Small Near-Earth Object Observing System (SNOOS)

A Modeling Approach for Architecture Effectiveness

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Contents

Executive Summary

Near-Earth Objects (NEOs) are comets and asteroids whose closest orbital approach pass the sun within 1.3 astronomical units (AU). Of criticality are Potentially Hazardous Objects (PHOs), a subset of the NEO population whose closest orbital approach passes the Earth within 0.05 AU (7.5M kilometers). It is well known that a NEO Earth-impact will deliver catastrophic consequences for the human species.

In 2005, U.S. Congress directed the National Aeronautics and Space Administration (NASA) to detect, catalog, and track NEOs greater than 140 meters in size. An Earth-impact of an asteroid greater than 140 meters can deliver enough kinetic energy to cause destruction on a scale ranging from continental devastation to the extinction of the human race. The Congressional directive mandates NASA to detect and catalog 90% of the statistically estimated large NEO (> 140 meters) population by 2020. Current NASA capability cannot meet this goal.

A Systems Engineering and Operations Research (SEOR) team of graduate students from George Mason University was motivated by the NASA effort, specifically, in regards to the small (30 - 140 meters) NEO subset of the population. Currently, ground-based NASA systems directed by Congress to observe the heavens are focused on searching for large NEOs. These systems are visible-band Charge-Coupled Devices (CCDs), and cannot physically detect small NEO signatures as a result of atmospheric absorbing bands. Space-based observation becomes necessary.

Small NEOs, ranging from 30 to 140 meters in size and which cannot be detected by current ground-based systems, can deliver enough kinetic energy to destroy local populaces, kill hundreds of thousands, and/or cause economic devastation (for example, the destruction of a financial center or an oil-producing infrastructure). The small PHO to large PHO ratio is roughly 36:1[(1)], resulting in a higher likelihood of a small NEO Earth-impact. Small NEOs pose a significant threat to life on Earth. No current or planned observation capability for these objects exists.

The SEOR team has designed a high-level architecture of a NEO observation system consisting of the capability gap-filling functions to aid the NASA goal. In addition, a quantitative modeling architecture was developed by the team to evaluate the potential effectiveness of various system alternatives (architectures), leading to a down selection of a recommended system architecture that can meet the NEO observation goal.

The resulting architecture designed by the SEOR team could potentially observe over 90% of a representatively modeled small NEO population within five years.

1.0 A Case for System Development

1.1 Background

In Dec. 2005, Congress asked that NASA plan, develop, and implement a Near-Earth Object Survey Program to detect, track, catalogue, and characterize the physical characteristics of Near-Earth objects (NEOs) equal to, or greater than, 140 meters in diameter in order to assess the threat of such NEOs impacting the Earth. It was determined that the goal of the Survey program would be to achieve 90% completion of its near-Earth object catalogue (by the end of 2020).

The SEOR team was motivated by the effort from NASA to survey 90% of NEOs greater than 140 meters in diameter, as NEOs pose a risk to life on earth. However the question is what, if anything should be done with respect to the much more numerous, smaller (less than 140 meters), but still potentially dangerous NEOs. There is an estimated population greater than 700,000 NEOs whose diameter falls between 30 and 140 meters. NEOs in this size range can destroy local areas.

In addition, a national and global security concern exists that a small NEO impact could be mistaken for a hostile weapon engagement. Reaction could include a retaliatory attack, possibly with weapons of mass destruction.

With the globalization of the world economy, when one country is affected by a significant event the rest of the world is also affected. A small NEO impact affecting a local area could have global consequences (for example, the destruction of an oil-producing area).

<u>Issue</u>

Congress mandated NASA to catalogue 90% of all NEOs larger than 140 meters by 2020. This project seeks to fill the existing detection gap for objects smaller than 140 meters.

<u>Recommendation</u>

The SEOR team recommends that NASA expand their search catalogue to include NEOs down to a 30 meter diameter. The team also recommends space-based observation with a visible-band sensor architecture defined in the proceeding sections in this document.

1.2 Justification

Small NEOs pose a significant threat given the higher estimated population and higher impact frequency than those of large NEOs. A national security concern has recently arisen in which a small NEO impact could be mistaken for a hostile weapon engagement. This could conceivably provoke a reaction that could include a retaliatory attack, possibly with weapons of mass destruction.

1.2.1 Small NEO Population

There is a greater estimated number of NEOs smaller than 140 meters that are not currently being targeted for the cataloging effort. Current ground based sensors are limited to search for objects that are greater than 140 meters in diameter.

Using the NEO population estimation equation from the NASA Small NEO Feasibility Study, the team obtained an estimate of the cumulative population of potentially hazardous NEOs. The cumulative population model for PHOs is:

$$N(>D) = 198D^{-2.354}$$

where N = the cumulative number of NEOs larger than diameter D in kilometers. Figure 1 shows the estimated population of small Potentially Hazardous Objects (NEOs) by size.

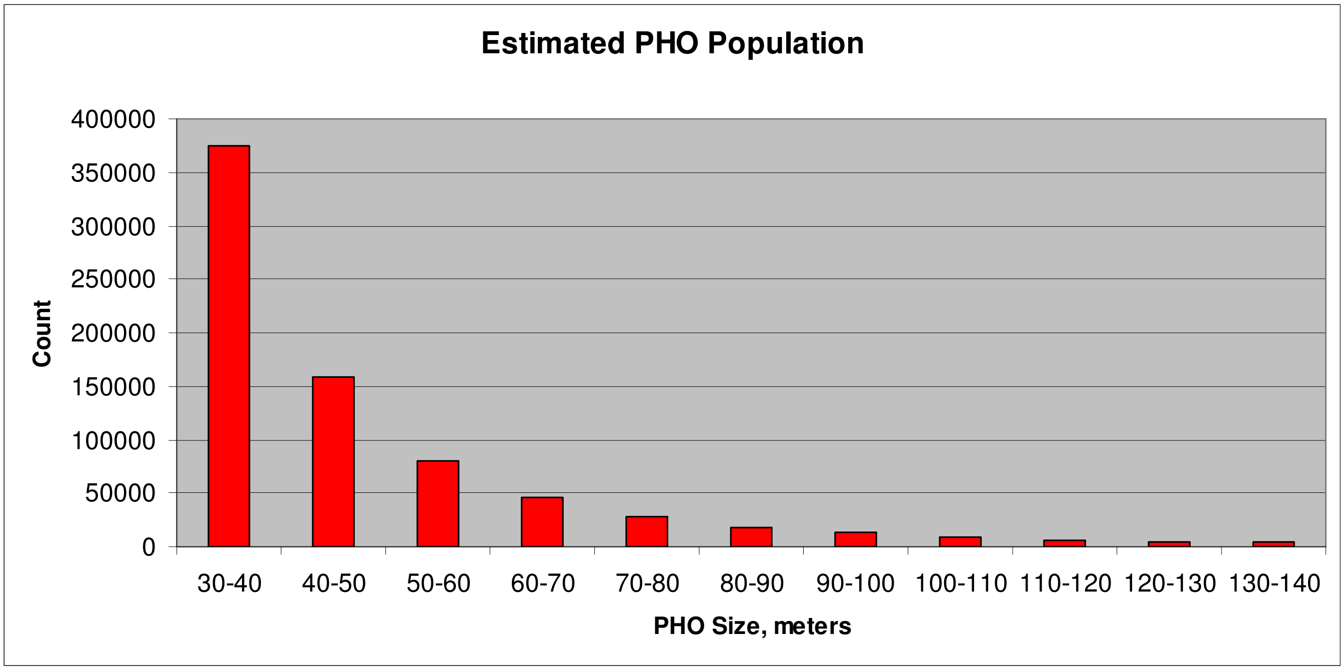

Figure 1: Estimated PHO Population[1]

1.2.2 Impact Risk

Small NEOs pose a significant threat given their higher estimated frequency of impact than large NEOs. Even if these small objects do not hit the ground; the atmospheric energy blast resulting from ablative breakup during atmospheric entry is strong enough to cause severe damage to small areas. Table 1 shows the impact frequency and impact energy distribution for objects smaller than 140 meters.

Table 1: Small NEO Energy Yield and Impact Frequency[1]

Size (meters)	Energy (Megatons)	Impact Frequency (years)
30	1.7	165
35	2.7	235
45	5.7	420
55	10.4	668
70	21.8	1200
90	45.6	2100
100	62.6	2700
110	83.3	3300
120	108.1	4000
130	137.5	4900
140	171.7	5800

1.2.3 Tunguska Event

The Tunguska Event, or Tunguska explosion, was a powerful explosion that occurred near the Podkamennaya (Lower Stony) Tunguska River in what is now Krasnoyarsk Krai of Russia, at around 7:14 a.m. on June 30, 1908. The NEO was approximately 60 meters in diameter. Estimates of the energy of the blast range from 5 megatons to as high as 30 megatons of TNT, with 10 to 15 megatons being the most likely equivalent energy yield. This is roughly equal to the United States' Castle Bravo thermonuclear explosion set off in late February 1954, about 1,000 times as powerful as the atomic bomb dropped on Hiroshima, Japan. The explosion knocked over an estimated 80 million trees over 2,150 square kilometers (830 square miles). It is estimated that the earthquake from the blast would have measured 5.0 on the Richter scale. An explosion of this magnitude is capable of destroying a large metropolitan area. Figure 2 illustrates a comparison of the area of Tunguska devastation to the National Capital Region.

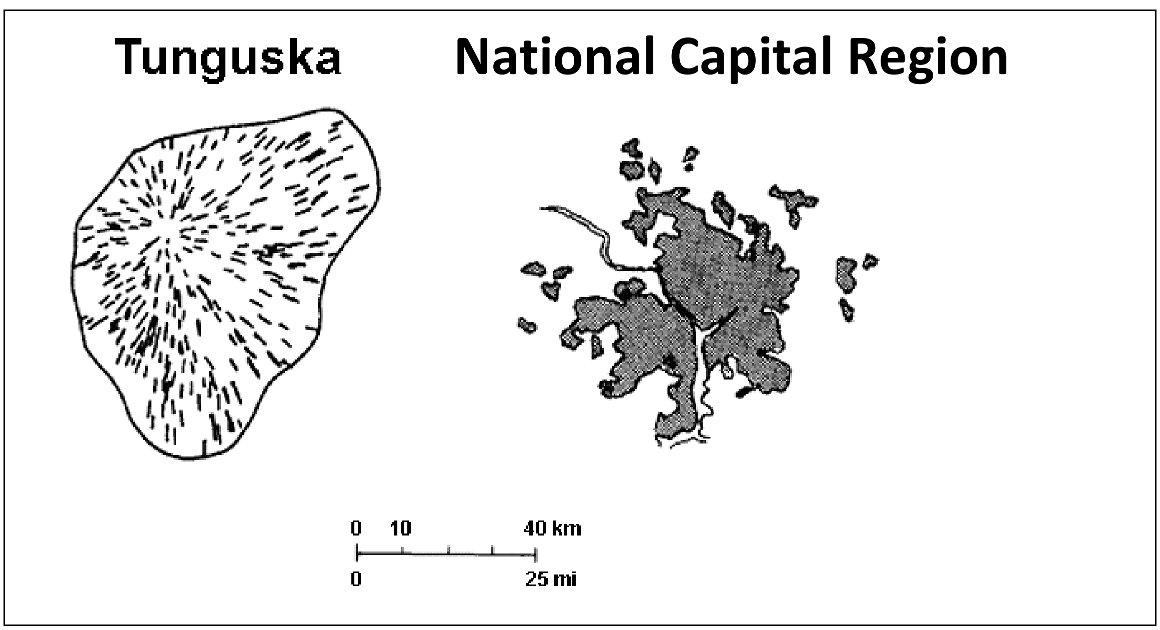

Figure 2: Area Comparison of Tunguska NEO Impact Event (Johnson)

1.2.4 Potential Global Effect of a Small NEO Impact

With the globalization of the world economy, when one country is affected by a significant event the rest of the world is also affected. A small NEO impact affecting a local area could have global consequences (for example, the destruction of an oil-producing area).

A Tunguska-like event happening today could have global consequences if occurring over a large metropolitan area. The destruction of a capital city or a major industrial center could produce severe global economic repercussions. A small NEO impacting a body of water could produce a tsunami similar to the 2004 earthquake in the Indian Ocean that spawned a devastating tsunami.

1.3 Problem Definition

1.3.1 Problem Statement

Small Near-Earth Objects (NEOs) pose a significant risk to life on Earth. No current or planned effort to detect these objects exists.

1.3.2 Capability Gap Analysis

Current ground-based observation systems (visible-band electro-optical telescopes) cannot physically perform the search for small NEOs due to their inability to observe small NEO visible signatures (NEO visible magnitude) as a result of endo-atmospheric absorbing bands. In astronomy, magnitude refers to the logarithmic measure of the brightness of an object in the visible-band portion of the electromagnetic spectrum. Current NASA-owned ground-based systems have a limiting magnitude of about 22 (i.e. they can only search for NEOs greater than140 meters in size for cataloging). For NEOs less than 140 meters in diameter it will become impossible to perform optical observation from the ground.

The following graph shows the absolute magnitude, H for NEOs less than 140 meters. H is defined as the apparent magnitude an object would have if it were at a standard luminosity distance (10 parsecs, 1 AU, or 100 km depending on object type) away from the observer.

Current ground-based observation systems are actively looking for larger NEOs (diameters greater than 140 meters) and therefore are not designed to search for small NEOs of which SNOOS is designed to observe. Current visible telescope systems can only operate during good weather and at night. Current ground-based systems have a limitation on the size of objects they can detect as evidenced by their limiting absolute magnitude, shown in Figure 3.

Figure 3 illustrates the need for space-based observation.

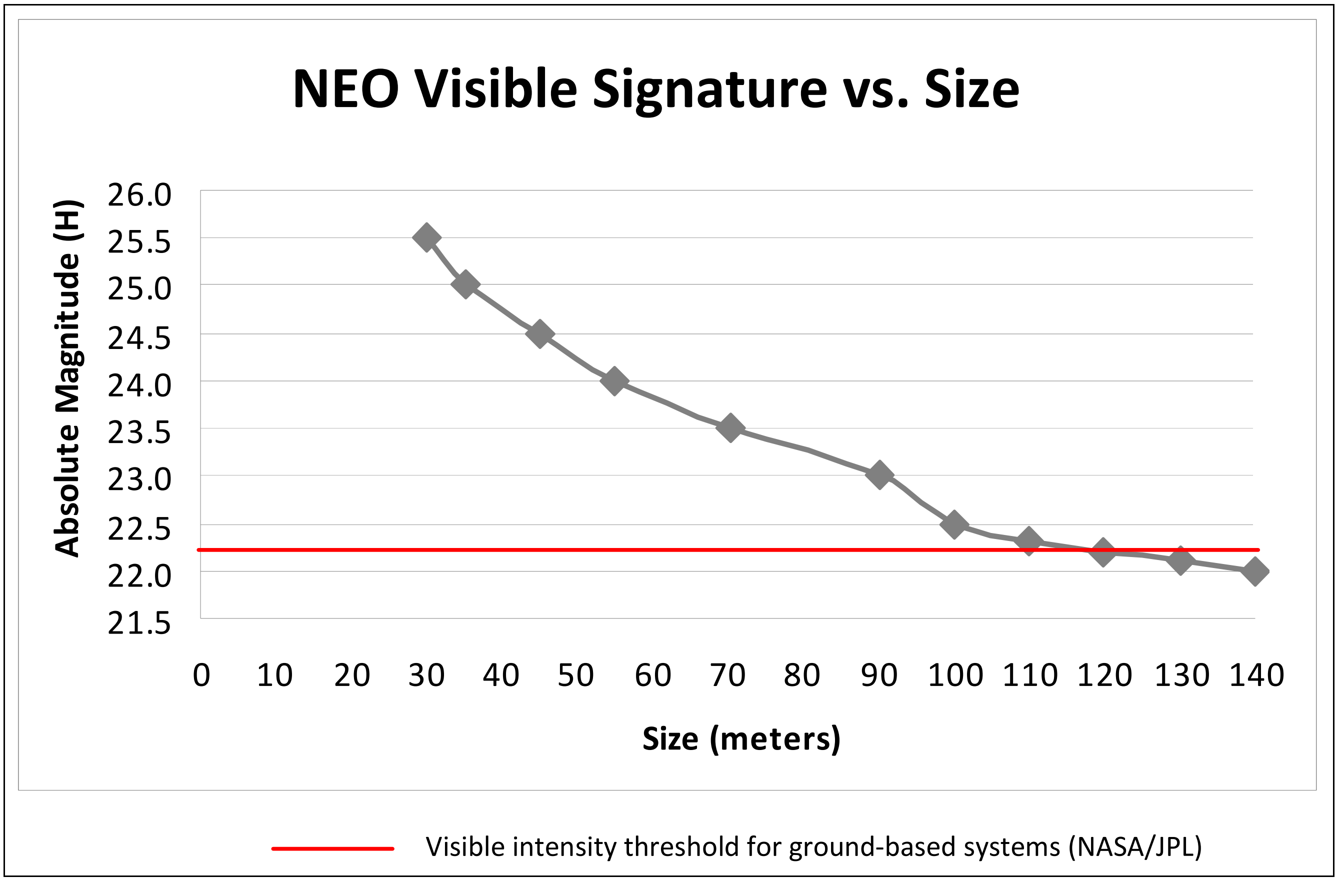

Figure 3: Limiting Magnitude of Current Ground-Based NEO Observation Systems (NASA)

1.4 SEOR Team Role and Project Scope

The SEOR team has identified the observation capability gap of existing ground-based systems. The SEOR team intends to propose a solution to observe the more numerous yet dangerous small NEO population. The SEOR team will deliver the following:

1. A high-level system architecture for small NEO observation (Section 3.0)

    - 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. An architecture for Effectiveness Analysis that quantitatively models how well alternative architectures perform (Section 5.0)

    - MOE = 90% observation capability
    - Select architecture for instantiation

3. Cost analysis for selected architecture

1.5 Policy

There are many reasons international cooperation and financial contribution to SNOOS development should be considered:

- The global consequences due to an impact by a NEO of any size
- The risk of human loss of life, infrastructure destruction, and economic devastation is shared by all nations
- Implementing a SNOOS is expensive
- In the event of a high likelihood NEO impact with Earth, a NEO deflection, destruction, or civilian evacuation mitigation strategy would be required. Such an endeavor should only be considered under an international framework

If international cooperation is considered there are several aspects of current policy to take into account:

- International Traffic in Arms Regulations (ITAR) prohibits the export of arms including satellites and satellite technology
- Data availability
- Measurement coordination
- Risk assessment responsibility
- Mitigation vs. Evacuation (Where would the evacuated people go? Would mitigation include space-based weapons?)

2.0 System Value Criteria

See Appendix A for the determination of SNOOS stakeholder value.

3.0 Functional Architecture

See Appendix C for the small NEO observation capability gap-filling Function Decomposition of SNOOS as well as system architecture.

4.0 System Requirements

See Appendix B for a listing of SNOOS functional and non-functional requirements.

5.0 Effectiveness Analysis

The purpose of the SEOR team's Effectiveness Analysis is to develop a quantitative modeling technique to evaluate the performance of alternative SNOOS architectures. The output of the Effectiveness Analysis is a system architecture that satisfies stakeholder needs and achieves the system goal (Measure of Effectiveness) of 90% small NEO observation capability. Figure 4 shows the architecture for the Effectiveness Analysis in terms of Input, Control, Output and Mechanisms (collectively, ICOMs).

The Effectiveness Analysis will be discussed in terms of input, control, output and mechanisms. Input consists of NEO Population Modeling and Function Decomposition alternatives. SNOOS Function Decomposition alternatives are combined via combinatory mathematics for instantiation as alternative system architectures for SNOOS. The control for the Effectiveness Analysis is computing power, which dictates how fast Effectiveness Analysis can be completed in a finite time period and determines how many alternative system architectures can be evaluated. Mechanisms include the software tools Satellite Took Kit (STK) and Matlab. Matlab is used to automate and control STK. STK is a physics-based tool that can model dynamic objects in space-based scenarios. A set of Matlab scripts were developed to model the Target NEOs and potential SNOOS architectures with STK. Additional Matlab scripts were developed for post-processing of the output data created by the STK model.

The desired output of the Effectiveness Analysis is the performance of each of the alternative architectures that once evaluated will allow one to be selected as the instantiation of SNOOS. This instantiation determines the number of sensors, locations (orbits), attitude, and pointing alternatives as functionally decomposed in Section 3.0. The alternative system architecture performances (output) are generated via STK, a tool that simulates orbital mechanics of space-based objects (i.e., orbiting asteroids and searching sensors). The following sections address each of the Effectiveness Analysis ICOMs in detail.

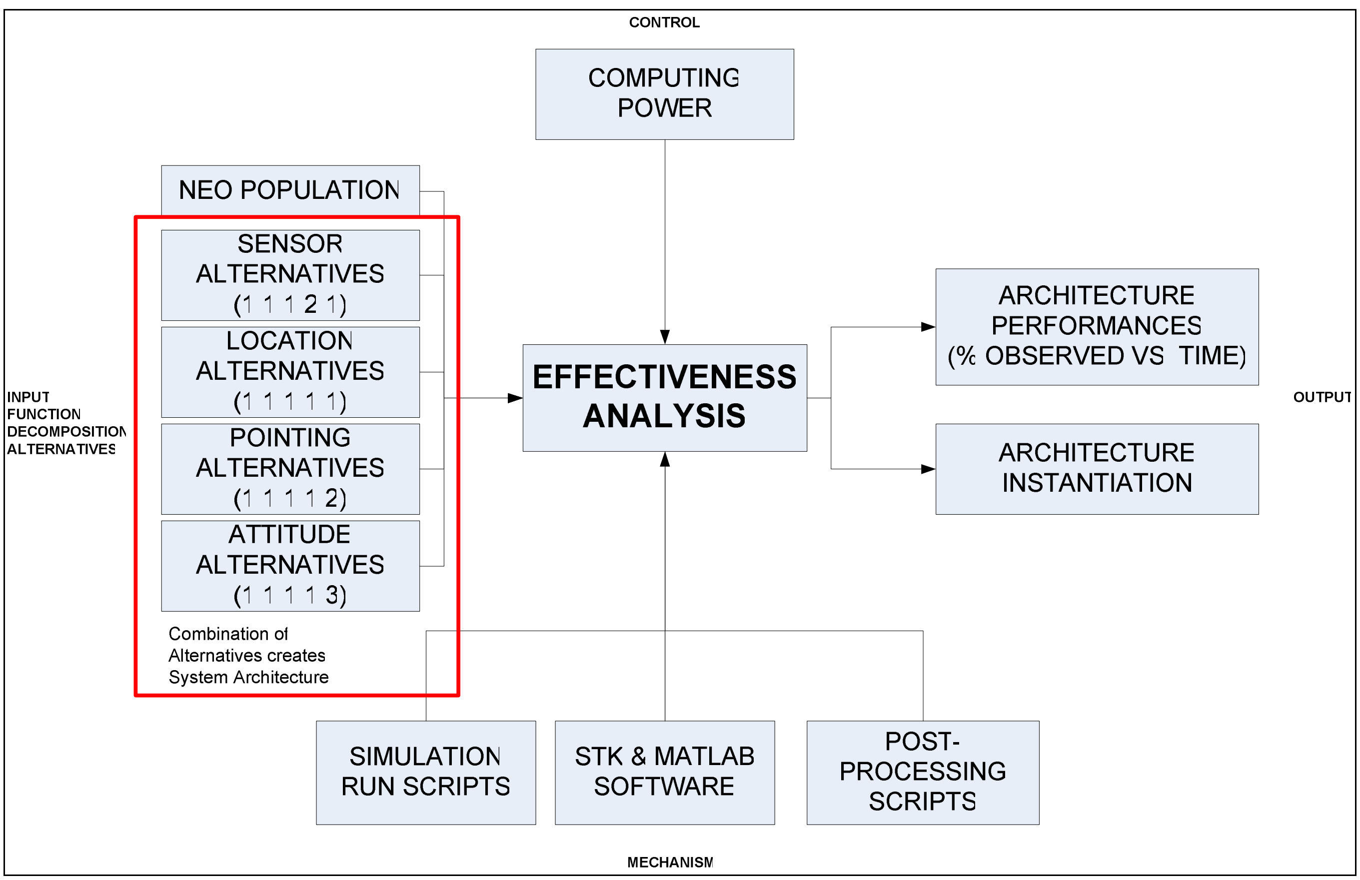

Figure 4: Effectiveness Analysis Methodology

5.1 Inputs

There are several inputs required for the SNOOS Effectiveness Analysis. NEO Population Modeling, NEO Population Input, and Function Decomposition Alternatives will each be discussed in detail.

5.1.1 NEO Population Modeling

The purpose of NEO population modeling is to generate a representative small NEO population for input to the STK simulation model. The NEO population input is constant across all simulation runs of various SNOOS architectures. This provides a deterministic number of targets for potential SNOOS architectures to observe, which in turn allows the SEOR team to determine which architecture(s) performs the best regarding NEO observation capability in time. The basis of NEO population modeling consists of collecting data on existing small NEO detections and statistical modeling of a small NEO population possessing characteristics of those that have currently been detected.

All NEOs that have been detected are cataloged on the NASA Near Earth Object Program website, located at http://neo.jpl.nasa.gov/cgi-bin/neo_elem. Of interest are NEOs between 30 and 140 meters in size. All detected NEOs were sorted and those with a size between 30 and 140 meters were entered into Excel for further analysis. There are 1,543 identified NEOs in the size range we are interested in analyzing.

Each NEO possesses a set of orbital parameters that define its physical size and shape, orientation of the orbit, and location of the NEO in it. Table 2 lists these orbital parameter definitions.

Table 2: NEO Orbital Parameter Definitions

Orbital Parameter	Unit of Measure	Description
Semi-major axis	AU	Similar to the radius of a circle, its length is the distance between the geometric center of the orbital ellipse with the periapsis (point of closest approach to the central body), passing through the focal point where the center of mass resides
Eccentricity		Shape of the ellipse, describing how flattened it is compared with a circle
Inclination	Degrees	Vertical tilt of the ellipse with respect to the reference plane, measured at the ascending node
Argument of Perihelion	Degrees	Defines the orientation of the ellipse (in which direction it is flattened compared to a circle) in the orbital plane as an angle measured from the ascending node to the semimajor axis
Mean Anomaly	Degrees	Defines the position of the NEO within its orbit
Longitude of Ascending Node	Degrees	Horizontally orients the ascending node of the ellipse (where the orbit passes upward through the reference plane) with respect to the reference frame's vernal point

Collected data of existing NEO detections were split into bins of 10 meters range sizes. Table 3 lists the current number of NEOs identified by NASA.

Table 3: NEO Size Bins and Number of Identified NEOs (http://neo.jpl.nasa.gov/cgi-bin/neo_elem)

NEO Size Range	Number of NEOs Identified by NASA
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

Within each bin, for each of the 6 orbital parameters, a probability distribution was fit to determine the distribution for that parameter. ARENA was used to fit the distributions for all parameters for all size bins. For instance, for the detected NEOs in the 30 to 40 meter bin for eccentricity, the distribution in Figure 5 was obtained. The distribution is a Beta distribution with parameters (2.83, 3.28).

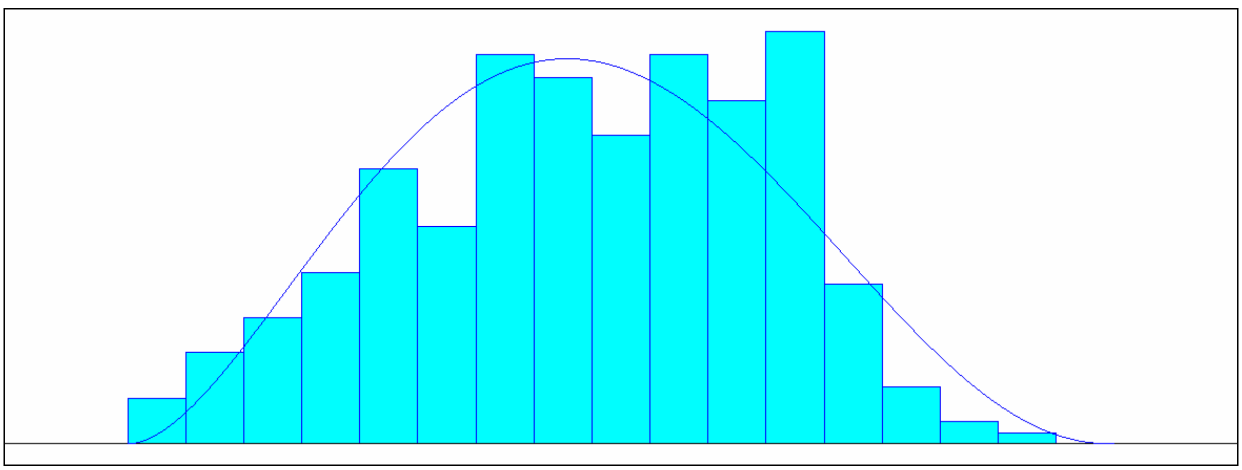

Figure 5: Distribution of Eccentricity for Detected NEOs in the 30m to 40m range

The results of best-fit probability distributions for the orbital parameters of existing NEO detections are shown in the following tables.

Table 4: Semi-major Axis Parameter Distributions

	Semi-major Axis (AU)	
Bin	Distribution	Parameters
30m to 40m	Triangular	(0.47, 1.29, 3)
40m to 50m	0.42 + Lognormal	(1.17, 0.605)
50m to 60m	0.48 + 2.52 * BETA	(2.24, 2.3)
60m to 70m	0.41 + 3.59 * BETA	(3.59, 6.05)
70m to 80m	0.49 + 2.51 * BETA	(2.36, 2.47)
80m to 90m	Triangular	(0.57, 1.34, 3)
90m to 100m	0.49 + 3.02 * BETA	(2.41, 3.21)
100m to 110m	Triangular	(0.49, 1.19, 3)
110m to 120m	Triangular	(0.55, 1.13, 2.88)
120m to 130m	0.53 + GAMMA	(0.317, 3.76)
130m to 140m	0.53 + 2.47 * BETA	(1.39, 1.63)

Table 5: Eccentricity Parameter Distributions

	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)

Table 6: Inclination Parameter Distributions

	Inclination (deg)	
Bin	Distribution	Parameters
30m to 40m	Gamma	(5.17, 1.47)
40m to 50m	Gamma	(5.75, 1.4)
50m to 60m	Lognormal	(9.71, 11.8)
60m to 70m	Gamma	(5.71, 1.53)
70m to 80m	Gamma	(6.16, 1.52)
80m to 90m	Gamma	(7.14, 1.47)
90m to 100m	Exponential	10.6
100m to 110m	Lognormal	(9.64, 10.3)
110m to 120m	1 + Exponential	10.7
120m to 130m	1 + 35 * BETA	(0.615, 1.65)
130m to 140m	44 * BETA	(0.718, 1.96)

Table 7: Argument of Perihelion Parameter Distributions

	Argument of Perihelion (deg)	
Bin	Distribution	Parameters
30m to 40m	360 * Beta	(1.1, 1.04)
40m to 50m	3 + 353 * Beta	(0.959, 0.876)
50m to 60m	357 * BETA	(0.833, 0.941)
60m to 70m	357 * BETA	(0.971, 0.876)
70m to 80m	359 * BETA	(0.759, 0.811)
80m to 90m	360 * BETA	(0.937, 0.921)
90m to 100m	360 * BETA	(0.972, 0.884)
100m to 110m	14 + 338 * BETA	(0.872, 1.03)
110m to 120m	352 * BETA	(1.41, 1.26)
120m to 130m	2 + 346 * BETA	(1.14, 1.18)
130m to 140m	Uniform	(8, 355)

Table 8: Longitude of Ascending Node Parameter Distributions

	Longitude of Ascending Node (deg)	
Bin	Distribution	Parameters
30m to 40m	1 + 359 * Beta	(0.837, 0.877)
40m to 50m	359 * Beta	(0.923, 1.05)
50m to 60m	5 + 352 * BETA	(0.844, 0.823)
60m to 70m	7 + 351 * BETA	(0.818, 0.868)
70m to 80m	Uniform	(0, 359)
80m to 90m	359 * BETA	(0.811, 0.934)
90m to 100m	2 + 358 * BETA	(0.809, 0.906)
100m to 110m	360 * BETA	(0.895, 0.941)
110m to 120m	Uniform	(10, 353)
120m to 130m	1 + 356 * BETA	(0.558, 0.658)
130m to 140m	7 + 329 * BETA	(0.754, 0.934)

The probability distributions determined above were used to create a representative small NEO population. Samples from each distribution (random number generation by size bin) were generated to create the cumulative small NEO population. Each generated NEO falls within the (orbital parameter's) distribution for that bin size for all of its orbital parameters. To model a representative scenario in STK, the number of generated NEOs are of similar proportions to the NEOs that have been detected.

Table 9 lists the modeled small NEO population.

Table 9: Modeled NEO Population

NEO Size (meters)	Estimated Population	% of Population	Number Sampled
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

5.1.2 NEO Population Input

The orbital parameters of each sampled NEO within the small NEO population are converted into STK commands. These commands generate the small NEO population within the simulation. Figure 6 displays the small NEO population within the STK GUI.

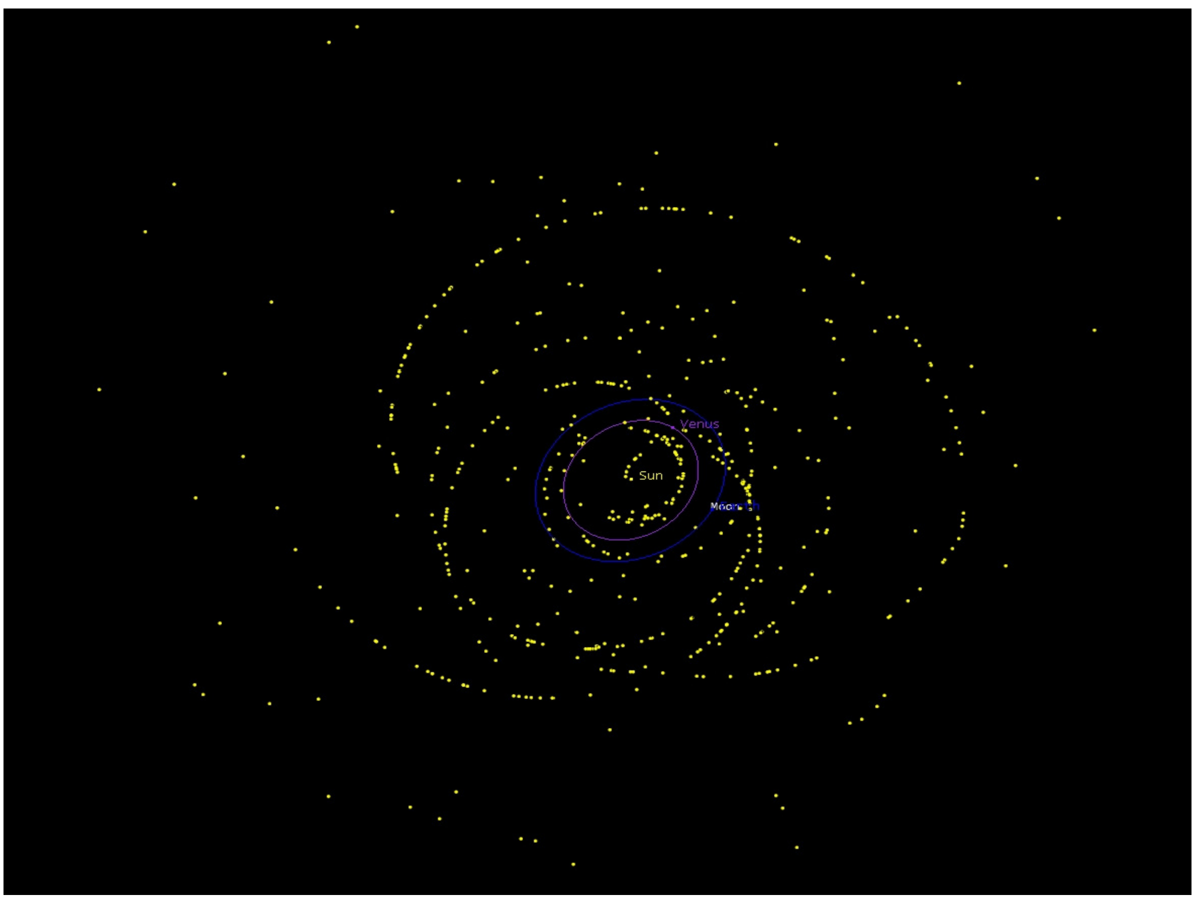

Figure 6: Small NEO Population

5.1.3 Function Decomposition Alternatives

Function Decomposition Alternatives consist of the type of sensor, the sensor locations (orbits), and the attitude of the sensor. Locations are chosen along with the attitude and spin or sweep rate of the sensor itself and defined in Table 10. Those sensors not orbiting Earth were given sweep rates equal to that of those orbiting Earth. This orbit information was converted into STK commands for each location chosen. Figure 7 shows all eight sensor locations at one instance in time. It is important to note that the sensors in Venus type orbit have a shorter period to complete one revolution around the Sun than those in an Earth type orbit (or those orbiting Earth) and thus each will have a different section of space in view.

Table 10: Sensor Location Definitions

Name	Description
sensor_sat_1	LEO sun-synchronous: RAAN = 330 degrees
sensor_sat_2	LEO sun-synchronous: RAAN = 220 degrees
sensor_sat_L_4	L4 orbit based on Earth's (60 degrees forward of Earth in direction of Earth's orbital motion)
sensor_sat_L_5	L5 orbit based on Earth's (60 degrees to the rear of Earth in direction of Earth's orbital motion)
sensor_sat_L_3	L3 orbit based on Earth's (180 degrees - opposite side of Earth's orbit from Earth)
sensor_sat_V1	20 degrees behind Venus
sensor_sat_V2	120 degrees from V1
sensor_sat_V3	120 degrees from V2

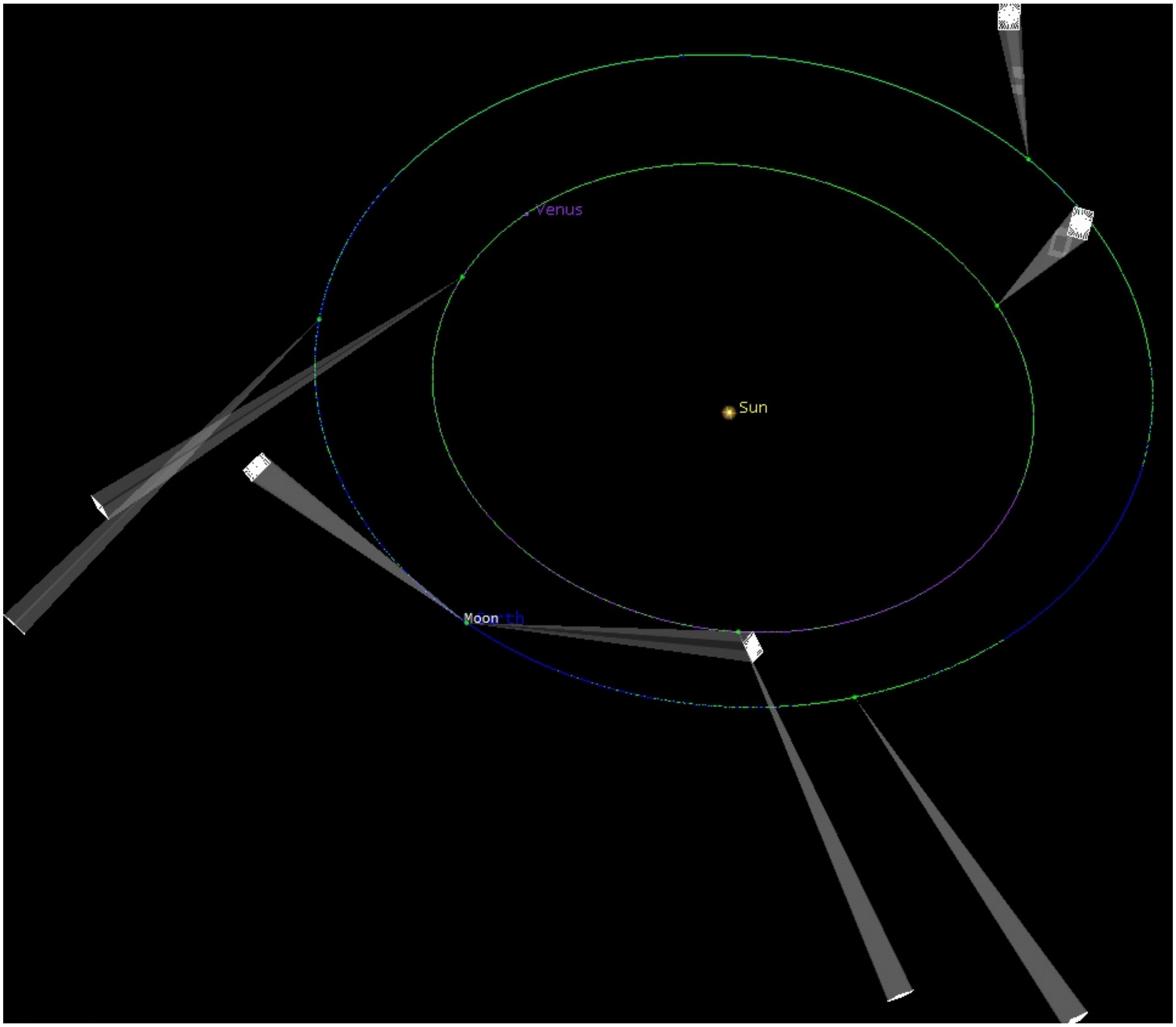

Figure 7: Sensor/Location/Pointing/Attitude Alternatives Modeling

5.2 Control

The control for the effectiveness analysis is computing power, which dictates how fast Effectiveness Analysis can be completed in a finite time period and determines how many alternative architectures can be evaluated. The team had only limited access to STK on a single computer for the duration of the project. If the team had access to multiple STK licenses, stronger computing power, and more time, more alternative SNOOS architectures could have been evaluated.

5.3 Output

The desired output of the Effectiveness Analysis is the performance of each of the alternative architectures that once evaluated will allow one to be selected as the instantiation of SNOOS. The SEOR team has defined the architecture Measure of Effectiveness (MOE) as the percentage of the entire NEO population input that can be observed by a single architecture in a period of time (years). The outputs for the Effectiveness Analysis (performance results) are discussed in Section 7.0.

5.4 Mechanisms

There are several mechanisms required for the SNOOS Effectiveness Analysis. Modeling Process and Post Processing will each be discussed in detail. Modeling assumptions and concerns will also be discussed.

5.4.1 Modeling Process

The engineering process shown in Figure 8, describes the steps required to model the NEO targets and the sensors to generate data to be post processed.

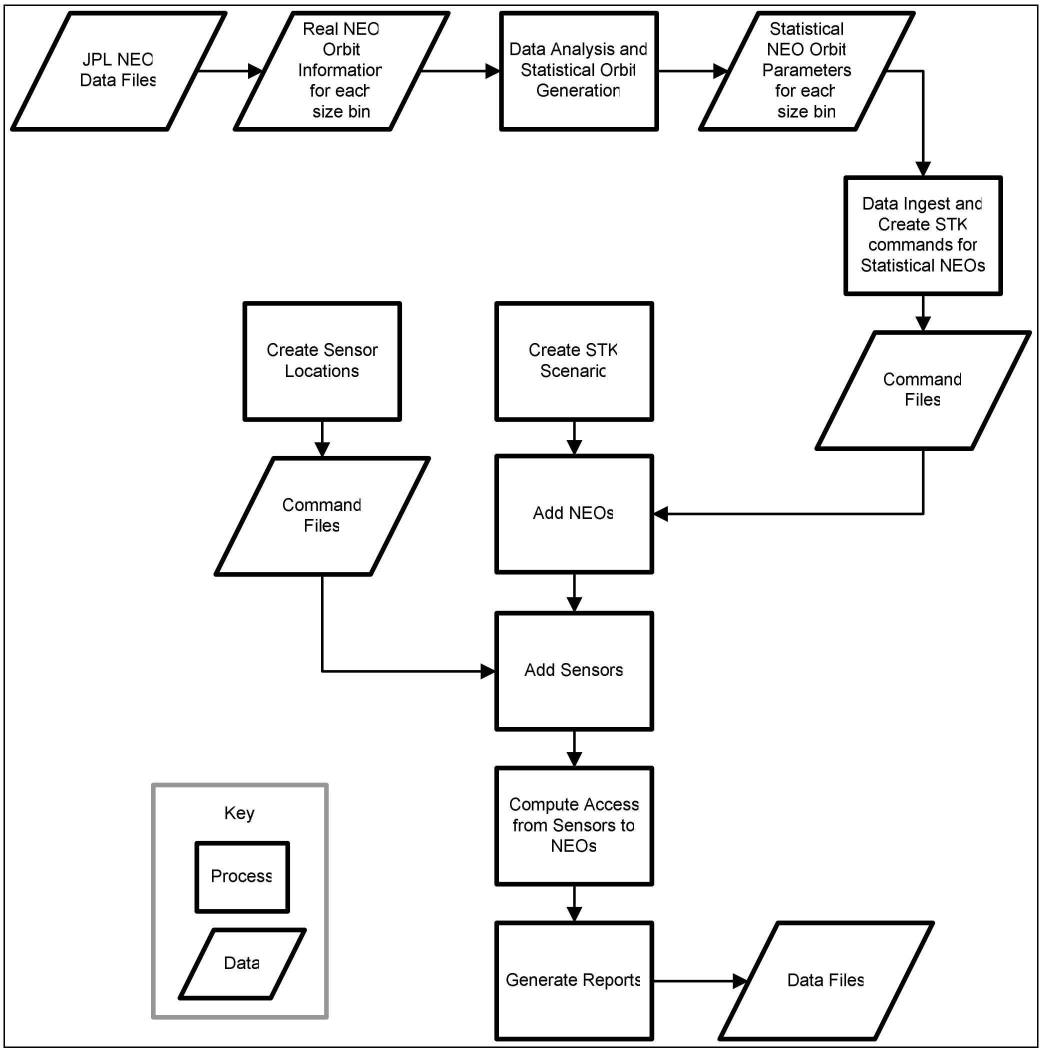

Figure 8: Effectiveness Analysis Process

Once the STK scenario was initialized, all of the NEO objects were added to the model. The sensors were added next. STK was then commanded to compute the observations of the target NEOs by the sensors. Once this access was computed a report was generated. This process had to loop over each set of target NEOs as it was found that too many objects run at once could crash the simulation. Additionally, there was a loop over time since if the simulation was run for long duration it could crash. This process was initially repeated for each sensor combination.

5.4.2 Modeling Assumptions

Sensor Range Assumption: The SEOR team assumes that each sensor will be able to observe a small NEO if the object in its orbit passes through the sensor's field of view (FOV). This is a simplification; ideally we would have the distance from the observing sensor to the sun, the sensor to the object and the distance between the sensor and the object to compute the relative magnitude. Generating this data would increase the run time for each iteration and would increase the complexity of the post processing. As such this assumption means the results will be best case.

Number of target NEOs: The SEOR team modeled 542 objects to help decrease size of the model and increase the run speed while maintaining the proportions of the different NEO size bins in the range of 30 to 140 meters. With increased computing power, the team would model a larger number of NEOs.

Time Step: STK calculates the exact position of the object's orbit once each time step. The team did a series of experiments with the time step ranging from the default of 60 seconds to 6000 seconds and if the time step is to big the object can "skip" through the FOV with out STK reporting an observation. Comparing the results for one specific set of NEO targets for one time period with time steps at 60 seconds and 600 seconds there were no differences. To increase the run time the team decided to use 600 second time steps.

5.4.3 Modeling Concerns

Initially, the team was concerned with the large amount of NEO objects and how to model these in STK. With the implementation chosen of using Matlab to control STK this became a non-issue. A Matlab script sets up the required commands for each target NEO and Sensor.

Run time was another concern and with the modeling assumptions discussed previously the run time decreased significantly (to 4-6 hours per run vs. 12 hours). Additionally, with the modified post processing steps discussed in Section 5.4.4 the run time can be further decreased.

The number of sensors that the team wished to model was initially three. This would provide a larger set of alternatives from which to select the best architecture. However, when the three sensors were all modeled the run time increased. For the purpose of this project modeling only one would still provide the benefit of determining the modeling process while still allowing the team to evaluate several architectures.

Another factor affecting the run time is the duration of each of the simulations. The team decided that a five year run time was sufficient for the project however this should be increased if subsequent work is continued.

5.4.4 Post Processing

The original post-processing method, as shown in Figure 9, is as follows:

- Reports generated by STK were searched for duplicates of the same sensor finding the same NEO target
- The remaining observations were time ordered
- Repeated NEO target observations were removed

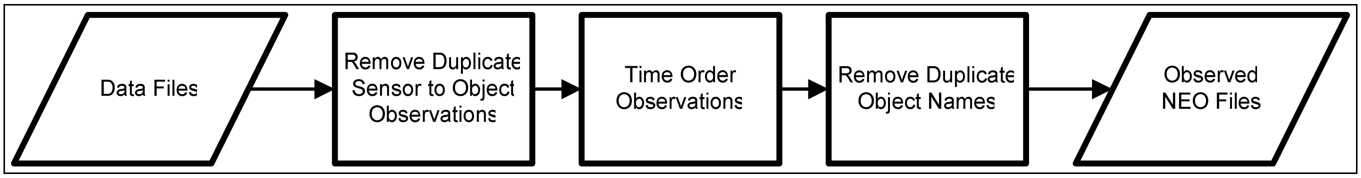

Figure 9: SNOOS Initial Post Processing Steps

Later it was determined that the only stochastic element of the SEOR team's Effectiveness Analysis was in the generation of NEO orbits themselves. Once the NEO target trajectory was selected (i.e. the random number generations), the problem became deterministic. This means that for the same time period and NEO orbital parameters, the sensor located at the same position would always see the same set of objects at the same time. Once this assumption was confirmed by conducting multiple simulation (STK) runs, the post-processing method was modified. This modified process is shown in Figure 10. The STK model could be run once with all eight sensors and the results post processed. We separated out each sensor's individual performance such that we could then combine them in all of the permitted possible combinations. These combinations could range from having 1 to all 8 sensor locations and the total number of allowed combinations (system architectures) that we were able to examine was 255. One "master" scenario, or architecture, was run, from which individual alternative architectures were able to be singled for an architecture by architecture performance evaluation.

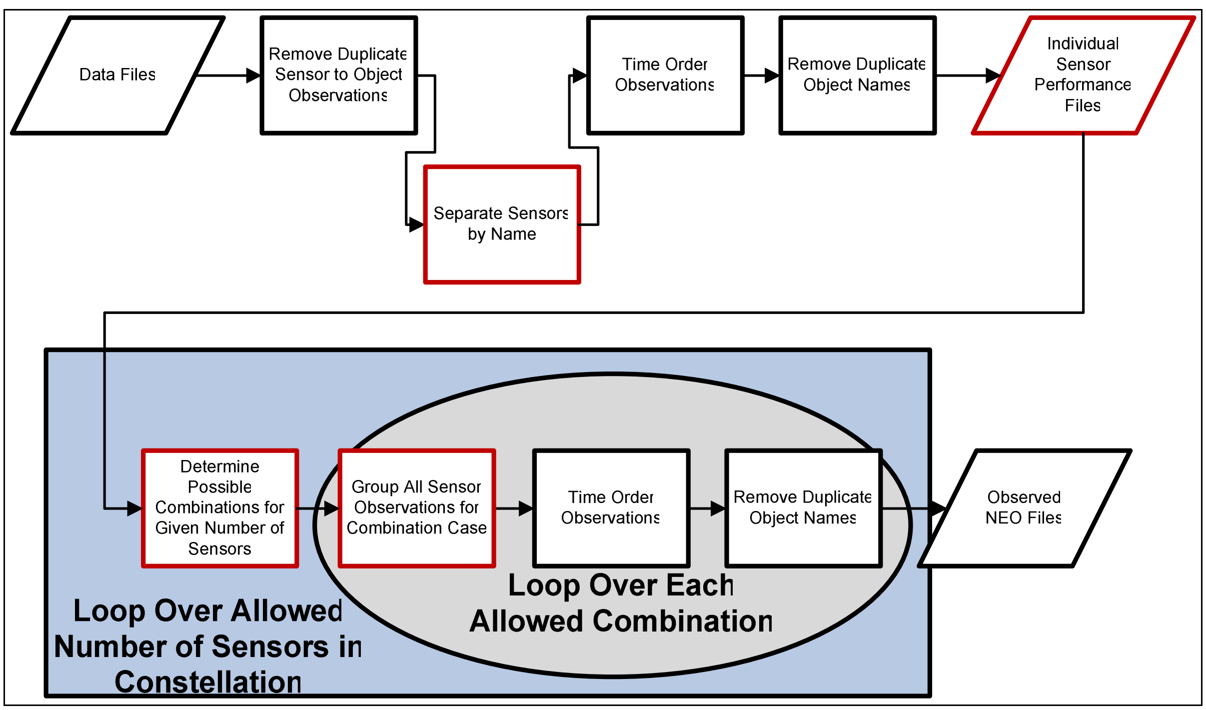

Figure 10: SNOOS Final Post Processing Method*

* Note: Items in red represent a change from the initial post processing steps.

6.0 Analysis of System Alternatives

Appendix D contains the SEOR team's method of evaluation of system alternatives.

7.0 Architecture Performance

Through the SEOR team's Effectiveness Analysis, 255 potential architectures combining the functional alternatives identified in Section 6 were simulated and their performances measured. Of the 255 architectures, 82 achieved the SEOR team's MOE of 90% NEO observation. Figure 11 shows the performance results for all 255 potential SNOOS architectures simulated through the SEOR team's Effectiveness Analysis.

It is important to note that even one space based sensor can contribute to the detection of a large portion of the target small NEOs, 60% to 78% depending on sensor location.

Table 11 lists the performance results of best and worst performing architecture alternatives meeting the system goal of 90% NEO observation. The cost disparity is a result of the number of sensors contained within the architectures as well as the launch vehicle costs to place those sensors at their respective locations in space. For a complete list of SNOOS alternative architecture performance results, see Appendix E.

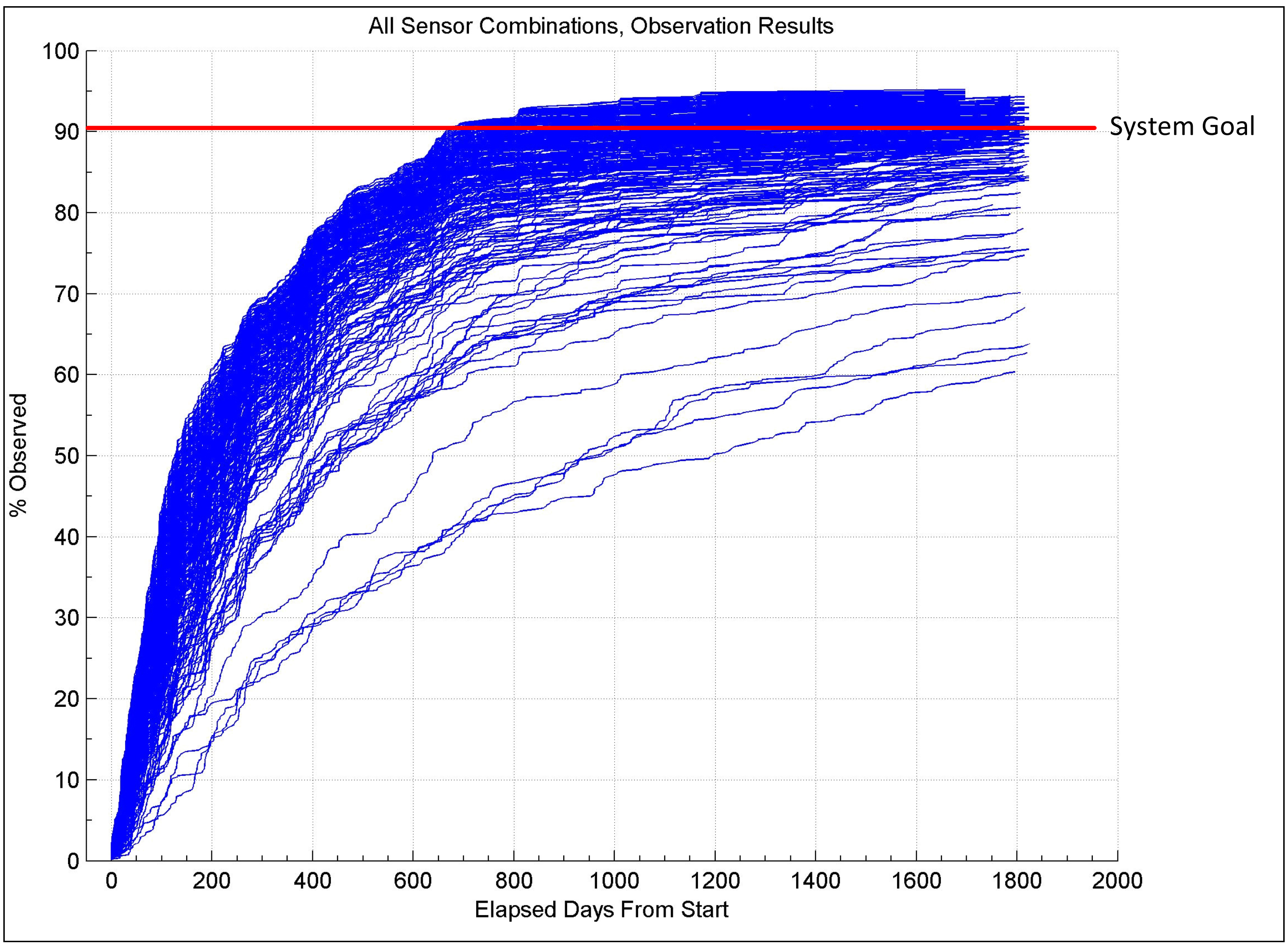

Figure 11: SNOOS Alternative Architecture Performances

Table 11: Min/Max Architecture Performances Meeting MOE

	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

The methodology developed for this Effectiveness Analysis, detailed in Figure 4, is shown to be reasonable via our results. As such, this methodology is sound for selecting one system architecture from among the alternatives to instantiate. Due to the project's limitations on total duration, only a small set of alternative architectures from the system architecture space are evaluated. The methodology could be further refined and applied to a much larger set of alternative architectures with an increased number of sensor types, locations, pointing schemes, search patterns, etc.

8.0 Instantiated System Architecture and Cost Analysis

8.1 Instantiated Architecture

Of the 255 possible SNOOS architectures simulated, architecture (case number) 131 was selected based on a simple cost/effectiveness ratio. The instantiated SNOOS architecture is depicted in Figure 12.

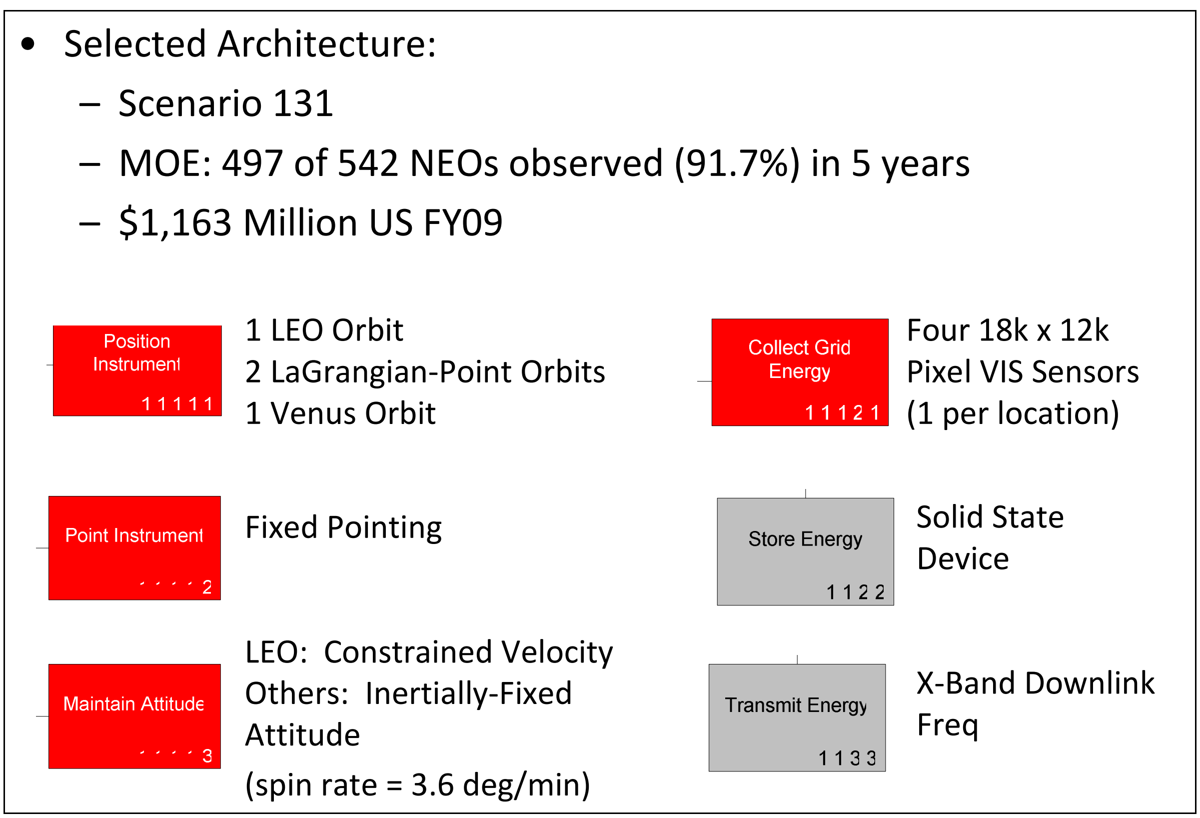

Figure 12: SNOOS Instantiated Architecture

8.2 Architecture Cost Analysis and Deployment

When determining the cost of the most appropriate means of detecting small NEOs, one needs to compare the cost of a particular sensor technology against the associated benefits. Space-based sensors incur greater costs, but provide a much better capability range and can be operated 24 hours a day regardless of weather. Ground-based sensors, on the other hand, are less expensive and allow for easier maintenance and upgrades, but have severely limited observational capability (limiting magnitudes), limited to nighttime operations and are subject to weather and atmospheric distortion.
The proceeding sections present the SEOR team's cost analysis methods for SNOOS architecture cost. Estimates are presented for space-based sensors, as SNOOS is a space-based observation system.

8.3 Cost Variables

The cost variables for space-based sensors are used from Reference 1. In the cost analysis estimates are generated for three different scenarios: a Sun-synchronous LEO orbiter, a sensor in a Halo orbit about the Sun-Earth L2 LaGrangian point (L2-Point) and a sensor in a Venus orbit. The estimates for these space-based sensors are broken down into platform (satellite) containing the sensor, mission operations, and launch vehicle cost. Tables 11 through 15 summarize the cost variables per architecture element.

Table 12: Launch Vehicle Cost by Orbit (Location)

Orbit (Location)	$M FY09
LEO	$64
L2	$71
Venus	$79

Table 13: 10-year Operation Cost Summary

Operation Type	$M FY09
LEO	$29
L2	$54
Venus	$74

Table 14: Visible-band Sensor Costs

Sensor	$M FY09
0.5 m	$23
1 m	$41
2 m	$83

Table 15: Sensor Platform (Satellite) Cost

Spacecraft	$M FY09
LEO	$78
L2	$88
Venus	$116

Table 16: Total Mission Cost Estimate

Space-Based Observation				
Mission	**Sensor Type + Platform + Ops**	**System Cost ($M FY09)**	**Launch Vehicle ($M FY09)**	**Mission Type Cost ($M FY09)**
Leo	0.5 m	$129	$64	$193
	1 m	$147	$64	$211
	2 m	$189	$64	$253
L2	0.5 m	$165	$71	$236
	1 m	$183	$71	$254
	2 m	$225	$71	$296
Venus	0.5 m	$213	$79	$292
	1 m	$231	$79	$310
	2 m	$273	$79	$352

8.4 Cost Model

The cost estimates presented here include development, construction, operation and launch vehicle for the sensor. Figure 13 illustrates the contributing cost variables in the calculation of SNOOS mission cost.

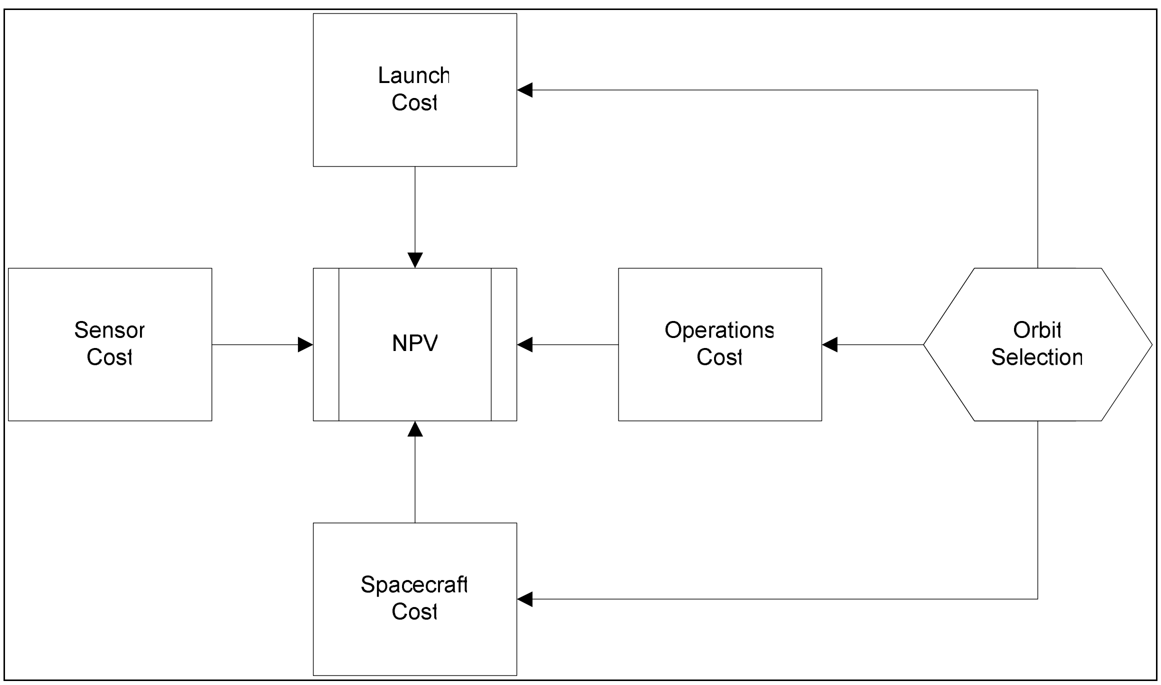

Figure 13: SNOOS Cost Influence Diagram

The first step in performing SNOOS cost analysis was to quantify each element of the influence diagram in terms of its statistical properties such as mean, standard deviation, and range.
Second, a Monte Carlo simulation with 10,000 iterations was performed. With this technique one takes a random sample from the probability distribution of each cost element. The sum of all randomly sampled cost elements is then taken to be one random sample of the total cost. The result of this process is a probability distribution of the cost estimate.

Cost uncertainty was identified and quantified. Uncertainty was quantified by the use of probability distributions on ranges of cost. Cost uncertainty was attributed to factors such as performance and weight characteristics, new technology, manufacturing initiatives, and schedules slips/delay/etc.

Figure 14 displays the results of the uncertainty analysis for the selected case scenario. The mean cost is estimated at $1,162 million, the standard deviation is $23.3 million, and the range of nearly all possible outcomes is from $1,092 million to $1,231 million. The mean, plus or minus one standard deviation, is the range in which one can be 68 percent sure that the true cost of the scenario will fall, in this case is between $1,138 million to $1,185 million. Figure 15 displays the potential deployment timeline for SNOOS and its sensors.

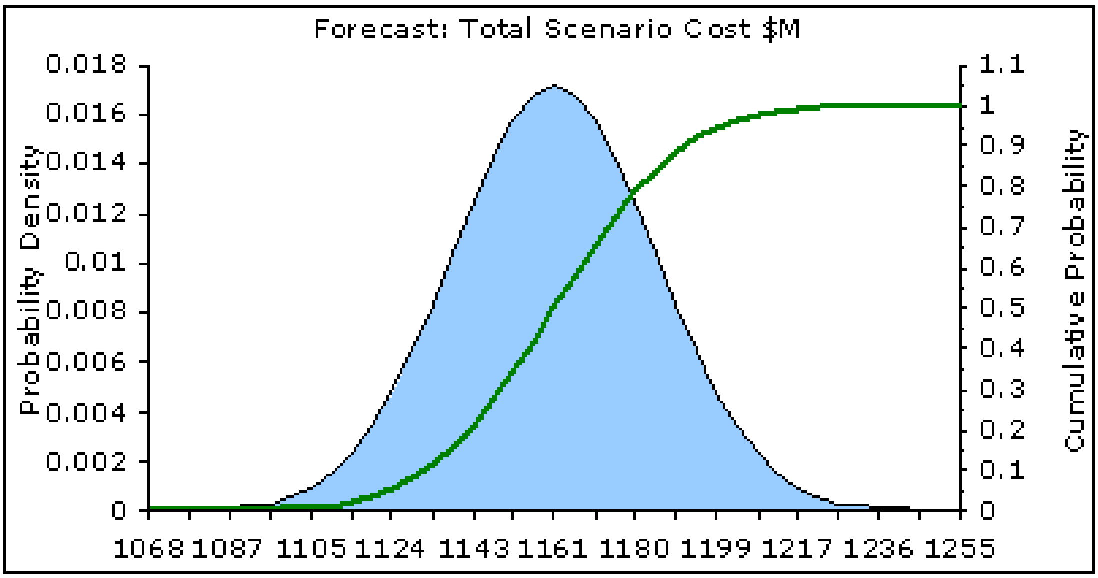

Figure 14: Cumulative and Probability Density Functions for SNOOS Mission Cost

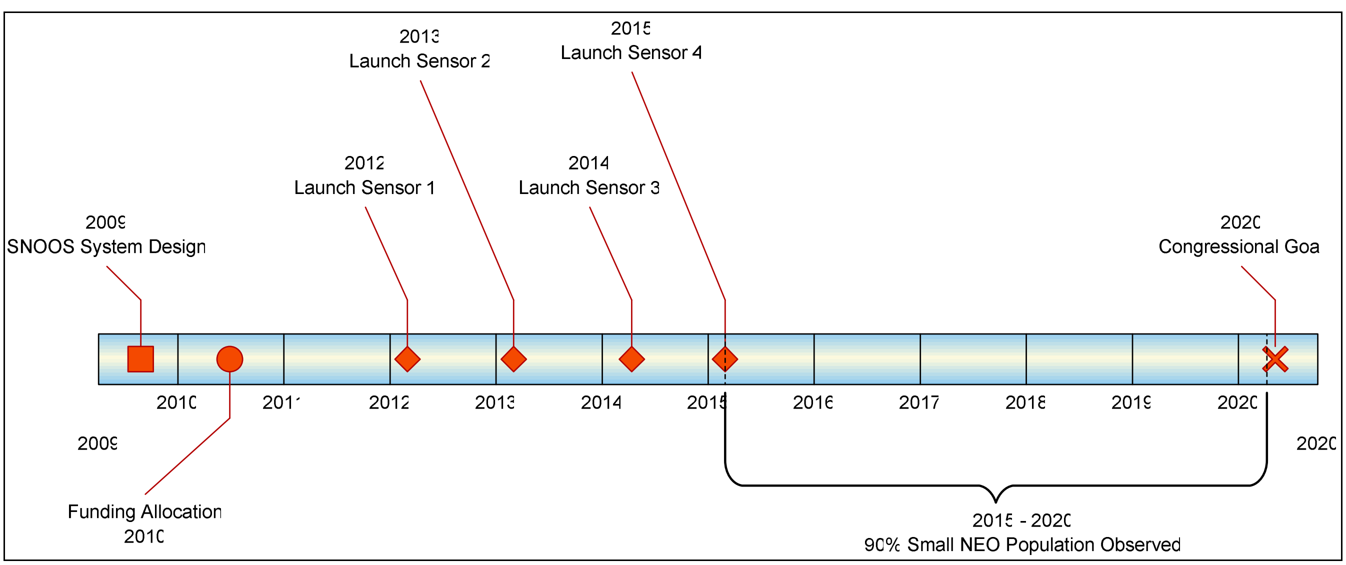

Figure 15: Potential SNOOS Deployment

Appendix A: SNOOS Stakeholder Value Determination

1 Purpose

The intent of this document is to summarize an exhaustive listing of Small Near-Earth Object Observing System (SNOOS) stakeholders and to determine each stakeholder's relative involvement (importance) with the system. The resulting effort is a focus on system parameters which when engineered correctly, provide the highest value for the dollar among the most important stakeholders.

2 Stakeholder Identification

2.1 U.S. Government

U.S. Government stakeholders involve government decision makers and federally funded organizations, ranging from Congress down to system operators and analysts that all have vested interests in system cost, performance, and operations.

U.S. NEO Governing Organization

The U.S. NEO governing organization is the lead SNOOS procuring organization. As part of its management of subsystems across the Planetary Defense System, the NEO governing organization also:

- Determines SNOOS operational policy
- Determines SNOOS program fiscal appropriations (i.e., contracts)
- Develops and implements NEO mitigation policy
- Procures NEO mitigation technology

U.S. Executive and Legislative Organization

The U.S. Legislative and Executive Organization is composed primarily of the Office of the President and the United States Congress. They are the purse holders and are primarily interested in SNOOS benefit/cost determination.

U.S. Military

The U.S. military could become primary system operators if determined by the U.S. NEO Governing Organization. In addition, the U.S. military may operate NEO mitigation techniques, especially if weaponized techniques are employed.

U.S. System Operators

U.S. System Operators, if other than the previous stakeholder group, perform the physical interaction with SNOOS. This primarily consists of system maintenance, system control, as well as reception of system data.

U.S. Analysis Community

This stakeholder group receives and analyzes SNOOS data. The analysis community is composed of federally funded government analysis agencies.

U.S. Emergency Response Agencies

U.S. Emergency Response Agencies are responsible for emplacing and executing mitigation techniques regarding near-earth object impacts on earth. This stakeholder group has a high interest in the accuracy of SNOOS observation data, as this determines the likelihood of object impact.

U.S. Law Enforcement Agencies

This stakeholder group assists with emergency response activities. In specific, this group also ensures rule of law remains in effect during the execution of mitigation techniques, as well as in the event of an object impact.

2.2 International Community

International Community stakeholders are roughly the equivalent U.S. functional stakeholder groups, but determined by the level of foreign involvement in SNOOS system development and operation. For our consideration, this can be determined by the level of financial input to the development of the system as well as policy regarding a mitigation technique.

International Governing Organization

Equivalent foreign stakeholder body to the U.S. NEO Governing Organization. However, this entity could come in the form of a single country, a consortium of countries, or an international body (e.g., European Union).

International Military Coalition

The foreign equivalent functioning stakeholder body to the U.S. Military.

International System Operators

The equivalent foreign stakeholder body to the U.S. System Operators.

International Analysis Community

The equivalent foreign stakeholder body to the U.S. Analysis Community. This group of stakeholders also includes foreign individuals and organizations outside of their respective governments, such as think tanks and industry.

International Emergency Response Organizations

The equivalent foreign stakeholder body to U.S. Emergency Response Organizations.

International Law Enforcement Agencies

The equivalent foreign stakeholder body to U.S. Law Enforcement Agencies.

2.3 Industry

The stakeholders in this functional group design, develop, and analyze system parameters and expected effectiveness.

System Developers

The System Developers consist of the organizations and individuals responsible for engineering the system.

Analysis/Research Community

The Analysis/Research Community consists of those performing similar functions to the U.S. Analysis Community, but may reside outside of the U.S. Government. These include universities, think tanks, and industry – all downstream consumers of system data.

SEOR Faculty

The SEOR faculty consists of the professors of Systems Engineering and Operations Research (SEOR) at George Mason University. These stakeholders hold a vested interest in the system to determine the practical level of SEOR program material that has been input to the system by its designers.

SEOR Project Team

The SEOR project team consists of contributing system modelers and designers from a functional engineering standpoint. This stakeholder group consists of candidate SEOR graduate students.

2.4 Other

Human Race

The last remaining stakeholder group consists of all human inhabitants of the earth whose primary interest in the system is assisting in the preservation of the species.

3 Stakeholder Needs Analysis

3.1 Key Stakeholder Identification

The stakeholders were assigned the following importance values. The values were determined by considering relative stakeholder weight to the system across financial, developmental, operational, and performance measuring contributions to the system.

Table 17: Stakeholder Weights

	Stakeholder	**Weight**
US Gov't	U.S. NEO Governing Organization	**1**
	U.S. Executive/Legislative	**0.8**
	U.S. Military	**0.9**
	U.S. System Operators	**0.8**
	U.S. Analysis Community	**0.8**
	U.S. Emergency Response Organizations	**0.3**
	U.S. Law Enforcement Agencies	**0.2**
Int'l Community	International Governing Organization	**0.9**
	International Military Coalition	**0.8**
	International System Operators	**0.8**
	International Analysis Community	**0.8**
	International Emergency Response Organizations	**0.3**
	International Law Enforcement Agencies	**0.2**
Industry	System Developers	**0.9**
	Analysis/Research Community	**0.6**
	SEOR Faculty	**0.9**
	SEOR Project Team	**0.9**
Other	Human Race	**0.1**

3.2 Needs Determination Heuristics

Stakeholder needs for a NEO Observing System were determined via the following heuristics:

1. Nominal system use cases
2. Capability gap analysis of current NEO Observing Systems
3. An evaluation of expected needs across the functional stakeholder spectrum
4. SEOR team methods for performing system effectiveness analysis prior to system development (operations research methods)

3.3 Use Cases

A set of nominal system use cases were developed to demonstrate how system actors (stakeholders) interact with the system. The actors involved perform the nominal actions, which when successfully executed demonstrate system value. The following sections detail each nominal use case.

Change Instrument Parameters

This use case demonstrates the scenario where a controllable instrument parameter needs to be changed to positively affect sensor performance. The use case is triggered by a member of the Operator and Analysis stakeholder groups requesting the change in system parameters (i.e., a data download, instrument re-targeting or temperature setpoint) and exits when the parameter is changed successfully. The use case diagram is presented in Figure 16. Table 18 documents the actions involved in the use case.

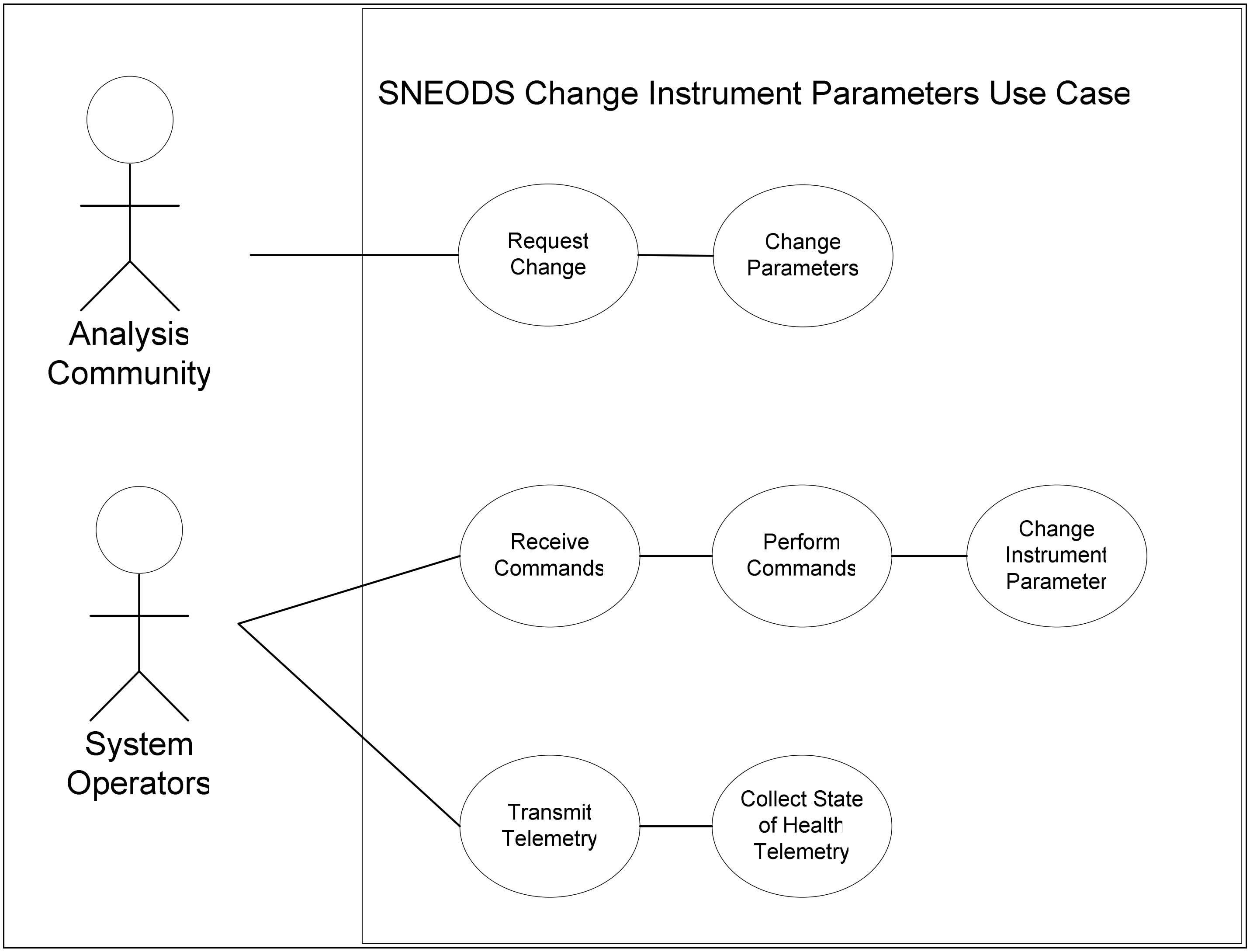

Figure 16: Use Case 1 – Change Instrument Parameters

Table 18: Use Case 1 – Change Instrument Parameters

Use Case:	**Change Instrument Parameters**	
Goal In Context:	Change the instrument parameters to affect the sensor performance.	
Scope:	SNOOS	
Pre-Condition:	System is operational	
Success End Condition:	Parameters set as commanded.	
Primary Actor:	System Operators	
Trigger Event:	Request for change in the instrument parameters.	
	Main Success Scenario	
Step	**Actor**	**Action Description**
1	Analysis Community	Requests a change to the parameters of the instrument
2	System Operators	Operators send commands to the system to change the parameters
3	System	Performs command
4	System	Collects State of Health telemetry
5	System Operators	Commands System to downlink telemetry
6	System	Downlinks telemetry
Related Information		
Schedule:	Periodically throughout life of the system	
Priority:	Must	

Transmit Data

This use case demonstrates the scenario where instrument data needs to be transmitted. The use case is triggered by an operational cadence for when the data storage device is full for the operational planning time period and ends when the data has been transmitted successfully. The use case diagram is presented in Figure 17. Table 19 documents the actions involved in the use case.

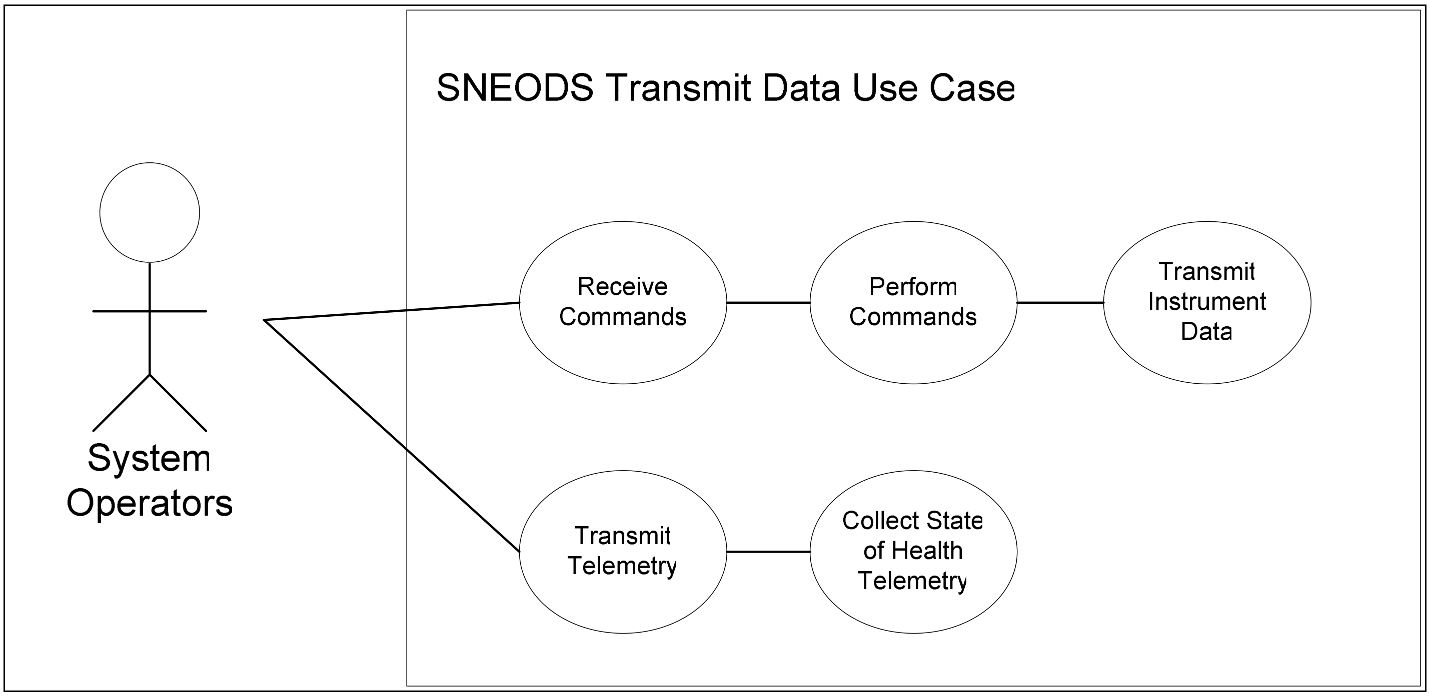

Figure 17: Use Case 2 – Transmit Data

Table 19: Use Case 2 – Transmit Data

Use Case:	**Transmit Instrument Data**	
Goal In Context:	Transmit the data generated by the instrument for use by external systems.	
Scope:	SNOOS	
Pre-Condition:	System is operational	
Success End Condition:	All data is transmitted successfully with no errors.	
Primary Actor:	System Operators	
Trigger Event:	The storage subsystem of SNOOS is nearly full.	
	Main Success Scenario	
Step	**Actor**	**Action Description**
1	System Operators	Operators send commands to the system to transmit instrument data
2	System	Performs command
3	System	Collects State of Health telemetry
4	System Operators	Commands System to downlink telemetry
5	System	Downlinks telemetry
Related Information		
Schedule:	Periodically throughout life of the system	
Priority:	Must	

Store Data

This use case demonstrates the scenario where the instrument data needs to be stored temporarily. The use case is triggered by the generation of instrument data and ends when the data is temporarily stored. The use case diagram is presented in Figure 18. Table 20 documents the actions involved in the use case.

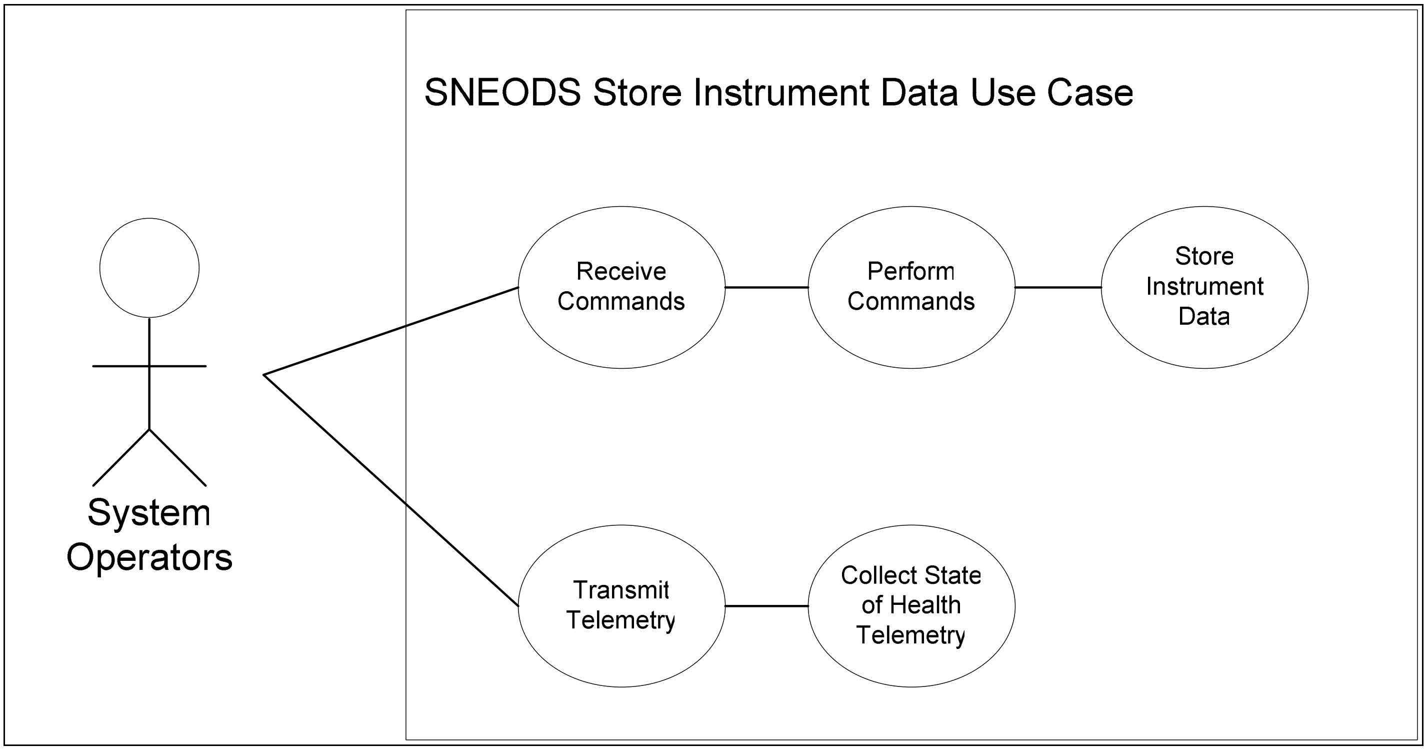

Figure 18: Use Case 3 – Store Data

Table 20: Use Case 3 – Store Data

Use Case:	**Store Instrument Data**	
Goal In Context:	Store the data generated by the instrument for transmission to the external system.	
Scope:	SNOOS	
Pre-Condition:	System is operational	
Success End Condition:	Data is temporarily stored on the system successfully.	
Primary Actor:	System Operators	
Trigger Event:	Data is generated continuously by the instrument and needs to be stored.	
	Main Success Scenario	
Step	**Actor**	**Action Description**
1	System Operators	Operators send commands to the system to store instrument data
2	System	Performs command
3	System	Collects State of Health telemetry
4	System Operators	Commands System to downlink telemetry
5	System	Downlinks telemetry

Related Information	
Schedule:	Periodically throughout life of the system
Priority:	Must

Change Pointing

This use case demonstrates the scenario where a change in instrument pointing needs to occur for a specific observation. The use case is triggered by a member of the Analysis Community requesting the change in pointing and ends when the desired pointing is changed successfully. The use case diagram is presented in Figure 19. Table 21 documents the actions involved in the use case.

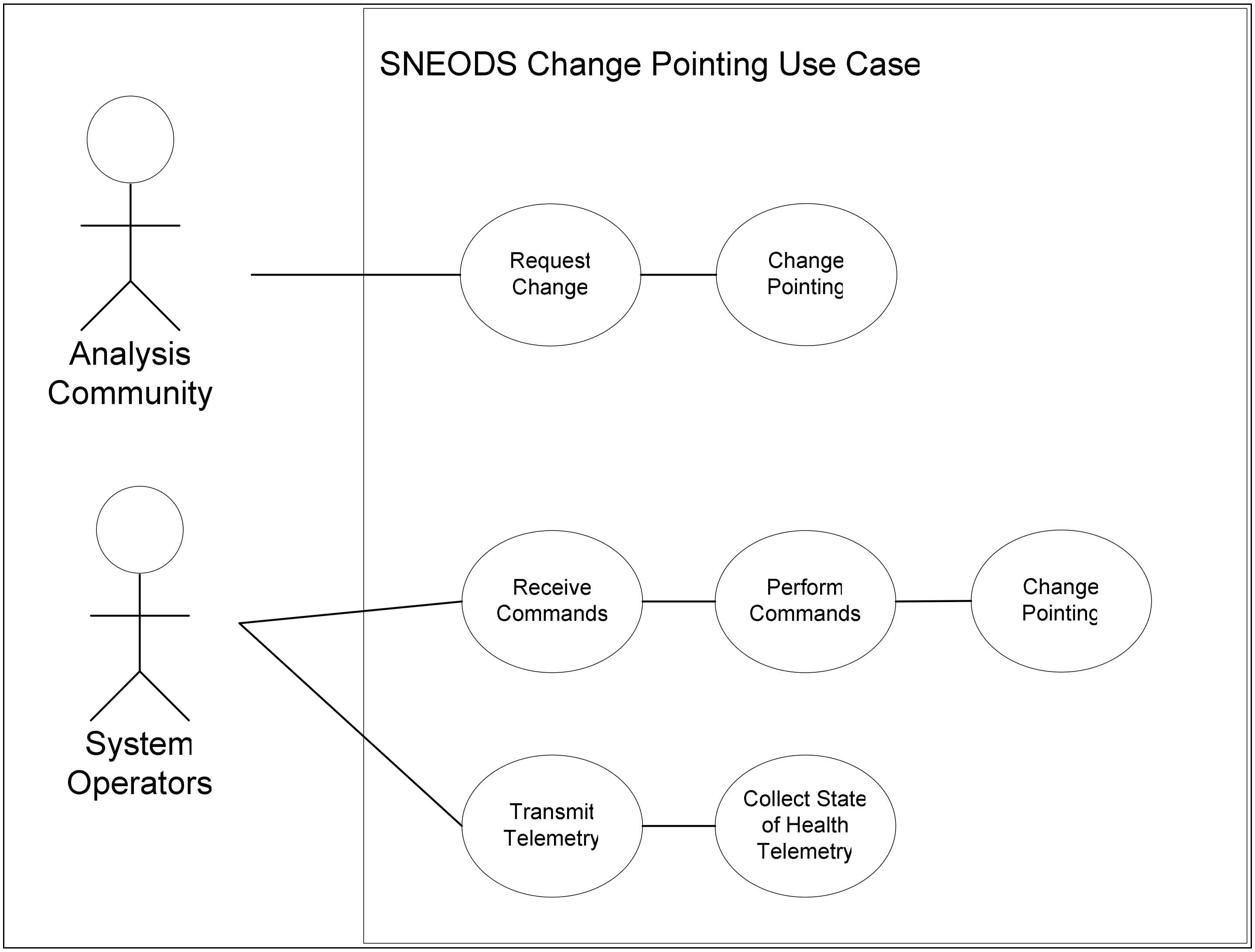

Figure 19: Use Case 4 – Change Pointing

Table 21: Use Case 4 – Change Pointing

Use Case:	**Change Pointing**	
Goal In Context:	Change the pointing of the instrument to target a certain section of space.	
Scope:	SNOOS	
Pre-Condition:	System is on orbit	
Success End Condition:	The pointing is changed correctly to target the correct section of space.	
Primary Actor:	System Operators	
Trigger Event:	A new pointing target is identified	
	Main Success Scenario	
Step	**Actor**	**Action Description**
1	Analysis Community	Requests a change to the pointing of the instrument
2	System Operators	Operators Send commands to the system to perform pointing change
3	System	Performs commanded maneuver
4	System	Collects State of Health telemetry
5	System Operators	Commands System to downlink telemetry
6	System	Downlinks telemetry
Related Information		
Schedule:	Periodically throughout life of the system	
Priority:	Must	

Change Timing

This use case demonstrates the scenario where a change in instrument timing needs to occur for a specific observation. The use case is triggered by a member of the Analysis Community requesting the change in timing and ends when the desired timing is changed successfully. The use case diagram is presented in Figure 20. Table 22 documents the actions involved in the use case.

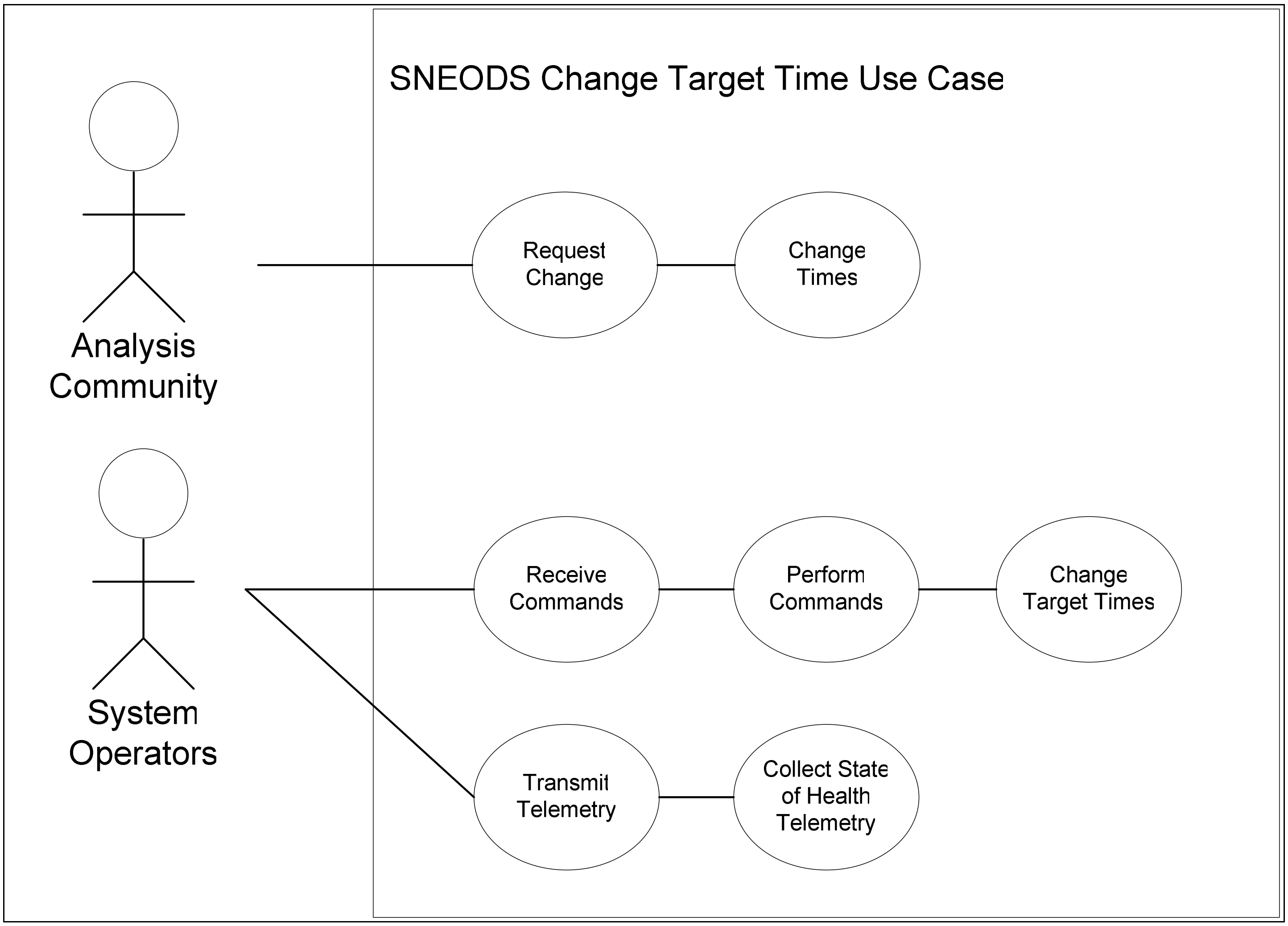

Figure 20: Use Case 5 – Change Timing

Table 22: Use Case 5 – Change Timing

Use Case:	**Change Target Times**	
Goal In Context:	Change the time the satellite system collects data	
Scope:	SNOOS	
Pre-Condition:	System is operational	
Success End Condition:	Target time is changed to desired option	
Primary Actor:	System Operators	
Trigger Event:	Request for new target time (collection timing)	
	Main Success Scenario	
Step	**Actor**	**Action Description**
1	Analysis Community	Requests a change to view a section of space at specific time
2	System Operators	Commands new time
3	System	Performs commanded adjustment
4	System	Collects State of Health telemetry
5	System Operators	Commands System to downlink telemetry
6	System	Downlinks telemetry
Related Information		
Schedule:	Periodically throughout life of the system	
Priority:	Must	

4 Capability gap analysis

The gap analysis preformed on currently operating systems used for Near Earth Object detection showed several interesting things as discussed in the business case. The current systems are actively looking for larger objects (diameters greater than 140 meters) and therefore are not designed to search for the smaller objects of interest to SNOOS. Current visible telescope systems can only operate during good weather at night. Current ground based systems have a limitation on the size of objects they can detect as evidenced by their limiting absolute magnitude. These factors influence stakeholder needs for SNOOS.

5 Operations Research Methods

In order to deliver meaningful results, the SEOR team will need to quantitatively evaluate potential system forms that can fulfill SNOOS stakeholder needs. One key method in determining whether stakeholder needs have been addressed is effectiveness analysis. This method involves operations research (OR) techniques that model attributes (data) of the potential system alternative forms in order to obtain a quantitative measure (measure of effectiveness – MOE) of how well the system is meeting stakeholder needs. In other words, the determination of stakeholder needs that can be physically modeled to show how stakeholders how well a system can physically perform (e.g. by a computer simulation), is a consideration in determining stakeholder needs.

6 Value Mapping

The stakeholder needs determination heuristics resulted in the following needs identification. The main needs of the Small Near-Earth Object Observing System are:

1. Detect Objects 30 – 140 meters in diameter
2. 24/7 Space Coverage
3. Data Management
4. Maximum Space Coverage
5. Object Impact Warning Time
6. System Cost Effectiveness
7. System Reliability

Each need was ranked via a multiplicative heuristic combining stakeholder weight and the value of each need to the stakeholder. The method results in a normalized matrix which sums the value of each need across all functional stakeholders to determine its relative value to SNOOS.

The need values range from zero to 0.5, where a score of zero indicates system capability of no importance to the stakeholder, where a score of 0.5 indicates critical system effectiveness for the stakeholder. Table 23 lists the definition of value by range for a specific stakeholder. Table 24 lists each stakeholder's need value as determined by the value mapping heuristic. Each need's weighted total score across all stakeholders is highlighted in yellow and also displayed in Figure 21.

Table 23: SNOOS Value Definition

Value Range	*Value Equivalence*
0 - 0.1	Of no or minimal importance
0.11 - 0.2	Importance a consideration
0.21 - 0.3	Somewhat important
0.31 - 0.4	Of high importance
0.41 - 0.5	Of critical importance

Table 24: SNOOS Need Analysis

	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	0.15	0.2	0.2	0.15	0.05	0.05	0.1	**1**
	U.S. Executive/Legislative	0.1	0.2	0.3	0.01	0.01	0.3	0.07	**0.8**
	U.S. Military	0.15	0.15	0.1	0.15	0.15	0.05	0.1	**0.9**
	U.S. System Operators	0.17	0.17	0.15	0.15	0.05	0.01	0.15	**0.8**
	U.S. Analysis Community	0.03	0.3	0.03	0.1	0.3	0.01	0.1	**0.8**
	U.S. Emergency Response Organizations	0.1	0.2	0.5	0.04	0.04	0.04	0.04	**0.3**
	U.S. Law Enforcement Agencies	0.1	0.2	0.5	0.04	0.04	0.04	0.04	**0.2**
Int'l Community	International Governing Organization	0.15	0.2	0.2	0.15	0.05	0.05	0.1	**0.9**
	International Military Coalition	0.15	0.15	0.1	0.15	0.15	0.05	0.1	**0.8**
	International System Operators	0.17	0.17	0.15	0.15	0.05	0.01	0.15	**0.8**
	International Analysis Community	0.03	0.3	0.03	0.1	0.3	0.01	0.1	**0.8**
	International Emergency Response Organizations	0.1	0.2	0.5	0.04	0.04	0.04	0.04	**0.3**
	International Law Enforcement Agencies	0.1	0.2	0.5	0.04	0.04	0.04	0.04	**0.2**
Industry	System Developers	0.125	0.125	0.125	0.125	0.125	0.125	0.125	**0.9**
	Analysis/Research Community	0.03	0.3	0.03	0.1	0.3	0.01	0.1	**0.6**
	SEOR Faculty	0	0.2	0.05	0.2	0.2	0.2	0.1	**0.9**
	SEOR Project Team	0.2	0.1	0.2	0.2	0.05	0.1	0.05	**0.9**
Other	Human Race	0.16	0.16	0.4	0.05	0.01	0.01	0.2	**0.1**
	Weighted Totals	1.37	2.22	1.97	1.53	1.48	0.88	1.18	

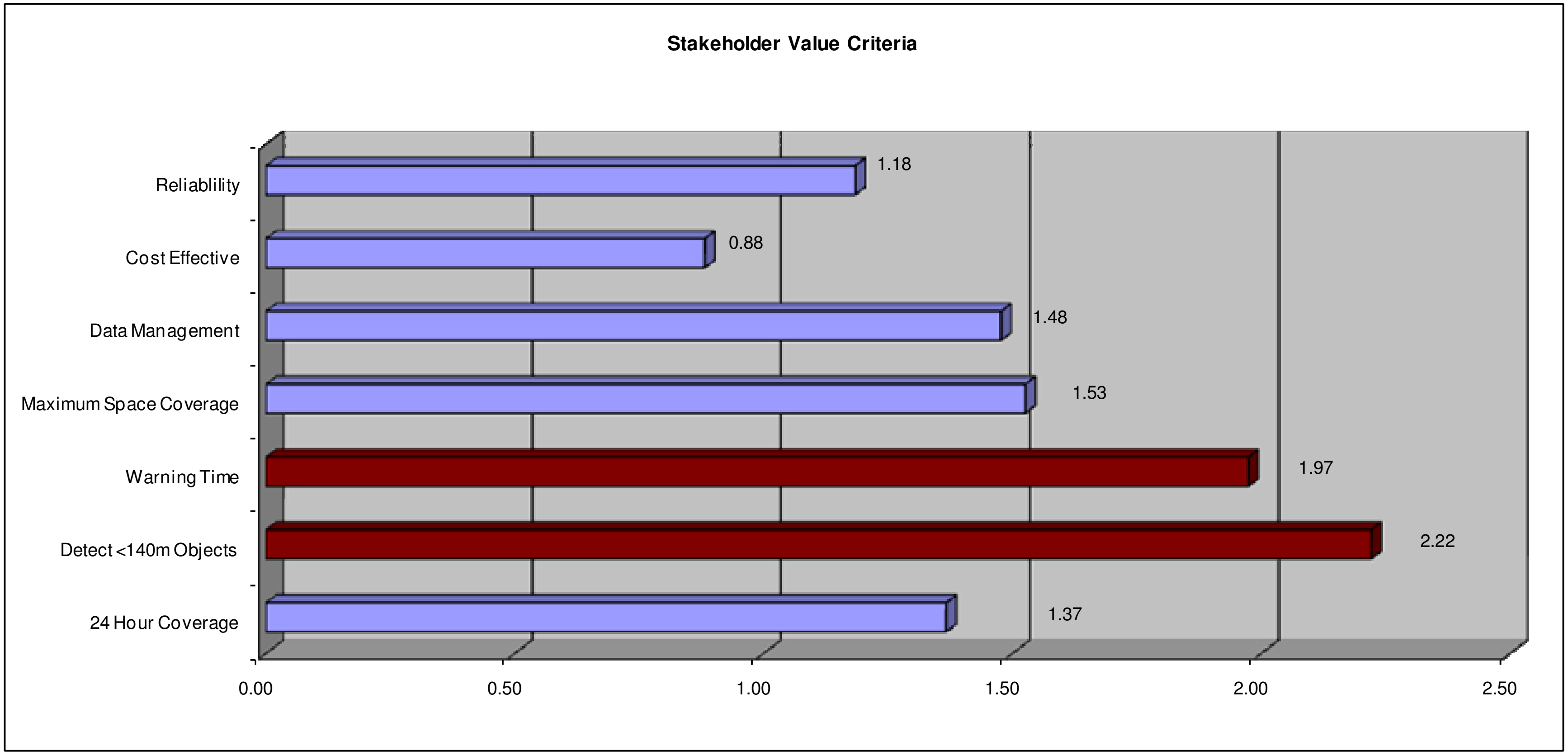

Figure 21: Stakeholder Value Criteria

6.1 Quality Function Deployment

The need analysis and stakeholder value mapping performed for SNOOS serves as input data for transformation of stakeholder value criteria in to design quality. The form by which this was method was executed consists of Quality Function Deployment (QFD). QFD transforms customer needs, or SNOOS value, into engineering characteristics so that metrics can be attained to measure how well stakeholder value is realized.

The following engineering characteristics provide metrics by which stakeholder value can be measured throughout SNOOS development:

- Instrument Performance
- Slewing
- Pointing Accuracy
- Instrument Location
- Mass
- Instrument Cost
- Data Storage Capacity
- Data Uplink
- Data Downlink
- Data Processing
- Bandwidth
- Reliability
- Power
- Mission Cost

Within the quality function deployment, each stakeholder need was ranked using the calculated weight listed in Table 24. Each need is coupled with the engineering characteristic to provide a quantitative measure of the relationship between need and the technical parameter, from an engineering standpoint. Figure 22 displays the relationship correlation scale between a need and the engineering characteristic.

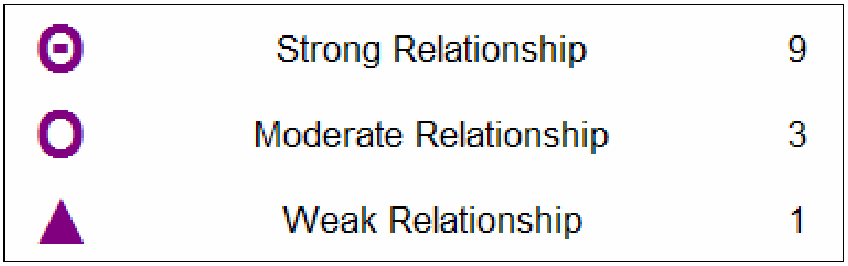

Figure 22: Relationship Correlation of Need and Engineering Characteristic

From the quality function deployment results illustrated in the QFD matrix in Figure 23, the top five performance parameters for design consideration are:

1. Data Downlink
2. Instrument Performance
3. Mission Cost
4. Data Storage
5. Time to Goal

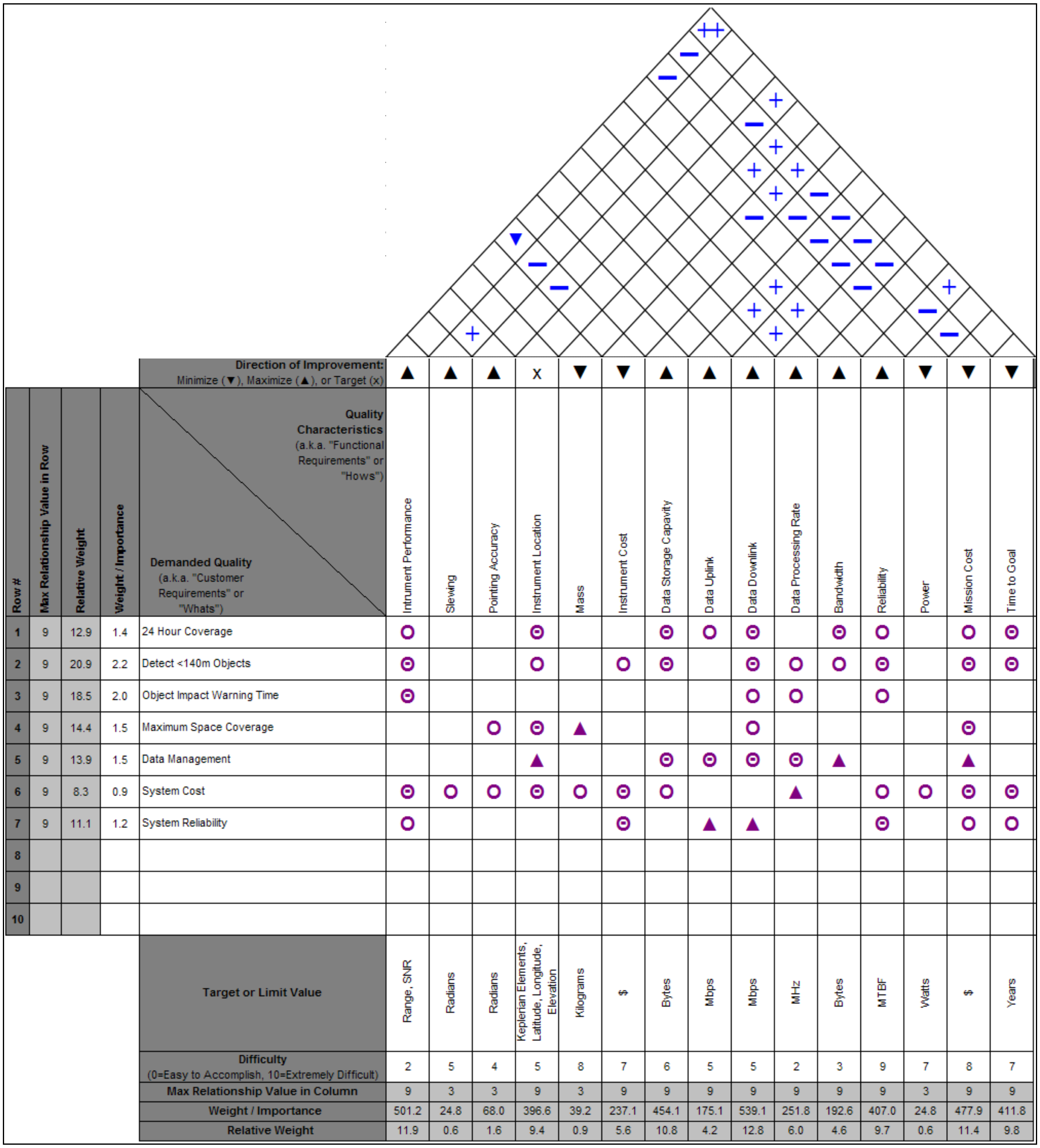

Figure 23: SNOOS Quality Function Deployment Matrix

7 System Development Process

The SNOOS developmental life cycle will take the form illustrated in Figure 24. Of paramount importance is the feedback control prior to the initiation of each subsequent system development function. Feedback regarding system development is attained through internal system engineering technical review as well as vetted system development process methods by key stakeholders. The feedback/validation processes allow for incremental verification of the system throughout the development life cycle.

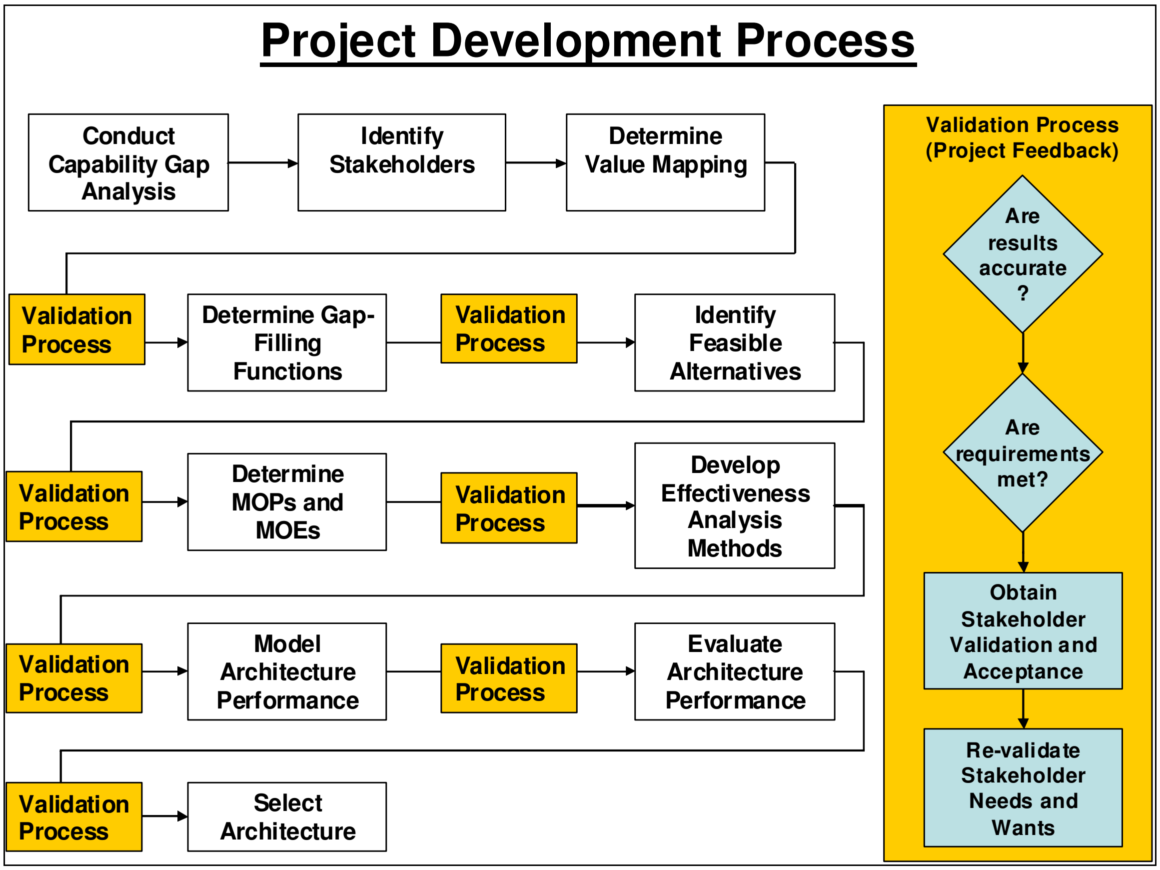

Figure 24: SNOOS Development Process

Appendix B: System Requirements

This requirements section provides a working set of functional requirements needed to perform an analysis of alternatives. The analysis of alternatives will result in down selection of candidate technologies to an optimal technology that most efficiently and effectively fulfills the requirements set to enable SNOOS functions.

B.1 Functional Requirements

This section contains the SNOOS functional requirements by major subsystem. The functional requirements in this section specify the functions that each subsystem must perform to produce the optimal system outputs.

B.1.1 Instrument Subsystem

This section details the functional requirements that must be met by the Instrument Subsystem.

B.1.1.1

The Instrument Subsystem shall be capable of capturing the selected energy form for Near-Earth Objects of sizes greater than 30 meters in diameter within a targeted grid.

B.1.1.2

The Instrument Subsystem shall be capable of capturing the selected ambient energy form of the targeted grid.

B.1.1.3

The Instrument Subsystem shall provide re-targeting capability.

B.1.1.4

The Instrument Subsystem shall provide orientation status feedback to external systems.

B.1.1.5

The Instrument Subsystem shall provide control capability to maintain orientation.

B.1.1.6

The Instrument Subsystem shall provide the ability to cumulatively target a 4 pi solid angle grid (full sky coverage).

B.1.1.7

The Instrument Subsystem shall provide health feedback status to external systems.
B.1.1.8

The Instrument Subsystem shall be controllable by external system command.

B.1.2 Data Storage Subsystem

This section details the functional requirements that must be met by the Data Storage Subsystem.

B.1.2.1

The Data Storage Subsystem shall provide the ability to store captured grid energy.

B.1.2.2

The Data Storage Subsystem shall provide redundant storage capability.

B.1.2.3

The Data Storage Subsystem shall store captured grid energy at the instrument rate of actively or passively collected energy.

B.1.2.4

The Data Storage Subsystem shall convert captured grid energy by the instrument into data storage format.

B.1.2.5

The Data Storage Subsystem shall maintain the captured grid observation data

B.1.2.6

The Data Storage Subsystem shall provide an interface to external systems.

B.1.2.7

The Data Storage Subsystem shall be controllable from external systems.

B.1.3 Data Transmission Subsystem

This section details the functional requirements that must be met by the Data Transmission Subsystem.

B.1.3.1

The Data Transmission Subsystem shall provide the ability to transmit stored grid data.

B.1.3.2

The Data Transmission Subsystem shall provide an interface to external systems for data reception.
B.1.3.3

The Data Transmission Subsystem shall provide the ability to receive control signals from external systems.

B.2 Non-Functional Requirements

This section contains the SNOOS non-functional requirements by non-functional requirement category.
Performance Requirements

B.2.1

The Instrument Subsystem shall capture the required energy to produce a false acceptance rate of less than less than 0.01.

B.2.2

The Instrument Subsystem shall capture the required energy to produce a false rejection rate of less than 0.01.

B.2.3

The Instrument Subsystem shall have a service life of no less than 17 years.

B.2.4

The Instrument Subsystem shall possess targeting precision greater than 1 arc second.

B.2.5

The Data Storage Subsystem shall possess the ability to store over 99% of the captured grid energy form over a selected grid range or time period.

B.3 Reliability Requirements

B.3.1

All major subsystems shall maintain an uptime percentage of no less than 97%.

B.4 Environmental Requirements

B.4.1

Deployment and operation of any SNOOS subsystem shall not interfere with external system operations.

B.4.2

Deployment and operation of any SNOOS subsystem shall adhere to environmental regulations set forth by local governments.

B.4.3

Deployment, operation, and decommissioning of SNOOS subsystems shall adhere to NASA Standard 8719.14.

Appendix C: SNOOS Function Decomposition and Functional Architecture

SNOOS is a system within the greater Planetary Defense Mission System (Figure 25). The high-level SNOOS architecture selected consists of three primary subsystems that provide the necessary functions and interface with external systems that provide SNOOS control (sensor re-targeting, attitude control, health monitoring, data transmission, etc.). The system functional decomposition is illustrated in Figure 26. The SNOOS major subsystems (Figure 27) are:

1. Instrument Subsystem
2. Data Storage Subsystem
3. Data Transmission Subsystem

C.1 Concept of Operations

SNOOS combines hardware (sensor instrumentation, power system, storage medium, etc.) and software to search defined sectors (grids) of space relative to earth surface positions, capture (sense) the grid, and transmit captured grid data to external systems performing data analysis, to include signature recognition in the presence of near-earth object(s) in the observed grid(s). The primary output of SNOOS is captured grid data for post-processing by external systems to detect the presence a NEO within that grid.

C.2 Overview of High-Level System Functions

The SNOOS subsystems are functionally decomposed (Figure 26) down to the level required to perform an analysis of alternatives required to down select an alternative technology/method for function instantiation.

Though the architecture presented for SNOOS is fairly high level, the alternatives under analysis comprise the most critical functions required of a sensor system needed to perform small NEO observation. In addition, a real-world system effectiveness evaluation method is executed by the SEOR team. As a result, the level of functional decomposition for SNOOS is primarily limited to high-level critical functions for which (1) the physical parameters of a space-based sensor system would encompass, and (2) the SEOR team possesses core competency and available tools to perform architecture performance evaluation. Low level functions such as data collection frequency, nozzle design for sensor attitude reorientation, or database classes are not considered.

This section details the inputs and function outputs performed by SNOOS, as illustrated in Figure 28. The system is further detailed in Integration Definition (IDEF) form for the decomposed subsystem functions and their respective inputs and outputs.

Figure 29, Figure 30, Figure 31, and Figure 32 detail the system architecture at the various levels of SNOOS functional hierarchy. The high-level system functions serve as input to the requirements derivation.

C.2.1 Capture Grid

Capture Grid (1.1.1) delivers and orients the sensor for the physical collection of grid energy by the instrument subsystem. This is performed in either an active or passive energy transmission.

C.2.2 Store Grid

Store Grid (1.1.2) converts the captured grid energy in to a recognizable data format and stores the data within the Data Storage Subsystem's hardware.

C.2.3 Transmit Grid

Transmit Grid (1.1.3) downlinks saved grid energy to earth-based ground stations. In addition, the Data Transmission Subsystem receives commands from external systems to re-orient sensors, check health status, etc.

C.3 Overview of Subsystems

C.3.1 Instrument Subsystem

The instrument subsystem consists of the physical sensing instruments that search the defined grid(s) for Near-Earth Objects. The instrument subsystem passively or actively collects energy from the observed grid for storage and transmission to external systems.

C.3.2 Data Storage Subsystem

The data storage subsystem stores the captured grid energy to a selected storage medium. The subsystem creates a repository of collected grid data, and is comprised of the hardware storage medium and the grid observation data.

C.3.3 Data Transmission Subsystem

The data transmission subsystem consists of the hardware components and transmission medium needed to transmit SNOOS grid data to external systems.

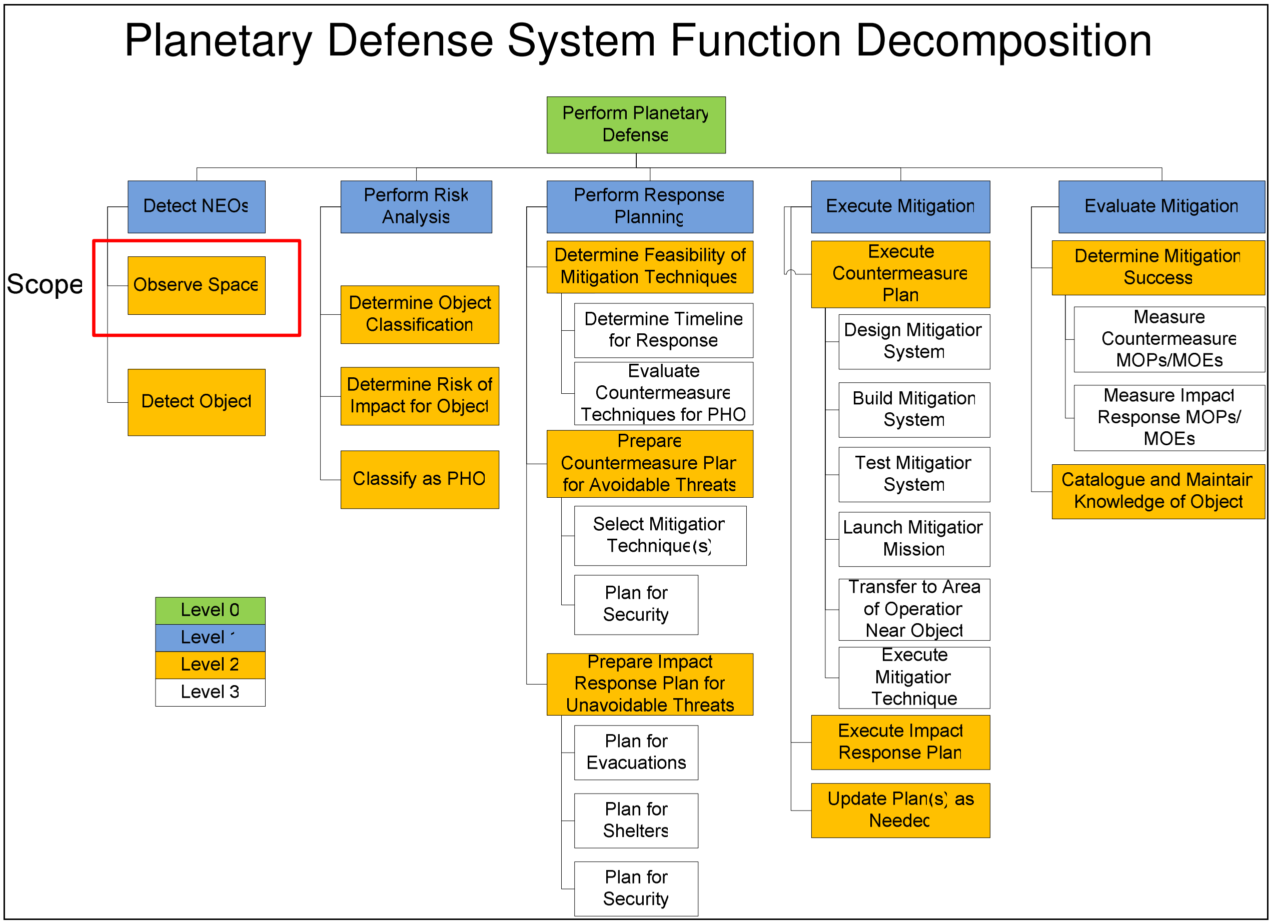

Figure 25: Planetary Defense System Architecture

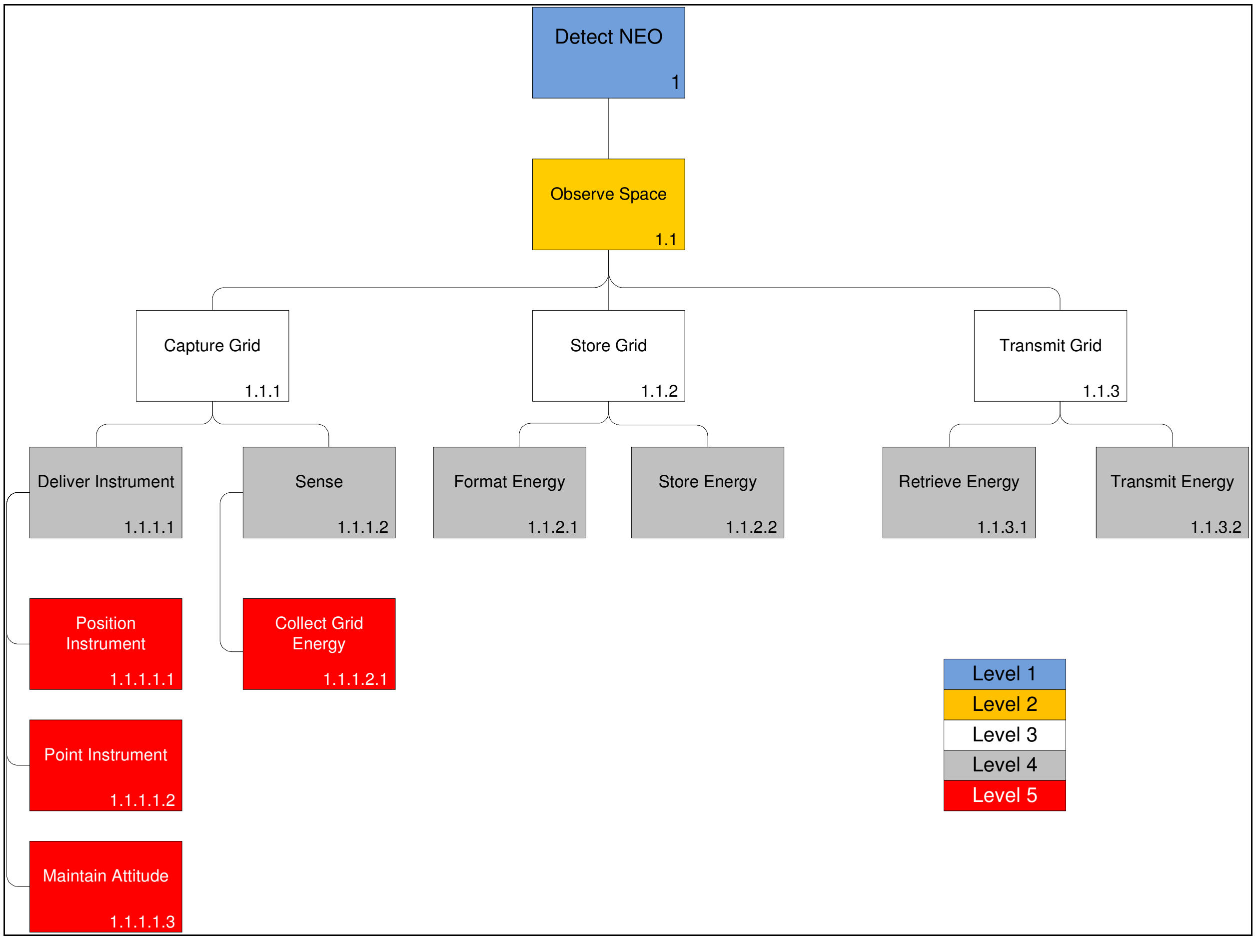

Figure 26: SNOOS Function Decomposition

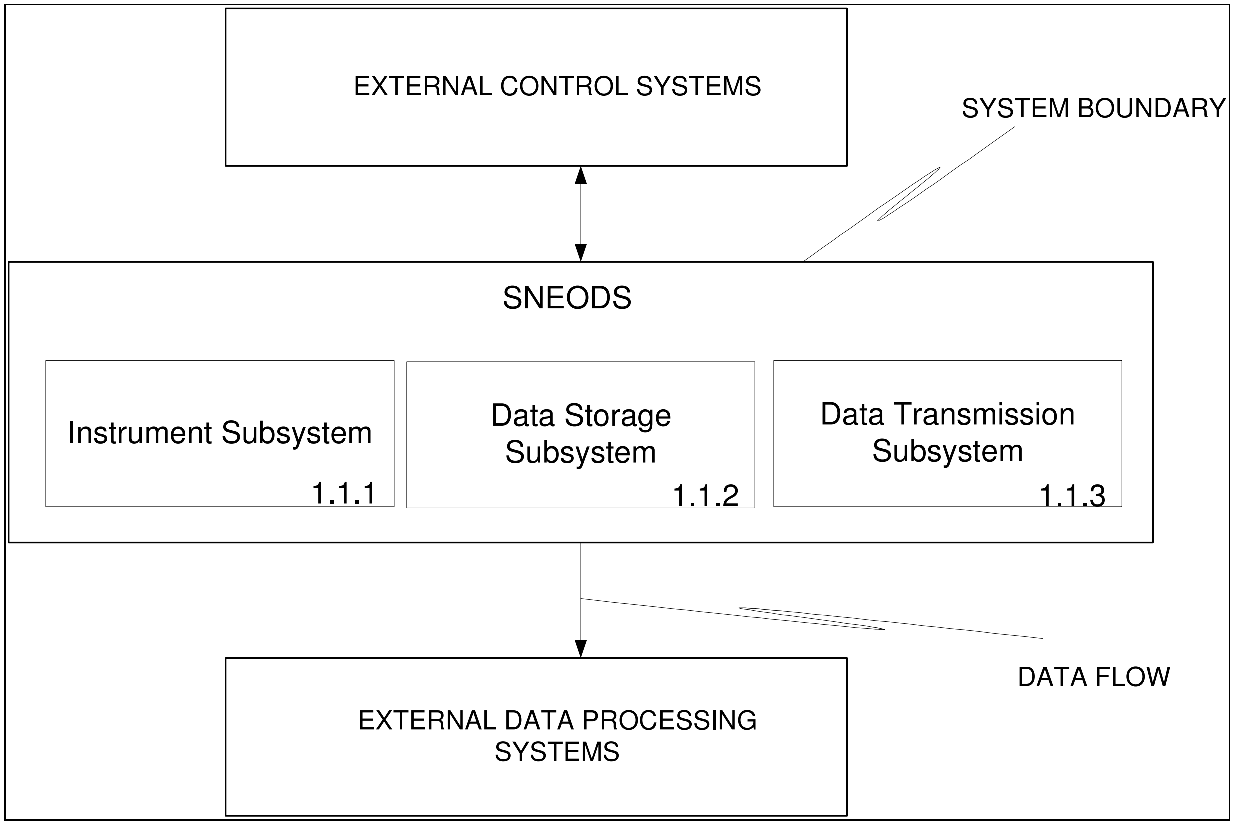

Figure 27: External Systems Diagram

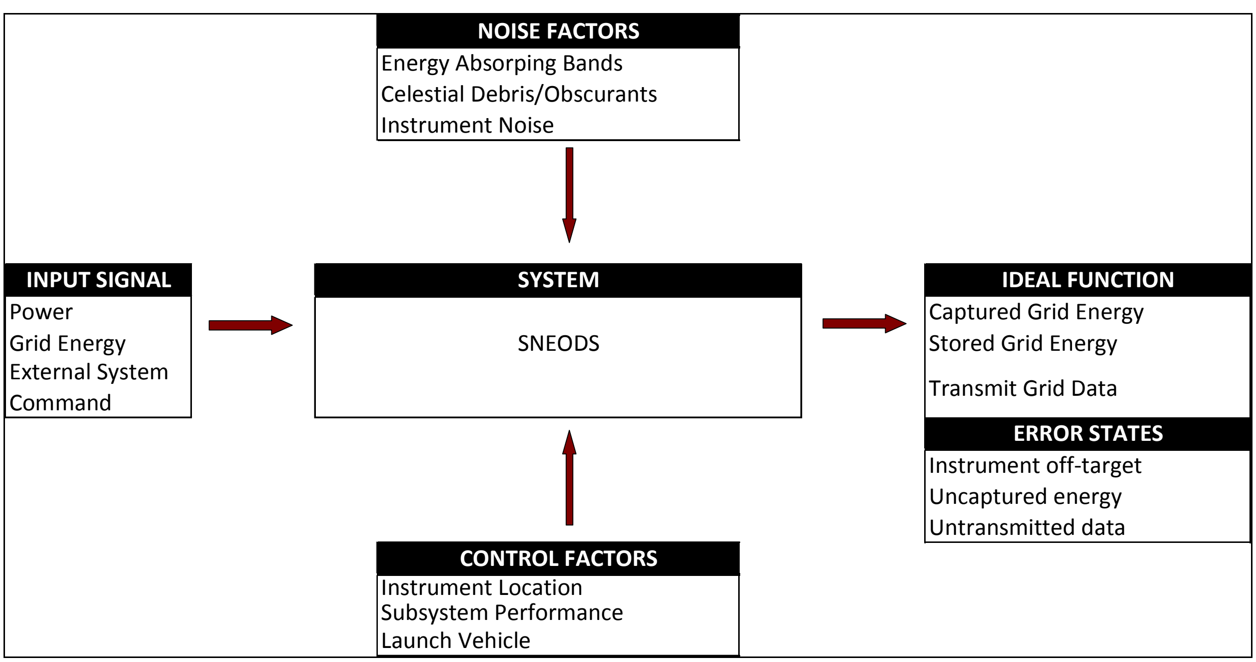

Figure 28: SNOOS p-Diagram

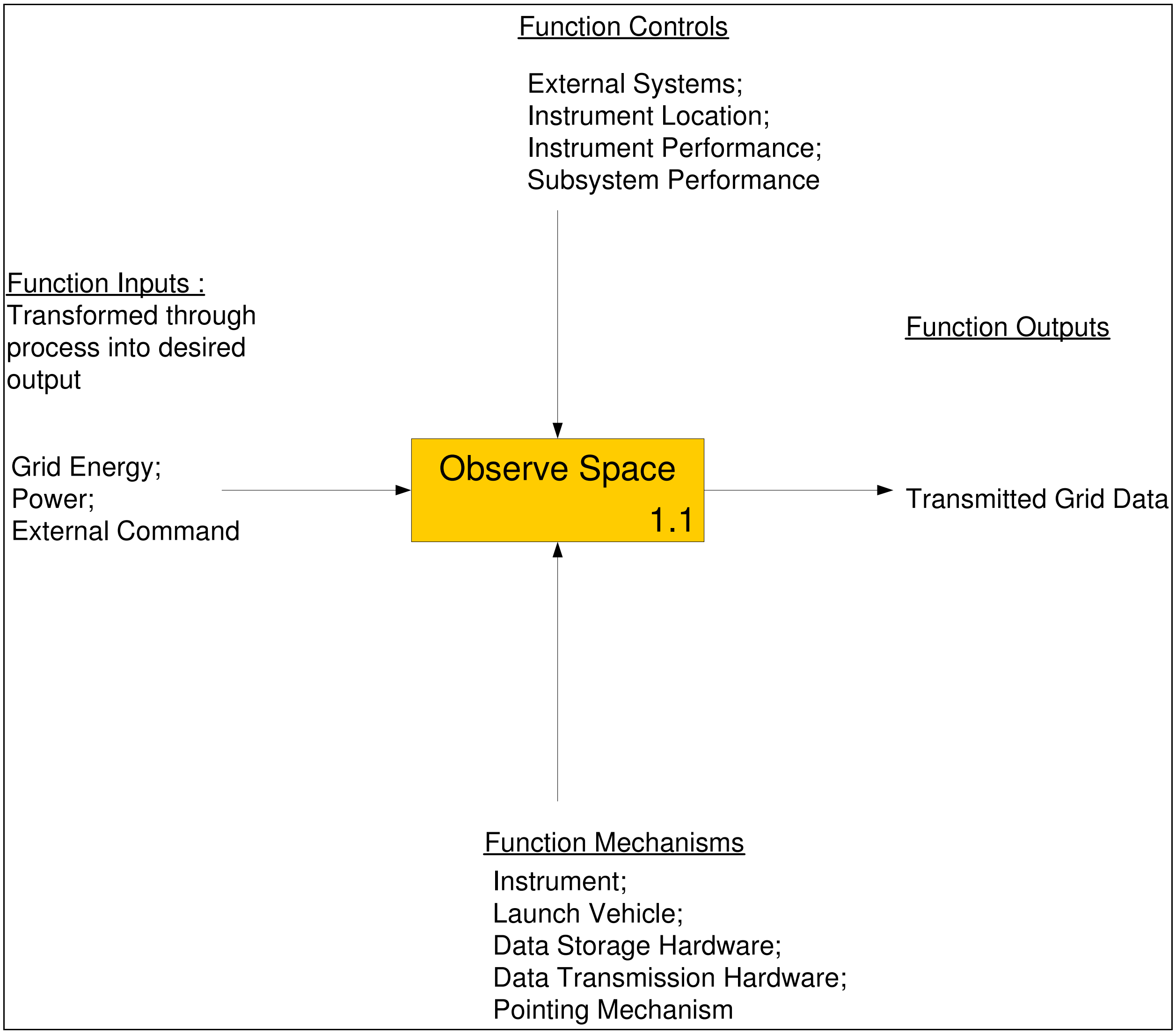

Figure 29: Level 1 Functional Architecture

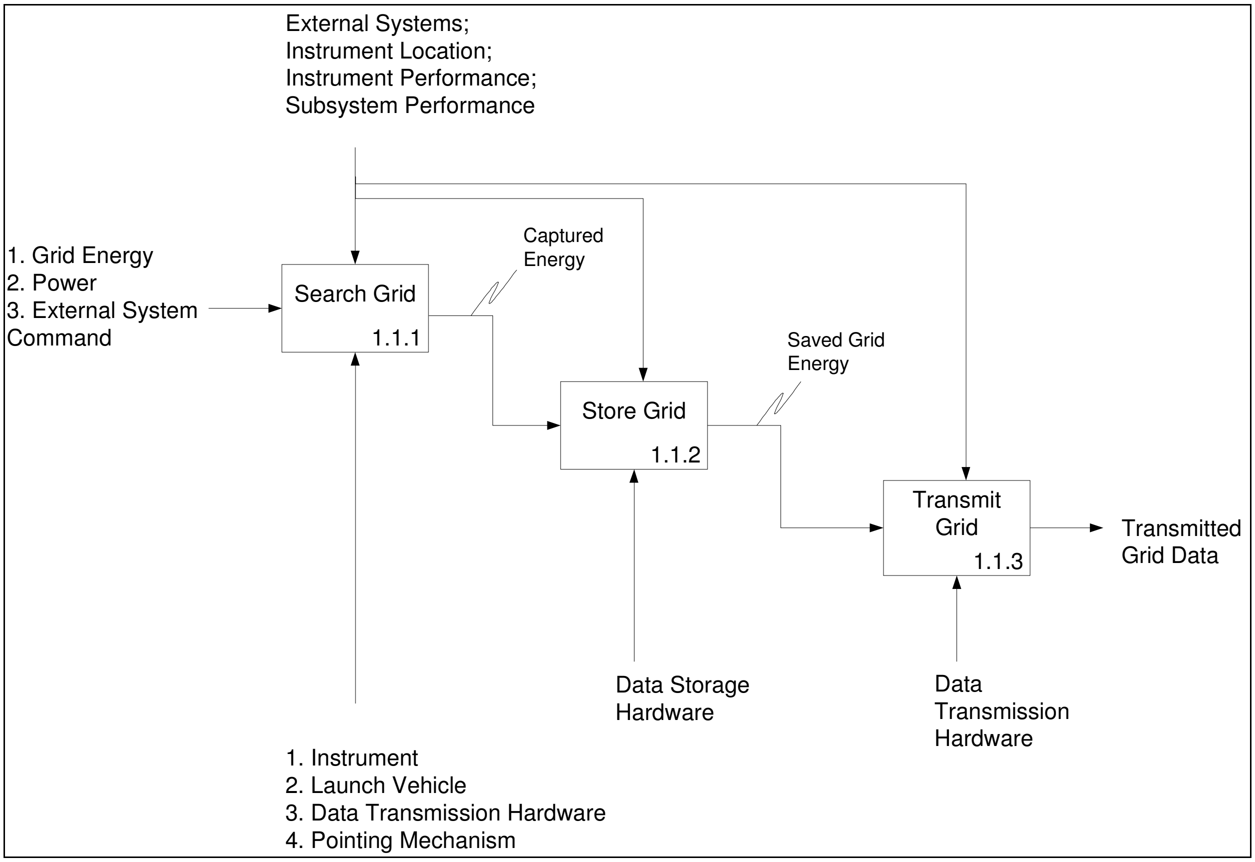

Figure 30: Level 2 Functional Architecture

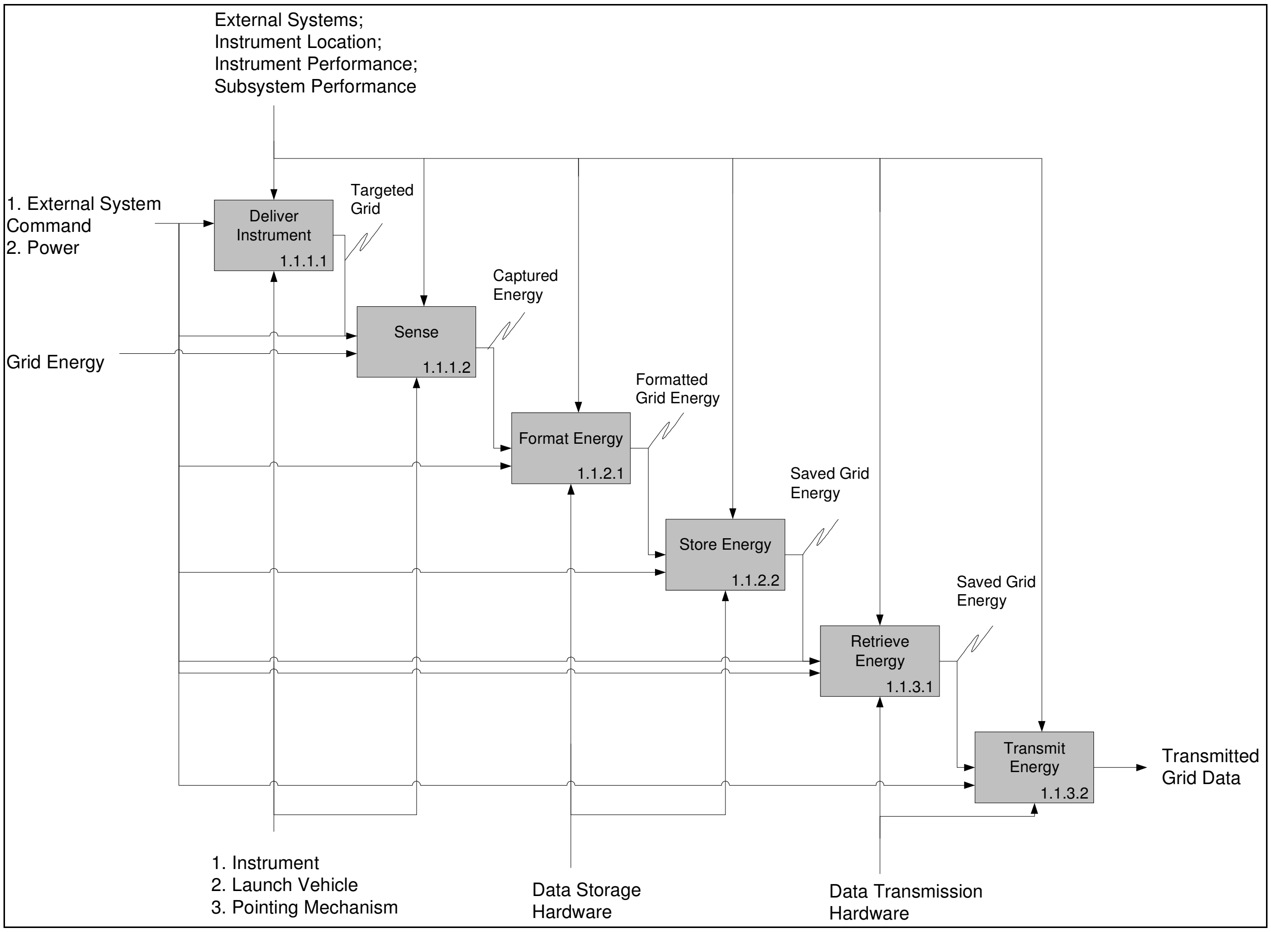

Figure 31: Level 3 Functional Architecture

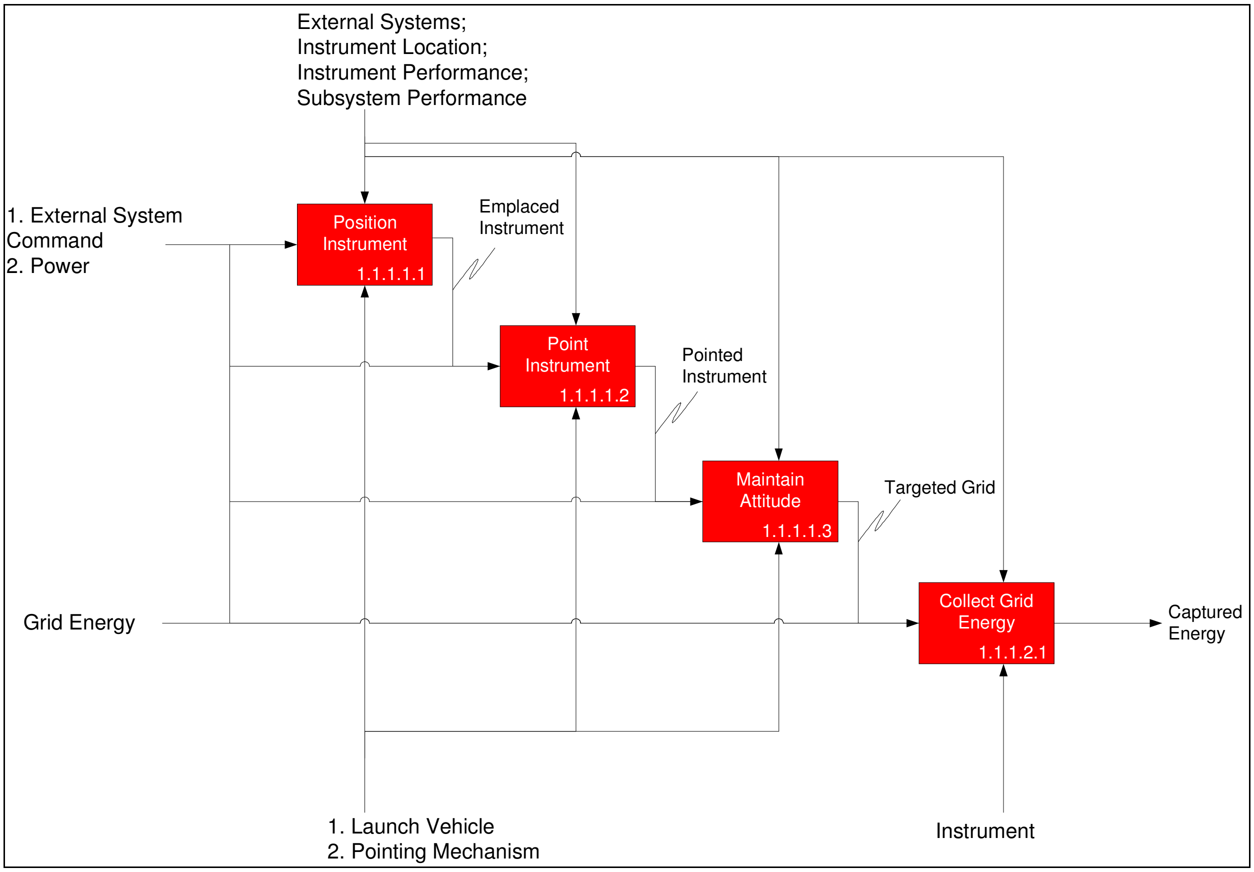

Figure 32: Level 4 Functional Architecture

Appendix D: Analysis of Function Alternatives

Purpose

The purpose of this document is to present the Analysis of Alternatives (AoA) methodology for the down selection of form instantiation required to deliver the functions of the Small Near Earth Object Observing System (SNOOS).

Specifically for this project, the critical function forms selected serve as the input variables to the SEOR team's Effectiveness Analysis architecture. As such, all possible combinations of function alternatives are created as potential "system architectures" and their respective performances are measured through the SEOR team's Effectiveness Analysis methodology in order to down select the best performing system architecture.

Evaluation Methods

The alternative forms under consideration to deliver SNOOS functions are evaluated at the lowest decomposed levels of the SNOOS functional architecture. Some functions are inherent (i.e. 1.1.3.1) within the hardware/code that would be required for instantiation and will not be evaluated.

The SNOOS alternatives are down selected based on two methods; an attribute scoring system relative to the class of alternatives being evaluated and the system measure of effectiveness (MOE) of NEO observation capability. The system MOE is quantitatively computed based on the SEOR team's effectiveness analysis of the system which involves a physics-based model simulating a combination of function alternatives (architecture candidates) and a modeled small NEO population. Thus, some alternatives will be evaluated based on the scoring system, while others, mainly the alternatives under the Instrument Subsystem (Function 1.1.1), will be evaluated based on the effectiveness analysis.

Within the scoring system, attribute values of the alternatives are determined based on the core competency of the of SEOR team; (1) SEOR team ability to model the attribute for effectiveness analysis, leading to form selection; (2) Domain knowledge of attribute characteristics based on research performed for the project as well as the team's professional arena (aerospace and sensors related job functions).

Table 25 lists the value hierarchy for the attribute under evaluation. A score of 5 indicates the attribute possesses the highest value for the function under analysis. The scoring system and the attributes under evaluation are rooted in the engineering quality function deployment (QFD). For example, an attribute of an alternative requiring a large-capacity, expensive power source would receive an attribute rating of 1 or 2 for the attributes of cost and power, where as an alternative requiring a smaller power source would receive a higher score.

Table 25: Alternative Attribute Scoring System

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

The analysis of alternatives for the Instrument Subsystem heavily ties in to the business model and cash flow analysis for this potential system. A higher cash flow for subsystem alternatives will provide more capability, which in turn will result in a higher MOE which is the accelerated cataloging of small Near Earth Objects (NEOs). A higher cash flow will provide a higher number of detectors, as well as the capability to deliver the detectors to more strategic locations (orbits) requiring more expensive launch vehicles.

Attributes of Alternatives

The attributes provided in this section are defined in order to determine weight (value) for a particular subsystem alternative under analysis. The attributes encompass criteria pertinent to the alternative being evaluated to deliver a specific subsystem function. Scoring of each alternative based on the relative attributes follows the SEOR team methodology outlined in Section 2.0.

Some of the attributes listed below are influenced by key engineering parameters (technical requirements) determined by SNOOS quality function deployment. Their scores are also coupled with other attributes, as determined by the QFD.

Modeling Capability

A measure of ease, or ability, for an alternative to be modeled by the SEOR team's method for effectiveness analysis

Cost

The monetary costs to develop, deploy, maintain, or otherwise achieve the alternative under consideration

24/7 Operational Capability

The ability for an alternative to maintain 27/4 functional capability

Field of View (FOV)

An angular measure of viewable space in which a given instrument can collect ambient energy

Power

The amount of electrical energy required for an alternative to physically operate. This attribute has a high correlation with 24/7, Cost, FOV, and Range attributes for Instrument alternatives. Mass (QFD) constraints are also a consideration here

Range

A generalized measure of distance for a given instrument's ability to capture grid/NEO energy

Reliability

A measure of mean time between failure (MTBF), packet loss rate, etc., for a given alternative

Mass

A measure of the amount of physical matter an alternative would require for instantiation, in kilograms

Storage Size

The maximum data storage capacity available to an alternative under consideration; heavily correlated with cost and mass attributes

Write Speed

The rate at which data can be stored to the alternative's medium

Read Speed

The rate at which stored data can be retrieved from the alternative's medium

Downlink Rate

The rate at which data can be transmitted by an alternative

Uplink Rate

The rate at which data (commands) can be received by a SNOOS subsystem

Ground Station Availability

The availability of ground-based stations to receive RF comms (data downlink) for SNOOS data transfer. A higher score indicates more available stations for data passing per time unit

Temperature Range

The required thermal operating range of an alternative; heavily correlated with mass and power attributes

NEO Observation Rate

The rate at which NEOs are observed as a result of the implementing the alternative. This attribute is measured as a percentage of NEOs observed of the total modeled population

Search Rate

The rate at which an instrument can search space. This attribute is heavily correlated with instrument performance. Too high a search rate may result in dimmer (smaller) NEOs being unobserved

Report Generation

The effectiveness analysis tool will have to be able to export intermediate results for analysis for each scenario (architecture) run. Parameters of interest include the distances between the sun, sensors and NEOs in addition to detection statistics

Orbital Mechanics

The capability or ease of the effectiveness analysis tool to correctly model the orbital mechanics data associated with small NEOs

Sensor Modeling

The capability of the effectiveness analysis tool to model alternative detection instruments and their respective performance characteristics (range, FOV, etc.)

Pointing Modeling

The effectiveness analysis tool will have to be able to account for how the sensor is pointing, as this affects space observation capability

Knowledge of Tool

This attribute determines the SEOR team's ability to utilize the tool for system effectiveness analysis, ranging from input data, model creation, execution, and output data generation

Access

If the SEOR team doesn't have access to the analysis tool in a timely fashion the tool would not be useful for the scope of this analysis

Functional Alternatives

Instrument Subsystem

The Instrument Subsystem is the most critical subsystem to address in terms of selecting alternatives. This is because the technology chosen for space observation and the placement of this technology affects NEO cataloging greater than the remaining subsystems.

Down selection of the alternatives will determine what instrument technology is selected to physically capture grid (space) energy needed to detect NEOs. In addition, the physical instrument location and attitude orientation must be selected in order to optimize the amount of space that can be targeted given the available number of detectors based on system cash flow.

The Instrument Subsystem alternatives also consist of the set of location/attitude alternatives whose attributes are able to be physically modeled by the SEOR team within the selected effectiveness analysis tool. The completion of the effectiveness analysis will yield a recommended set of alternatives given a cash flow model outlined in the SNOOS Business Case.

Position Instrument Alternatives

Table 26 lists the alternatives for the Position Instrument function and attributes for evaluation.

Table 26: Position Instrument Alternatives

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			

Alternative 1: Low Earth Orbit

Modeling Capability	[5]
Cost	[5]
NEO Observation Rate	[TBD BY EFFECTIVENESS ANALYSIS]
Total	TBD BY EFFECTIVENESS ANALYSIS

Alternative 2: L-Point(s) Orbit

Modeling Capability	[5]
Cost	[3]
NEO Observation Rate	[TBD BY EFFECTIVENESS ANALYSIS]
Total	TBD BY EFFECTIVENESS ANALYSIS

Alternative 3: Venus Orbit

Modeling Capability	[5]
Cost	[2]
NEO Observation Rate	[TBD BY EFFECTIVENESS ANALYSIS]
Total	TBD BY EFFECTIVENESS ANALYSIS

Alternative 4: LEO + LPO

Modeling Capability	[5]
Cost	[2]
NEO Observation Rate	[TBD BY EFFECTIVENESS ANALYSIS]
Total	TBD BY EFFECTIVENESS ANALYSIS

Alternative 5: LEO + VO

Modeling Capability	[5]
Cost	[2]
NEO Observation Rate	[TBD BY EFFECTIVENESS ANALYSIS]
Total	TBD BY EFFECTIVENESS ANALYSIS

Alternative 6: LPO + VO

Modeling Capability	[5]
Cost	[1]
NEO Observation Rate	[TBD BY EFFECTIVENESS ANALYSIS]
Total	TBD BY EFFECTIVENESS ANALYSIS

Alternative 7: LEO + LPO + VO

Modeling Capability	[5]
Cost	[2]
NEO Observation Rate	[TBD BY EFFECTIVENESS ANALYSIS]
Total	TBD BY EFFECTIVENESS ANALYSIS

Selected alternative to deliver the Position Instrument function (1.1.1.1.1) under the Instrument Subsystem: **TBD BY EFFECTIVENESS ANALYSIS**

Point Instrument Alternatives

Table 27 lists the alternatives for the Point Instrument function and attributes for evaluation.

Table 27: Point Instrument Alternatives

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

Alternative 1: Fixed Pointing

Modeling Capability	[5]
Search Rate	[4]
Cost	[2]
Total	11

Alternative 2: Independent Pointing

Modeling Capability	[2]
Search Rate	[3]
Cost	[2]
Total	7

Selected alternative to deliver the Point Instrument function (1.1.1.1.2) under the Instrument Subsystem: Fixed Pointing

<u>Maintain Attitude Alternatives</u>

Constrained Anti-Earth and Constrained Velocity attitudes produce very similar results for LEO orbits. Both (paired with our sensor selection and its FOV) guarantee that the sensor never sees the Earth, nor the sun if a sun synchronous orbit is selected. An Inertial attitude would have to be carefully chosen to keep the sensor from seeing the sun.

Additionally, orbit and orientation selections are very closely related and the SNOOS team must only consider combinations that do not point the instrument at the sun. Table 28 lists the alternatives for the Maintain Attitude function and attributes for evaluation.

Table 28: Maintain Attitude Alternatives

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

Alternative 1: Inertial Attitude

Modeling Capability	[4]
Search Rate	[TBD BY EFFECTIVENESS ANALYSIS]
Total	TBD BY EFFECTIVENESS ANALYSIS

Alternative 2: Constrained Anti-Earth

Modeling Capability	[5]
Search Rate	[TBD BY EFFECTIVENESS ANALYSIS]
Total	TBD BY EFFECTIVENESS ANALYSIS

Alternative 3: Constrained Velocity

Modeling Capability	[5]
Search Rate	[TBD BY EFFECTIVENESS ANALYSIS]
Total	TBD BY EFFECTIVENESS ANALYSIS

Selected alternative to deliver the Maintain Attitude function (1.1.1.1.3) under the Instrument Subsystem:

TBD BY EFFECTIVENESS ANALYSIS

Collect Energy Alternatives

Table 29 lists the alternatives for the Position Instrument function and attributes for evaluation.

Table 29: Collect Energy Alternatives

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

Alternative 1: Radar

Power Consumption	[2]
24/7 Capability	[3]
Cost	[2]
Range	[5]
FOV	[1]
Cost	[2]
Reliability	[4]
Total	22

Alternative 2: Laser

Power Consumption	[2]
24/7 Capability	[3]
Cost	[2]
Range	[4]
FOV	[1]
Cost	[2]
Reliability	[4]
Total	18

Alternative 3: Infrared

Power Consumption	[1]
24/7 Capability	[4]
Cost	[1]
Range	[5]
FOV	[5]
Cost	[1]
Reliability	[4]
Total	21

Alternative 4: Visible

Power Consumption	[5]
24/7 Capability	[4]
Cost	[5]
Range	[3]
FOV	[5]
Cost	[5]
Reliability	[4]
Total	31

Selected alternative to deliver the Collect Energy function (1.1.1.2.1) under the Instrument Subsystem: **Visible Band Sensor**

Data Storage Subsystem

Table 30 lists the alternatives for the Store Energy function and attributes for evaluation.

Table 30: Store Energy Alternatives

<table>
<tr><th>Function</th><th>Alternatives</th><th colspan="6">Attributes</th></tr>
<tr><td rowspan="3">Store Energy (1.1.2.2)</td><td>Solid State Drive (SSD)</td><td rowspan="3">Power Consumption</td><td rowspan="3">Cost</td><td rowspan="3">Storage Size</td><td rowspan="3">Write Speed</td><td rowspan="3">Read Speed</td><td rowspan="3">Reliability</td></tr>
<tr><td>Hard Disk Drive (HDD)</td></tr>
<tr><td>Magnetic Tape</td></tr>
</table>

Alternative 1: Solid State Drive (SSD)

Power Consumption	[5]
Cost	[2]
Storage Size	[4]
Write Speed	[5]
Read Speed	[5]
Reliability	[5]
Total	26

Alternative 2: Hard Disk Drive (HDD)

Power Consumption	[2]
Cost	[4]
Storage Size	[4]
Write Speed	[3]
Read Speed	[3]
Reliability	[3]
Total	18

Alternative 3: Magnetic Tape Drive (MTD)

Power Consumption	[3]
Cost	[5]
Storage Size	[2]
Write Speed	[1]
Read Speed	[1]
Reliability	[3]
Total	15

Selected alternative to deliver the Store Energy function (1.1.2.2) for the Data Storage Subsystem: **Solid State Drive (SSD)**

Data Transmission Subsystem

Table 31 lists the alternatives for the Transmit Energy function and attributes for evaluation.

Table 31: Transmit Data Alternatives

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				

Alternative 1: S-band Transmission

Power Consumption	[5]
Downlink Rate	[1]
Uplink Rate	[1]
GSA	[5]
Total	12

Alternative 2: X-band Transmission

Power Consumption	[4]
Downlink Rate	[3]
Uplink Rate	[3]
GSA	[5]
Total	15

Alternative 3: Ku-band Transmission

Power Consumption	[1]
Downlink Rate	[4]
Uplink Rate	[4]
GSA	[2]
Total	11

Alternative 3: Ka-band Transmission

Power Consumption	[1]
Downlink Rate	[5]
Uplink Rate	[5]
GSA	[3]
Total	14

Selected alternative to deliver the Transmit Energy function (1.1.3.2) for the Data Transmission Subsystem: **X-band Frequency**

Effectiveness Analysis Tool Selection

While many computational languages or simulation tools would be able to model potential SNOOS effectiveness analysis and compute the system MOE for a variety of alternative architectures, a few were selected to be evaluated based on availability and core competency of the SEOR team to utilize. Table 32 lists the alternatives for the Effectiveness Analysis tool for architecture performance evaluation.

Table 32: Effectiveness Analysis Modeling Tool Alternatives

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

Alternative 1: Matlab

Report Generation	[2]
Orbital Mechanics	[3]
Sensor Modeling	[2]
Pointing Modeling	[2]
Tool Knowledge	[4]
Access	[3]
Total	16

Alternative 2: Satellite Tool Kit (STK)

Report Generation	[5]
Orbital Mechanics	[5]
Sensor Modeling	[5]
Pointing Modeling	[5]
Tool Knowledge	[4]
Access	[3]
Total	27

Alternative 3: C/C++

Report Generation	[2]
Orbital Mechanics	[2]
Sensor Modeling	[2]
Pointing Modeling	[2]
Tool Knowledge	[1]
Access	[3]
Total	12

Selected alternative to model SNOOS effectiveness analysis: **Satellite Tool Kit (STK).**

Appendix E: Complete Alternative Architecture List

Case (Architecture) Number	Case Sensor Components							
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							
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						
case_0037	sat_1	sat_2	sat_L_3					

Case (Architecture) Number	Case Sensor Components							
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 (Architecture) Number	Case Sensor Components							
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					
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				
case_0098	sat_1	sat_2	sat_L_4	sat_L_5				
case_0099	sat_1	sat_2	sat_L_4	sat_V1				
case_0100	sat_1	sat_2	sat_L_4	sat_V2				
case_0101	sat_1	sat_2	sat_L_4	sat_V3				
case_0102	sat_1	sat_2	sat_L_5	sat_V1				
case_0103	sat_1	sat_2	sat_L_5	sat_V2				
case_0104	sat_1	sat_2	sat_L_5	sat_V3				
case_0105	sat_1	sat_2	sat_V1	sat_V2				
case_0106	sat_1	sat_2	sat_V1	sat_V3				
case_0107	sat_1	sat_2	sat_V2	sat_V3				
case_0108	sat_1	sat_L_3	sat_L_4	sat_L_5				
case_0109	sat_1	sat_L_3	sat_L_4	sat_V1				
case_0110	sat_1	sat_L_3	sat_L_4	sat_V2				
case_0111	sat_1	sat_L_3	sat_L_4	sat_V3				
case_0112	sat_1	sat_L_3	sat_L_5	sat_V1				
case_0113	sat_1	sat_L_3	sat_L_5	sat_V2				
case_0114	sat_1	sat_L_3	sat_L_5	sat_V3				
case_0115	sat_1	sat_L_3	sat_V1	sat_V2				

Case (Architecture) Number	Case Sensor Components							
case_0116	sat_1	sat_L_3	sat_V1	sat_V3				
case_0117	sat_1	sat_L_3	sat_V2	sat_V3				
case_0118	sat_1	sat_L_4	sat_L_5	sat_V1				
case_0119	sat_1	sat_L_4	sat_L_5	sat_V2				
case_0120	sat_1	sat_L_4	sat_L_5	sat_V3				
case_0121	sat_1	sat_L_4	sat_V1	sat_V2				
case_0122	sat_1	sat_L_4	sat_V1	sat_V3				
case_0123	sat_1	sat_L_4	sat_V2	sat_V3				
case_0124	sat_1	sat_L_5	sat_V1	sat_V2				
case_0125	sat_1	sat_L_5	sat_V1	sat_V3				
case_0126	sat_1	sat_L_5	sat_V2	sat_V3				
case_0127	sat_1	sat_V1	sat_V2	sat_V3				
case_0128	sat_2	sat_L_3	sat_L_4	sat_L_5				
case_0129	sat_2	sat_L_3	sat_L_4	sat_V1				
case_0130	sat_2	sat_L_3	sat_L_4	sat_V2				
case_0131	sat_2	sat_L_3	sat_L_4	sat_V3				
case_0132	sat_2	sat_L_3	sat_L_5	sat_V1				
case_0133	sat_2	sat_L_3	sat_L_5	sat_V2				
case_0134	sat_2	sat_L_3	sat_L_5	sat_V3				
case_0135	sat_2	sat_L_3	sat_V1	sat_V2				
case_0136	sat_2	sat_L_3	sat_V1	sat_V3				
case_0137	sat_2	sat_L_3	sat_V2	sat_V3				
case_0138	sat_2	sat_L_4	sat_L_5	sat_V1				
case_0139	sat_2	sat_L_4	sat_L_5	sat_V2				
case_0140	sat_2	sat_L_4	sat_L_5	sat_V3				
case_0141	sat_2	sat_L_4	sat_V1	sat_V2				
case_0142	sat_2	sat_L_4	sat_V1	sat_V3				
case_0143	sat_2	sat_L_4	sat_V2	sat_V3				
case_0144	sat_2	sat_L_5	sat_V1	sat_V2				
case_0145	sat_2	sat_L_5	sat_V1	sat_V3				
case_0146	sat_2	sat_L_5	sat_V2	sat_V3				
case_0147	sat_2	sat_V1	sat_V2	sat_V3				
case_0148	sat_L_3	sat_L_4	sat_L_5	sat_V1				
case_0149	sat_L_3	sat_L_4	sat_L_5	sat_V2				
case_0150	sat_L_3	sat_L_4	sat_L_5	sat_V3				
case_0151	sat_L_3	sat_L_4	sat_V1	sat_V2				
case_0152	sat_L_3	sat_L_4	sat_V1	sat_V3				
case_0153	sat_L_3	sat_L_4	sat_V2	sat_V3				
case_0154	sat_L_3	sat_L_5	sat_V1	sat_V2				

Case (Architecture) Number	Case Sensor Components						
case_0155	sat_L_3	sat_L_5	sat_V1	sat_V3			
case_0156	sat_L_3	sat_L_5	sat_V2	sat_V3			
case_0157	sat_L_3	sat_V1	sat_V2	sat_V3			
case_0158	sat_L_4	sat_L_5	sat_V1	sat_V2			
case_0159	sat_L_4	sat_L_5	sat_V1	sat_V3			
case_0160	sat_L_4	sat_L_5	sat_V2	sat_V3			
case_0161	sat_L_4	sat_V1	sat_V2	sat_V3			
case_0162	sat_L_5	sat_V1	sat_V2	sat_V3			
case_0163	sat_1	sat_2	sat_L_3	sat_L_4	sat_L_5		
case_0164	sat_1	sat_2	sat_L_3	sat_L_4	sat_V1		
case_0165	sat_1	sat_2	sat_L_3	sat_L_4	sat_V2		
case_0166	sat_1	sat_2	sat_L_3	sat_L_4	sat_V3		
case_0167	sat_1	sat_2	sat_L_3	sat_L_5	sat_V1		
case_0168	sat_1	sat_2	sat_L_3	sat_L_5	sat_V2		
case_0169	sat_1	sat_2	sat_L_3	sat_L_5	sat_V3		
case_0170	sat_1	sat_2	sat_L_3	sat_V1	sat_V2		
case_0171	sat_1	sat_2	sat_L_3	sat_V1	sat_V3		
case_0172	sat_1	sat_2	sat_L_3	sat_V2	sat_V3		
case_0173	sat_1	sat_2	sat_L_4	sat_L_5	sat_V1		
case_0174	sat_1	sat_2	sat_L_4	sat_L_5	sat_V2		
case_0175	sat_1	sat_2	sat_L_4	sat_L_5	sat_V3		
case_0176	sat_1	sat_2	sat_L_4	sat_V1	sat_V2		
case_0177	sat_1	sat_2	sat_L_4	sat_V1	sat_V3		
case_0178	sat_1	sat_2	sat_L_4	sat_V2	sat_V3		
case_0179	sat_1	sat_2	sat_L_5	sat_V1	sat_V2		
case_0180	sat_1	sat_2	sat_L_5	sat_V1	sat_V3		
case_0181	sat_1	sat_2	sat_L_5	sat_V2	sat_V3		
case_0182	sat_1	sat_2	sat_V1	sat_V2	sat_V3		
case_0183	sat_1	sat_L_3	sat_L_4	sat_L_5	sat_V1		
case_0184	sat_1	sat_L_3	sat_L_4	sat_L_5	sat_V2		
case_0185	sat_1	sat_L_3	sat_L_4	sat_L_5	sat_V3		
case_0186	sat_1	sat_L_3	sat_L_4	sat_V1	sat_V2		
case_0187	sat_1	sat_L_3	sat_L_4	sat_V1	sat_V3		
case_0188	sat_1	sat_L_3	sat_L_4	sat_V2	sat_V3		
case_0189	sat_1	sat_L_3	sat_L_5	sat_V1	sat_V2		
case_0190	sat_1	sat_L_3	sat_L_5	sat_V1	sat_V3		
case_0191	sat_1	sat_L_3	sat_L_5	sat_V2	sat_V3		
case_0192	sat_1	sat_L_3	sat_V1	sat_V2	sat_V3		
case_0193	sat_1	sat_L_4	sat_L_5	sat_V1	sat_V2		

Case (Architecture) Number	Case Sensor Components							
case_0194	sat_1	sat_L_4	sat_L_5	sat_V1	sat_V3			
case_0195	sat_1	sat_L_4	sat_L_5	sat_V2	sat_V3			
case_0196	sat_1	sat_L_4	sat_V1	sat_V2	sat_V3			
case_0197	sat_1	sat_L_5	sat_V1	sat_V2	sat_V3			
case_0198	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V1			
case_0199	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V2			
case_0200	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V3			
case_0201	sat_2	sat_L_3	sat_L_4	sat_V1	sat_V2			
case_0202	sat_2	sat_L_3	sat_L_4	sat_V1	sat_V3			
case_0203	sat_2	sat_L_3	sat_L_4	sat_V2	sat_V3			
case_0204	sat_2	sat_L_3	sat_L_5	sat_V1	sat_V2			
case_0205	sat_2	sat_L_3	sat_L_5	sat_V1	sat_V3			
case_0206	sat_2	sat_L_3	sat_L_5	sat_V2	sat_V3			
case_0207	sat_2	sat_L_3	sat_V1	sat_V2	sat_V3			
case_0208	sat_2	sat_L_4	sat_L_5	sat_V1	sat_V2			
case_0209	sat_2	sat_L_4	sat_L_5	sat_V1	sat_V3			
case_0210	sat_2	sat_L_4	sat_L_5	sat_V2	sat_V3			
case_0211	sat_2	sat_L_4	sat_V1	sat_V2	sat_V3			
case_0212	sat_2	sat_L_5	sat_V1	sat_V2	sat_V3			
case_0213	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V2			
case_0214	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V3			
case_0215	sat_L_3	sat_L_4	sat_L_5	sat_V2	sat_V3			
case_0216	sat_L_3	sat_L_4	sat_V1	sat_V2	sat_V3			
case_0217	sat_L_3	sat_L_5	sat_V1	sat_V2	sat_V3			
case_0218	sat_L_4	sat_L_5	sat_V1	sat_V2	sat_V3			
case_0219	sat_1	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V1		
case_0220	sat_1	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V2		
case_0221	sat_1	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V3		
case_0222	sat_1	sat_2	sat_L_3	sat_L_4	sat_V1	sat_V2		
case_0223	sat_1	sat_2	sat_L_3	sat_L_4	sat_V1	sat_V3		
case_0224	sat_1	sat_2	sat_L_3	sat_L_4	sat_V2	sat_V3		
case_0225	sat_1	sat_2	sat_L_3	sat_L_5	sat_V1	sat_V2		
case_0226	sat_1	sat_2	sat_L_3	sat_L_5	sat_V1	sat_V3		
case_0227	sat_1	sat_2	sat_L_3	sat_L_5	sat_V2	sat_V3		
case_0228	sat_1	sat_2	sat_L_3	sat_V1	sat_V2	sat_V3		
case_0229	sat_1	sat_2	sat_L_4	sat_L_5	sat_V1	sat_V2		
case_0230	sat_1	sat_2	sat_L_4	sat_L_5	sat_V1	sat_V3		
case_0231	sat_1	sat_2	sat_L_4	sat_L_5	sat_V2	sat_V3		
case_0232	sat_1	sat_2	sat_L_4	sat_V1	sat_V2	sat_V3		

Case (Architecture) Number	Case Sensor Components							
case_0233	sat_1	sat_2	sat_L_5	sat_V1	sat_V2	sat_V3		
case_0234	sat_1	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V2		
case_0235	sat_1	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V3		
case_0236	sat_1	sat_L_3	sat_L_4	sat_L_5	sat_V2	sat_V3		
case_0237	sat_1	sat_L_3	sat_L_4	sat_V1	sat_V2	sat_V3		
case_0238	sat_1	sat_L_3	sat_L_5	sat_V1	sat_V2	sat_V3		
case_0239	sat_1	sat_L_4	sat_L_5	sat_V1	sat_V2	sat_V3		
case_0240	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V2		
case_0241	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V3		
case_0242	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V2	sat_V3		
case_0243	sat_2	sat_L_3	sat_L_4	sat_V1	sat_V2	sat_V3		
case_0244	sat_2	sat_L_3	sat_L_5	sat_V1	sat_V2	sat_V3		
case_0245	sat_2	sat_L_4	sat_L_5	sat_V1	sat_V2	sat_V3		
case_0246	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V2	sat_V3		
case_0247	sat_1	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V2	
case_0248	sat_1	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V3	
case_0249	sat_1	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V2	sat_V3	
case_0250	sat_1	sat_2	sat_L_3	sat_L_4	sat_V1	sat_V2	sat_V3	
case_0251	sat_1	sat_2	sat_L_3	sat_L_5	sat_V1	sat_V2	sat_V3	
case_0252	sat_1	sat_2	sat_L_4	sat_L_5	sat_V1	sat_V2	sat_V3	
case_0253	sat_1	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V2	sat_V3	
case_0254	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V2	sat_V3	
case_0255	sat_1	sat_2	sat_L_3	sat_L_4	sat_L_5	sat_V1	sat_V2	sat_V3

Appendix F: Complete Listing of Alternative Architecture Performances

Architecture	NEOs Observed	% Observed (MOE)
case_0001	370	68%
case_0002	380	70%
case_0003	340	63%
case_0004	327	60%
case_0005	346	64%
case_0006	409	75%
case_0007	404	75%
case_0008	423	78%
case_0009	420	77%
case_0010	466	86%
case_0011	439	81%
case_0012	455	84%
case_0013	458	85%
case_0014	467	86%
case_0015	464	86%
case_0016	456	84%
case_0017	437	81%
case_0018	447	82%
case_0019	455	84%
case_0020	465	86%
case_0021	461	85%
case_0022	405	75%
case_0023	411	76%
case_0024	461	85%
case_0025	456	84%
case_0026	475	88%
case_0027	407	75%
case_0028	457	84%
case_0029	450	83%
case_0030	459	85%
case_0031	458	85%
case_0032	460	85%
case_0033	464	86%
case_0034	468	86%
case_0035	468	86%
case_0036	462	85%
case_0037	483	89%

Architecture	NEOs Observed	% Observed (MOE)
case_0129	489	90%
case_0130	495	91%
case_0131	497	92%
case_0132	491	91%
case_0133	497	92%
case_0134	502	93%
case_0135	498	92%
case_0136	501	92%
case_0137	503	93%
case_0138	489	90%
case_0139	491	91%
case_0140	488	90%
case_0141	498	92%
case_0142	497	92%
case_0143	493	91%
case_0144	496	92%
case_0145	496	92%
case_0146	494	91%
case_0147	497	92%
case_0148	482	89%
case_0149	485	89%
case_0150	491	91%
case_0151	490	90%
case_0152	491	91%
case_0153	492	91%
case_0154	488	90%
case_0155	493	91%
case_0156	492	91%
case_0157	499	92%
case_0158	491	91%
case_0159	490	90%
case_0160	487	90%
case_0161	497	92%
case_0162	495	91%
case_0163	501	92%
case_0164	498	92%
case_0165	506	93%

Architecture	NEOs Observed	% Observed (MOE)
case_0038	457	84%
case_0039	466	86%
case_0040	471	87%
case_0041	482	89%
case_0042	476	88%
case_0043	483	89%
case_0044	492	91%
case_0045	488	90%
case_0046	496	92%
case_0047	497	92%
case_0048	473	87%
case_0049	483	89%
case_0050	486	90%
case_0051	478	88%
case_0052	482	89%
case_0053	491	91%
case_0054	482	89%
case_0055	496	92%
case_0056	491	91%
case_0057	490	90%
case_0058	472	87%
case_0059	482	89%
case_0060	479	88%
case_0061	490	90%
case_0062	494	91%
case_0063	464	86%
case_0064	480	89%
case_0065	480	89%
case_0066	478	88%
case_0067	479	88%
case_0068	484	89%
case_0069	481	89%
case_0070	486	90%
case_0071	486	90%
case_0072	484	89%
case_0073	433	80%
case_0074	475	88%
case_0075	474	87%
case_0076	483	89%
case_0077	477	88%

Architecture	NEOs Observed	% Observed (MOE)
case_0166	506	93%
case_0167	502	93%
case_0168	508	94%
case_0169	509	94%
case_0170	509	94%
case_0171	508	94%
case_0172	512	94%
case_0173	498	92%
case_0174	500	92%
case_0175	495	91%
case_0176	507	94%
case_0177	504	93%
case_0178	502	93%
case_0179	507	94%
case_0180	503	93%
case_0181	501	92%
case_0182	507	94%
case_0183	500	92%
case_0184	507	94%
case_0185	505	93%
case_0186	509	94%
case_0187	505	93%
case_0188	509	94%
case_0189	509	94%
case_0190	507	94%
case_0191	509	94%
case_0192	513	95%
case_0193	509	94%
case_0194	504	93%
case_0195	501	92%
case_0196	511	94%
case_0197	509	94%
case_0198	495	91%
case_0199	501	92%
case_0200	503	93%
case_0201	502	93%
case_0202	502	93%
case_0203	504	93%
case_0204	500	92%
case_0205	504	93%

Architecture	NEOs Observed	% Observed (MOE)
case_0078	476	88%
case_0079	486	90%
case_0080	484	89%
case_0081	490	90%
case_0082	486	90%
case_0083	476	88%
case_0084	474	87%
case_0085	476	88%
case_0086	484	89%
case_0087	486	90%
case_0088	480	89%
case_0089	484	89%
case_0090	484	89%
case_0091	480	89%
case_0092	487	90%
case_0093	491	91%
case_0094	499	92%
case_0095	492	91%
case_0096	503	93%
case_0097	505	93%
case_0098	479	88%
case_0099	489	90%
case_0100	492	91%
case_0101	487	90%
case_0102	490	90%
case_0103	495	91%
case_0104	488	90%
case_0105	500	92%
case_0106	496	92%
case_0107	496	92%
case_0108	495	91%
case_0109	494	91%
case_0110	502	93%
case_0111	500	92%
case_0112	498	92%
case_0113	504	93%
case_0114	503	93%
case_0115	507	94%
case_0116	504	93%
case_0117	506	93%

Architecture	NEOs Observed	% Observed (MOE)
case_0206	506	93%
case_0207	508	94%
case_0208	502	93%
case_0209	501	92%
case_0210	497	92%
case_0211	506	93%
case_0212	504	93%
case_0213	493	91%
case_0214	494	91%
case_0215	497	92%
case_0216	500	92%
case_0217	499	92%
case_0218	498	92%
case_0219	504	93%
case_0220	510	94%
case_0221	510	94%
case_0222	511	94%
case_0223	509	94%
case_0224	513	95%
case_0225	511	94%
case_0226	511	94%
case_0227	513	95%
case_0228	515	95%
case_0229	511	94%
case_0230	508	94%
case_0231	504	93%
case_0232	513	95%
case_0233	511	94%
case_0234	511	94%
case_0235	508	94%
case_0236	511	94%
case_0237	514	95%
case_0238	513	95%
case_0239	512	94%
case_0240	504	93%
case_0241	505	93%
case_0242	507	94%
case_0243	509	94%
case_0244	508	94%
case_0245	507	94%

Architecture	NEOs Observed	% Observed (MOE)
case_0118	494	91%
case_0119	497	92%
case_0120	490	90%
case_0121	504	93%
case_0122	500	92%
case_0123	498	92%
case_0124	505	93%
case_0125	499	92%
case_0126	497	92%
case_0127	505	93%
case_0128	486	90%

Architecture	NEOs Observed	% Observed (MOE)
case_0246	500	92%
case_0247	513	95%
case_0248	512	94%
case_0249	514	95%
case_0250	516	95%
case_0251	515	95%
case_0252	514	95%
case_0253	514	95%
case_0254	509	94%
case_0255	516	95%

Appendix G: References

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