DISSERTATION

CISLUNAR SYSTEM OF SYSTEMS ARCHITECTURE EVALUATION AND OPTIMIZATION

Submitted by

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ABSTRACT

CISLUNAR SYSTEM OF SYSTEMS ARCHITECTURE EVALUATION AND OPTIMIZATION

Cislunar space is the next frontier of space exploration, but a sustainable architecture is lacking. Cislunar space is considered a complex system of systems because it consists of multiple independent systems that work together to deliver unique capabilities. The independent systems of the cislunar system of systems include the communications, navigation, and domain awareness systems. Additionally, the methodology to design, evaluate and optimize a complex system of systems has not been published. To close the gap, a comprehensive needs analysis is performed for cislunar space. Next, model-based systems engineering is used to design the cislunar system of systems. The cislunar architectures are designed in terms of constellations and payloads. The architectures are each evaluated in terms of cost and performance. An appropriate optimization algorithm is found for the system of systems, and the results of the optimization are evaluated using multiple techniques for comparison.

A literature review is included on the topics of cislunar architectures, system of systems, model-based systems engineering, system architecture evaluation, and system architecture optimization. During the research of cislunar architectures, a needs analysis is completed which identifies the three primary missions planned for cislunar space and eight supporting functions to provide the infrastructure for the primary missions. The primary missions identified include science, commerce, and defense. The eight supporting functions identified include transportation, communication, domain awareness, service, energy, shelter, and control. Technologies and

programs are identified for each supporting function, included gaps in needed technology or programs. For the evaluation and optimization of the system of systems, the supporting functions are down-selected to include only the three necessary supporting functions for any operations in cislunar space: communications, navigation, and domain awareness.

A system architecture is developed using Systems Modeling Language in Cameo Systems Modeler™. The model is designed using the Model-based Systems Architecture Process which includes the design of the Operational Viewpoint, Logical/Functional Viewpoint, and Physical Viewpoint. The Operational Viewpoint includes structural, behavioral, data, and contextual perspectives. The Logical/Functional Viewpoint includes structural, behavioral, data, and contextual perspectives. The Physical Viewpoint includes design, standards, data, and contextual perspectives. Each of these perspectives are represented in the form of Cameo Systems Modeler™ diagrams or tables. Diagrams include block definition diagrams, internal block diagrams, use case diagrams, activity diagrams, and sequence diagrams.

Additional modeling concepts beyond the Model-based Systems Architecture Process are included in the Cameo Systems Modeler™ model and analysis of the model. These topics include allocating requirements, stereotypes, patterns in architecture decisions, architecture optimization, verification, validation, complexity, and open systems architecture.

Cislunar constellations and payloads are designed which account for the cislunar physical environment. Six constellations are designed to be included in the optimization algorithm. These constellations include Lagrange light, Lagrange medium, Lagrange heavy, Earth-based, Earth plus Moon, and Earth plus Lagrange. These constellations essentially represent the location of the bus while the payloads provide the functionality of the system. Payloads are designed for the supporting functions deemed essential for a basic cislunar infrastructure, which are communications, navigation, and domain awareness. The optimization algorithm runs through each possible combination of payload and bus, including any opportunities to integrate multiple payloads on a single bus. The total number of possible architecture combinations for the optimization algorithm is 288.

The payload sensors are modeled in Systems Tool Kit and evaluated for physical performance. Additionally, each payload and bus possibility are evaluated for cost using the Unmanned Space Vehicle Cost Model and professional estimates. The performance and cost metrics are used in the optimization algorithm.

The optimization algorithm uses multi-objective optimization with an integer linear program. The result of the optimization algorithm is a pareto front of the highest-performance, lowest-cost architectures. The architectures along the pareto front are evaluated using multi-criteria decision making with and without evidential reasoning to find the "best" architecture. A Kiviat chart assessment is also performed, though this method is shown to not be practical for the cislunar application.

The model and conclusions of the dissertation are validated using a variety of industry-accepted techniques. The cislunar architectures are validated via peer-review. The performance evaluations are validated via a validated physics model. The cost evaluations are validated by a validated cost-model when possible and by peer-review. The optimization algorithm is validated by comparison to a manual optimization method. The Cameo Systems Modeler™ model is validated using validation techniques internal to the tool.

Suggestions for future work are presented. Future work could include fully integrating the Cameo Systems Modeler™ model with the Systems Tool Kit model, providing improved cost estimates, using alternative optimization parameters, adding supporting functions as they are identified, evaluating the architectures using additional metrics, evaluating additional constellations, applying integration at the functional level, or assessing non-homogenous requirements.

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Chapter 1. INTRODUCTION

1.1 PROBLEM STATEMENT

The second space race has begun; this time it is in cislunar space. China is aggressively establishing a presence in cislunar space while the United States (US) is working to re-establish a presence [1]. Within the US, National Aeronautics and Space Administration (NASA) and the United States Space Force (USSF) are partnering with industry to further their scientific, commercial, and defensive priorities. Holistic and integrated systems architectures are needed to support long-term operations within economic and physical constraints [2]. This dissertation proposes an architecture model for a sustainable cislunar system.

Additionally, research is lacking in the areas of system of systems evaluation and optimization. The cislunar system is defined as a system of systems, but systems engineering procedures have not been developed which would enable decision makers to design architectures in this area. This dissertation offers a methodology to design, evaluate, and optimize architectures for a system of systems.

1.1.1 RESEARCH QUESTIONS

The following three research questions are guides for the research performed for this dissertation. Brief answers are given for each while the bulk of the dissertation answers each question in more detail.

1.1.1.1 WHICH EVALUATION TECHNIQUE, OR TECHNIQUES, ARE BEST APPLIED TO A CISLUNAR SYSTEM?

The selection of evaluation parameters is a critical step in architecture evaluation. For the cislunar system, the evaluation parameters are chosen as cost and performance because the supporting functions can be evaluated equally and objectively at the system of systems level.

Cost is evaluated using validated cost models and industry expertise is used where cost models do not exist. Performance is evaluated by calculating the coverage in a physical environment.

In the Literature Review, four evaluation techniques are assessed for their applicability to cislunar System-of-Systems (SoS). In theory, Multi-Criteria Decision Making (MCDM) with Evidential Reasoning (ER) is researched to be the best technique for large, complex systems and is used for the cislunar system of systems evaluation.

1.1.1.2 Which optimization technique, or techniques, are best applied to a cislunar system?

Due to the SysML structure of the cislunar system model, non-differential optimization techniques are needed. These are broadly categorized into direct, stochastic, and population algorithms. A direct algorithm is used with a branch-and-bound technique to automate the optimization process. The direct algorithm is an integer linear programming method known as intlinprog which allows automated updates with the SysML model. Additionally, the objective function and constraints are linear, allowing a Linear Program (LP) technique to be utilized. Since the cislunar system is evaluated with multiple parameters, a Multi-Objective Optimization (MOO) technique is used while iteratively optimizing the LP.

1.1.1.3 What special consideration must be made when evaluating a System of Systems when compared to evaluating a single system?

A SoS is more complex and has more uncertainty than an individual system. Model-Based Systems Engineering (MBSE) offers continuity and validation across the SoS as inevitable change occurs. Additionally, enterprise-level objectives are needed to guide the SoS design throughout development, which can be incorporated and updated across the system using MBSE.

To evaluate the SoS, it is important to consider the stakeholder concerns at the enterprise-level when choosing evaluation parameters and prioritizing these parameters. A SoS has much more complexity and uncertainty than a single system, which should be considered during evaluation.

1.1.2 Research Tasks

The following four research tasks are determined as the main deliverables defining the dissertation work. Summaries are given for each task while the bulk of the dissertation describes each task in more detail.

1.1.2.1 Perform needs analysis of comprehensive cislunar space system

The needs analysis is performed in the Cislunar Architectures section of the Literature Review. The three primary missions and eight supporting functions are identified during research of all current and planned cislunar missions.

1.1.2.2 Develop a functional architecture of cislunar space to identify any gaps in current or planned cislunar efforts

The Literature Review indicates gaps in current architectures and drives the development of the cislunar domains of the functional architecture. Missing functionality for each supporting function is included in the literature review.

The functional architecture is modeled using Cameo Systems Modeler™ and detailed in the SysML Model of the dissertation. The functional architecture models the eight overarching domains with BDDs, IBDs, ACTs, SDs, contextual diagrams, and key interfaces.

1.1.2.3 Evaluate an integrated cislunar architecture which includes all necessary supporting functions and primary missions.

For this dissertation, the minimum necessary supporting functions for operations in cislunar space include communications, navigation, and domain awareness [3]. The primary missions are the users which rely on these functions.

Prior to optimization, each potential architecture is evaluated for cost and performance. Validated cost models are used, and professional estimates are made where models do not exist. To evaluate for performance, each architecture combination is modeled in a physics environment and the coverage volume is calculated. The cost and performance metrics are used to optimize the architecture.

After optimization, MCDM with ER, MCDM without ER, and a Kiviat Chart Assessment are used on the five optimal architectures of the pareto front.

1.1.2.4 Optimize Integrated Cislunar Architecture

A mixed-integer linear programming algorithm is used within a MOO technique to find a pareto front of optimal architectures. Details of the objective function and constraint definitions are included in Section 3.6.

1.2 Dissertation Overview

This dissertation provides the background research, methodology, and application necessary for the evaluation and optimization of a cislunar space system.

Chapter 1 includes the problem statement and dissertation overview. The problem statement details the dissertation tasks and research questions used to guide the research of cislunar space systems. In the dissertation overview, the contents of the dissertation are outlined.

Chapter 2 includes the literature review, where background research is provided for cislunar architectures, system of systems, model-based systems engineering, system architecture evaluation, and system architecture optimization.

In 0, the approach for the dissertation work is provided. An overview of the Systems Modeling Language (SysML) cislunar model is included with applicable diagrams extracted from the model. The physics of cislunar space is explored and used to derive the assumptions for payload design. The architecture evaluation approach is given, which describes the constellation designs, performance metrics, and cost metrics. Then, the optimization algorithm is detailed.

In Chapter 4, the approach is applied to the cislunar SoS to yield the results. First, the evaluation aspects of the dissertation are applied to the cislunar model. Second, the optimization techniques are applied to the cislunar SoS. A discussion of the results is included.

Finally, Chapter 5 provides a summary of the dissertation. Main conclusions are provided. A summary of the model and methodology validation is written. The dissertation concludes with recommendations for future work.

Chapter 2. LITERATURE REVIEW

2.1 LITERATURE REVIEW INTRODUCTION

Extensive research has been conducted on the topics of cislunar architectures, SoS, MBSE, system architecture evaluation, and system architecture optimization. This dissertation attempts to integrate these topics. A cislunar architecture with multiple independent missions and functions is a SoS, so special consideration must be made to develop an architecture for a SoS. Due to the substantial number of functions and relationships of a cislunar system, MBSE will be necessary to automate the architecture design. Architecture evaluation is a well-researched topic but has not yet been applied to an integrated cislunar SoS. Finally, many optimization techniques exist which have the potential of finding an ideal cislunar SoS.

The Literature Review documents the background necessary for a dissertation on cislunar systems architectures. In Section 2.1.1, an overview of research in cislunar space is presented, including details on the primary missions, and supporting functions identified for a cislunar architecture. Section 2.1.2 documents research on SoS. Section 2.1.3 presents background on MBSE relevant for system architecture modeling. In Section 2.1.4.3, System architecture evaluation parameters, strategies, and cislunar applications are given. Finally, Section 2.1.5 reveals relevant optimization algorithms and optimization applications in cislunar space.

2.1.1 CISLUNAR ARCHITECTURES

2.1.1.1 CISLUNAR ARCHITECTURES INTRODUCTION

Plans are well underway to establish operations in cislunar space. Planned missions can be broadly categorized as science, commercial, or defense missions. Supporting functions are broadly categorized as transportation, communication, navigation, situational awareness, service, energy, shelter, and control. Details of potential solutions and identified gaps are given in the following sections.

Figure 1 shows a gray area which defines the volume of cislunar space used in this dissertation. Cislunar space encompasses the area beyond geosynchronous orbits (GEO) to the orbit of the Moon including the areas surrounding each Lagrange point. The Earth-Moon system has five Lagrange points, which are points of gravitational equilibrium, providing opportunities for orbits with low station keeping fuel requirements and long dwell times of the Earth-Moon system. Lagrange points 1 and 2 are specifically advantageous due to their proximity to the Moon, where most operations are planned to occur.

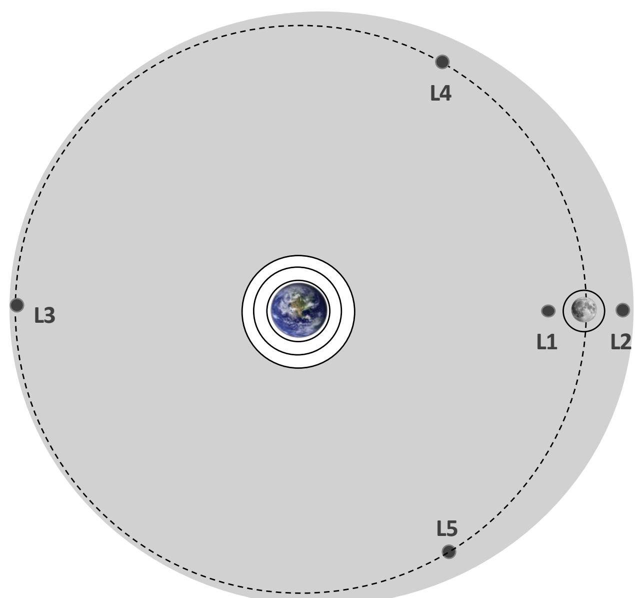

Figure 1 Cislunar Space with Lagrange Points

The Lunar Exploration Analysis Group (LEAG) released a Lunar Exploration Roadmap in 2016 outlining the following major themes and goals:

1. Science Theme:

a. Understand the formation, evolution, and current state of the Moon

b. Use the Moon as a "witness plate" for solar system evolution

c. Use the Moon as a platform for Astrophysical, Heliophysical, and Earth-Observing studies

d. Use the unique lunar environment as research tool

2. Feed Forward Theme:

a. Identify and test technologies on the Moon to enable robotic and human solar system science and exploration

b. Use the Moon as a testbed for mission operations and exploration techniques to reduce the risks and increase the productivity of future missions to Mars and beyond

c. Preparing for future missions to other airless bodies

3. Sustainability Theme:

a. Maximize Commercial Activity

b. Enable and Support the Collaborative Expansion of Science and Exploration

c. Enhance Security, Peace, and Safety [4]

From the LEAG Roadmap, which includes detailed lunar goals, the primary missions are identified as science, commerce, or defense.

Research has identified transportation, communication, navigation, domain awareness, service, energy, shelter, and control as the minimum necessary supporting functions for the primary missions. Within these functions are included the subfunctions documented in Figure 2.

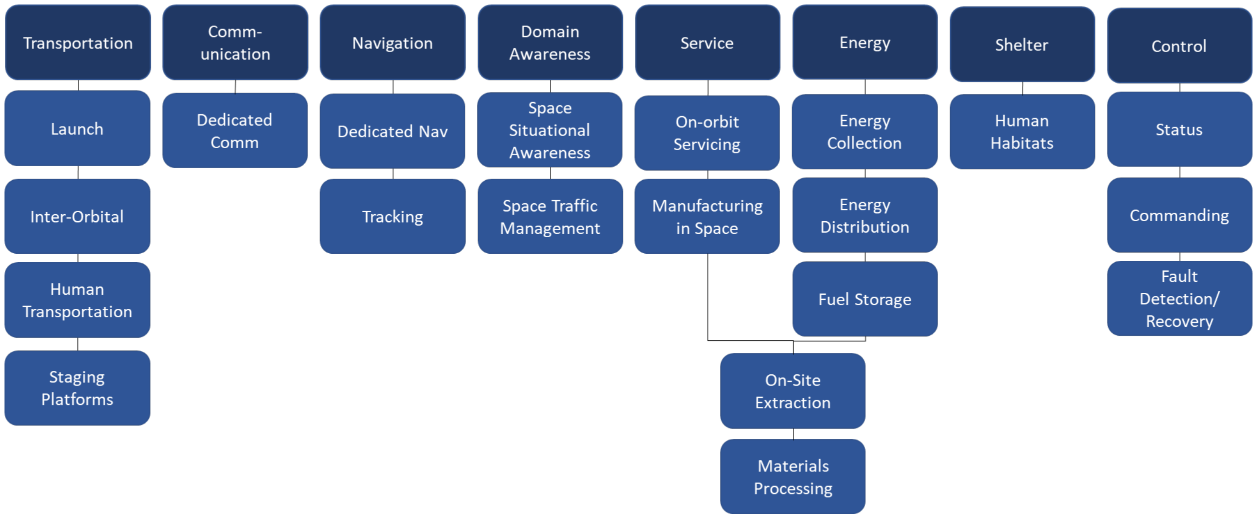

Figure 2 Supporting Functions Mapping

2.1.1.2 Primary Missions

2.1.1.2.1 Primary Missions Introduction

The following sections provide the main plans and research for the primary missions in cislunar space: science, commerce, and defense.

2.1.1.2.2 Science Missions

In the 2020 National Space Policy of the United States of America, guidance is provided that the US will expand space exploration efforts, starting with the Moon. The national space policy also guides civil space, such as NASA, to partner with commercial entities on cislunar projects including transport of crew and cargo. National goals include establishing a human presence on the Moon by 2024 with a sustained presence by 2028 [5].

NASA is actively working to pursue the guidance given in the National Space Policy. NASA's science goals at the Moon include:

- Understanding planetary perspectives

- Understanding volatile cycles
- Interpreting the impact history of the Earth-Moon system
- Revealing the record of the ancient sun
- Observing the universe from a unique location
- Conducting experimental science in the lunar environment
- Investigating and mitigating exploration risks to humans [6]

NASA's early plans for cislunar space identified missions to include servicing, assembling, and exploration. These early plans identified cislunar space as most interesting due to its location beyond the Van Allen belts, and the L2 Lagrange point as a link to future missions beyond the Moon [7]. NASA has developed the Artemis program to systematically develop technologies to establish a sustainable human presence on the moon. Some of the partnering agencies for this complex architecture include the Canadian Space Agency (CSA), the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), the Russian Space Agency (Roscosmos) and US industries [6]. The Artemis plan is enabled by key products including the Space Launch System (SLS) rocket, Orion spacecraft, supporting Exploration Ground System (EGS), Gateway outpost, and Human Landing System (HLS) [6].

The European Space Agency (ESA) has established an effort independent from NASA called the Moonlight initiative. The Moonlight initiative project is planned to enable exploration of the Moon with a constellation of lunar satellites dedicated to communications and navigation, projected for operations by the late 2020s. This effort is designed to support a sustained human presence on the Moon enabling efficient scientific exploration [8].

The nature of science is that discovery leads to more questions, which requires a flexible and adaptable supporting architecture, serving the functions of transportation, communication, navigation, domain awareness, service, energy, shelter, and control once full cislunar operations are in effect.

2.1.1.2.3 Commerce Missions

Through NASA's partnerships with industry, many commercial missions will emerge to turn a profit in cislunar space. Most notably, transporting humans from the Gateway to the Moon will be a servicing function of the HLS provided by SpaceX [6].

In-Situ Resource Utilization (ISRU) will be another government-led, commercial endeavor. Thanks to the Lunar Reconnaissance Orbiter (LRO), many resources have been discovered on the Moon's surface including valuable water deposits which are necessary for a sustained presence on the Moon [9]. Once an established supporting architecture is developed, then commercial entities will have the ability to access the profitable mission of ISRU, analogous to gas stations on Earth.

There are some key technologies and infrastructures needed to enable the commercialization of cislunar space. These include:

- Water extraction technology
- Oxygen production technology
- Electric-class fission power systems
    - Twin Reactors
    - Brayton Power Conversion Unit
    - Fold-out Radiator System

- Refueling infrastructure
- Reusable crew cargo transportation system [10]

The following missions have been proposed as potentially profitable endeavors in cislunar space:

- Water mining
- Metal mining
- On-orbit manufacturing
- In-space transportation
- Cislunar stations
- Lunar landers
- Lunar base
- Advanced orbital services
- Satellites services
- Off-earth science
- Beamed power [11]
- Tourism [12]

Several of these missions (e.g., cislunar stations, lunar landers, etc.) may first be completed by government agencies, such as NASA, to achieve science objectives. In the long term, the missions can transition to commercial entities for profit.

2.1.1.2.4 Defense Missions

Cislunar space is written as "The Next Military Frontier" due to the need to survey and protect assets [13]. These needs will be fulfilled by government agencies in the Department of

Defense (DoD) such as the USSF and the Space Development Agency (SDA). These agencies will be required to monitor all assets while conducting space battle management command and control. This function is currently being performed by the Combined Space Operations Center (CSpOC), but the capabilities of this center only extend to orbits just beyond GEO. More capable sensors will be needed to fill the gap between GEO and the Moon.

In competition with DoD goals, China has plans to have a permanent presence on the Moon by 2024. Due to China's structure which has integrated ties between civil and military priorities, a Chinese presence on the Moon can be seen as a military power move. China and Russia are collaborating on lunar exploration efforts, driving an even greater need for defense missions in cislunar space [14]. China and Russia will likely also establish defensive space missions with similar defense needs and modified implementations. In this dissertation, "defense" missions include missions conducted by the US and its allied nations.

In response to a perceived future military threat, the Chief Scientist of the USSF announced three missions which include:

1. Protect US interests in space
2. Deter aggression in, from, and to space
3. Conduct space operations [15]

Short-term goals for the USSF include digital engineering, resilience, situational awareness, joint command and control, intrusion, and autonomy. Mid-term goals include cislunar operations and space logistics. Long term goals include cislunar space power, space access, new missions, and autonomous space conflict [15]. Programs are already underway to meet these goals. The Defense Advanced Research Projects Agency (DARPA) has already chosen three companies to test nuclear thermal propulsion in space [16]. This is part of DARPA's Demonstration Rocket for Agile Cislunar Operations (DRACO) program.

The SDA has announced plans for a defense-oriented architecture in cislunar space which is planned to provide the function of deterrence. The proposed architecture has four parts:

1. Low Earth Orbit (LEO) sensors facing outwards for tracking beyond GEO.
2. Two satellites in Earth Highly Elliptical Orbit (HEO) providing alternative angles for tracking.
3. Sensors in lunar orbit.
4. Three Advanced Maneuvering Vehicles (AMV) [17].

This architecture is designed to meet six defense-related goals:

- Low-Latency Data transfer for rapid battle management
- Transmit/Receive Wideband Data for detailed threat assessment
- Demonstrate Limited battle management command, control, and communication (BMC3)
- Transport Bulk Integrated Broadcast System (IBS) Data for standardization of communication services[1]
- Send Link-16 Messages to warfighters on the ground[2]

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[1] The "transport bulk IBS data" goal is not necessarily a benefit for defense in cislunar space. This is an emergent goal of the SDA cislunar architecture.

[2] The "Link-16 messages" goal is not necessarily a benefit for defense in cislunar space. This is an emergent goal of the SDA cislunar architecture.

- Demonstrate Common Relative Time Reference for robust, resilient navigation [18]

The defense mission is often decoupled from science and commercial efforts because of the focus on security. The defense mission can utilize common transportation functions, but typically relies on a trusted source for communication and navigation.

While cooperation is the preferred mode of operations between nations, this is not always possible due to conflicts of interest. The alternative is to employ defensive measures to ensure the mission is complete.

2.1.1.2.5 Primary Missions Conclusions

In conclusion, there are many plans to utilize cislunar space for a variety of needs. Science missions aim to gain understanding of the moon and use the moon as a staging ground for further exploration of the solar system. Commerce missions aim to provide services, such as transportation, and the mining and manufacturing of lunar resources. Finally, the defense missions aim to protect the nation and space assets.

2.1.1.3 Supporting Functions

2.1.1.3.1 Supporting Functions Introduction

The next sections provide summaries of the main supporting functions found in the research of cislunar space utilization. These functions include transportation, communication, navigation, domain awareness, service, energy, shelter, and control.

2.1.1.3.2 Transportation Function

The first identified function is transportation, which includes moving payloads from the Earth to lunar orbit, moving payloads between LEO and lunar orbit, lunar staging platforms, and human transportation. Table 1 shows a summary of the identified programs for cislunar transportation and identifies no need for additional programs or technology. Details of each of these technologies and programs are provided throughout this section.

Table 1 Transportation Function Summary

Identified Technologies and Programs	NASA SLS ULA ACES NASA CLPS LST Aerobraking Electric Propulsion NASA Orion Capsule NASA ICPS NASA HLS NASA Gateway NASA Gateway PPE NASA Gateway HALO NASA CAPSTONE
Technology and Programs Needed	None identified

NASA's SLS rocket is a critical enabling technology to transport payloads from Earth to the Moon and lunar orbits. United Launch Alliance (ULA) has also designed technologies specifically for cislunar applications. The system would use liquid oxygen and liquid hydrogen propulsion with fuels derived from the Moon. Upper stages of cislunar rockets could use the

Advanced Cryogenic Evolved Stage (ACES), in development by ULA [19]. ACES has the sustainability feature of being refueled by resources found on the Moon [19]. Fuel mining is discussed further in Section 2.1.1.3.7. The NASA SLS and ULA ACES meet the identified need for inter-orbital transportation [20].

NASA's Commercial Lunar Payload Services (CLPS) is an effort with commercial launch providers to deliver payloads from Earth to the surface of the Moon. CLPS is part of the Artemis program and began in 2021. SpaceX has won five out six of the CLPS contracts and ULA won the sixth. The rockets which will carry these six missions include the Falcon 9, Falcon Heavy, and Vulcan [21].

A supplement to the transportation of payloads from Earth to near the Moon has been proposed as the Lunar Space Tug (LST). LST is a reusable electric transportation concept. This concept would greatly increase the sustainability of missions to and from the Moon [22]. The LST is designed to bring a habitat or resupply mission from LEO to lunar orbit and back [23]. LST architectures could be specifically designed for the intended payload or could be designed for flexibility to transport a variety of payloads [23]. Flexible architectures are more expensive to design and build but tend to be cheaper over time when compared to non-flexible architectures. For each kilogram sent to LEO, transportation costs are decreased by 50%, excluding initial set-up costs [24]. For programs greater than 10-years, these cost savings come to fruition for a sustainable architecture [24]. This research suggests that concepts like LST provide cost savings over the long-term.

Another concept for transportation from LEO to the L1 proposed by ULA is to re-use the upper stage engine and utilize aerobraking [25]. Aerobraking with the upper stage from lunar back to LEO allows a fuel savings of up to 72% [25]. This method would require a vehicle with a low ballistic coefficient, on-board cooling options, and a targeting strategy [25]. This strategy could be coupled with the LST to conduct more fuel-efficient transfers.

Electric Propulsion (EP) has been researched for efficient lunar transportation. Due to the dynamics of the Circular Restricted Three Body Problem (CR3BP), the change in velocity (delta-V) needed to maneuver in cislunar space can be very low. EP has been shown as an optimal way to transfer between Distant Retrograde Orbit (DRO) and Halo Orbits [26].

The Orion capsule more specifically serves the function of human transportation to the Moon. Orion utilizes the interim cryogenic propulsion stage (ICPS) to reach an apogee of 59,000 miles, and then performs a translunar injection maneuver using the Orion service module [6]. The Orion Capsule is planned to be used exclusively for science missions.

The HLS is another component necessary for NASA's human exploration objectives. The HLS will be developed and built by commercial companies who will compete for servicing contracts. NASA is paving the way for a commercial and profitable infrastructure in cislunar space.

NASA's comprehensive plan includes many technologies which cover the transportation function needed to get payloads into cislunar space. The Gateway, an outpost in lunar orbit, includes the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO) [6]. While early Artemis missions plan to go directly to the Moon to meet exploration objectives, the Gateway provides a staging point and is a necessary component of a sustainable architecture.

The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) launched in June 2022, preceding the Gateway. It is the first CubeSat in cislunar space with a mission to test the stability of Gateway's planned orbit, a near-rectilinear halo orbit (NRHO) [27]. NRHO's are nearly polar orbits about the Moon.

Research on ideal orbits for a staging platform has concluded that the most favorable orbits for a platform such as Gateway are near rectilinear orbits (NRO) [28]. NROs are highly elliptical orbits with large coverage over the northern or southern pole, depending on mission needs. Staging missions are important to decrease transportation costs, but flexibility must be considered to incorporate a wide array of missions. The Gateway architecture does provide a more flexible architecture for lander resources, providing sustainable lunar exploration [29].

The transportation supporting function has several proposed physical architectures, with efforts led by NASA, SpaceX, and ULA. The SLS is designed for transportation from Earth to the Moon. The LST is proposed for transportation between LEO and lunar orbit and could be coupled with aerobraking to reduce fuel costs. The Orion capsule and subsystems are in work by NASA to serve as human transportation. Finally, NASA's Gateway serves as a staging point in lunar orbit allowing increased access to the Moon. The next section documents the communication needs which enable cislunar utilization.

2.1.1.3.3 Communication Function

Communication is a necessary function for all robotic spacecraft or human spaceflight. Communication can be accomplished using Earth-based systems, space-based platforms, or lunar platforms. A dedicated communication system is necessary to communicate over a great distance, support a growing number of users, and to reach areas of space obscured by the Moon. Table 2 shows a summary of the identified programs for cislunar communication and identifies needs additional programs and technology. The technologies and programs are detailed throughout this section.

Table 2 Communications Function Summary

Identified Technologies and Programs	LunaNet Laser communication SDA cislunar architecture UHF communication SCPS transport protocol Cubesat Constellations
Technology and Programs Needed	Relay link or 50-meter ground antennas

NASA currently utilizes the Swedish Space Corporation (SSC) ground antennas for Lunar communications. These antennas are located across the globe and offer data rates from 5 kbps – 80 Mbps in S, X, and Ka band [30]. NASA is also developing technology to perform laser communications from Earth to the Moon. In 2013, NASA successfully demonstrated a laser communication link with a data rate of 622 Mbps – six times faster than any previous lunar communications link [31]. The laser communications terminal even has lower Size Weight and Power (SWaP) than traditional radio-based terminals. The terminal was flown on the Lunar Atmosphere and Dust Environment Explorer (LADEE) satellite. Compared to radio-based terminals, the terminal was half the weight and 25 percent less power [31].

The SDA cislunar architecture includes plans for communication and navigation functions. The plan includes data transport using narrowband ultra-high frequency (UHF) as well as a common time reference, independent from the Global Positioning System (GPS) [18]. Information is not readily available on the robustness of this architecture, but it will likely be highly independent from any civil or commercial efforts to maintain high levels of security and trust.

Research on various protocols for cislunar communication has considered the need for long links and possible delays in the communication relay. Interoperability is found to be a necessary feature of a communication architecture in cislunar space [32]. Disruption Tolerant Networking (DTN) is found to be preferred to traditional Transmission Control Protocol (TCP). DTN is found to be most effective for links ranging from 30 minutes to 8 hours and able to overcome poor bit error rates (BER). One of the greatest challenges of communications in cislunar space is having an acceptable BER. The properties of DTN are most ideal for a cislunar communication architecture [33]. Another protocol which has been shown to have adequate performance in cislunar communications is Space Communication Protocol Standards-Transport Protocol (SCPS-TP). This protocol had performance of nearly 5,000 bytes per second at a BER of 10^{-5} [34]. The generally accepted threshold for space communications BER is 10^{-5}, so this protocol meets the minimum standard [35].

One proposed physical architecture for communications includes placing satellites at L2, L3, L4, and L5. This architecture allows communications between the far side of the Earth and the far side of the Moon. Excluding the poles, this architecture provides 98.95% coverage of the Moon and 99.1% coverage of the Earth. Ground antennas supporting this concept would need to be at least fifty meters in diameter [36]. This concept would require technological development as most satellite communication antennas are typically 7 – 13 meters in diameter.

Another physical architecture proposed for lunar communication is a “flower constellation” of CubeSats around the Moon. This constellation would have repeating ground traces and great lunar coverage. Unfortunately, due to the variability of the lunar gravitational field, these orbits are unstable and require ample fuel for station keeping. Depending on thruster efficiency, the lifetime of these constellations is estimated to be 100-800 days [37].

NASA has proposed the use of a flexible communication architecture known as Lunanet. Lunanet would include “nodes” of satellites which would contribute to a distributed network on and near the Moon. More specifically, a constellation of CubeSats in 100 km altitude orbits about the Moon is proposed. These CubeSats would use optical communication for more focused communications. This architecture is found to provide sufficient data transfer between low lunar orbit (LLO) and Earth [38]. The NASA SpaceCube Intelligent Multi-Purpose System is a small satellite system which allows developers to mix and match 1U CubeSat payloads for missions such as intelligence processing, communication, navigation, and cybersecurity. A network of SpaceCubes has been proposed for use as Lunanet nodes [39].

Communications architectures are in work by the SDA and NASA. SDA’s architecture includes Earth-orbiting relay satellites, while NASA’s architecture consists of lunar orbiting nodes. Dedicated communications architectures must include the features of interoperability, flexibility, and standardization. In the next section, the navigation function is detailed, which has a coupled architecture with the communications function due to the similar RF characteristics.

2.1.1.3.4 Navigation Function

Navigation is a necessary function for any space system. Navigating at the Moon will be especially challenging due to the increased distance from terrestrial navigation systems and obscuration by the Moon. A dedicated system is needed for accurate navigation near the Moon. Table 3 shows a summary of the identified programs for cislunar navigation and identifies the need for a dedicated Lunar Navigation Satellite System (LNSS). The technologies and programs are detailed throughout this section.

Table 3 Navigation Function Summary

Identified Technologies and Programs	GNSS Space Service Volume LunaNet LuGRE HDTV signals DSN
Technology and Programs Needed	LNSS

Lunar missions can conduct some limited navigation near the Moon using already existing Global Navigation Satellite Systems (GNSS). A study of navigation near the moon using only GPS and Galileo have shown benefits which include:

- Improved navigation performance
- Quicker trajectory maneuver recovery
- Reduced need for on-board clocks
- Increased satellite autonomy
- Better performance in lunar orbit [40]

NASA's Bobcat-1 mission was sent into LEO to test key receiver technologies to support future navigation using six existing GNSS constellations. The receiver technologies from this mission are planned to be used for future NASA missions at and near the Moon [41]. The Magnetosphere Multi-Scale (MMS) mission tested GNSS receiver performance at an altitude beyond GEO with an apogee of 152,900 km. Results from the MMS mission showed a maximum position error of fifty meters [42]. Data from the MMS mission was used for analysis of a transfer to a near-rectilinear halo orbit. The analysis showed that with a high gain antenna, the simulated receiver had a maximum outage of 11 minutes and could see at least one GPS signal 99% of the time [43]. These are impressive results that show the feasibility of initial limited lunar navigation using existing systems. The first mission planned to utilize GNSS signals on the Moon is the Lunar GNSS Receiver Experiment (LuGRE), a partnership mission between NASA and the Italian Space Agency. LuGRE is part of NASA's CLPS program. It is planned to land on the Moon in 2023 to receive GNSS signals [44].

GNSS navigation near the Moon has limitations due to poor signal geometry (known as Dilution of Precision (DOP)), weak signals near the Moon, and the obscuration of the Moon. A hybrid approach utilizing GNSS and cislunar navigation satellites provides improved performance and coverage. To support the NASA Gateway concept, a need for a LNSS has been identified [12]. A constellation of eleven satellites in lunar orbit is found to sufficiently supplement current GNSS signals for missions to the Moon and near the Moon [12].

Cislunar navigation research has shown that libration points can be used for an effective cislunar navigation architecture. Placing four satellites in stable orbits about L1, L2, L4, and L5 can provide accuracies of tens of meters for satellites in trans-lunar and lunar orbit [45]. The L1 and L2 points are unstable in the Earth-Moon system, but stable families of orbits exist about these points known as Halo orbits and Lyapunov orbits [45]. Figure 1 shows a diagram of the

Earth-Moon libration points, also known as Lagrange points. The gray area of the figure shows the region of cislunar space.

Alternatively, research shows that navigation could be performed using high-definition television (HDTV) signals. The coverage of these signals is excellent due to global prevalence. Satellite navigation using high-definition television signals has been proven feasible in DRO and lunar halo orbits [46]. DRO's are a class of orbits around the moon which are highly stable due to the gravitational effects of the CR3BP. Unfortunately, HDTV signals from Earth would not solve the issue of poor DOP.

As a supplement to a navigation constellation, on-board autonomy is suggested to provide necessary performance [47]. This concept will be most useful during early cislunar missions when a full constellation around the Moon is not available. On-board autonomy could include inertial measurement units coupled with high-performing star trackers for attitude calculations. The Orion capsule, planned for human transportation to the Moon, is designed with a backup autonomous navigation system which uses an autonomous onboard targeting algorithm during short-term loss of contact with ground systems [48].

The LRO has paved the way for navigation on the Moon by mapping the surface of the moon and locating ideal areas for exploration [9]. Mapping is an important navigation function of lunar-based operations that is often overlooked as solutions tend to focus on systems which mimic a GNSS for the Moon.

A concept for precise positioning using surface-based pseudolites has been researched as a feasible solution. The pseudolite system is designed to cover a 10-kilometer radius around the lunar south pole and would integrate with LunaNet, described later in this section. Prototype software defined radio (SDR) transmitters and receivers were tested terrestrially and proved to have accuracies of less than 10 meters [49]. This positioning system could provide supplemental navigation for lunar surface navigation requiring greater precision.

The subfunction of tracking is included in navigation. Tracking in cislunar space would be an extension of current tracking networks with sensors placed in cislunar orbits or on the lunar surface. For accurate tracking, it is important to optimize trajectories to avoid sun-exclusion angles [50]. When conducting tracking, methods of Earth-based ground networks and the Linked Autonomous Interplanetary Satellite Orbit Navigation (LiAISON) have been compared. The LiAISON method has advantages of increased accuracy and coverage while the Earth-based method is less costly [51].

Early Artemis missions plan to use the already existing Deep Space Network (DSN) for communication and navigation. While this is sufficient for a single mission or prototypes, the network will soon be overburdened by the numerous missions planned for cislunar space [6]. Later missions will utilize a flexible communications and navigation architecture known as LunaNet. LunaNet provides a scalable architecture, utilizing government and commercial assets around the Moon. Each asset would be a node of the architecture providing one or all the architecture functions which include networking services, navigation signals, and situational alerts [52].

NASA has the most comprehensive plans for a dedicated lunar navigation system. To perform tracking, Earth-based systems can be used, but will need to be supplemented by a lunar system in the future as the number of lunar missions increases. The next section documents the domain awareness function, which utilizes parts of the navigation architecture to perform its subfunctions.

2.1.1.3.5 Domain Awareness Function

Domain awareness is needed by science, commerce, and defense for surveillance and collision avoidance. The USSF defines domain awareness as "identification, characterization, and understanding" of objects in space [53]. For this dissertation, domain awareness focuses on the identification aspect of domain awareness, which includes tracking the object in orbit. Characterization requires highly accurate sensors placed near the objects under surveillance, which is simply not feasible in the incredible volume of cislunar space. Additionally, understanding the object requires human-in-the-loop, which is performed in the intelligence cell of a space operations center. The solutions presented in this dissertation focus on the technologies needed for domain awareness.

Due to the dynamics of the CR3BP, there are certain stable orbits which are more prone to collect objects. The L1 transfer manifold, L4 Lagrange point, and L5 Lagrange point have been found to be highly stable and susceptible to orbital debris collection [54]. Proper situational awareness can prevent satellite collisions from both natural and human-made objects, avoiding massive collections of orbital debris. Table 4 shows a summary of the identified programs for cislunar domain awareness and identifies critical needs. Details are provided throughout this section.

Table 4 Domain Awareness Function Summary

Identified Technologies and Programs	SSN CHPS
Technology and Programs Needed	Sensors of lunar surface, especially poles Sensors of lunar orbits

	Sensors of cislunar orbits

Cislunar domain awareness offers unique challenges due to the large distance and enormous volume requiring monitoring. A global network of Earth-based sensors is required to maintain tracking of cislunar objects. Even with global sensors, there will be times that certain objects will not be observable due to visibility constraints and the brightness of the object [55].

The domain awareness function of Earth-orbiting satellites currently is met by the DoD using the Space Surveillance Network (SSN). This network consists of Earth-based and space-based sensors which track objects up to GEO and slightly beyond. This is approximately one-tenth of the distance needed to track objects near the Moon. The Air Force Research Laboratories (AFRL) has solicited contracts for the Cislunar Highway Patrol System (CHPS) which will conduct domain awareness near the Moon for research and development. Initial plans have shown that this mission will be challenging due to modeling third body effects, the enormous volume of space (1000 times more than Earth to GEO), the Moon's brightness, and the large data transfers [56]. An architecture for tracking objects in cislunar space is proposed by the SDA, but whether this tracking information will be made public for civil or commercial users is unknown. For this reason, the subfunction of situational awareness for collision avoidance is missing in the cislunar architectures provided by NASA and SDA.

Research conducted at Air University has been conducted which identifies a comprehensive framework for situational awareness, tailored for the USSF. The research found that places of strategic significance in cislunar space include:

- Hohmann transfer from Earth orbit to the far side of the Moon

- Hohmann transfer from Earth orbit to L1
- Hohmann transfer from L1 to the far side of the Moon
- Stable elliptic lunar orbit
- Lunar North and South poles [57]

Research from the University of Colorado Boulder found that Earth-based sensors are insufficient for cislunar observations. An observer placed near the L2 equilibrium point can observe L2 orbits uninterrupted. A DRO has good visibility of cislunar space, but experiences outages of L2 orbits. Lunar based observers require three stations to view L2 orbits [58]. Additional research is needed for observation of other orbits in cislunar space, including transfer orbits, quasi-periodic orbits, as well as L1-, L3-, L4-, and L5-family orbits.

Optimal domain awareness architectures have been studied and compared with respect to solar exclusion angles, solar phase angles, and lunar exclusion angles. The results found that an ideal architecture would consist of four satellites in LEO in the Earth-Moon plane [59].

Existing cislunar architectures proposed by NASA and SDA are lacking domain awareness functions. Domain awareness is necessary to prevent satellite collision and to monitor satellite activity for safety. The next section, service function, details the features needed for a sustainable cislunar architecture.

2.1.1.3.6 Service Function

Sustainable operations in cislunar space will require servicing spacecraft, including the subfunctions of on-orbit servicing, manufacturing in space, on-site extraction, and materials processing. The subfunctions of the service function work together to increase the lifetime of satellites, reducing program costs overall. The costs that would have been used for launching additional satellites or landers can be diverted towards servicing already existing satellites. In comparison to the automobile market, rather than buying a new car from the dealer every time a part breaks, a car can be repaired and maintained for drastically lower costs. Table 5 shows a summary of the identified program for space service and identifies needed programs for this function.

Table 5 Service Function Summary

Identified Technologies and Programs	MEV
Technology and Programs Needed	Cislunar service satellites ISRU

On-orbit servicing is an identified need for a sustainable cislunar architecture. The current approach to space is to launch a new satellite to replace an old or broken satellite, but this strategy is unsustainable for cislunar space because the access cost is substantially greater than LEO, MEO, or GEO satellites. Servicing satellites would also require the subfunction of standardization to limit the cost of the servicing infrastructure [20]. Northrup Grumman has taken a step forward in space vehicle servicing with the Mission Extension Vehicle (MEV). The first two MEV missions successfully docked to GEO satellites and extended their lives by providing fuel and extended maneuvering capabilities. The next generation of MEV is the Mission Extension Pod which is a smaller package only providing orbit control. A more advance planned service vehicle is the Mission Robotic Vehicle (MRV), which performs all the functions of the MEV with additional service capabilities [60]. These geostationary missions are necessary first steps to establishing a cislunar service capability.

In-space servicing will also drive the need for manufacturing in space. On-site extraction and materials processing will need to be performed to sustain the servicing functions [20]. These functions have the potential for profitability and will likely be led by the commercial missions conducting ISRU.

Cislunar space logistics systems have been identified as low-cost solutions for repair, refueling, and reconstitution from GEO to the Moon. Cislunar orbits about Lagrange point L1 or L2 are ideal staging points due to the low-fuel transfers to manifolds with can reach all cislunar space, even down to GEO [61].

A servicing infrastructure would require satellites dedicated to this function, but these have not been identified in published cislunar architectures. The next section details the energy function which is tightly coupled with service due to the need for on-site extraction and materials processing.

2.1.1.3.7 Energy Function

Energy, which includes fuel and power, will be a key function in a cislunar architecture. Energy collection, energy distribution, fuel storage, on-site extraction, and materials processing subfunctions must be considered in the architecture [20]. Table 6 Table 5shows a summary of the identified program for cislunar energy and identifies needed programs for this function.

Table 6 Energy Function Summary

Identified Technologies and Programs	Lunar Surveying Missions
Technology and Programs Needed	Cislunar refueling satellites ISRU

Like the service function, the energy function drives the need for on-site extraction, and materials processing. These functions offer profitability and will likely be accomplished by commercial entities. Lunar surveying missions have identified several potential sources for mining, including water, Helium-3, rare Earth metals (REM) and lunar soil. Lunar water can be converted to rocket fuel and Helium-3 is considered as a potential element for nuclear fusion [62].

Both fuel and power will require standardization for any asset needing to take advantage of these resources [20].

2.1.1.3.8 Shelter Function

Cislunar space is a challenging place for humans to survive. The Moon harbors dangerous levels of radiation from cosmic rays and solar flares. These radiation sources cause the lunar regolith to become radioactive [63]. The lack of breathable air is another aspect of lunar exploration that must be considered. To keep biological beings safe while traveling through cislunar space and while working on the surface of the Moon, shelter is necessary. Table 7 shows a summary of the identified program for cislunar shelter and identifies no additional programs for this function.

Table 7 Shelter Function Summary

Identified Technologies and Programs	HALO
Technology and Programs Needed	None Identified

NASA's HALO is a module on the Gateway designed to keep astronauts safe while orbiting the Moon. HALO will have living quarters, docking ports, and control of the Gateway.

As part of the Artemis Base Camp, NASA also plans to build the habitable mobility platform which would allow two crew members to live and work on the lunar surface for 30-45 days [6].

Using lunar regolith, it is possible to reduce the amount of radiation transmitted to a human on the Moon. Simulations show that lunar regolith can shield against neutrons similar to aluminum, reducing radiation transmission by more than 50% [64]. Harnessing the plentiful resource of lunar regolith is a powerful strategy for establishing shelter on the Moon. On-site manufacturing will need to be well established to build a structure of lunar regolith.

NASA's first human missions to the Moon are planned for 2024 and a sustained human presence is planned for 2028. Initial shelter capabilities will be needed for early human missions while a robust infrastructure will be required by 2028.

2.1.1.3.9 Control Function

The control function includes the data flows of status, commanding, and fault detection/recovery. Control systems include the ground control centers, satellite telemetry, tracking and control (TT&C) subsystems, and operators. Ground antennas are considered part of the communication function and are heavily utilized by the control function. Control systems exist for Earth-orbiters which need modification for use in cislunar space. Cislunar space requires a control system which can account for the 3-body dynamics of the Earth-Moon system. During preliminary missions to the Moon, dedicated control systems for each mission will be sufficient. As the number of missions operating near the Moon increases, an integrated control system will be required to reduce costs and increase system efficiency. Table 8 shows a summary of the identified program for cislunar control and identifies no additional programs for this function.

Table 8 Control Function Summary

Identified Technologies and Programs	Cislunar catalog
Technology and Programs Needed	None Identified

The AFRL Space Vehicles Directorate is researching cislunar control functions. The cislunar catalog is listed as a priority effort which compensates for the orbital dynamics found in cislunar space. Additionally, cislunar operator interfaces are in development which help with the visualization of this new domain and associated dynamics [65].

2.1.1.3.10 Supporting Functions Conclusion

The functions of transportation, communication, navigation, situational awareness, service, energy, and control are necessary to support the primary missions in cislunar space. Transportation functions include launch and lunar orbiters used as staging points. Communication and navigation functions are presented as necessary functions for all cislunar missions. Situational awareness is necessary for surveillance and collision avoidance but is lacking in cislunar plans. Service functions include on-orbit servicing and manufacturing. Energy functions include energy collection, energy distribution, and fuel storage. Service and energy functions include standardization, on-site extraction, and materials processing. The shelter function includes human habitation. Control functions include commanding, status, and fault detection/recovery.

2.1.1.4 Cislunar Architectures Conclusion

Figure 3 shows a mapping of the primary missions to supporting functions. Science missions require transportation, communication, navigation, domain awareness, shelter, and control. Commerce missions require transportation, communication, navigation, domain awareness, shelter, and control. Defense missions require transportation, communication, navigation, domain awareness, and control. Future science, commerce, and defense missions will require a more robust infrastructure with service and energy functions to drive down the cost of access to cislunar space.

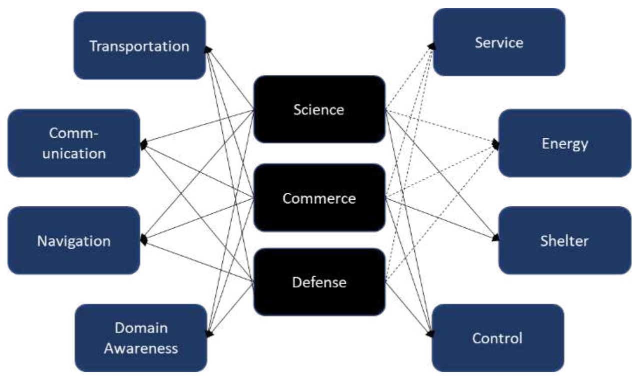

Figure 3 Map of Primary Missions to Supporting Functions

Cislunar space is the next frontier of space exploration and utilization. The primary missions planned on or near the moon include science, commerce, and defense. As operations grow in cislunar space, a comprehensive and sustainable supporting architecture will be needed which includes the functions of transportation, communication, navigation, domain awareness, service, energy, shelter, and control. NASA has plans for the transportation, communication, navigation, and shelter functions with the Artemis program. The SDA has plans for an independent architecture of communication, navigation, and domain awareness functions. AFRL is researching the domain awareness and control functions. Funded plans are lacking for service, and energy functions. Research has been conducted for each supporting function, however, a comprehensive plan for an integrated cislunar space architecture is lacking. A summary of the gaps identified in the cislunar architecture is provided in Table 9.

Table 9 Summary of Cislunar Architecture Gaps

Function	**Gaps identified based on identified technologies and programs**
Transportation	None identified
Communications	Relay link or 50-meter ground antennas
Navigation	Lunar Navigation Satellite System (LNSS)
Domain Awareness	Sensors of lunar surface, especially poles Sensors of lunar orbits Sensors of cislunar orbits
Service	Cislunar service satellites In-Situ Resource Utilization (ISRU)
Energy	Cislunar refueling satellites In-Situ Resource Utilization (ISRU)
Shelter	None identified
Control	None identified

2.1.2 SYSTEM OF SYSTEMS

A system can be defined as "A set of interrelated components functioning together towards some common objective(s) or purpose(s)" [66]. For instance, a communications satellite has many subsystems working to keep the satellite functioning to allow the payload to make a communications link with another node – this is a system. A SoS can be defined as "a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities" [67]. Expanding on the communications satellite example, the SoS would include a navigation satellite providing positioning to the system, a satellite sensing other satellites for collision avoidance, the satellites being observed accomplishing a classified mission, a control system providing status and commanding for the system, and any other contributing system to the SoS. This level of complexity requires appropriate system engineering methods. A complex system is sometimes confused with a SoS. A complex system has many interrelated subsystems and components which exhibit emergent behavior over time but is not necessarily a SoS. SoS's are comprised of individual and valid systems working together with disparate authority [68].

Traditional, document-based Systems Engineering is limited in its ability to engineer complex SoS's. Traditional practices have lack of precision and clarity with SoS design because SoS's have blurred system boundaries and requirements are not as straightforward. A SoS typically evolves greatly over time – more than a single system. Systems within a SoS can become intertwined, leading to greater complexity [69]. The level of complexity of a system can be measured by determining the number and complexity of each system interaction and the global effect on the architecture. Research shows that it is possible for complexity and modularity to both increase – they do not inherently have an inverse relationship [70]. The complexity of a system or SoS is important during design through operation.

Complexity can be managed as a risk, bringing awareness to areas of the system prone to emergent behavior. For example, a new heavy-list rocket being designed for missions to the Moon is a complex system. The propulsion, guidance, and structural subsystems would all require new technologies that must be integrated and have complexity within themselves. Early in system design, each subsystem would have their own level of complexity, and therefore risk – there are many unknowns at this point. As the system matures, prototypes can be developed and tested allowing some emergent behaviors to become known. The complexity, and risk, would still exist until the day the rocket is launched operationally and for the years of operational use. Complex systems have some level of uncertainty and risk involved throughout their lifecycles.

The DoD released a guide for engineering SoS's. This guide lists the core elements of engineering a SoS to be:

1. Translate SoS objectives into high-level SoS requirements
2. Understand constituent systems and relationships
3. Assess SoS performance
4. Develop, evolve, and maintain architecture
5. Monitor and assess changes
6. Address requirements and solution options
7. Orchestrate upgrades [67]

SoS design requires consideration of enterprise-level objectives in concert with system-level objectives. One proposed method for dealing with the new requirements of SoS is to quantify system attributes into Quality Attributes (QAts) and assess them against performance measures to compare alternative architectures [71]. This is a systematic approach for evaluating SoS architectures.

2.1.3 Model-Based Systems Engineering

MBSE is a powerful technique used during concept development through test and deployment of a system. MBSE is used instead of document-based engineering to create efficiency while engineering a system. The model built using MBSE can be used throughout the system lifecycle and updated easily as the design evolves.

SysML is a graphical modeling language that is ideal for Systems Engineering (SE) applications. The fundamental pillars of SysML include structure, behavior, requirements, and parametrics. Using SysML, a complete architecture can be designed with different viewpoints. Three minimum viewpoints in architecture design are recognized as: operational, logical, and physical [72]. The architectures designed using MBSE can be evaluated in an Analysis of Alternatives to determine the "best" design. Architecture evaluation techniques are further detailed in Section 2.1.4.

An MBSE methodology is defined as a collection of processes, methods, and tools. The leading methodologies with their associated approach(es), language(s), and artifact(s) are shown in Table 10.

Table 10 MBSE Methodologies

Methodology	Approach	Language(s)	Artifact(s)

IBM[3] Telelogic Harmony-SE	"service request-driven"	OMG[4] SysML	requirements analysis system functional analysis architectural design [73]
INCOSE[5] OOSEM[6]	top-down, model-based	OMG SysML	analyze stakeholder needs define system requirements define logical architecture synthesize candidate allocated architectures optimize and evaluate architectures validate and verify system [73]
IBM RUP SE[7] for MDSD[8]	"divide and conquer" system decomposition	UML[9], SysML	context diagram use case model requirements diagram analysis model [74]
Vitech MBSE	engineer the system horizontally, then vertically	MBSE SDL[10]	behavior analysis architecture analysis design verification and validation source requirements analysis [73]
JPL[11] SA[12]	model- and state-based control architecture	SQL[13]-compliant	state-based behavioral modeling state-based software design goal-directed operations engineering [73]

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[3] International Business Machines

[4] Object Management Group

[5] International Council on Systems Engineering

[6] Object-Oriented Systems Engineering Method

[7] Rational Unified Process for Systems Engineering

[8] Model-Driven Systems Development

[9] Unified Modeling Language

[10] System Definition Language

[11] Jet Propulsion Laboratory

[12] State Analysis

[13] Structured Query Language

Dori OPM[14]	every known entity is an object or a process which exist in a state	OPL[15]	systems diagram [73]

Digital Mission Engineering (DME) is a type of MBSE which links a physics-based model throughout the lifecycle of the system. DME has been shown to decrease the time needed for planning, tool development, setup, and trades by fifty percent when compared to traditional design methods [75]. The physics-based model can be built horizontally, then vertically, meaning a low-fidelity system can be designed first and detail can be added as the design matures. This is a powerful way to find design discrepancies efficiently to reduce risk in the design.

MBSE is a time-saving technique which can be used throughout the system lifecycle in the long-run. Like most SE techniques, MBSE requires the most time and energy up-front to define the model and input the data. Once the initial effort is complete, the time-savings occurs during system design, evaluation, operations, and disposal. MBSE also offers cost and time savings when pieces of the model can by re-used in new or modified designs. When applying MBSE, it is important to consider the problem under consideration and focus modeling efforts on the intended solution [76]. There are many methodologies of MBSE depending on the application desired. DME can lead to a more robust MBSE design which integrates physics-based models throughout the lifecycle to reduce risk. An integrated physics-based model is

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[14] Object-Process Methodology

[15] Object-Process Language

beneficial for space systems. The complexity of a space system of systems (SoS), such as a cislunar space architecture, could greatly benefit from the rigor of MBSE. This concept would require integrating multiple models because it is unlikely that each cislunar system would use the same tools and languages.

2.1.4 System Architecture Evaluation

2.1.4.1 System Architecture Evaluation Introduction

Systems Engineering processes are used throughout the lifecycle of a system, from Concept Development to Engineering Development to Post-development. Concept Development includes the Needs Analysis, Concept Exploration, and Concept Definition. The Concept Definition includes the completion of the Analysis of Alternatives, Functional Architecture, and Physical Architecture [77]. The main task of the analysis of alternatives is to complete the system architecture evaluation. The breakdown of these Systems Engineering processes with the focus on system architecture is shown in Figure 4.

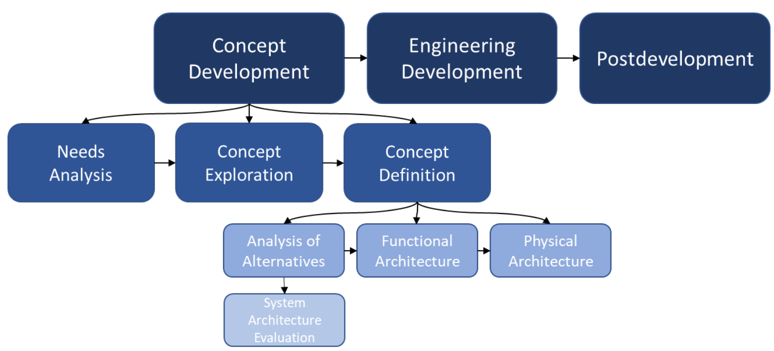

Figure 4 Architecture Evaluation in Systems Engineering Process

The following sections provide details on evaluation parameters, common architecture evaluation strategies, and an application of architecture evaluation to cislunar space.

2.1.4.2 Evaluation Parameters

Flexibility is a positive characteristic of modern space systems to allow for adaptability as requirements change or to allow for upgradability as the system lifecycle evolves. However, designing for flexibility can be challenging. To evaluate designs for flexibility, six parameters can be used to account for flexibility. These six parameters can be assigned weight to tailor to the system architect's needs:

- System boundary
- System aspect
- Time window of interest
- Uncertainty profile
- Degree of access
- Value delivery response to change [78]

While these six parameters have been researched and applied to the flexibility characteristic, they could be applied to other characteristics during architecture evaluation.

Autonomy is an additional characteristic that is highly desired in space systems. Autonomy can be challenging to design for but can reap many cost-saving benefits in the system lifecycle due to reduced operating costs. Deep space systems, including cislunar systems, require a higher level of autonomy than Earth-orbiting systems due to the long communication delays and lack of constant coverage. Autonomy can be modeled in mission planning algorithms to inform the evaluation of different architectures [79].

Another useful characteristic in system architecture design is modularity. Accounting for modularity early in the design lifecycle has been shown to reduce the overall schedule and cost of the system [80]. Designing for modularity is essential for a cislunar architecture which includes the service function. Modular systems and subsystems allow for ease of serviceability and upgradability.

Research suggests that uncertainty is an important criterion to consider during architecture evaluation [81]. Stakeholder ambiguity is a common issue during system design, but research suggests that this ambiguity can be designed for. The sources of ambiguity can be characterized and modeled to make assessments to the architecture trade space [82]. Portfolio theory, which is often applied to economics, can be used to manage uncertainty in space system design. By applying this theory, individual designs are assessed in terms of uncertainty and the designs are carried throughout the project in a portfolio, reducing the project's overall uncertainty or risk [83]. This strategy reduces the overall program risk because many architecture options are available if one becomes incompatible. Applying portfolio theory is also costly or time-consuming because the current design must maintain compatibility with a portfolio of architectures.

System maturity is an additional characteristic which can be included in architecture evaluation. Maturity can be measured by Technology Readiness Level (TRL) and Integration Readiness Level (IRL). TRLs are typically measured on a scale of one to nine which low-maturity technology assigned low TRL levels. The concept of IRL has been proposed to measure the maturity of integration of technological elements. An assessment of the component TRLs with interface IRLs would provide an overall System Readiness Level (SRL) [84]. The SRL could be used to provide a quantitative assessment of the proposed architecture maturity. Another extension of the concept of TRL is Human Readiness Level (HRL) which consists of nine levels ranging from research and development to technology demonstration ending in production and deployment [85]. TRL, IRL, SRL, and HRL are all quantitative measures to assess system architectures.

For each architecture evaluation method listed below, the selecting the evaluation criteria is a critical and highly subjective task. There are two key issues which lead to a poor selection of evaluation criteria. First, interdisciplinary aspects of the system make criteria interdependent. Second, a lack of information early in the system design cycle leads to picking poor criteria selection. These issues can lead to conflicting criteria and lack of reference for acceptable criteria ranges [86].

2.1.4.3 Architecture Evaluation Strategies

MBSE is a useful technique to help automate architecture evaluation rather than evaluating each considered by hand. Research of MBSE during architecture evaluation has found that it is more illuminating to evaluate criteria in an integrated manner rather than individually. For instance, if a set of space architectures are evaluated for communication data rates, operations costs, and system risks, these can be considered collectively and not as individual criteria. Another effective technique to apply during system architecture evaluation is to apply information quality theory by re-using relevant design aspects from similar systems and focusing efforts where updates to the design are needed, such as cost data. This technique reduces system development costs and increases team performance due to the "momentum" gained by the system designers [87]. It is also possible to apply feedback during system architecture evaluation. Feedback would allow the system architect to update user parameters as more information becomes known about the system, leading to a more appropriate final architecture [88]. The evaluation strategies listed below follow linear processes, without feedback, for the system architect to systematically evaluate architectures.

2.1.4.3.1 Architecture Tradeoff Analysis Method

The Architecture Tradeoff Analysis Method (ATAM) is a linear method of assessing architectures. It was designed for software systems, but the concepts could apply to non-software systems. The steps of the method include:

1. Presentation
    a. Present the ATAM
    b. Present business drivers
    c. Present architecture
2. Investigation and Analysis
    a. Identify architectural approaches
    b. Generate quality attribute utility tree
    c. Analyze architectural approaches
3. Testing
    a. Brainstorm and prioritize scenarios
    b. Analyze architectural approaches
4. Reporting
    a. Present Results [89]

One of the benefits of using ATAM is the strong tie to the stakeholders. During the presentation and reporting phases of ATAM, the entire architecting team meets, including customers, architects, users, maintainers, managers, testers, etc. [89] The main disadvantage of ATAM is the lack of feedback opportunities. For instance, if new information is found during investigation or testing, there is no opportunity to improve the architecture. The team must move forward with the initially presented architectures.

2.1.4.3.2 Quality Attribute Workshop

The Quality Attribute Workshop (QAW) is a system architecture evaluation method which analyzes the model against critical attributes. The attributes are assessed subjectively by analyzing behavior of the model in certain scenarios [90]. This method is highly dependent upon the architect's interpretation of the analyzed behavior.

2.1.4.3.3 Kiviat Chart Assessment Method

A Kiviat chart, also known as a spider chart, is a way to graphically display data with multiple variables to assess performance and weaknesses. In the Kiviat chart assessment method, key performance attributes are identified and assessed for each identified architecture. Using the Kiviat charts, the architect can visually assess if an architecture possesses the needed qualities. A quantitative assessment can also be obtained by calculating the area of each polygon [91]. An example of a Kiviat chart is shown in Figure 5.

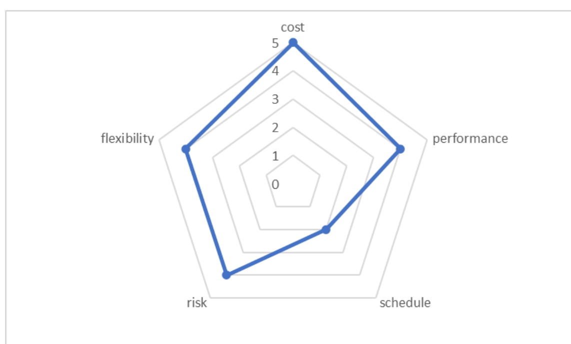

Figure 5 Example Kiviat Chart

This method is vulnerable to the selection of appropriate key performance attributes. Like many architecture evaluation methods, the selection of performance attributes is often the driving factor in determining the best architecture. These attributes are highly subjective to the opinions of the stakeholders early in the system lifecycle. The Kiviat visualization also lacks the ability to show priority or weights to the key performance attributes. This method has the benefit of being highly visual, which can make assessment of architecture strengths and weaknesses easier for the system architect.

2.1.4.3.4 MULTI-CRITERIA DECISION MAKING WITH EVIDENTIAL REASONING

MCDM is a powerful architecture assessment method because it can be applied to SoS's. The first step in MCDM is to define the quality attributes (high level characteristics), sub-attributes (mid-level characteristics), and measures (low-level characteristics). ER can be applied with MCDM to handle quantitative and qualitative attributes. ER assesses each attribute using measurable grades, a belief structure, and fuzzy linguistic variables. An extended decision matrix is utilized which assigns a grade to each attribute and then the degree of certainty that the grade can be applied [90] [92].

MCDM with ER has the advantage of allowing the architect to make assessments even when there is uncertainty, absence of data, incomplete attribute descriptions, random nature, or fuzziness in grades [90]. The architect must be willing to carry this risk and uncertainty through system design. As certainty is gained during design, it can be beneficial to re-evaluate the lower levels of the architecture.

When applying MCDM with ER, weighting must be applied, and the scores must be scaled. Subjective, objective, and integrated weighting methods exist for decision making. For a scientific and academic application of MCDM, an objective weighting method is preferred. Objective methods include the entropy method, mean weight, standard deviation, statistical variance procedure, and idea point method. For a system where little is known of stakeholder preference, the mean weight method is preferred. In the mean weight method, all criteria are weighted equally. In this method, scores are calculated on a linear scale to ensure equal weighting. [93]

2.1.4.4 Architecture Evaluation Applied to Cislunar Space

System architecture evaluation techniques have been applied to cislunar situational awareness systems. Research has recognized that existing situational awareness systems are insufficient for cislunar applications. For this specific application, the fitness metrics of performance (ability to track on object) and cost are deemed most appropriate. System performance is found to be heavily influenced by the physics of cislunar space, including solar exclusion angle, solar phase angle, and lunar exclusion angles. An integrated physics model, used in DME, is helpful in this case. For the architectures evaluated, the highest performing and most cost efficient is found to be a four-satellite LEO constellation in the Earth-Moon plane [59]. An example of a 4-satellite coplanar constellation with zenith-facing sensors is shown in Figure 6

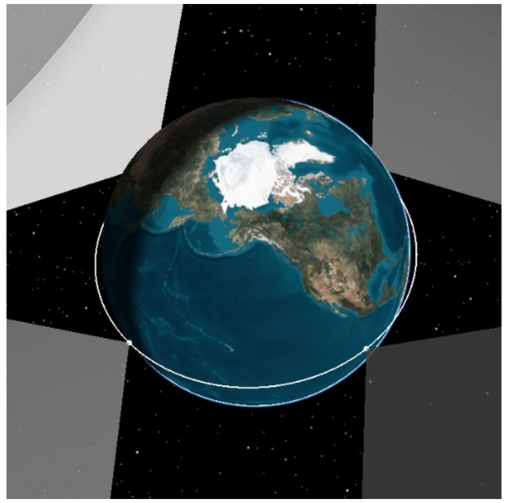

Figure 6 Coplanar Space Domain Awareness Constellation

Evaluations of the other supporting functions and primary missions is lacking research. This dissertation proposes to close the gap by evaluating and optimizing an integrated cislunar architecture.

2.1.4.5 System Architecture Evaluation Conclusion

This section provided evaluation parameters, architecture evaluation strategies, and an evaluation applied to cislunar space. The evaluation parameters highlighted include flexibility, autonomy, modularity, and uncertainty. The architecture evaluation strategies include Architecture Tradeoff Evaluation Method, Quality Attribute Workshop, Kiviat Chart Assessment, and Evidential Reasoning. Finally, the application of cislunar system architecture evaluation is applied to a domain awareness system.

2.1.5 System Architecture Optimization

2.1.5.1 System Architecture Optimization Introduction

After system architecture evaluation, then optimization can be performed. Optimization is also performed during the Analysis of Alternatives phase of the Systems Engineering processes, as shown in Figure 7. Optimization is not a required step in the Systems Engineering processes.

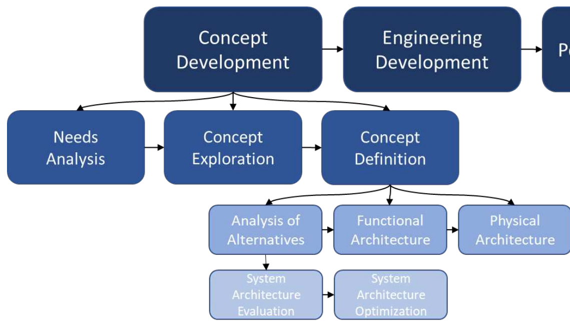

Figure 7 Architecture Optimization in Systems Engineering Process

The following sections provide details on optimization strategies, focusing on strategies relevant to cislunar systems, and optimization applications in cislunar systems.

2.1.5.2 System Architecture Optimization Strategies

Many strategies exit for optimizing problems depending on the requirements of the problem. The two main classes of optimization techniques include differential (bracketing, local descent, first-order, second order) and non-differential (direct, stochastic, population). Table 11 shows these seven optimization algorithms, a description, and examples of each.

Table 11 Optimization Algorithms [94]

Name	**Description**	**Examples**
Bracketing Algorithms	One input variables and single optimal solution within a known range Requires differentiable objective function	Fibonacci Search Golden Section Search Bisection Method
Local Descent Algorithms	More than one input and single global optimal solution Requires differentiable objective function	Line Search
First-Order Algorithms	Use first derivative to search the space Requires differentiable objective function	Gradient Descent Momentum Adagrad

		RMSProp Adam Stochastic Gradient Descent Batch Gradient Descent Mini-Batch Gradient Descent
Second-Order Algorithms	Use second derivative to search the space Requires the Hessian matrix Requires differentiable objective function	Newton's Method Secant Method Quasi-Newton Method
Direct Algorithms	Single global optimal solution Known as "pattern search" because geometric shapes are used	Cyclic Coordinate Search Powell's Method Hooke-Jeeves Method Nelder-Mead Simplex Search
Stochastic Algorithms	Use randomness in search procedure Able to overcome incorrect local optimal solutions	Simulated Annealing Evolution Strategy Cross-Entropy Method
Population Algorithms	Stochastic algorithms that maintain a pool of candidate solutions Use for challenging problems with noisy function evaluations Able to overcome incorrect local optimal solutions	Genetic Algorithms Differential Evolution Particle Swarm Optimization

For problems involving architectures of systems and SoS's, a single input algorithm is not appropriate because a system inherently has multiple inputs. A differential objective function is not available for this class of problems, so non-differential techniques must be utilized. Assuming a single optimal solution is not appropriate for this problem type because local optimal solutions often exist in these complex systems. The remaining algorithms include direct, stochastic, and population algorithms.

2.1.5.2.1 Direct Algorithms

The direct algorithm utilizes geometric shapes to search the space. To guarantee that the global optimum is found using a direct algorithm, an exhaustive search must be executed. This may be prohibitively expensive depending on the search space. A non-exhaustive search comprises of dividing the search space into rectangles which are potentially optimal. Optimality is calculated using Lipschitz continuity. The optimal rectangles are continuously divided into smaller optimal rectangles until the local optimum is found. [95]

2.1.5.2.2 Stochastic Algorithms

Stochastic algorithms are used in optimization when randomness is present in the objective function or constraints [96]. Stochastic algorithms can also, or exclusively, use random iteration methods. Using random iteration is also known as stochastic search. Stochastic optimization can be divided into two main methods:

- Single stage problems
  - Find a single optimal solution
- Multistage problems
  - Find an optimal sequence [96]

Stochastic methods tend to be able to find global optimal solutions rather than incorrectly converging on a local solution. Due to the heuristic nature of these algorithms, it is considered best practice to run the algorithm, or algorithms, multiple times to compare algorithms and evaluate the result [97].

2.1.5.2.3 Population Algorithms

Population algorithms are sometimes called genetic algorithms because of their use of natural selection and gene combinations. A simple genetic algorithm has the following steps:

1. Generate a population of solutions and evaluate each "fitness"
2. Generate "offspring" from that population using a crossover operator

3. “Mutate” each crossover solution
4. Assign a “fitness” value to each mutated solution
5. The most fit solutions become part of the new population
6. Continue the above steps until the stopping criteria are met [98]

Genetic algorithms can be assessed for multi-objective optimization and are a good fit for cislunar systems optimization problems. In multi-objective optimization, the solution can be optimized to the pareto front. The pareto front describes a curve of the possible optimal solutions [99]. In reference to the optimization steps outline above, the pareto front defines the stopping conditions of the optimization algorithm.

2.1.5.3 Optimization Applied to Model-Based Systems Engineering

MBSE can be utilized to automate the optimization of systems within a SoS. To use MBSE, a reference architecture is developed and then parameters are modified and evaluated until optimality is reached [100]. Defense acquisition programs typically follow highly manual processes when conducting Analysis of Alternatives, which prevents optimization of systems with any level of complexity. MBSE overcomes this barrier allowing even large defense programs to apply optimization to architecture design [101].

2.1.5.4 Optimization Applied to Cislunar Space

The Multi Objective Genetic Algorithm (MOGA) has been applied to satellite constellation optimization. In this application, reproduction and mutation are utilized and the constellation is optimized for number of orbital planes, satellites per plane, orbit altitude, and inclination angle [102]. In cislunar space, optimal constellation around the Moon can be designed for communication, navigation, and situational awareness. Early missions to the Moon likely won’t have robust constellations of satellites, but as the number of missions to the Moon grows, the supporting infrastructure will need to grow to reduce the cost of access to cislunar space.

Optimization can be applied at more detailed levels of a cislunar system of systems. For example, trajectory optimization is an essential part of mission planning for individual cislunar missions. Low thrust technologies, such as electric propulsion and solar cells, offer ten times more efficient travel to the Moon when compared to traditional chemical rocket. Low thrust trajectories require more complicated astrodynamics modeling over impulse maneuvers because the thrust is being applied almost continuously throughout flight. Additionally, the three-body dynamics of the Earth-Moon system further complicate the astrodynamics models. Algorithms do exist which optimize low-thrust trajectories in cislunar space [103].

Genetic algorithms have also been used to optimize trajectories in cislunar space. An optimal trajectory between a Lagrange point, L1 or L2, to GEO is one which considers a Sun-exclusion zone constraint which allows for maximum tracking throughout the trajectory. Alternatively, trajectories can be designed which remain in the Sun-exclusion zone for the entire duration. This stealth feature would be desirable for some defense missions that need to be unseen. When optimized for fuel and time of flight, the trajectory which is constrained to remain in the Sun-exclusion zone is found to need significantly more fuel than a trajectory that does not have the Sun-exclusion zone constraint. When the amount of time in the Sun-exclusion zone was decreased, the optimal trajectory had a feasible fuel need [104]. In this scenario, the variables of time in Sun-exclusion zone, fuel, and time of flight can be constrained to meet mission requirements while optimized using a genetic algorithm.

2.1.5.5 System Architecture Optimization Conclusion

System architecture optimization methods are attractive ways to find the “best” architecture for a given problem. For cislunar systems, the most applicable optimization methods include stochastic and population algorithms. Model-based systems engineering can be used in architecture optimization to automate the algorithms. Genetic algorithms have been used to optimize satellite constellations and cislunar trajectories, but research is needed to apply optimization techniques to the architecture of a cislunar system. This dissertation attempts to address the need for an optimal cislunar architecture.

2.1.6 Literature Review Conclusions

This Literature Review began with detailed summaries of research of cislunar space and planned programs. The primary missions of science, commerce, and defense are identified. Supporting functions are identified as transportation, communication, navigation, situational awareness, energy, service, shelter, and control. For each supporting function, identified gaps in planned technologies and programs are provided. Next, research on SoS is presented due to the SoS nature of a cislunar architecture. Relevant MBSE concepts are described. Then, system architecture evaluation is presented in terms of evaluation parameters, evaluation strategies, and examples of applications. Finally, relevant system architecture optimization strategies and applications are detailed. These are the main topics identified and researched for a dissertation on cislunar systems architectures. Approach

Chapter 3. METHODOLOGY

3.1 MODEL-BASED SYSTEMS ARCHITECTURE PROCESS

For this dissertation, a Cameo Systems Modeler^{TM} Systems Modeling Language (SysML) model of a Cislunar Space Systems Architecture is created using the Model-Based Systems Architecture Process (MBSAP). First, background on SysML is provided. Next, an Architecture Overview and Summary is provided with details of the architecture development with a programmatic perspective. Finally, the three viewpoints are detailed: the Operational Viewpoint (OV), the Logical/Functional Viewpoint (LV), and the Physical Viewpoint (PV). The most relevant parts of the model are presented for the design of the cislunar system of systems. Additional model elements are included in APPENDIX B.

In the first viewpoint, several parts of the OV are populated. The Functional and Nonfunctional requirements are listed in a table and requirements diagram including a requirement identification (ID), name, text, and category. The structural perspective of the operational viewpoint is shown using a domain diagram with actors, interactions, and specifications. The behavioral perspective is populated with a Use Case diagram (UC). The use case diagram included the use cases of "PerformScienceMission", "PerformCommerceMission", and "PerformDefenseMission". The contextual perspective is shown including environment, users, external system capabilities, and legal constraints. All relevant contextual information found to date is shown in the contextual perspective.

The second viewpoint, the LV, is populated starting with the structural perspective. A diagram of the structural decomposition of the navigation domain is shown. In the contextual perspective of the logical viewpoint, four categories are shown including enterprise design drivers, nonfunctional requirements, customer artifacts, and policies/mandates.

In the third viewpoint, the PV, detailed design of the model is accomplished. Example specifications are shown for the detailed design of SysML blocks and interface blocksFor the standards perspective, the appropriate standards are listed for safety, information systems, human factors, navigation, communications, and transportation.

3.1.1 Systems Modeling Language Background

SysML is the universally accepted language for modeling in MBSE. In SysML, the primary classifiers include block, part, interface, actor, value type, and signal. A block describes an instance with shared characteristics; the block is the basic element used in SysML. Examples of using blocks in a Block Definition Diagram (BDD) and internal block diagram (IBD) are shown in Figure 8 and Figure 9. A part is a subset of a block. Examples of parts are shown in the third IBD of Figure 9. An interface describes a set of operations specifying a service or function, usually implemented in a port. Figure 9 shows several examples of port interfaces in an IBD. An actor specifies an external entity. Actors are commonly used in a UC, as shown in Figure 10, but can also exist in BDDs. A value type is a property or operation describing a block. Examples of values and operations are shown in Figure 10 within the Part1 and Part2 blocks of the third IBD. A signal is a general type of interaction between model elements. Example signals can be found in Figure 8, Figure 9, and Figure 10 with each interaction between blocks, parts, actors, and ports. [105]

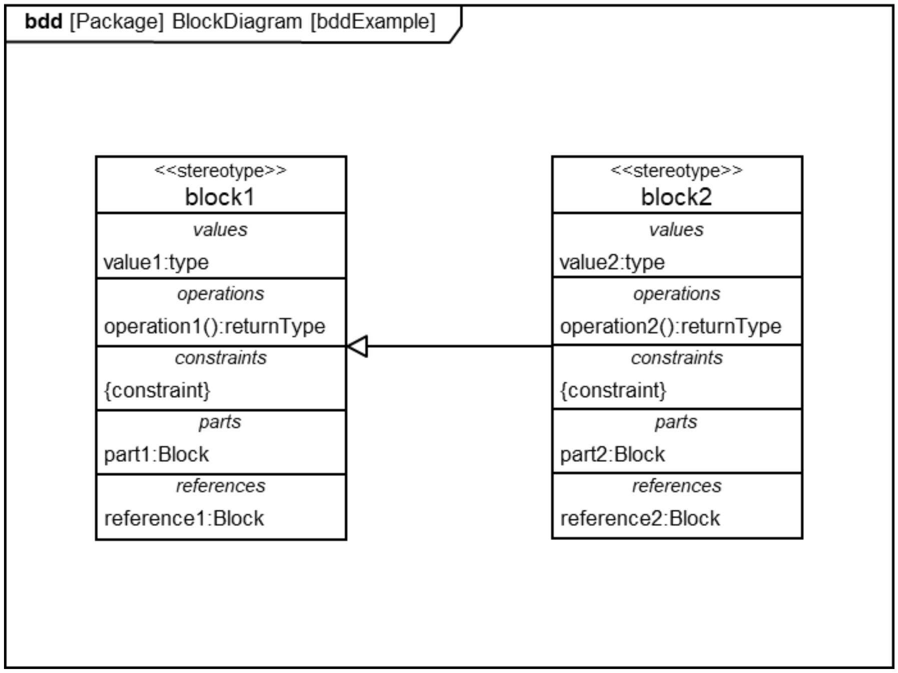

Figure 8 Block Definition Diagram

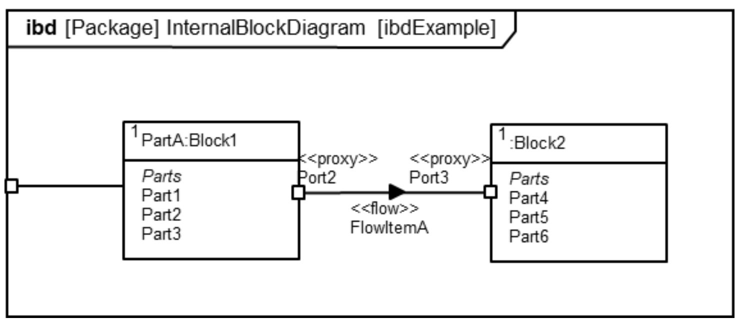

Figure 9 Internal Block Diagrams

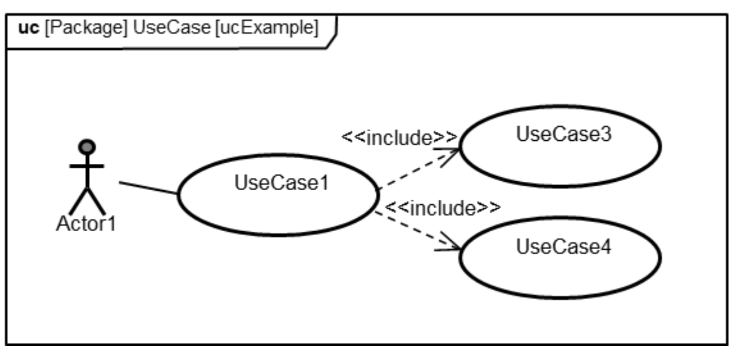

Figure 10 Elements of a Use Case Diagram

Relationships and behaviors for SysML classifiers are modeled in diagrams which include package diagram, requirement diagram, parametric diagram (PAR), BDD, IBD, UC, STM, ACT, and SD. The package diagram shows the overall structure of the model, like a file folder structure. The requirements diagram is a specialized diagram which shows the relationships between system requirements. A PAR is used to model mathematical relationships and constraints. The BDD models the relationships between block while the IBD models the internal structure of a block. The UC models units of behavior, including relationships with actors. The STM models stateful behavior which are triggered by events. The ACT models flow-based behavior. The SD models message-based behaviors. [105] Figure 11 includes a structural decomposition of the SysML diagrams, including their relationships to Unified Modeling Language (UML). UML is the parent language to SysML.

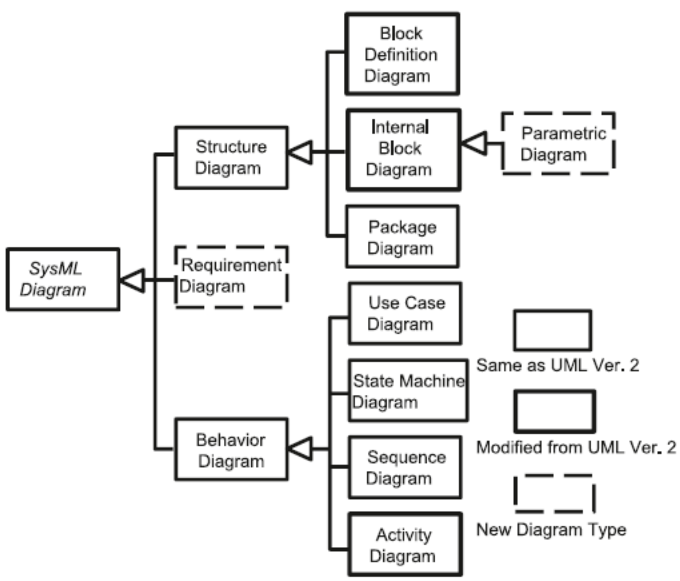

Figure 11 SysML Diagrams [105]

This dissertation follows the MBSAP methodology for building the model in Cameo Systems Modeler^{TM}. MBSAP provides a systematic process for building the system architecture.

This process guides the system architect to build-out the three viewpoints (operational, logical/functional, physical) with appropriate perspectives. For the OV, perspectives include structural, behavioral, data, services, and contextual. For the LV, perspectives include structural, behavioral, data, services, and contextual. For the PV, the perspectives include design, standards, data, services, contextual. The mapping of viewpoints to perspectives is summarized in Table 12. [105]

Table 12 Viewpoints to Perspectives Mapping

	Structural	Behavioral	Design	Standards	Data	Services	Contextual
OV	X	X			X	X	X
LV	X	X			X	X	X
PV			X	X	X	X	X

Additional viewpoints can be populated depending on the focus of the architecture. Common examples of these focused viewpoints include Runtime Viewpoint, Hardware Viewpoint, Network Viewpoint, Communications Viewpoint, Security Viewpoint, and System Administration Viewpoint. [105]

3.1.2 Architecture Overview and Summary

This section provides an Architecture Overview and Summary for the SysML model.

3.1.2.1 Executive Summary

This Architecture Overview and Summary describes the organization and content of the Cislunar Space Systems Architecture. The following sections describe the architecture identification & description, architecture model & artifacts, purpose & viewpoint, context, rules & criteria, and findings. The Architecture Overview is updated as the architecture effort progresses.

3.1.2.2 Architecture Identification and Description

3.1.2.2.1 General

The Cislunar Space Systems Architecture describes the infrastructure necessary for missions in cislunar space. Missions include:

- Science
- Commerce
- Defense

Identified supporting functions are modeled in the architecture and include:

- Transportation
- Communication
- Navigation
- Domain Awareness
- Energy
- Service
- Shelter
- Control

3.1.2.2.2 Assumptions and constraints

3.1.2.2.2.1 Assumptions

- The users of the system include science, commerce, and defense missions
- Upcoming missions are considered when funded, including:
  - Artemis Missions
  - Cislunar Highway Patrol System

- Missions included in the system are those supported/funded by the United States and its allies

3.1.2.2.2.2 Constraints

- The system shall function in the harsh cislunar environment
- The system shall use commercial off-the-shelf (COTS) technology or technology that is predicted to be available in the considered timeline

3.1.2.2.3 ARCHITECTURE DEVELOPMENT RESOURCES

This architecture is developed in conjunction with Laura Duffy's dissertation work. Architecture development began in SYSE-567 coursework, continued during SYSE-667 coursework, and reached a baseline version during dissertation work.

3.1.2.2.4 SCOPE

The architecture includes artifacts in accordance with the MBSAP methodology that define the Operational, Logical/Functional, and Physical Viewpoints. Focus will be on diagrams that support the dissertation research questions and tasks.

3.1.2.2.4.1 Research Questions

- Which evaluation technique, or techniques, are best applied to a cislunar system?
- Which optimization technique, or techniques, are best applied to a cislunar system?
- What special consideration must be made when evaluating a System of Systems when compared to evaluating a single system?

3.1.2.2.4.2 Research Tasks

- Perform needs analysis of comprehensive cislunar space system

- Develop a functional architecture of cislunar space to identify any gaps in current or planned cislunar efforts
- Evaluate an integrated cislunar architecture which includes all necessary supporting functions and primary missions.
- Optimize integrated cislunar architecture

3.1.2.3 ARCHITECTURE MODEL AND ARTIFACTS

3.1.2.3.1 PRIMARY ARTIFACTS

The following artifacts are developed and used to define the Cislunar Space Systems Architecture.

1. Operational Viewpoint
   a. Contextual Perspective
      i. Operational Context Diagram (UC)
      ii. Architecture Overview and Summary Information
   b. Structural Perspective
      i. Domain Composition Diagram (BDD)
      ii. Domain Interaction Diagram (IBD)
      iii. Specifications
   c. Behavioral Perspectives
      i. Use Cases Diagram (UC)
      ii. Activity Diagrams (ACT)
      iii. Specifications
   d. Data Perspective
      i. Conceptual Data Model (BDD)

2. Logical/Functional Viewpoint
    a. Structural Perspective
        i. BDDs
        ii. IBDs
    b. Behavioral Perspective
        i. Sequence Diagrams (SD)
    c. Data Perspective
        i. Logical Data Model (BDD)
    d. Contextual Perspective
        i. Logical Context Diagram (UC)
3. Physical Viewpoint
    a. Design Perspective
        i. BDDs
        ii. IBDs
        iii. Specifications
    b. Standards Perspective
        i. Standards table
    c. Data Perspective
        i. Physical Data Model (BDD)

3.1.2.3.2 Architecture Timeline and Evolution

The Cislunar Space Systems Architecture describes the architecture at the point-in-time of the dissertation research completion. The architecture timeline includes:

- Fall 2021 – SYSE 567 course – preliminary architecture development

- Spring 2022 – SYSE 667 course – final architecture development
- Summer 2022 – dissertation work – application of evaluation and optimization techniques to the architecture
- Fall 2022 – dissertation work – baseline the model

3.1.2.3.3 Organizations Involved

The architecture is built in support of a dissertation for the Colorado State University (CSU) Systems Engineering (SE) department. It includes inputs from the National Aeronautics and Space Administration (NASA) and United States Space Force (USSF) personnel and documentation.

3.1.2.4 PURPOSE AND VIEWPOINT

3.1.2.4.1 Architecture Purposes and Uses

The purpose of the architecture is to answer the research questions and tasks as defined above.

3.1.2.4.2 Architecture Analysis

The physical aspects of the cislunar architecture are modeled in Ansys Government Initiatives (AGI) Systems Tool Kit (STK) [106]. This software enables the modeling of the physical environment of cislunar space.

Matrix Laboratory (MATLAB®) is utilized to apply optimization techniques to the architecture [107].

3.1.2.4.3 Stakeholder Perspectives

The stakeholders of this architecture include the Doctor of Philosophy (PhD) student, Laura Duffy, and the PhD committee: Dr. Jim Adams, Dr. Ron Sega, Dr. Daniel Herber, Dr. Doug Fankell. During the Preliminary Examination, the following stakeholder concerns were noted:

- How will the SYSE-567 model be used, and will it be expanded upon?
- What aspect will be optimized?
- How will the model be validated?
- How will the effort be constrained in scope?

3.1.2.5 Context

3.1.2.5.1 Mission Objectives

The mission objectives of the development of the cislunar architecture are to:

- Identify and fill any gaps in the system
- Develop an integrated, holistic cislunar system

3.1.2.5.2 Architecture Status

The architecture is in baseline version and ready for analysis.

3.1.2.5.3 Tools and Formats

The architecture will be developed in Cameo Systems Modeler™ 19.0. Certain physical aspects will be modeled in STK. MATLAB® is used for optimization.

3.1.2.5.4 Organizational Context

The system architect is the PhD student, who is directly advised by Dr. Jim Adams and is graded by Systems Engineering instructor, Dr. Daniel Herber.

3.1.2.6 Rules and Criteria

3.1.2.6.1 General

Key References and Standards which drive the Cislunar Space System include:

-The Artemis Plan

- Applying model-based systems engineering to architecture optimization and selection during system acquisition

- The Lunar Exploration Roadmap

- LunaNet Standards

- A Primer on Cislunar Space

- ISO/IEC/IEEE 42030 Software, systems and enterprise — Architecture evaluation framework

3.1.2.6.2 Quality attributes

Some system characteristics and Quality Attributes which have been identified as stakeholder concerns and documented as System Nonfunctional Requirements include:

-Modularity

-Cybersecurity (securability)

-Physical security (securability)

-Safety of Life (safety)

-Classification (securability)

-Scalability

-Lifetime (sustainability)

-Openness (accessibility)

3.1.2.6.3 GOVERNANCE

As the architecture evolves, governance is enforced during graded events of SYSE-667 and during weekly tag-ups with the PhD advisor.

3.1.2.7 FINDINGS

3.1.2.7.1 ANALYSIS RESULTS

Details of the analysis of the architecture are provided in Chapter 4 of the dissertation.

3.1.2.7.2 RECOMMENDATIONS

- Key findings published during Fall 2022
- Architecture updated based on analysis results

3.1.3 OPERATIONAL VIEWPOINT

The OV is the first viewpoint in MBSAP. The OV provides artifacts used in the foundation of system design, including preliminary dialogs with stakeholders [105]. First, the structural perspective is modeled with all domains. In the behavioral perspective, preliminary Use Cases are defined. Within the data perspective, a Conceptual Data Model (CDM) is architected. Finally, in the contextual perspective, the operational context is captured.

3.1.3.1 Requirements

The requirements are documented in a requirements diagram and requirements table. Cameo Systems Modeler™ automatically links all requirements by their respective requirement ID, so if an update is made, it will propagate throughout the model. Requirements are linked to blocks via the <<satisfy>> relationship, which is visualized in Figure 12. The requirements names and descriptions are easily accessible in Figure 13.

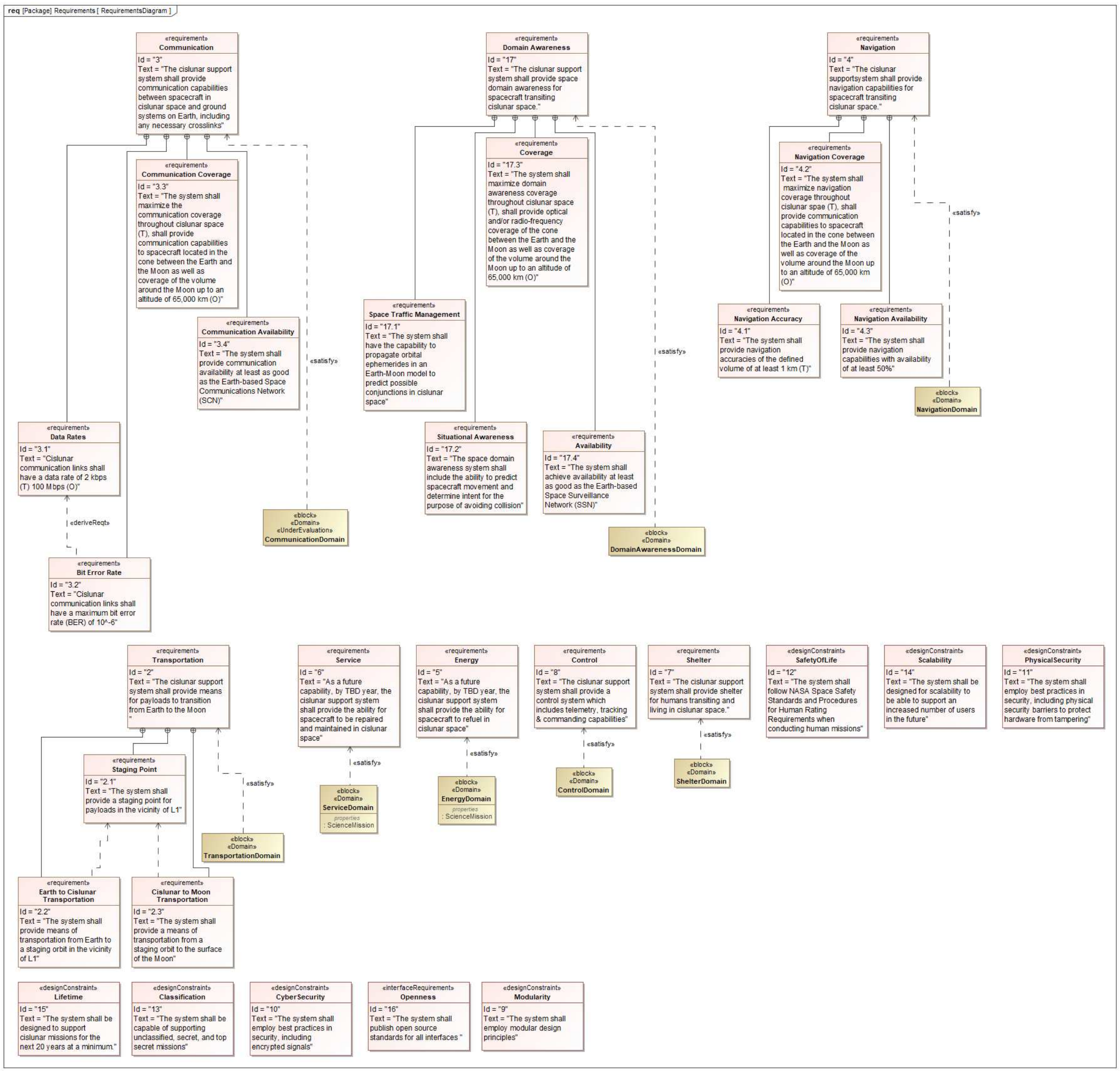

Figure 12 Requirements Diagram

#	△ Name	Text
1	2 Transportation	The cislunar support system shall provide means for payloads to transition from Earth to the Moon
2	2.1 Staging Point	The system shall provide a staging point for payloads in the vicinity of L1
3	2.2 Earth to Cislunar Transportatio	The system shall provide means of transportation from Earth to a staging orbit in the vicinity of L1
4	2.3 Cislunar to Moon Transportatio	The system shall provide a means of transportation from a staging orbit to the surface of the Moon
5	3 Communication	The cislunar support system shall provide communication capabilities between spacecraft in cislunar space and ground systems on Earth, including any necessary crosslinks
6	3.1 Data Rates	Cislunar communication links shall have a data rate of 2 kbps (T) 100 Mbps (O)
7	3.2 Bit Error Rate	Cislunar communication links shall have a maximum bit error rate (BER) of 10^-6
8	3.3 Communication Coverage	The system shall maximize the communication coverage throughout cislunar space (T), shall provide communication capabilities to spacecraft located in the cone between the Earth and the Moon as well as coverage of the volume around the Moon up to an altitude of 65,000 km (O)
9	3.4 Communication Availability	The system shall provide communication availability at least as good as the Earth-based Space Communications Network (SCN)
10	4 Navigation	The cislunar supportsystem shall provide navigation capabilities for spacecraft transiting cislunar space.
11	4.1 Navigation Accuracy	The system shall provide navigation accuracies of the defined volume of at least 1 km (T)
12	4.2 Navigation Coverage	The system shall maximize navigation coverage throughout cislunar spae (T), shall provide communication capabilities to spacecraft located in the cone between the Earth and the Moon as well as coverage of the volume around the Moon up to an altitude of 65,000 km (O)
13	4.3 Navigation Availability	The system shall provide navigation capabilities with availability of at least 50%
14	5 Energy	As a future capability, by TBD year, the cislunar support system shall provide the ability for spacecraft to refuel in cislunar space
15	6 Service	As a future capability, by TBD year, the cislunar support system shall provide the ability for spacecraft to be repaired and maintained in cislunar space
16	7 Shelter	The cislunar support system shall provide shelter for humans transiting and living in cislunar space.
17	8 Control	The cislunar support system shall provide a control system which includes telemetry, tracking & commanding capabilities
18	9 Modularity	The system shall employ modular design principles
19	10 CyberSecurity	The system shall employ best practices in security, including encrypted signals
20	11 PhysicalSecurity	The system shall employ best practices in security, including physical security barriers to protect hardware from tampering
21	12 SafetyOfLife	The system shall follow NASA Space Safety Standards and Procedures for Human Rating Requirements when conducting human missions
22	13 Classification	The system shall be capable of supporting unclassified, secret, and top secret missions
23	14 Scalability	The system shall be designed for scalability to be able to support an increased number of users in the future
24	15 Lifetime	The system shall be designed to support cislunar missions for the next 20 years at a minimum.
25	16 Openness	The system shall publish open source standards for all interfaces
26	17 Domain Awareness	The cislunar support system shall provide space domain awareness for spacecraft transiting cislunar space.
27	17.1 Space Traffic Management	The system shall have the capability to propagate orbital ephemerides in an Earth-Moon model to predict possible conjunctions in cislunar space
28	17.2 Situational Awareness	The space domain awareness system shall include the ability to predict spacecraft movement and determine intent for the purpose of avoiding collision
29	17.3 Coverage	The system shall maximize domain awareness coverage throughout cislunar space (T), shall provide optical and/or radio-frequency coverage of the cone between the Earth and the Moon as well as coverage of the volume around the Moon up to an altitude of 65,000 km (O)
30	17.4 Availability	The system shall achieve availability at least as good as the Earth-based Space Surveillance Network (SSN)

Figure 13 Requirements Table

3.1.3.2 Structural Perspective

The Domain Diagram is a BDD showing each of the eight domains, or supporting functions, as associations of the CislunarSystem block, shown in Figure 14. Additionally, key actors' relationships are defined for the ScienceMission, CommerceMission, DefenseMission, and SatelliteOperator. The stereotype "UnderEvaluation" is applied to the blocks which will be evaluated and optimized in this dissertation and these blocks are highlighted blue.

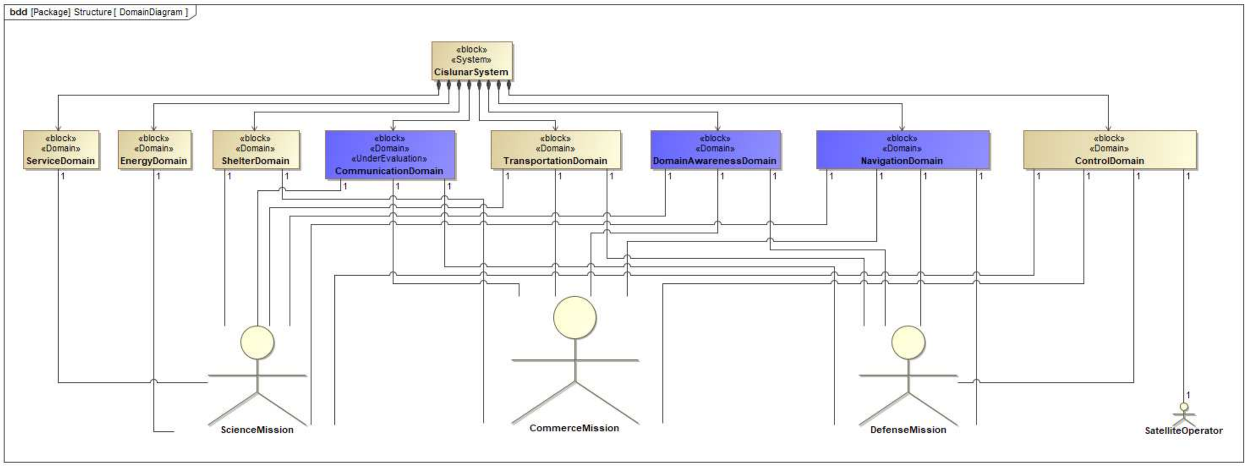

Figure 14 Domain BDD

3.1.3.3 BEHAVIORAL PERSPECTIVE

Use case development is key for the behavioral perspective of the OV. A UC defines primary mission threads for each user, shown in Figure 15. The need for a SatelliteOperator actor is identified during use case modeling.

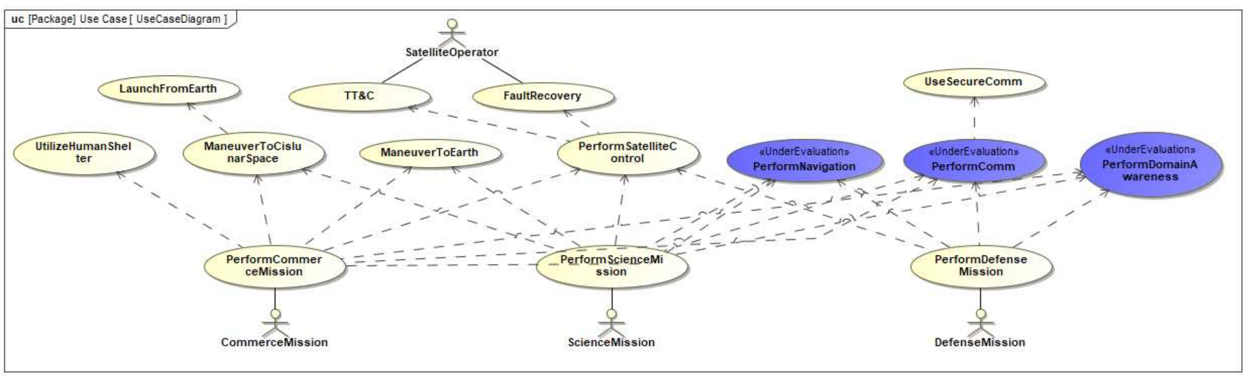

Figure 15 Use Case Diagram

3.1.3.4 CONTEXTUAL PERSPECTIVE

Finally, the contextual perspective of the OV is modeled using a UC. The system context at the OV includes environment, users, external system capabilities, and legal constraints, all shown in Figure 16.

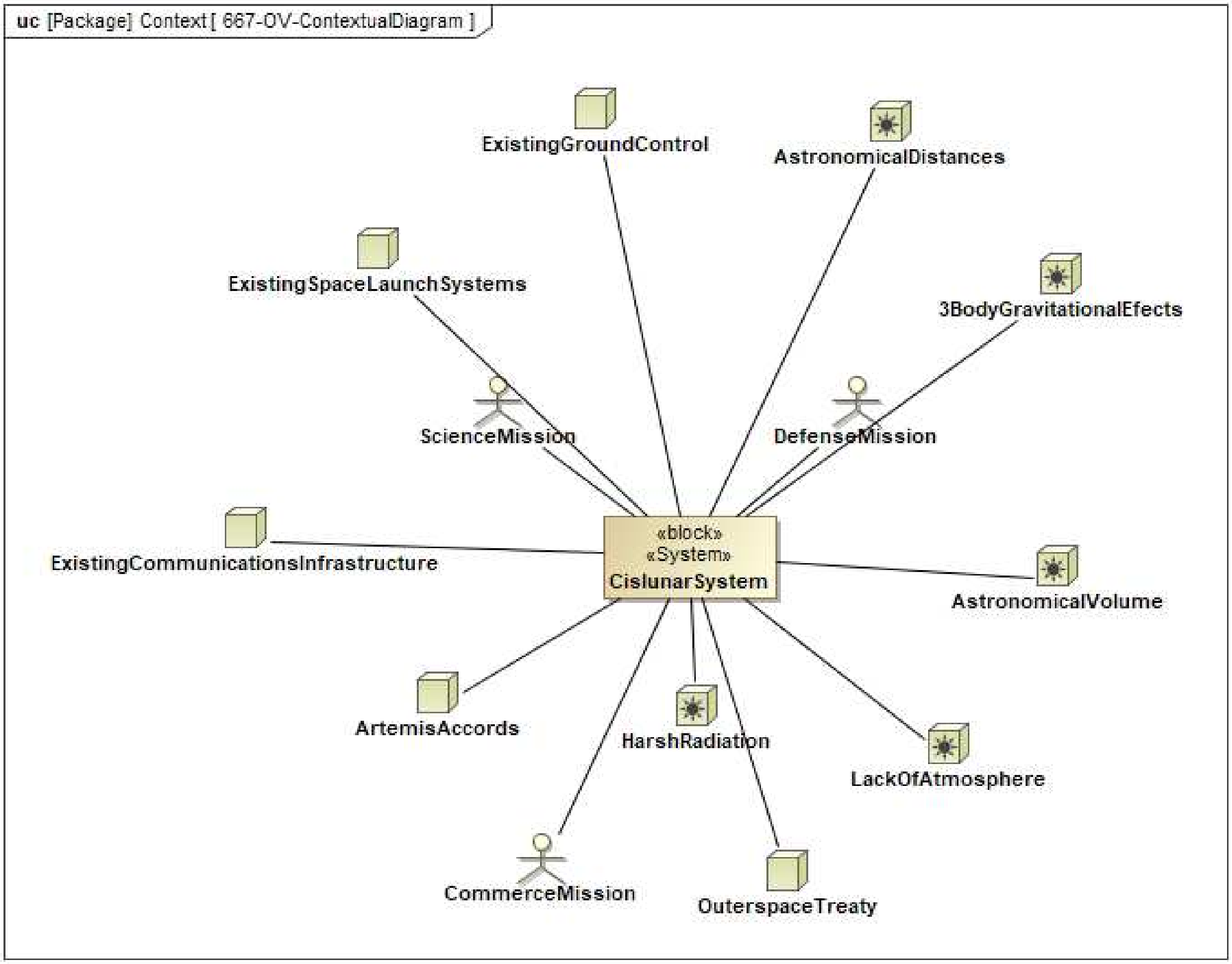

Figure 16 OV Contextual Diagram

3.1.4 Logical/Functional Viewpoint

In the LV, the solution is designed to meet requirements. Included in the structural perspective are block decomposition BDDs and IBDs. Finally, the contextual perspective looks deeper into the system context. [105]

3.1.4.1 Structural Perspective

For the structural perspective of the LV, the domains are decomposed to the level of blocks/parts. These BDDs are included in the model but not shown in this paper. Examples of parts in the cislunar system include satellites, control stations, monitoring stations, interfaces, etc.

An example domain decomposition is shown for the navigation domain in Figure 17. The decomposition includes internal blocks, interfaces, and external blocks.

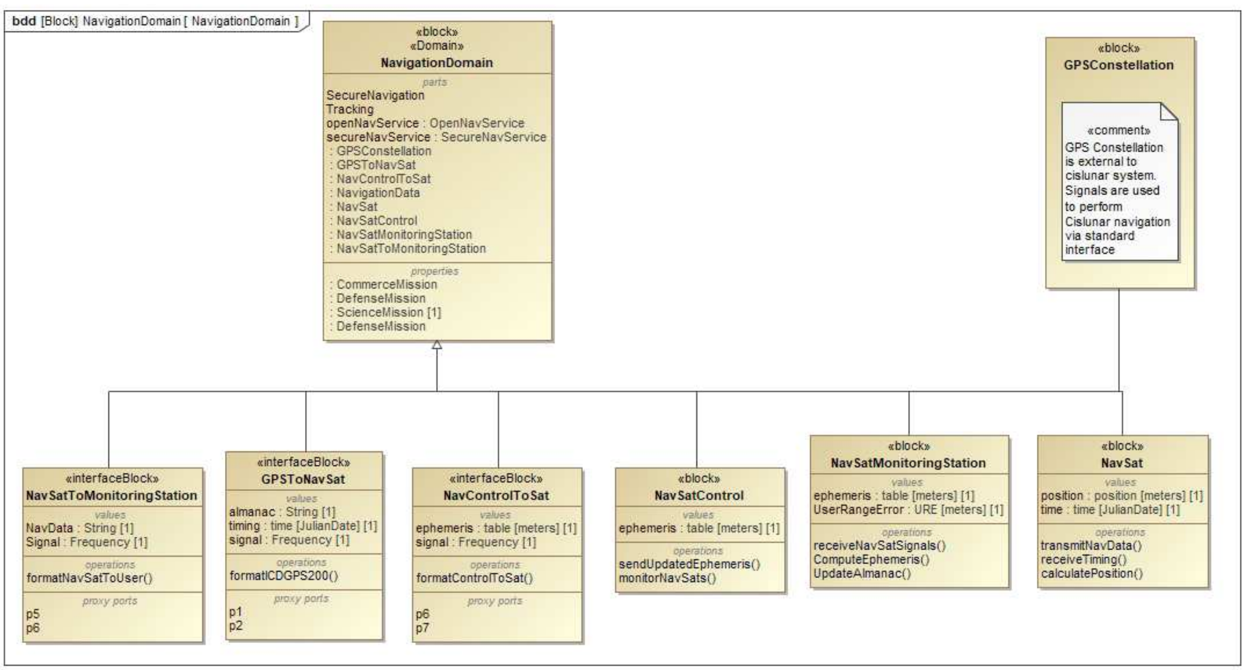

Figure 17 Navigation Domain BDD

3.1.4.2 Contextual Perspective

In the LV contextual perspective, the enterprise design drivers, nonfunctional requirements, customer artifacts, and policies/mandates are identified, shown in Figure 18.

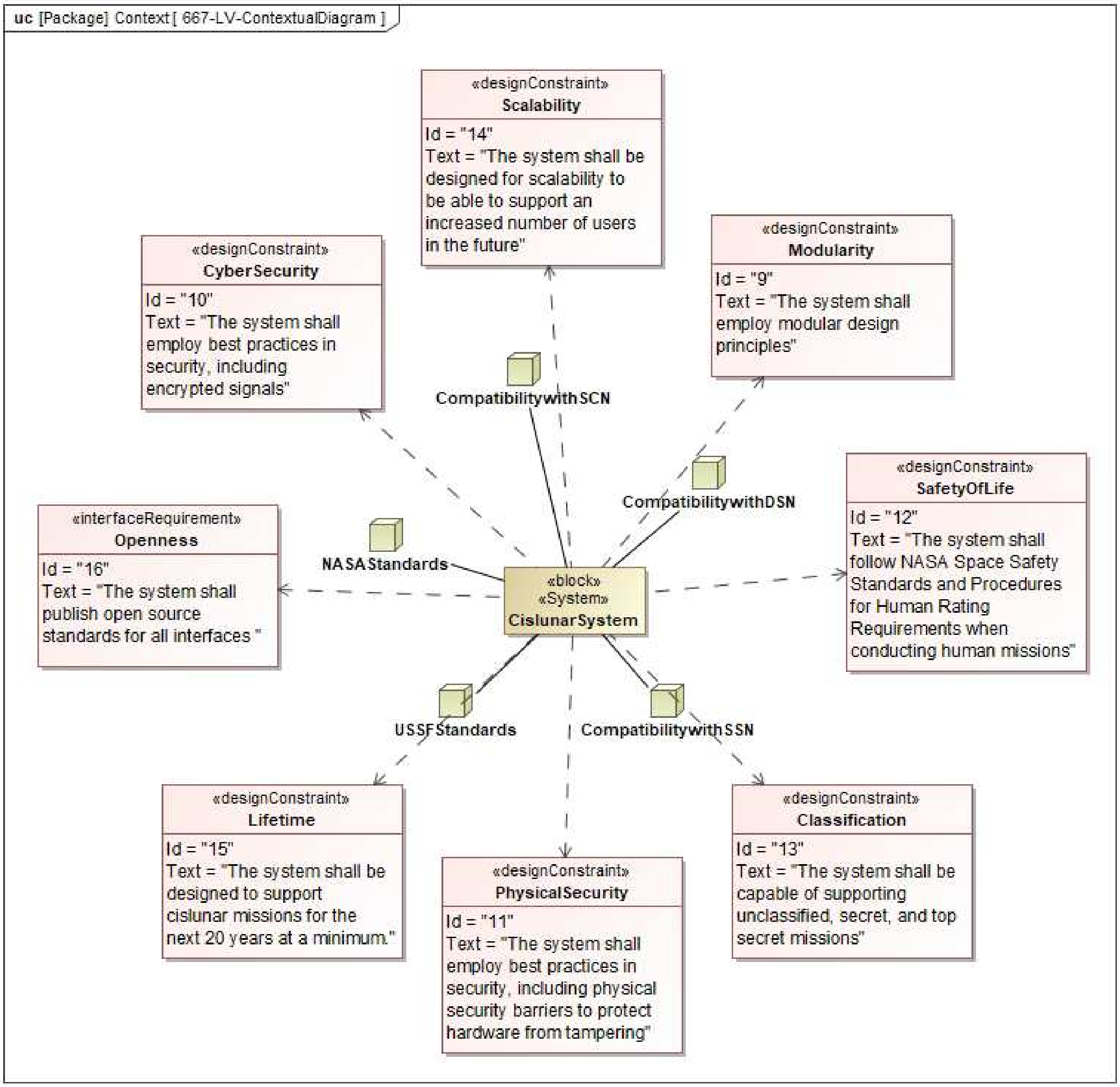

Figure 18 LV Contextual Diagram

3.1.5 Physical Viewpoint

3.1.5.1 Structural Perspective

For the PV structural perspective, additional detail is added to block and interface block specifications. Details include ports, properties, operations, etc. Figure 19 shows an example specification for the navigation satellite block.

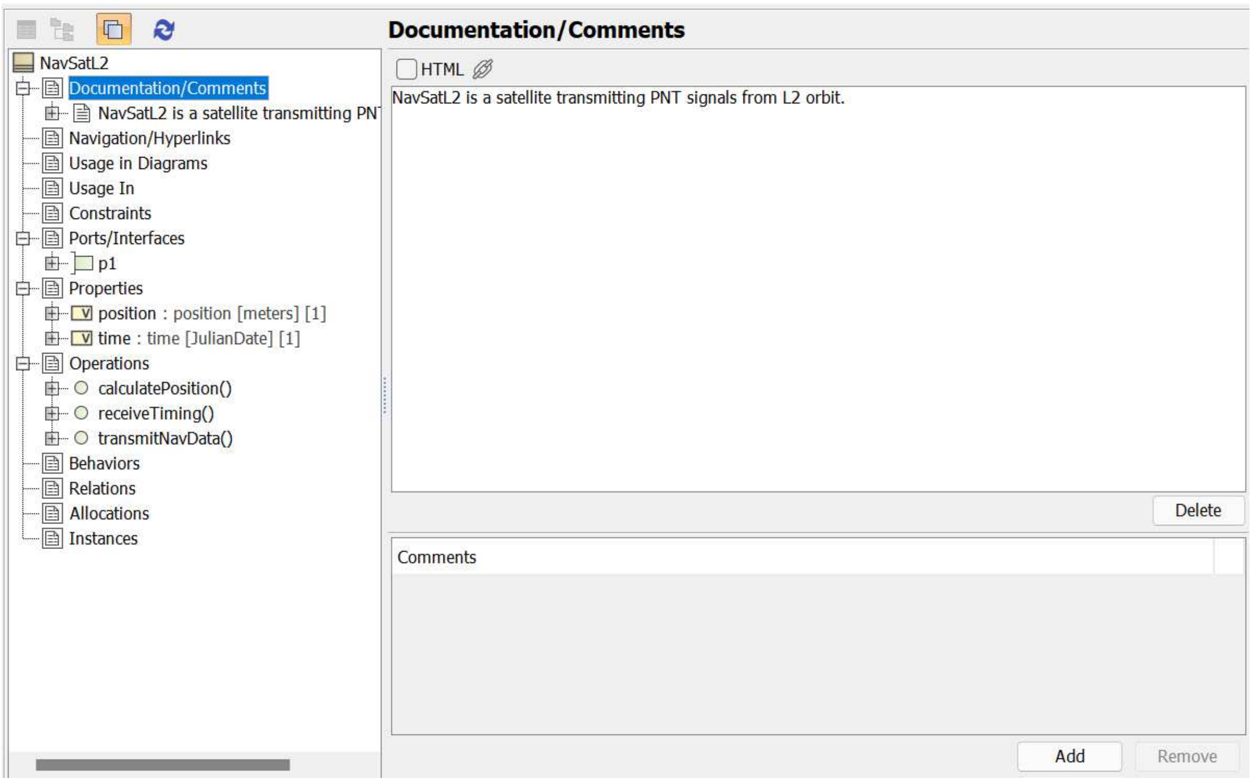

Figure 19 Navigation Satellite Specification

Additionally in the PV structural perspective, detailed interfaces and ports are defined. An example IBD is shown in Figure 20 for the navigation domain detailing the numerous interactions within this domain.

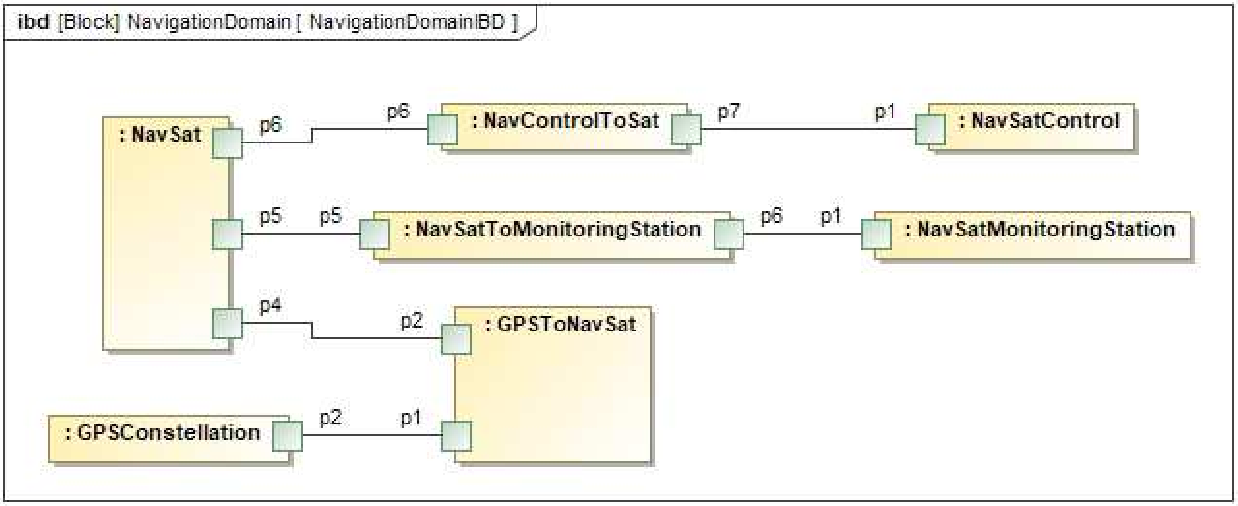

Figure 20 Navigation Domain IBD

3.1.5.2 STANDARDS PERSPECTIVE

For the standards perspective, key standards are identified for each domain. These standards are implemented in the SysML model as requirements to ensure the system follows applicable standards. Example standards for the Control Domain are shown in Table 13.

Table 13 Control Standards Table

Enterprise Control Service	Standards
Security	Public Key Infrastructure (PKI) Encrypted Protocol
Transport	File Transfer Protocol (FTP) Space-Ground Link Services (SGLS) Universal S-band (USB)
Data Description	Tracking, Telemetry, and Commanding (TT&C)
Resource Management	Simple Network Management Protocol (SNMP)

3.1.6 MODEL-BASED SYSTEMS ARCHITECTURE PROCESS CONCLUSIONS

Details of the Cameo Systems Modeler^{TM} SysML model of a Cislunar Space Systems Architecture are presented in this section. These details include a background on SysML, an Architecture Overview and Summary, and the three viewpoints are detailed: the OV, the LV, and the PV. The viewpoints are used to model the physical and behavioral interactions of the cislunar system elements. The next section details modeling concepts which are not included in the SysML model but are important for understanding the system dynamics of a cislunar system.

3.2 Architecture Modeling Concepts

Additional modeling beyond the MBSAP viewpoints of OV, LV, and PV is presented in this section. These additional modeling techniques are detailed in this section and include allocating requirements; modeling stereotypes; patterns in architecture decisions; architecture optimization; verification and validation; complexity; and Open Systems Architecture.

3.2.1 Allocate Requirements

For automated verification of the model, the requirements must be allocated to block. Figure 21 shows all system-level requirements allocate to blocks while Figure 22 shows a zoomed image to the service block, showing the <<satisfy>> relationship used in requirements mapping.

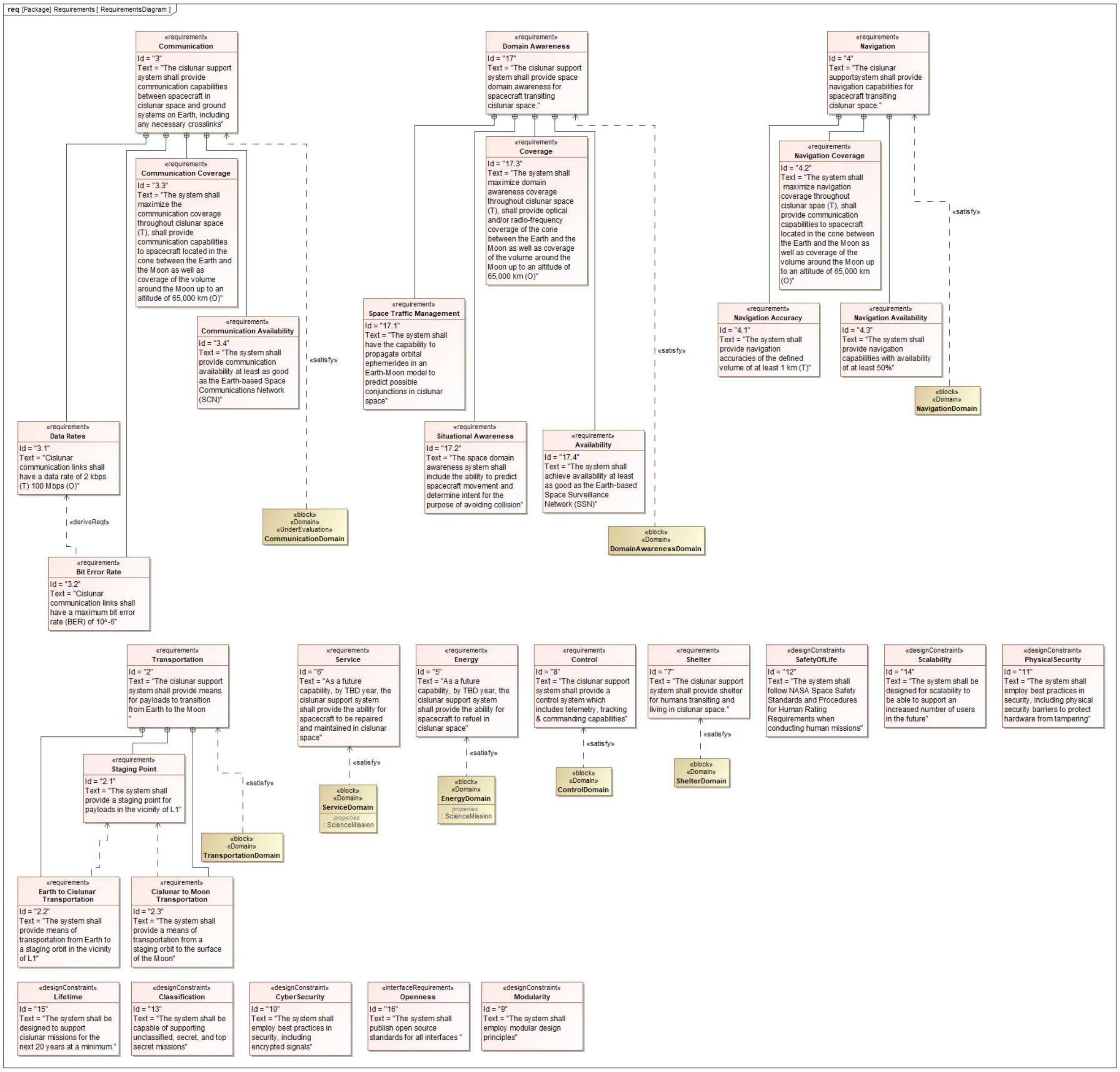

Figure 21 Requirements Allocated to Blocks

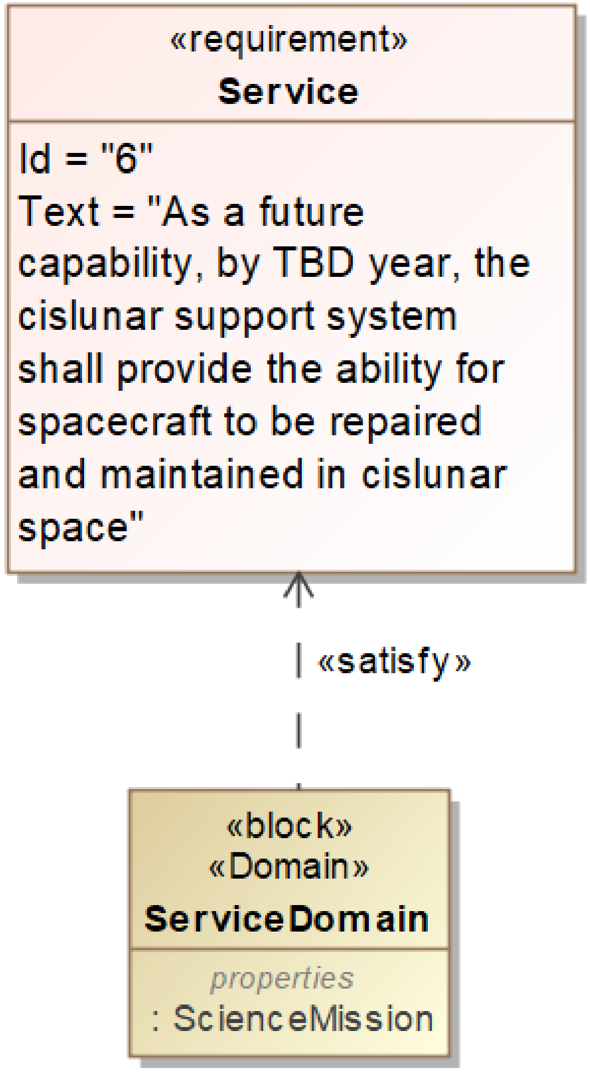

Figure 22 Requirements Allocated to Blocks Zoomed

3.2.2 Stereotypes

Through the development of the cislunar model, several stereotypes have been defined for various relationships or block types. Abstract and InfoElement are used to define data types. A ServiceInterface is used in the service perspectives. Domain defines an overarching domain block. Figure 23 shows these specialized stereotypes in a profile diagram.

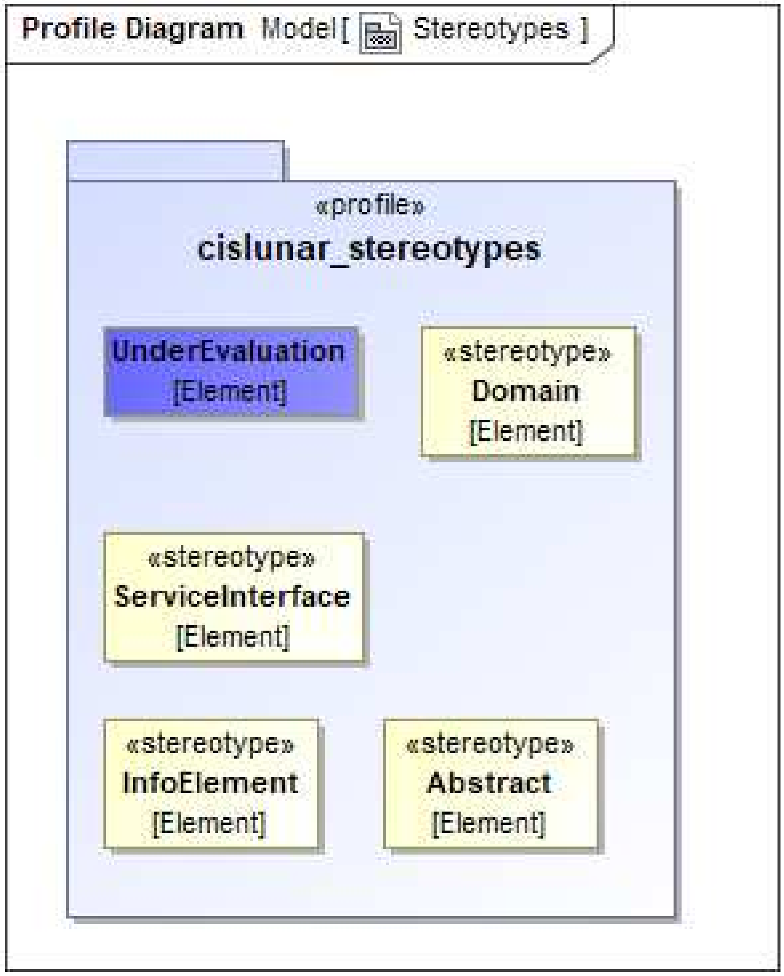

Figure 23 Stereotypes

3.2.3 Patterns in Architecture Decisions

There are six canonical classes of architecture decision patterns: combining, down-selecting, assigning, partitioning, permuting, and connecting. [108] Each decision pattern is described in its applicability to the cislunar architecture. Additionally, the set of alternatives is explored to define the decision space.

3.2.3.1 Set of Alternatives

First, a Set of Alternatives table is created and displayed in Table 14. The cislunar architecture has eight total domains. Down-selecting is applied in Section 3.2.3.5, resulting in the communication, navigation, and domain awareness domains as the only domains for evaluation and optimization.

Table 14 Set of Alternatives

Decision	Set of Alternatives
Communication Constellation	{lagrange_light, lagrange_medium, lagrange_heavy, earth_based, earth_plus_lunar, earth_plus_lagrange}
Navigation Constellation	{lagrange_light, lagrange_medium, lagrange_heavy}
Domain Awareness Constellation	{earth_based, earth_plus_lunar}
Integrated Communication and Navigation	{no, yes}
Integrated Communication and Domain Awareness	{no, yes}
Integrated Navigation and Domain Awareness	{no, yes}

This leads to 6*3*2*2*2*2=288 total possible architectures. A combining algorithm is applied with the constraints shown in Table 15 to determine how many feasible architectures are possible due to restrictions in integration.

Table 15 Constellation Constraints

If	Then
communication and navigation constellations are not equal	integrated communication and navigation = no
communication and domain awareness constellations are not equal	integrated communication and domain awareness = no
navigation and domain awareness constellations are not equal	integrated navigation and domain awareness = no

When constraints are applied which restrict the integration opportunities to only those with matching constellations, the result is 54 possible architectures.

3.2.3.2 Combining

Given that the architecture decisions can be represented simply in this table format, it seems the best pattern to apply would be the combining pattern, where “each decision has its own discrete set of options, and an architecture fragment is defined by choosing exactly one option from each decision." [108]

3.2.3.3 Assigning

The assigning pattern requires multiple sets of entities. The scope of the cislunar system does not seem to require the assigning pattern to this architecture decision space since exists one set of decision entity: the constellation type. [108]

3.2.3.4 Partitioning

The partitioning pattern does not seem to apply because there is not a set of entities which needs to be grouped into subsets. [108]

3.2.3.5 Down-selecting

The down-selecting pattern is already applied in the creation of Table 14. The domain of transportation is found to be already prominently researched and optimized for cislunar space, so is not included for decision-making. The Energy and Service domains, though necessary in a sustainable and economical long-term architecture, are not required for preliminary missions to cislunar space. Additionally, the technologies for Energy and Service payloads are in early technological development and not ready for incorporation into a mature architecture. The Shelter function is required for human travel but does not have a decision space due to limited technologies. A human-rated capsule is required and will be sent on the optimal trajectory, without affecting architectural decisions of the cislunar support system. Similarly, the Control function is very necessary, but does not affect the trade space of the physical architecture which is under evaluation. [108]

Additionally, down-selecting is applied when determining which constellations can meet requirements for each domain. For example, the navigation domain does not include Earth-based transmitters because these would cause self-interference with space-based navigation systems. [108]

3.2.3.6 Connecting

The connecting pattern could provide use in this architecture decision process since the three chosen domains do require ample amounts of connectivity/networking to relay data to/from satellites. However, the connecting pattern focuses on the connections/edges of the nodes, whereas the architecture decisions defined above are focused on the physical locations of nodes. [108]

3.2.3.7 Permuting

The permuting pattern offers an excellent strategy for handling the large trade space of architecture possibilities. An optimization algorithm could be applied between each permutation to attempt to converge on an optimal architecture instead of evaluating the entire architecture trade space. [108]

3.2.4 Architecture Optimization

The architecture is optimized in terms of cost (which is a function of mass), percent coverage of communication constellation, percent coverage of navigation constellation, percent coverage of domain awareness constellation. Cost should be minimized while coverage is maximized. The generic method for optimizing the model is shown below:

1. Populate libraries in MATLAB® with values extracted from STK physics-based software. These represent the physical blocks of the model.

2. Code the objective function directly in MATLAB®.

3. Use an optimization algorithm in MATLAB® for each iteration.

4. For the final architecture chosen, update the Cameo Systems Modeler™ model for architecture evaluation.

Details of the optimization algorithm are available in 3.6.1.

3.2.5 Verification and Validation

For verification of the architecture, the SysML model can be utilized. Verification activities can be modeled as a <<testcase>> and linked to requirements via <<verify>> dependencies. This results in a Verification Cross Reference Matrix (VCRM), which is used to populate the Test Plan. SysML <<blocks>> can be linked to a <<testcase>> via the association relationship for automated verification of the model. [109]

Validation focuses on the correctness of the architecture model. The model must be validated against initial stakeholder concerns and needs. Specifically, the OV is validated by comparing the Concept of Operations (CONOPs) with the initial stakeholder needs and iteratively updating the CONOPs and requirements until needs are met. [105]

3.2.6 Complexity

The Cislunar Space System is a complex-adaptive system due to the varying number of independent agents which includes the science, commerce, and defense users that change over time. [110]

There are many dimensions of complexity to describe a system. The first, “sheer size”, would classify the Cislunar Space System as a complex system because it is a System-of-Systems (SoS). Each domain of the Cislunar Space System can be classified as its own system.

The “sheer size” is modeled in the Structural Perspective of the Operational Viewpoint, shown in Section 3.1.3.2. The second, “relationships”, applies to Cislunar Space System because this system bring together ground-based control networks with radiofrequency (RF) communication networks to connect with satellites moving in highly dynamics environments. Integrating many types of relationships adds to complexity. An example of the “relationships” complexity is modeled in the Structural Perspective of the Logical/Functional Viewpoint, shown in Section 3.1.4.1. The third, “heterogeneity”, similarly leads to complexity due to the many technologies from ground-software, space-software, RF-links, ground-hardware, space-hardware, and human operators. The fourth, “nonlinearities”, has not been directly observed through modeling yet, but with the large number of varying operators anticipated, emergent behavior is likely. The fifth, “human variables,” has been addressed as a known complexity factor due to the varying number of human operators interacting with the system. The “human variables” are modeled in the Behavioral Perspective of the Operational Viewpoint, shown in Section 3.1.3.3. The sixth, “knowledge limitations”, is a relevant area of complexity for cislunar space because the systems will be operating in a widely unknown area. In fact, many of the preliminary missions are focused on gathering knowledge for a future sustainable architecture. The “knowledge limitations” are modeled in the Contextual Perspective of the Operational Viewpoint, shown in 3.1.3.4. The seventh, “exogenous factors”, is interestingly relevant because space laws are vague and not easily enforces. Cislunar space has even been compared to the wild west. This will certainly lead to emergent behavior on a geopolitical context. [110]

Many of these complex factors are not readily in control of the Systems Engineer. For the example of varying number of operators, strict interface control can help operators interact with the system in a plug-and-play manner. Outside of these interfaces, flexibility should be incorporated into the system to allow the system to support the needs of most of the users and to adapt to user needs over time. [110]

A complex SoS, such as the Cislunar Space System, has unique considerations during design and evaluation when compared to an individual system. Complex systems have a higher degree of uncertainty than simpler systems, which must be accounted for. Section 4.2.1 shows the results of evaluating a SoS with uncertainty as a factor. Uncertainty is accounted for in the evaluation by applying Evidential Reasoning.

3.2.7 Open Systems Architecture

3.2.7.1 Measures of openness

Modularity: the existing architecture is built with modularity in mind. Since the goal with the architecture is to optimize, the components must have clear boundaries. Functions are assigned to physical components in a modular fashion, based on the overarching domains. The three main functions of concern are completely isolated in the architecture with interfaces designed such that integration is possible at the physical layer during the optimization process.

Loose coupling: like modularity, the existing architecture is designed to minimize dependencies among the elements. This is accomplished during the needs analysis, which identifies the overarching domains, each containing unique functions. Interactions between these domains is very minimal except for control, which is required for each domain to function through data transfer. The control domain (and therefore architecture coupling) cannot be further minimized without losing required functionality.

Standardization: standardization is greatly considered during the design of the existing architecture. Existing space standards are incorporated into the requirements, as advised by the

International Council on Systems Engineering (INCOSE). For critical interfaces where standard do not exist, this architecture provides the backbone for government organizations (like NASA or USSF) to develop standards.

Other: openness is even built into the existing architecture's requirements, stating "The system shall publish open-source standards for all interfaces."

3.2.7.2 OPEN STANDARDS

Domain Awareness: data formats are already established through USSF's domain awareness systems. Some data formats need to be updated (and standardized) to incorporate cislunar and lunar orbital elements because existing data sets are for earth-orbiting missions. Earth-centered orbital elements become inaccurate when propagated in cislunar space.

Transportation standards: the system utilizes pre-existing ground infrastructure (launch pads, launch integration facilities). The staging orbit function does not have open standards, but through the implementation of a staging orbit, standards can be derived.

Communication standards: communication data links use pre-established data formats (e.g., SGLS, USB) and use allocated spectrum (e.g., S-Band, Ka-Band, etc.).

Navigation: the system utilizes pre-existing navigation standards through the published Global Positioning System (GPS) Interface Control Documents (ICD). The exception is that the cislunar-based transmitter will need additional message fields to account for the non-standard GPS orbit. This non-standard message needs to be published for the receiver to incorporate.

Energy, Service, Shelter: these are low technology readiness level (TRL) functions. As they are proven through spaceflight, standards can be developed and published.

Control: data formats are highly standardized, and the system can take advantage of the wide array of published standards for data formats.

3.2.7.3 Open Systems Architecture Questionnaire [111]

The following italicized text is taken directly from the Open Systems Architecture (OSA) Questionnaire while non-italicized text answers the questions as applied to the cislunar system.

1) *Modular designs based on standards, with loose coupling and high cohesion, that allow for the independent acquisition of system components:*

   a) *Does the system design decouple hardware, operating system, and middleware from applications?*

The system design does decouple hardware from software through the distribution of functions among the domains.

   b) *Can the computing hardware be upgraded without the necessity to change the operating system, middleware, or applications?*

The computing hardware can certainly be upgraded as the system changes because the control system is based on software, which can be installed on any compatible machine.

   c) *Are the functional components of the system well defined with clearly specified behaviors and interfaces?*

The functional components are well defined for the navigation, communication, and domain awareness domains. These are the domains for which the architecture is able to be optimized due to high technology-readiness levels and high needs for a comprehensive architecture.

d) *Are the software development environment tools for each application "industry standard", and openly available as a set of products?*

The software is developed with “openness” and “standardization” as key requirements.

2) *Enterprise investment strategies that maximize the reuse of proven hardware system designs (these questions apply when a system is being developed as an element of a larger enterprise):*

a) *Has the system development program investigated potential reusable/modifiable components from other programs?*

The system is building upon existing enterprise systems (e.g., Space Communications Network, Space Surveillance Network), with necessary additions for cislunar applications.

b) *Are development contractors/subcontractors incentivized to identify potential reuse candidates from a broad spectrum of providers?*

Contractors/subcontractors should be incentivized for reuse at the contractual level. The current system design does not have that level of detail.

c) *Does the development program use, modify, or extend data models, service taxonomies, and other potentially reusable elements?*

The architecture does use existing data models for space systems as they can easily incorporate cislunar needs.

d) *Has the system development been planned to include separate contracts/product procurements for the various components of the system in a “best of breed” strategy?*

The system is structured modularly such that components can be contracted in a “best of breed” strategy. The current system design does not have that level of detail.

e) *Have incentive structures such as tiered fees and future business opportunities been built into the program plan and contracts to reward cooperation and collaboration among the architect, integrator, and component providers?*

Cooperation and collaboration will be key with this system development, especially in the development of interfaces and standards. This has not been accounted for in the current system as contracts and Request for Proposals (RFP) have not been developed.

f) *Does the system development program exploit and contribute to repositories of reusable architecture and design artifacts, including reference architectures?*

This current architecture provides a reference architecture with specific implementations based off this reference architecture.

3) *Enhanced life cycle sustainment for software-intensive systems through proven technology insertion and software product upgrade techniques:*

a) *Does the system development program include provisions for long-term technology refreshment, additional/enhanced software capabilities, emerging technologies and products, and other evolutionary measures to maintain operational effectiveness and affordability?*

The system is required to function for 20-years. This may require 1-2 technology refreshments within the lifecycle. Since the system is built with modularity and standard open interfaces, additional technology can be incorporated (unlike most legacy space systems).

b) *Does the system design promote lower life cycle costs by leveraging modularity to reduce the effort and cycle time of system modernization?*

Like the above statement, modularity is incorporated to reduce life cycle cost.

c) *Does the system design appropriately exploit commodity COTS computing and networking hardware to reduce procurement and maintenance costs?*

COTS components are used in the design of this system. In fact, all physical components used in the optimization algorithm are COTS.

d) *Are decisions to use specific COTS products supported by test results, architectural suitability, "best value" assessments, etc.?*

Specific COTS components are chosen based on SWAP requirements. "Best value" assessments have not been made except to simply minimize cost/mass and maximize performance/coverage.

4) *Reduce development risk by maintaining the transparency of system designs, continuous design disclosure, and peer reviews:*

a) *Are the system/subsystem/component/application specifications and design data available to a broad cross-section of potential providers?*

Transparency and openness are built into the system requirements.

b) *Are the end-users and other system stakeholders included in the system design and upgrade process as well as the training definition?*

The End-users and stakeholders were involved in the system design, specifically NASA stakeholders provided feedback. As the design matures beyond an academic/conceptual level, a more formal feedback loop with stakeholders will need to be established.

c) *Are independent reviews of system designs, component selections, risk assessments and mitigation plans, integration, and test plans, etc. conducted on a periodic basis?*

While in the academic/conceptual phase, independent reviews are periodically provided by professors and advisors. If the design matures, more appropriate stakeholders will need to periodically review the architecture.

5) *Effective use of data rights to promote initial and subsequent competitive procurements and access to alternative solutions and sources, across the system life cycle*

a) *Have the appropriate data rights been obtained with each system component, especially software applications?*

While software/hardware components may be proprietary to the contractor, the interfaces to these components are required to be published.

b) *If a product contains proprietary elements, are the license requirements for use clearly documented, and those proprietary elements segregated with well-defined interfaces such that modification of another component will not require modification of the proprietary product?*

The system does not have designated contractors, but once contracts are written, clear license requirements will need to be known by the system architect. Additionally, the contractors should be key stakeholders in interface working groups.

c) *Have the asset packages (i.e., the deliverables) been reviewed prior to Government acceptance to ensure that they reflect the agreed-upon licenses and data rights markings?*

The system does not have designated contractors nor current deliverables. Once the system does have deliverables, the government will certainly need to review deliverables for licensing/data rights.

3.2.8 Architecture Modeling Concepts Conclusions

In this section, modeling beyond the MBSAP viewpoints is presented and includes allocating requirements; modeling stereotypes; patterns in architecture decisions; architecture optimization; verification and validation; complexity; andOpen Systems Architecture. These concepts collectively inform the design of the architecture in real-world context, though are not formally included in the MBSAP.

3.3 Cislunar Physics

Section 2.1.1 of the Literature Review provides a brief overview of the Earth-Moon three body system, including the location of the five Lagrange points. Orbits around these Lagrange points are particularly advantageous due to the low stationkeeping requirements and relative positioning to the Moon. The trade space for Lagrange orbits is huge and considered out of scope for this dissertation. In this dissertation, a satellite in orbit about a specified Lagrange point is assumed to be within 60,000 km in any direction of the Lagrange point.

This section details the constellation design and payload design of the cislunar system. Six constellations are designed in cislunar space which include Lagrange orbits, Earth-based, and Moon-based sensor locations. Payloads are designed for each supporting function of the optimization trade space: communication, navigation, and domain awareness. The appropriate physics of cislunar space are modeled in the design of each constellation and payload.

3.3.1 Constellation Design

In Section 3.2.3, the constellation trade space is briefly introduced. Six possible constellations are proposed: Lagrange light, Lagrange medium, Lagrange heavy, Earth-based, Earth plus Moon, and Earth plus Lagrange. Each of these constellations are defined below. Future research could include additional constellation designs for a larger trade space.

3.3.1.1 Lagrange Light

The Lagrange light is designed to be a cheap space-based constellation with good coverage of a high-priority area of interest: the Moon. L1 and L2 offer the best coverage of the Moon as they are located closest to the Moon. Additionally, L1 and L2 are located on opposite sides of the Moon and have visibility of the Earth-facing and non-Earth facing sides of the Moon. A notional figure of the Lagrange light constellation is depicted by the blue regions in Figure 24. The sensors shown are only meant to depict direction; sensor ranges are defined in Section 3.3.2.

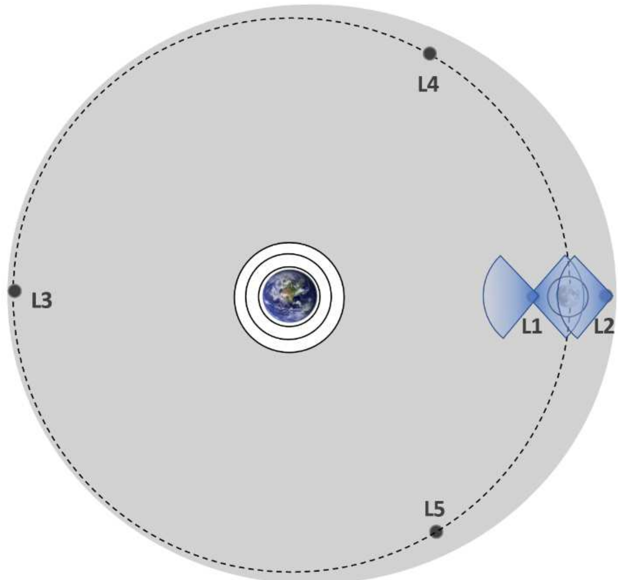

Figure 24 Lagrange Light Constellation

3.3.1.2 Lagrange Medium

The Lagrange medium constellation is designed to be a mid-cost constellation with good coverage of the Moon and the transit corridor between the Earth and the Moon. The Lagrange medium areas of coverage are depicted by the blue areas of Figure 25. The sensors shown are only meant to depict direction; sensor ranges are defined in Section 3.3.2.

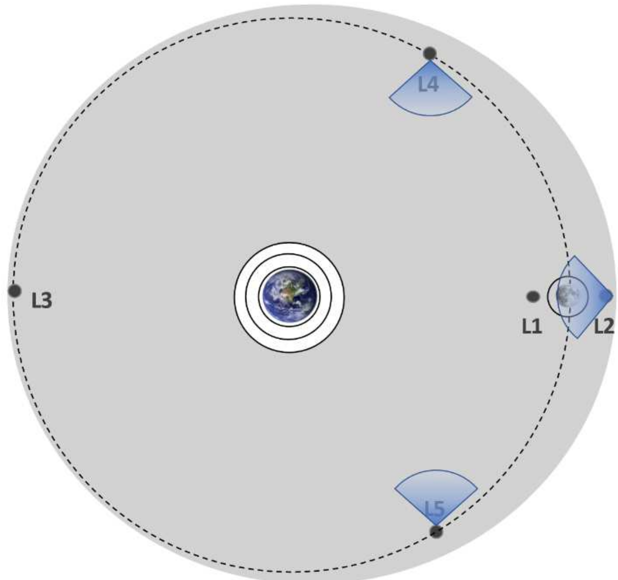

Figure 25 Lagrange Medium Constellation

3.3.1.3 Lagrange Heavy

The Lagrange heavy constellation is the most expensive and most robust space-based constellation. This constellation takes advantage of all five Lagrange points for excellent coverage of the entire cislunar volume. A notional figure of the Lagrange heavy constellation is depicted by the blue regions in Figure 26. The sensors shown are only meant to depict direction; sensor ranges are defined in Section 3.3.2.

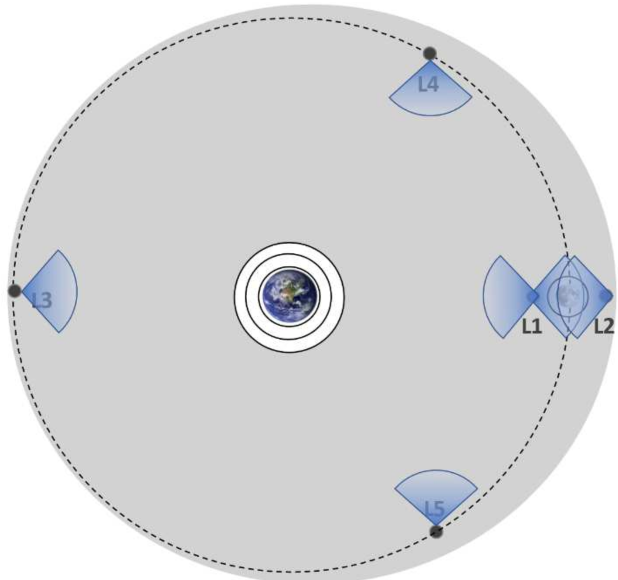

Figure 26 Lagrange Heavy Constellation

3.3.1.4 Earth-Based

The Earth-based constellation offers an alternative to the space-based constellations. This constellation would provide the advantage of no launch costs and offers the ability for regular maintenance. Four sensors are placed as close to the equator as physically possible to cover the Earth-Moon plane as much as possible. The actual placement of these sensors are Ascension Island, Diego Garcia, California, and Australia. A notional figure of the Earth-based constellation is depicted by the blue regions in Figure 27. The sensors shown are only meant to depict direction; sensor ranges are defined in Section 3.3.2.

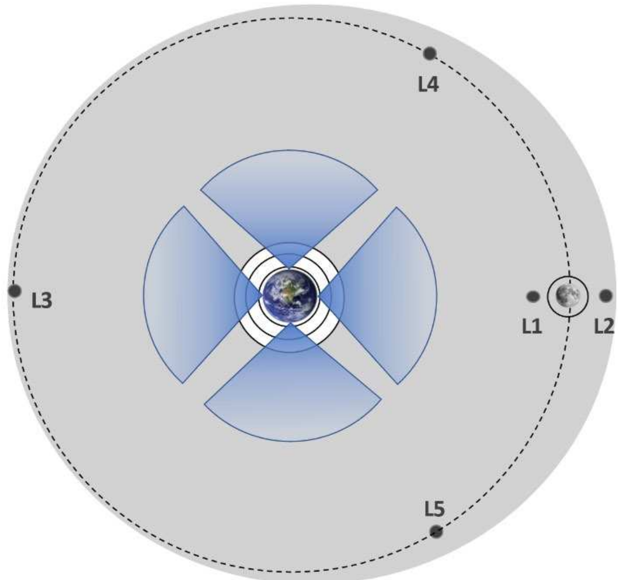

Figure 27 Earth-Based Constellation

3.3.1.5 EARTH PLUS MOON

The Earth plus Moon constellation is designed to cover a large volume of cislunar space, including lunar orbits, with only terrestrial sensors. Four sensors are placed on each body as close to the equator as physically possible. The Earth-based sensors are in Ascension Island, Diego Garcia, California, and Australia. The Moon-based sensors are placed as Earth-facing, anti-Earth-facing, velocity-direction, anti-velocity-direction. A notional figure of the Earth plus Moon constellation is depicted by the blue regions in Figure 28. The sensors shown are only meant to depict direction; sensor ranges are defined in Section 3.3.2.

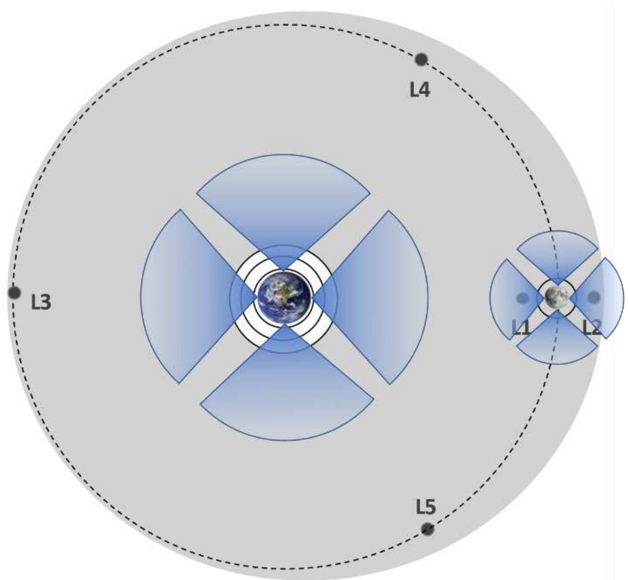

Figure 28 Earth plus Moon Constellation

3.3.1.6 Earth plus Lagrange

The Earth plus Lagrange constellation is designed to cover a large volume of cislunar space, including lunar orbits, with terrestrial and space-based sensors. Four sensors are placed on Earth as close to the equator as physically possible. The Earth-based sensors are located in Ascension Island, Diego Garcia, California, and Australia. The space-based sensors are located at L1 and L2. A notional figure of the Earth plus Lagrange constellation is depicted by the blue regions in Figure 29. The sensors shown are only meant to depict direction; sensor ranges are defined in Section 3.3.2.

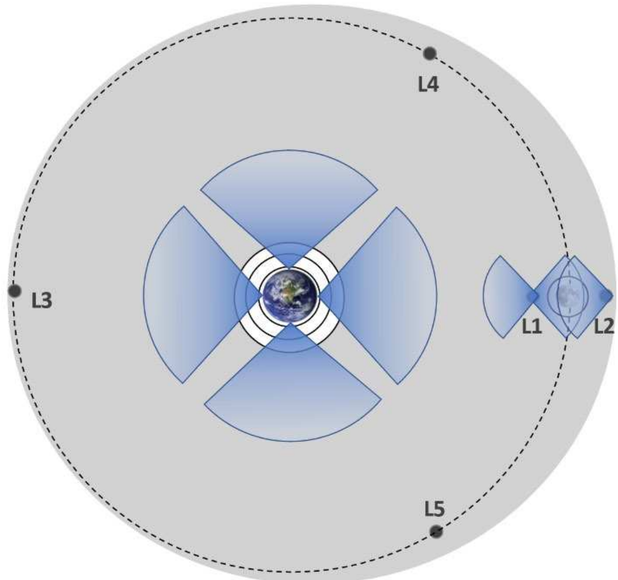

Figure 29 Earth plus Lagrange

3.3.2 Payload Design

The design of the payload defines the sensor range and bandwidth for each of the functions: communications, navigation, and domain awareness. Assumptions were made to restrict the decision space to the scope of this dissertation. Future research could modify these assumptions to current technology capabilities.

3.3.2.1 Communications Payload

The communications sensor is designed to manage the most stressing case: the link from L2 back to Earth. This range is approximately 450,000 km. The link budget in Table 16 shows that a link margin of at least 3 dB can be achieved for these ranges, even using a space-based bus. Ka band is chosen as a common, yet effective, frequency for space communications.

Table 16 Communications Link Budget [112]

Description	Gain/Loss (dB)	Notes
HPA[16] Power	16 dBW	Assume 30 GHz, 40 W [113], 20% efficiency [113], 100% duty cycle
Cable Loss	-1 dB [112]	
Filter Loss	-0.5 dB [112]	
Truncation Loss	-0.3 dB [112]	Results in 14.2 dB power at antenna
Antenna Gain	52 dB	Assume 2-meter antenna[17]
Transmit design margin	1 dB [112]	Results in EIRP[18] = 65.2 dBW
Path loss	-235.2 dB	Assume range of 458,788 km[19]
Atmospheric loss	-2 dB [112]	
Rain loss	-8 dB [112]	Results in RSS[20] = -180 dBW
Receiver Antenna Gain	66 dB	Assume 2-meter receive antenna[21]
Insertion losses	-1 dB [112]	Results in receive signal power = -115 dBW

---

[16] High Power Amplifier

[17] 2-meter antenna can be accommodated on standard spacecraft bus and results in necessary antenna gain.

[18] Effective Isotropic Radiated Power

[19] Range calculated for worst-case link of L2 to Earth.

[20] Received Signal Strength

[21] 2-meter antenna can be accommodated on standard spacecraft bus and meets antenna gain requirements.

Boltzmann's Constant	228.6 dBW/k/Hz	
System Noise Temperature	-24 dBK	Assume 290 K [114]
Receiver Noise Bandwidth	-80 dB-Hz[22]	Assume 100 Mbps[23] Results in SNR[24] = 9.6 dB, Eb/No = 9.6 dB
Eb/No Threshold	4.5 dB [115]	Results in 4.5 dB link margin

The 450,000 km range is used for the space-based and terrestrial applications. Due to mechanical limitations, the space-based gimbaled antenna has a half beamwidth of 36-degrees while the terrestrial-based antenna has a half beamwidth of 45-degrees. [112]

3.3.2.2 Navigation Payload

The navigation payload sensor is designed to cover the full range of the Earth to the Moon. This includes the range from L4 or L5 to the Earth and Moon as well. Table 17 shows the link budget for the navigation sensor, which achieves a margin of greater than 3 dB.

The navigation transmitter is also designed to meet the accuracy requirements specified by NASA in the LunaNet Interoperability Specification. The minimum requirement for navigation is specified to be on the order of a kilometer in 3-dimensional position [116].

The navigation satellites require Delta-Differential One-Way Ranging (Delta-DOR) for determining accurate satellite positioning of the transmitters [117]. For missions at lunar distances, delta-DOR results in orbital ephemeris errors of 37-meters [118]. To calculate the Signal in Space Range Error (SISRE) a weighting is applied based on the altitude of the

---

[22] Receiver Noise Bandwidth is calculated based on 100 Mbps data rate.

[23] 100 Mbps used for most stressing use-case of high-definition video.

[24] Signal to Noise Ratio

transmitter. For a GEO satellite, the A and C weighting is 1/126 [119]. For a Lagrange satellite, the altitude is 9.1 times greater than a GEO satellite, so the along-track (A) and cross-track (C) weighting is assumed to be 1/1147. Due to the weightings of the altitude at Lagrange orbit, the along-track and cross-track errors become negligible, so the main error source is in the ranging term. The ranging (R) weighting asymptotically approaches 1 with a value of 0.99 at GEO, so a value of 1 is assumed for the Lagrange satellite [119]. The cislunar navigation satellite uses the same Rubidium clock as the GPS satellite constellation, so the clock error is assumed to match the worst-case of the GPS constellation, which is 0.30 ns [120]. To calculate the SISRE, the following equation is used [119].

$$SISRE = \sqrt{(w_R * R - c * dt)^2 + {w_{A,C}}^2 * (A^2 + C^2)}$$

Where:

$$w_R, w_{A,C} = altitude\ weightings$$

$$c = speed\ of\ light$$

$$R, A, C = radial, along\ track, and\ cross\ track\ errors$$

$$dt = clock\ offset$$

The resulting SISRE of the navigation transmitter positioned in a Lagrange orbit is 36.9-meters, which is well under the NASA requirements of "on the order of a kilometer." The cislunar navigation is based upon the legacy GPS constellation to maintain backwards compatibility and for the use of COTS receivers. Any doppler shift resulting from movement of the receiver spacecraft relative to movement of the cislunar transmitter will need to be accounted for in the receiver algorithms. The doppler shift is considered out of scope for the study of the cislunar SoS. The GPS constellation uses an Earth-based reference frame, so the cislunar navigation system in this dissertation will also use an Earth-based reference frame. Once surveyed sites are available on the Moon, it is recommended that receivers in the vicinity of the Moon should utilize a Moon-based reference system for more accurate navigation. Alternative navigation methodologies are available and can be studied for future work.

Table 17 Navigation Link Budget

Description	Gain/Loss (dB)	Notes
HPA Power	20 dBW	Assume 1.57542 MHz[25], 100 W [113], 50% duty cycle [117], 60% efficiency [113]
Cable Loss	-1 dB [117]	
Filter Loss	-0.5 dB [117]	
Truncation Loss	-0.3 dB [117]	Results in 18.2 dB power at antenna
Antenna Gain	6 dB	Assume patch antenna with 65-deg beamwidth [117]
Transmit design margin	-1 dB [117]	Results in EIRP = 23.2 dBW
Path loss	-208.1 dB	Assume range of 384,400 km[26] Results in RSS = -184.9 dBW
Receiver Antenna Gain	3 dB	Assume standard GPS patch antenna [117]
Insertion losses	-1 dB [117]	Results in receive signal power = -182.9 dBW
Boltzmann's Constant	228.6 dBW/K/Hz	
System Noise Temperature	-24.6 dBK	Assume 290 K [117]

[25] Current Global Positioning System (GPS) L1 frequency.

[26] Distance from Earth to Moon is used as the design distance for Lagrange transmitters.

Receiver Noise Bandwidth	-63 dB-Hz [117]	Results in pre-correlation SNR = -41.9 dB
Post-correlation Receiver Bandwidth	17 dB-Hz [117]	Assume 50 Hz[27]
Correlation Processing Gain	46 dB [3]	Results in C/No = 21.1 dB-Hz
C/No threshold	15 dB-Hz [121]	Results in 6.1 dB link margin

The navigation sensor does not have terrestrial applications due to interference to the existing navigation constellations. The space-based sensor is assumed to have a range of 384,400 km and a half-beamwidth of 32.5 degrees. [117]

3.3.2.3 Domain Awareness Payload

Current domain awareness sensors typically use optical or Radio Detection and Ranging (RADAR) technologies. In cislunar space, optical sensors cannot achieve the necessary ranges and resolutions for a feasible application. Using the optical equation, the boundary cases can be quickly examined to eliminate the optical sensor as an option.

$$r = 2.44 * R * \lambda / D \tag{1}$$

Where:

$$r = resolution$$

$$R = Range$$

$$\lambda = wavelength$$

[27] 50 Hz standard for coarse acquisition (C/A) code [112]

$$D = Diameter \; [122]$$

Applying this equation to a visible wavelength of $500 * 10^{-9}\ m$, assuming a range of 60,000 km (which would provide some coverage if positioned at L1 or L2), and a resolution of 1 m (would see larger spacecraft, but not necessarily cubesats), an infeasible lens diameter of 73.2 m is required. Alternatively, assuming a resolution of 1 m, lens diameter of 5.4 m (largest payload diameter of current rockets), and visible wavelength of $500 * 10^{-9}\ m$, a range of 4,400 km can be achieved [123] [124]. A sensor with such low range and coverage would not see any orbits of interest from the constellations described in the above sections. If the visible-wavelength sensor is assumed to have a range of 60,000 km and diameter of 5.4 m, then the result is a resolution of 13.6 m. This sensor would not be able to view any human-made objects. Alternative wavelengths are examined, and a summary of results are provided in Table 18.

Table 18 Optical Sensor Trade Space

Wavelength	Required Diameter (assume range=60,000 km and resolution=1 m)	Maximum Feasible Range (assume diameter=5.4 m and resolution=1 m)	Maximum Feasible Resolution (assume diameter=5.4 m and range=60,000 km)
UV[28] (100 nm)	15 m	22,000 km	3 m
Visible (500 nm)	73 m	4,400 km	14 m
IR[29] (700 nm)	103 m	3,200 km	19 m

Next, the feasibility of the RADAR transmitter is explored. The results for RADAR are more reasonable for cislunar space, though require significant power. The RADAR equation

[28] Ultra-Violet

[29] Infrared

shown below requires a fourth root to calculate the range, making the antenna gain and wavelength critical design parameters.

$$R_{max} = \sqrt[4]{\frac{P_s G^2 \lambda^2 \sigma}{(4\pi)^3 k T L_{tot}}} \tag{2}$$

Where:

$$R_{max} = maximum\ range$$

$$P_s = peak\ pulse\ power$$

$$G = antenna\ gain$$

$$\lambda = wavelength$$

$$\sigma = radar\ cross\ section$$

$$k = Boltzmann's constant$$

$$T = Noise\ temperature$$

$$L_{tot} = Total\ Losses$$

Due to different power requirements, each application of the RADAR system is evaluated separately and summarized in Table 19. X-band is chosen as a high-performing frequency band that conforms to the United States Department of Commerce Frequency Allocation [125].

Table 19 Cislunar RADAR [3]

	Earth	Lunar	Space
P_s	1,000,000 W	300,000 W	20,000 W

τ	0.5 s	0.5 s	0.5 s
G	75.3 dB[30]	69.2 dB[31]	67.5 dB[32]
λ	0.030 m	0.030 m	0.030 m
σ	1 m^2	1 m^2	1 m^2
k	1.38E-23	1.38E-23	1.38E-23
T	290 K [113]	290 K [113]	290 K [113]
L_{tot}	10.8 dB	8.8 dB	8.8 dB
R_{max}	271,000 km	112,000 km	8,600 km

The maximum ranges in Table 19 show feasibility for the Earth-based and Moon-based applications. However, the space-based RADAR does not meet the minimum range requirement of 60,000 km (based on the distance from L1 or L2 to the Moon). The space-based RADAR is not included in the architecture evaluations.

Due to limitation of the phased array technology, the maximum half-beamwidth is 50-degrees for the domain awareness sensor. [3] The domain awareness sensor is designed to have a resolution of at least 1-meter. This resolution would likely accomplish the subfunctions of identification and tracking for medium and large spacecraft. The array of phased arrays RADAR system is also advantageous in that it can view multiple objects in the beam simultaneously as it sweeps in azimuth and elevation.

RADAR systems can be mono-static or multi-static. The system is monostatic, rather than multi-static. A multi-static RADAR system has diversity in frequency, polarization, or

[30] Assumes 56-meter phased-array diameter due to Earth-based application [118]

[31] Assumes 28-meter phased-array diameter due to Moon-based application [118]

[32] Assumes 5.4-meter antenna diameter due to launch vehicle restrictions [121]

geometry. This RADAR system does not have the advantages of a multi-static system, such as better fidelity of target signatures [126].

The domain awareness payload is unique in that it has different sensors for each application: Earth-based, Moon-based, space-based, while the communications and navigation payloads have the same sensors for each application. The domain awareness sensor uses RADAR which is highly constrained by power. The power sources are researched based on the application to maximize the sensor range. In contrast, the navigation and communication sensors are designed to accommodate the space-based application, which is the most power-limiting. The space-based communication and navigation sensors happen to cover the entire range necessary for cislunar space from Earth or the Moon, so the power-constrained sensor is used for all three applications.

3.3.3 CISLUNAR PHYSICS CONCLUSION

This section provided the underlying assumptions used to design the cislunar constellations and payloads. The cislunar constellations include Lagrange Light, Lagrange Medium, Lagrange Heavy, Earth-based, Earth plus Moon, and Earth plus Lagrange. A summary of the communications, navigation, and domain awareness sensors are provided in Table 20.

Table 20 Payloads Summary

	Range	Beamwidth
Communications Space-Based	450,000 km	± 36.0-degrees
Communications Earth- or Moon-Based	450,000 km	± 45.0-degrees
Navigation	384,400 km	± 32.5-degrees
Domain Awareness Moon-Based	112,000 km	± 50.0-degrees
Domain Awareness Earth-Based	270,000 km	± 50.0-degrees

The next section details the assumptions used to evaluate the costs of each constellation and payload combination.

3.4 ARCHITECTURE COST EVALUATION

To find the optimal architecture, the system cost is included. This section details the assumptions and models used to estimate the cost of each architecture. Payload and bus cost estimates are included for each supporting function to be optimized. Other system costs (design, integration, test, ground support, disposal, etc.) are assumed to be similar among each architecture and therefore not included for the optimization algorithm.

3.4.1 BUS COST ESTIMATES

The bus is defined as the necessary infrastructure to support operations of the payload. Supporting operations include power, thermal control, attitude control, and launch as necessary. The bus exists for space-based, Earth-based, and Moon-based payloads. The bus for each supporting function is assumed to be the same mass and therefore the same cost.

3.4.1.1 GROUND BUS

Ground includes Earth-based systems only since these would not require any launch. The ground bus is estimated to cost $5M based on a professional estimate. [127]

3.4.1.2 SPACE BUS

Space bus includes space-based and Moon-based systems because these systems require launch. Each bus is estimated to cost $50M in hardware plus $200M in launch based on a professional estimate. [128]

3.4.1.3 INTEGRATED BUS

When payloads are integrated on a single bus, the cost of the bus increases, but remains less than if the payloads were on independent. Integrated buses are modeled with the following functions:

$$Cost_{doublebus} = Cost_{bus} + \frac{1}{2} Cost_{bus} \tag{3}$$

$$Cost_{triplebus} = Cost_{doublebus} + \frac{1}{2} Cost_{doublebus} \tag{4}$$

Where:

$$Cost_{bus} = \$5M \; for \; ground$$

$$Cost_{bus} = \$250M \; for \; space$$

The integrated bus equations are very simple with the results being an integrated bus is cheaper than two separate buses, but more expensive than a single bus. Future work could include improving the integrated bus model.

3.4.2 Payload Cost Estimates

Each function has its own payload cost estimate. The assumptions underlying these cost estimates are shown in the sections below.

3.4.2.1 Communications Payload Cost Estimate

Each communications space payload is assumed to be \$13.6M. The components of the communications payload are shown in Table 21 which uses the Unmanned Space Vehicle Cost Model (USCM) [129]. Critical components are marked with a quantity of two. The USCM uses earth-orbiting satellite components (from LEO to GEO) with Commercial Off the Shelf (COTS) components. Cislunar components will need more radiation hardening, which would increase the cost. This is a place for future research.

COTS components do have a success history in missions beyond GEO. NASA has successfully operated the Mars Science Lander, known as Curiosity, with COTS components. In particular, the Synchronous Dynamic Random Access Memory (SDRAM) is a COTS solution. Radiation-related errors with the SDRAM were overcome using error detection and correction (EDAC) [130].

Table 21 Communications Space Payload Cost [112]

Component	Quantity	Cost ($K)
GPS Receiver	1	$50
OCXO[33]	2	$183
Encryption	2	$446
Payload Control	2	$810
Relay Transceiver	1	$1,586
Relay Antenna (2-meter)	1	$6,104
Mission Transceiver	1	$1,586
Mission Antenna (1-meter)	1	$1,423
Total		$13,627

The communications ground payload cost is estimated to be $1M using a professional estimate based on industry experience. This cost can be updated in future research iterations with actual ground cost models.

3.4.2.2 Navigation Payload Cost Estimate

[33] Oven-Controlled Chrystal Oscillator

The navigation payload is estimated to cost $33M. The component costs are also estimated using USCM and shown in Table 22. Critical components are marked with a quantity of two.

Table 22 Navigation Payload Cost [117]

Component	Quantity	Cost ($K)
GPS Receiver	2	$50
RAFS[34]	2	$1,548
OCXO	2	$183
Encryption	2	$446
Signal Generator	2	$5,804
Amplifier	2	$8,237
Antenna	2	$260
Total		$33,056

3.4.2.3 Domain Awareness Payload Cost Estimate

The domain awareness space payload cost is estimated to be $4.269B. The component costs are also estimated using USCM and shown in Table 23. Critical components are marked with a quantity of two.

Table 23 Domain Awareness Space Payload Cost [3]

Component	Quantity	Cost ($K)
GPS Receiver	1	$50
OCXO	2	$183
Encryption	2	$446
Payload Control and AESA[35]	1	$1,562
Crosslink Controller	2	$435
Crosslink Antenna	1	$529
Total per Satellite		$4,269

[34] Rubidium Atomic Frequency Standard

[35] Active Electronically Steerable Antenna

Satellites in Constellation	1,000	$4,269
Total per "Payload"		$4,269,000

The domain awareness ground payload cost is estimated to be $10M using a professional estimate based on industry experience. This cost can be updated in future research iterations with actual ground cost models.

3.4.3 Cost Model Conclusions

Cost estimates in this dissertation are created using USCM and professional estimates. Table 24 shows a summary of the cost estimates driving the optimization of the architectures.

Table 24 Cost Estimates Summary

Name	**Cost ($M)**
Communications Space Payload	$13.6
Communications Ground Payload	$1
Navigation Payload	$33
Domain Awareness Ground Payload	$10
Single Bus	$50
Integrated Double Bus	$75
Integrated Triple Bus	$112.5

3.5 Architecture Performance Evaluation

This section details the performance evaluation of each architecture using the sensor performance and constellation geometry detailed in Section 3.3. The performance metric evaluated is sensor coverage. STK is used to calculate coverage in a physically accurate environment. Coverage is calculated by computing the surface area covered at each radial volume with 5-degree granularity. Radii from the Earth are evaluated from 50,000 km to 400,000 km at 50,000 km increments. This covers the volume just above geosynchronous orbit (GEO) to just beyond the Moon's orbit. Radii from the Moon are evaluated from the 1,737.4 km to 60,000 km at 20,000 km increments. This includes the Moon's surface to L1 and L2 orbits. The additional measurements around the Moon give higher values and weighting to lunar coverage versus Earth coverage, which is consistent with stakeholder needs according to planned cislunar missions.

Alternative evaluations can be considered, depending on stakeholder concerns. For instance, a stakeholder may want to prioritize the coverage in the trans-lunar region (the volume directly between the Earth and the Moon). Another stakeholder may want to prioritize the region closest to the Moon, including Low-Lunar Orbit (LLO). To accommodate these priorities, and appropriate weighting strategy can be used for the spheres assessed in the performance evaluation. For the dissertation, stakeholder needs have not been communicated to indicate any prioritization, so equal weightings are applied for the Earth and Moon spheres assessed.

3.5.1 Communications Performance

The communications sensor is evaluated for all six architectures. Figure 30 shows the six communications architectures modeled in a physically accurate environment using STK.

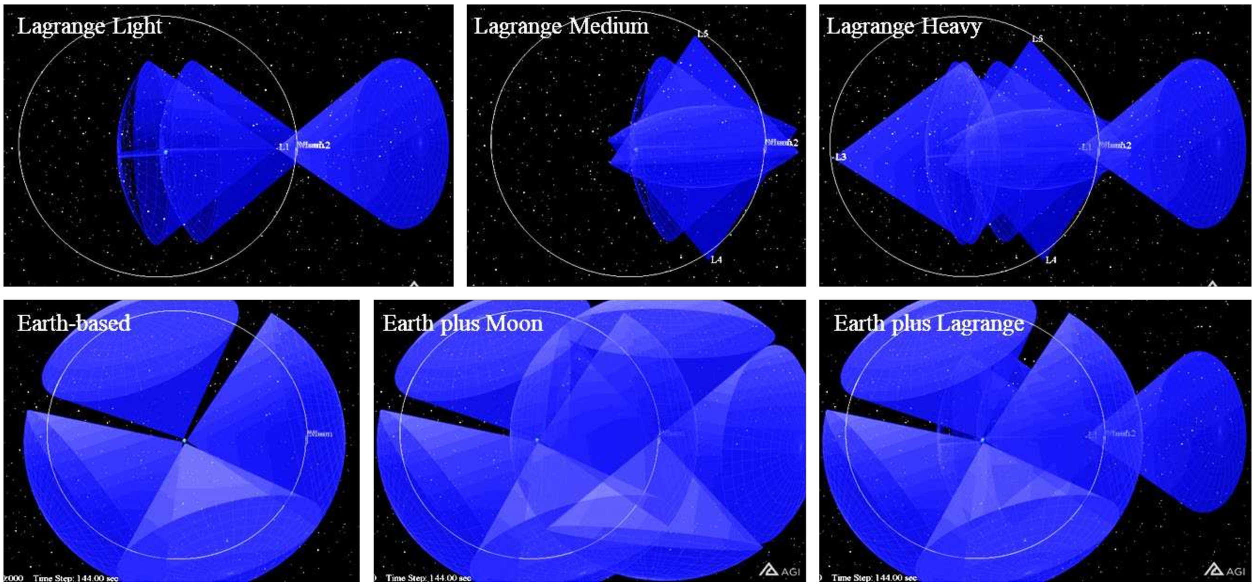

Figure 30 Communications Architectures

At each of the specified radii, the coverage area is calculated and shown in Figure 31. Note that the coverage is scaled by 10^{11} to make the numbers more digestible. From the architecture coverage chart, it appears that the constellations with Earth-based sensors outperform the constellations with only space-based constellations.

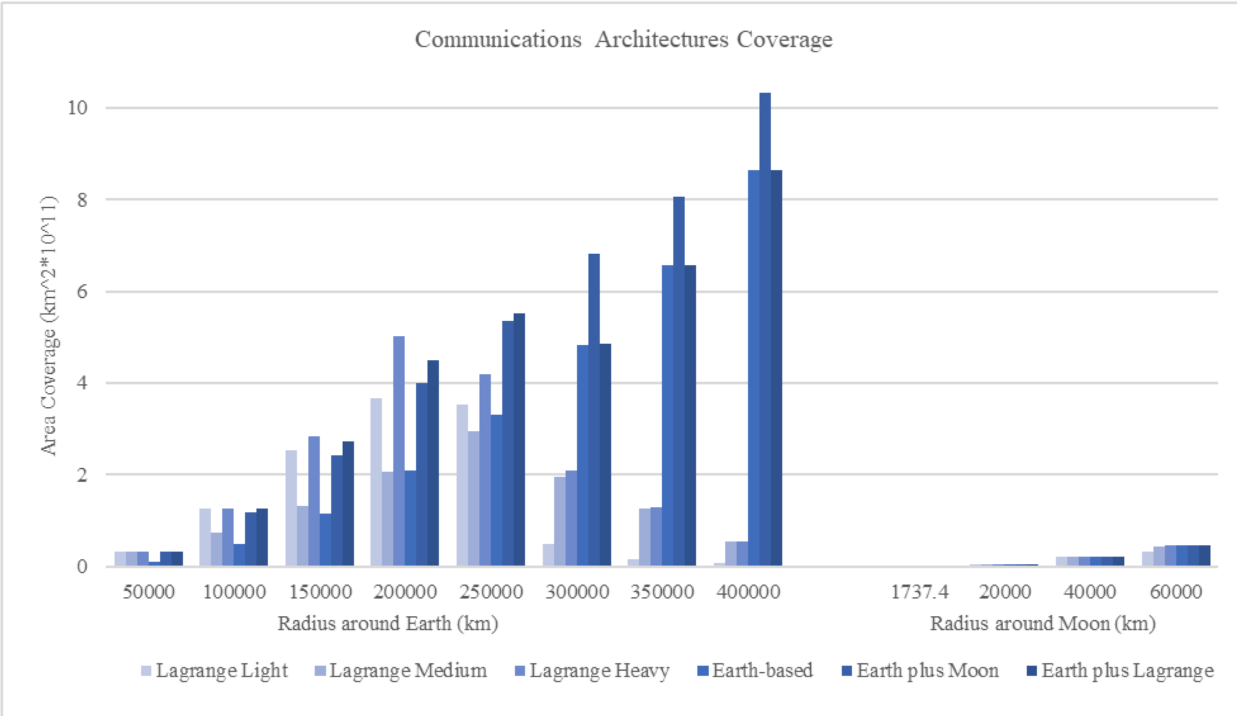

Figure 31 Communications Architectures Coverage

Table 25 summarizes the total coverage, and therefore performance, of each communications architecture. Interestingly, Lagrange medium performs worse than Lagrange light, even though Lagrange medium has more sensors than Lagrange light. This result is because the Lagrange medium sensors have significant overlap in the area between the Earth and the Moon. The worse performing communications constellation is Lagrange medium while the best performing is Earth plus Moon.

Table 25 Communications Architectures Results

Constellation	**Performance ($km^2 * 10^{11}$)**
Lagrange Light	12.632
Lagrange Medium	11.816
Lagrange Heavy	18.224
Earth-based	27.920
Earth plus Moon	39.181
Earth plus Lagrange	35.089

3.5.2 NAVIGATION PERFORMANCE

The navigation sensor is evaluated for all three applicable architectures. Figure 32 shows the three navigation architectures modeled in a physically accurate environment using STK.

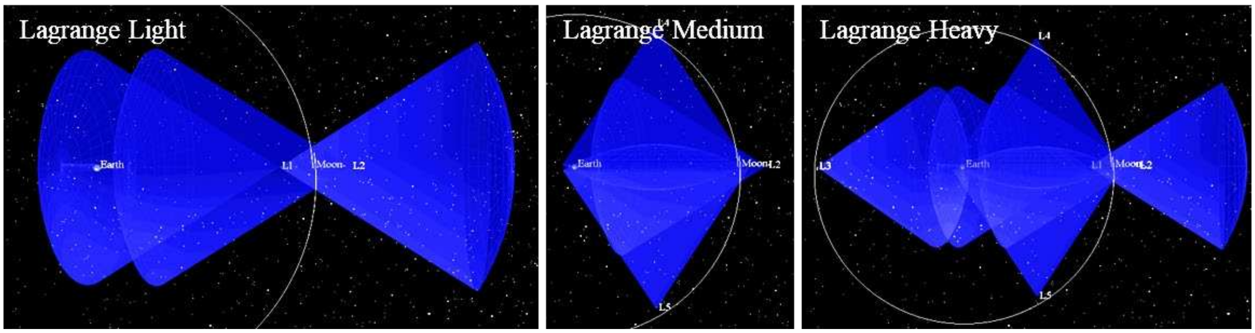

Figure 32 Navigation Architectures

At each of the specified radii, the coverage area is calculated and shown in Figure 33. Note that the coverage is scaled by 10^{11} to make the numbers more digestible. From the architecture coverage chart, it appears that Lagrange heavy outperforms the other architectures at every radius.

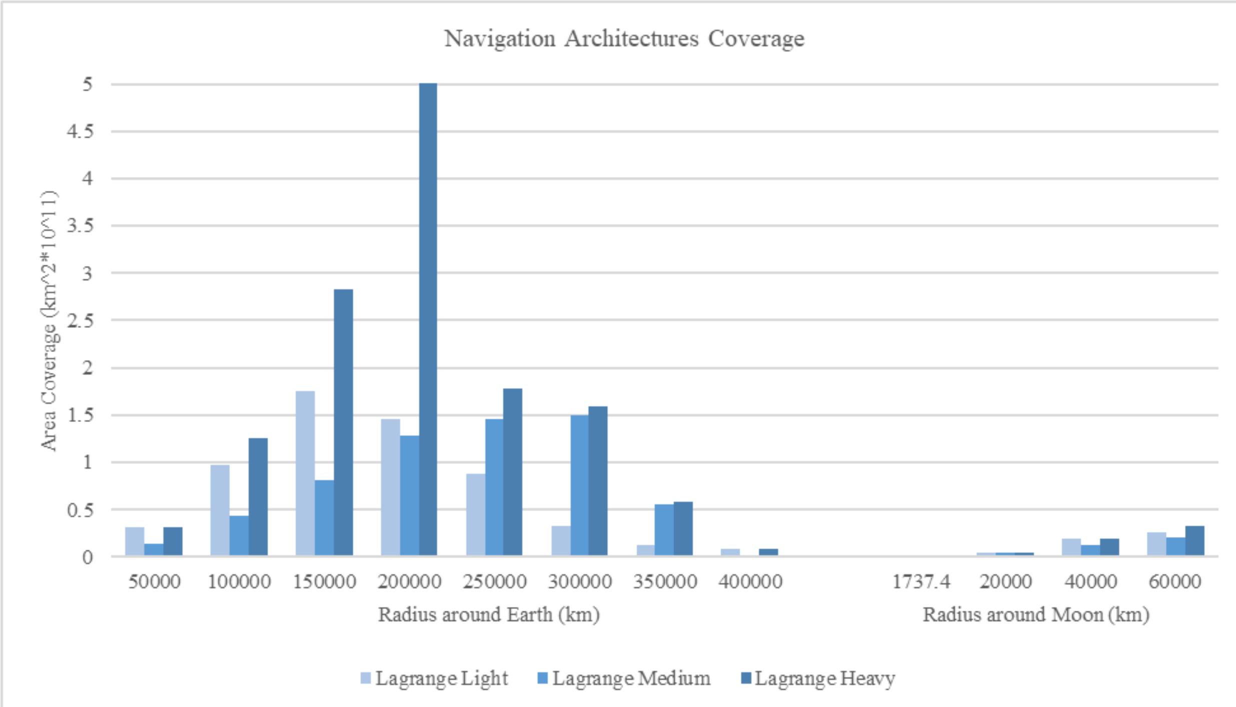

Figure 33 Navigation Architectures Coverage

Table 26 summarizes the total coverage, and therefore performance, of each navigation architecture. The worse performing navigation constellation is Lagrange light while the best performing is Lagrange heavy.

Table 26 Navigation Architectures Results

Constellation	**Performance ($km^2 * 10^{11}$)**
Lagrange Light	6.405
Lagrange Medium	6.593
Lagrange Heavy	14.093

3.5.3 Domain Awareness Performance

The domain awareness sensor is evaluated for the two feasible architectures. Figure 34 shows two domain awareness architectures modeled in a physically accurate environment using STK.

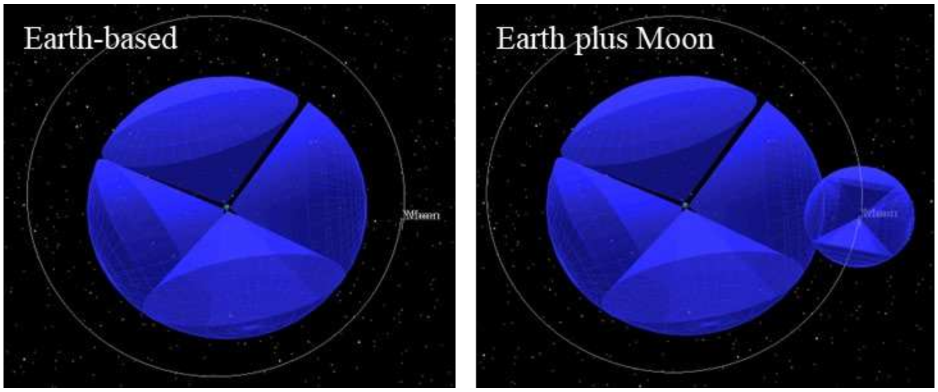

Figure 34 Domain Awareness Architectures

At each of the specified radii, the coverage area is calculated and shown in Figure 35. Note that the coverage is scaled by 10^{11} to make the numbers more digestible. From the architecture coverage chart, it appears that the Earth-based sensors dominate the performance results.

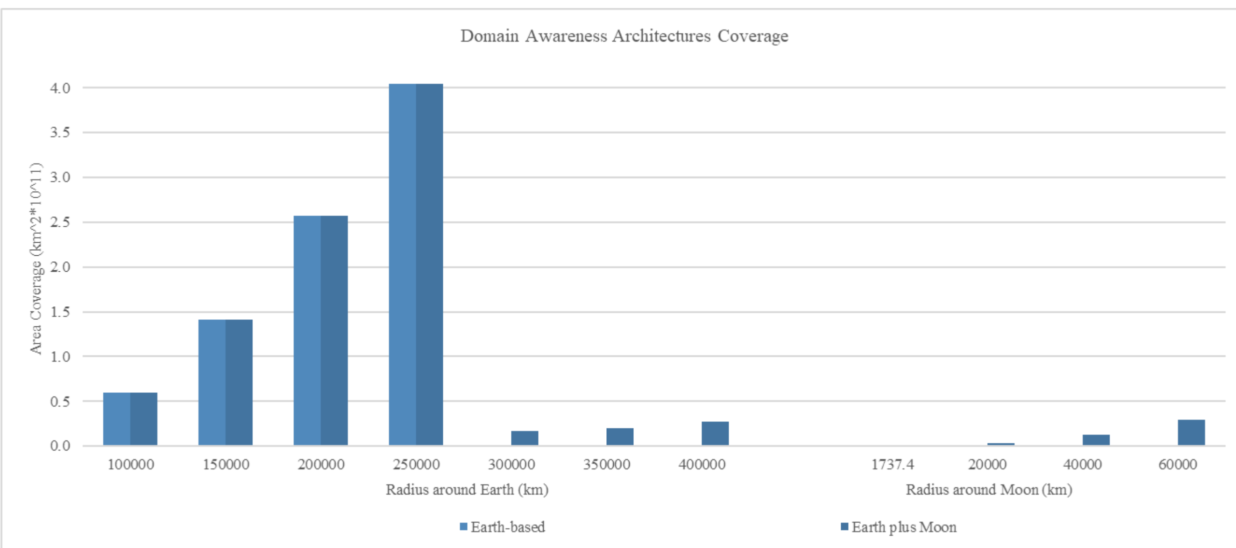

Figure 35 Domain Awareness Architectures Coverage

Table 27 summarizes the total coverage, and therefore performance, of each domain awareness architecture. The Earth plus Moon performs better than the Earth-based constellation.

Table 27 Domain Awareness Architectures Results

Constellation	**Performance ($\boldsymbol{km^2 * 10^{11}}$)**
Earth-based	8.760
Earth plus Moon	9.861

3.5.4 Architecture Performance Evaluation Conclusions

Each supporting function's payload performance is evaluated for each possible constellation using the STK physics-based modeling software. The performance metrics are used in the optimization algorithm to find the optimal architecture. The optimization algorithm is detailed in the following section.

3.6 Architecture Optimization

This section details the optimization algorithm and evaluation strategies used to assess the resulting Pareto front.

3.6.1 Optimization Algorithm

3.6.1.1 Integer Linear Program

The first method presented for optimizing the cislunar system uses the Integer Linear Program function in MATLAB. This method is robust and can be used as the cislunar system grows in complexity. An alternative, simpler algorithm is also presented which works for the cislunar system.

The cislunar system is optimized to minimize cost while maximizing performance. This is accomplished using a multi-objective optimization (MOO) strategy. The optimization function is weighted and optimized for each value of α as defined in the equation below:

$$\min_{x} = \alpha * \boldsymbol{cost} - (1 - \alpha) * \boldsymbol{performance}$$

Where

$$\alpha = \{1:1:100\}$$

$$\boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \end{bmatrix} \equiv costs\ of \begin{bmatrix} communication = lagrange\ light \\ communication = lagrange\ medium \\ communication = lagrange\ heavy \\ communication = earthbased \\ communication = earth\ plus\ moon \\ communication = earth\ plus\ lagrange \\ navigation = lagrange\ light \\ navigation = lagrange\ medium \\ navigation = lagrange\ heavy \\ domain\ awareness = earthbased \\ domain\ awareness = earth\ plus\ moon \end{bmatrix}$$

$$\boldsymbol{x} = \begin{bmatrix} x_{12} \\ x_{13} \\ x_{14} \\ x_{15} \\ x_{16} \\ x_{17} \\ x_{18} \\ x_{19} \\ x_{20} \\ x_{21} \\ x_{22} \end{bmatrix} \equiv performance\ of \begin{bmatrix} communication = lagrange\ light \\ communication = lagrange\ medium \\ communication = lagrange\ heavy \\ communication = earthbased \\ communication = earth\ plus\ moon \\ communication = earth\ plus\ lagrange \\ navigation = lagrange\ light \\ navigation = lagrange\ medium \\ navigation = lagrange\ heavy \\ domain\ awareness = earthbased \\ domain\ awareness = earth\ plus\ moon \end{bmatrix}$$

The constraints are defined as:

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 = 1\ (only\ one\ communications\ constellation)$$

$$x_7 + x_8 + x_9 = 1\ (only\ one\ navigation\ constellation)$$

$$x_{10} + x_{11} = 1\ (only\ one\ domain\ awareness\ constellation)$$

$$x_{1\ldots11} = x_{12\ldots22} \; (ensures\ same\ constellation\ for\ cost\ and\ performance\ evaluations)$$

The weighted function is optimized at each iteration using the intlinprog function in MATLAB®. The intlinprog function requires the following inputs for this application: [131]

- f – objective function (defined above in terms of cost, performance, and α)
- intcon – indicates the components of x that are integer-valued
- Aeq – linear equality constraints matrix
- beq – linear equality constraints vector
- lb – lower bounds of x
- ub – upper bounds of x

The resulting optimal architectures are then plotted for cost and performance which reveals the optimal pareto front.

3.6.1.2 Pareto Front Search

A less computationally heavy algorithm can be used for the cislunar system in its current scope. The method is described below:

1. Find all cost and performance values for each architecture combination.
    a. For the cislunar system, 288 combinations exist
2. Find the Pareto front for the resulting cost and performance values
    a. This can be accomplished by visual inspection, or by implementing a MATLAB function such as paretosearch

3.6.2 Optimization Evaluation

The resulting architectures of the Pareto front are then evaluated using Multicriteria Decision Making (MCDM) with Evidential Reasoning (ER), MCDM without ER, and a Kiviat chart assessment.

For each evaluation technique, an appropriate weighting must be established. In this dissertation, the weighting is chosen such that each resulting value has a unique score. This is determined by increasing the weighting distribution until unique scores are achieved. Linear weighting is implemented in this dissertation, though it is possible to use nonlinear weighting if it can be justified for that application. For MCDM with ER, first the cost and performance are scaled such that each value has a unique score.

Evidential Reasoning is used to account for the uncertainty of a system. A complex SoS has a higher degree of uncertainty than an individual system. The uncertainty must be accounted for in the evaluation of these complex system. Evidential reasoning is applied to the cislunar system using the following certainty values. Uncertainty is calculated as 1 minus the certainty value.

$$Earth\ based\ certainty = 95\%$$

$$Space\ based\ certainty = 90\%$$

$$Moon\ based\ certainty = 85\%$$

The certainty scores are chosen to provide diversity among the final scores. Scores are compared with and without ER to see this effect. Earth-based constellations are given the highest certainty because these systems have the highest history of implementation. Space-based are given less certainty than Earth-based because there is less practice implementing these systems. Moon-based is given the smallest certainty score because there is the least amount of practice in this area. Even with little practice in Moon-based systems, a certainty of 85% is still used because a Moon-based program would have a large funding source and would require a high-enough certainty to justify the large costs.

Evaluating the architectures with evidential reasoning is synonymous with evaluating architecture for risk. The lowest certainty architectures have the highest risk.

The score for each architecture is then calculated using the following equation:

$$architecture\ score = (\alpha_1 * parameter_1 + \cdots + \alpha_n * parameter_n) * certainty$$

Where:

$$\alpha_1 + \cdots + \alpha_n = 1$$

For the cislunar system, the following equation is used which incorporated the cost and performance parameters with equal weights.

$$architecture\ score = (0.5 * cost + 0.5 * performance) * lowest\_certainty$$

For MCDM without ER, the same weighting strategy is applied, but the score is calculated with the following equation:

$$architecture\ score = 0.5 * cost + 0.5 * performance$$

For the Kiviat Chart assessment, more than two evaluation criteria are needed. Additional criteria are created by subdividing performance into communications, navigation, and domain awareness. The performance weights are recalculated based on the individual performance of each supporting function. Each architecture is plotted in a Kiviat Chart and then the area of each chart is calculated for an objective assessment.

3.6.3 Architecture Optimization Conclusion

After evaluating each architecture for cost and performance, the cislunar system architecture is optimized and the resulting Pareto front is evaluated, resulting in the "best" system architecture. The optimization technique used is a linear program within a multi-objective optimization loop. Evaluation techniques include MCDM with ER, MCDM without ER and Kiviat chart assessment.

Chapter 4. RESULTS

4.1 RESULTING PARETO FRONT

The cislunar optimization algorithm, defined in Section 3.6, is applied with the performance and cost metrics previously defined, resulting in a pareto front with four optimal architectures. The Pareto front which maximizes performance and minimizes cost is plotted in Figure 36. The optimal front runs from the lowest-cost, lowest-performance architecture to the highest-cost, highest-performance architecture. While 288 possible architecture combinations existed, only four exist along the Pareto front. The x-value corresponds to the architecture cost while the y-value corresponds to the architecture performance. Each architecture includes one communication constellation, one navigation constellation, one domain awareness constellation. For each architecture, if an integration opportunity exists, it is described. If no integration opportunities exist, then the architecture is described as "no integrated constellations."

Note that if an architecture results in an integrated bus, these architectures must be assessed for feasibility. The payloads are designed to be power-constrained such that multiple payloads can exist on a single COTS bus, reducing hardware costs. However, this integration opportunity may not be advantageous to the lifecycle considerations of the system. Integration may require additional engineering effort, adding cost and delaying the deployment of the system. Additionally, the cyber requirements of each system may be incompatible such that integration no longer makes sense. This additional feasibility assessment is not considered in scope of the dissertation but should be considered in any operational system.

4.1.1.1 INTEGER LINEAR PROGRAM RESULTS

The first method uses a computationally intensive process with the MATLAB function intlinprog. While this method does work for the cislunar system, it can be described as excessive for the system, as it is currently scoped.

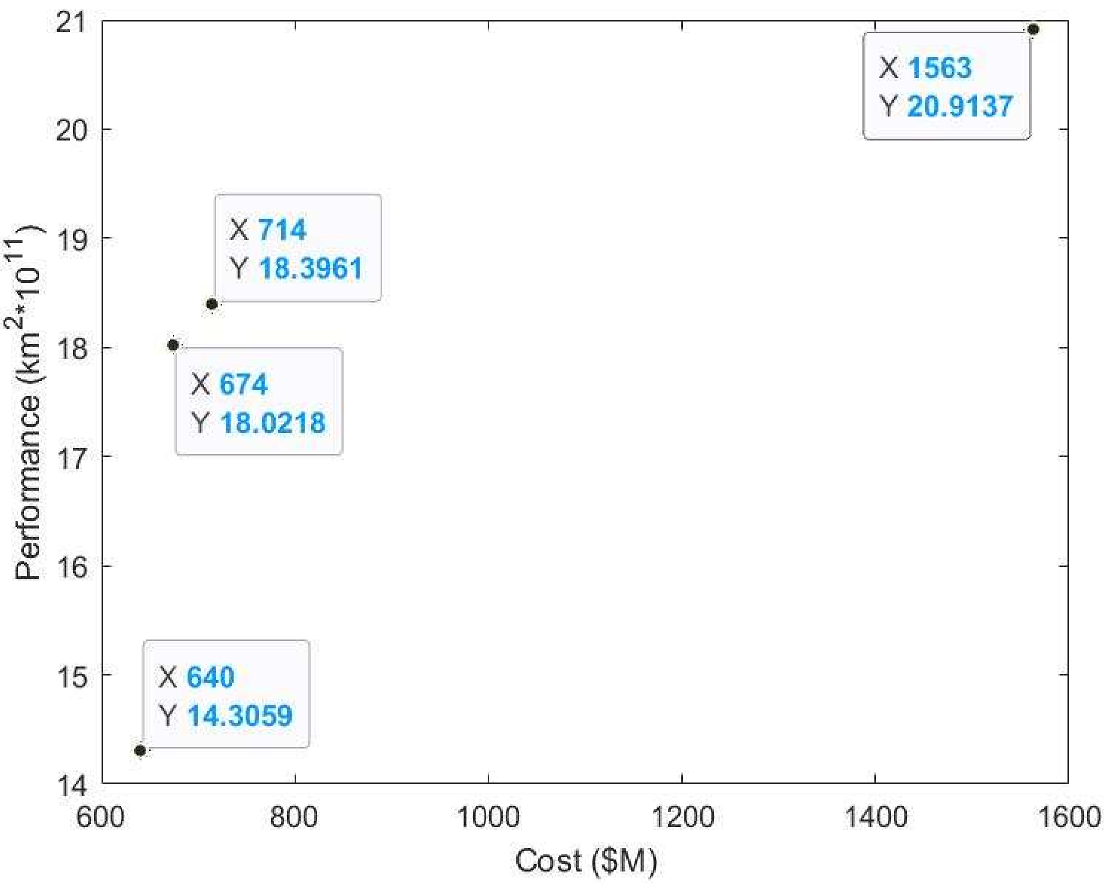

Figure 36 Pareto Front from Integer Linear Program

4.1.1.2 Pareto Front Results

The second method takes all 288 architecture possibilities and finds the Pareto Front. The method uses a weighted sum approach to find the convex, exact Pareto front. This is a more efficient method for the current cislunar system. The same four optimal points are found as presented in the previous method. The results are presented in Figure 37.

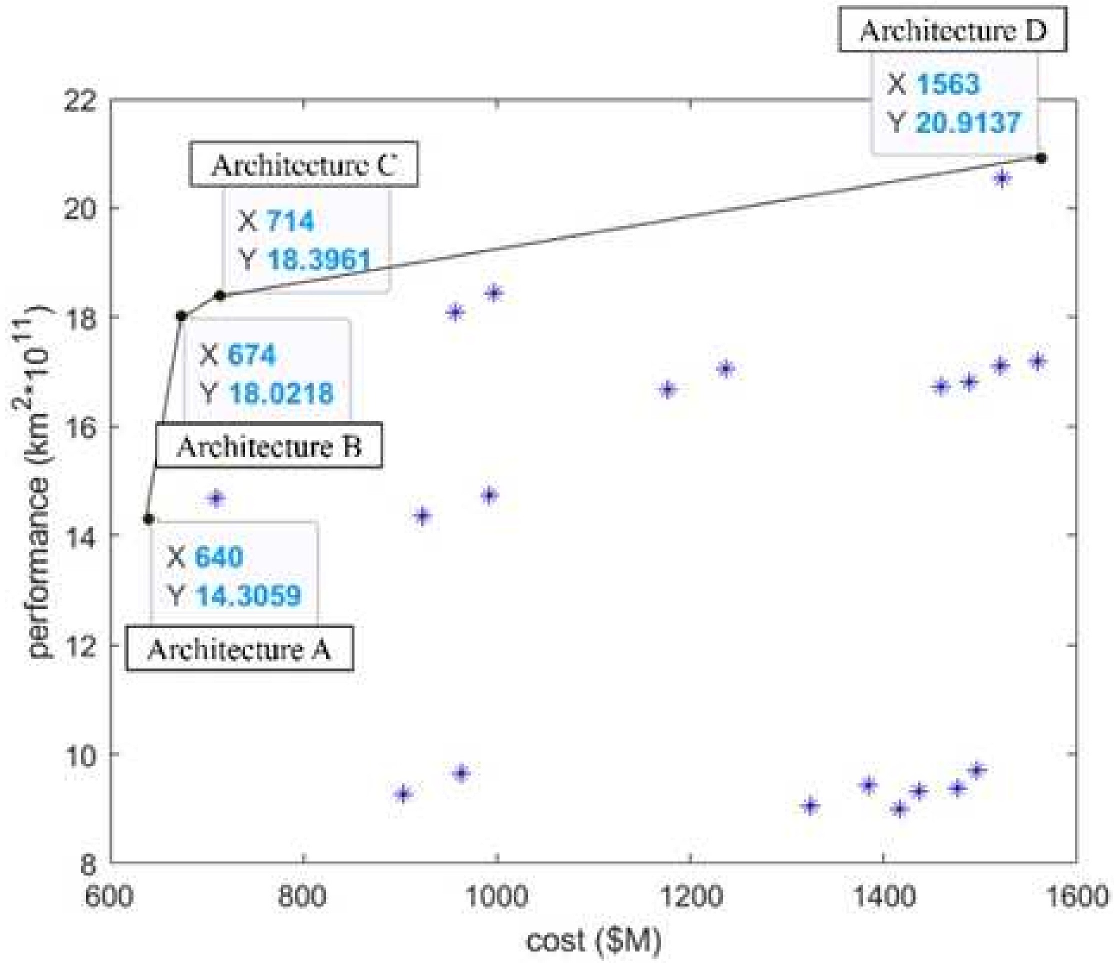

Figure 37 Pareto Front from Pareto Search

4.1.1.3 Pareto Frontier

An additional method is explored to find the optimal architectures, which uses a Pareto Frontier, or Pareto Curve, search algorithm. This algorithm is non-convex and curves along the optimal boundary to find the optimal points. In this technique, six points are identified, though two points are below the exact optimal boundary. The Pareto Frontier is presented in Figure 38. For this dissertation, the four points along the exact Pareto front will be used in the optimal evaluations.

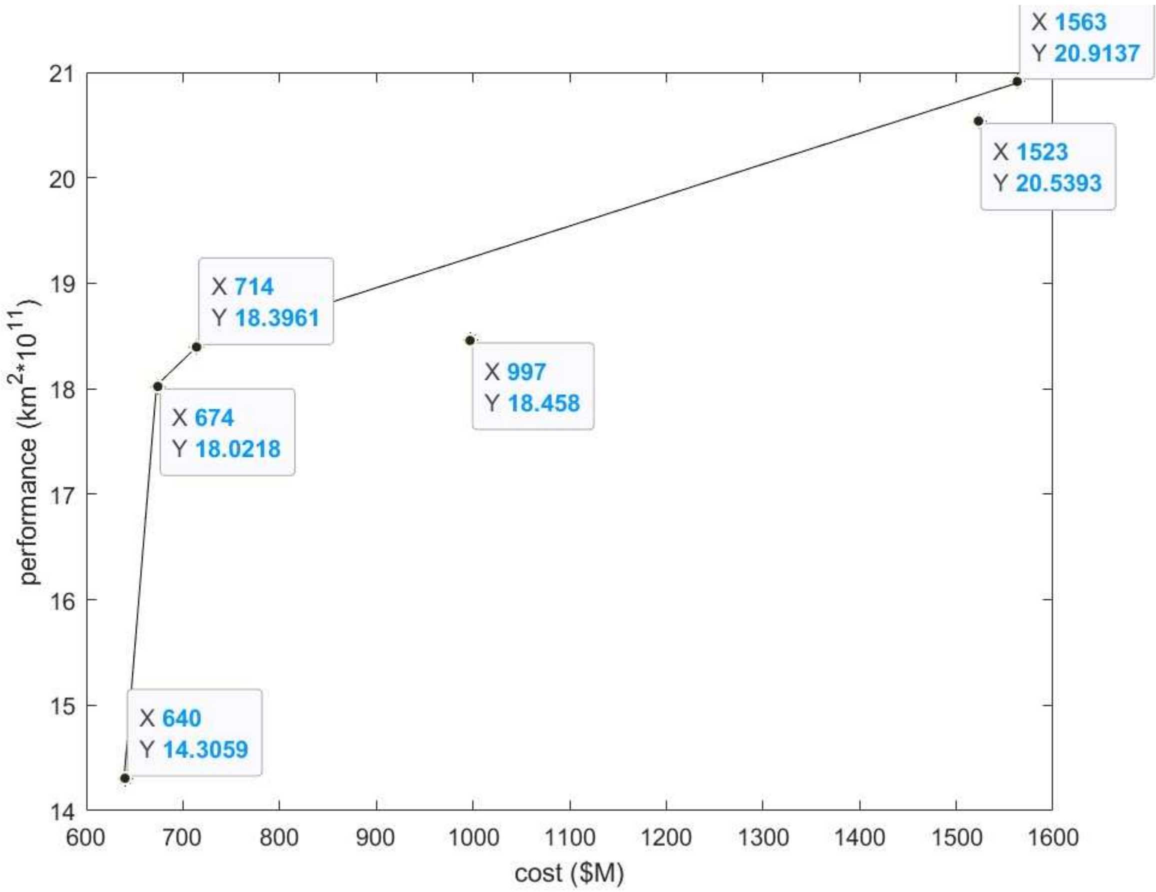

Figure 38 Pareto Frontier

4.1.1.4 Resulting Architectures

These four points correspond to the architectures listed in Table 28. The architecture labels, A-D, will be used for the remainder of the dissertation. The architectures are listed from lowest-cost, lowest-performance to highest-cost, highest-performance. Constellation definitions are provided in Section 3.3.1.

Table 28 Optimal Architectures

Architecture	Cost ($M)	Performance (km^2*10^11)	Constellations
A	640	14.3059	communications constellation = earth-based navigation constellation = lagrange light domain awareness constellation = earth-based

			communications and domain awareness integrated
B	674	18.0218	communications constellation = earth plus moon navigation constellation = lagrange light domain awareness constellation = earth-based no integrated constellations
C	714	18.3961	communications constellation = earth plus moon navigation constellation = lagrange light domain awareness constellation = earth plus moon communications and domain awareness integrated
D	1563	20.9137	communications constellation = earth plus moon navigation constellation = lagrange heavy domain awareness constellation = earth plus moon communications and domain awareness integrated

If Architecture A is held as the baseline and compared with the higher-cost architectures as percent increase in performance, the cost does not rise as much for architectures B and C. For architecture D, the cost increases significantly more than performance. The performance comparison is shown in Table 29. This means that a performance increase is less costly for architectures B and C while it is more costly for architecture D. This can be observed visually by the shape of the pareto front in Figure 36.

Table 29 Architecture Comparisons

Architecture	Cost ($M)	Percent Increase in Cost	Performance (km^2*10^11)	Percent Increase in Performance
A	640	na	14.3059	na
B	674	5%	18.0218	26%
C	714	12%	18.3961	29%
D	1563	144%	20.9137	46%

4.1.2 PARETO FRONT CONCLUSIONS

The cislunar optimization algorithm results in four optimal architectures along the pareto front. The pareto front exhibits asymptotic behavior, meaning that the cost increases faster than the performance.

The four optimal architectures identified by the pareto front are evaluated in the next section. Evaluation techniques include Multi-Criteria Decision Making (MCDM) with Evidential Reasoning (ER), MCDM without ER, and Kiviat chart assessment.

4.2 Optimization Results Evaluation

This section details the evaluation of the pareto front architectures. First, MCDM with ER is used to find the best architecture while accounting for uncertainty. Second, MCDM without ER is used to see how uncertainty affects the results. Finally, a Kiviat chart is assessed to validate the results.

4.2.1 Multi-Criteria Decision Making with Evidential Reasoning

MCDM with ER is researched to be the most appropriate evaluation technique for complex System-of-Systems (SoS) like the cislunar system. This technique includes measures for uncertainty in the evaluation scores.

First, the cost and performance values are weighted on a scale from one to thirty. A range of thirty is chosen to increase the fidelity of the evaluation. This fidelity allows unique scores for each cost/performance value. The weighted values used in the MCDM evaluations are shown in Table 30.

Table 30 MCDM Weights

Cost Range ($M)	Score	Performance Range (km^2*10^11)	Score

1563	-	1532	1	14.3	-	14.5	1
1533	-	1501	2	14.6	-	14.7	2
1502	-	1471	3	14.8	-	15.0	3
1472	-	1440	4	15.1	-	15.2	4
1441	-	1409	5	15.3	-	15.4	5
1410	-	1378	6	15.5	-	15.6	6
1379	-	1348	7	15.7	-	15.8	7
1349	-	1317	8	15.9	-	16.1	8
1318	-	1286	9	16.2	-	16.3	9
1287	-	1255	10	16.4	-	16.5	10
1256	-	1225	11	16.6	-	16.7	11
1226	-	1194	12	16.8	-	16.9	12
1195	-	1163	13	17.0	-	17.2	13
1164	-	1132	14	17.3	-	17.4	14
1133	-	1102	15	17.5	-	17.6	15
1103	-	1071	16	17.7	-	17.8	16
1072	-	1040	17	17.9	-	18.1	17
1041	-	1009	18	18.2	-	18.3	18
1010	-	978	19	18.4	-	18.5	19
979	-	948	20	18.6	-	18.7	20
949	-	917	21	18.8	-	18.9	21
918	-	886	22	19.0	-	19.2	22
887	-	855	23	19.3	-	19.4	23
856	-	825	24	19.5	-	19.6	24
826	-	794	25	19.7	-	19.8	25
795	-	763	26	19.9	-	20.0	26
764	-	732	27	20.1	-	20.3	27
733	-	702	28	20.4	-	20.5	28
703	-	671	29	20.6	-	20.7	29

672	-	640	30	20.8	-	20.9	30

When these weights are applied using the score definition defined in Section 3.6.2 which equally weights cost and performance, architecture C is found to be best. The scores for MCDM with ER are shown in Table 31. ER certainty scores are calculated by using the least-certain constellation implementation in the entire architecture.

Table 31 MCDM with ER Results

Architecture	**Cost**	**Cost Score**	**Performance**	**Performance Score**	**Certainty**	**Score**
A	640	30	14.3	1	90%	14.0
B	674	29	18.0	17	85%	19.6
C	714	28	18.4	19	85%	20.0
D	1563	1	20.9	30	85%	13.2

A sensitivity analysis is performed to see how the "best" architecture shifts as the cost and performance priorities are shifted. Architecture D is ideal when cost is weighted from 0.0 – 0.2 while architecture C is ideal when cost is weighted from 0.3 – 0.6. Architecture B is best for costs weights of 0.7-0.8. Architecture A is ideal for cost weights of 0.9-1.0.

Table 32 MCDM with ER Sensitivity

MCDM with ER			
Cost Weight	Performance Weight	Score	Architecture
0	1	25.5	D
0.1	0.9	23	D
0.2	0.8	20.6	D

0.3	0.7	18.4	C
0.4	0.6	19.2	C
0.5	0.5	20	C
0.6	0.4	20.7	C
0.7	0.3	21.6	B
0.8	0.2	22.6	B
0.9	0.1	24.4	A
1	0	27	A

4.2.2 MULTI-CRITERIA DECISION MAKING WITHOUT EVIDENTIAL REASONING

MCDM without ER is used to evaluate the pareto front architectures. The same weights defined in Table 30 are used, but percent certainty is not included in the score. When cost and performance are weighted equally, architecture C is found to be the best architecture. This matches the result found when ER is included in the evaluation. MCDM without ER scores for each architecture are displayed in Table 33. Note that Architecture B performed almost as well as Architecture C with a score only 2% lower.

Table 33 MCDM without ER Results

ID	Cost	Performance	Score
A	30	1	15.5
B	29	17	23
C	28	19	23.5
D	1	30	15.5

A sensitivity analysis is performed for MCDM without ER to see how the ideal architecture shifts as stakeholder priorities shift. The sensitivity results are shown in Table 34.

Like MCDM with ER, architecture D is ideal for cost weights of 0.0 – 0.2 while architecture C is ideal for cost weights of 0.3 – 0.6. Unlike MCDM with ER, architecture B is ideal for cost weights of 0.7-0.9. Also different from MCDM with ER, architectures A is considered ideal only for cost weight of 1.0, when performance is not a factor. Since certainty is not evaluated in MCDM without ER, the architectures will always be listed from highest cost / highest performance to lowest cost / lowest performance.

Table 34 MCDM without ER Sensitivity

MCDM without ER			
Cost	Performance	Score	Architecture
0	1	30	D
0.1	0.9	27.1	D
0.2	0.8	24.2	D
0.3	0.7	21.7	C
0.4	0.6	22.6	C
0.5	0.5	23.5	C
0.6	0.4	24.4	C
0.7	0.3	25.4	B
0.8	0.2	26.6	B
0.9	0.1	27.8	B
1	0	30	A

Table 35 shows a comparison of the results of MCDM with and without ER as cost and performance weights are shifted. As noted above, the only performance differences occur for the cost weights of 0.9. This is highlighted in the table with italics and underline. Note that without uncertainty accounted for, Architecture A only results as optimal when performance is not included in the evaluation. The difference between Architecture A and B is that Architecture A is evaluated for space-based certainty (90%) while Architecture B is evaluated for moon-based certainty (85%). With only one value differed between MCDM with ER and MCDM without ER, in can be concluded that the cislunar SoS is not heavily influenced by uncertainty, as defined. Further refinement of the uncertainty values could result in more variance between the results with or without ER.

Table 35 MCDM comparison

Cost	**Performance**	**MCDM with ER**	**MCDM without ER**
0	1	D	D
0.1	0.9	D	D
0.2	0.8	D	D
0.3	0.7	C	C
0.4	0.6	C	C
0.5	0.5	C	C
0.6	0.4	C	C
0.7	0.3	B	B
0.8	0.2	B	B
0.9	***0.1***	***A***	***B***
1	0	A	A

4.2.3 Kiviat Chart Assessment

For the Kiviat chart assessment, more criteria are needed than cost and performance. Cost and performance are subdivided for each payload. Bus costs remain separate from payload due to integration. Due to different ranges, the weights for each score are reassessed and summarized in

Table 36. Weights are assessed on a range from one to fifty because this fidelity ensures that each unique performance or cost value maps to a unique weight.

Table 36 Kiviat Chart Weights

Payload Performance				Payload Cost				Bus Cost			
Range			Score	Range			Score	Range			Score
39.2	-	38.5	50	4.0	-	7.2	50	530.0	-	545.6	50
38.4	-	37.9	49	7.3	-	10.4	49	545.7	-	561.2	49
37.8	-	37.2	48	10.5	-	13.7	48	561.3	-	576.8	48
37.1	-	36.6	47	13.8	-	16.9	47	576.9	-	592.4	47
36.5	-	35.9	46	17.0	-	20.1	46	592.5	-	608.0	46
35.8	-	35.2	45	20.2	-	23.3	45	608.1	-	623.6	45
35.1	-	34.6	44	23.4	-	26.5	44	623.7	-	639.2	44
34.5	-	33.9	43	26.6	-	29.8	43	639.3	-	654.8	43
33.8	-	33.3	42	29.9	-	33.0	42	654.9	-	670.4	42
33.2	-	32.6	41	33.1	-	36.2	41	670.5	-	686.0	41
32.5	-	32.0	40	36.3	-	39.4	40	686.1	-	701.6	40
31.9	-	31.3	39	39.5	-	42.6	39	701.7	-	717.2	39
31.2	-	30.7	38	42.7	-	45.9	38	717.3	-	732.8	38
30.6	-	30.0	37	46.0	-	49.1	37	732.9	-	748.4	37
29.9	-	29.3	36	49.2	-	52.3	36	748.5	-	764.0	36
29.2	-	28.7	35	52.4	-	55.5	35	764.1	-	779.6	35
28.6	-	28.0	34	55.6	-	58.7	34	779.7	-	795.2	34
27.9	-	27.4	33	58.8	-	62.0	33	795.3	-	810.8	33
27.3	-	26.7	32	62.1	-	65.2	32	810.9	-	826.4	32
26.6	-	26.1	31	65.3	-	68.4	31	826.5	-	842.0	31
26.0	-	25.4	30	68.5	-	71.6	30	842.1	-	857.6	30
25.3	-	24.8	29	71.7	-	74.8	29	857.7	-	873.2	29
24.7	-	24.1	28	74.9	-	78.1	28	873.3	-	888.8	28
24.0	-	23.4	27	78.2	-	81.3	27	888.9	-	904.4	27
23.3	-	22.8	26	81.4	-	84.5	26	904.5	-	920.0	26
22.7	-	22.1	25	84.6	-	87.7	25	920.1	-	935.6	25
22.0	-	21.5	24	87.8	-	90.9	24	935.7	-	951.2	24
21.4	-	20.8	23	91.0	-	94.2	23	951.3	-	966.8	23
20.7	-	20.2	22	94.3	-	97.4	22	966.9	-	982.4	22
20.1	-	19.5	21	97.5	-	100.6	21	982.5	-	998.0	21
19.4	-	18.9	20	100.7	-	103.8	20	998.1	-	1013.6	20
18.8	-	18.2	19	103.9	-	107.0	19	1013.7	-	1029.2	19
18.1	-	17.5	18	107.1	-	110.3	18	1029.3	-	1044.8	18
17.4	-	16.9	17	110.4	-	113.5	17	1044.9	-	1060.4	17

16.8	-	16.2	16	113.6	-	116.7	16	1060.5	-	1076.0	16
16.1	-	15.6	15	116.8	-	119.9	15	1076.1	-	1091.6	15
15.5	-	14.9	14	120.0	-	123.1	14	1091.7	-	1107.2	14
14.8	-	14.3	13	123.2	-	126.4	13	1107.3	-	1122.8	13
14.2	-	13.6	12	126.5	-	129.6	12	1122.9	-	1138.4	12
13.5	-	13.0	11	129.7	-	132.8	11	1138.5	-	1154.0	11
12.9	-	12.3	10	132.9	-	136.0	10	1154.1	-	1169.6	10
12.2	-	11.6	9	136.1	-	139.2	9	1169.7	-	1185.2	9
11.5	-	11.0	8	139.3	-	142.5	8	1185.3	-	1200.8	8
10.9	-	10.3	7	142.6	-	145.7	7	1200.9	-	1216.4	7
10.2	-	9.7	6	145.8	-	148.9	6	1216.5	-	1232.0	6
9.6	-	9.0	5	149.0	-	152.1	5	1232.1	-	1247.6	5
8.9	-	8.4	4	152.2	-	155.3	4	1247.7	-	1263.2	4
8.3	-	7.7	3	155.4	-	158.6	3	1263.3	-	1278.8	3
7.6	-	7.1	2	158.7	-	161.8	2	1278.9	-	1294.4	2
7.0	-	6.4	1	161.9	-	165.0	1	1294.5	-	1310.0	1

Using these weights for each of the four architectures results in the Kiviat charts shown in Figure 39. Starting from the top-most point and moving clockwise, the seven points evaluated are communication payload cost, navigation payload cost, domain awareness payload cost, bus cost, communication performance, navigation performance, and domain awareness performance.

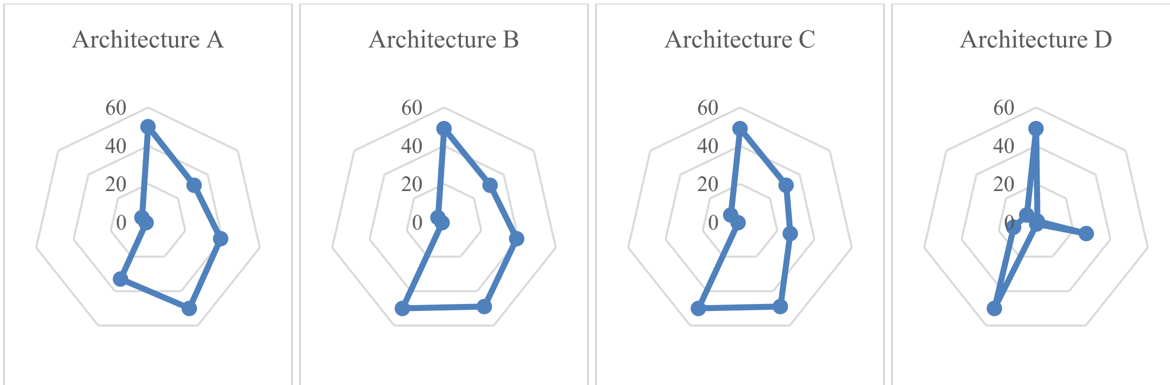

Figure 39 Kiviat Charts

From the above charts, architecture D is the least ideal while architectures A, B, and C have similar areas visually. For an objective score, the area of each shape is calculated and divided by the total possible area for a weighted score, shown in Table 37.

Table 37 Kiviat Scores

Architecture	Area (unitless)	Area Max (unitless)	Score (Area/Area Max)
A	2578	7578	2.7
B	2869	7578	3.0
C	2533	7578	2.7
D	437	7578	0.5

The objective scores result in Architecture B as the most ideal using the Kiviat chart method. This differs from the MCDM results because of the way the criteria were weighted. For the Kiviat chart, seven criteria were evaluated while four out of the seven were cost parameters. With the MCDM evaluation, performance and cost were weighted equally. With four out of seven parameters used for cost, the Kiviat chart result skews towards a low-cost option as more ideal than the mid- or high-cost option. Given that the weights are skewed towards cost, the Kiviat chart assessment is not ideal for the cislunar architecture.

4.2.4 OPTIMIZATION RESULTS EVALUATION CONCLUSION

Determining the optimal architecture requires input from the stakeholder to specify the prioritization of cost vs. performance. Assuming that cost and performance are equally weighted, the optimal architecture is found to be Architecture C:

- communications constellation = earth plus moon
- navigation constellation = Lagrange light
- domain awareness constellation = earth plus moon
- communications and domain awareness integrated

MCDM with and without ER both result in architecture C as the optimal solution when cost and performance are equally weighted. MCDM with ER differs from MCDM without ER at one out of eleven data points. The difference occurs when cost is weighted very high, and performance is weighted very low.

Kiviat chart assessment is implemented, but not ideal for this application due to the manipulation of the data which resulting in a skewing towards the cost metrics. To implement Kiviat chart assessment, four metrics are cost-related while three metrics are performance-related, resulting in Architecture A (the lowest-cost, lowest-performance architecture) as optimal.

The next section steps through the validation techniques used in each section of the dissertation.

4.3 VALIDATION

Validation is defined as "The process of determining the degree to which a [simulation] model and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model." [132] Common model validation techniques include:

- Comparison to Other Models
- Face Validity
- Historical Data Validation
- Parameter Variability – Sensitivity Analysis
- Predictive Validation [133]

This validation definition and these techniques are applied to each appropriate section of the dissertation work, including cislunar architectures literature review, performance evaluation, cost evaluation, the optimization algorithm, and the SysML model.

4.3.1 Cislunar Architectures Validation

Section 2.1.1 of the Literature Review presents a compilation of the latest systems and research completed on cislunar architectures. A paper containing this research was peer-reviewed, published, and presented at the Institute of Electrical and Electronics Engineers (IEEE) International Systems Conference 2022. [134] The validation method used is "Face Validity".

4.3.2 Performance and Cost Evaluation Validation

Each architecture is evaluated for coverage performance characteristics in Section 3.5. These coverage characteristics are calculated in a realistic physics environment using Systems Tool Kit (STK). This software package propagates satellites using High-Precision Orbital Propagator (HPOP) including N-body effects from the Sun and Moon. STK uses a validated physics model for all propagations. [135] The STK model is independently validated by its developers.

The sensor performance is calculated using link budgets, validated in peer-reviewed publications. The navigation sensor performance was peer-reviewed, published, and presented at Institute of Navigation (ION) Joint Navigation Conference (JNC) in 2021. [117] The communications sensor performance was peer-reviewed and presented at the 2021 Cislunar Security Conference. [112] The domain awareness sensor performance was peer-reviewed, published, and presented at ION JNC 2022. [136] Link budgets are validated using "Historical Data Validation" while all sensor performances are validated with "Face Validity".

Similarly, costs are validated using existing models and peer-review opportunities. Component costs are estimated using the non-proprietary version of the Unclassified Satellite Cost Model (USCM). For components not included in USCM, professional estimates are used and then validated in peer-reviewed conference publications. [136] USCM costs are independently validated by USCM developers while professional estimate costs are validated by "Face Validity".

4.3.3 Optimization Algorithm Validation

The optimization algorithm is described in Section 3.6.1. The resulting Pareto front is shown again in Figure 40 for comparison with additional figures in this section.

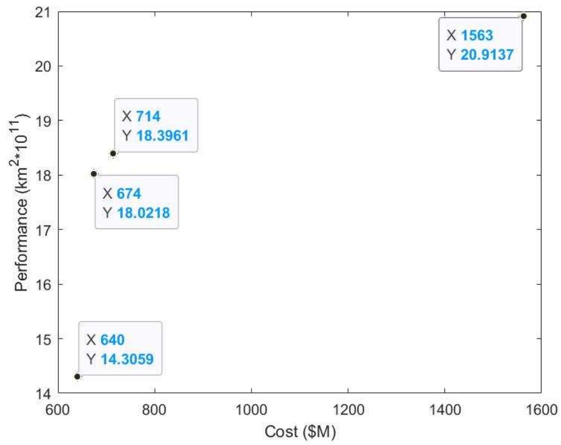

Figure 40 Pareto Front

To validate the resulting pareto front, all 288 possible architectures are plotted in Figure 41. The 288 architecture configurations were determined in Section 3.2.3.

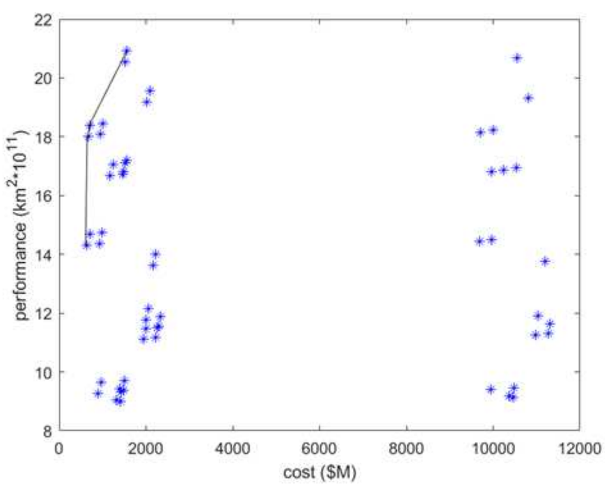

Figure 41 All Architectures

The lowest cost, highest performance Pareto front is at the far left of Figure 41. To see the Pareto front more clearly, the cost axes is zoomed to $400M - $1600M, shown in Figure 42. Additionally, lines are drawn along the Pareto front to clearly differentiate the four optimal points. The point values in Figure 40 are compared with those in Figure 42 and found to be identical.

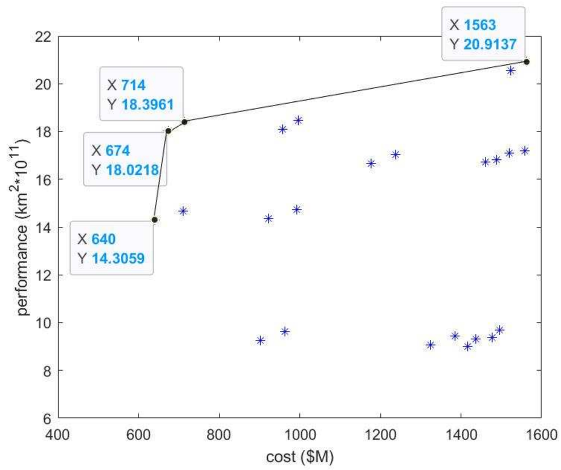

Figure 42 All Architectures Zoomed

Timing analysis is performed on the optimization algorithm. Running the optimization algorithm takes 1.648343 seconds to identify the Pareto Front, while plotting the results of all 288 architectures takes 0.333877 seconds plus several minutes to parse the data. Considering the plot of all architectures takes considerable time to parse the data, the optimization algorithm is a much more efficient method of finding the Pareto front. Table 38 shows the timing data for each optimization method in a side-by-side comparison. The optimization algorithm is orders of magnitude better.

Table 38 Optimization Timing Analysis

Method	Time to Complete
Optimization Algorithm	<2 seconds
Manual Analysis of All Architectures	>300 seconds

The optimization algorithm is validated by “Comparison to Other Models”, where the other model is running all architecture options.

4.3.4 Systems Modeling Language Model Validation

The SysML model is built in Cameo Systems Modeler™, which provides validation strategies for the entire model or parts of the model. Invalid model elements are marked as "error", "warning", or "info". [137] Cameo Systems Modeler™ validation is run on the SysML model resulting in no fatal errors. No comparable models exist for a cislunar system, so the internal Cameo Systems Modeler™ validation is the validation method used.

4.3.5 Optimal Cislunar Architectures Validation

The optimal cislunar architectures are validated using the "compare to other models" method. Unfortunately, research on an integrated model of communications, navigation, and domain awareness does not exist. But each function can be compared to previously researched models.

For the communications system, research has resulted in a proposed physical architecture placing satellites at Earth-Moon L2, L3, L4, and L5 [36]. This would be comparable to the Lagrange Heavy constellation of this dissertation, which includes L1, L2, L3, L4 and L5. The previous research does differ from the scope of this dissertation because it does not study Earth-based or Moon-based architectures as options for an optimal communications architecture. Another optimal communications system proposed uses a "flower constellation" of cubesats around the Moon [37]. This second study is designed for a specific user on or near the Moon, whereas this dissertation optimizes for the entire volume of cislunar space. Neither of these studies match the results of the optimal communications architectures, which included Earth-based and Earth-plus-Moon. The differences in optimal architectures between previous research and this dissertation are due to (1) scope of physical architectures under study, (2) differing user requirements, and (3) optimizing for a single system rather than a system of systems.

For the navigation system, previous research has resulted in an effective architecture of satellites in Earth-Moon L1, L2, L4, and L5 orbits, which is most comparable to the Lagrange Medium constellation in this dissertation [45]. The previous study differs from the research in this dissertation because it focuses on satellites in trans-lunar and lunar orbit whereas the dissertation optimizes the entire volume of cislunar space. Additionally, the previous research includes dilution of precision it the performance calculations, whereas the dissertation only uses coverage. The optimal navigation architectures in this dissertation include the Lagrange Light and Lagrange Heavy constellations. The differences in optimal architectures between previous research and this dissertation are due to (1) differing user requirements, (2) differing evaluation parameters, and (3) optimizing for a single system rather than a system of systems.

For the domain awareness system, an architecture of optical sensors have been studied for use in cislunar space [59]. The study evaluates this architecture using solar exclusion angles, solar phase angles, and lunar exclusion angles, which are not relevant evaluation parameters for the RADAR system used in this dissertation. Additionally, resolution requirements are not discussed in previous research, whereas the system in this dissertation is designed to meet resolution requirements. Regardless, the resulting optimal optical architecture includes a constellation of Low Earth Orbit satellites in the Earth-Moon plane. The feasibility calculations included in this dissertation show that the RADAR payload far outperforms the optical sensor for cislunar applications, which is why RADAR is chosen for the domain awareness sensor. The resulting optimal domain awareness architectures in this dissertation include Earth-based and Earth-plus-Moon. Terrestrial solutions are necessary for RADAR due to the high power demands. The differences in optimal architectures between previous research and this dissertation are due to (1) differing requirements, (2) differing evaluation parameters, and (3) optimizing for a single system rather than a system of systems.

4.3.6 Validation Conclusions

Validation techniques are applied to all appropriate sections of the dissertation, including: cislunar architectures literature review, performance evaluation, cost evaluation, the optimization algorithm, and the SysML model. The cislunar architectures are validated using “face validity” by peer-reviewed publication. Performance metrics are found using a validated physics-modeling tool: STK. Cost metrics are determined using validated models when necessary and by “face validity” via peer-reviewed publication when necessary. The optimization algorithm is validation by “comparison to other models”, where the other model is an algorithm of all possible architectures, and the optimal front is found manually. The SysML model is validated using Cameo’s internal validation techniques.

In the next section, a summary of conclusions is provided along with recommendations for future work.

Chapter 5. SUMMARY

5.1 SUMMARY OF CONCLUSIONS

This section provides a summary of all conclusions made in the dissertation. The research and work leading to the conclusions can be found in the referenced sections.

Chapter 1 provides the dissertation overview, problem statement, and literature review. The dissertation begins with a summary of the research questions and research tasks guiding the dissertation research. The research questions and tasks collectively summarize the research contributions of this dissertation.

The research questions are summarized below:

1. Which evaluation technique, or techniques, are best applied to a cislunar system?
    a. Multi-Criteria Decision Making (MCDM) is found to be the best technique for evaluating the cislunar systems.
2. Which optimization technique, or techniques, are best applied to a cislunar system?
    a. Multi-Objective Optimization (MOO) with a Linear Program (LP) is found to be the best technique for the cislunar system application.
3. What special consideration must be made when evaluating a System of Systems (SoS) when compared to evaluating a single system?
    a. A System of Systems, when compared to a single system, requires clear communication across the lifecycle with the ability to evolve with enterprise-level concerns, resulting in the need for an architecture developed using Model-Based Systems Engineering. Additionally, uncertainty must be considered during evaluation.

The research tasks are summarized below:

1. Perform needs analysis of comprehensive cislunar space system
    a. The needs analysis is performed during the Literature Review. The three primary missions and eight supporting functions are identified during research of all current and planned cislunar missions.
2. Develop a functional architecture of cislunar space to identify any gaps in current or planned cislunar efforts
    a. A Gap Analysis is completed during the background research on cislunar architectures, included in Section 2.1.1.3, and in the creation of Cislunar Activities Roadmap, included in APPENDIX A. Existing and missing functionality for each supporting function is included in the summary tables throughout Section 2.1.1.3.
    b. The functional architecture is modeled using Cameo Systems Modeler. The functional architecture includes appropriate Block Definition Diagrams (BDD), Internal Block Diagrams (IBD), Activity Diagrams (ACT), Sequence Diagrams (SD), contextual diagrams, and key interfaces.
3. Evaluate an integrated cislunar architecture which includes all necessary supporting functions and primary missions.
    a. The cislunar architectures are evaluated for the three necessary supporting functions: communications, navigation, and domain awareness. These functions support the primary mission, which are the users or "actors" of the system.

b. Prior to optimization, each potential architecture is evaluated for cost and performance. The cost and performance metrics are used to optimize the architecture.

c. After optimization, MCDM with Evidential Reasoning (ER), MCDM without ER, and a Kiviat Chart Assessment are used on the five optimal architectures of the pareto front.

4. Optimize integrated cislunar architecture

   a. A mixed-integer linear programming algorithm is used within a MOO technique to find a pareto front of optimal architectures. Four optimal architectures are found within the trade space of varying cost and performance.

Chapter 2 provides a summary of all research and programs in cislunar space is provided. From this research, the three primary missions and eight supporting functions are identified. The primary missions include science, commerce, and defense. The eight supporting functions include transportation, communication, navigation, domain awareness, service, energy, shelter, and control. For each supporting function, the ***programs*** and ***technology*** needed are identified. For transportation, no additional programs or technology are needed. For communication, the identified program is a relay link, and the identified technology includes a 50-meter ground antenna. For navigation, the program needed is a Lunar Navigation Satellite System (LNSS). For domain awareness, the programs needed include sensors of the lunar surface, sensors of lunar orbits, and sensors of cislunar orbits. For the service function, the program needed includes cislunar service satellite while the technology needed is in-situ resource utilization (ISRU). For energy, the program needed includes cislunar refueling satellite while the technology needed is ISRU. For shelter, no additional programs or technology are needed. For control, no additional programs or technology are needed. Note that although eight total supporting functions are identified, only communication, navigation, and domain awareness are selected as the three functions to evaluate and optimize in this dissertation because they provide the critical infrastructure for a cislunar system. Additionally, research is presented on SoS, MBSE, system architecture evaluation, and system architecture optimization. With this background research established, the next step for dissertation work is to detail the approach for developing, evaluating, and optimizing the architectures.

0 provides the methodology and relevant steps used to conduct the dissertation work, including the SysML model, architecture modeling concepts, cislunar physics, architecture cost evaluation, architecture performance evaluation, and architecture optimization. The Cameo Systems Modeler™ SysML model is presented using the Model-Based Systems Architecture Process (MBSAP), including a background on SysML, an Architecture Overview and Summary, and the three viewpoints: the Operational Viewpoint (OV), the Logical/Functional Viewpoint (LV), and the Physical Viewpoint (PV). The viewpoints are used to model the physical and behavioral interactions of the cislunar system elements. Modeling concepts beyond MBSAP are presented, including allocating requirements; modeling stereotypes; layered architecture; executable architectures; patterns in architecture decisions; architecture optimization; verification and validation; complexity; networking; Open Systems Architecture; and cybersecurity. These concepts collectively inform the design of the architecture in real-world context, though are formally included in the MBSAP. The six constellations and payload sensors for communication, navigation, and domain awareness are designed and proved to be feasible in the cislunar environment. Details the payload and bus cost estimates, including integrated bus cost estimates, are presented. The cost estimates in this dissertation include results from validated cost models

and estimates from industry experts. Each supporting function's payload performance is evaluated for each possible constellation using the STK physics-based modeling software. The performance and cost metrics are used in the optimization function. The optimization algorithm and the evaluation techniques used for the resulting pareto front are presented. The optimization technique used is a linear program within a multi-objective optimization loop. Evaluation techniques MCDM with ER, MCDM without ER and Kiviat chart assessment. With the approach detailed, the next step is to apply the evaluation and optimization to the cislunar system to gather the results.

Chapter 4 provides the optimization results, an evaluation of the optimization results, and a summary of validation techniques used in the dissertation. First, the resulting Pareto front is presented. The cislunar optimization algorithm results in four optimal architectures along the Pareto front. The Pareto front exhibits asymptotic behavior, meaning that the cost increases faster than the performance. Next, the optimization results are evaluated using MCDM with ER, MCDM without ER, and a Kiviat chart assessment. Assuming that cost and performance are equally weighted, the optimal architecture is found to be Architecture C. MCDM with and without ER both result in architecture C as the optimal solution when cost and performance are equally weighted. MCDM with ER differs from MCDM without ER at one out of eleven data points. The Kiviat chart assessment is found to not be ideal for this application because it skews strongly towards the low-cost options. Validation techniques are applied to all appropriate sections of the dissertation, including: cislunar architectures literature review, performance evaluation, cost evaluation, optimization algorithm, and SysML model. The cislunar architectures are validated using "face validity" by peer-reviewed publication. Performance metrics are found using a validated physics-modeling tool: STK. Cost metrics are determined using validated models when available and by “face validity” via peer-reviewed publication when necessary. The optimization algorithm is validated by “comparison to other models”, where the other model is an algorithm of all possible architectures, and the optimal front is found manually. The SysML model is validated using Cameo’s internal validation techniques.

5.2 Research Contributions

The research in this dissertation provides significant contributions to the academic areas of Astronautical Engineering and Systems Engineering.

In Astronautical Engineering, the research area of cislunar space is comprehensively studied. A needs analysis of cislunar space is performed, which identifies the three primary missions planned to operate and the eight supporting functions necessary for the missions to operate. A SysML model is presented for the cislunar system of systems. The SysML model is a crucial component of architecture design due to the complexity of the cislunar system of systems. The physics of cislunar space are explored. Six constellations are designed within the circular restricted three-body problem to meet the initial operational requirements. Additionally, payload sensors are designed to maximize the effectiveness of communication, navigation, and domain awareness functions in cislunar space. The sensors are modeled within each constellation and the coverage performance is measured. This research provides great insights for organizations planning to deploy to the enormous, and dynamic, environment of cislunar space.

In Systems Engineering, several gaps in research are filled by providing processes for designing, evaluating, and optimizing a large, complex system of systems. The complexity of a system of systems requires model-based systems engineering, rather than document-based systems engineering, during the design. The model-based systems architecture process is presented for this purpose. In scoping the system of systems, a process for determining a set of alternatives is given. Next, appropriate enterprise-level evaluation parameters are chosen and used to evaluate the hundreds of architecture options. An optimization algorithm is presented which can handle multiple parameters in a non-differentiable environment; this is the multi-objective optimization with integer linear program. The results of the optimization algorithm are then evaluated using multiple techniques, while multi-criteria decision making is found to be the most appropriate for system of systems as it accounts for the uncertainty.

In summary, this dissertation provides novel research to the areas of Astronautical Engineering, specifically cislunar applications, and Systems Engineering, specifically in designing system of systems.

5.3 Future Work

The future work section details scopes of effort that would provide benefit to the research in this dissertation. Topics for future work include simulation, costing, additional parameters, additional supporting functions, additional metrics, additional constellations, integrating the functional architecture, and non-homogenous requirements.

5.3.1 Simulation

A simulation that can be useful in for this model would be to link the Cameo Systems Modeler™ model to Systems Tool Kit (STK) via ModelCenter. Since access to ModelCenter is not available for this dissertation, the simulation is described in theory. Using STK, values can be populated into the Cameo Systems Modeler™ model and the performance predicted over time. For instance, the communication and navigation satellites values can include coverage and SNR. The domain awareness satellites values can include coverage. These five values can be simulated over time (because the satellites are moving in orbit) which would give performance metrics of these functions. The metrics can also be tied to the requirements to ensure that the designed system meets requirements. Using this simulation, SysML model requirements can be automatically verified.

5.3.2 Cost Estimates

Some of the cost estimates for this dissertation were conducted using professional estimates from industry subject matter experts. For more accurate results, future work can include cost estimates from validated models. Specifically, the model for the integrated bus could be replaced with more accurate equations. Also, the component costs which are based on earth-orbiting satellites should be improved to include additional shielding.

5.3.3 Optimization Parameters

Future work can use different optimization parameters, resulting in different optimal architectures. For instance, the cost can be held constant at some reasonable number based on a program budget while the performance is optimized for all three supporting functions. Alternatively, the supporting functions can be weighted depending on stakeholder priorities. For instance, if a defense stakeholder wanted to prioritize domain awareness, then that function can be given a higher weight than communication or navigation for performance and cost.

5.3.4 Additional Supporting Functions

Eight total supporting functions were found in the background research of this dissertation, though the three critical functions were chosen for evaluation and optimization. Future work can include additional supporting functions with cost and performance parameters. Some of these functions can be integrated as well. For instance, the service and energy functions are highly coupled, resulting in integration opportunities.

5.3.5 Additional Metrics

For the performance evaluation of each constellation, only the coverage metric is evaluated. Additional metrics can provide further insight into the architecture's performance, especially if additional supporting functions are added. For instance, dilution of precision (DOP) is an important metric for the navigation function.

5.3.6 Additional Constellations

Six constellations are designed in this dissertation. There are many more constellations which exist in the cislunar trade space. Based on the research in this dissertation, it is suggested that future research should first look at more options for hybrid solutions of earth plus space.

5.3.7 Integrating Functional Architecture

This dissertation addresses a strategy for integrating different payloads onto a single bus, which is an integration of the physical layer of the architecture. Future research could address integrating functions at the functional/logical layer of the architecture. For instance, current strategies for space-based communication and navigation are integrating these functions together such that a single signal could provide both functions.

5.3.8 Non-homogenous Requirements

For this dissertation, a simplification is made to the requirements by assuming that all three primary missions have the same basic requirements. The requirements studied include the worst-case requirements such that the architecture provides the necessary functionality for all three missions. Future research could include developing an architecture that provides different requirements for different missions. As an example, a defense user may want an increased level of fidelity for domain awareness for a specific period. The architecture could be designed to provide the flexibility to meet these time- and quality-based requirements.

5.3.9 Future Work Conclusions

This dissertation provides a starting point for many avenues of additional research. The dissertation work can be replicated using 0 and then expanded upon. Suggested topics for future work include simulation, improved cost estimates, varied optimization parameters, additional supporting functions, additional metrics, additional constellations, integrating the functional architecture, and non-homogenous requirements.

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APPENDIX A. CISLUNAR ACTIVITIES ROADMAP

Organization	Program	Deployment Schedule	Orbital Location	Primary Mission	Sub-Missions	Functions	Sub-Functions
Lunar Exploration Analysis Group (LEAG)	Lunar Exploration Roadmap	unknown	multiple	science	science theme		
					feed forward theme		
					sustainability theme		
International Space Exploration Coordination Group (ISECG)	Global Exploration Roadmap	unknown	multiple	science	human exploration		
					human habitation		
						transportation	
National Aeronautics and Space Administration (NASA)	Gateway (Power and Propulsion Element, Habitation and Logistics Outpost, Deep Space Logistics)	2024	near-rectilinear halo orbit (NRHO)	science	human exploration		
						transportation	robotic staging point
							human staging point
						service	
	LunaNet	unknown	lunar orbit			navigation	
						communication	
	SLS	unknown	translunar			transportation	
	Orion	2024	translunar			transportation	human transportation
	Artemis Base Camp	unknown	lunar surface	science	human exploration		
	Commercial Lunar Payload Services	2024	lunar orbit lunar surface	commerce			
						transportation	lunar landers
	Human Landing Services	2021 (preliminary design review)	unknown	commerce			
						transportation	human transportation
	Exploration Ground Systems	unknown	terrestrial			transportation	launch

	Deep Space Network	2024	terrestrial			communication	
	Volatiles Investigating Polar Exploration Rover	2023	lunar surface	science	soil samples		
	Lunar Ground Stations	unknown	lunar surface			control	tt&c
	Exploration Extravehicular Activity System	unknown	unknown			communication	
						transportation	Human Transportation
	Lunar Terrain Vehicle	2024	lunar surface			transportation	Surface Transportation
	Habitable Mobility Platform	unknown	lunar surface			transportation	Surface Transportation
						communication	
						shelter	
	Foundation Surface Habitat	unknown	lunar surface	science	human habitation		
						communication	
						shelter	
	Lunar/Mars Surface Power	unknown	lunar surface			energy	nuclear fission power
							ISRU
	Lunar Surface Innovation Initiative	unknown	lunar surface			energy	ISRU
	Lunar GNSS Receiver Experiment (LuGRE)	2023	lunar surface			navigation	
	Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE)	2022	near-rectilinear halo orbit (NRHO)			navigation	
European Space Agency (ESA)	Moon Village	unknown	unknown	science	human exploration		
				commerce	tourism		
	Moonlight Initiative	late 2020's	unknown			navigation	
						communication	

	European Large Logistic Lander	late 2020's	unknown			transportation	uncrewed / supply
	Lunar pathfinder spacecraft	2022	unknown			communication	relay
Luxembourg Space Agency	Space Resources Advisory	unknown	n/a	commerce	policy		
United Launch Alliance (ULA)	Cislunar-1000	unknown	translunar	commerce			
						transportation	
Spudis Lunar Resources	Develop Cislunar Space Next	unknown	unknown	science			
						transportation	
Orbital ATK / Northrup Grumman	On-Orbit Servicing	2020	GEO			service	
AFRL	Cislunar Highway Patrol System (CHPS)	unknown	unknown			space domain awareness	
	Autonomous Depot Operations in XGEO (ADOX)	unknown	unknown			service	assembly & manufacturing
						energy	refueling

APPENDIX B. ADDITIONAL MODEL DIAGRAMS

The ACT is a key tool in the behavioral perspective. The ACT in **Error! Reference source not found.** shows a mission thread of a science mission with activities linked to appropriate blocks and actors.

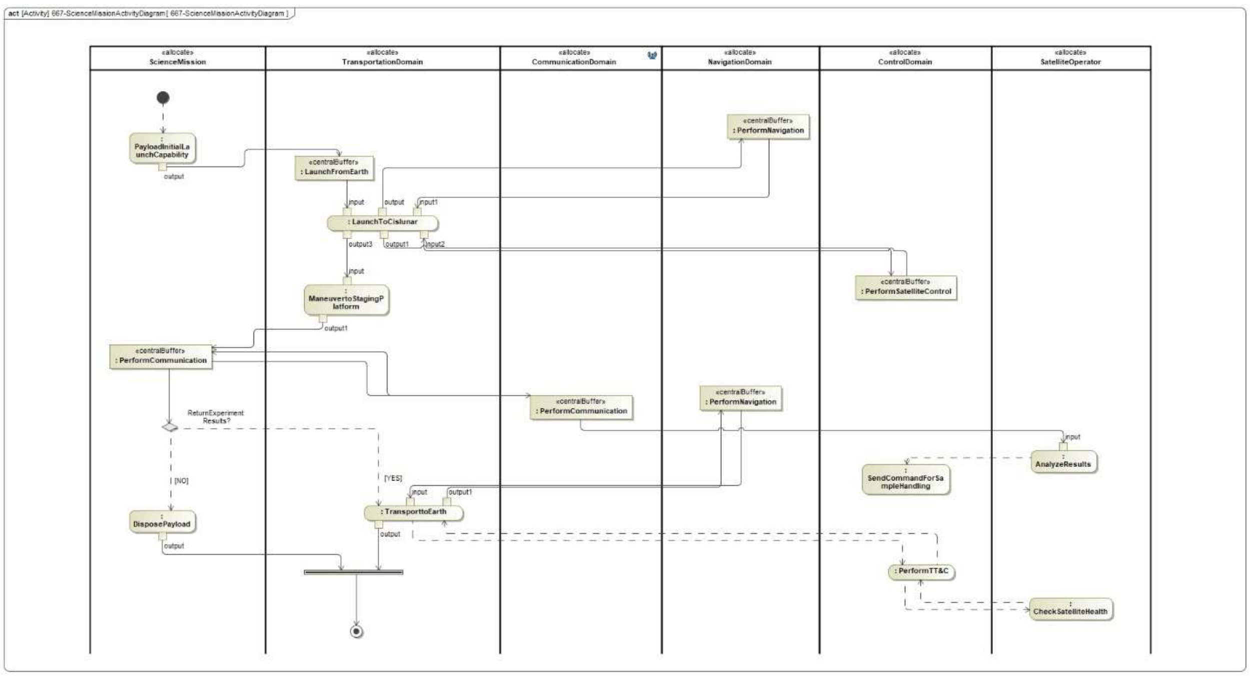

Figure 43 Activity Diagram

The primary data entities discovered in requirements analysis include:

- Control Data
  - TelemetryTracking&Control
    - Telemetry
    - Tracking
    - Commands
  - FaultDetectionRecovery

        ▪ Anomaly Resolution

    o Payload Data

    o Navigation Data

        ▪ Navigation Message

For the data perspective, the CDM is defined with foundation data classes shown in Fig. 3. Since all data flows through the control system, TelemetryTrackingControl, FaultDetectionRecovery, PayloadData, and NavigationData are generalizations of ControlData. Note that data blocks are stereotyped as <<InfoElement>> and therefore <<abstract>>.

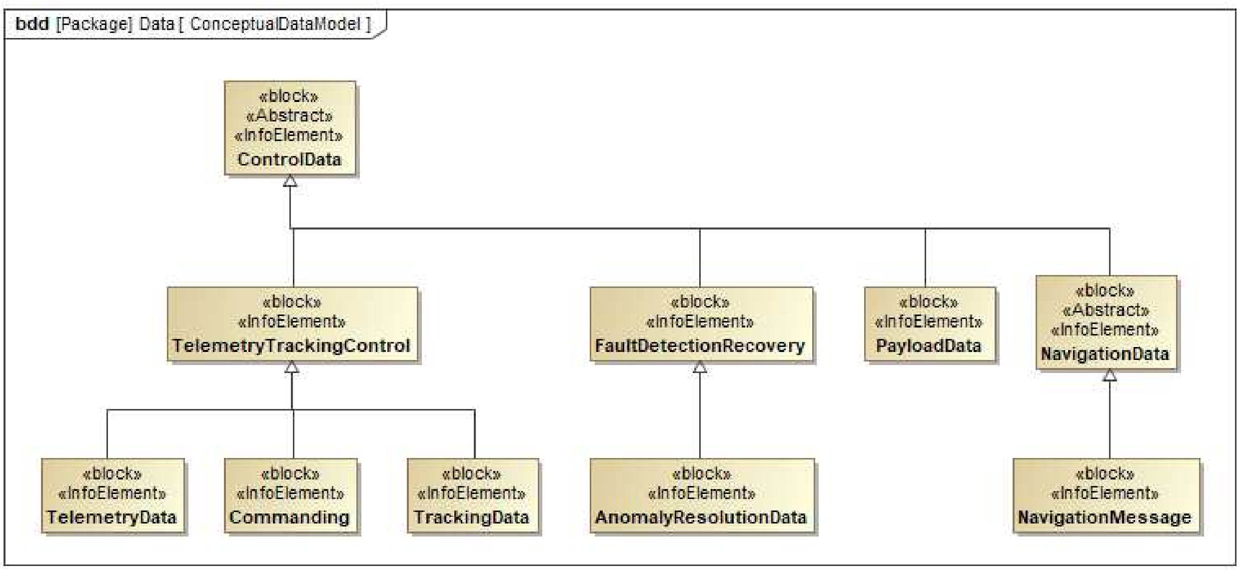

Figure 44 Conceptual Data Model

Table 39 shows a mapping of system services down to blocks. Communication, navigation, and transportation services are included as these are the most likely domains to be able to implement a service-oriented architecture (SOA).

Table 39 Service to Blocks Mapping

System Service	Use Cases	Domains	Domain Services	Blocks

CommunicationService	PerformCommunication	CommunicationDomain	OpenCommService	L1CommSat
	TT&C		SecureCommService	GroundAntenna
	UseSecureComm		TT&Cservice	
NavigationService	PerformNavigation	NavigationDomain	OpenNavService	GPSConstellation
			SecureNavService	NavSatL2
				NavSatL4
				NavSatL5
TransportationService	PerformScience	TransportationDomain	LaunchfromEarth	Launch Vehicle
	PerformCommerce		ManeuverToCislunar	
	PerformDefense		ManeuverToEarth	

The first diagram of the LV behavioral perspective is the STM. This diagram models stateful behavior, specifically for the communications domain shown in Figure 45.

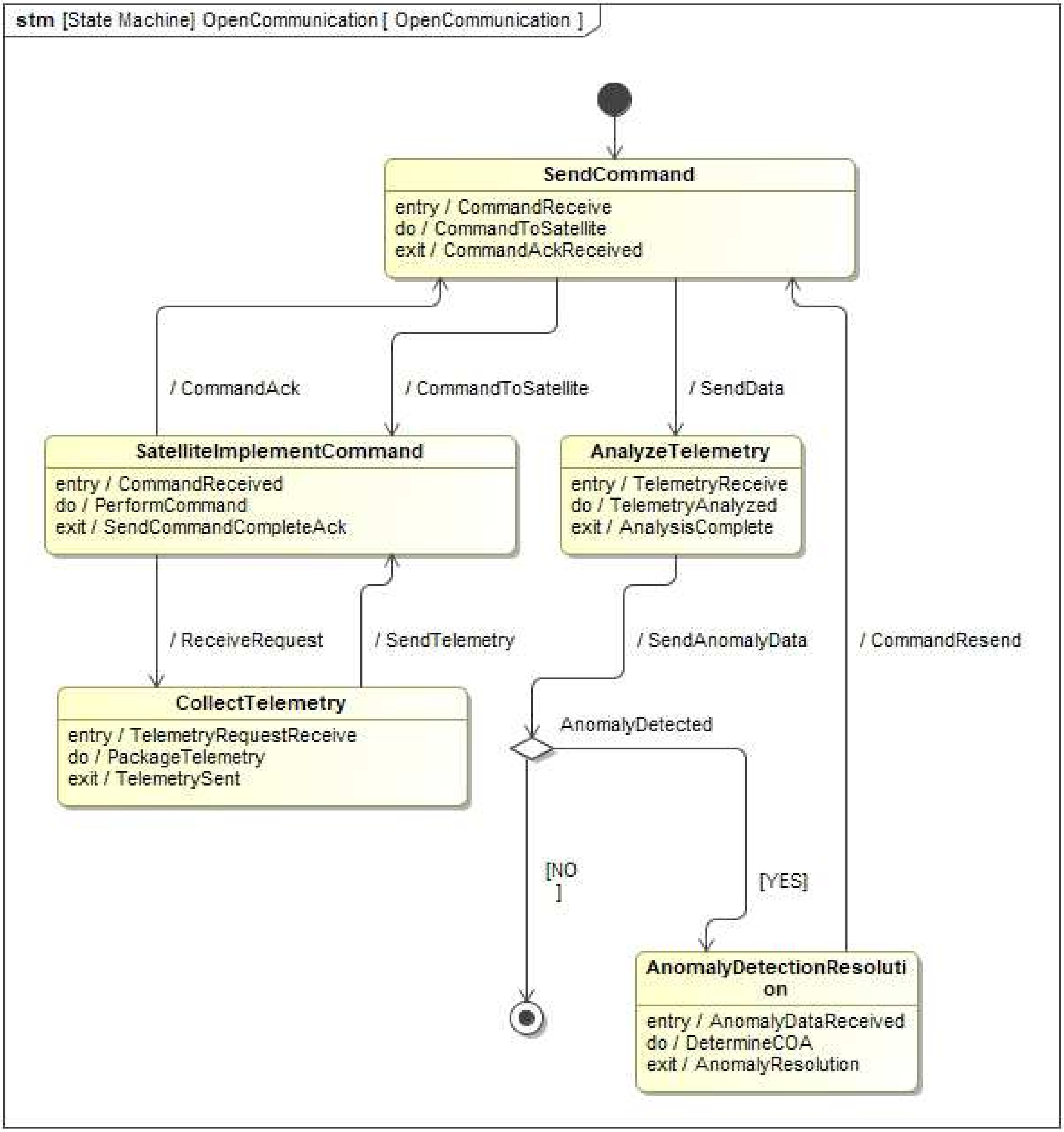

Figure 45 State Machine Diagram

The LV behavioral perspective includes a SD with timing analysis. Included in this paper is an SD of the AnomalyResolution thread. Lifelines are assigned to the operator and each data source: commands, telemetry, anomalies. Additionally, timing analysis is shown with {min…

max} values for each interaction. The sequence diagram for AnomolyResolution is shown in Figure 46.

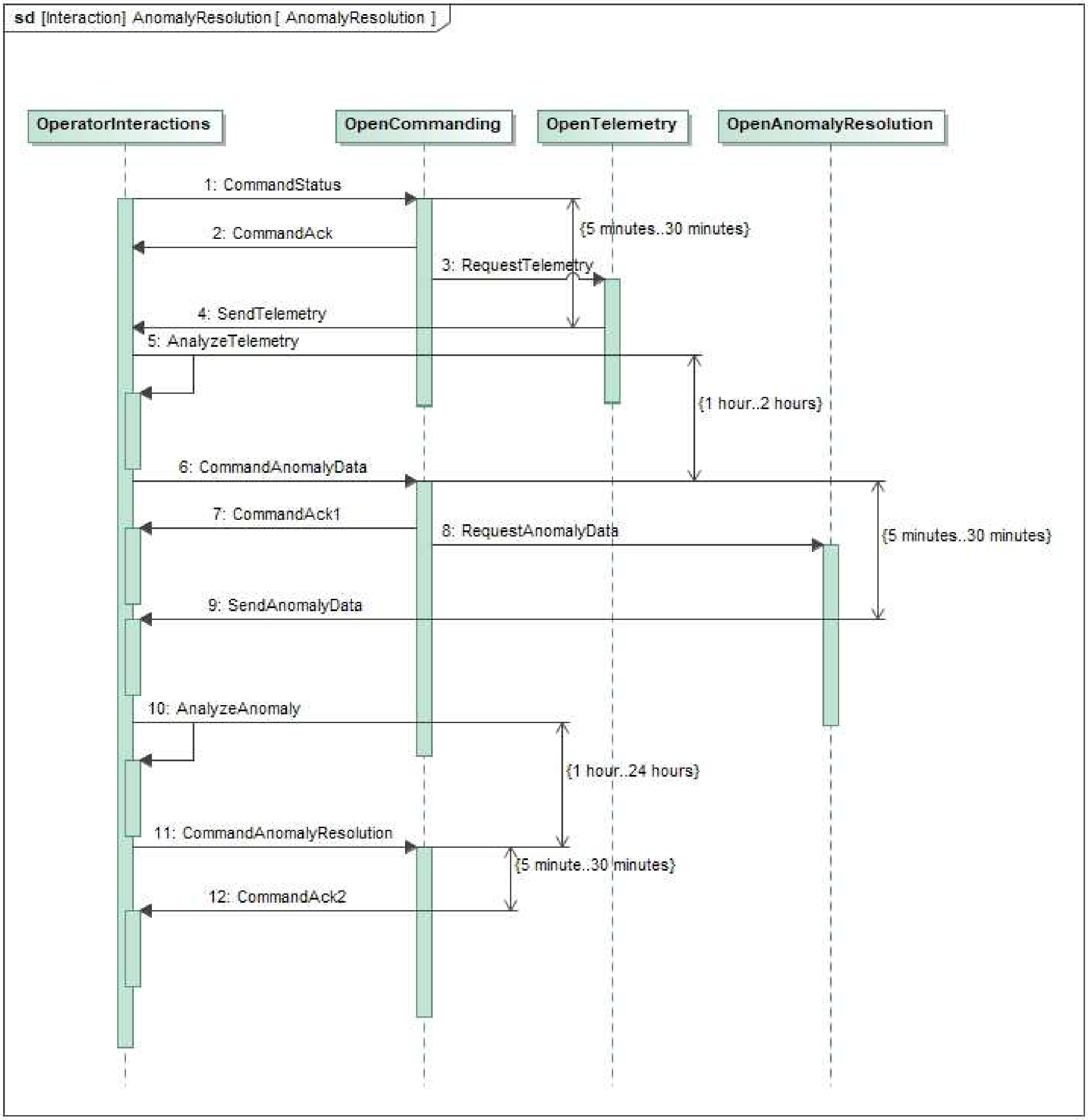

Figure 46 Sequence Diagram

In the data perspective, the CDM is decomposed to include data values and operations to build-out the Logical Data Model (LDM). Figure 47 shows the associations of communication data into control data and navigation data. Additionally, detailed data values and operations are defined for each data point. Data is expected in each domain of the cislunar system, thought the diagrams focus on communications, control, and navigation data.

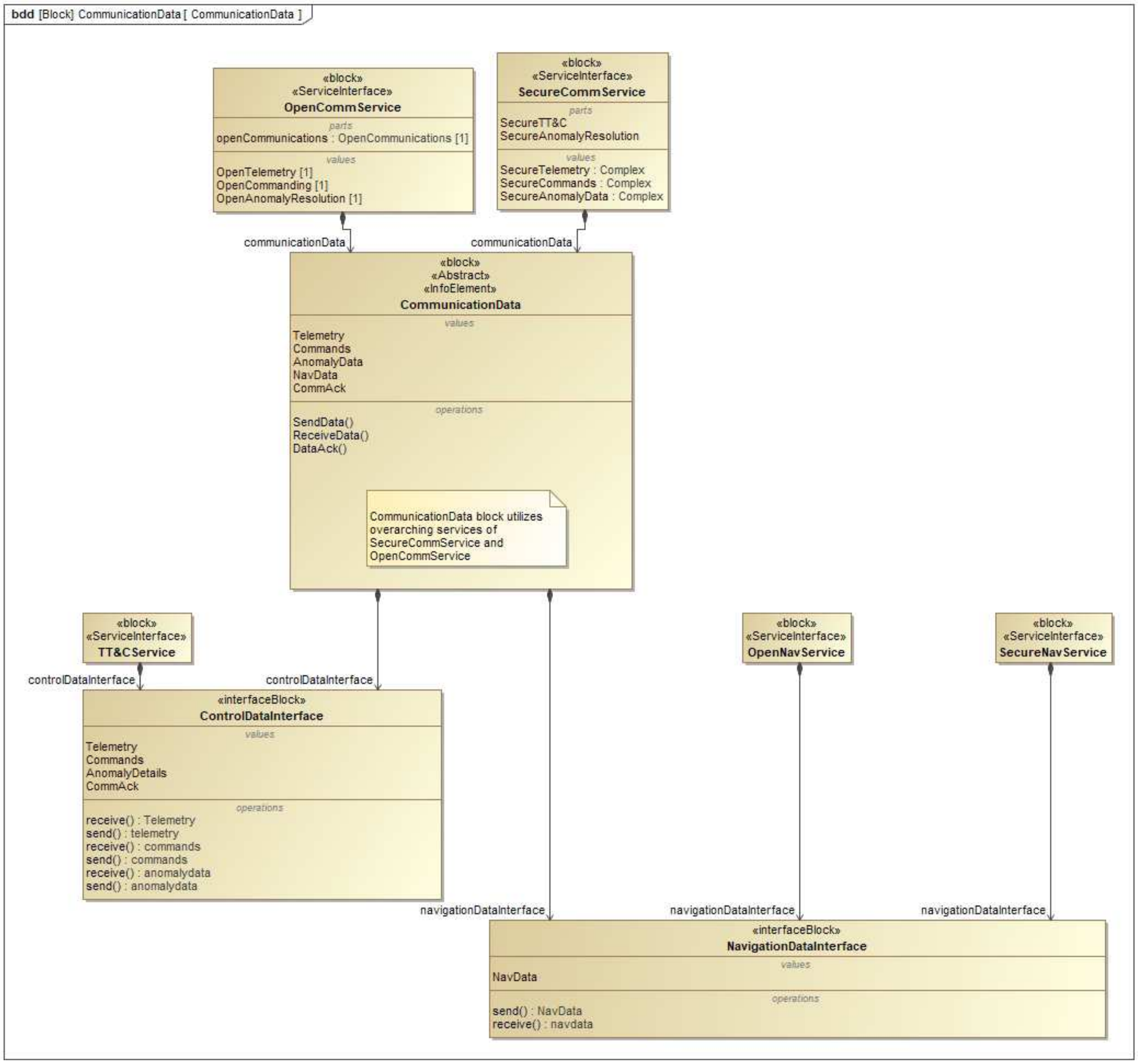

Figure 47 Communication Data LDM

In Figure 48, the control data is further defined by its components: Telemetry, Tracking, and Control (TT&C) and Fault Detection, Isolation, and Recovery (FDIR). Values and operations are defined for each block in the control data diagram.

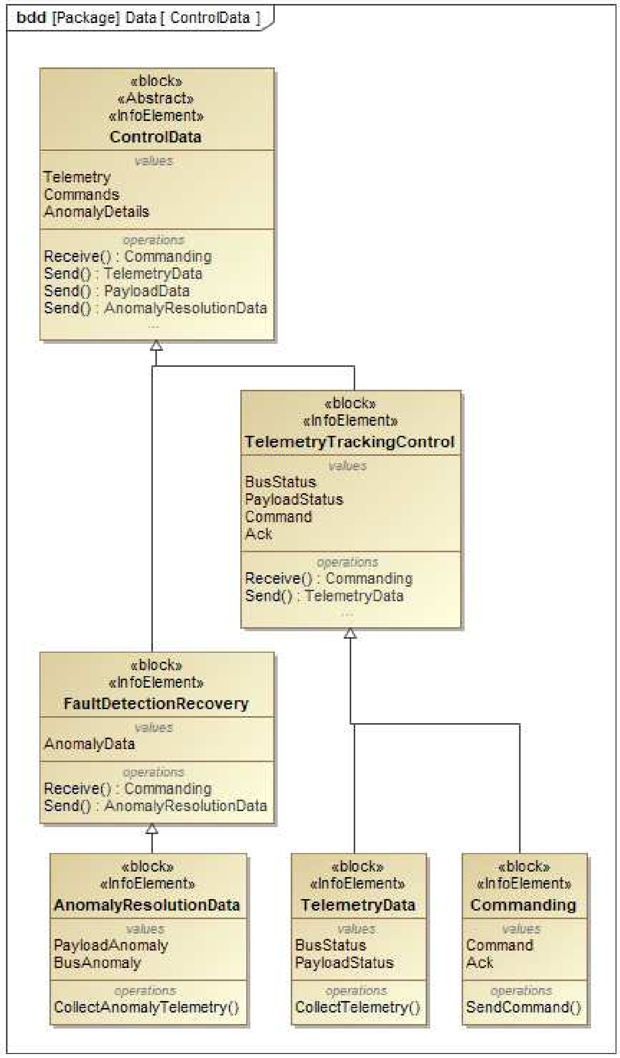

Figure 48 Control Data LDM

Figure 49 further decomposes the navigation data into the sub-block of the navigation message with appropriate values and operations.

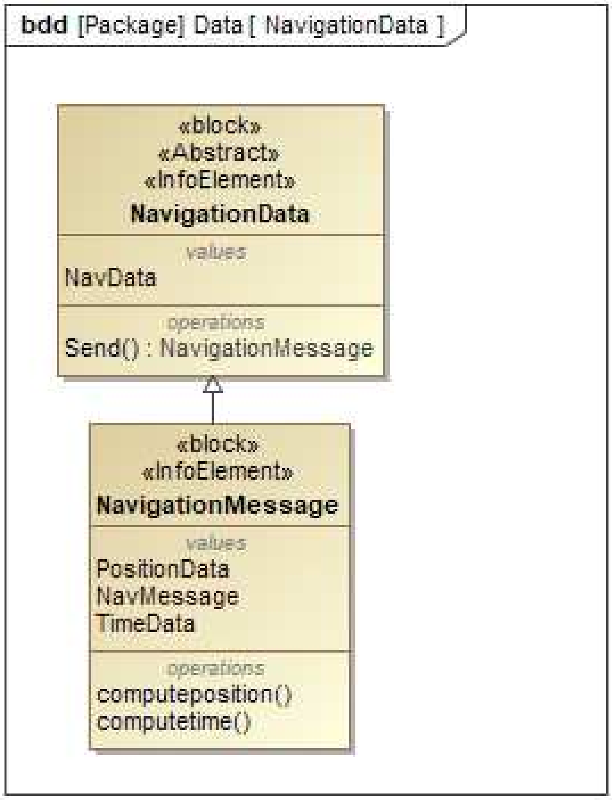

Figure 49 Navigation Data LDM

In the LV, the service taxonomy is further decomposed from the system service to the level of parameters. This mapping is detailed in Table 40 for the communication service.

Table 40 Service to Operations Mapping

System Service	Use Cases	Domains	Domain Services	Blocks	Parameters
Communication Service	PerformCommunication	Communication Domain	OpenCommService	L1 CommSat	TT&Cdata AnomalyData MissionData
	TT&C		SecureCommService	GroundAntenna	TT&Cdata AnomalyData MissionData
	UseSecureComm		TT&Cservice		
Navigation Service	PerformNavigation	Navigation Domain	OpenNavService	GPSConstellation	PositionData NavMessage TimeData

				NavSatL2	PositionData NavMessage TimeData TT&C
			SecureNavService	NavSatL4	PositionData NavMessage TimeData TT&C
				NavSatL5	PositionData NavMessage TimeData TT&C
Transportation Service	PerformScience	Transportation Domain	LaunchfromEarth	Launch Vehicle	FuelRequired FuelAvailable LaunchWindow ManeuverWindow
	PerformCommerce		ManeuverToCislunar		
	PerformDefense		ManeuverToEarth		

A layered architecture concept is used to model SOA. **Error! Reference source not found.** shows the overarching services and their flows in a layered SOA. **Error! Reference source not found.** shows the interfaces within the Control Service.

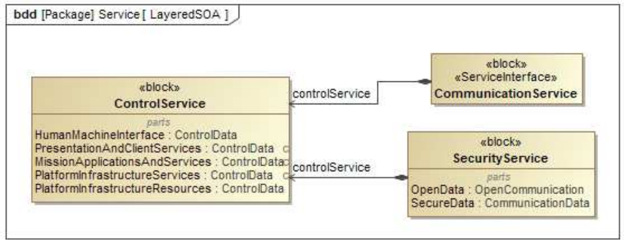

Figure 50 Layered SOA BDD

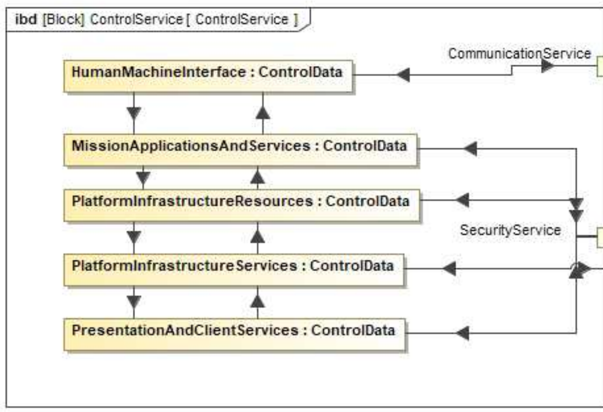

Figure 51 Layered SOA IBD

Error! Reference source not found. shows three equations within the communications domain. The first equation calculates the link delay based on the range of the satellite. The second equation calculates the mass based on the number of satellites and size of the satellite bus. The final equation uses a cost model to calculate the cost based on the mass. These parameters are used to assess system performance and costs used in optimization and evaluation.

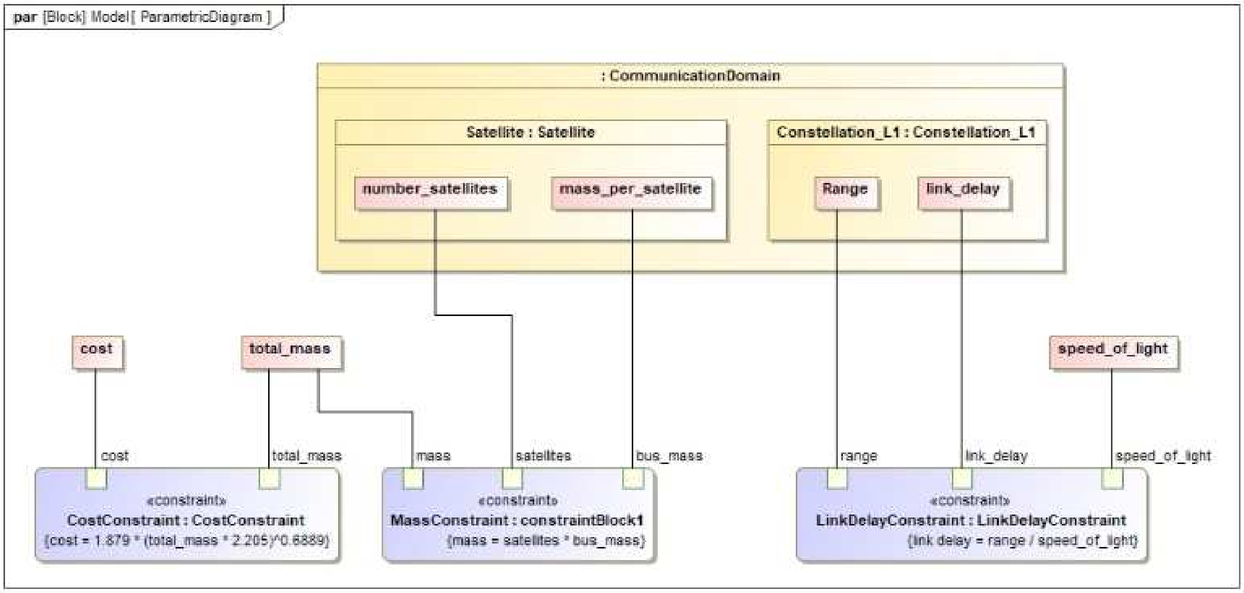

Figure 52 Parametric Diagram

Error! Reference source not found. shows an implementation of a local area network (LAN) and a wide area network (WAN) set-up for the cislunar control system. The internal network, LAN, connects the space operator with the internal server and communications antenna. The communications antenna uses an RF signal to get data to/from the space-based objects. The LAN is connected to an external network via WAN. Data transferred via WAN includes other satellite ephemerides, contact schedules, and other mission-specific data that should be shared among different missions.

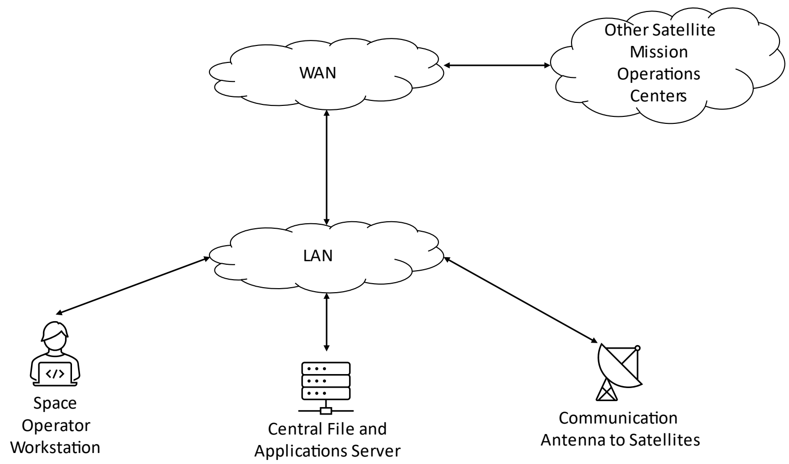

Figure 53 Networking Diagram

Error! Reference source not found. shows the network methodology implemented as an IBD within the Control Domain.

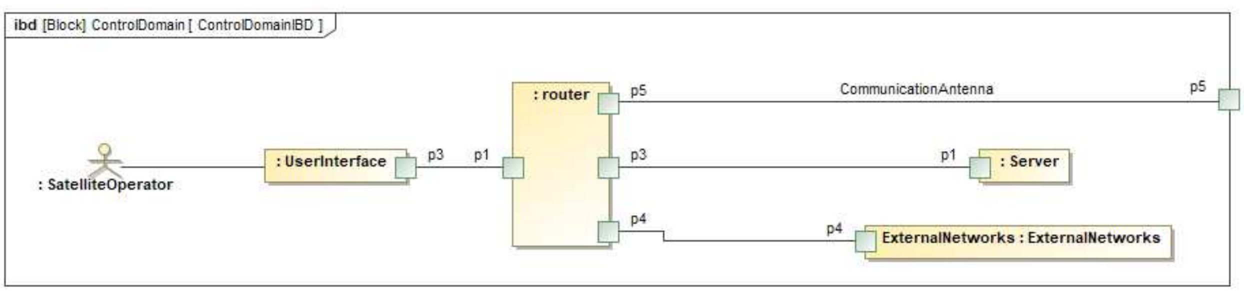

Figure 54 Control Domain IBD

The following table compares the networking approaches to primary SysML modeling diagrams. The linear bus approach is chosen for the cislunar system to maximize compatibility with legacy space systems.

Network Approach	Activity	Sequence	State Machine Diagram
Linear Bus	Diagram documents linear flows and actions, easy to implement linear bus architecture.	Diagram can show User interactions and timing, easy to implement linear bus	Diagram can describe the state changes in a linear bus architecture. State machines better used for more complex behaviors.

Ring	Activity diagram better shows linear flows of actions but can only show one thread of the ring implementation.	Sequence diagram better shows linear interactions but can show one thread of the ring implementation.	State machine diagram is an excellent way to show the cyclic behavior of the ring architecture.
Star/Tree	Activity diagram shows the linear flows and actions with loops to document the to/from nature of the hub.	Sequence diagram can show the linear interactions and timing with loops to document the to/from nature of the hub.	State machine diagram can accurately document the state transitions between the systems and hubs of the star/tree.
Star-of-Stars	Activity diagram can document an example thread but may not accurately depict all possible flows due to non-linear structure of star-of-stars architecture.	Activity diagram can document an example thread but may not accurately depict all possible interactions due to non-linear structure of star-of-stars architecture.	State machine diagram is best diagram to implement this nonlinear, complex architecture.

The assets in the cislunar system which require cyber protection are within the control domain. This is where the user interface (UI) and all data flows reside. Vulnerabilities include physical attack, insider threat, and malware.

Security controls that could mitigate the primary vulnerabilities include access control, personnel training, and firewalls.

During system development and procurement, cybersecurity must be considered, especially the following steps:

- Information Protection Needs (Include Abuse Cases in Software (SW) Requirements/Use Cases)
- Security Requirements Analysis (include security risk analysis in requirements, architecture, and design)
- Embed Security Architecture Elements (include security functions and features in the design)
- Embed Security Functions/Features (include testable security functions and features in requirements)

- SW Development Security Testing (include vulnerability detection in design and code reviews; include risk-based security vulnerability testing and scanning during development and in system test)
- SW Security Test (perform penetration testing during system test and operations)
- Deployment (implement software on secure, hardened servers with no access by programmers to the production environment; retest regularly for security and patch any vulnerabilities discovered or reported)

The control domain contains the boundary security features, modeled in an IBD in **Error! Reference source not found.**.

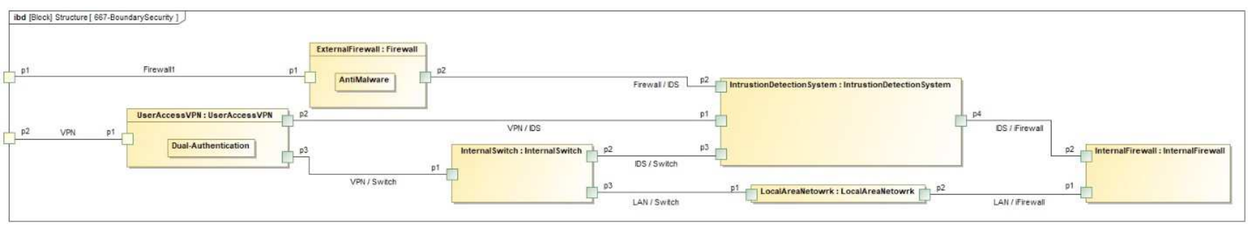

Figure 55 Boundary Security IBD

Two-factor user authentication is also implemented in the control domain for additional cybersecurity. This is a behavioral feature and modeled in a SD in **Error! Reference source not found.**.

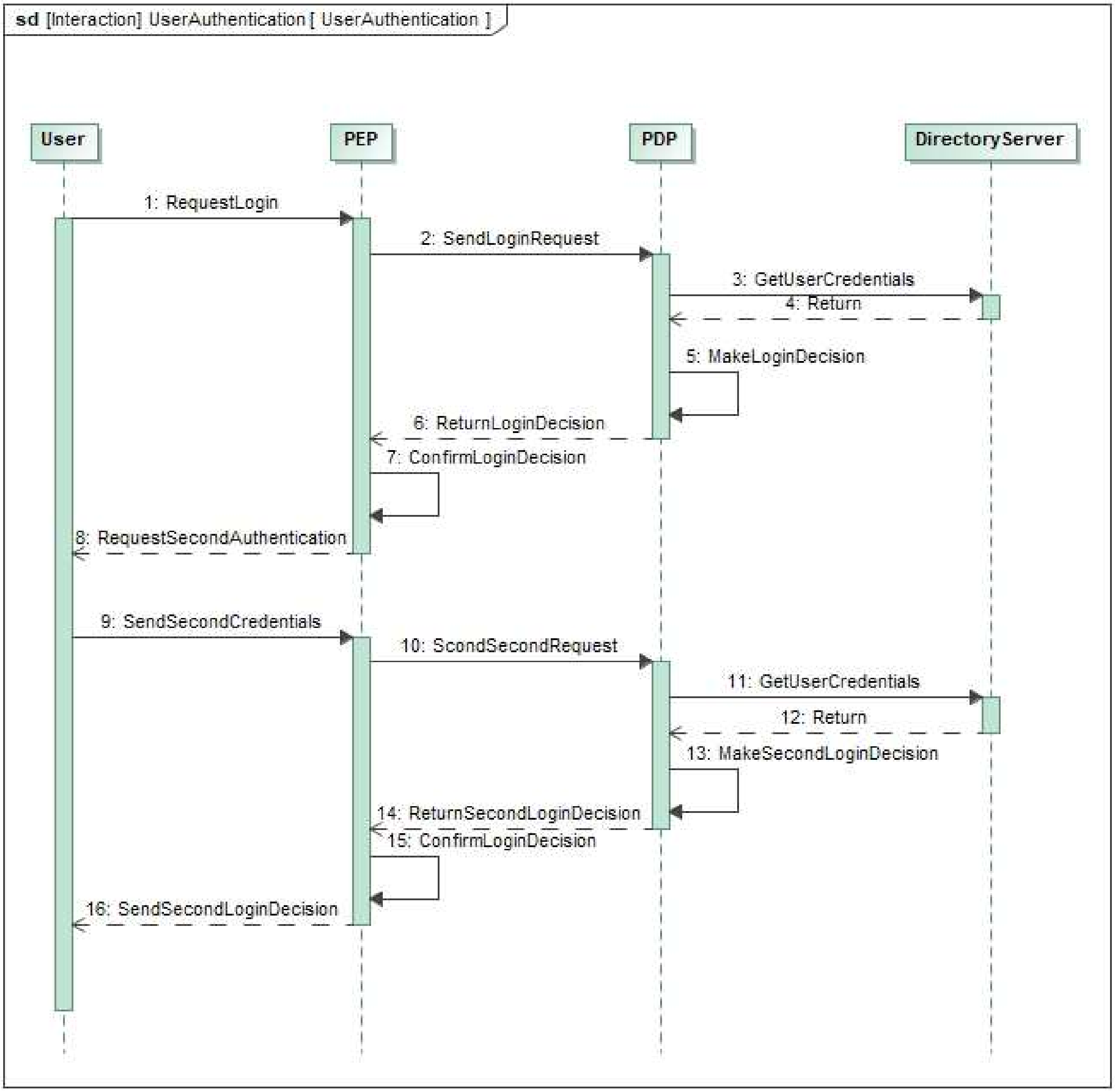

Figure 56 Two-Factor Authentication SD

APPENDIX C. A PROCESS FOR EVALUATING AND OPTIMIZING A SYSTEM OF SYSTEMS APPLIED TO CISLUNAR SPACE

The following paper was submitted to the Open Journal of Systems Engineering on January 20, 2023. The paper is pending feedback.

A Process for Evaluating and Optimizing a System of Systems Applied to Cislunar Space

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Abstract – This paper offers a systematic method for evaluating and optimizing a system of systems. This method is applied to a cislunar system of systems. A needs analysis is performed, identifying the key functions of the system of systems. The Model-Based System Architecture Process is applied for preliminary design of the system of systems. The problem is scoped using down-selection and developing a set of architecture alternatives. Evaluation parameters are chosen and used to evaluate the set of architectures. The resulting architectures are optimized using Multi-Objective Optimization, resulting in a Pareto Front. The few architectures of the Pareto Front are evaluated using Multi-Criteria Decision Making with Evidential Reasoning, which incorporates uncertainty. This method results in an ideal architecture, or a set of ideal architectures, which can be presented to the system of systems stakeholders.

Keywords - system of systems, system architecture, cislunar

I. PROBLEM STATEMENT

The process presented in this paper provides a systematic method for evaluating a large, complex System of Systems (SoS). The method is applied to a cislunar SoS, which includes the communication, navigation, and domain awareness functions necessary for operations beyond Earth to the Moon. A well-defined process becomes most important when large costs are needed to deploy the SoS. For the cislunar SoS, the architecture costs range from $500M to $1.5B, justifying the need for an objective evaluation method.

This paper provides a process for the design, evaluation, and optimization of a SoS with an example application. The processes are applied to a cislunar SoS to provide an example for each methodology. The complexity of a SoS requires Model-Based Systems Engineering (MBSE), rather than document-based systems engineering, during the system design phase [1]. The Model-Based Systems Architecture Process (MBSAP) is applied for this purpose [2]. In scoping the SoS, a process for determining a set of alternatives is given. Next, appropriate enterprise-level evaluation parameters are chosen and used to evaluate the hundreds of architecture options. An optimization algorithm is presented which can handle multiple parameters in a non-differentiable environment; this is the multi-objective optimization with integer linear program. The results of the optimization algorithm are then evaluated using multiple techniques. Multi-Criteria Decision Making (MCDM) with Evidential Reasoning (ER) is found to be the most appropriate for SoS as it accounts for the uncertainty [3]. This process can be applied to a variety of SoS evaluation and optimization problems. Fig. 1 shows an activity diagram modeling the architecture evaluation and optimization process documented in this paper.

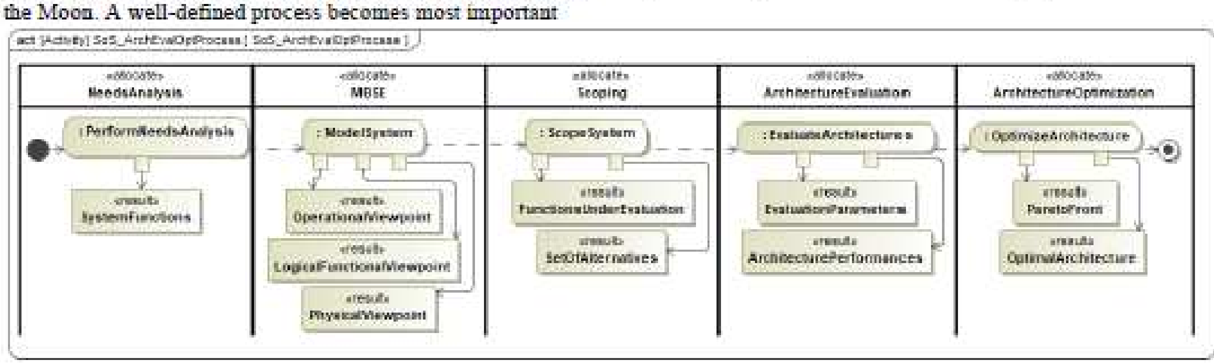

Fig. 1 SoS Architecture Evaluation and Optimization Process

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In the remainder of the paper, Section II provides a summary of relevant work completed in the field of SoS evaluation. Section III defines the cislunar application and provides the results of a needs analysis for cislunar operations. Section IV summarizes the method for modeling a SoS including an application of MBSAP. Section V provides the process for scoping the problem, including down-selecting and developing the set of alternatives. Section VI describes the process of architecture evaluation using MCDM with ER. Section VII defines the method for optimizing the architecture. Finally, Section VIII summarizes the conclusions of the paper, including recommendations for additional research.

II. RELEVANT WORK

Research suggests that uncertainty is an important criterion to consider during architecture evaluation [4]. Stakeholder ambiguity is a common issue during system design. Research suggests that this ambiguity can be designed for. The sources of ambiguity can be characterized and modeled to make assessments to the architecture trade space [5].

The Architecture Tradeoff Analysis Method (ATAM) is a linear method of assessing architectures. It was designed for software systems, but the concepts can apply to non-software systems [6]. The main disadvantage of ATAM is the lack of feedback opportunities. For instance, if new information is found during investigation or testing, there is no opportunity to improve the architecture.

The Quality Attribute Workshop (QAW) is a system architecture evaluation method which analyzes the model against critical attributes. The attributes are assessed subjectively by analyzing behavior of the model in certain scenarios [7]. This method is highly dependent upon the architect's interpretation of the analyzed behavior.

A Kiviat chart, also known as a spider chart, is a way to graphically display data with multiple variables to assess performance and weaknesses. Using Kiviat charts, the architect can visually assess if an architecture possesses the needed qualities. A quantitative assessment can also be obtained by calculating the area of each polygon [8]. This method is vulnerable to the selection of appropriate key performance attributes. The Kiviat visualization also lacks the ability to show priority or weights to the key performance attributes.

MCDM is a powerful architecture assessment method because it can be applied to a SoS. The first step in MCDM is to define the quality attributes (high level characteristics), sub-attributes (mid-level characteristics), and measures (low-level characteristics). ER can be applied with MCDM to handle quantitative and qualitative attributes. ER assesses each attribute using measurable grades, a belief structure, and fuzzy linguistic variables. An extended decision matrix is utilized which assigns a grade to each attribute and then the degree of certainty that the grade can be applied [3] [9]. This method was researched to be useful in SoS evaluation and is used in this paper during the evaluation of the Pareto optimal architectures [3].

III. DEFINING CISLUNAR

In this paper, cislunar space is defined as the volume of space beyond Geosynchronous orbit (GEO) to the Moon's orbit, including the five Earth-Moon Lagrange points. Lagrange points are points of gravitational equilibrium which can be used for orbits with long dwell times relative to the Moon's orbit [10]. Fig. 2 shows the defined volume space with Earth and Moon pictured as references.

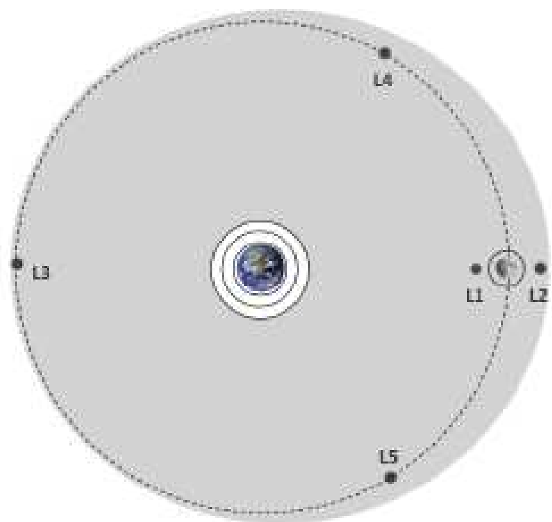

Fig. 2 Cislunar Space

A needs analysis of cislunar space identifies 3 primary missions and 8 supporting functions necessary for cislunar operations [11]. The primary missions are the planned users of cislunar space. The primary missions are Science, Commerce, and Defense. The supporting functions provide the necessary infrastructure for cislunar operations. The functions include Transportation, Communication, Navigation, Domain Awareness, Service, Energy, Shelter, and Control [11]. The architectures in this paper focus on providing the necessary supporting functions for initial operations in cislunar space. A mapping of service to functions with the critical functions highlighted is shown in Fig. 3.

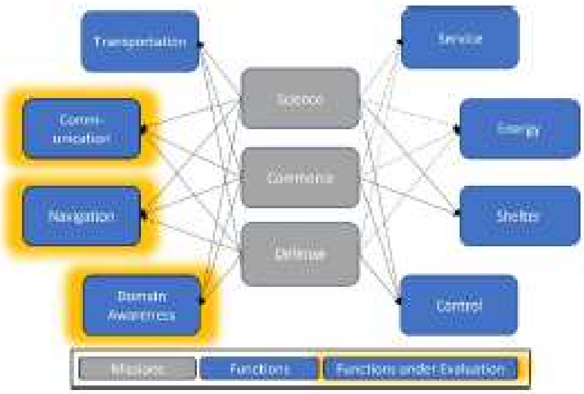

Fig. 3 Mapping Missions to Functions

IV. MODELING THE SYSTEM OF SYSTEMS

A. METHOD

MBSE is a tool which allows systems engineering to manage complex systems. MBSE allows the systems engineer to build an integrated digital model of the system, rather than following traditional document-based systems engineering. The model can be easily updated throughout the lifecycle of the system. The updates are automatically propagated throughout the model and checked for validity. With large, complex systems with numerous components and interfaces, MBSE is needed to ensure design changes are compatible across the system [2].

One method for implementing MBSE is the MBSAP. MBSAP is chosen because it offers a framework and methodology for systematic application of MBSE to a wide range of systems during and beyond system design [12]. MBSAP prescribes a method for developing architectures using Systems Modeling Language (SysML). MBSAP utilizes three viewpoints to design and decompose the architecture to the necessary level of detail. The viewpoints include Operational Viewpoint (OV), Logical/Functional Viewpoint (LV), and Physical Viewpoint (PV) [2]. In the OV, the system boundary, context, domains, primary behaviors, and primary data content are modeled. In the LV, the domain decomposition, behavioral decomposition, and logical data model are modeled. In the PV, the physical components, standards profile, and physical data model are modeled [2].

For each viewpoint, several perspectives can be included for that phase of design. TABLE I outlines each viewpoint with corresponding perspectives and example diagrams [2].

TABLE I MBSAP MAPPING [2]

Viewpoint	Perspectives	Example SysML Diagrams
OV	Structural	Block Definition
	Behavioral	Use Case
	Data	Block Definition
	Services	Table
	Contextual	Use Case
LV	Structural	Internal Block
	Behavioral	Activity
	Data	Block Definition
	Services	Table
	Contextual	Use Case
PV	Design	Block Specifications
	Standards	Table
	Data	Internal Block
	Services	Interface Block Specifications
	Contextual	Use Case

The System Architect must use best judgement and knowledge of the system requirements to determine which diagrams aid in the design of a specific system. The SysML model is a powerful tool throughout the lifecycle of the system, including design, development, operations, and disposal. This paper focuses on modeling for the purpose of designing architectures for evaluation.

B. APPLICATION

For the Cislunar SoS, MBSAP is applied to design the architecture which drives the evaluation and optimization of the SoS. Diagrams for each viewpoint are developed specifically for the needs of architecture evaluation and optimization. Example diagrams are shown in this paper[1].

1) CISLUNAR OPERATIONAL VIEWPOINT

In the OV, the structural perspective is designed with a domain decomposition diagram, the behavioral perspective is designed with a use case diagram, and the contextual perspective is designed with a use case diagram.

The domain diagram uses a block definition diagram (BDD) to specify the key relationships between block and users, shown in Fig. 4. The primary missions are modeled as actors, separate from the blocks which compose the cislunar SoS model. Blocks which are considered for evaluation are tagged with the “UnderEvaluation” stereotype and highlighted in blue.

The SoS-level use cases are specified in a Use Case Diagram (UC). The use cases document key behavioral relationships

[1] The full SysML model is available at https://github.com/lauraduffy-astro/cislunar

between actors and system use cases, shown in Fig. 5. The use cases are decomposed to a level such that necessary functions for primary missions are identified.

For the contextual perspective, a UC can be used to document contextual relationships within the SysML model. System context for the OV includes environment, users, external system capabilities, and legal constraints.

2) *CISLUNAR LOGICAL/FUNCTIONAL VIEWPOINT*

In the LV, the structural perspective is decomposed with internal block diagrams and the behavioral perspective is decomposed with timing analysis in a sequence diagram. While these diagrams do inform the more detailed design of the architecture, they do not drive the architecture evaluation or optimization in this paper.

3) *CISLUNAR PHYSICAL VIEWPOINT*

In the PV, the structural perspective is further decomposed with block specifications and the standards perspective is designed with a table. While these diagrams do inform the more detailed design of the architecture, they do not drive the architecture evaluation or optimization in this paper. The cislunar PV is presented in this paper after the evaluation and optimization process is applied.

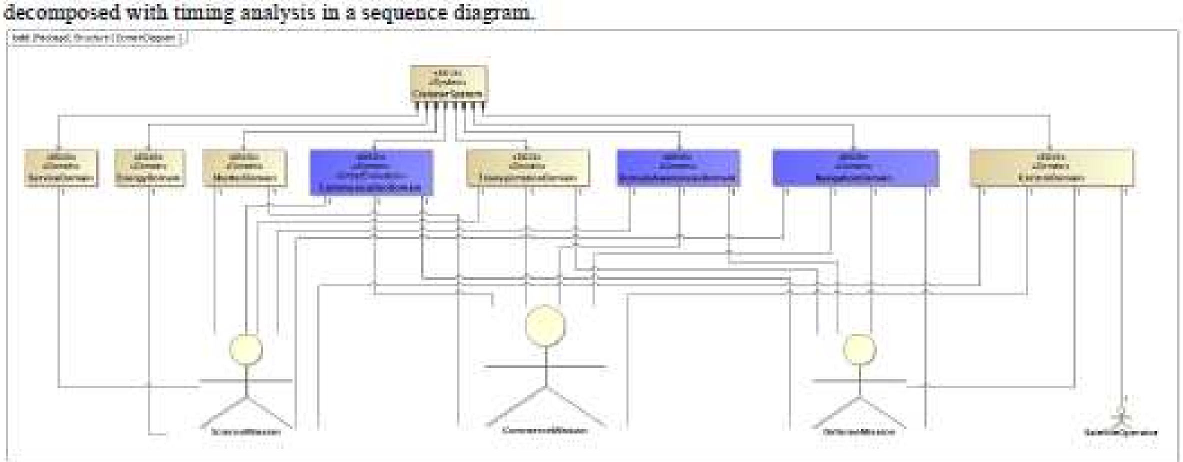

Fig. 4 Domain Diagram

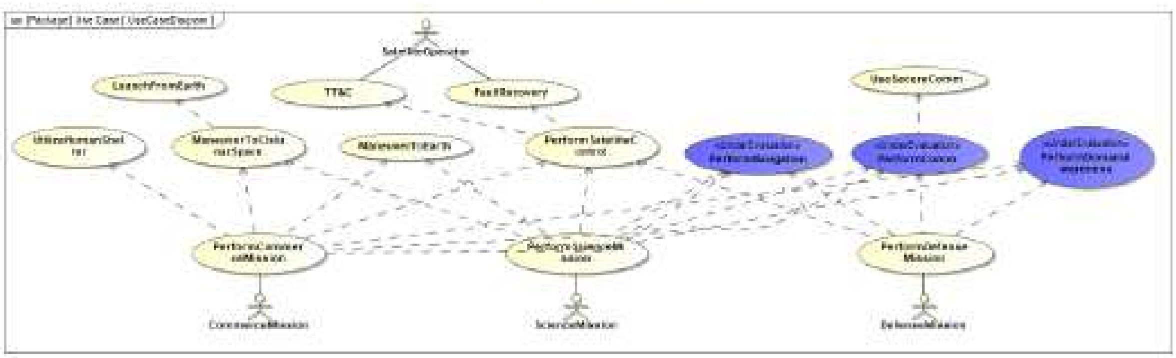

Fig. 5 Use Case Diagram

V. SCOPING THE PROBLEM

A. *DOWN-SELECTING*

1) *METHOD*

With a large SoS, scoping the problem in terms of the stakeholder concerns and enterprise level needs more efficiently identifies candidate architectures. Solving a SoS in its entirety requires vast resources due to high levels of uncertainty, complexity, and emergent behavior. For any SoS, the system architect must identify the key functions necessary for operating across the enterprise. Down-selecting specifically includes choosing a subset among a set of architecture possibilities [13].

As a preliminary down-selecting method, the SoS requirements can be used as constraints to eliminate architectures which do not meet requirements. For instance, the stakeholder may have a budget which constrains the set of possible architectures Additionally, down-selecting is applied when the scope of the study is applied. Finally, a physics model can be incorporated while down-selecting to further constrain the set of architecture alternatives.

2) *APPLICATION*

Starting with the 8 supporting functions, the cislunar system can be classified as a complex SoS. Initial architecture studies are scoped such that the focus is on the functions necessary for initial operations. The bare-minimum functions identified for initial cislunar operations include Communications, Navigation, and Domain Awareness [14]. These 3 functions in combination are still defined as a SoS, therefore special design processes must be used, including looking at enterprise-level objectives and accounting for uncertainty [3].

A physics model is applied during the down-selection of the cislunar architectures with the Navigation and Domain Awareness constellations. Due to the presence of navigation satellite systems, the cislunar Navigation system cannot transmit from Earth because this would cause interference with legacy navigation systems [15]. Additionally, space-based domain awareness transmitters are found to be insufficient to meet the requirements of cislunar space, so only terrestrial applications are assessed for domain awareness [14].

B. *SET OF ALTERNATIVES*

1) *METHOD*

For each function identified during down-selecting, an appropriate set of alternatives must be found. For this step in the process, it is important to incorporate stakeholder needs and engineering expertise to formulate useful and feasible options. The set of alternatives can be operational, logical/functional, or physical depending on the nature of the function. The set of alternatives must remain within the problem scope and constraints may need to be applied in this step of the process. Each additional architecture option for the functions causes exponential growth in the number of possible architectures [13]. TABLE II shows an example set of alternatives for generic functions. In this example, only 4 alternatives are chosen for the three functions, but this results in 4*4*4=64 possible architectures. 64 architectures are not easily processed manually and likely would need an evaluation and optimization method as presented in this paper.

TABLE II EXAMPLE SET OF ALTERNATIVES

Function	Set of Alternatives
Function A	{alternative_1, alternative_2, alternative_3, alternative_4}
Function B	{alternative_1, alternative_2, alternative_3, alternative_4}
Function C	{alternative_1, alternative_2, alternative_3, alternative_4}

A complete architecture resulting from this Set of Alternatives would have one alternative for each function. For example, Architecture A could have Function A as alternative_2, Function B as alternative_1, and Function C as alternative_2.

2) *APPLICATION*

For the cislunar system, a feasible set of alternatives is designed for each of the 3 supporting functions, as well as opportunities for integration. The alternatives presented are physical constellations of transmitters in space, on the Moon, on Earth, or a combination of those locations. The transmitter is a generic term in this paper that could refer to the communication radio-frequency (RF) transmitters, the navigation RF transmitters, or the domain awareness RADAR transmitters. The integration opportunities emerge when two functions are co-located – allowing for cost-savings on the infrastructure needed to support the transmitters. The payloads are designed such that multiple payloads can exist on a single commercial off-the-shelf (COTS) bus, reducing hardware costs. Note that if an architecture results in an integrated bus, these architectures must be assessed for feasibility. This integration opportunity may not be advantageous to the lifecycle considerations of the system. Integration may require additional engineering effort, adding cost and delaying the deployment of the system.

The Communication constellation has 6 alternatives, the Navigation constellation has 3 alternatives, the Domain Awareness constellation has 3 alternatives, and each integration opportunity presented 2 more alternatives. This leads to a total of 6*3*3*2*2*2 = 432 possible architecture combinations. The integrated architectures are constrained such that the transmitters must be co-located for the functions to be considered for integration. After these constraints are applied, 54 architectures remain for optimization and evaluation.

The constellations are represented be indexes 0 to 5 while the integration opportunities are represented by indexes 0 to 1.

TABLE III SET OF ARCHITECTURE ALTERNATIVES

Function (variable)	Set of Alternatives
Communication Constellation (x_1)	{lagrange_light, lagrange_medium, lagrange_heavy, earth_based, earth_plus_lunar, earth_plus_lagrange}
Navigation Constellation (x_2)	{lagrange_light, lagrange_medium, lagrange_heavy}
Domain Awareness Constellation (x_3)	{earth_based, earth_plus_lunar, earth_plus_lagrange}
Integrated Communication and Navigation (x_4)	{no, yes}
Integrated Communication and Domain Awareness (x_5)	{no, yes}
Integrated Navigation and Domain Awareness (x_6)	{no, yes}

Where: $0 \leq x_1 \leq 5; 0 \leq x_2 \leq 2; 3 \leq x_3 \leq 5;$

$0 \leq x_4, x_5, x_6 \leq 1;$ *and* $x_1, x_2, x_3, x_4, x_5, x_6$ *are integers*

VI. ARCHITECTURE EVALUATION

A. METHOD

Choosing appropriate evaluation parameters, and weightings, is the most critical step of architecture evaluation. A poor set of evaluation parameters can lead to a sub-optimal architecture that does not meet system needs [6]. The system architect must consider stakeholder concerns and enterprise-level needs when choosing evaluation parameters. First, the system architect should consider the prioritization of stakeholder needs when choosing the most important evaluation parameters. Next, relevancy should be considered. In traditional systems engineering, cost, performance, and schedule tend to be highly relevant evaluation parameters to begin any architecture study [16]. Finally, the parameters should limit the architecture results to fall within the original enterprise-level needs.

B. APPLICATION

For the cislunar SoS, the evaluation parameters chosen are cost and performance. Cost is important for any system that will be deployed because stakeholders have a budget. Government stakeholders typically must remain below some budget threshold, while commercial stakeholders generally prefer to minimize cost in general. The performance is an important measure of the system to ensure requirements are met. The cislunar SoS evaluation focuses on the physical deployments, and performance, of the transmitters. For performance, the coverage of the transmitters is used as the evaluation parameter as this can be equally compared for each function and is critical to stakeholder concerns.

1) CISLUNAR COST

For cost evaluation, each transmitter and transmitter location is evaluated. Cost models are used when available and subject matter expert (SME) estimates are used when cost models do not exist. For satellite-based transmitters, the Unmanned Space Vehicle Cost Model (USCM) can be used [17]. For Earth-based and Moon-based transmitters, SME estimates are required because cost models are not published. A summary of each transmitter and bus cost estimate is provided in TABLE IV. The cost metrics in TABLE IV are used in the architecture optimization.

TABLE IV COST SUMMARY [14] [15] [18]

Name	Cost ($M)
Communications Space Transmitter	$13.6
Communications Ground Transmitter	$1
Navigation Transmitter	$33
Domain Awareness Ground Transmitter	$10
Single Bus	$50
Integrated Double Bus	$75
Integrated Triple Bus	$112.5

2) CISLUNAR PERFORMANCE

For the cislunar performance, each function transmitter is designed using physics-based link budgets for each implementation. The Communications transmitter uses a Ka-band patch antenna. The Navigation transmitter uses an L-band patch antenna. The Domain Awareness transmitter uses a unique design of a phased arrays performing RADAR ranging on X-band to achieve the greatest range for a space-based transmitter [14]. The specifications for each payload design are defined in TABLE V.

TABLE V PAYLOAD TRANSMITTER PERFORMANCE [14] [15] [18]

Type	Range	Beamwidth
Communications Space-Based	450,000 km	± 36.0-degrees
Communications Earth- or Moon-Based	450,000 km	± 45.0-degrees
Navigation	384,000 km	± 32.5-degrees
Domain Awareness Moon-Based	112,000 km	± 50.0-degrees
Domain Awareness Earth-Based	271,000 km	± 50.0-degrees

Each function transmitter is evaluated for each constellation in terms of coverage. The architectures are modeled in a physics-based environment using Systems Toolkit (STK) [19]. The coverage is calculated as the surface area of spheres of coverage from Earth orbit to lunar orbit. Additional spheres of coverage are calculated from the Moon's surface to the altitude of the L1 and L2 Lagrange points. The results are scaled by 10^{11} to make the numbers more digestible.

The performance results of each payload/constellation combination are shown in TABLE VI. Note that only the space-based constellations are evaluated for the navigation function because an Earth-based constellation would interfere with the nominal Global Positioning System (GPS) signal [15]. Also, the space-based domain awareness constellations are not evaluated because space-based transmitters do not meet the performance requirements of cislunar space [14].

TABLE VI CONSTELLATION PERFORMANCE

	Constellation	**Performance ($km^2 * 10^{11}$)**
Communication	Lagrange Light	12.632
	Lagrange Medium	11.816
	Lagrange Heavy	18.224
	Earth-based	27.920
	Earth plus Moon	39.181
	Earth plus Lagrange	35.089
Nav-igation	Lagrange Light	6.405
	Lagrange Medium	6.593
	Lagrange Heavy	14.093
Domain Awareness	Earth-based	8.760
	Earth plus Moon	9.861
	Earth plus Lagrange	9.159

The results of the cost estimates in TABLE IV and the performance metrics in TABLE VI are used in the architecture optimization.

VII. ARCHITECTURE OPTIMIZATION

A. METHOD

1) OPTIMIZATION ALGORITHM

If more than one evaluation parameter, or stakeholder objective, is chosen, then multi-objective optimization (MOO) must be utilized [20]. With a relatively small amount of architecture options, a simple MOO algorithm can be used as outlined below.

1. Generate a matrix of all architecture combination metrics
2. Find the Pareto Front

Note that the Pareto Front finds the minimum of each value. To maximize the value of a parameter, the negative of that value must be used [21].

An example output of the above algorithm is shown in Fig. 6. A two-dimensional set of 25 random integers are populated and plotted. The Pareto Front algorithm then finds the non-dominated values of the set. This set forms the non-convex Pareto front, or true Pareto front [21].

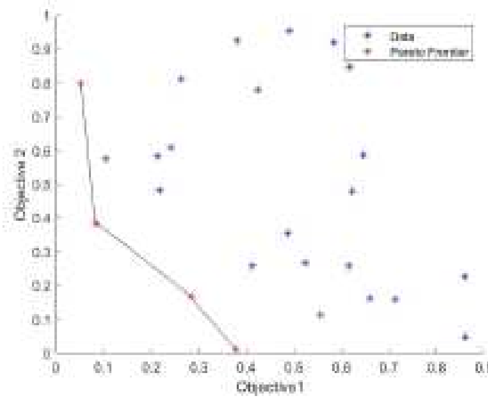

Fig. 6 Example Pareto Front

2) OPTIMIZATION EVALUATION

The Pareto front algorithm results in several optimal architectures, depending on the weights of each evaluation parameter. These optimal architectures can then be evaluated, allowing the system architect to find the ideal architecture. Prior to evaluating, the results of each parameter must be scaled such that the parameters have equal weighting. The fidelity of the scaling should be chosen such that each parameter result has a unique score. Then, the evaluation method can be applied. For a SoS, the ideal method of evaluation is MCDM with Evidential Reasoning (ER) [3]. MCDM evaluates architectures in terms of parameter weightings while ER incorporates uncertainty into the evaluation [9]. Uncertainty is an important consideration for a large, complex SoS with unknowns. To evaluated with MCDM, the following equation is used:

$$architecture\ score =$$

$$(\alpha_1 * parameter_1 + \cdots + \alpha_n * parameter_n) * certainty$$

Where: $\alpha_1 + \cdots + \alpha_n = 1$ [3]

The weightings, α, should be chosen with stakeholder concerns in mind.

B. APPLICATION

1) CISLUNAR OPTIMIZATION RESULTS

For the cislunar SoS, the performance is maximized, and the cost is minimized as shown in the following objective function:

$$\min_{x} \alpha * \boldsymbol{cost}(x_1 \ldots x_6) - (1-\alpha) * \boldsymbol{performance}(x_1 \ldots x_6)$$

Where: $\alpha = \{1:1:100\}$

The plot of architectures which results from the 54 architecture combinations is found and shown in Fig. 7.

The Pareto front is identified in Fig. 7 and zoomed for clarity in Fig. 8. This is a true Pareto front with only the highest-performance, lowest-cost architectures identified as optimal. A convex Pareto front can be found and evaluated, if desired. However, for this application, the convex Pareto solutions do not show advantages in performance and cost when compared to the non-convex Pareto optimal solutions. The non-convex Pareto Front results in the four architectures detailed in Fig. 9.

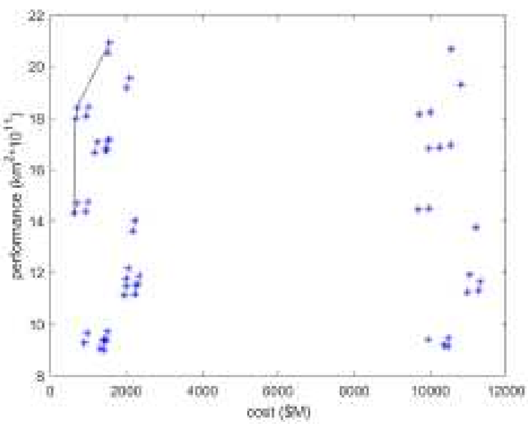

Fig. 7 Cislunar Pareto Front

The four optimal architectures are evaluated using MCDM with ER. The labels A-D are used for the remainder of the paper.

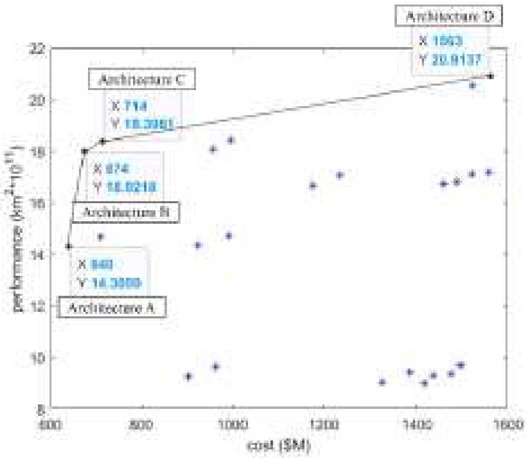

Fig. 8 Cislunar Pareto Front Zoomed

Fig. 9 Optimal Architectures

2) CISLUNAR OPTIMIZATION RESULTS EVALUATION

The cislunar SoS parameters are first scaled such that each result has a unique score. The fidelity of scaling required is 30. The uncertainty of each architecture is determined by choosing the least certain physical instantiation in the architecture, using the following values. The values are determined simply by history of implementation. Earth-based systems have the highest certainty because they have the most history, while Moon-based have the lowest certainty because they have very little history of implementation. These uncertainty values are notional to show the process of applying ER to a SoS. Future work could include alternative uncertainty values based on updated estimates.

$$Earth\ based\ certainty = 95\%$$

$$Space\ based\ certainty = 90\%$$

$$Moon\ based\ certainty = 85\%$$

With equal cost and performance weightings, the ideal architecture is found to be Architecture C, as shown in TABLE VII.

TABLE VII CISLUNAR EQUAL-WEIGHTED EVALUATION RESULTS

Arch-itecture	Cost Score	Performance Score	Certainty	Score
A	30	1	90%	14.0
B	29	17	85%	19.6
C	28	19	85%	20.0
D	1	30	85%	13.2

Since various stakeholders may prioritize cost and performance differently depending on mission, MCDM with ER is applied with cost and performance weightings varied. As the weights are varied, the ideal architecture shifts from the highest cost, highest performance to the lowest cost, lowest performance. All architectures are represented by the weighted approach, detailed in TABLE VIII.

TABLE VIII CISLUNAR WEIGHTED EVALUATION RESULTS

Cost Weight	Performance Weight	Score	Architecture
0	1	25.5	D
0.1	0.9	23	D
0.2	0.8	20.6	D
0.3	0.7	18.4	C
0.4	0.6	19.2	C
0.5	0.5	20	C
0.6	0.4	20.7	C
0.7	0.3	21.6	B
0.8	0.2	22.6	B
0.9	0.1	24.4	A
1	0	27	A

The weighted table allows the system architect to consider enterprise-level needs before choosing the ideal architecture.

VIII. FINDINGS

A. *CONCLUSIONS*

A method for evaluating and optimizing a System of Systems (SoS) is presented and applied to the cislunar system. First, a needs analysis is performed to identify the necessary system functions. Second, preliminary architecture design is accomplished using Model-Based System Architecture Process (MBSAP). Third, the problem is scoped using down-selection and a set of alternatives is developed. Fourth, the evaluation parameters are selected, and the architectures are evaluated in terms of those parameters. Fifth, an optimization algorithm is applied which finds a Pareto Front of the optimal architectures, and these architectures are evaluated using Multi-Criteria Decision Making (MCDM) with Evidential Reasoning (ER).

For the cislunar SoS application, the method is applied with the following results. First, the needs analysis results in 8 supporting functions for cislunar operations. Second, the preliminary architecture design is created using SysML with a Domain Diagram, Use Case Diagram, and Contextual Diagram. Third, down-selection is applied resulting in three necessary functions. A set of alternatives is developed resulting in 432 architecture alternatives. Fourth, the architectures are evaluated in terms of cost and performance. Fifth, the optimization algorithm results in a Pareto front of 4 optimal architectures. Optimization evaluation is applied resulting in Architecture C as the optimal cislunar architecture.

The method presented in this paper offers a systematic method for designing an optimal SoS. By optimizing the SoS, rather than individual systems, the SoS is cost- and performance-optimized at the enterprise-level. The enterprise-level objectives can be accounted for during the preliminary SoS design, decreasing the likelihood of redesign later in the system lifecycle. Additionally, the method accounts for uncertainty during architecture evaluation, which is a key characteristic of a complex SoS.

B. *RECOMMENDATIONS*

For future work, it would be interesting to apply this method to alternative systems. Additionally, sensitivity analysis can be applied to the cislunar metrics. Sensitivity analysis would be especially beneficial in the cost metrics and the uncertainty values.

The cislunar optimization study could also be expanded. The cost estimates could be updated to reflect more accurate cost model predictions, rather than SME estimates. Schedule could be added to the Architecture Evaluation step. The optimization parameters could be updated to represent stakeholder concerns. For instance, a stakeholder may want to prioritize the communications constellation. Additional supporting functions could be added to the architecture and evaluated using the process outlined in this paper. Finally, the uncertainty values could be updated to reflect application specific values.

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APPENDIX D. OPTIMIZED DESIGN OF AN INTEGRATED CISLUNAR COMMUNICATIONS, NAVIGATION, AND DOMAIN AWARENESS SYSTEM OF SYSTEMS

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Optimized Design of an Integrated Cislunar Communications, Navigation, and Domain Awareness System of Systems

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ABSTRACT This paper presents a process for designing an integrated system of systems architecture applied to cislunar space. A needs analysis reveals that critical operations in cislunar space requires communication, navigation, and domain awareness functions. These functions are used to design a trade space of physical constellations for evaluation. Payloads are designed for each of the functions to meet the requirements of cislunar space operations. Each payload-constellation combination is evaluated for cost and performance, where performance is measured as the transmitter coverage. All resulting architectures are then optimized to find the few Pareto optimal options. The Pareto optimal architectures are evaluated using Evidential Reasoning to find the optimal cislunar architecture. This process can be applied to similar system of systems to design, evaluate, and optimize the architecture.

INDEX TERMS Aerospace engineering, Design optimization, Moon, Performance evaluation, Radar remote sensing, Satellite navigation systems, Space communications, Space exploration, Space missions, Space technology, Systems engineering and theory, System of systems.

I. INTRODUCTION

The next space race has begun in cislunar space [1]. Missions are already underway in cislunar space, though the necessary supporting infrastructure for a sustainable architecture is lacking [2]. This paper presents a systematic process for designing a physical architecture for cislunar space. A needs analysis of cislunar space identifies three critical functions for initial operations in cislunar space: communications, navigation, and domain awareness [2] [3]. To construct architectures in cislunar space, this paper presents constellations with payload transmitters that are designed for the three critical functions. The transmitter is a generic term in this paper that could refer to the communication radio-frequency (RF) transmitters, the navigation RF transmitters, or the domain awareness RADAR transmitters. Opportunities to co-locate transmitters are included in the study to reduce overall cost, though added complexity due to integrated transmitters is not considered in the evaluation. Each architecture is evaluated in terms of cost and performance, resulting in 432 possible architecture combinations. Multi-Objective Optimization (MOO) is implemented to find a Pareto front resulting in four optimal architectures. The optimal architectures are evaluated using Multi-Criteria Decision Making (MCDM) with Evidential Reasoning (ER), resulting in the ideal architecture within the scope of this study.

This paper provides an optimized architecture solution for a cislunar SoS to meet the current published cislunar requirements, detailed throughout this paper [4]. Assumptions have been made to design a feasible system given the many unknowns in the cislunar mission trade space. The final architecture is optimized to provide communications, navigation, and domain awareness functions to the largest feasible volume of cislunar space given size, weight, power, and cost constraints. The final architecture does not always provide all three functions to the entire volume of cislunar space. Additionally, a user operating in this architecture may not receive all three functions at a certain position since each function has different performance based on the function's requirements and constraints. The SoS is constrained by costs, physics, and current technology. To assess this as a SoS, the user requirements have been consolidated to the enterprise level such that the SoS provides the same level of service to each user mission. For this paper, the requirements are assumed to be the same for all missions.

The process presented in this paper provides a systematic method for evaluating a large, complex system of systems. A well-defined process becomes most important when large costs are needed to deploy the SoS. For the cislunar system of systems, the architecture costs range from $500M to $1.5B, justifying the need for an objective evaluation method. Additionally, designing for the entire SoS rather than each individual system offers a lower-cost, higher-performing SoS at the enterprise level.

II. PROBLEM STATEMENT

This paper closes a gap in research on cislunar space by providing a holistic and integrated approach to architecture design for cislunar space. The method used to design, evaluate, and optimize is specific to a System of Systems (SoS). First, a needs analysis is performed to identify the functions necessary. The functions are scoped such that only the necessary functions for initial operations are studied. Next, the payload transmitters for the supporting functions are designed. Then, a set of relevant and functional constellations are designed to support the payload transmitter deployment. Constellations include Earth-based, Moon-based, and space-based transmitters. Each possible architecture is then evaluated for cost and performance. Next, the evaluated architectures are optimized for cost and performance, including integration opportunities, resulting in a Pareto front. Finally, the set of optimal architectures is evaluated using MCDM with ER. The result is an optimal physical architecture with the locations and specifications of each transmitter. As cislunar operations mature, these preliminary designs can be quickly updated to provide the most accurate results for current operations.

III. RELATED WORK

Research has been completed which includes studies of physical architectures providing a single function. An integrated study of the multiple functions required for cislunar space is lacking. The first cislunar integrated study is offered in this paper.

For the communication system, a proposed physical architecture for communications included placing satellites at Earth-Moon (EM) Lagrange points: L2, L3, L4, and L5. This architecture allowed communications between the far side of the Earth and the far side of the Moon. Excluding the poles, this architecture provided 98.95% coverage of the Moon and 99.1% coverage of the Earth [5]. This study's results are used to design the space-based constellations in this paper. However, the study did not include Earth-based or Moon-based architectures, which causes the results to differ from this paper's results. Another physical architecture proposed for lunar communication was a "flower constellation" of CubeSats around the Moon. The flower constellation had repeating ground traces and great lunar coverage [6]. The CubeSat constellation was designed for a specific user need near the Moon while this paper includes the entire volume of cislunar space.

A study of cislunar navigation systems found that EM Lagrange points can be used for an effective cislunar navigation architecture. Placing four satellites in stable orbits about L1, L2, L4, and L5 can provide accuracies of tens of meters for satellites in trans-lunar and lunar orbit [7]. A similar constellation in this paper is found to be optimal for the navigation solution alone. However, when combined in the integrated architecture, a less robust constellation is found to be optimal for the entire system of systems.

For the domain awareness function, optical architectures have been studied and compared with respect to solar exclusion angles, solar phase angles, and lunar exclusion angles. The results found that an ideal architecture would consist of four satellites in LEO in the EM plane [8]. The process used in the optical study is like the study in this paper because cost and performance are evaluated for each architecture. The optical study, however, does not include a resolution requirement for the cislunar object. This paper studies the resolution of objects using optical technologies and finds that the space-based optical sensor is infeasible in cislunar space.

IV. DEFINING CISLUNAR

In this paper, cislunar space is defined as the volume of space beyond Geosynchronous orbit (GEO) to the Moon's orbit, including the five Lagrange points. Lagrange points are points of gravitational equilibrium which can be used for orbits with long dwell times relative to the Moon's orbit [9]. Fig. 1 shows the defined volume space with Earth and Moon pictured as references. Figure 1 also depicts the five EM Lagrange points.

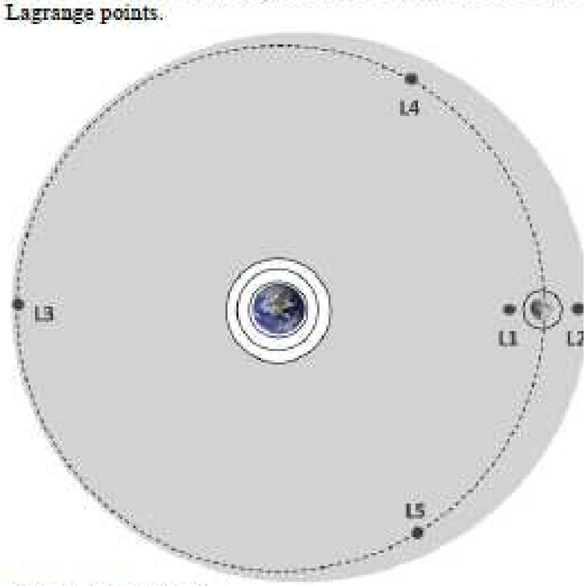

FIGURE 1. Cislunar Space

A. PRIMARY MISSIONS AND SUPPORTING FUNCTIONS

A needs analysis of cislunar space identifies 3 primary missions and 8 supporting functions necessary for cislunar operations [2]. The primary missions are the planned users of cislunar space. The cislunar missions are science, commerce, and defense. The supporting functions provide the necessary infrastructure for cislunar operations. The functions include transportation, communication, navigation, domain awareness, service, energy, shelter, and control. The architectures in this paper will focus on providing the necessary supporting functions for initial operations in cislunar space. Initial operations will require communication, navigation, and domain awareness as the necessary infrastructure [2] [3]. A mapping of service to functions is shown in Figure 2 with the critical functions highlighted.

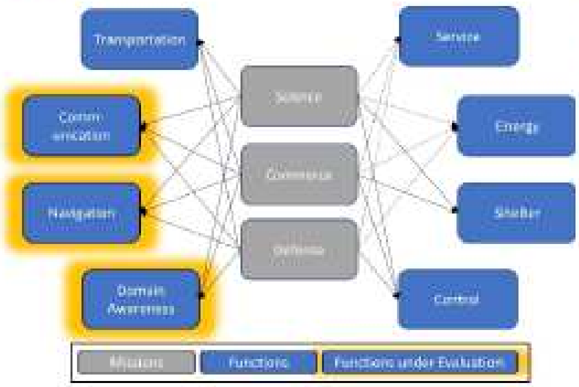

FIGURE 2. Mapping Services to Functions

V. SCOPING THE PROBLEM

The cislunar system has multiple missions and supporting functions, and therefore can be classified as a complex system of systems [10]. Initial architecture studies should focus on the functions necessary for initial operations. The bare-minimum functions identified for initial cislunar operations are communications, navigation, and domain awareness [2] [3]. These 3 functions in combination are still defined as a system of systems because each function is a system itself. Special design processes must be used for system of systems beyond the standard processes for a system. The systems engineering process for a SoS must include examining enterprise-level objectives and accounting for uncertainty [10] [11].

VI. CISLUNAR ARCHITECTURE DESIGN

A payload "transmitter" is defined as the hardware necessary to provide the function of communications, navigation, or domain awareness. The "bus" is defined as the necessary hardware infrastructure to support the payload, whether the payload is in space, on Earth, or on the Moon. The constellation is defined as the physical locations of multiple payload and bus combinations. Each cislunar architecture consists of a payload transmitter for each supporting function, located on a bus of the supporting infrastructure for the payload, operating in a constellation configuration.

A. CONSTELLATION DESIGN

A set of constellations are designed to constrain the decision space. The constellations are designed based on a literature review of cislunar architectures and knowledge of the dynamics of cislunar space [2]. The five constellations chosen are known as Lagrange light, Lagrange medium, Lagrange heavy, Earth-based, Earth plus Moon, and Earth plus Lagrange. Each constellation is depicted with notional transmitters, showing direction but not magnitude or beamwidth. Actual payload transmitter magnitudes and beamwidths are defined in part B. of this section.

The Lagrange light is designed to be a low-cost space-based constellation with good coverage of a high-priority area of interest: the vicinity of the Moon. L1 and L2 offer the best coverage of the Moon as they are located closest to the Moon. Additionally, L1 and L2 are located on opposite sides of the Moon and have visibility of the Earth-facing and non-Earth facing sides of the Moon. A notional figure of the Lagrange light constellation is depicted by the blue regions in Figure 3.

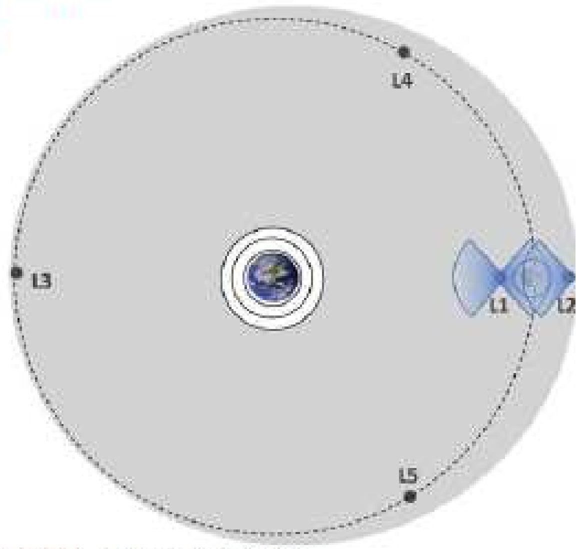

FIGURE 3. Lagrange Light Constellation

The Lagrange medium constellation is designed to be a mid-cost constellation with good coverage of the Moon and the transit corridor between the Earth and the Moon. The Lagrange medium areas of coverage are depicted by the blue areas of Figure 4.

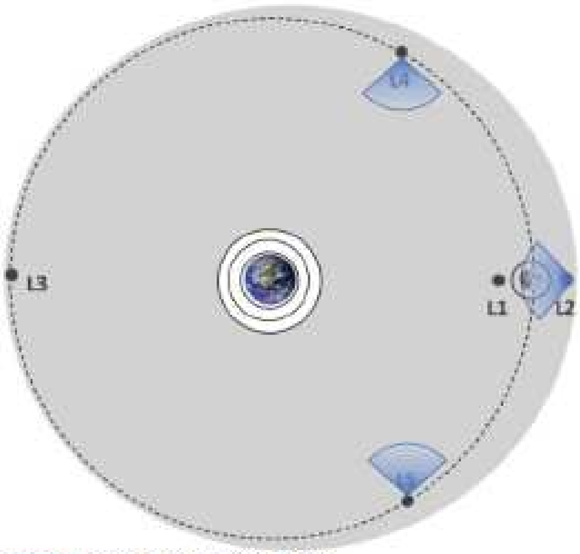

FIGURE 4. Lagrange Medium Constellation

The Lagrange heavy constellation is the most expensive and most robust space-based constellation. This constellation takes advantage of all five Lagrange points for excellent coverage of the entire cislunar volume. A notional figure of the Lagrange heavy constellation is depicted by the blue regions in Figure 5.

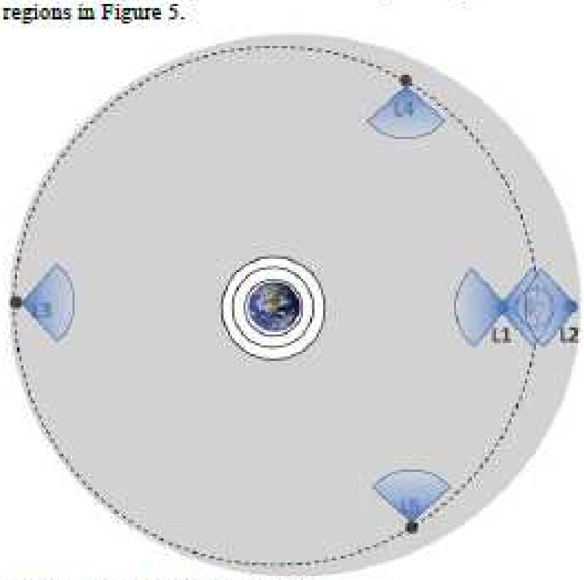

FIGURE 5. Lagrange Heavy Constellation

The Earth-based constellation offers an alternative to the space-based constellations. This constellation would provide the advantage of no launch costs and offers the ability for regular maintenance. Four transmitters are placed as close to the equator as physically possible to cover the Earth-Moon plane as much as possible. The actual placement of these transmitters are Ascension Island, Diego Garcia, California, and Australia. A notional figure of the Earth-based constellation is depicted by the blue regions in Figure 6.

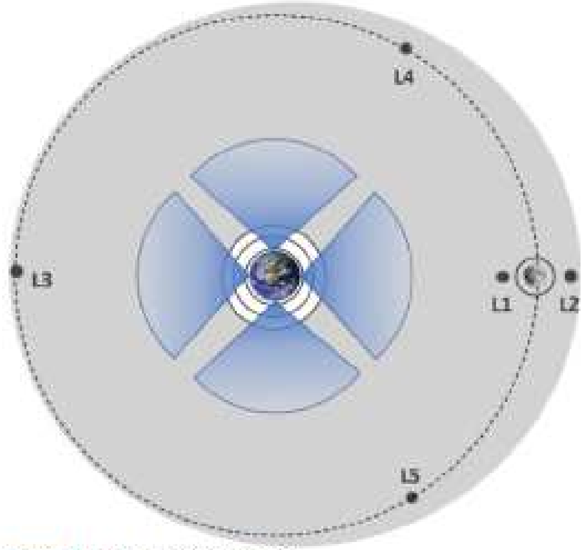

FIGURE 6. Earth-Based Constellation

The Earth plus Moon constellation is designed to cover a large volume of cislunar space, including lunar orbits, with only terrestrial transmitters. Four transmitters are placed on each body as close to the equator as physically possible. The Earth-based transmitters are in Ascension Island, Diego Garcia, California, and Australia. The Moon-based transmitters are placed as Earth-facing, anti-Earth-facing, velocity-direction, anti-velocity-direction. A notional figure of the Earth plus Moon constellation is depicted by the blue regions in Figure 7.

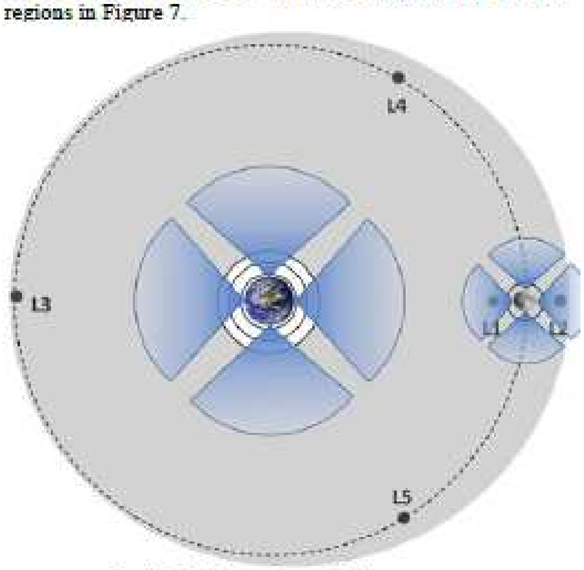

FIGURE 7. Earth Plus Moon Constellation

The Earth plus Lagrange constellation is designed to cover a large volume of cislunar space, including lunar orbits, with terrestrial and space-based transmitters. Four transmitters are placed on Earth as close to the equator as physically possible. The Earth-based transmitters are in Ascension Island, Diego Garcia, California, and Australia. The space-based transmitters are located at L1 and L2. A notional figure of the Earth plus Lagrange constellation is depicted by the blue regions in Figure 8.

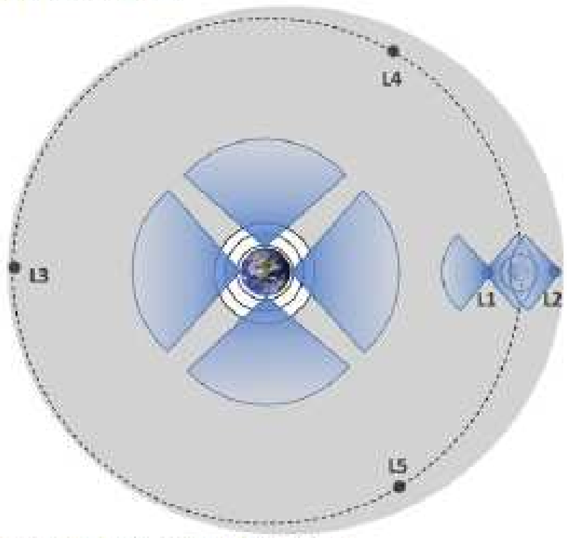

FIGURE 8. Earth Plus Lagrange Constellation

B. PAYLOAD DESIGN

A payload transmitter is designed for the communications, navigation, and domain awareness functions. Each transmitter is modeled using physics-based link budgets which result in a transmitter range and bandwidth for all functions.

The communications link budget is used to design a transmitter with a range of 450,000 km and a coverage half angle of 45-degrees that meets the known and assumed communications requirements [12]. The 45-degree half angle is used for the coverage performance calculations because the antenna is designed to be gimbaled to maximize the volume of coverage [12]. The actual beamwidth of the antenna is very narrow to accommodate the high gain requirements of cislunar communications. The link budget is detailed in Table I. The communication payload is designed to meet the minimum required link budget of 3 dB. For lunar communications, NASA uses 3 dB as the required link margin [13].

TABLE I
COMMUNICATIONS LINK BUDGET

Description	Gain/Loss (dB)	Notes
High Power Amplifier (HPA) Power	16 dBW	Assume 30 GHz, 40 W [14], 20% efficiency [14], 100% duty cycle
Cable Loss	-1 dB [12]	
Filter Loss	-0.5 dB [12]	
Truncation Loss	-0.3 dB [12]	Results in 14.2 dB power at antenna
Antenna Gain	52 dB	Assume 2-meter antenna[1]
Transmit design margin	1 dB [12]	Results in Effective Isotropic Radiated Power (EIRP) = 65.2 dBW
Path loss	-235.2 dB	Assume range of 458,788 km[2]
Atmospheric loss	-2 dB [12]	
Rain loss	-8 dB [12]	Results in Received Signal Strength (RSS) = -180 dBW
Receiver Antenna Gain	66 dB	Assume 2-meter receive antenna[3]
Insertion losses	-1 dB [12]	Results in receive signal power = -115 dBW
Boltzmann's Constant	228.6 dBW/k/Hz	
System Noise Temperature	-24.6 dBK	Assume 290 K [15] Results in C/No = 89.0 dB
Receiver Noise Bandwidth	-80 dB-Hz[4]	Assume 100 Mbps[5] Results in Signal to Noise (SNR) Ratio = 9 dB, Eb/No = 9 dB
Eb/No Threshold	4.5 dB [16]	Results in 4.5 dB link margin

Similarly, the navigation payload transmitter is designed to meet NASA's 3dB link margin requirement and is detailed in the link budget in Table II. The resulting transmitter has a range of 384,000 km and a half beamwidth of 32.5-degrees [17]. The navigation payload is also designed to meet NASA's threshold positional accuracy requirement of "on the order of km orbital position accuracy," published in the LunaNet Interoperability Specification Document [4].

To calculate this, the Signal-in-Space Range Error (SISRE) is calculated using equation (1) [18].

$$SISRE = \sqrt{(w_R * R - c * dt)^2 + w_{A,C}{}^2 * (A^2 + C^2)} \quad (1)$$

Where:

$$w_R, w_{A,C} = altitude\ weightings$$

$$c = speed\ of\ light$$

$$R, A, C = radial, along\ track, and\ cross\ track\ errors$$

$$dt = clock\ offset$$

[1] 2-meter antenna can be accommodated on standard spacecraft bus and results in necessary antenna gain.

[2] Range calculated for worst-case link of L2 to Earth.

[3] 2-meter antenna can be accommodated on standard spacecraft bus and meets antenna gain requirements.

[4] Receiver Noise Bandwidth is calculated based on 100 Mbps data rate.

[5] 100 Mbps used for most stressing use-case of high-definition video.

The weighting associated with the along-track (A) and cross-track (C) for a geostationary (GEO) satellite is 1/126 [18]. For a Lagrange satellite, the altitude is 9.1 times greater than GEO, so a weighting of 1/1147 is used. This causes the A and C errors to be negligible. The navigation system requires Delta-Differential One-Way Ranging (Delta-DOR) to determine the satellite ephemeris. For missions at lunar distances, the delta-DOR results in orbital errors of 37-meters in the radial direction [19]. The ranging (R) weighting asymptotically approaches 1 with a value of 0.99 at GEO, so a value of 1 is assumed for the Lagrange satellite [18]. The navigation system uses the same Rubidium clock as the GPS satellite constellation, so the clock error is assumed to match the worst-case of the GPS constellation, which is 0.30 ns [20]. The resulting SISRE of the navigation transmitter positioned in a Lagrange orbit is 36.9-meters, which is well under the NASA's threshold requirements of "on the order of km orbital position accuracy" [4].

The cislunar navigation is based upon the legacy GPS constellation to maintain backwards compatibility and for the use of COTS receivers [17]. Any doppler shift resulting from movement of the receiver spacecraft relative to movement of the cislunar transmitter will need to be accounted for in the receiver algorithms. The doppler shift is considered out of scope for the study of the cislunar SoS. The GPS constellation uses an Earth-based reference frame, so the cislunar navigation system in this paper will also use an Earth-based reference frame [17]. Once surveyed sites are available on the Moon, it is recommended that receivers in the vicinity of the Moon should utilize a Moon-based reference system for more accurate navigation.

TABLE II
NAVIGATION LINK BUDGET

Description	Gain/Loss (dB)	Notes
HPA Power	20 dBW	Assume 1575.42 MHz[6], 100 W [14], 50% duty cycle [17], 60% efficiency [14]
Cable Loss	-1 dB [17]	
Filter Loss	-0.5 dB [17]	
Truncation Loss	-0.3 dB [17]	Results in 18.2 dB power at antenna
Antenna Gain	6 dB	Assume patch antenna with 65-deg beamwidth [17]
Transmit design margin	-1 dB [17]	Results in EIRP = 23.2 dBW
Path loss	-208.1 dB	Assume range of 384,400 km[7] Results in RSS = -184.9 dBW
Receiver Antenna Gain	3 dB	Assume standard GPS patch antenna [17]
Insertion losses	-1 dB [17]	Results in receive signal power = -182.9 dBW

Description	Gain/Loss (dB)	Notes
Boltzmann's Constant	228.6 dBW/K/Hz	
System Noise Temperature	-24.6 dBK	Assume 290 K [15]
Receiver Noise Bandwidth	-63 dB-Hz [17]	Results in pre-correlation SNR = -41.9 dB
Post-correlation Receiver Bandwidth	17 dB-Hz [17]	Assume 50 Hz[8]
Correlation Processing Gain	46 dB [17]	Results in C/No = 21.1 dB-Hz
C/No threshold	15 dB-Hz [21]	Results in 6.1 dB link margin

Domain awareness includes the subfunctions of object detection, tracking, identification, and characterization [22]. In this paper, the domain awareness transmitter fulfills the function of object detection and tracking. The functions of identification and characterization require additional data collection and human-in-the-loop (HITL) intervention, which is not included in this cislunar SoS [22]. The domain awareness transmitter is designed to achieve a minimum resolution of 1-m^2. This is assumed to be the resolution requirement for cislunar domain awareness because no requirement has been published, but 1-m^2 resolution is able to see many standard satellite buses anticipated to operate in cislunar space [23].

Current domain awareness sensors typically use optical or Radio Detection and Ranging (RADAR) technologies. The domain awareness payload is challenging to design because it is difficult to get the necessary ranges for cislunar space of the cislunar volume using traditional optical or RADAR transmitters. Optical lenses must be enormous to cover the distances needed, while RADAR is power hungry due to the signal bouncing off the object and effectively traveling twice as far as a one-way transmitted signal.

The feasibility of an optical sensor is first explored. An optical sensor is governed by the optical resolution equation (2).

$$r = 2.44 * R * \lambda / D \tag{2}$$

Where:

$r = resolution$

$R = Range$

$\lambda = wavelength$

$D = Diameter$ [24]

Due to the size of the launch vehicle, the maximum diameter of the sensor is assumed to be 5.4 meters [25]. In cislunar space, the minimum usable range of a sensor is

[6] Current Global Positioning System (GPS) L1 frequency.
[7] Distance from Earth to Moon is used as the design distance for Lagrange transmitters.

[8] 50 Hz standard for coarse acquisition (C/A) code [16]

assumed to be 60,000 kilometers, which would allow an L1 or L2 satellite to view orbits near the Moon [3]. Additionally, the minimum required resolution for a space object is assumed to be 1-m^2, as defined previously in this section. Examining the ultraviolet (UV), visible, and infrared (IR) wavelengths results in the trade space of optical sensor performance summarized in Table III.

To meet the minimum range and resolution requirements, the required sensor diameter is 15-meters, which is significantly higher than any current space-based or Earth-based optical lens [26]. This makes space-based optical an infeasible solution for cislunar domain awareness.

TABLE III
OPTICAL SENSOR TRADE SPACE

Wavelength	Required Diameter (assume range=60,000 km and resolution=1 m)	Maximum Feasible Range (assume diameter=5.4 m and resolution=1 m)	Maximum Feasible Resolution (assume diameter=5.4 m and range=60,000 km)
UV (100 nm)	15 m	22,000 km	3 m
Visible (500 nm)	73 m	4,400 km	14 m
IR (700 nm)	103 m	3,200 km	19 m

Next, the feasibility of the RADAR transmitter is explored. To calculate the specifications of the transmitters, the RADAR equation (3) is computed for each physical application of the transmitter. X-band is chosen as a high-performing frequency band that conforms to the United States Department of Commerce Frequency Allocation [27]. The range for each application is shown in Table IV. All domain awareness transmitters in this paper have a half beamwidth of 50-degrees due to limitations of the phased array [28].

$$R_{max} = \sqrt[4]{\frac{P_s \tau G^2 \lambda^2 \sigma}{(4\pi)^3 kTL_{tot}}} \tag{3}$$

Where:

$$R_{max} = maximum\ range$$

$$P_s = peak\ pulse\ power$$

$$\tau = transmit\ pulse\ duration$$

$$G = antenna\ gain$$

$$\lambda = wavelength$$

$$\sigma = radar\ cross\ section$$

$$k = Boltzmann's constant$$

$$T = Noise\ temperature$$

$$L_{tot} = Total\ Losses$$

TABLE IV
DOMAIN AWARENESS LINK BUDGET [3]

	Earth	Lunar	Space
P_s	1,000,000 W	300,000 W	20,000 W
τ	0.5 s	0.5 s	0.5 s
G	75.3 dB[9]	69.2 dB[10]	52.8 dB[11]
λ	0.030 m	0.030 m	0.030 m
σ	1 m^2	1 m^2	1 m^2
k	1.38E-23	1.38E-23	1.38E-23
T	290 K [14]	290 K [14]	290 K [14]
L_{tot}	10.8 dB	8.8 dB	8.8 dB
R_{max}	271,000 km	112,000 km	8,600 km

The maximum ranges in Table IV show excellent feasibility for the Earth-based and Moon-based applications. However, the space-based RADAR does not meet the minimum range requirement of 60,000 km, so it is not included in the architecture evaluations.

RADAR systems can be mono-static or multi-static. A multi-static RADAR system has diversity in frequency, polarization, or geometry and is advantageous over a mono-static system due to better fidelity of target signatures [29]. The system designed in this paper is monostatic, rather than multi-static, for simplicity of modeling and a focus on the SoS architecture. Future research of a cislunar SoS could investigate a multi-static solution.

The domain awareness payload is unique in that it has different transmitters for each application: Earth-based, Moon-based, and space-based. The communications and navigation payloads have the same transmitters for each application. The domain awareness transmitter uses RADAR which is highly constrained by power. The power sources are researched based on the application to maximize the transmitter range. In contrast, the navigation and communication transmitters are designed to accommodate the space-based application, which is the most power-limiting. The space-based communication and navigation transmitters happen to cover the entire range necessary for cislunar space from Earth or the Moon, so the power-constrained transmitter is used for all three applications.

VII. CISLUNAR ARCHITECTURE EVALUATION

Each cislunar architecture consists of a payload transmitter in a constellation for the three functions of communication, navigation, and domain awareness. Additionally, if payloads are co-located, they are considered

[9] Assumes 56-meter phased-array diameter due to Earth-based application [3].

[10] Assumes 28-meter phased-array diameter due to Moon-based application [3].

[11] Assumes 5.4-meter antenna diameter due to launch vehicle restrictions [25].

as integrated on a single bus as a cost-savings effort. The payloads are designed such that multiple payloads can exist on a single COTS bus, reducing hardware costs. Note that if an architecture results in an integrated bus, these architectures must be assessed for feasibility. This integration opportunity may not be advantageous to the lifecycle considerations of the system. Integration may require additional engineering effort, adding cost and delaying the deployment of the system. The added integration cost due to complexity is not included in this study.

The total number of possible architecture combinations consists of the set of alternatives in TABLE V, which results in 6*3*3*2*2*2=432 total possible architectures for evaluation. The integrated architectures are constrained such that the sensors must be co-located for the functions to be considered for integration. After these constraints are applied, 54 architectures remain for optimization and evaluation. Each architecture is evaluated in terms of cost and performance.

TABLE V
SET OF ALTERNATIVES

Decision	Set of Alternatives
Communication (Comm) Constellation	{lagrange_light, lagrange_medium, lagrange_heavy, earth_based, earth_plus_lunar, earth_plus_lagrange}
Navigation (Nav) Constellation	{lagrange_light, lagrange_medium, lagrange_heavy}
Domain Awareness (DA) Constellation	{earth_based, earth_plus_lunar, earth_plus_lagrange}
Integrated Comm and Nav	{no, yes}
Integrated Comm and DA	{no, yes}
Integrated Nav and DA	{no, yes}

A. COST EVALUATION

For cost evaluation, each transmitter and transmitter location are evaluated. Cost models are used when available and subject matter expert (SME) estimates are used when cost models do not exist. For satellite-based transmitters, the Unmanned Space Vehicle Cost Model (USCM) [30] can be used. For Earth-based and Moon-based transmitters, SME estimates are required [3]. A summary of each transmitter and bus cost estimate is provided in Table VI.

TABLE VI
COST SUMMARY [3]

Name	Cost ($M)
Communications Space Transmitter	$13.6
Communications Ground Transmitter	$1
Navigation Transmitter	$33
Domain Awareness Ground Transmitter	$10
Single Bus	$50
Integrated Double Bus	$75
Integrated Triple Bus	$112.5

B. PERFORMANCE EVALUATION

Each function transmitter is evaluated for each constellation in terms of coverage. The architectures are modeled in a physics-based environment using Systems Toolkit (STK) [31]. The coverage is calculated as the surface area of spheres of coverage from Earth orbit to the Moon's orbit. Additional spheres of coverage are calculated from the Moon's surface to the altitude of the L1 and L2 Lagrange points. The coverage spheres have equal weightings in this analysis. A stakeholder could incorporate weights to the areas of coverage of greatest importance. The results are scaled by 10^{11} to make the numbers more digestible.

For the communication constellations, the performance results are shown in Table VII.

TABLE VII
COMMUNICATION PERFORMANCE

Constellation	Performance ($km^2 * 10^{11}$)
Lagrange Light	12.632
Lagrange Medium	11.816
Lagrange Heavy	18.224
Earth-based	27.920
Earth plus Moon	39.181
Earth plus Lagrange	35.089

For the navigation constellations, the performance results are shown in Table VIII. Note that only the space-based constellations are evaluated because an Earth-based constellation would interfere with the nominal Global Positioning System (GPS) signal [17].

TABLE VIII
NAVIGATION PERFORMANCE

Constellation	Performance ($km^2 * 10^{11}$)
Lagrange Light	6.405
Lagrange Medium	6.593
Lagrange Heavy	14.093

For the domain awareness constellations, the performance results are shown in Table IX. Note that space-based constellations are not assessed because range requirements cannot be met by a space-based RADAR.

TABLE IX
DOMAIN AWARENESS PERFORMANCE

Constellation	Performance ($km^2 * 10^{11}$)
Earth-based	8.760
Earth plus Moon	9.861
Earth plus Lagrange	9.159

The cost and performance metrics are used to evaluate each architecture. A plot of all architectures after integration constraints are applied is shown in Figure 9. The integration constraints result in a total of 54 architectures for the optimization algorithm.

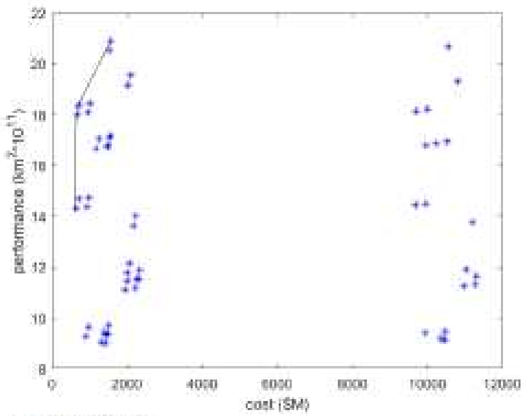

FIGURE 9 Pareto Front

VIII. CISLUNAR ARCHITECTURE OPTIMIZATION

A multi-objective optimization (MOO) algorithm is used to optimize the 54 architecture results. The resulting Pareto front is then evaluated to find the ideal architecture.

A. OPTIMIZATION RESULTS

The architectures are optimized using MOO to find the highest-performance, lowest-cost architectures. The following objective function is shown in equation (4) and used to identify the optimal architectures.

$$\min_{f(x)} = \alpha * \boldsymbol{cost} - (1 - \alpha) * \boldsymbol{performance} \quad (4)$$

Where:

$$\alpha = \{1:1:100\}$$

The problem as defined, is a linear program (LP) with integer results. Due to the relatively small number of results, the Pareto front can be found from a plot of the results matrix [32]. For this application, the cost is minimized and the performance in maximized. The resulting Pareto front identifies four optimal architectures, shown in Figure 9 and zoomed in Figure 10.

This is a non-convex Pareto front with only the highest-performance, lowest-cost architectures identified as optimal. A convex Pareto front can be found and evaluated, if desired. However, for this application, the convex Pareto solutions do not show advantages in performance and cost when compared to the non-convex Pareto optimal solutions.

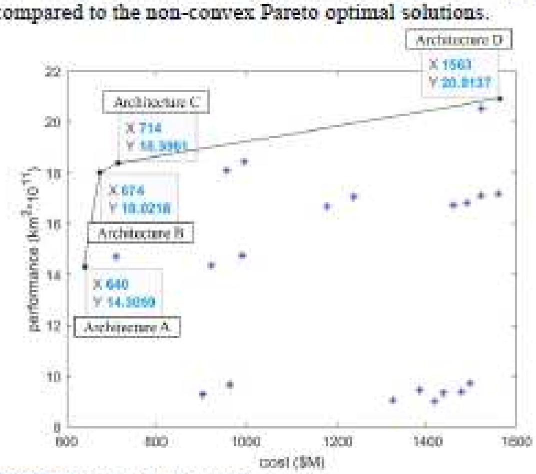

FIGURE 10 Pareto Front Zoomed

The four optimal architectures correspond to the constellations defined in Table X. The labels A-D are used for the remainder of the paper. These four architectures are evaluated to find the ideal architecture.

TABLE X
OPTIMAL ARCHITECTURES

Architecture	Architecture Cost ($M)	Architecture Performance (km^2*10^11)	Constellations
A	640	14.3059	communications constellation = earth-based navigation constellation = lagrange light domain awareness constellation = earth-based communications and domain awareness integrated
B	674	18.0218	communications constellation = earth plus moon navigation constellation = lagrange light domain awareness constellation = earth-based no integrated constellations
C	714	18.3961	communications constellation = earth plus moon navigation constellation = lagrange light domain awareness constellation = earth plus moon communications and domain awareness integrated
D	1563	20.9137	communications constellation = earth plus moon navigation constellation = lagrange heavy domain awareness constellation = earth plus moon communications and domain awareness integrated

B. OPTIMIZATION EVALUATION

The four optimal architectures are evaluated using MCDM with ER [33]. This method incorporated uncertainty into the evaluation, which is essential when evaluating a system of systems (SoS) [11]. To evaluate with MCDM, the cost and performance values are scaled such that each result has a unique value. Then, the MCDM equation is applied, shown in equation (5).

$$score = (0.5 * cost + 0.5 * performance) * certainty \quad (5)$$

Where:

$$Earth\ based\ certainty = 95\%$$

$$Space\ based\ certainty = 90\%$$

$$Moon\ based\ certainty = 85\%$$

This equation assumes equal weighting of cost and performance. The weightings used in this paper are notional, based on industry experience in each location. Earth-based has the most experience in applications, so the highest certainty is used. The next highest experience location is space-based. The lowest experience, and lowest certainty, is given to the Moon-based applications. The weights can be modified to accommodate stakeholder priorities.

The MCDM with ER method results in scores for each of the four optimal architectures. The scores are listed in Table XI with Architecture C identified as the ideal architecture.

TABLE XI
OPTIMIZATION EVALUATION RESULTS

Architecture	Cost Score	Performance Score	Certainty	Score
A	30	1	90%	14.0
B	29	17	85%	19.6
C	28	19	85%	20.0
D	1	30	85%	13.2

IX. FINDINGS

A. CONCLUSIONS

The process in this paper offers a systematic method for designing an optimal system of systems (SoS) with the potential for expanding to other systems. An integrated approach for SoS design, as opposed to designing each system individually, allows for an optimal comprehensive architecture at the enterprise level while meeting enterprise-level objectives.

In the emerging area of cislunar space, a more comprehensive architecture is of value for the upcoming missions to cislunar space. A needs analysis identifies three critical functions for initial operations in cislunar space: communications, navigation, and domain awareness. Six constellations are designed to accommodate the unique dynamics of cislunar space. Payload transmitters are designed to meet the requirements of cislunar operations. Architectures are populated for each transmitter/constellation combination and evaluated in terms of cost and performance. 432 architectures result from the evaluation. A multi-objective optimization technique is used to find the Pareto front of the architectures. Four optimal architectures result and are evaluated using Multi-criteria Decision Making (MCDM) with Evidential Reasoning (ER), which incorporates uncertainty into the evaluation. The final recommended architecture from this study has the communications and domain awareness functions as Earth plus moon constellation, and the navigation function as a Lagrange light constellation.

B. RECOMMENDATIONS

This study offers a systematic process for designing, evaluating, and optimizing cislunar architectures. This process can be utilized by stakeholders such as NASA or the DoD to design a space system of systems for cislunar or other areas of interest.

The cislunar optimization study could also be expanded. The cost estimates could be updated to reflect more accurate cost model predictions, rather than SME estimates. The optimization parameters could be updated to represent stakeholder concerns. For instance, a stakeholder may want to prioritize the communications constellation. Additional supporting functions could be added to the architecture and evaluated in using the process outlined in this paper. Additional metrics can be added for evaluation. For example, the navigation constellation can be evaluated for a navigation-specific metric such as Dilution of Precision (DOP). The RADAR system specifically could be re-designed to include multi-static options. Finally, alternative constellations could easily be added to the trade space.

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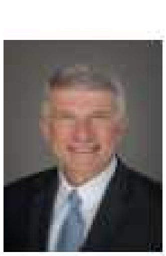

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LIST OF ABBREVIATIONS

Abbreviation	Definition
ACES	Advanced Cryogenic Evolved Stage
ACT	Activity Diagram
AESA	Active Electronically Steerable Antenna
AFRL	Air Force Research Laboratory
AGI	Ansys Government Initiatives
AMV	Advanced Maneuvering Vehicle
ATAM	Architecture Tradeoff Analysis Method
BDD	Block Definition Diagram
BER	Bit Error Rate
BMC3	Battle Management Command, Control, and Communication
CAPSTONE	Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment
CDM	Conceptual Data Model
CHPS	Cislunar Highway Patrol System
CLPS	Commercial Lunar Payload Services
CONOPs	Concept of Operations
COTS	Commercial Off-The-Shelf
CR3BP	Circular Restricted Three Body Problem
CSA	Canadian Space Agency
CSpOC	Combined Space Operations Center
CSU	Colorado State University
DARPA	Defense Advanced Research Projects Agency
DME	Digital Mission Engineering
DoD	Department of Defense
DOP	Dilution of Precision
DRACO	Demonstration Rocket for Agile Cislunar Operations
DRO	Distant Retrograde Orbit
DSN	Deep Space Network
DSN	Deep Space Network
DTN	Disruption Tolerant Networking
EGS	Exploration Ground System
EIRP	Effective Isotropic Radiated Power
EP	Electric Propulsion
ER	Evidential Reasoning
ESA	European Space Agency
FDIR	Fault Detection, Isolation, and Recovery
FTP	File Transfer Protocol

GEO	Geosynchronous Orbit
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HALO	Habitation and Logistics Outpost
HDTV	High-Definition Television Signals
HEO	Highly Elliptical Orbit
HLS	Human Landing System
HPA	High Power Amplifier
HPOP	High-Precision Orbital Propagator
HRL	Human Readiness Level
IBD	Internal Block Diagram
IBM	International Business Machines
IBS	Integrated Broadcast System
ICD	Interface Control Document
ICPS	Interim Cryogenic Propulsion Stage
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
ION	Institute of Navigation
IR	Infrared
IRL	Integration Readiness Level
ISRU	In-Situ Resource Utilization
JAXA	Japan Aerospace Exploration Agency
JNC	Joint Navigation Conference
JPL	Jet Propulsion Laboratory
LADEE	Lunar Atmosphere and Dust Environment Explorer
LAN	Local Area Network
LDM	Logical Data Model
LEAG	Lunar Exploration Analysis Group
LEO	Low Earth Orbit
LiAISON	Linked Autonomous Interplanetary Satellite Orbit Navigation
LLO	Low Lunar Orbit
LNSS	Lunar Navigation Satellite System
LP	Linear Program
LRO	Lunar Reconnaissance Orbiter
LST	Lunar Space Tug
LuGRE	Lunar GNSS Receiver Experiment
LV	Logical/Functional Viewpoint
MATLAB®	Matrix Laboratory
MBSAP	Model-Based Systems Architecture Process
MBSE	Model-Based Systems Engineering
MCDM	Multi-Criteria Decision Making

MEV	Mission Extension Vehicle
MMS	Magnetosphere Multi-Scale
MOGA	Multi Objective Genetic Algorithm
MOO	Multi-Objective Optimization
MRV	Mission Robotic Vehicle
NASA	National Aeronautics and Space Administration
NRHO	Near-Rectilinear Halo Orbit
NRO	Near Rectilinear Orbit
OCXO	Oven-Controlled Chrystal Oscillator
OMG	Object Management Group
OOSEM	Object-Oriented Systems Engineering Method
OPL	Object-Process Language
OPM	Object-Process Methodology
OSA	Open Systems Architecture
OV	Operational Viewpoint
PAR	Parametric Diagram
PhD	Doctor of Philosophy
PKI	Public Key Infrastructure
PPE	Power and Propulsion Element
PV	Physical Viewpoint
QAt	Quality Attribute
QAW	Quality Attribute Workshop
RADAR	Radio Detection and Ranging
RAFS	Rubidium Atomic Frequency Standard
REM	Rare Earth Metal
RF	Radio Frequency
RFP	Request for Proposal
Roscosmos	Russian Space Agency
RSS	Received Signal Strength
RUP SE	Rational Unified Process for Systems Engineering
SA	State Analysis
SCPS	Space Communication Protocol Standards
SD	Sequence Diagram
SDA	Space Development Agency
SDL	System Definition Language
SDR	Software Defined Radio
SDRAM	Synchronous Dynamic Random Access Memory
SE	Systems Engineering
SGLS	Space-Ground link Service
SLS	Space Launch System
SNMP	Simple Network Management Protocol
SNR	Signal to Noise Ratio

SOA	Service-Oriented Architecture
SoS	System-of-Systems
SQL	Structured Query Language
SRL	System Readiness Level
SSC	Swedish Space Corporation
SSN	Space Surveillance Network
STK	Systems Tool Kit
STM	State Machine Diagram
SW	Software
SWaP	Size Weight and Power
SysML	Systems Modeling Language
TCP	Transmission Control Protocol
TP	Transport Protocol
TRL	Technology Readiness Level
TT&C	Telemetry Tracking & Control
UC	Use Case Diagram
UHF	Ultra-High Frequency
UI	User Interface
ULA	United Launch Alliance
UML	Unified Modeling Language
UML	Unified Modeling Language
US	United States
USB	Universal S-Band
USCM	Unmanned Space Vehicle Cost Model
USSF	United States Space Force
UV	Ultra-Violet
VCRM	Verification Cross Reference Matrix
WAN	Wide Area Network