

## Optimal Utility and Design of a Resource-constrained Small Satellite Constellation for Cislunar Space Using Autonomy

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### Abstract

The NewSpace age has reshaped the future of space systems, driving a growing demand for advanced methodologies to govern and operate them efficiently. Given current trends, it is imperative to define, align, and implement processes that can be systematically integrated into space systems to ensure optimal and effective operations in the Cislunar domain. Existing methods fall short of meeting these demands, particularly in the harsh and dynamic Cislunar environment, which faces increasing congestion, debris accumulation, and mission complexity. This challenge extends beyond Earth orbits to the lunar region, where strategic infrastructure is being planned to support future exploration and research. Small satellites (<100 kg) play a vital role in emerging Cislunar operations. Globally, they are already being utilized for a variety of Earth-based applications and, more recently, for scientific and technological demonstrations around the Moon. However, their constrained onboard resources limit operational flexibility, necessitating intelligent and adaptive solutions. This paper addresses the critical issue of resource management within small satellite constellations through a novel methodology called In-loop Resource Adaptation (ILRA). ILRA leverages inter-satellite links (ISLs) for dynamic information exchange and optimal in-orbit resource utilization, enabling a balanced and scalable form of autonomy. The proposed approach is supported by robust autonomous strategies, validated through simulations and visual demonstrations, and analyzed across key operational parameters. This methodology is positioned to address pressing challenges in Cislunar operations—such as congestion, debris, and sustainable resource usage—ensuring long-term mission resilience. The paper concludes with a discussion on comparative insights and future directions.

**Keywords: Autonomy, Small satellites, Operations, Cislunar, Resource Management, Space Environment**

### Nomenclature

$\alpha$  - Horizontal distance between the LEO satellite and  $m^{th}$  user during the  $n^{th}$  TS.

$\beta$  - represents the geometric angle corresponding to the remaining service coverage arc length of the LEO satellite to the  $m^{th}$  user during the  $n^{th}$  TS.

$R_{\oplus}$  – Radius of Earth

H – Altitude of the LEO satellites

$P_r$  - Power received

$P_t$  - Transmitter power

$G_t$  - Transmitter gain

$L_{fs}$  - Free space losses

$L_m$  - Miscellaneous losses

D – Diameter of the antenna used

### Acronyms/Abbreviations

ILRA – In-loop Resource Adaptation

COTS – Commercially Off-the-shelf

MLO – Medium Lunar Orbits

LEO – Low-earth Orbits

ILRA – In-loop Resource Adaptation

AI – Artificial Intelligence

NRHO – Near Rectilinear Halo Orbits

RAAN – Right Ascension of the Ascending Node

ISL – Inter-satellite Links

Delta V ( $\Delta V$ ) – Variation in the velocity of objects

## 1. Introduction

The challenges posed by the NewSpace era are getting fierce and the need to develop specific innovation in space systems is inevitable. Small satellites are one prominent contributor in this competence of building efficient and durable space systems. The accelerating progress of the NewSpace era has transformed how space systems are conceptualized, developed, and operated. With increasing global interest in sustainable lunar exploration, the Cislunar region—spanning from geostationary orbit to lunar orbit—has emerged as a strategic frontier. It presents unique scientific, economic, and geopolitical opportunities, as well as significant operational challenges. Upcoming missions from national space agencies and commercial ventures aim to establish long-term infrastructure in this region, including orbital waystations, communication relays, surface habitats, and logistics support systems. These developments require reliable, autonomous, and resource-efficient space assets capable of operating in a far more complex environment than traditional Earth-centric missions.

One class of space assets that has rapidly grown in relevance is that of small satellites, typically under 100 kilograms. These platforms offer a cost-effective, rapidly deployable solution for mission support, technology demonstration, and scientific data collection. The miniaturization of spacecraft subsystems, combined with the advances in commercial-off-the-shelf (COTS) components, has made it possible to launch constellations of small satellites that can cooperate and collectively achieve mission objectives that once required larger, monolithic systems. However, the transition from LEO-based operations to the Cislunar environment introduces a new set of constraints. The region is characterized by gravitational perturbations influenced by both Earth and Moon, higher communication latencies and reduced ground station visibility, dynamic radiation environments, and increasing congestion and debris risks due to mission proliferation.

These conditions impose severe limitations on ground-based control, necessitating onboard autonomy for both decision-making and resource management. While autonomy has been explored in LEO operations—especially for data routing, attitude control, and fault tolerance—autonomy for operational sustainability in Cislunar constellations is still an emerging area. A major challenge lies in the resource constraints of small satellites. Power, computational capability, thermal margins, and communication bandwidth are often tightly budgeted, and their management becomes more complex in a distributed constellation. Furthermore, coordinating actions across multiple spacecraft—each with varying resource statuses and mission priorities—demands real-time decision-making supported by reliable inter-satellite communication.

Literature indicates a series of developments in this field of research and the concern for resource allocation among small satellite constellations as a challenge to be analyzed. This requires methodologies and a creative vision to design the elements of the system at a high standard, minimizing the impact of cost, with the understanding of withstanding the Cislunar environment. In this direction, [1] presented the dynamic programming for the LEO constellations for efficient navigational resource allocation which is the most critical factor in determining the long-term mission planning and objectives to be attained. Similarly, [2] innovates with a unified framework for NGSO satellite constellations which gives a different prospect of utilizing resources efficiently. Mega constellations have a bit of different challenges to address and [3] gives an integrated computing technique to enhance the adaptability of such constellations. The communications in constellations have a bigger and prominent usage which is addressed in [4] for resource allocation effectively with a cooperative satellite approach.

Non-terrestrial networks are also utilized in resource allocation with a dedicated sensing and communications to resolve resource issues onboard [5]. Routing for inter-satellite communications is also addressed over time with several articles and is one of the major concerns in recent times [6]. The beam-hopping based satellite systems with spectrum sharing is also coming in utilization significantly [7] along with hierarchical dynamic computation offloading [8] is coming into practice for making significant impact on their utility in small satellite constellations. The DRL-based method is also used for addressing the latency issues in order by allocating the service efficiently in LEO satellite networks [9] which is unique in this implementation and aligns a new era of communications with sufficient resource allocations. Again, the approach for the mega constellations will be a bit different and some making use of the networked telemetry system [10] gives sufficient scope for the research to built on and new techniques that can be proposed solving other major issues.

To address this gap, this paper proposes a novel framework termed In-loop Resource Adaptation (ILRA). The ILRA methodology integrates resource-awareness directly into the operational control loop of the satellite, enabling adaptive in-orbit decision-making that considers both internal system states and external environmental conditions. The key enabler for this approach is the use of Inter-Satellite Links (ISLs), which facilitate decentralized cooperation among satellites in a constellation. ILRA provides the following major advantages such as enabling real-time information exchange across the constellation to support cooperative resource planning, embeds resource management objectives within the control algorithm, making each satellite's operations adaptive to its current energy, thermal, and

computational state. This supports scalable autonomy in Cislunar conditions without constant ground intervention. While past research has addressed aspects such as ISL communication topologies, link budget optimization, and federated task management, this work diverges in a few critical ways. First, this work targets Cislunar orbital regimes, which differ significantly from LEO/MEO architectures in dynamics, visibility, and operational constraints. Second, this work treats resource utilization as an active, optimized variable in satellite control, rather than a passive constraint. Finally, this work presents an autonomous in-loop strategy, leveraging ISLs, that is implementable on resource-constrained onboard processors, making it viable for small satellite missions.

A visual simulation environment has been developed to assess the method’s performance under various orbital configurations and mission conditions, including high-debris regions and communication-limited phases. To structure this contribution, the remainder of the paper is organized as Section 2 questions the essential needs of today’s space systems with critical problem to be addressed in extensive urgency. Section 3 provides a focused improvisation with the methodology proposed on the current state of Cislunar operations, small satellite capabilities, and prior ISL-based coordination methods, emphasizing the gaps this paper addresses.

Section 4 outlines the architectural foundation of the ILRA methodology with dedicated dynamics involved and significant contributions possible with equations. Section 5 presents the control framework and resource adaptation logic, including how ISL data feeds into in-orbit decision-making with visual set-ups and demonstrations on how this can be a gamechanger if implemented with a standard process. Section 6 details the results demonstrating the variation in environment parameters, and performance metrics used for validation of the proposed methodology. Section 7 discusses the results, providing both quantitative evaluations and qualitative insights into the approach’s operational feasibility. Section 7 concludes the paper and proposes future work directions, including operations-in-the-loop validation and extended mission scenarios.

This will be depicted with Fig. 1. as below displaying the major role of small satellites in a complex operation of Cislunar zone. As the massive need for optimal utility of the resources grow in this region of operations, it is inevitable to plan, organize, innovate, and develop solutions beyond traditional systems that have been used over years. The NewSpace welcomes the competence through logic, autonomy, sciences, and engineering capabilities in years to come.

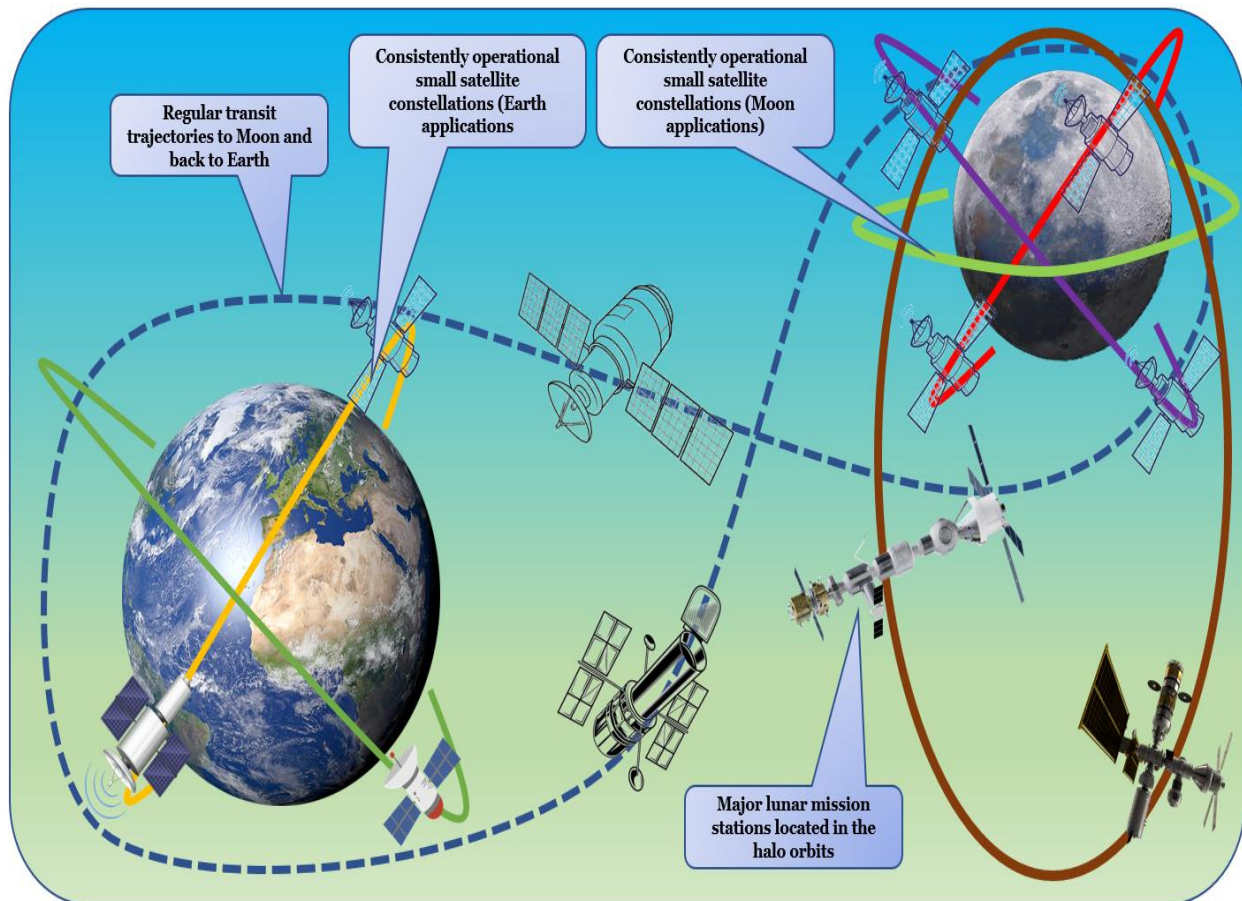


Fig. 1. Cislunar operations during the peak mission deployments

## 2. Problem Definition

The increasing interest in sustained lunar operations and deep-space exploration has led to a significant focus on the Cislunar region as a future operational hub. Multiple stakeholders—ranging from national space agencies to commercial operators—are advancing plans to deploy infrastructure in Cislunar space, including lunar orbiting platforms, communication relays, navigation aids, and scientific instruments. With this anticipated growth comes the pressing need to manage complex constellations of spacecraft, particularly small satellites, in a region that is dynamically and operationally distinct from Earth-centric orbits.

Unlike low Earth orbit (LEO), where constellations benefit from strong ground coverage and established control mechanisms, Cislunar orbits suffer from:

- Highly perturbed dynamical environments, particularly in near-rectilinear halo orbits (NRHOs) and other three-body regimes,
- Limited opportunities for frequent ground communication, especially in lunar far-side orbits,
- Increased communication latency and propagation delay due to the Earth-Moon distance,
- Operational constraints due to power cycling, thermal limits, and variable sunlight exposure,
- A rise in projected space traffic and potential debris buildup, especially with commercial lunar payload deliveries increasing.

In such an environment, conventional centralized control architectures and static planning methodologies are insufficient. They rely heavily on ground-based updates, are not responsive to real-time disturbances, and do not scale efficiently with constellation size. Furthermore, current autonomous techniques are often tailored for attitude control or isolated maneuvers, rather than for collaborative constellation-wide resource and trajectory optimization.

The specific problem this paper addresses is the lack of adaptive, resource-aware autonomy frameworks for small satellite constellations operating in Cislunar space. These platforms are constrained by:

- Limited onboard energy, often relying on intermittent solar exposure;
- Restricted computational and memory resources;
- Tight communication windows due to orbital geometry;
- High  $\Delta V$  costs for corrective maneuvers in unstable orbits;
- Decentralized data availability, especially when not all satellites have access to the same environmental data or ground support.

In the context of these constraints, trajectory planning and resource management cannot be treated as independent problems. A maneuver that optimizes coverage or link visibility may drain power or increase thermal loads. Similarly, energy-saving modes may limit maneuvering capabilities. The problem is inherently multi-objective and dynamic, requiring decisions that are responsive to real-time internal state (resource level, system health) and external conditions (link availability, proximity, environmental factors).

To effectively address this, there is a need for:

1. In-situ decision-making capabilities that can dynamically respond to changing system and mission states without reliance on ground intervention.
2. A framework to enable inter-satellite information exchange, allowing the constellation to operate as a collaborative network rather than as isolated units.
3. An in-loop resource optimization technique that adapts trajectory strategies based on real-time trade-offs between energy, communication, maneuverability, and mission priority.
4. The ability to scale this approach to constellations of varying sizes and mission objectives, ensuring compatibility with upcoming Cislunar architectures.
5. Addressing the major environmental concerns in the recent times where missions are growing and the debris as well. The balance this, the resource allocation and management are a primary requirement using autonomy as its best. The major elements of this aspect will be discussed in detail in this paper.

This paper proposes the In-loop Resource Adaptation (ILRA) framework to meet this need. ILRA links trajectory decisions to onboard resource states via cooperative ISL-driven autonomy, enabling satellites to optimize their orbits and operations collectively and adaptively. Fig. 2 and 3 portray the major need of the hour and the urgency to attain it in the recent times significantly. Addressing these issues considering today’s major concerns of operations and environmental conditions, the technique of ILRA will be discussed extensively in a structural and constructive manner. Later, the simulations will be built on this concept, and results will be displayed and discussed with the respect to the role of resource allocation in small satellite constellations.



Fig. 2. Critical elements of the Resource allocations in small satellite constellations

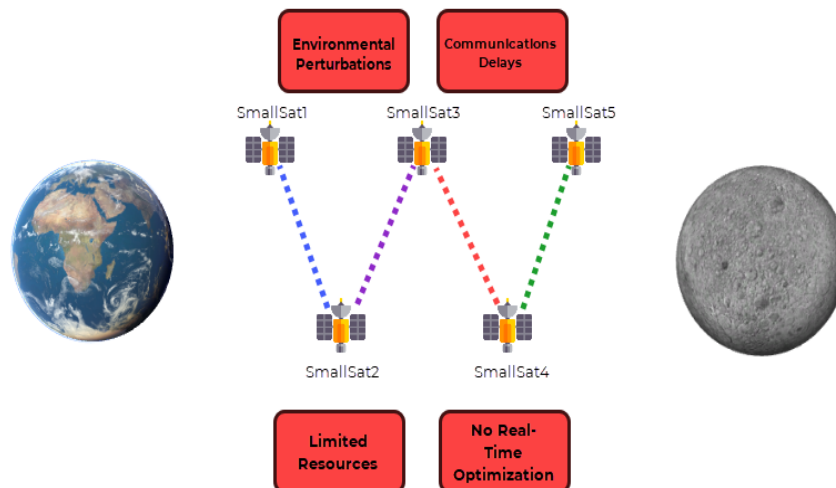


Fig. 3. Problem in transit trajectories in an inertial view

### 3. Methodology

As proposed, the In-loop Resource Adaptation (ILRA) is a dynamic, real-time resource optimization framework that operates *within the control or decision loop* of a system. Unlike conventional resource management (which reacts to predefined events or schedules), ILRA uses continuous feedback and real-time context-awareness to adapt system resources *on the fly*. With this technique, various computing and communication systems are used to enhance performance by adapting resource allocation **within an operational loop**. Unlike traditional resource adaptation, which often works in a **reactive** or **open-loop** manner, ILRA integrates resource management directly into the system's real-time operational processes, making it **adaptive, predictive, and self-optimizing**.

#### 3.1 Key characteristics

The characteristics define the way the process will be aligned to perform the best of the resource allocation in operations of the small satellite constellations. The defining characteristics include:

- **Closed-loop system:** Feedback is continuously monitored to influence the next decisions.
- **Embedded intelligence:** Machine learning or rule-based logic adapts the behavior.
- **Multidimensional optimization:** Considers energy, communication, computation, thermal load, etc.
- **Decentralized execution:** Especially useful in constellations where centralized control is infeasible.

ILRA is based on the principles of **closed-loop control** and **adaptive learning**, ensuring that resource allocation is continuously optimized based on real-time feedback. The core elements of ILRA include:

- **In-loop feedback mechanisms:** Monitors real-time system performance and adjusts resource distribution dynamically.
- **Cognitive AI and Machine Learning:** Enhances decision-making by predicting workload variations and optimizing resources accordingly.
- **Multi-objective optimization:** Balances trade-offs between multiple competing system constraints (e.g., power efficiency vs. computational performance).

#### 3.2 Why ILRA for small satellites?

##### **Cislunar Operations Are Challenging:**

- Complex gravitational dynamics (N-body problem).
- Communication delays (e.g., Earth-Moon distance ~1.28s one-way [11]).
- Sparse infrastructure → limited opportunities for ground-based control.

##### **Small Satellites Are Resource-Constrained:**

- Limited onboard power, data storage, computation.
- No room for excess redundancy.
- Often operate autonomously due to limited visibility.

##### **ILRA fills the gap by:**

- Enabling **in-orbit autonomous decision-making**.
- Maintaining **operational stability** under varying conditions.

- Improving **ISL usage efficiency**, reducing link conflicts and downtime.
- **Balancing energy** use intelligently across mission phases.

### 3.3 Application scenarios

The primary scenarios this paper focuses on are shown in Table 1 below.

Table 1. Scenarios of focus (Cislunar domain)

Scenario	ILRA Function
Dynamic Link Management	Switches ISLs based on performance and priority in real time.
Energy Aware Scheduling	Delays or throttles data processing under low solar input.
Bandwidth Allocation	Distributes communication slots fairly and based on task criticality.
Fault Resilience	Reassigns tasks across the constellation when a node is degraded.
Decentralized coordination	Each satellite makes local decisions while synchronizing globally.

### 3.4 Contrast with traditional methodologies

The method to adaptively allocate the resources is a challenging pathway but with efficient utility of autonomy and its inbuilt features, an intelligent and active adaptation of the resource utility in space is possible and can be a breakthrough in coming years. Small satellites, specifically compact sizes, are imposed with a larger challenge to optimally utilize mission resources, especially when acting as a single satellite within a larger constellation. Hence, all factors are taken into consideration to formulate a synergetic and comprehensive system of operations in the form of an In-loop Resource Adaptation (ILRA) framework. The difference in this system compared to traditional methods, if adapted and implemented well, will begin a new phase of space exploration with autonomous operations. Table 2 represents the comparison which can act as a catalyst in future implementations of the small satellite constellations with better prospects and ability to perform independently for a longer duration in Cislunar space.

Table 2. The characteristic comparison of traditional methods and ILRA

Feature	Traditional Resource Allocation	In-loop Resource Allocation
Approach	Static or periodic adaptation	Continuous, real-time adaptation
Feedback Mechanism	Open-loop or delayed	Closed-loop with real-time updates
Optimization Strategy	Fixed/predefined rules	AI-driven, adaptive learning
Efficiency	Less adaptive to dynamic conditions	Highly optimized for changing conditions
Fault Tolerance	Limited adaptability to failures	Self-correcting and resilient
Adaptivity	Low – Periodic or manual	High – Continuous and AI driven
Feedback Use	Minimal	Central to the loop
Scalability	Poor in distributed networks	High – scales across the nodes
Real-Time Performance	Reactive	Predictive and Proactive
Ground Dependence	High	Low and Autonomous

Once given this, the way forward to allocate the suitable dynamics for the smoother execution of the constellation propagation and the parameters defining the autonomous resource allocation and exchange among the satellites while in the constellation. This is only possible with vigilant and spontaneous responsiveness in the satellites to analyse their situations on orbit and take actions for calling adjustments in their resources as they propagate with any halts during operations. This also expands the life span of the constellation reducing cost that require additional satellites. The following sections will take this vision forward by incorporating this methodology in the small satellite constellation in the Cislunar domain with variety of conditions and local environments of the defined operations. It is a sincere attempt to address serious issues to align Cislunar operations in a specific and reliable manner that can be retained for years to come and contribute substantially towards sustainability.

#### 4. Aligned Dynamics – Operations and Resource Control

Once the method is defined, specific dynamics are then defined, arranged, and sorted according to situations and conditions involved during constellation operations. The following expressions have been built to navigate through the major simulations performed for this paper.

First, the primary characteristic for the propagation scenarios within an operational environment, defining the mobility model for the small satellite constellation, are defined. For this, the pertinent geometric relationship and link budget calculations have been considered while simulating constellations for both Moon and Earth respectively [12].

The geometric relationship between the LEO and MLO satellites with the end-users are expressed as:

$$\beta_{m,n} = \arccos\left(\frac{-R_{\oplus} \cos \alpha_{m,n}}{R_{\oplus} + H}\right) + \arccos\left(\frac{R_{\oplus}}{R_{\oplus} + H}\right) - \Pi + \alpha_{m,n} \quad (1)$$

When  $0^{\circ} < \alpha_{m,n} < 90^{\circ}$ ,  $\beta_{m,n}$  can be expressed as:

$$\beta_{m,n} = \alpha_{m,n} - \arccos\left(\frac{(R_{\oplus} + H) \cos \alpha_{m,n}}{R_{\oplus} + H}\right) \quad (2)$$

The linear distance between the satellite and the  $m^{\text{th}}$  user during the  $n^{\text{th}}$  TS when  $0^{\circ} < \alpha_{m,n} < 90^{\circ}$  is given as:

$$D_{m,n} = \frac{(R_{\oplus} + H) \sin\left(\arccos\left(\frac{R_{\oplus}}{R_{\oplus} + H}\right) - \beta_{m,n}\right)}{\cos \alpha_{m,n}} \quad (3)$$

The resource allocation for the communications are referred from [13] which aligns a multi-beam and a link model needs to be defined as

$$P_r = \frac{P_t * G_t * G_r}{L_{fs} * L_m} \quad (4)$$

Reformed version is given as:  $P_r = P_t + G_t + G_r - L_{fs} - L_m$

Both transmitter and receiver gains [14] are calculated as

$$G = 10 \log_{10} \left( \frac{4\pi A}{\lambda^2} \right) \quad (5)$$

Where,  $A$  represents the area and  $\lambda$  represents the wavelength. With a free space loss as

$$L_{fs} = 10 \log_{10} \left( \frac{\lambda}{4\pi * R * 1000} \right)^2 \quad (6)$$

Where,  $R$  represents the range. To calculate the link margin,  $LKM$ , the received power and sensitivity [15] must be considered. For receiver power, the path loss is calculated using the Friis transmission equation.

$$P_r = P_t * \frac{\lambda^2}{4\pi^2 * R^2} * G_T * G_r \quad (7)$$

Where,  $P_t$  represents the transmitted power, and  $G$  represents the gain of the transmitting and receiving antennas respectively. The sensitivity,  $s$ , is determined by the receiver type used. For this paper, we have modelled optical transmitter technologies which are suitable from a power consumption standpoint. In both cases, we assume that the receiver's performance is 1000 photons per bit, which is a conservative and easy-to-obtain performance level using COTS detector technology such as Avalanche Photodiode Detectors (APDs) [16, 17].

$$LKM = P_r - s \quad (8)$$

However, in a very dynamic environment, the latencies have to be thoroughly considered and [12] is referred back to adapt an expression which takes these factors into consideration as below:

$$T = \sum_{m=1}^M T_m = \sum_{m=1}^M \frac{Q_m \sum_{n=1}^N \delta_{m,n}}{\sum_{n=1}^N \delta_{m,n} C_{m,n}} \quad (9)$$

Overall, the resources in various forms get uniformly allocated with ILRA in main execution and simulated for results. These will be incorporated in the simulations with solar radiation pressure included in the perturbation model. . The following section will develop a set-up and configure the small satellite constellations as required for both Earth and Moon. This is followed by in-depth analysis.

## 5. Set-up and Simulations

### 5.1 Earth-based Set-up

The Earth-based set up is designed considering the critical local environment and the conditions that a constellation with small satellites that would experience while being executed for the mission objectives that are to be achieved. For this paper, the primary focus is maintained on the challenges that a constellation could go through in implementing its mission objectives under constraints of being a small satellite fleet with size and weight limitations and also the environmental endurance that they could sustain in a long-term mission operation. All these factors, have been taken in due consideration and the autonomous constellation is built utilizing the proposed methodology in Section 3. The Table 3 and Fig. 4-6 represent the portrayals of the Earth-based constellations within the boundaries of the Cislunar space.

Table 3. Configuration detailing the designed small satellite constellation (Earth Side of the Cislunar space)

Parameters	Value
Orbits	7
Semi-major Axis	7000~10,000 Kms.
Inclinations	0~90 Deg.
No. of small satellites	14
Perturbations	SRP, Atm. Drag
Ground stations	4 (distinctively placed globally)
Step size	15~300 Sec.

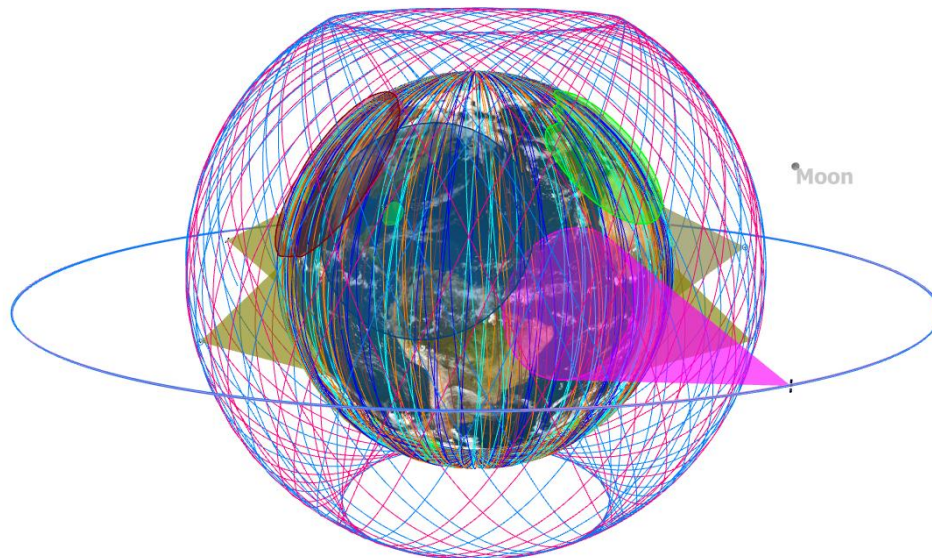


Fig. 4 Multi-layered orbital orientation in a constellation (Body frame)

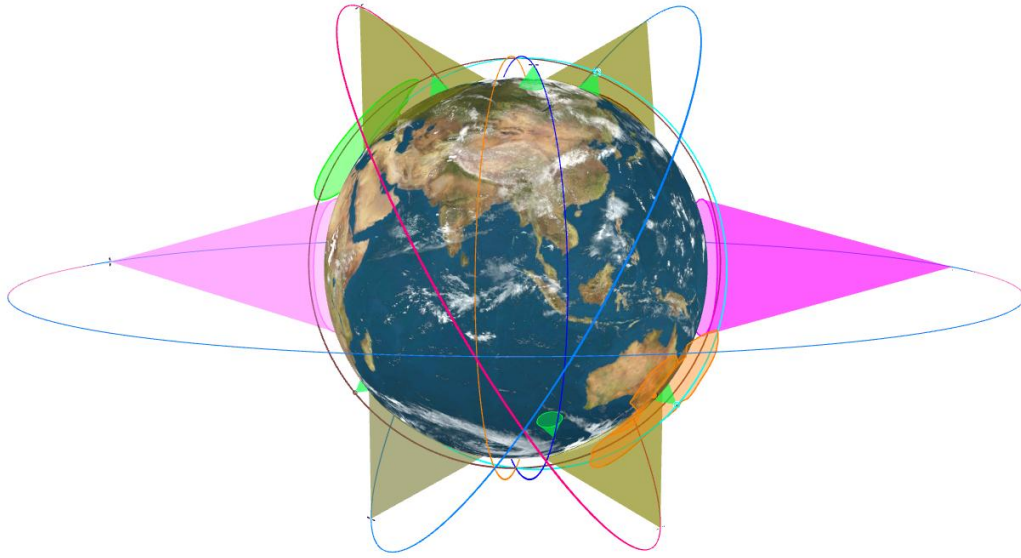


Fig. 5 Satellite propagation with different sensing abilities in multiple orbits

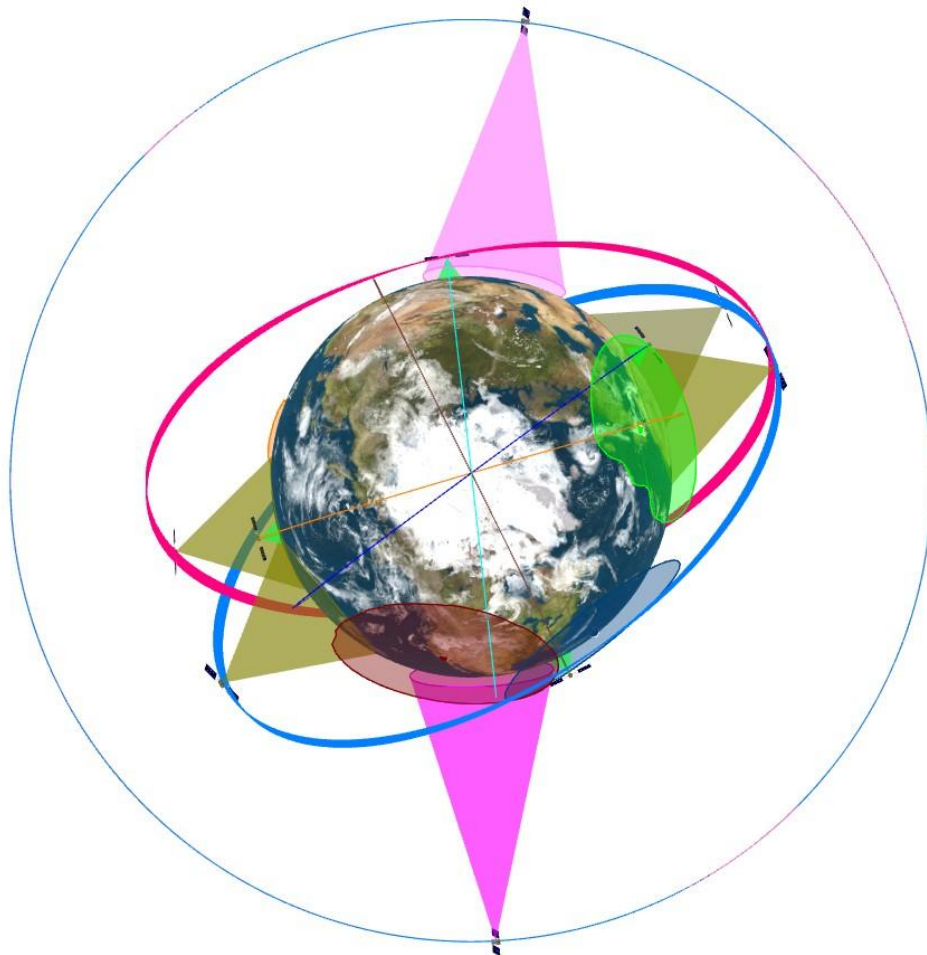


Fig. 6 A global view of all the orbits in a constellation (operational view)

5.1.1. Simulations (Multi-parametric Assessment) – Earth case

Based on the set-up aligned, the small satellite constellations and their resource allocation primarily depends on the trajectories being selected to reach the end-user autonomously using the defined technique. Considering all these factors together, some important orbital parameters have been chosen which are critical for optimizing the tracks the constellation follows during their execution. These results will be discussed later in the paper (discussions section) and the Fig. 7-10 represent the orientation of these parameters with the given set-up and the operations being executed for defined period of the mission.

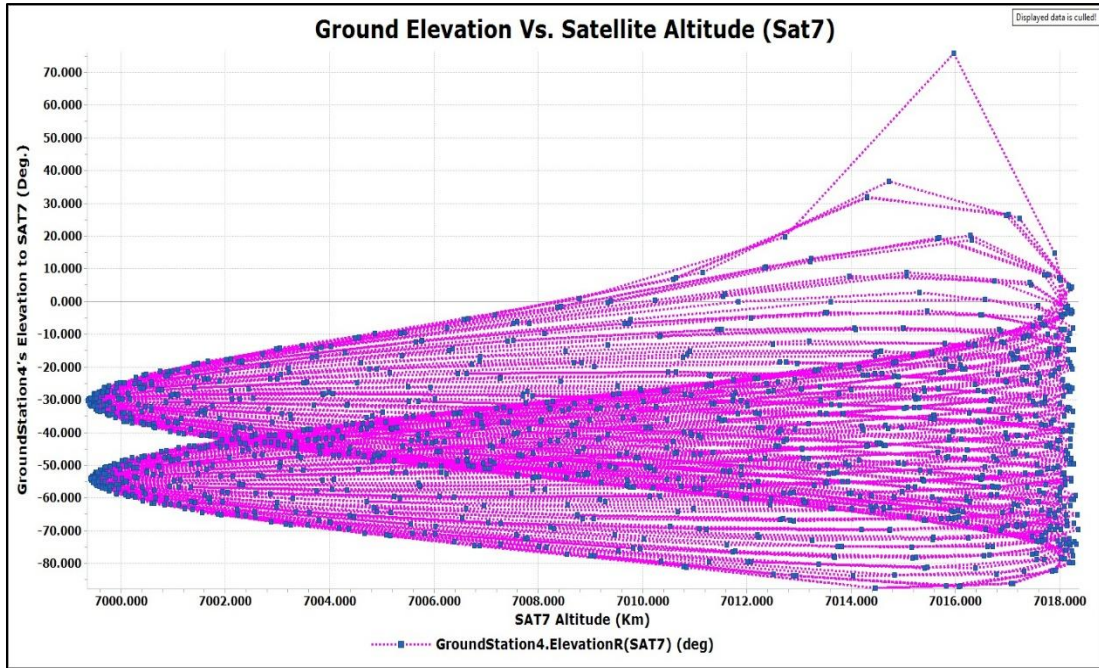


Fig. 7 Ground parameters varying with the changing altitude of the satellite (Deg. – Km.)

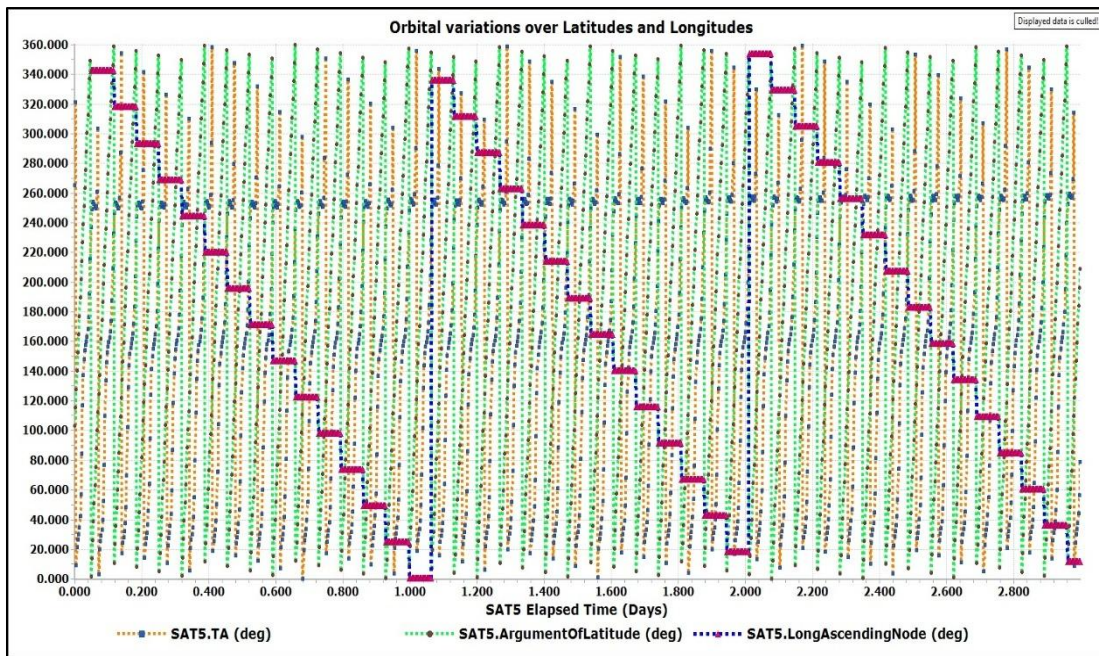


Fig. 8 Orbital parametric variations over the latitudes and longitudes of the Earth

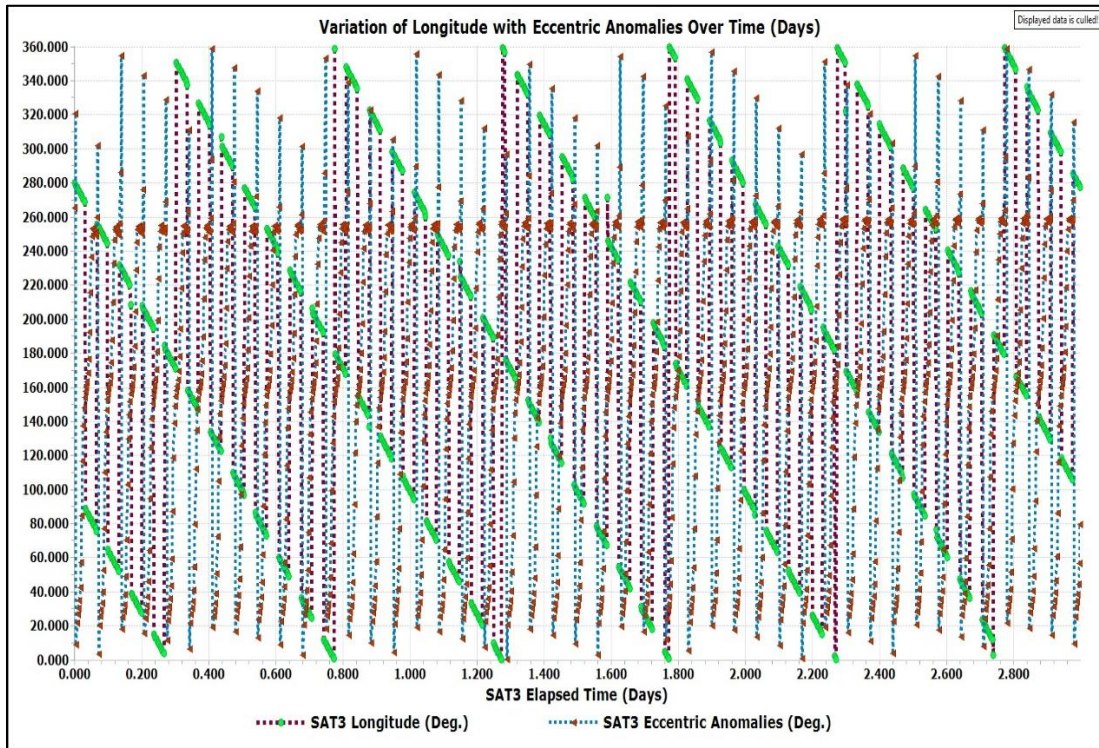


Fig. 9 Variations of the Longitude changes of Earth with satellite’s Eccentric anomalies

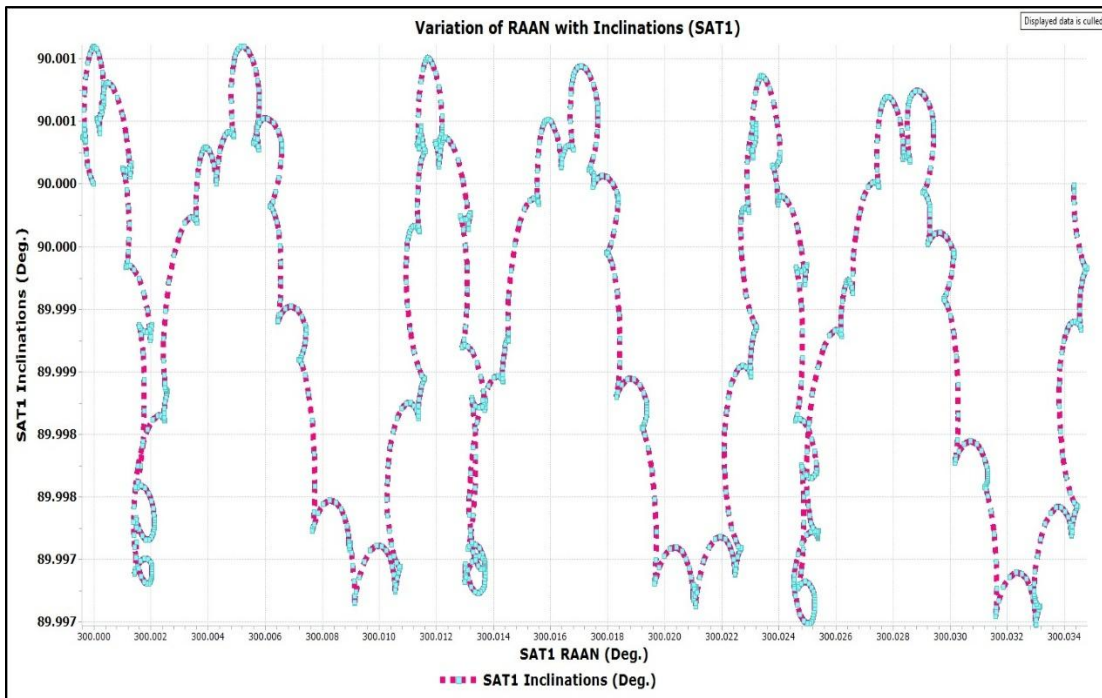


Fig. 10 Distinctive changes in RAAN with varying inclinations (Deg.)

These factors influence the performance of the constellation with small satellites extensively if the mission is for a long time and the objectives to be achieved are demanding with resource utility. Hence, these play a vital role during the operations. The role of the method proposed in this paper will contribute in resource allocation with better constellation tracks and their trajectories respectively.

### 5.1.2. Simulations (Optical Communications Optimization) – Earth case

Throughout this paper the challenges imposed on small satellites have been highlighted including the specific need for utilizing and optimizing optical communications within the larger ILRA framework. While optical communications still incur challenges such as line-of-sight availability, beam divergence and loss, and atmospheric disturbances, optical communications offer high data rates compared to traditional RF communications which is imperative for ILRA to be successful.

The table below reflects COTS technologies allowing for rapid development with flight tested hardware. With a wavelength of 1550 nm the losses due to attenuation become less problematic compared to lower wavelengths [18]. A bit rate of 100 Mbps is representative of the Tesat Spacecom CubeLCT (Laser Communication Terminal) which was selected due to its size and power consumption. A diameter of 20 cm was selected which is the equivalent to SpaceX Starlink Laser Terminal. High-performance SmallSats which are designed for high-data rate ISLs in from LEO can have a diameter ranging between 20 to 50 cm. While larger telescopes collect more photons, allowing higher bit rates, are desirable, they are larger in size and consume more power for stabilization and pointing. Dark current is modelled due to its contributions to noise and signal degradation. For the simulated Avalanche Photodiode (APD) receivers, InGaAs APDs, the dark current ranges from 1-10  $\mu$ A depending on the temperature and bias voltages.

Table 4. Configuration detailing the transmitter and receiver hardware (Earth Side of the Cislunar space)

General Optical Link Parameters		Value
Modulation Type	OOK-RZ	
Wavelength	1550 nm	
Bit Rate	100 Mbps	
Transmitter Parameters		Value
Beam Divergence	10.4 $\mu$ rad	
Pointing Loss	-1.78 dB	
Receiver Parameters		Value
Telescope Diameter	20 cm	
Dark Current	1-10 $\mu$ A	
Sensitivity	-46.4 dBm	

Utilizing FreeFlyer’s optimization and optical link capabilities, the constellation designed in section 5.1.1 was re-evaluated to minimize the link margin. There are many factors which impact link margin for ISLs which include path loss, atmospheric effects, pointing accuracy, signal to noise ratio (SNR), hardware, and frequency selection. For the purposes of constellation design, path loss, due to distance between the satellites, was determined to be the biggest factor. For the purposes of this paper, the results shown are for a single satellite representing the transmitter hardware and the rest of the constellation representing the receiver hardware. Figure 11 represents the optimal constellation design; wherein, the optimizer reduces the link margin by calculating the maximum number of connections at each step during propagation. The connections, visualized as the blue vectors between satellites in Fig. 11, are determined by line-of-sight visibility and the resulting link margin is reliant on the range between the two satellites as shown in Figures 12 and 13 respectively.

There is going to be immense need for the optical communications as the Cislunar missions rage through year-by-year and making a major void to be achieved by the space systems developers. Small satellite constellations with Inter-satellite Links (ISLs) will act as a catalyst in evolving, operating, and maintaining the Cislunar operations efficiently for long term missions. The chaos with multiple missions, debris, and dynamically changing space environment will require robust systems with balanced utility of the autonomy for sustained operations.

Confining to the parametric measures mentioned in the tables above, the simulations were planned, designed, and simulated to gather data with the given setup and orientation of the small satellites in the constellation. This particular optimized autonomous communication with optical ISLs will push several boundaries to utilize such technology in the coming years. The question is that how much optical communication will be enough to sufficiently support the operations in Cislunar operations with given resources allocations.

Optical communication plays a pivotal role in enabling high-bandwidth, low-latency data transfer across the vast distances of cislunar space, where traditional RF systems face significant limitations in power efficiency and data rates. With increasing lunar exploration and the rise of distributed satellite networks between Earth and the Moon, the need for robust, high-throughput communication becomes critical. Optical links offer higher data rates, enhanced security through narrow beam widths, and reduced susceptibility to electromagnetic interference, making them ideal for

supporting scientific payloads, autonomous operations, and real-time navigation. As the cislunar domain evolves into a hub for space infrastructure and human presence, optical communication stands as the backbone of efficient and scalable connectivity.

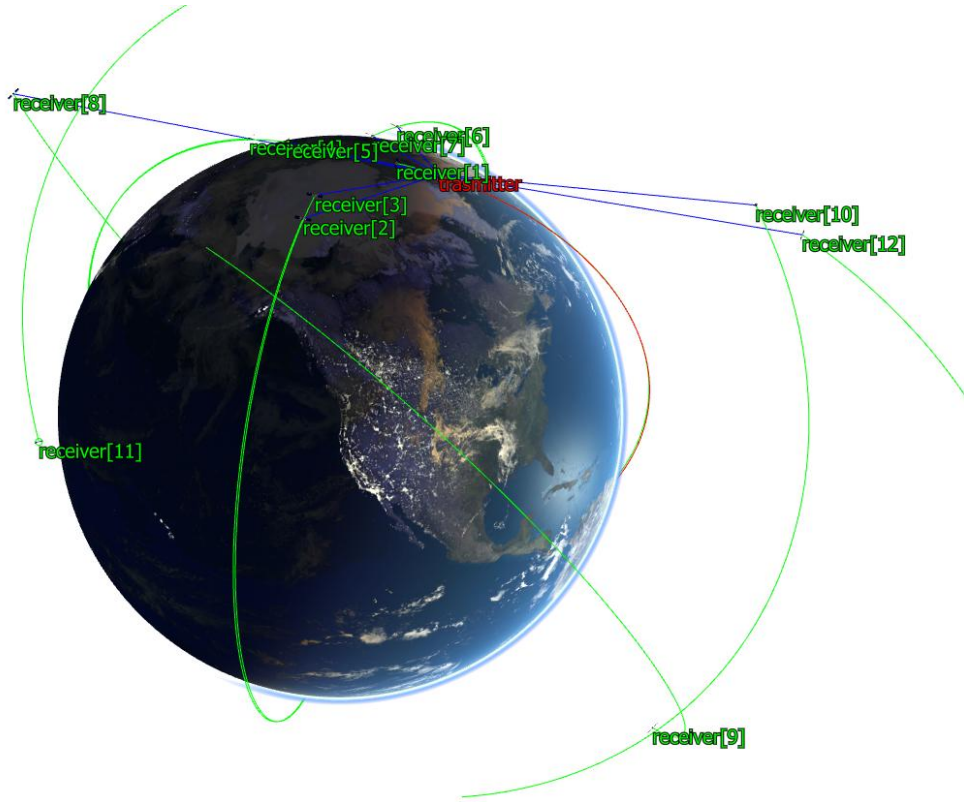


Fig. 11 Optimal constellation with optical links at peak link margin

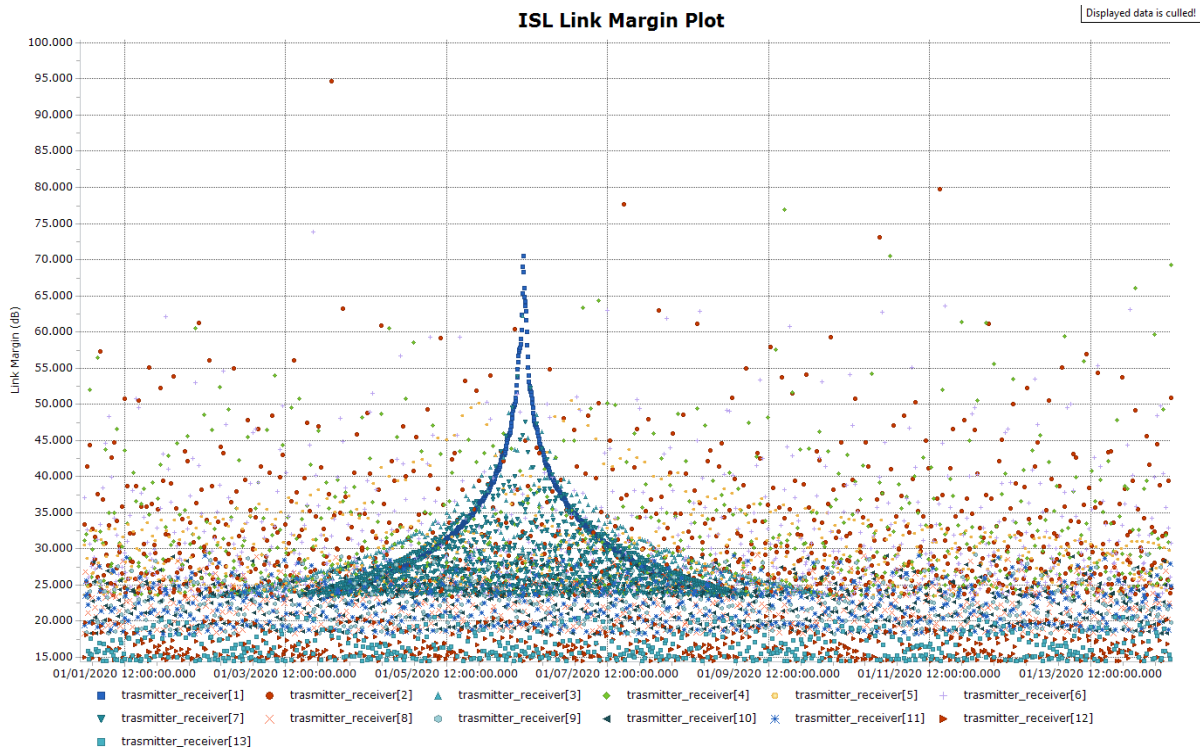


Fig. 12 ISL Link Margin (Earth Based Constellation)

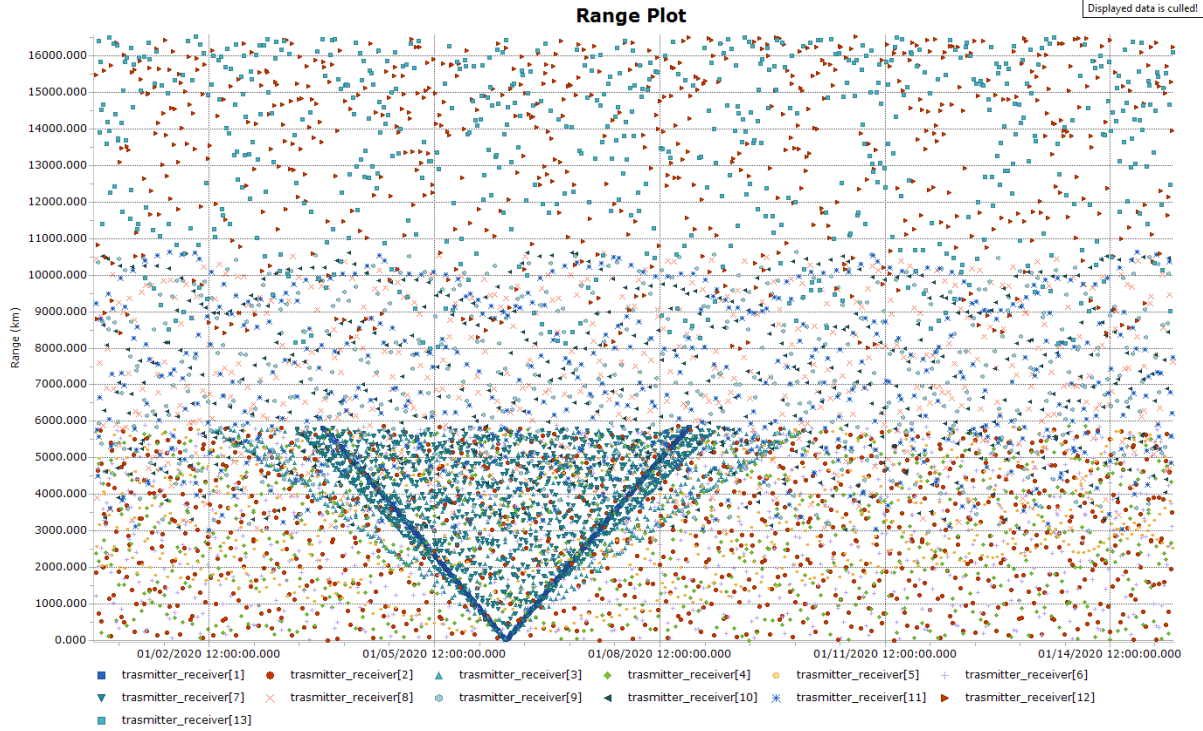


Fig. 13 Range between transmitter and receiver (Earth Based Constellation)

### 5.2 Moon-based Set-up

The Moon-based constellation will also constitute the role of the Artemis mission in the NRHO. There is no consideration for further missions in the NRHOs after Artemis arrives with Gateway. The CAPSTONE-type mission can be one defining milestone achieved which will help other small satellite missions aligning towards the futuristic missions in the coming years. It is to be understood is that the race towards Moon is intensive and the ways to develop systems, retain, and maintain the resources for a long-term specifically if the small satellites as constellation support the Artemis mission significantly. Hence, the set-up and simulations with the local environmental conditions play a vital role in resource allocation and execution for deeper analysis and implementation of these results in the smooth, precise, and continuity in execution of the Cislunar operations. Table 5 and Fig. 14-17 respectively.

Parametric analysis is a critical tool for designing and optimizing the operations of small satellite constellations in the highly dynamic and uncertain environment of cislunar space. By systematically varying mission parameters—such as orbital configurations, communication link budgets, power constraints, and sensor coverage—engineers can evaluate performance trade-offs, identify sensitivities, and make informed decisions under uncertainty. In cislunar operations, where gravitational perturbations, signal delays, and limited ground contact impose complex constraints, parametric studies enable robust mission planning and predictive autonomy. They also facilitate rapid response to evolving mission requirements by allowing operators to simulate "what-if" scenarios, evaluate failure modes, and reconfigure assets with confidence. Ultimately, parametric analysis empowers resilient and efficient operations, supporting everything from optimal station-keeping strategies and communication scheduling to dynamic task allocation in autonomous multi-satellite systems.

Table 5. Configuration detailing of the designed small satellite constellation (Moon Side of the Cislunar space)

Parameters	Value
Orbits	8 (One NRHO for Artemis)
Semi-major Axis	3000~10,000 Kms.
Inclinations	0~90 Deg. (constellation orbits); NRHO
No. of small satellites	15 (including an Artemis mission)
Perturbations	Earth, Moon, SRP
Ground stations	5 (distinctively placed on Moon; mainly focused on poles)
Step size	15~300 Sec.



Fig. 14. Cislunar orientation with constellation propagation over Moon with NRHO (Artemis)

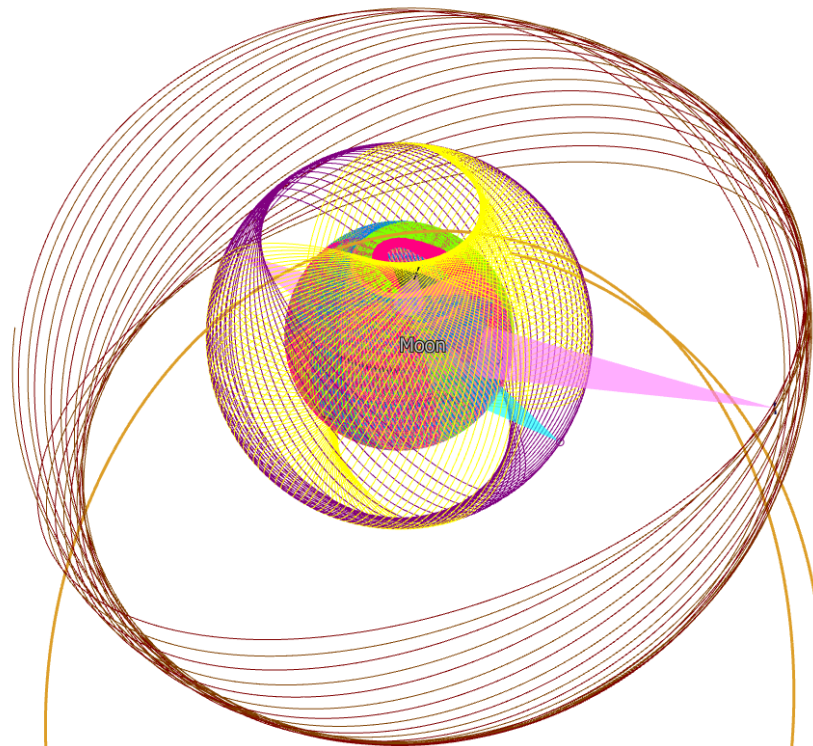


Fig. 15 Constellation propagation in body frame (Moon side of operations)

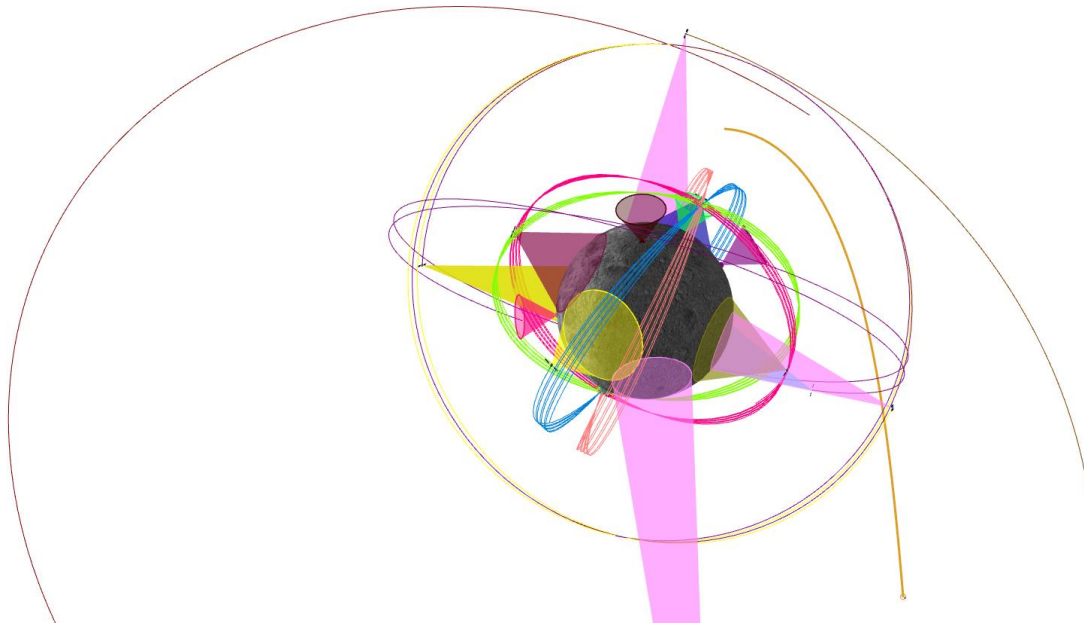


Fig. 16 Inertial frame of operations with small satellite constellation in view

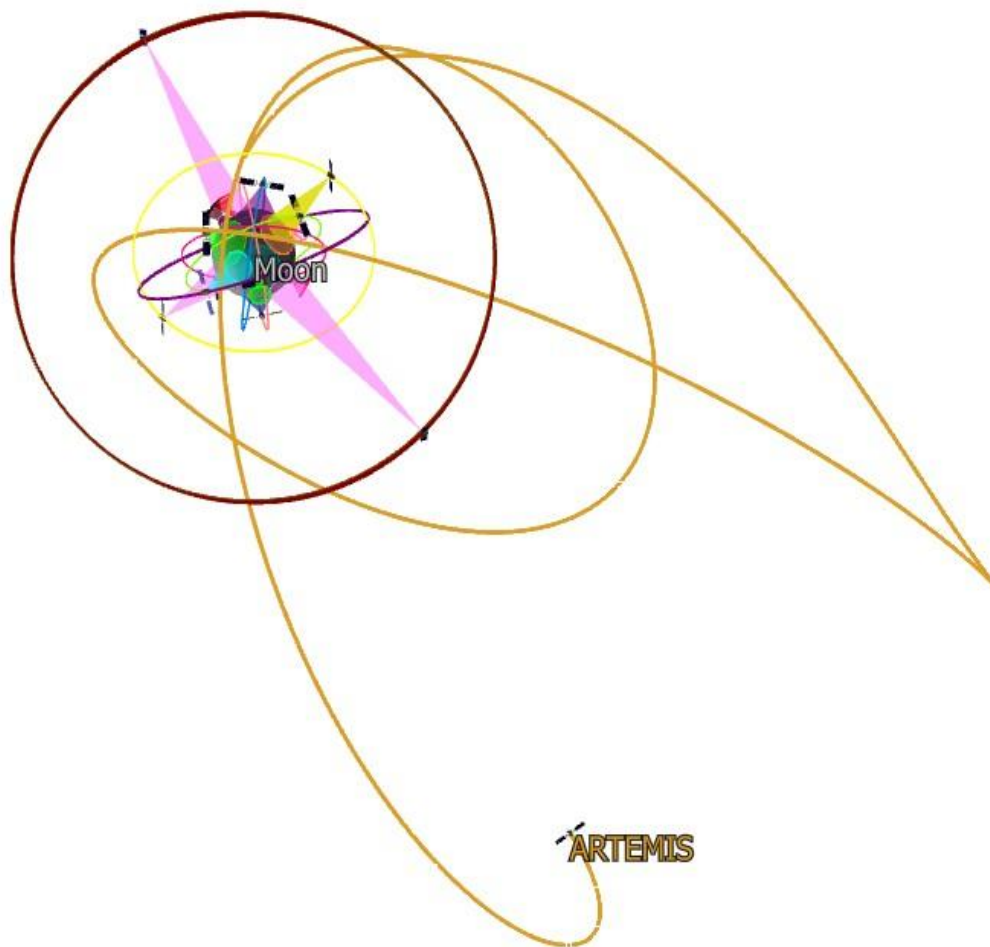


Fig. 17 Constellation operations in wider view while Artemis (Gateway) executes its mission

5.2.1. Simulations (Multi-parametric Assessment) – Moon case

The Moon’s side of the constellations operate in a heavy influence of Solar Radiation Pressure (SRP) and local perturbations due to thin atmosphere and lower gravity on Moon. This needs to be simulated with essential parameters that will be responsible for the resource management over Moon and also coordinate the resources after landings from Artemis. This needs to be critically discussed and implemented with variety of simulations but this paper will focus on the resource allocation in alignment with the set-up above and the methodology proposed. Fig. 18-22 brings about the significant analysis with the form of multi-parametric assessment of the constellation and Artemis execution in a single frame.

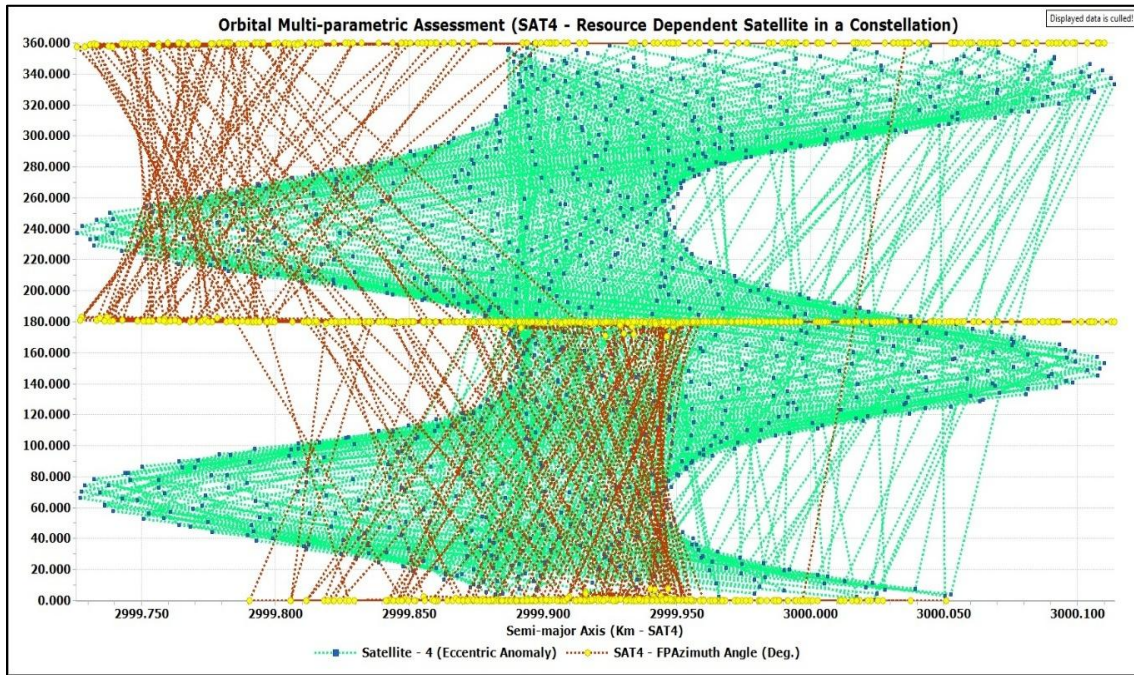


Fig. 18 Multi-orbital parametric assessment with SAT-4 as a reference

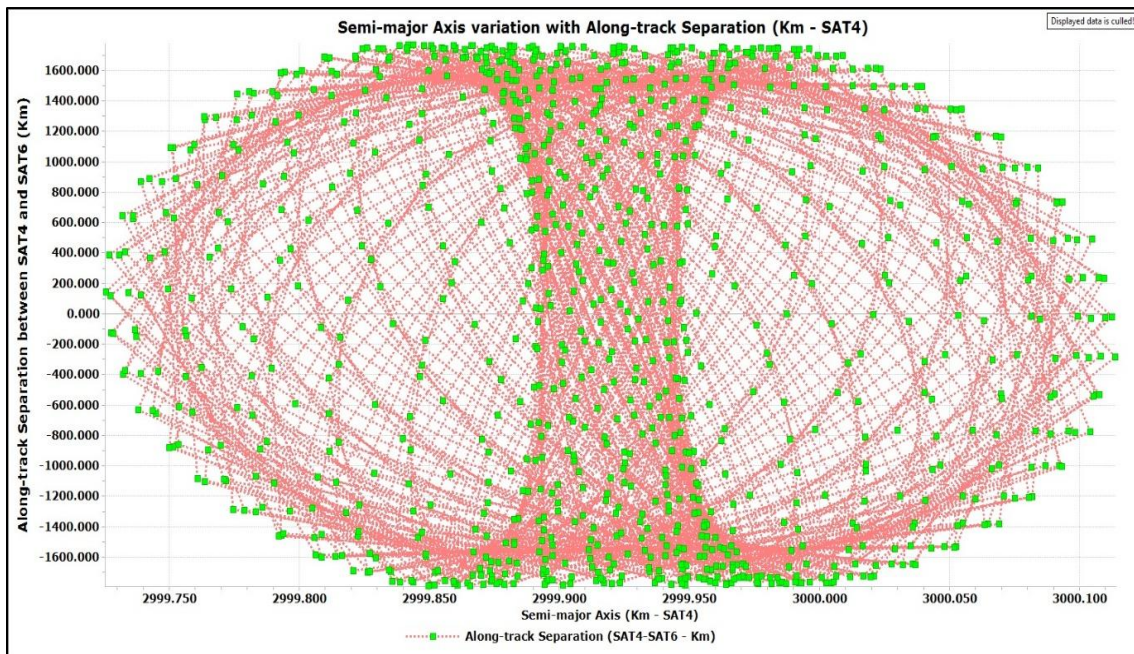


Fig. 19 Relative motion navigation assessment among the constellated small satellites

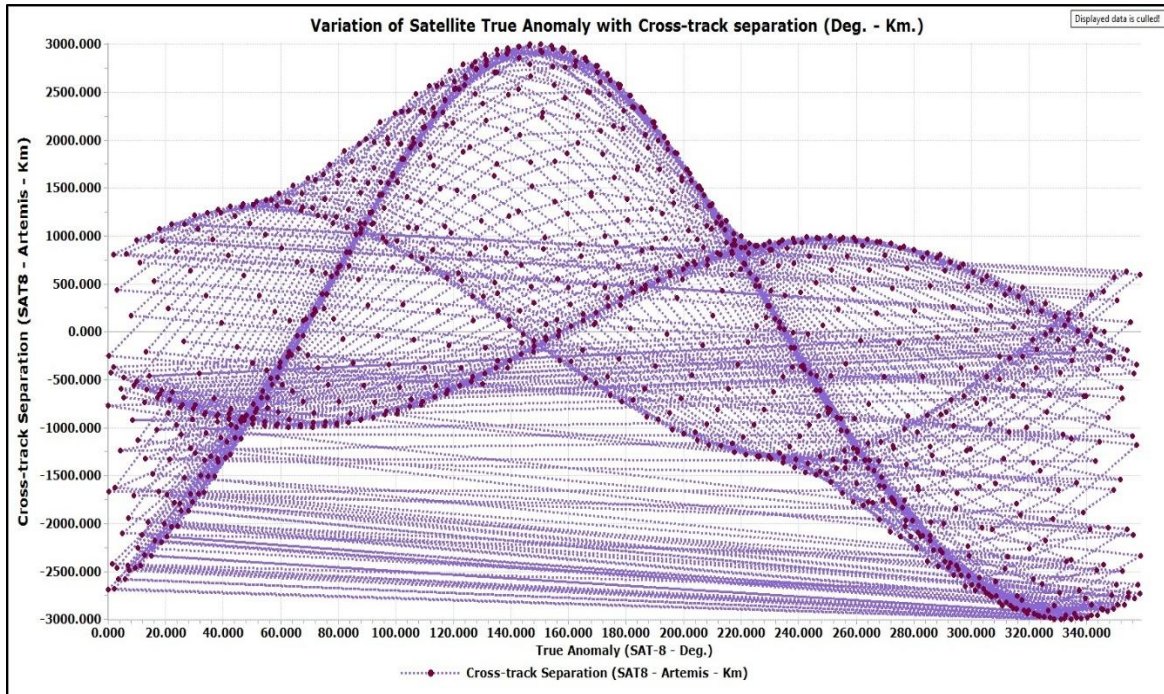


Fig. 20 Relative motion navigation among constellated small satellite and the Artemis (Gateway)

**Variation of Azimuth and Elevation Over Approaching Ground Stations (Constellation and Artemis)**

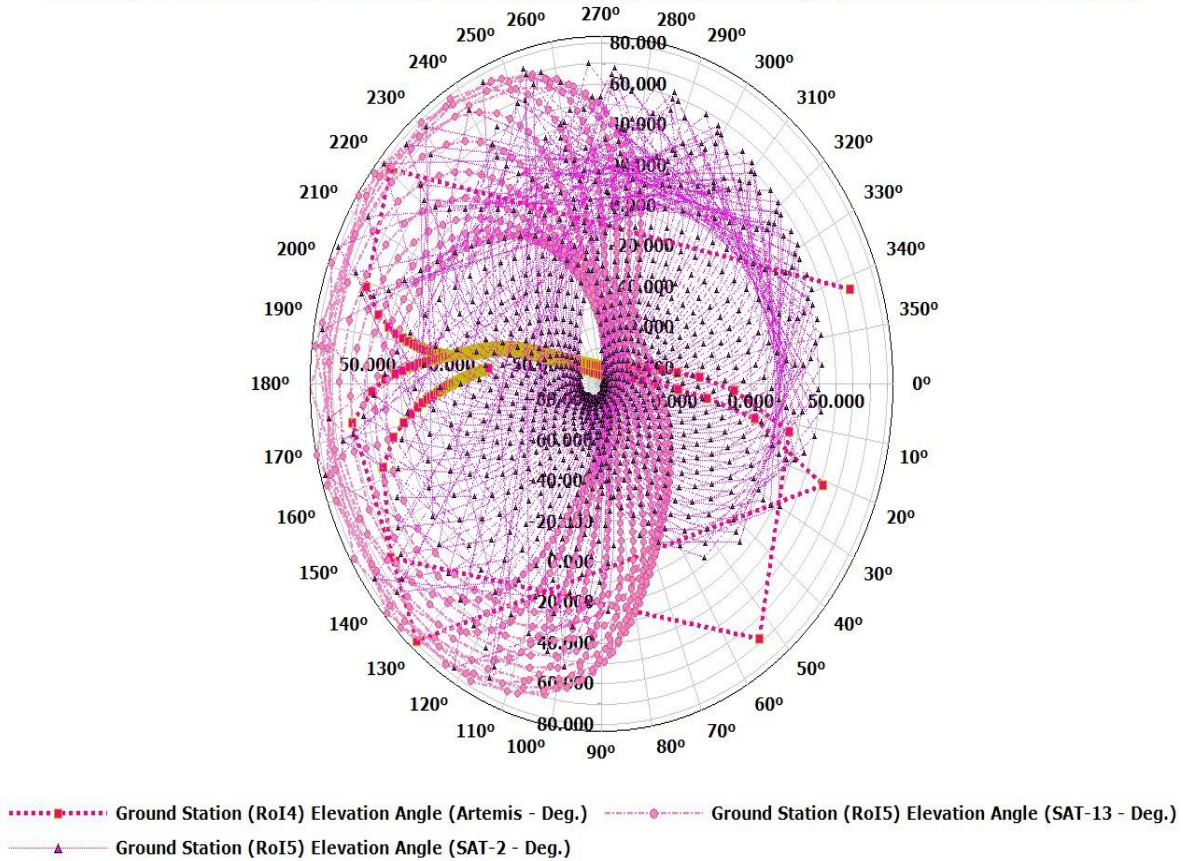


Fig. 21. Ground base-related parametric assessment with each approaching small satellite.

### 5.2.2. Simulations (Optical Communications Optimization) – Moon case

For lunar orbiting spacecraft optical communications present several advantages and disadvantages when compared to Earth orbiting spacecraft. Because there is no atmosphere on the Moon, there are no atmospheric turbulence effects such as scintillation, rain attenuation, or cloud cover to consider. These factors are a significant advantage for optical communication as the absence of atmospheric interference ensures that optical links will remain stable, and the system will be able to maintain higher data rates without needing to account for weather-related signal attenuation. While the lack of an atmosphere has proven advantages, high precision pointing is still required especially considering the relative velocity between the spacecraft.

The constellation designed in section 5.2.1 includes a variety of LLO, MLO, and NRHO satellites which each offer distinct advantages for the ILRA framework. The spacecraft in LLO can be used for detailed lunar observations and orbital operations while also offering proximity passes to drive down the link margin. The satellites in MLO can be used as a communication relay between the satellites in LLO and NRHO or back to Earth. While operating a spacecraft in MLO brings additional challenges such as station keeping, for the purposes of this paper, the MLO spacecraft were included for redundancy and predictable alignment windows. To ensure the beam stays sufficiently focused across the long distance between the MLO spacecraft and LLO spacecraft, beam divergence is carefully controlled in this simulation. This is specifically important because path loss increases with distance, as described by the inverse square law. Additionally, even with increased radiation shielding, dark current will be higher for the lunar spacecraft considering dark current typically increases with higher temperatures. Along with the increased temperatures or introduction of higher temperature fluctuations, higher radiation leading to higher leakage current, and radiation-induced degradation are considered.

The table below reflects the COTS technologies presented in Table 4 with necessary adjustments for lunar orbiting spacecraft.

Table 6. Configuration detailing the transmitter and receiver hardware (Moon Side of the Cislunar space)

<b>General Optical Link Parameters</b>		<b>Value</b>
Modulation Type	OOK-RZ	
Wavelength	1550 nm	
Bit Rate	100 Mbps	
<b>Transmitter Parameters</b>		<b>Value</b>
Beam Divergence	10.4 $\mu$ rad	
Pointing Loss	-1.78 dB	
<b>Receiver Parameters</b>		<b>Value</b>
Telescope Diameter	20 cm	
Dark Current	5-30 $\mu$ A	
Sensitivity	-39.1 dBm	

Utilizing the same approach mentioned in section 5.1.1, FreeFlyer’s optimization and optical link capabilities was used to reevaluate the constellation designed in section 5.2.1. For the purposes of this simulation, the results shown are for a single satellite representing the transmitter hardware and the rest of the constellation representing the receiver hardware. Figure 22 represents the optimal constellation design; wherein, the optimizer reduces the link margin by calculating the maximum number of connections at each step during propagation. The connections, visualized as the blue vectors between satellites in Fig. 22, are determined by line-of-sight visibility and the resulting link margin is reliant on the range between the two satellites as shown in Figures 23 and 24 respectively.

As lunar exploration advances toward sustained human and robotic presence, the formation of small satellite constellations in lunar orbit becomes essential for persistent coverage, autonomous operations, and distributed sensing. These constellations can provide continuous relay services, real-time situational awareness, and support for navigation and science missions. Optical communication from these lunar constellations back to Earth is crucial to overcome the bandwidth and latency limitations of RF systems, ensuring rapid, secure, and high-capacity data transfer. By leveraging laser links, these constellations can support high-volume scientific data downlink, resilient inter-satellite networking, and seamless integration with terrestrial infrastructures—thereby enabling a scalable and intelligent lunar communications architecture.

Laser-based links enable gigabit-per-second downlinks, precise pointing, and enhanced signal integrity, which are vital for handling the increasing volume of scientific and telemetry data expected from future lunar assets. Moreover, the integration of optical inter-satellite links (OISLs) within the constellation enables resilient, self-organizing

networks that can dynamically route information, adapt to mission needs, and function autonomously in shadowed or communication-challenged regions. Ultimately, such architectures are not just enablers of lunar sustainability—they represent the cornerstone for a scalable, intelligent, and interoperable space communications infrastructure extending beyond Earth orbit.

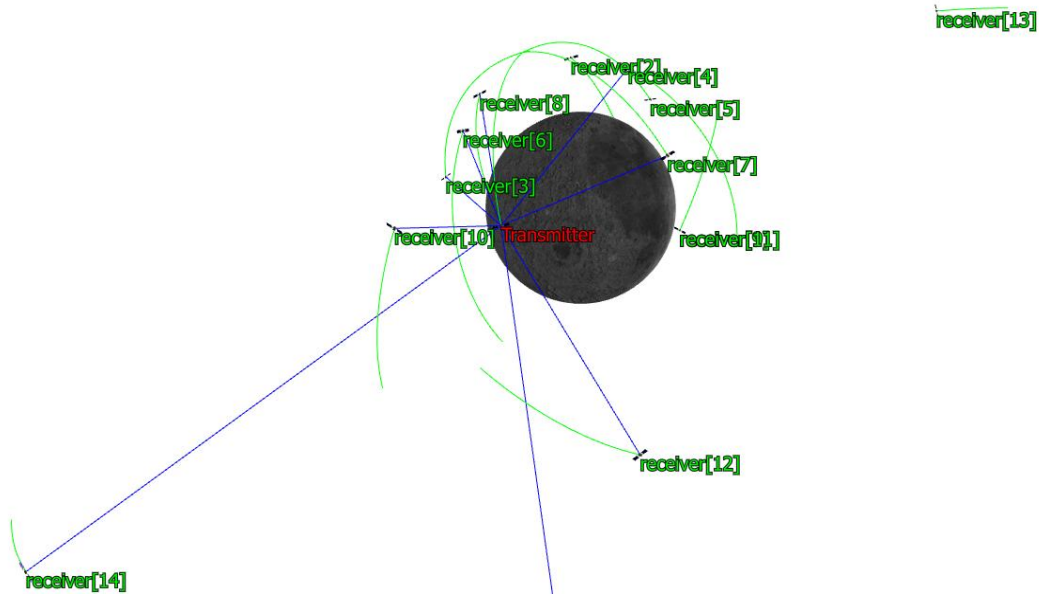


Fig. 22 Optimal constellation with optical links at peak link margin

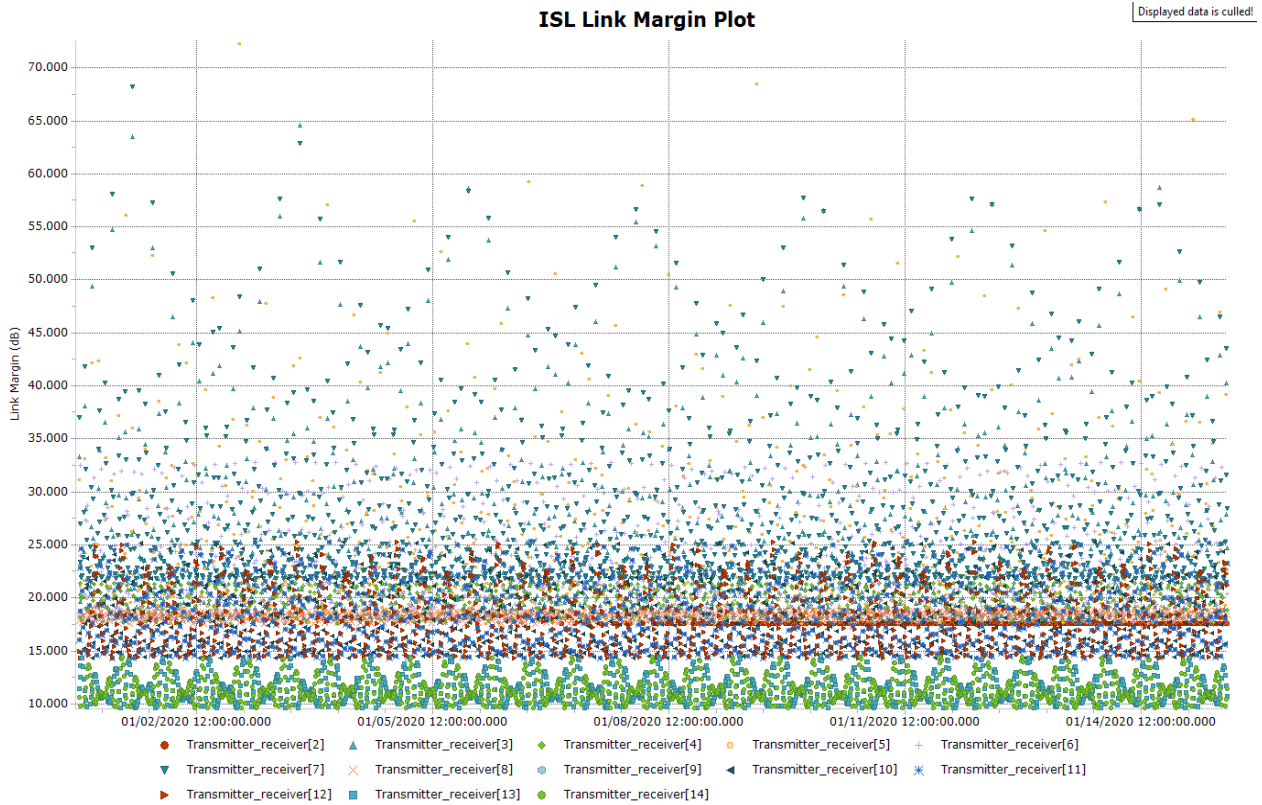


Fig. 23 Range between transmitter and receiver (Moon Based Constellation)

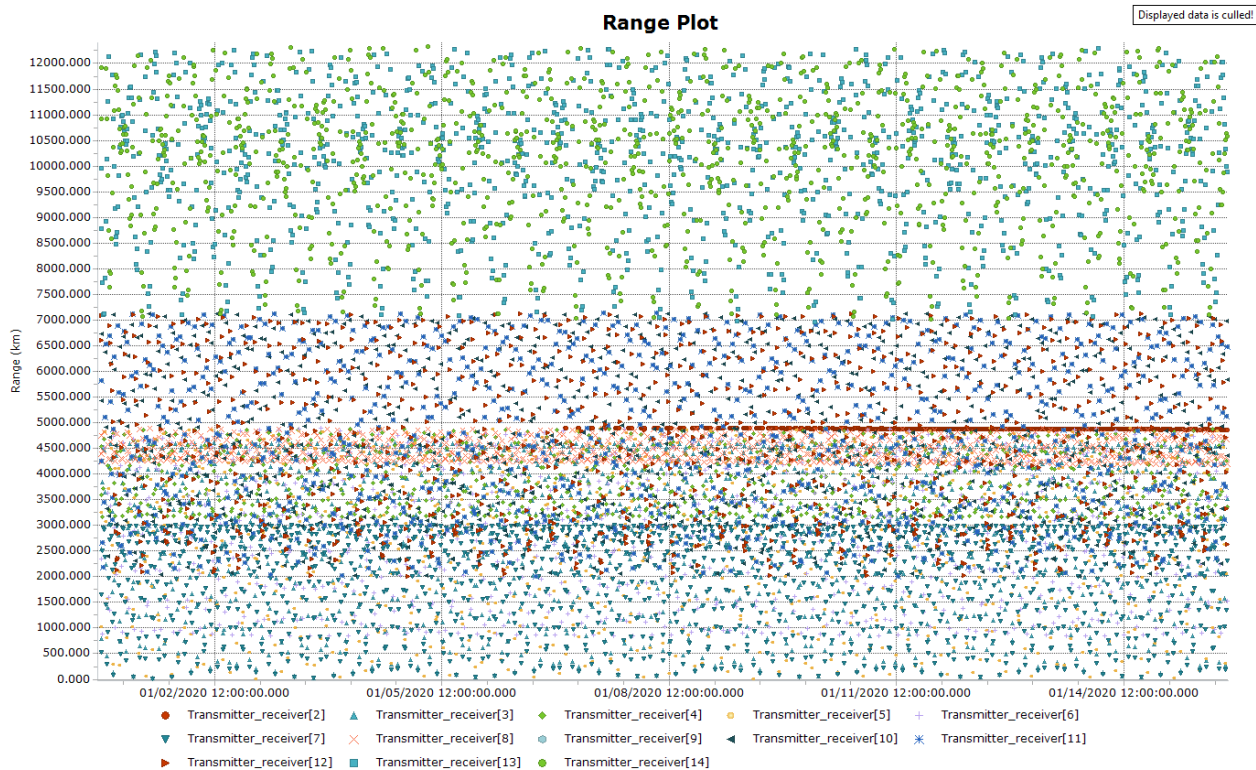


Fig. 24 Range between transmitter and receiver (Moon Based Constellation)

## 6. Discussion

The implementation of In-Loop Resource Adaptation (ILRA) within small satellite constellations operating in the Cislunar domain marks a significant step toward achieving sustained autonomy under resource-constrained and communication-limited conditions. The simulation results and system evaluations presented in this paper underscore ILRA's ability to adaptively balance competing mission requirements—such as power usage, link scheduling, and onboard processing—through real-time feedback and distributed intelligence. Notably, ILRA's closed-loop architecture enables the system to remain operationally efficient even under dynamic orbital configurations, varying environmental loads, and intermittent inter-satellite visibility. This discussion examines the practical implications of ILRA, highlights its performance trade-offs, and explores how it compares with traditional static or rule-based resource management strategies currently used in small satellite missions.

The increasing momentum toward establishing a sustained presence in Cislunar space has introduced an urgent need for efficient, autonomous, and scalable operational frameworks. As mission architectures evolve to include complex logistics, communication relays, scientific observation, and support for human exploration, the role of small satellite constellations has shifted from auxiliary systems to core mission enablers. However, their inherent limitations—such as restricted power budgets, processing capacity, and communication bandwidth—pose significant challenges to long-duration, high-tempo operations. These limitations are further amplified by the Cislunar environment, which features highly perturbed orbital regimes, intermittent ground contact, and increasing spatial congestion. In this context, the optimal allocation of onboard resources becomes not just a performance consideration but a mission-critical necessity. Without intelligent resource management, small satellites risk premature degradation, communication failures, and compromised mission outcomes. Thus, there is an immediate and strategic demand for in-orbit decision-making frameworks that can dynamically adapt to real-time constraints, enabling constellations to operate collaboratively and efficiently in this rapidly evolving operational domain.

Section 2 takes a lead in this paper to define the problem and narrow down the urgent needs of the operations in the Cislunar space specifically with regard to the utility of the small satellite constellations and their effective resource allocation and maintenance over longer missions. This has been consistently seen as a void that has to be considered with autonomy as a prime factor to balance the needs in the Cislunar space effectively. This has been the core objective of designing this research with a focus to overcome the issues with the defined methodology of ILRA in Section 3 that will be optimal, significant, and adaptable for constellations to execute their missions as required.

Section 4 gets through the essential dynamics that are utilized for addressing the challenges in the trajectory planning for resources and allocating them for small satellites in constellations considering that they have been phenomenal in their performance in the recent past missions. Hence, these constellations need a dynamic approach to develop and implement the methodology proposed in this paper. The major constraints have been taken into consideration along with the crucial parameters to be utilized efficiently in proper set-up and propagative frames of the satellite navigation and making sure that autonomy is precisely incorporated for appropriate resource allocation, maintenance significantly utilizing the on-board and on-ground autonomy.

Section 5 brings about the major set-up and orientation of the constellation designs for the Earth and Moon within the frame of Cislunar operations. A lot of trials have been made to make optimal constellation design that will serve the resource utility efficiently in a long run. Hence, the designs were finalized according to the local environments and the orientations needed for their respective operating bodies (Earth or Moon) within Cislunar zone. This has been a sincere effort towards a sustainable journey towards stable and long-term operations of Cislunar space with small satellite constellations as significant contributors.

Section 5.1.1 portrays the parametric analysis of the Earth-side of the Cislunar Space with the designed small satellite constellation operating in the given environment. Fig. 7 to Fig. 10 represent various parameters being analyzed while the constellation is being propagated under the local environment rigorously to ascertain the need of the hour and get the best of the outcomes to ensure sustainable operations in Cislunar domain. Fig. 7 has detailed in the plot the variation of the ground station elevation with the varying altitude of the satellites in constellation. This is significant to monitor and align in continuity and autonomously to smoothly and precisely navigate in aggressively dominant space perturbations due to changing environmental conditions in due course of their propagative time. The plot shows the variations with reference to SAT7 and small out of pattern strong variations may happen due to swiftly changing environmental conditions but overall remains stable. Hence, Autonomy needs to be deployed to ensure these spikes suddenly do not cause adverse issues on the satellite system during the operations.

Fig. 8 has a different perspective to share regarding this propagation of the constellation. The changes of the orbital elements over the latitudes and the longitudes are of significant importance on the Earth's side of the Cislunar space. The latitude and longitude of a satellite's ground track on Earth are direct manifestations of its orbital elements, especially inclination, right ascension of the ascending node (RAAN), and true anomaly. The inclination governs the maximum and minimum latitudes the satellite can reach, essentially defining the north-south boundaries of its coverage. Meanwhile, the longitude of the satellite's sub-point is influenced by the satellite's progression through its orbit (true anomaly and RAAN) and Earth's rotation, which causes the ground track to shift westward over successive orbits. These geographic projections are crucial for planning communication access, energy usage, and task scheduling, as satellites may encounter varying resource demands depending on the Earth regions they overfly—such as higher downlink loads over ground stations or increased thermal loads near the equator. In ILRA, this geographic dependency plays a pivotal role in predicting and adapting resource allocation in real time. Fig. 8 shows the essence of this through analysing the parameters that are significant in the stability of the satellite in a constellation. True Anomaly, Argument of Latitude, and the Longitudinal Ascending Node show essential anomalies that can originate from the continuous propagation of the satellites in alter the orbit if needed under specific use of autonomy.

Fig. 9 brings about the contrast between the longitudinal movement of the satellites with varying the Eccentric Anomalies of the satellites in constellation. In a small satellite constellation, the variation between geographic longitude and eccentric anomaly captures the interplay between orbital mechanics and Earth-fixed operations. While eccentric anomaly represents the satellite's position along its elliptical orbit in a purely Keplerian frame, the corresponding longitude of the sub-satellite point shifts due to Earth's rotation. This contrast becomes especially pronounced in elliptical orbits, where satellites move faster near perigee and slower near apogee, causing non-uniform ground track spacing. As a result, satellites may dwell longer over certain longitudes and zip past others, leading to unequal coverage density and fluctuating resource demands (e.g., for downlink, ISL handovers, or power management). Understanding this relationship is essential for ILRA-based systems, as it enables dynamic prediction of where and when onboard resources will be most strained—allowing the constellation to adjust operations proactively for maximum efficiency and mission coverage. This has been captured through this plot over a satellite elapsed time for the period of propagation as shown. This will also guide in use of autonomy with given parametric data available for taking decisions in uncertain and disturbed situations.

Fig. 10. presents a different side of this analysis with variation of the RAAN with inclinations of the satellites in constellations over a period of time in propagation. The cloud-like structures that can be seen the plot are the cycles of the propagation of the satellite in question passing through the same point of the orbit defined over and over again with variations in the integrity of the orbit during that propagation. This means even though these cycles are autonomously maintained over a long period in time, there will be variations (in a minor level) in each cycle during propagation due to continuous changes in the operational scenarios, environment, and the conditions evolving on-orbit time-to-time.

Hence, these small bubble-like structures in each cycle need to be monitored significantly by autonomy to see any sharp variations are observed and needs an action to make changes in the orbital elements if required. This is in continuity with the phenomena observed with Fig. 8 as well.

Section 5.1.2 explained and expanded on the optical communication optimization for the Earth’s side of the cislunar space with a defined orientation. A complete explanation was given and results plotted respectively. Both the plots have been emphasized with details of the essence and critical need of it to secure the communication resources with OISL in the near future with proper budgeting and optimization efficiently over a long time. This is a contribution of a unique importance and will contribute further in the development of the constellations in the near future.

After the Earth’s side of the Cislunar space is fully represented and analysed, Section 5.2.1 portrays the parametric analysis of small satellite constellation of the Moon’s side of the Cislunar space. Fig. 18 brings out the analysis portraying the variations of the eccentric anomalies with Flight path azimuth angles over time with reference to the SAT4 in the defined constellation. The eccentric anomaly offers a precise mathematical indicator of SAT4’s position along its elliptical orbit, while the flight path azimuth angle reflects the direction of the satellite’s velocity vector with respect to the local lunar surface, projected onto a reference plane. The interplay between these two parameters becomes crucial in a Cislunar setting, where the gravitational field is significantly perturbed by three-body influences (Earth-Moon-spacecraft). As SAT4 progresses through its orbit, changes in eccentric anomaly correspond to varying orbital speeds, especially near periselene and aposelene (analogous to perigee/apogee). These speed changes, in turn, impact the rate and direction of orbital curvature, captured through the evolving azimuth angles. The plot thus reveals not only the non-linear motion characteristics of SAT4 but also highlights potential pointing, coverage, or maneuver planning constraints. Within the ILRA framework, this analysis helps predict regions where control actions, power consumption, or ISL alignment may need adaptive reallocation, supporting more intelligent and context-aware resource distribution across the constellation.

Fig. 19 plots the variations of the semi-major axis of a satellite in constellation (SAT4) with the Along-track separation with SAT6 in continuity of propagation along the given orbits and the elapsed time as shown. This is an important contribution towards the relative motion navigation and its relation with the orbital elements of the constellation. This will be deployed with autonomy to ensure the safety of the constellation over a long duration of operations. This plot provides valuable insight into the relative motion and spacing dynamics within the constellation, especially under the influence of lunar perturbations and orbital drift. The semi-major axis, being a key determinant of orbital period, directly governs the rate at which SAT4 completes its orbit compared to SAT6. Small differences in the semi-major axis can accumulate over time, causing significant changes in along-track spacing—either increasing separation (drift apart) or causing convergence, which may necessitate active separation control. The observed pattern reflects how even minor orbital adjustments or natural perturbations can lead to relative positional changes between satellites in the same orbital plane. For ILRA-based resource adaptation, tracking these variations is critical, as changes in along-track separation affect inter-satellite link quality, latency, and load balancing potential. Maintaining a desired separation range ensures effective ISL coordination, distributed tasking, and collision avoidance, particularly when no centralized control is available. This figure thus underlines the importance of integrating orbital dynamics awareness into real-time resource and communication strategies in small satellite constellations.

On a different perspective, Fig. 20 gives a major push towards aligning the variations of the True Anomaly with the Cross-track separations of the satellites in constellation. This gives ample data and strength to the autonomously operating satellites in a constellation and maintain their existence for a long time without any specific human intervention. This shows a significant insight into the spatial dynamics of the constellation by aligning the variations of the True Anomaly with the Cross-track separation between satellites. The True Anomaly, representing the actual angular position of a satellite along its orbit at a given time, is directly tied to the satellite’s phase progression. When analyzed in conjunction with Cross-track separation which measures the relative displacement between satellites in the direction perpendicular to their orbital plane which reveals how orbital geometry evolves over time due to both natural perturbations and design asymmetries in inclination, RAAN, or argument of latitude. In particular, the plot captures the moments when satellites deviate from their nominal orbital planes, highlighting times of maximum spatial dispersion or alignment. Such behavior is critical in constellation operations, as excessive cross-track separation can degrade inter-satellite link performance, reduce collaborative sensing coverage, and increase the need for corrective maneuvers. For the ILRA framework, this figure reinforces the need for real-time adaptation of communication and control strategies based on evolving orbital states. Recognizing when cross-track variations coincide with specific true anomaly ranges enables predictive planning for data relay, power budgeting, and ISL management—enhancing constellation stability and coordination in the Cislunar domain.

Finally, taking the ground autonomy into the consideration is inevitable to provide a synchronized operation for a long time with precision and consistency. Fig. 21 gives the multi-parametric operations details with parametric orientation of elevations angles from satellites as well as the Artemis’ Gateway mission. First plot was with ground

station RoI4 elevation angle with the Artemis’ gateway variation, second plot gives the ground station RoI5 elevation angle with respect to the SAT13, and finally the plot giving the variation of the ground elevation angle of RoI5 with the SAT2. The reason for arranging the results in this way is to make sure the analysis of the individual satellites with respect to the ground stations along with the orientation of the Gateway with respect to the same ground stations on Moon. Ground stations defined on Moon are the communication bases after crew or systems landing in the near future or the ones already there performing difference technology and science demonstrations and experimentations on Moon. Post Artemis-2, this will intensify and become a core portion of the Cislunar operations. Hence, the ground elevations data will help autonomy perform the best to ensure the shortest and precise orbits for the given small satellite constellation in the lunar operating conditions.

The Section 5.2.2 again represents the Optical Communication Optimization for the Moon’s side of the Cislunar space. The explanations for this aspect are given in the section itself and further work on this is still to be continued further in the near future. This is been a significant achievement to orient the resource allocation through the link budgeting and optimization for the small satellite constellations. Optimizing optical communication for the Moon-facing side of the Cislunar space is becoming increasingly critical as lunar missions’ transition from short-term exploration to sustained operations. Unlike traditional RF systems, optical links offer significantly higher data rates, lower latency, and enhanced directionality, making them ideal for handling the growing volume of scientific data, surface imagery, and autonomous navigation updates generated around the Moon. However, the Moon’s far side, often shadowed from direct Earth contact, presents unique challenges including limited line-of-sight visibility, dynamic obstruction by the lunar terrain, and high-precision pointing requirements. To overcome these, optimization strategies must account for satellite positioning, orbital dynamics, and adaptive resource scheduling to maintain stable and high-throughput optical links.

This becomes especially vital for relay satellites operating in halo orbits or near-rectilinear halo orbits (NRHOs), which serve as critical intermediaries between lunar assets and Earth. In this context, integrating ILRA-like adaptive frameworks can significantly enhance link availability and energy efficiency by adjusting beam steering, power levels, and relay handovers in real time. Ultimately, optimized optical communication will be foundational to enabling high-fidelity scientific collaboration, real-time teleoperations, and autonomous infrastructure development on and around the Moon.

## 7. Conclusion

This paper introduced and explored the concept of In-Loop Resource Adaptation (ILRA) as a robust, scalable, and intelligent methodology for managing operations within small satellite constellations deployed in the increasingly dynamic and congested Cislunar space. Recognizing the limitations of conventional open-loop planning and resource management—especially under the constraints of limited power, communication windows, and computational capacity—ILRA was proposed as a closed-loop, adaptive framework that tightly couples decision-making with real-time resource monitoring and feedback.

By integrating cognitive AI techniques, inter-satellite communication (ISLs), and resource-aware control logic, ILRA enables each satellite to autonomously evaluate its operational state and adjust task execution, data routing, and energy consumption accordingly. The system continuously adapts to changes in the orbital environment, link availability, and mission priority, making it particularly suited for decentralized operations in the Cislunar domain, where ground access is sparse and latency is significant.

Through a series of simulations and architectural insights, we demonstrated that ILRA can significantly improve resource utilization efficiency, reduce communication conflicts, and extend the operational longevity of resource-constrained platforms. Furthermore, ILRA's in-loop feedback mechanism supports mission resilience by enabling real-time fault mitigation, load balancing, and adaptive scheduling based on situational awareness.

As the space community prepares for sustained lunar presence and the rise of complex Cislunar infrastructure, ILRA offers a critical step forward in enabling autonomous, resilient, and intelligent satellite networks. Future work will focus on hardware-in-the-loop testing, extending ILRA to heterogeneous satellite swarms, and integrating it with federated learning architectures for even greater mission-level autonomy.

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## References

- [1] S. Wang, X. Tang, J. Li et al., Navigation Resource Allocation Algorithm for LEO Constellations Based on Dynamic Programming, *Remote Sensing – MDPI*, 16 (12): 2231 (2024) 1-21. DOI: 10.3390/rs16122231.
- [2] N. Pachler, J. J. G. Luis, E. F. Crawley, B. Cameron, A Unified Resource Allocation Framework and Impact Evaluation for NGSO Satellite Constellations, *International Journal of Satellite Communications and Networking*, 43:2 (2025) 77-96. DOI: 10.3390/rs16122231
- [3] T. Huang, Z. Fang, T. Qinqin et al., Integrated Computing and Networking for LEO Satellite Mega-Constellations: Architecture, Challenges and Open Issues, *IEEE wireless Communications*, 99 (2024) 1-9.
- [4] G. Wang, F. Yang, J. Song, Z. Han., Resource Allocation and Load Balancing for Beam Hopping Scheduling in Satellite-Terrestrial Communications: A Cooperative Satellite Approach, *IEEE transactions on Wireless Communications*, 24 (2025) 1339-1354.
- [5] I. Levya-Mayorga, F. Saggese, L. Li, P. Popovski, Integrated Sensing and Communications for Resource Allocation in Non-Terrestrial Networks, *IEEE Transactions on Wireless Communications*, arXiv:2407.06705, 2025.
- [6] Z. Yao, J. Zhou, L. Xiao et al., LEO intersatellite Communications: From Routing to Resource Allocation, *IEEE Vehicular Technology Magazine*, (2025) 2-12. 10.1109/MVT.2025.3530393
- [7] M. Zhang, X. Yang, Z. Bu., Resource Allocation for Beam-Hopping Based Satellite Systems With Spectrum Sharing, *IEEE Access*, 12 (2024) 1-11. Doi: 10.1109/ACCESS.2024.0429000
- [8] G. Xiangqiang, Y. Hu, Y. Shao et al., Hierarchical Dynamic Resource Allocation for Computation Offloading in LEO Satellite Networks, *IEEE Internet of Things*, 11 (2024) 19470-19484.
- [9] Y. Zhao, Z. Jiaen, Z. Chen, X. Wang, A DRL-Based Satellite Service Allocation Method in LEO Satellite Networks, *MDPI – Aerospace*, 11:5:386 (2024) 1-17. DOI: 10.3390/aerospace11050386
- [10] G. Zeng, Y.Zhan, H. Xie, C. Jiang, Resource Allocation for Networked Telemetry System of Mega LEO Satellite Constellations, *IEEE Transactions on Communications*, 70 (2022) 8215-8228. DOI: 10.1109/TCOMM.2022.3214895
- [11] NASA, Seeing the Earth, Moon, and the Sun to Scale, link: [https://www.grc.nasa.gov/www/k-12/Numbers/Math/Mathematical\\_Thinking/seeing\\_the\\_earth\\_moon.htm](https://www.grc.nasa.gov/www/k-12/Numbers/Math/Mathematical_Thinking/seeing_the_earth_moon.htm) (Accessed on: 2025.03.28)
- [12] C. Lu, J. Shi, B. Li, X. Chen., Dynamic resource allocation for low earth orbit satellite networks, *Journal of Physical Communications*, 67 (2024) 102498.
- [13] Y. Huang, S. WU, Z. Zeng et al., Sequential dynamic resource allocation in multi-beam satellite systems: A learning-based optimization method, *Chinese Journal of Astronautics*, 36 (2023) 288-301.
- [14] D. Giggenbach, M. Knopp, C. Fuchs, Link budget calculation in optical LEO satellite downlinks with on/off-keying and large signal divergence: A simplified methodology, *International Journal of Satellite Communications and Networking*, 2023;41:460-476
- [15] Fahim, M., and Sadeghi, M. Prediction Methods Required for the Design of Free Space Optical (FSO) Links. *Semantic Scholar*, 2007, <https://www.semanticscholar.org/paper/9c4dd2159467f23d97031c99128d5f5823f459af>.
- [15] Stephen B Alexander. *Optical communication receiver design*, volume 37. Society of Photo Optical, 1997.
- [16] D. Caplan. *Laser communication transmitter and receiver design*. In A. K. Majumdar and J. Ricklin, editors, *Free-Space Laser Communications: Principles and Advances*, Volume 2. Springer, 2010.
- [17] Medina, I., Hernandez-Gomez, J. J., Couder-Castaneda, C. Impact of atmospheric turbulence on OOK and BPSK modulations for satcom optical uplink, *Telecommunications Systems* (2024) 86:25-37