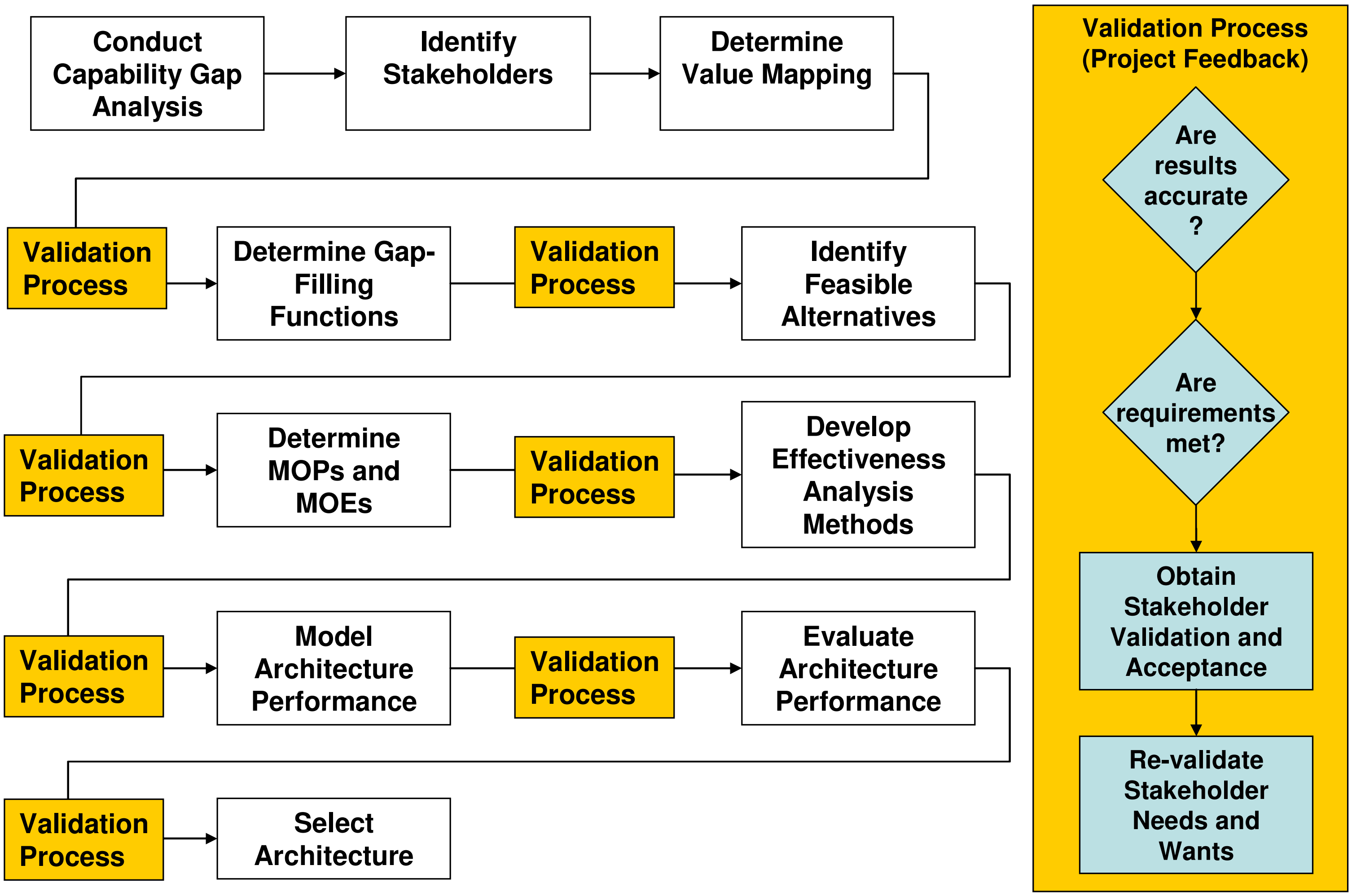
Team Role

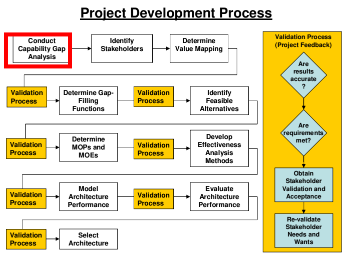
- Identify the observation capability gap and propose a solution to observe the more numerous small NEO population
- **Project scope**:

1. Develop a high-level system architecture for small NEO observation (The S.E.)
   - Identify the functions needed to perform small NEO observation
   - Identify the alternatives capable of assisting in meeting the system goal (Measure of Effectiveness - MOE)
2. Perform Effectiveness Analysis to quantitatively model how well alternative architectures perform (The O.R.):
   - Measure alternative architectures' performance
   - Instantiate architecture using SEOR Team decision criteria

System Engineering [1/11]

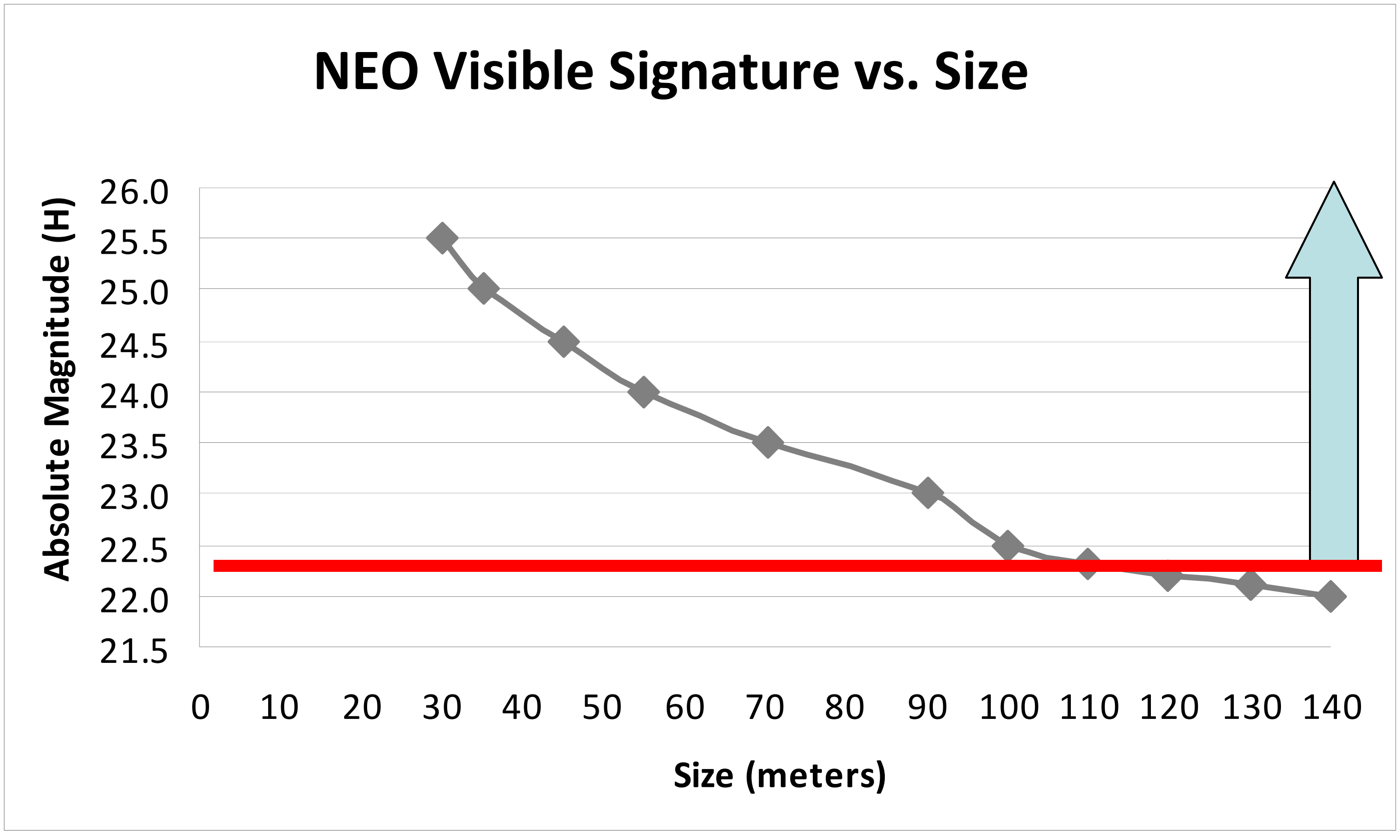
Project Development Process





System Engineering [2/11]

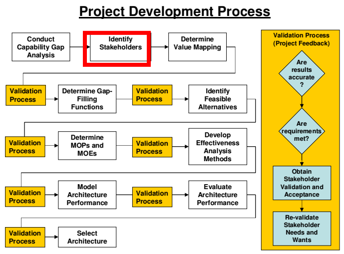
Identify Capability Gap



Not observable by ground-based systems

Observation threshold for ground-based systems (NASA/JPL)

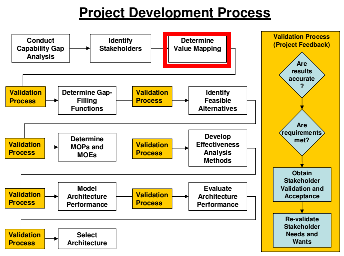
Space-Based Optical Observation Needed



System Engineering [3/11]

Identify Stakeholder Needs

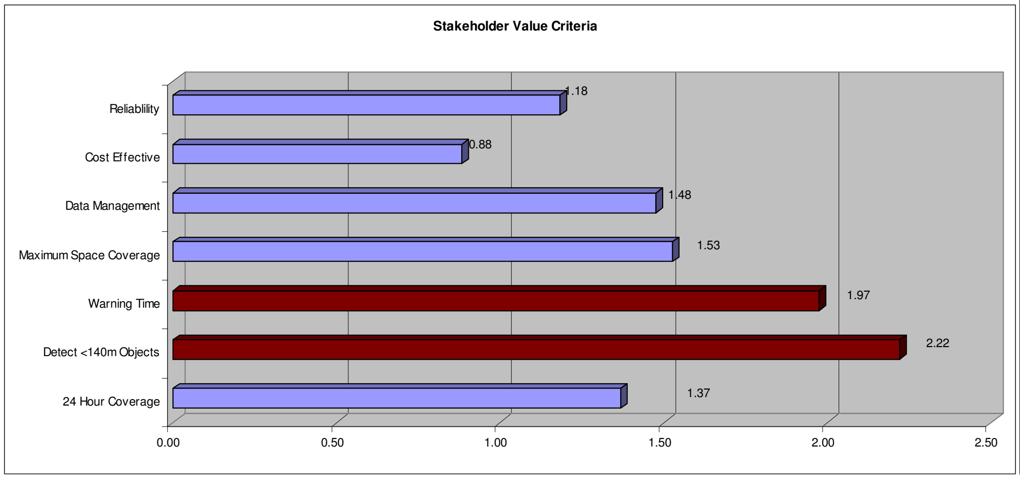
	Stakeholder/Need	24 Hour Coverage	Detect <140m Objects	Warning Time	Maximum Space Coverage	Data Management	Cost Effective	Reliablility	**Stakeholder Weight**
U.S. Gov't	U.S. NEO Governing Organization	0.150	0.200	0.200	0.150	0.050	0.050	0.100	**1.000**
	U.S. Executive/Legislative	0.100	0.200	0.300	0.010	0.010	0.300	0.070	**0.800**
	U.S. Military	0.150	0.150	0.100	0.150	0.150	0.050	0.100	**0.900**
	U.S. System Operators	0.170	0.170	0.150	0.150	0.050	0.010	0.150	**0.800**
	U.S. Analysis Community	0.030	0.300	0.030	0.100	0.300	0.010	0.100	**0.800**
	U.S. Emergency Response Organizations	0.100	0.200	0.500	0.040	0.040	0.040	0.040	**0.300**
	U.S. Law Enforcement Agencies	0.100	0.200	0.500	0.040	0.040	0.040	0.040	**0.200**
Int'l Community	International Governing Organization	0.150	0.200	0.200	0.150	0.050	0.050	0.100	**0.900**
	International Military Coalition	0.150	0.150	0.100	0.150	0.150	0.050	0.100	**0.800**
	International System Operators	0.170	0.170	0.150	0.150	0.050	0.010	0.150	**0.800**
	International Analysis Community	0.030	0.300	0.030	0.100	0.300	0.010	0.100	**0.800**
	International Emergency Response Organizations	0.100	0.200	0.500	0.040	0.040	0.040	0.040	**0.300**
	International Law Enforcement Agencies	0.100	0.200	0.500	0.040	0.040	0.040	0.040	**0.200**
Industry	System Developers	0.125	0.125	0.125	0.125	0.125	0.125	0.125	**0.900**
	Analysis/Research Community	0.030	0.300	0.030	0.100	0.300	0.010	0.100	**0.600**
	SEOR Faculty	0.000	0.200	0.050	0.200	0.200	0.200	0.100	**0.900**
	SEOR Project Team	0.200	0.100	0.200	0.200	0.050	0.100	0.050	**0.900**
Other	Human Race	0.160	0.160	0.400	0.050	0.010	0.010	0.200	**0.100**
	Weighted Totals	1.367	2.221	1.974	1.526	1.477	0.882	1.184	



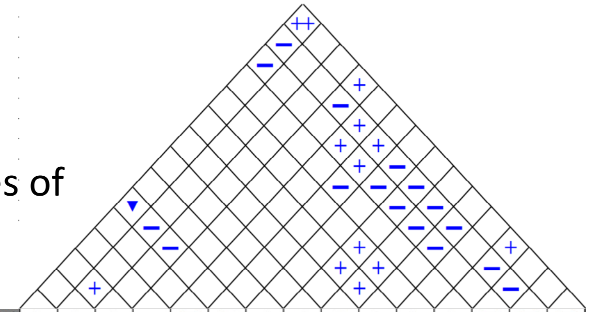
System Engineering [4/11]

Value Mapping

Value Criteria



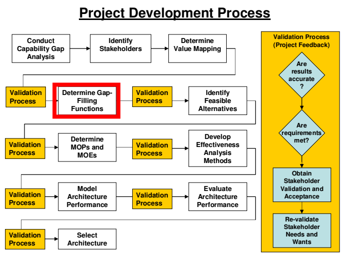
Technical Measures of Performance



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x) / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Intrument Performance	Slewing	Pointing Accuracy	Instrument Location	Mass	Instrument Cost	Data Storage Capacity	Data Uplink	Data Downlink	Data Processing Rate	Bandwidth	Reliability	Power	Mission Cost	Time to Goal
				Direction of Improvement	▲	▲	▲	x	▼	▼	▲	▲	▲	▲	▲	▲	▼	▼	▼
1	9	12.9	1.4	24 Hour Coverage	○			⊙			⊙	○	⊙		⊙	○		○	⊙
2	9	20.9	2.2	Detect <140m Objects	⊙			○		○	⊙		⊙	○	○	⊙		⊙	⊙
3	9	18.5	2.0	Object Impact Warning Time	⊙								○	○		○			
4	9	14.4	1.5	Maximum Space Coverage			○	⊙	▲				○					⊙	
5	9	13.9	1.5	Data Management				▲			⊙	⊙	⊙	⊙	▲			▲	
6	9	8.3	0.9	System Cost	⊙	○	○	⊙	○	⊙	○			▲		○	○	⊙	⊙
7	9	11.1	1.2	System Reliability	○					⊙		▲	▲			⊙		○	○
8																			
9																			
10																			
				Target or Limit Value	Range, SNR	Radians	Radians	Keplerian Elements, Latitude, Longitude, Elevation	Kilograms	$	Bytes	Mbps	Mbps	MHz	Bytes	MTBF	Watts	$	Years
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	2	5	4	5	8	7	6	5	5	2	3	9	7	8	7
				Max Relationship Value in Column	9	3	3	9	3	9	9	9	9	9	9	9	3	9	9
				Weight / Importance	501.2	24.8	68.0	396.6	39.2	237.1	454.1	175.1	539.1	251.8	192.6	407.0	24.8	477.9	411.8
				Relative Weight	11.9	0.6	1.6	9.4	0.9	5.6	10.8	4.2	12.8	6.0	4.6	9.7	0.6	11.4	9.8

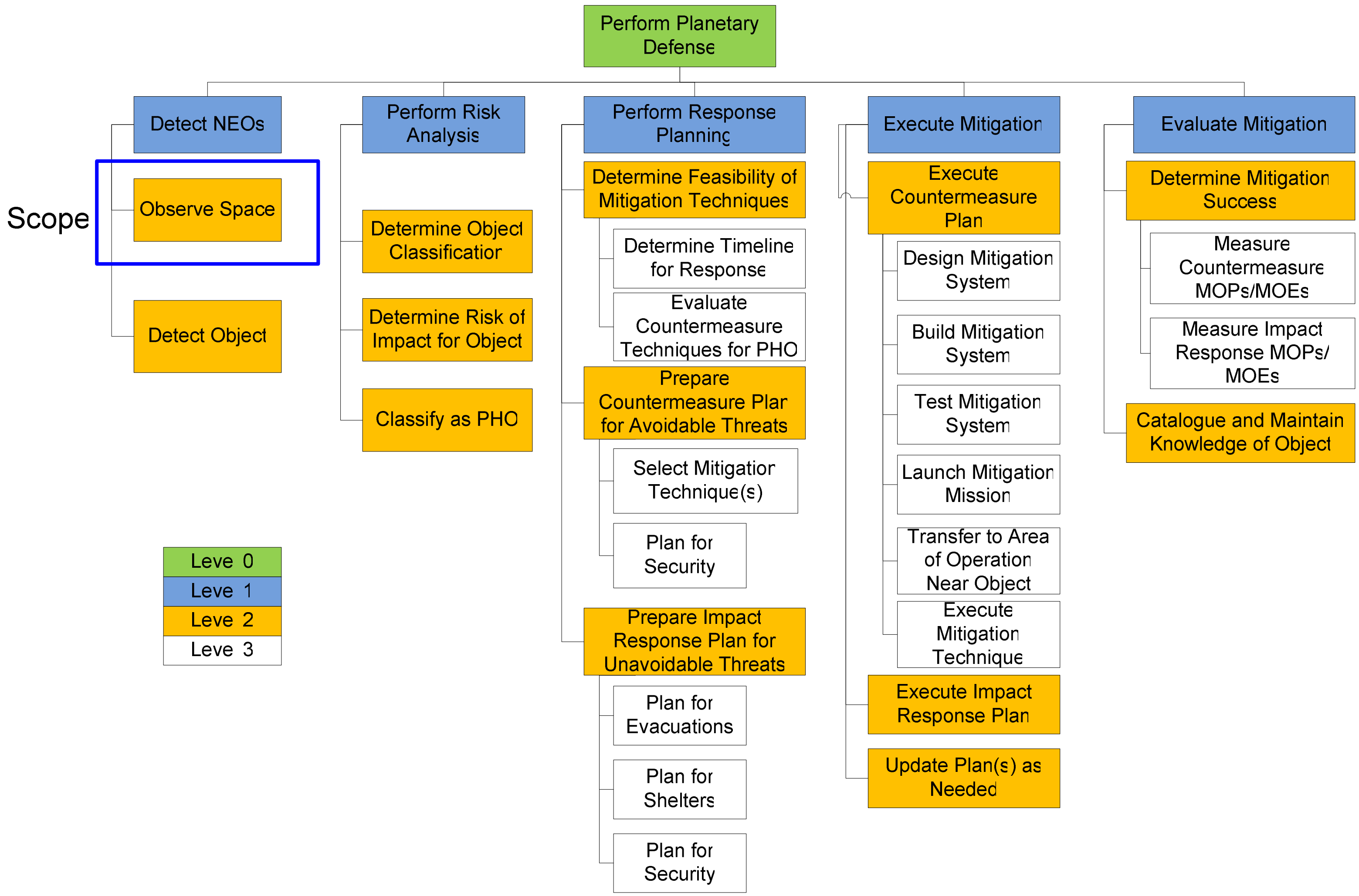
Top Design Considerations for Alternatives:

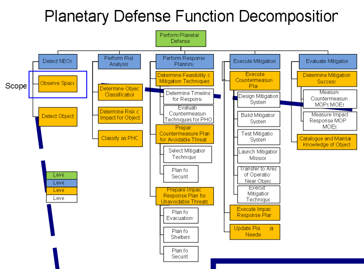
1. **Data Downlink**
2. **Sensor Performance**
3. **Mission Cost**
4. **Time to Goal**



System Engineering [5/11]

Planetary Defense Function Decomposition





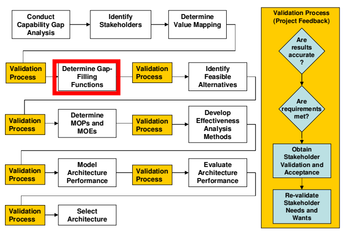
System Engineering [6/11]

Capability Gap Filling Functions

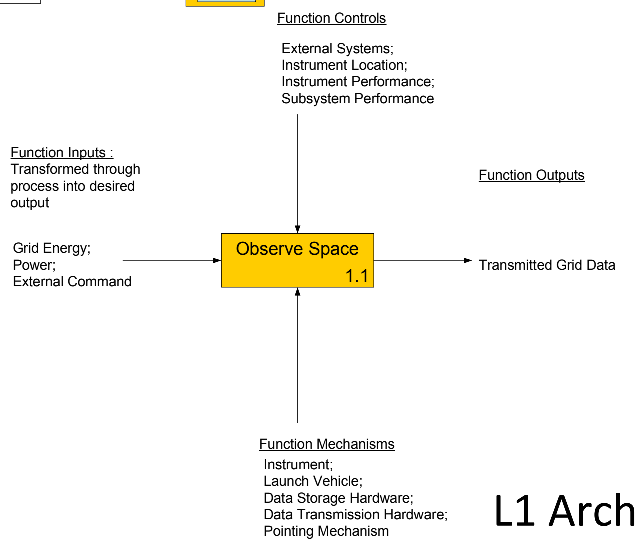
SNOOS System-of-Systems View

System Engineering [7/11]

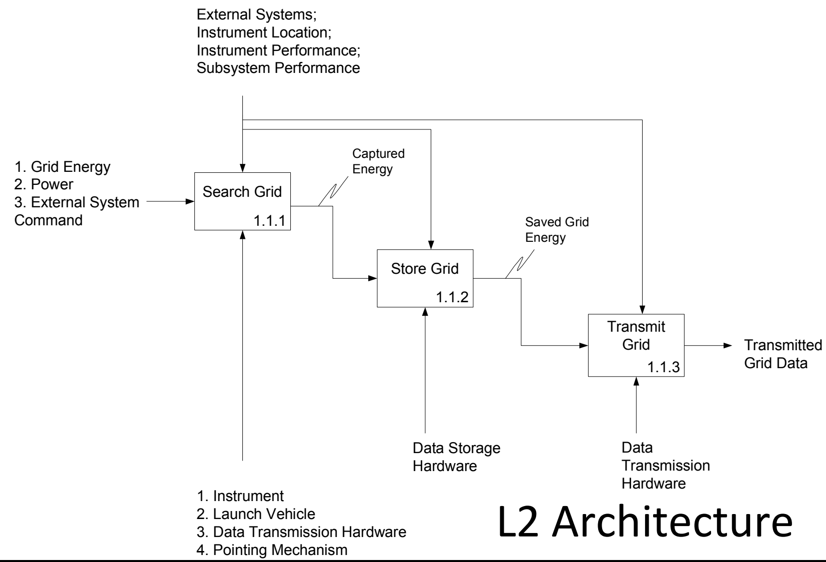
Project Development Process



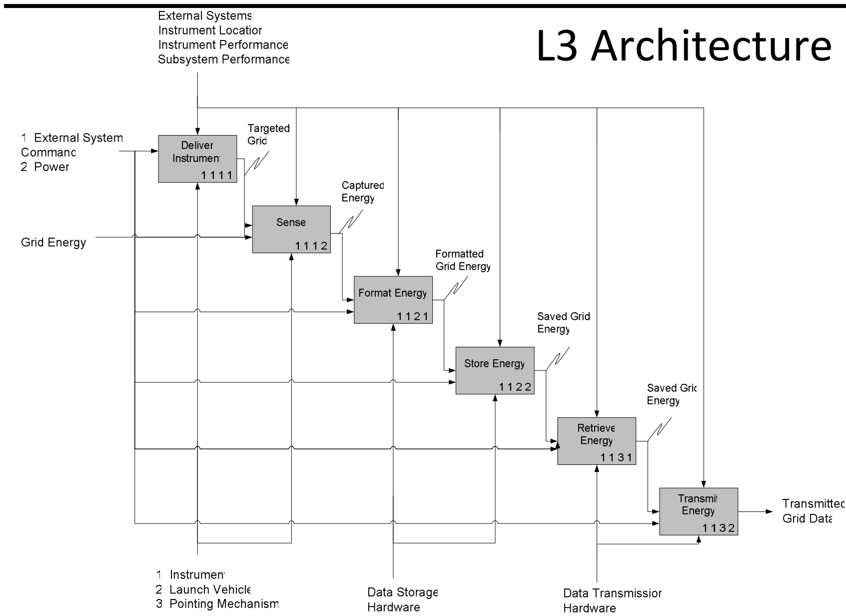
Capability Gap Filling Functions



L1 Architecture

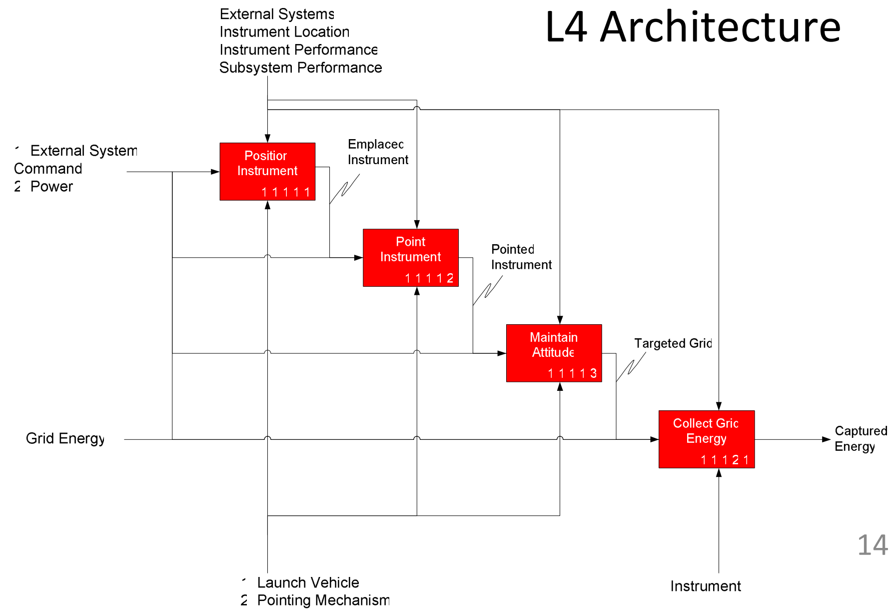


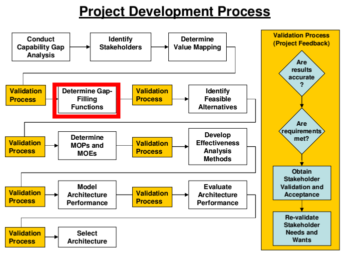
L2 Architecture



L3 Architecture

L4 Architecture

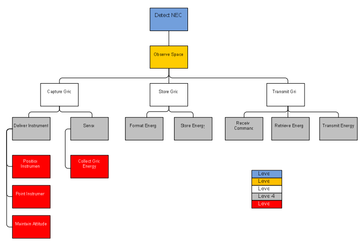




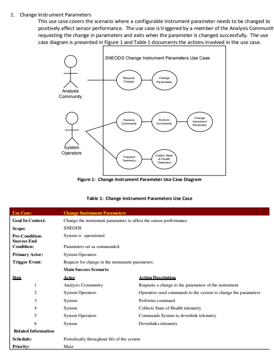
System Engineering [8/11]

Requirements Development

Function Decomposition

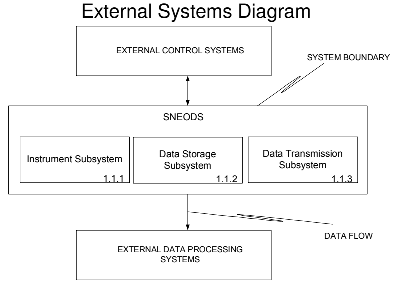


Use Cases



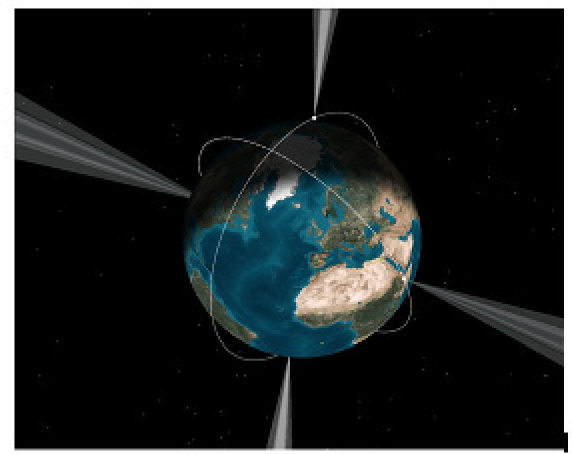
System Diagrams

External Systems Diagram



System Requirements

Small Near-Earth Object Observing System (SNOOS)



System Requirements Specification

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Spring 2009

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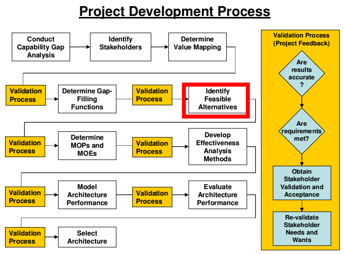
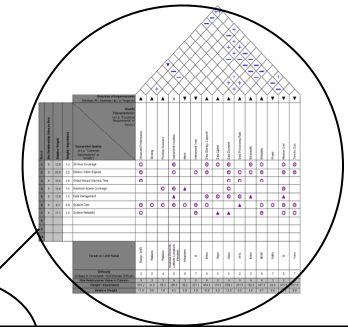


System Engineering [9/11]

QFD



Identify Alternatives

Function Decomposition

Position Instrument 1.1.1.1.1

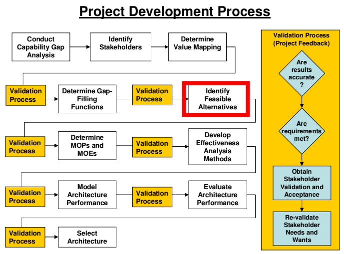
Function	Alternative	Attributes		
Position Instrument (1.1.1.1.1)	Low Earth Orbit (LEO)	Modeling Capability	Cost	NEO Observation Rate
	L-Point(s) Orbit (LPO)			
	Venus Orbit (VO)			
	LEO + LPO			
	LEO + VO			
	VO + LPO			
	LEO + LPO + VO			

Point Instrument 1.1.1.1.2

Function	Alternative	Attributes	
Point Instrument (1.1.1.1.2)	Fixed Pointing	Modeling Capability	Search Rate
	Independent Pointing		

Maintain Attitude 1.1.1.1.3

Function	Alternative	Attributes	
Maintain Attitude (1.1.1.1.3)	Inertial Attitude	Modeling Capability	Search Rate
	Constrained Anti-Earth		
	Constrained Velocity		



System Engineering [10/11]

Identify Alternatives

Function Decomposition

Collect Grid Energy
1.1.1.2.1

Function	Alternatives	Attributes						
Collect Energy (1.1.1.2.1)	Radar	Power Consumption	Cost	24/7 Capability	Range	FOV	Cost	Reliability
	Laser							
	Infrared							
	Visible							

Store Energy
1.1.2.2

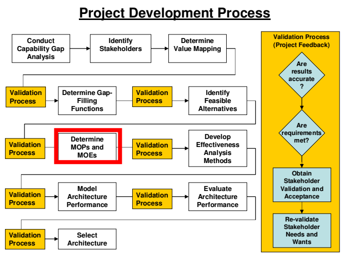
Function	Alternatives	Attributes					
Store Energy (1.1.2.2)	Solid State Drive (SSD)	Power Consumption	Cost	Storage Size	Write Speed	Read Speed	Reliability
	Hard Disk Drive (HDD)						
	Magnetic Tape						

Transmit Energy
1.1.3.3

Function	Alternatives	Attributes			
Transmit Energy (1.1.3.2)	S-Band	Power	Downlink Rate	Uplink Rate	Ground Station Availability (GSA)
	X-Band				
	Ku-Band				
	Ka-Band				

EFFECTIVENESS ANALYSIS

Alternative	Attributes					
Matlab	Report Generation	Orbital Mechanics	Sensor Modeling	Pointing Modeling	Knowledge of Tool	Access
STK						
C++						



System Engineering [11/11]

Evaluation Methods

Attribute Score	*Definition*
5	Most Desirable
4	↓
3	
2	
1	Least Desirable

\+

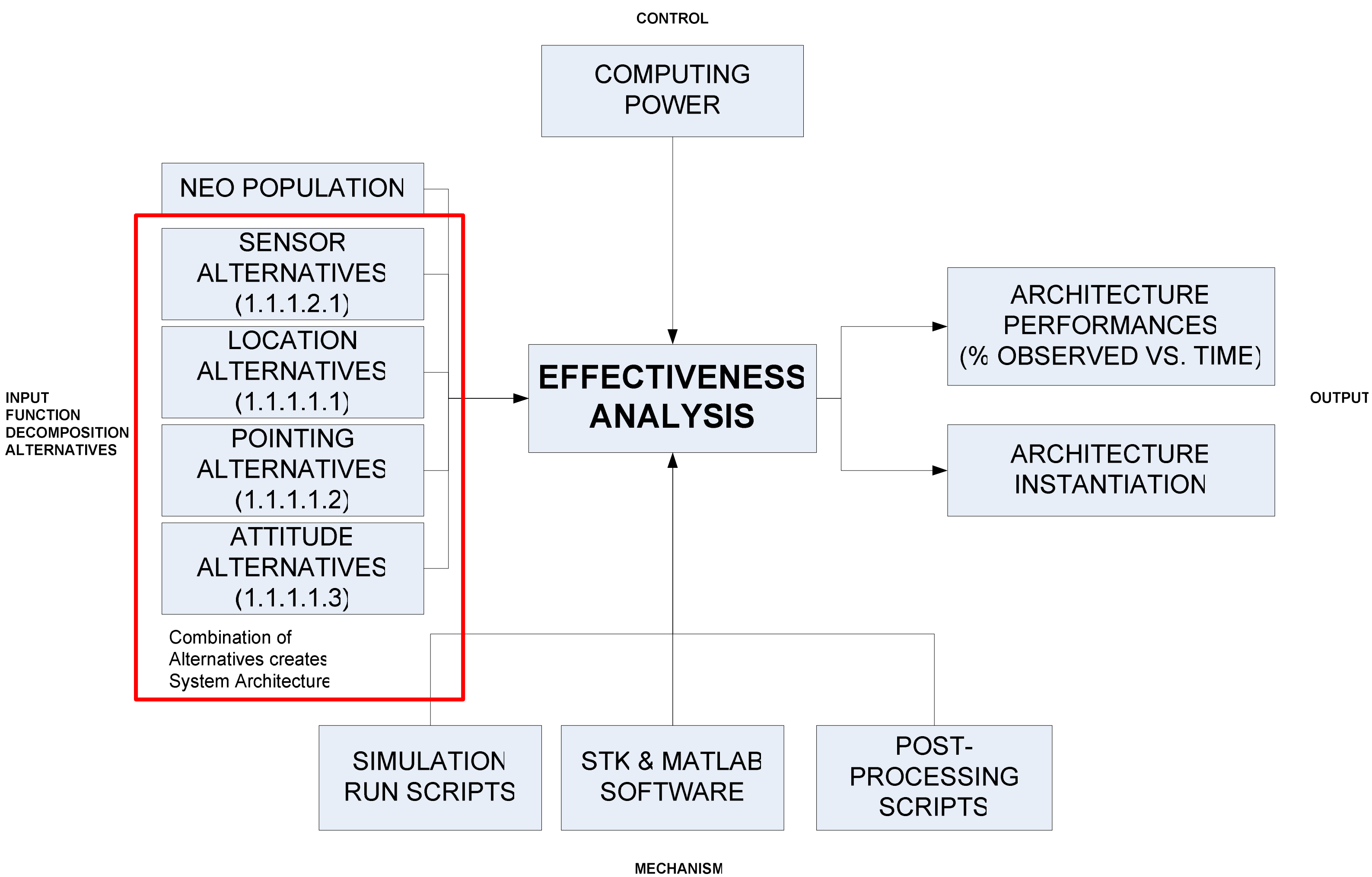
<u>SNOOS Measures of Effectiveness (MOE):</u>

1. How many NEOs does the selected architecture observe?
2. How long will this take?

MOE = 90% observation capability

Effectiveness Analysis

- Satellite Took Kit (STK) is the tool selected to evaluate architecture performance (measures the MOE)
- STK is a physics-based tool that models dynamic objects in space-based scenarios



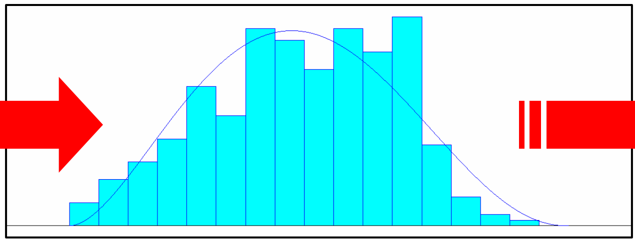
NEO Population Modeling

- **Purpose**: Create a representative small NEO population for architecture alternatives to observe
- **Process**:
  1. Collect historical NEO observation data (orbital parameters) from NASA/JPL
  2. Best-fit orbital parameters to probability distributions (ARENA)
  3. Input random numbers into the distribution equations to generate representative NEO parameters
  4. Input small NEO population into STK
  - **66 distributions (6 per NEO size bin); 3252 random parameters generated**

Historical NEO Data

Bin Size	Number of NEO's Identified
30 to 40 meters	296
40 to 50 meters	234
50 to 60 meters	172
60 to 70 meters	162
70 to 80 meters	119
80 to 90 meters	135
90 to 100 meters	195
100 to 110 meters	90
110 to 120 meters	44
120 to 130 meters	47
130 to 140 meters	49

ARENA Modeling:
Best Fit Distributions



Random Number Generation (Orbits)

	Eccentricity	
Bin	Distribution	Parameters
30m to 40m	Beta	(2.83, 3.28146)
40m to 50m	Beta	(2.29, 2.44135)
50m to 60m	Beta	(3.12, 4.194)
60m to 70m	Triangular	(0, 0.531, 0.85)
70m to 80m	0.01 + 0.85 * BETA	(3.66, 3.68)
80m to 90m	Normal	(0.428, 0.175)
90m to 100m	Normal	(0.432, 0.175)
100m to 110m	Triangular	(0.04, 0.467, 0.78)
110m to 120m	0.01 + 0.87 * BETA	(2.33, 2.78)
120m to 130m	Triangular	(0.02, 0.522, 0.88)
130m to 140m	Beta	(3.81, 3.46814)

Small NEO Population Input

NEO Size (meters)	Estimated Population	% of Population	Number Generated
30-40	374503	50.5	253
40-50	158025	21.3	107
50-60	79812	10.8	54
60-70	45314	6.1	31
70-80	27940	3.8	19
80-90	18317	2.5	13
90-100	12593	1.8	13
100-110	8991	1.2	13
110-120	6621	0.8	13
120-130	5002	0.7	13
130-140	3862	0.5	13

NEO Population: 542 small NEOs

Effectiveness Analysis Run Matrix

One Sensor

case_0001	sat_1
case_0002	sat_2
case_0003	sat_L_3
case_0004	sat_L_4
case_0005	sat_L_5
case_0006	sat_V1
case_0007	sat_V2
case_0008	sat_V3

Two Sensors

case_0009	sat_1	sat_2
case_0010	sat_1	sat_L_3
case_0011	sat_1	sat_L_4
case_0012	sat_1	sat_L_5
case_0013	sat_1	sat_V1
case_0014	sat_1	sat_V2
case_0015	sat_1	sat_V3
case_0016	sat_2	sat_L_3
case_0017	sat_2	sat_L_4
case_0018	sat_2	sat_L_5
case_0019	sat_2	sat_V1
case_0020	sat_2	sat_V2
case_0021	sat_2	sat_V3
case_0022	sat_L_3	sat_L_4
case_0023	sat_L_3	sat_L_5
case_0024	sat_L_3	sat_V1
case_0025	sat_L_3	sat_V2
case_0026	sat_L_3	sat_V3
case_0027	sat_L_4	sat_L_5
case_0028	sat_L_4	sat_V1
case_0029	sat_L_4	sat_V2
case_0030	sat_L_4	sat_V3
case_0031	sat_L_5	sat_V1
case_0032	sat_L_5	sat_V2
case_0033	sat_L_5	sat_V3
case_0034	sat_V1	sat_V2
case_0035	sat_V1	sat_V3
case_0036	sat_V2	sat_V3

Three Sensors

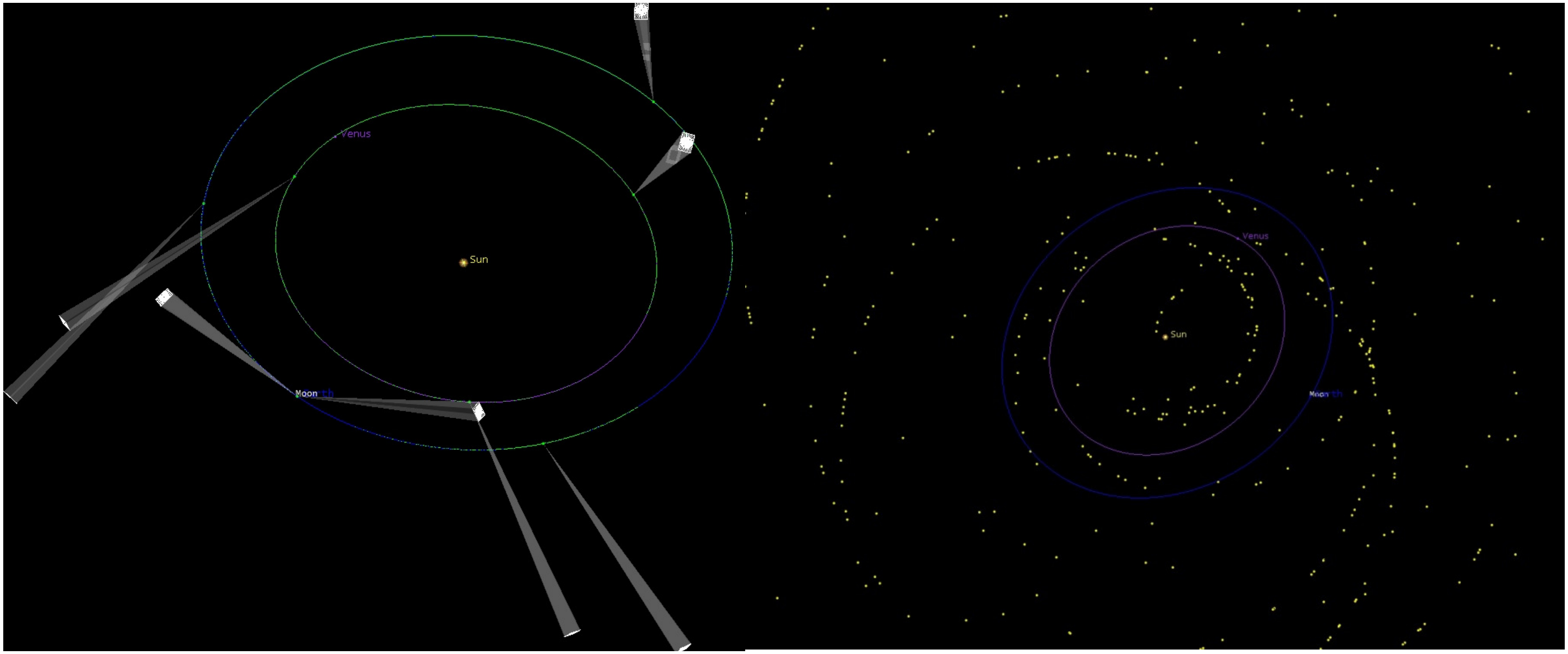
case_0037	sat_1	sat_2	sat_L_3
case_0038	sat_1	sat_2	sat_L_4
case_0039	sat_1	sat_2	sat_L_5
case_0040	sat_1	sat_2	sat_V1
case_0041	sat_1	sat_2	sat_V2
case_0042	sat_1	sat_2	sat_V3
case_0043	sat_1	sat_L_3	sat_L_4
case_0044	sat_1	sat_L_3	sat_L_5
case_0045	sat_1	sat_L_3	sat_V1
case_0046	sat_1	sat_L_3	sat_V2
case_0047	sat_1	sat_L_3	sat_V3
case_0048	sat_1	sat_L_4	sat_L_5
case_0049	sat_1	sat_L_4	sat_V1
case_0050	sat_1	sat_L_4	sat_V2
case_0051	sat_1	sat_L_4	sat_V3
case_0052	sat_1	sat_L_5	sat_V1
case_0053	sat_1	sat_L_5	sat_V2
case_0054	sat_1	sat_L_5	sat_V3
case_0055	sat_1	sat_V1	sat_V2
case_0056	sat_1	sat_V1	sat_V3
case_0057	sat_1	sat_V2	sat_V3
case_0058	sat_2	sat_L_3	sat_L_4
case_0059	sat_2	sat_L_3	sat_L_5
case_0060	sat_2	sat_L_3	sat_V1
case_0061	sat_2	sat_L_3	sat_V2
case_0062	sat_2	sat_L_3	sat_V3
case_0063	sat_2	sat_L_4	sat_L_5
case_0064	sat_2	sat_L_4	sat_V1
case_0065	sat_2	sat_L_4	sat_V2
case_0066	sat_2	sat_L_4	sat_V3
case_0067	sat_2	sat_L_5	sat_V1
case_0068	sat_2	sat_L_5	sat_V2
case_0069	sat_2	sat_L_5	sat_V3
case_0070	sat_2	sat_V1	sat_V2
case_0071	sat_2	sat_V1	sat_V3
case_0072	sat_2	sat_V2	sat_V3
case_0073	sat_L_3	sat_L_4	sat_L_5
case_0074	sat_L_3	sat_L_4	sat_V1
case_0075	sat_L_3	sat_L_4	sat_V2
case_0076	sat_L_3	sat_L_4	sat_V3
case_0077	sat_L_3	sat_L_5	sat_V1
case_0078	sat_L_3	sat_L_5	sat_V2
case_0079	sat_L_3	sat_L_5	sat_V3
case_0080	sat_L_3	sat_V1	sat_V2
case_0081	sat_L_3	sat_V1	sat_V3
case_0082	sat_L_3	sat_V2	sat_V3
case_0083	sat_L_4	sat_L_5	sat_V1
case_0084	sat_L_4	sat_L_5	sat_V2
case_0085	sat_L_4	sat_L_5	sat_V3
case_0086	sat_L_4	sat_V1	sat_V2
case_0087	sat_L_4	sat_V1	sat_V3
case_0088	sat_L_4	sat_V2	sat_V3
case_0089	sat_L_5	sat_V1	sat_V2
case_0090	sat_L_5	sat_V1	sat_V3
case_0091	sat_L_5	sat_V2	sat_V3
case_0092	sat_V1	sat_V2	sat_V3

Four Sensors

Case Number	Case Sensor Mix			
case_0093	sat_1	sat_2	sat_L_3	sat_L_4
case_0094	sat_1	sat_2	sat_L_3	sat_L_5
case_0095	sat_1	sat_2	sat_L_3	sat_V1
case_0096	sat_1	sat_2	sat_L_3	sat_V2
case_0097	sat_1	sat_2	sat_L_3	sat_V3

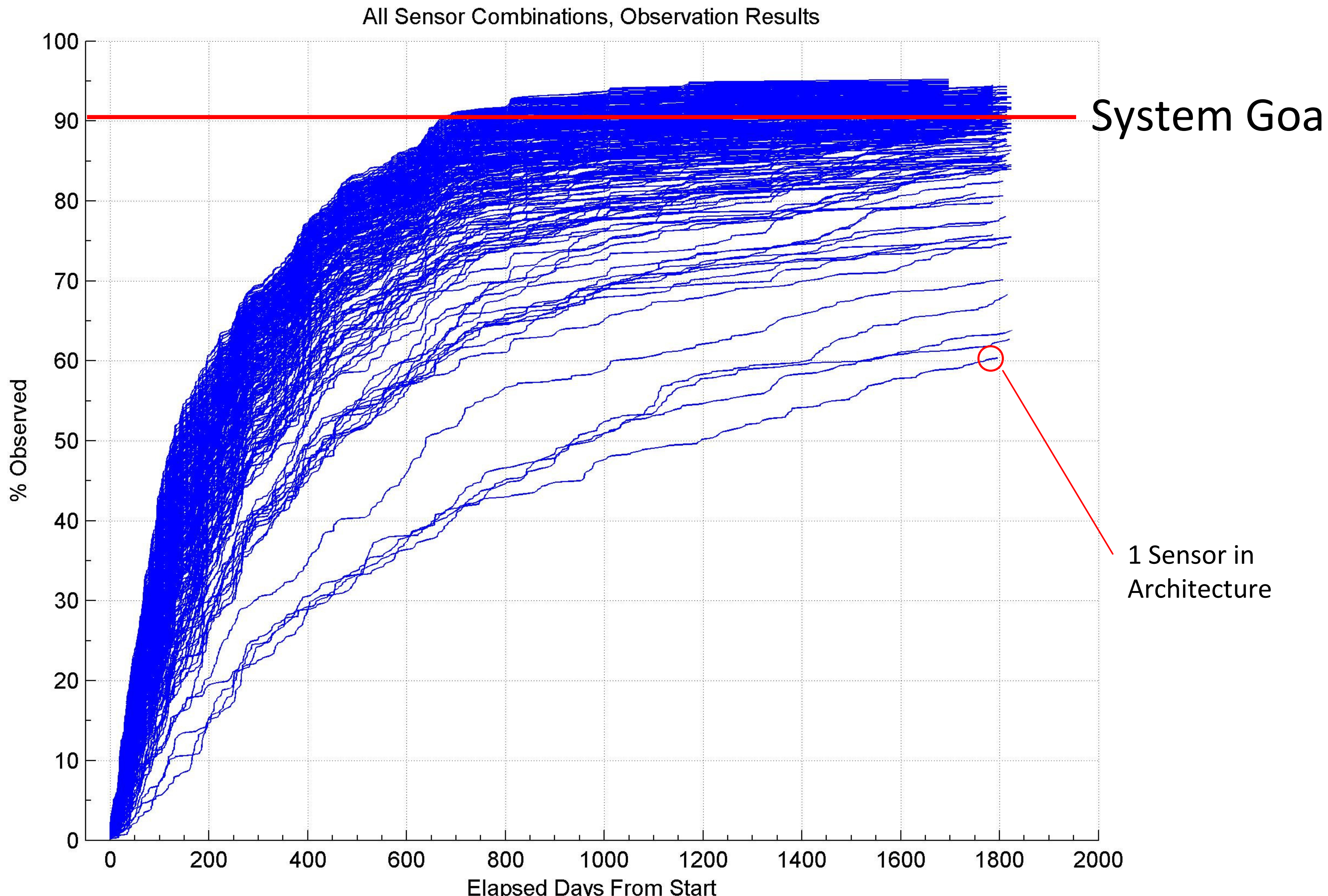
- 255 Scenarios or cases (subset shown)
  - Non-repeating combinations of sensors
  - From 1 sensor to 8 per Architecture Alternative
- Each scenario = Architecture Alternative
- Each Architecture Alternative combines:
  - No. of Sensors
  - Sensor Location
  - Sensor Pointing
  - Sensor attitude

Sensor/Location/Pointing/Attitude Modeling



Combination of function alternatives creates system architecture alternatives (the solution space)

Architecture Performance [1/2]



Architecture Performance [2/2]

- 82 Architectures observe ≥ 90% of small NEO population
- Cost Effectiveness computed for all 82 architectures
  - Lowest ratio selected as instantiated architecture
- Cost disparity a result of # of sensors and location (including launch vehicle costs) in each architecture

	Architecture (Case_No.)	NEOs Observed	% Observed (MOE)	Cost ($ Billion US FY09)	$ / % Observed
MIN	**140**	**488**	**90**	**$1.162**	**$12.9M**
MAX	**255**	**516**	**95**	**$2.232**	**$23.5M**
SELECTED	**131**	**497**	**92**	**$1.163**	**$12.6M**

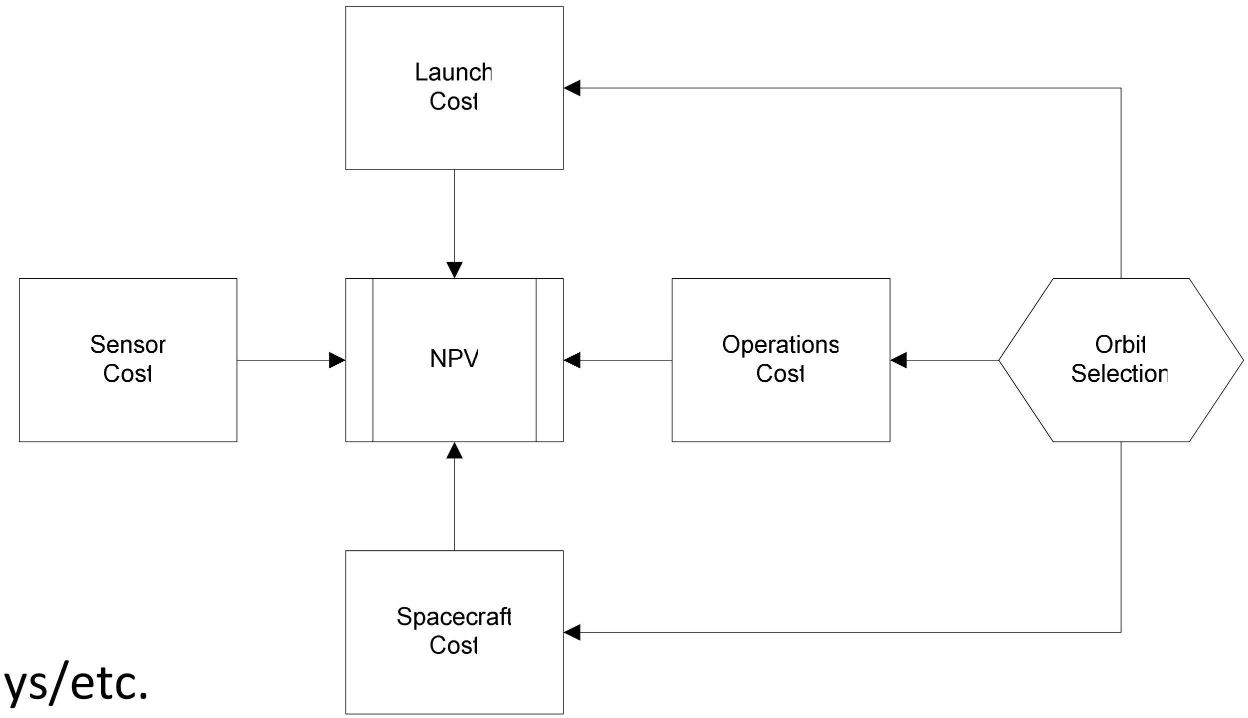
Instantiated Architecture

- Scenario 131
- MOE: 497 of 542 NEOs observed (91.7%) in 5 years
- $1.163 Billion US FY09

Function	Instantiation
Position Instrument 1.1.1.1.1	1 LEO Orbit 2 LaGrangian-Point Orbits 1 Venus Orbit
Point Instrument 1.1.1.1.2	Fixed Pointing
Maintain Attitude 1.1.1.1.3	LEO: Constrained Velocity Others: Inertially-Fixed Attitude (spin rate = 3.6 deg/min)
Collect Grid Energy 1.1.1.2.1	Four Visible-band Sensors (1 per orbit)
Store Energy 1.1.2.2	Solid State Device
Transmit Energy 1.1.3.3	X-Band Downlink Freq

Architecture Cost Analysis [1/2]

- Cost variables:
    - Sensor
    - Launch Vehicle
    - Satellite cost
    - Operations cost
- Uncertainties:
    - Schedule slips/delays/etc.
    - Technology failures
    - Performance
    - Weight Characteristics
    - New Technology
    - Manufacturing Initiatives



Architecture Cost Analysis [2/2]

Analysis conducted with a Monte Carlo Simulation model

•Random sample of the probability distribution of each cost variable

•Sum of all randomly sampled cost variables is one random sample of the total cost

Output:

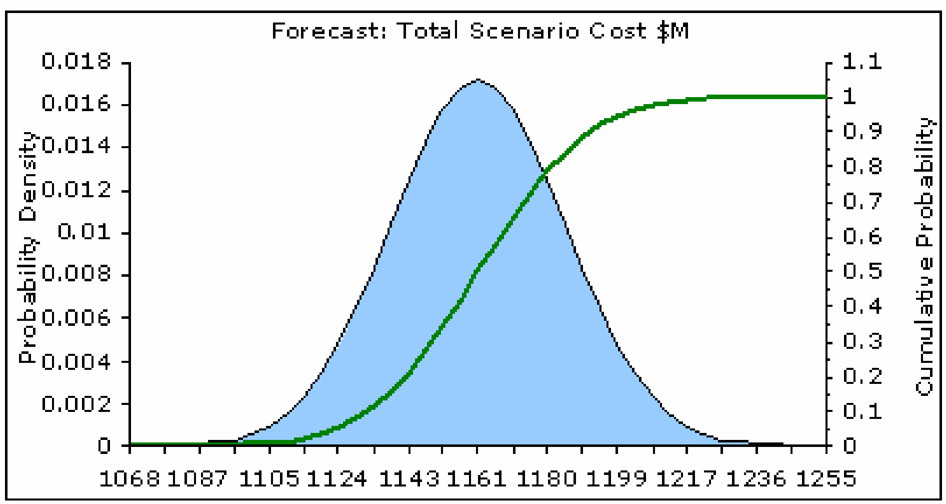
•Probability distribution of the total cost

•Mean cost is estimated at $1.163 Billion

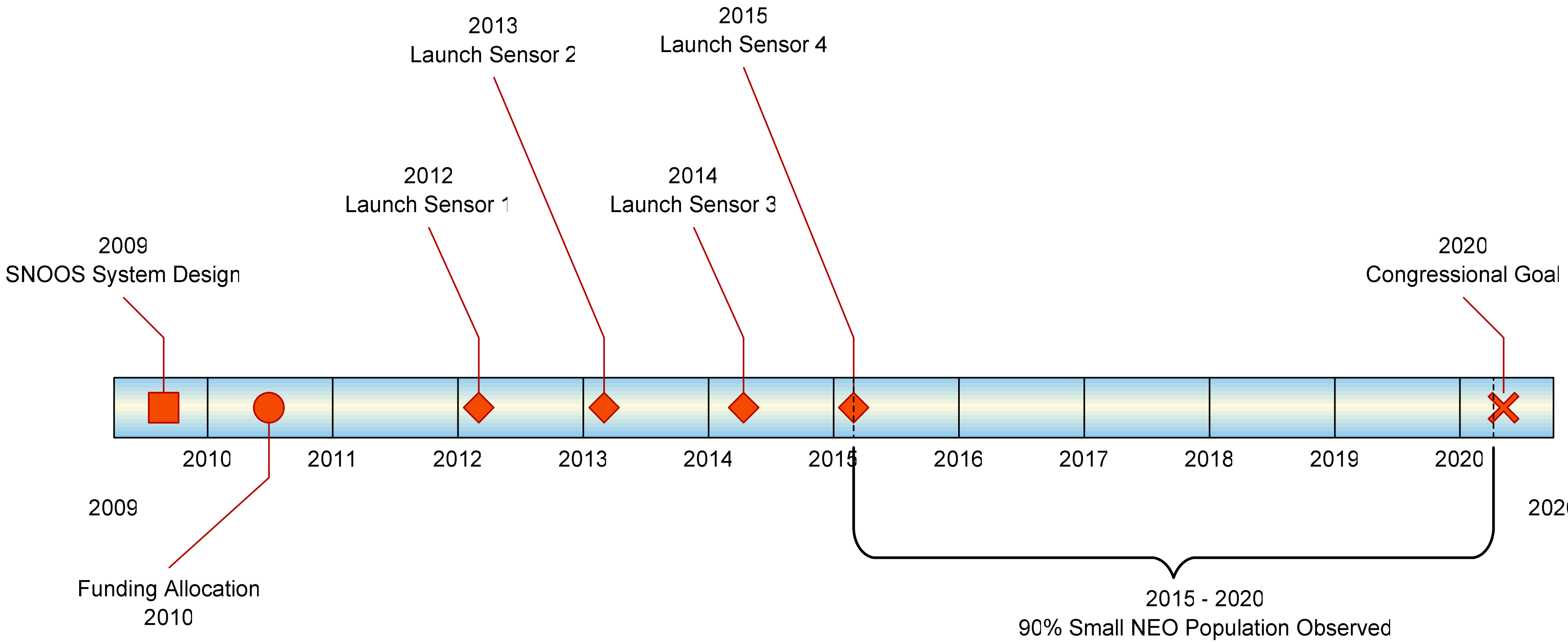
•The standard deviation is $23.3 Million

•The range of all possible outcomes is from $1.092 to $1.231 Billion

•68% confidence that the true cost will fall between $1.138 to $1.185 Billion



System Deployment Example



Effectiveness Analysis Methodology

1. Determine system goal (observation %, time to goal, or alternate MOE)
2. Obtain sensor performance characteristics
3. Generate representative NEO population (probabilistic)
4. Generate alternative system architectures (alternative function combinations = the solution space)
5. Input the population and the system architecture into the selected modeling tool
6. Simulate the orbital mechanics of each system architecture alternative
7. Collect simulation output data and perform post-processing (# NEOs observed in a finite time period)
8. Analyze the data (cost/benefit analysis)
9. Choose the most effective alternative architecture

Follow-on Work Recommendations

1. ***Generate ENTIRE NEO population:***
   - Small + Large NEOs ~ 6 million random number generations
2. ***Sensitivity analysis***
   - Higher fidelity input data
   - More sensor alternatives
   - More location alternatives
   - Requires time + incredible computing power
3. ***Time-to-deploy analysis***
   - "Turn on" sensor(s) at year X to simulate sensor interval launches
   - Evaluate architecture performance curves
4. ***Alternate MOE: average architecture warning time***
5. ***SEOR Project on alternate Planetary Defense Mission Function***
   - Detect NEO
   - Determine NEO governing organization, funding source & policies

QUESTIONS

SNOOS Project Website:

http://mason.gmu.edu/~eedward8/planetary_defense.htm

BACK UP

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Modeling Concerns

- Semi-Automatic: Use of Matlab to script commands required to set up scenario of objects and sensors
  - Otherwise we would have to enter each object by hand
- Size of model
  - 542 NEOs + sensor satellites
  - **Each "architecture" scenario run = 4+ hours**
- Run time a major concern (we need to actually deliver results)
  - Time step size of orbital dynamics is critical – too high a step size causes a NEO to "skip"' through the sensor's FOV
  - Number of sensors modeled (went from 3 to 1)
- Data Analysis
  - Simulation output extremely dependent on input data
  - **Computing power is major limiting factor in our simulation**

Effectiveness Analysis Methodology

- **Original Engineering Process**
- Loop over each set of NEOs for each time block (50 objects for 6 months was found to work best)
- Loop over time for total simulation time
- Loop over the different sensor configurations
- **Modified Engineering Process**
- However, only NEO orbit is stochastic -- run STK simulation with all sensors
    - Greatly reduces overall run time