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MISSION AND OPERATIONS PLANNING FOR SMALL-SATELLITE CONSTELLATIONS USING AUTONOMOUS SYTEMS

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Abstract

The NewSpace Era has bought an ample of opportunities to explore the near and deep regions of the space. Small satellites have been growing in their potential and value significantly. The space industry is moving continuously towards benchmarking the LEO operations with every new launch to make the space economy more feasible for experimenting new technologies. Small satellites are pioneering the technical advancement over past two decades. The small satellite constellations are of major importance since its inception as they portray enough capability to replace traditional satellites. This paper will focus on the small satellite (under 500 kilograms) constellation mission planning with a unique prospective and two novel techniques introduced with their algorithms. The technologies developed for LEO have to be used for the real-time applications like disaster management. The way of optimally deploying satellites to form a stable constellation is presented through an autonomous system named Controlled Deployment of satellites (CODES) for operations in a stable and cost-effective manner. A sincere effort has been made towards this direction to make sure a series of creative approaches are planned and executed for a better utilization of the LEO region with minimum satellites. Another major reason for this system to be developed to avoid atmospheric damage of the Earth and obstructions to the other scientific missions. Too many satellites for a single constellation may also not be feasible and practical in thriving LEO region. Hence, a responsible approach was designed to make sure that the optimal and controlled constellations are deployed with enhanced performance over a long period of time. A detailed explanation from literature study, concept design, evolution and adaptation of this proposed technique, simulations of the proposed technique will be presented in this paper using (CODES) and a strategic methodology. This system will enable operator to decide on when and where a satellite is needed for reaching out an end-user based on sequentially implemented parameters of satellites and ground stations. In conclusion, the results and overall impact of this approach on the constellation and the earth’s environment is discussed in detail with future prospects of this research. Not only for the LEO region, the scenarios of utilizing this research for the entire CisLunar space based small satellite missions around the Moon with uniquely designed MLO region is also detailed simultaneously to form a support system for the Artemis mission in near future.

Keywords: Small satellites, Constellation, Mission planning, Controlled Deployment of Satellites (CODES), CisLunar, NewSpace

Nomenclature

Θ_i -flexibility at i^{th} target; t_j -minimum transition time between two given targets; T_u -targets not scheduled yet; Ω_{ij} - observation time windows with a start time e_{ijq} and the end time l_{ijq}; α_i -biased-priority at i^{th} target; $\bar{\varpi}_i$ -conjugate outcome of target i; μ & λ -two instance-depended tune parameters; φ_i -contention at i^{th} target; ε_{ic} -conflict set at subinterval c; $\eta(c)$-conflict set at subinterval c; δ_i - need at i^{th} target; ν_i - windows at i^{th} target; tw_i - time windows at i^{th} target; (i,n) - n^{th} time window of the i^{th} target; ϑ -priority value; ∂ -opportunities to make a target approach; N -time frame; λ & Γ - weights of priority values and time frame; Cw- sum of crucial targets in focus; θ_i - pitch angle.

Acronyms/Abbreviations

CODES – Controlled Deployment of satellites; MLO – Medium Lunar Orbit

1. Introduction

The small satellites have been an important portion of the NewSpace era. The challenges and demands to cater the best to its fulfilment as an objective remains to be the need of the hour. The competence and meeting the actual requirements of the end users play a vital role in defining the quality or the value of that asset as a scientific or technological mission. The small satellites within the 500-kilogram limit have a very important role in NewSpace revolution as they give a chance to revive the traditional way of scientific exploration and knowing what lies beyond and what has not been seen or experienced yet. The balance of cost, resources and innovative technology is a must in solving the real-time concerns and reaching out to the optimal solutions for the betterment of the society and its wellbeing. As the small satellites have been trailed with several mission and have gathered tremendous momentum in past two decades, the scope to research and embark on exploring the meaningful areas of exploration is becoming competitive and extensively challenging. But the amount of excitement and scope it provides in return is humongous and paves an important path for not only Earth orbits but makes a serious effort in supporting the deep space exploration including the Moon and its hiding mysteries.

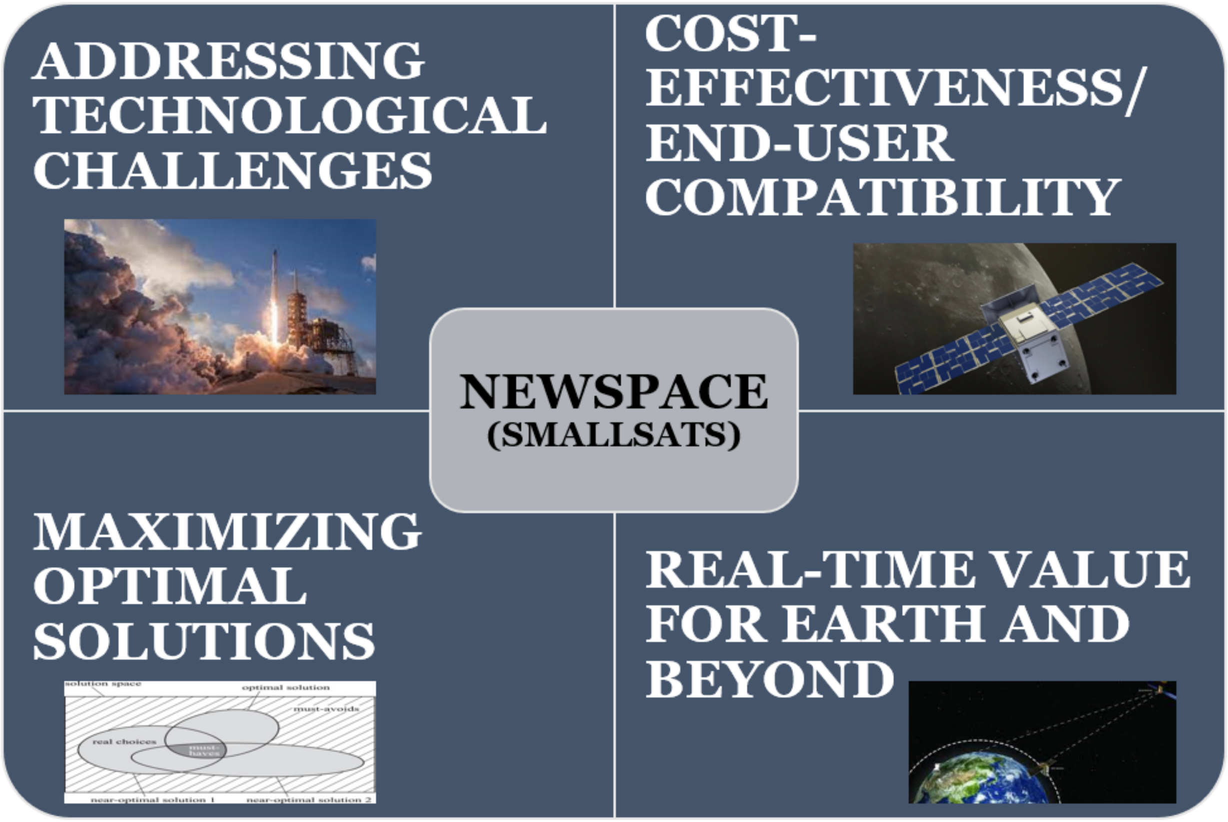


Fig. 1. NewSpace requirements for small satellites (images courtesy: CAPSTONE/Literature)

In order to utilize best of these valuable technological assets in the form of small satellites, there have been several variations proposed in the recent past to attain major applications like disaster management and monitoring issues. One of them is making of the constellations, swarms, formation flying and related ideas to enhance the overall utility and potential of these satellites. Primarily constellations have been a crucial talk of the town due to its better capabilities to deliver the maximum outcomes with minimum inputs and resource utilization. Major players in the industry like CAPELLA SPACE, SpaceX, ICEYE, OneWeb have already made an impressive start to this challenging technology and operations implementation since a decade. This has left a huge scope for research and development for the academicians and professionals to revolutionize the cost effectivity and optimal approaches overall to substantially marginalize the demand to supply with these cutting-edge technologies through productive methodologies and knowhows. Scientific and technological outreach is significantly being implemented and is taken as an unavoidable challenge for the advancement of the space systems and its distributed systems like constellations.

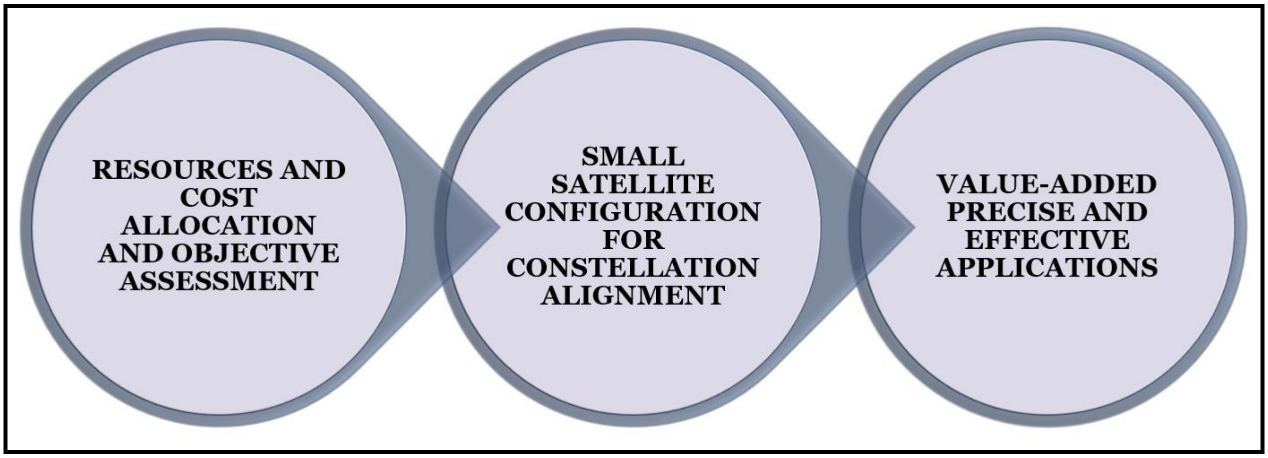


Fig. 2.Implementation and alignment process of the small satellite constellations

Though it is effectively implemented globally, the challenges persist for sufficient and efficient maintenance for a given lifecycle. The global small satellite constellation and its operation is not only about the optimization of the coverage but also optimally assigned satellites to complete certain task in a given time and have comprehensive coverage and reach out to the end user in time. Hence, the challenges need to be addressed timely to avoid latencies and conjunction along with making an effective result oriented long-term constellation for disaster management applications for Earth and tracking/relay applications for CisLunar region as a whole respectively. Few of the major challenges are depicted in the figure below:

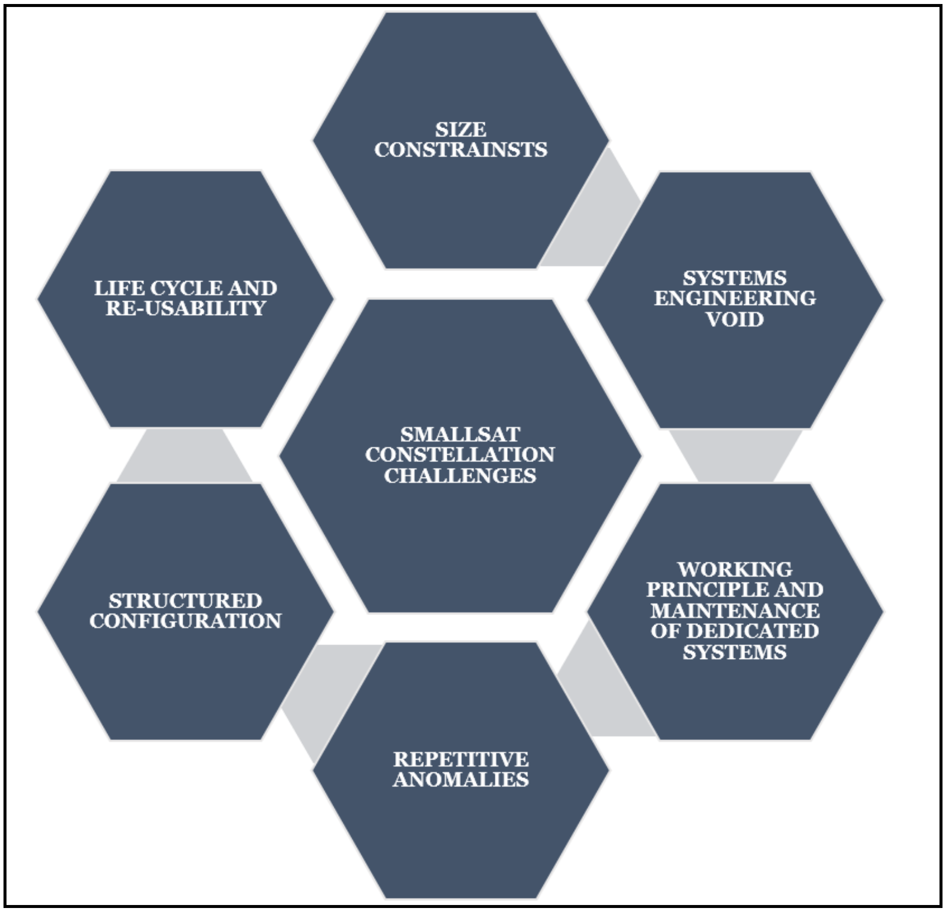


Fig. 3 Small satellite constellation challenges in real-time development and operations

There has been a significant on-going research in this area of forming and maintaining the constellations with small satellites with several innovative ideas and a purpose to align with them. It is the need of the hour to make significant impact through autonomy to be synchronized with the small satellites (<500 kilograms) as they have already proven history of delivering the required in real-time applications for imaging and several other solutions for Earth and beyond. In the similar direction, [1] provides extensive detailing of the internal organization and the major parameters involved in the design and development of the satellite constellations. Not only designing a reasonable constellation with small satellites, [2] has given a pattern-based optimization for complex regional coverage analysis which can be one of the upgrades to the present-day techniques to solve the coverage and its optimization problem. The importance of modelling is not to be left out during the execution of the constellation design for a given purpose which [3] demonstrates a framework for the same and gives a software-defined process to get a module operated by the concept of the data hybrid. On the similar lines, [4] comes up with an optimal walker constellation approach for global navigation and Augmentation system which is a large-scale real-time application in this area of expertise. The coding portions of the constellations play a vital role in aligning the satellites in particular formation to execute the given task as [5] determines the trigonometric and genetic algorithms to design and analyse the satellite constellations respectively. It has been noted through literature review that small satellites and their constraints are to be well determined along with the configuration design to make enough room for the satellites coordinating in a constellation for a given lifecycle.

The space economy today is widely depending on the small satellite market and their constellations. According to GlobeNewswire, it is estimated that this particular industry is going to be a one trillion-dollar economy by 2029 and can be a massive and competent for Low-earth and CisLunar orbits in near future. The latest trends to predict the actual numbers in small satellite constellations in recent times is pictorially depicted in Fig. 4 as shown below which are referenced from [6]:

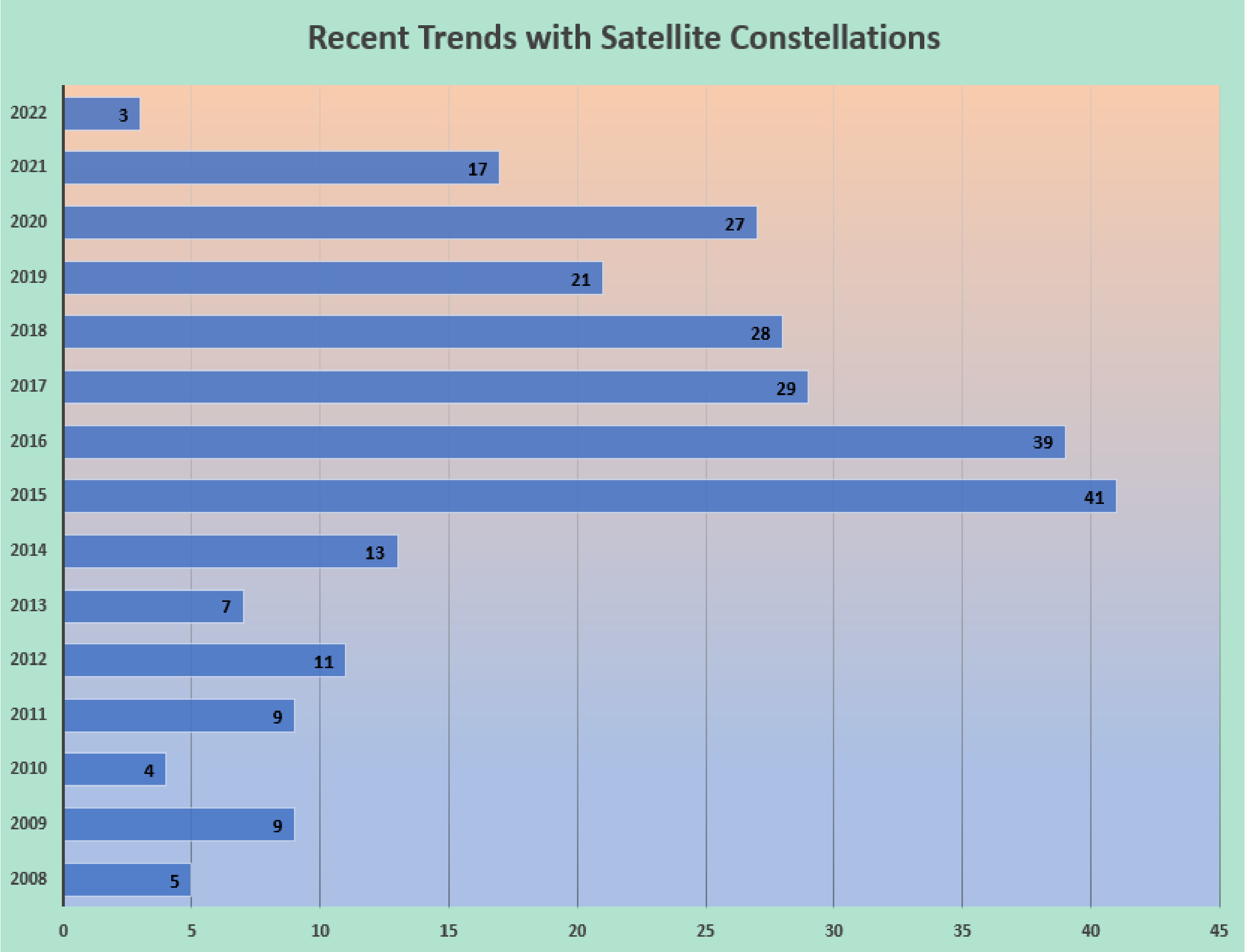


Fig. 4. Recent Trends with Satellite Constellations

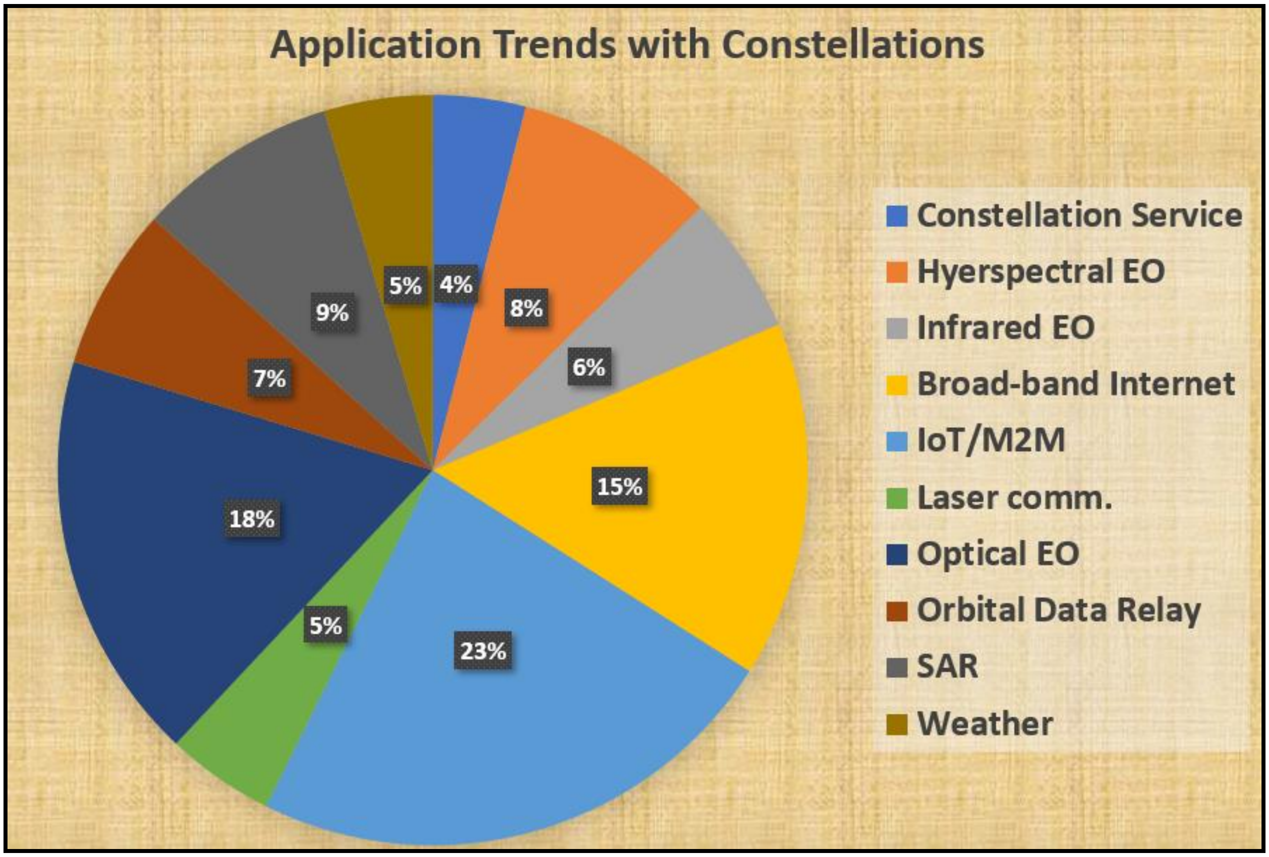


Fig. 5. Trending applications of small satellite constellations in recent years

Even after such progressive development of constellations globally, the concerns with its operation and handling under severe space environmental conditions is still questionable and has a huge scope for research and advancement. This paper will focus on such mainstream issues and target the real-time solutions to them as realistically as possible. Managing a constellation of a reasonable size is a task coming with several difficulties and unknown anomalies. They also add significant operational and maintenance costs if not planned according to certain space standards and increasing debris, perturbational changes and solar radiation pressure across the entire CisLunar Space (which indeed includes LEO, GEO, LLO, NRHO regions) respectively. Simple propagation and reduced complexity in determining the end user needs, comes with a requirement to develop scientifically demanding and creatively controllable constellations which are only possible with compact and sustainable small satellite systems. The basic functional alignment of a small satellite constellation is given as in Fig. 6.

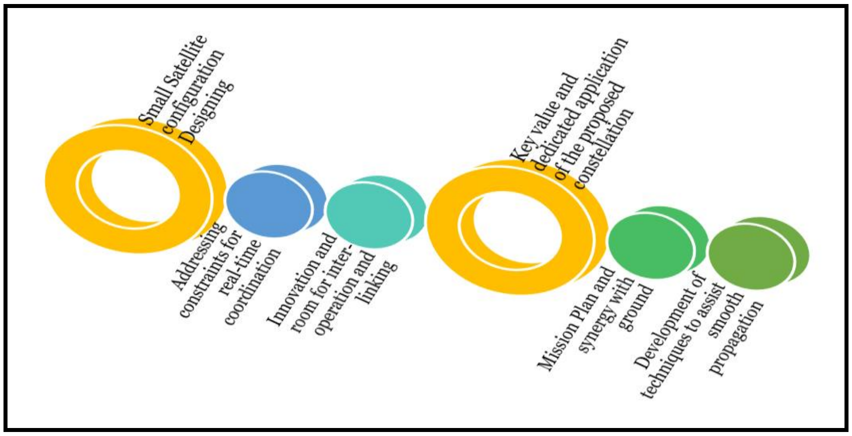


Fig. 6. Steps in determining small satellite constellation constraints and alignment process

1.1. Problem Definition

This paper will mainly focus on the mission planning and operations of the small satellite constellations using the autonomous systems and techniques. The main reason for this is that the major earth observation applications like disaster management through effective and timely earth observation and data relay. This is not only for the quick and effective transmission of the data but also to maintain the relative positioning and sequential scheduling of the satellites when in same or the different planes/orbits of a constellation. Natural disasters have taken away millions of lives and assets worth billions of dollars in just a span of a year as mentioned by United Nations Office for Disaster Risk Reduction (UNDRR) [7]. Hence, the constellations to be used as extremely crucial tools for managing these catastrophic events is inevitable and most valuable in this NewSpace Era. This is not only specific to Earth orbits but also to deep space research and exploration. Hence the cislunar space entirely was researched as a primary focus to determine valuable and optimal solutions to this region as it hold higher significance in this age of space competence and continuous development.

Having said this, the research presented in this paper primarily focuses the Low-earth orbits which are dynamics and have tremendous value for imaging/data transmission point of view (for applications specific to disaster management) and also CisLunar space specific to unique Near-rectilinear Halo Orbits (NRHO) respectively. The reason for selecting NRHO from the cislunar region is that they were unexplored yet until CAPSTONE [8] arrived to this space in later part of 2022. It is a strategic space where Artemis’ Gateway will be placed and have importance for human and systems navigation from Moon to other planets in near future.

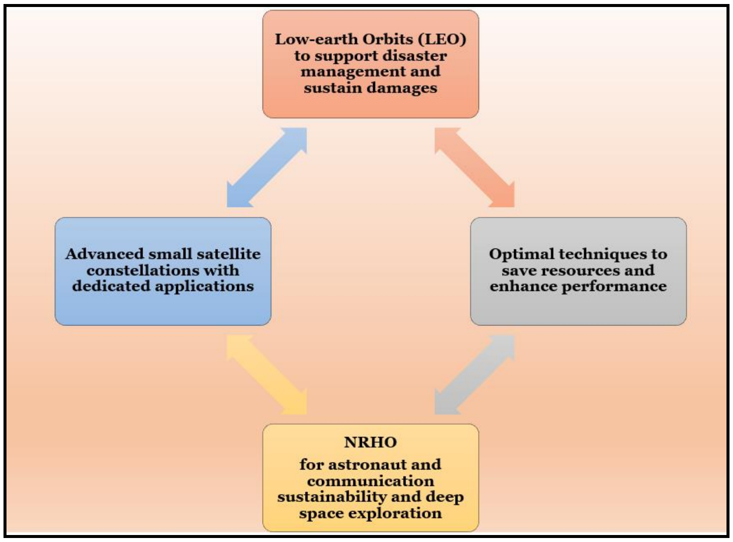


Fig. 7. Fundamental direction of the proposed research

As the figure above presents a basic foundational background and motivation of this research, this paper will address some of the key issues of the small satellite constellations. This is with respect to their management and initial steps towards a long-term sustainability and endurance under severe space environment in cislunar space as a whole. This will focus all the major aspects of the cislunar region (which includes LEO, GEO, MEO, LLO, NRHO orbits) extensively but the primary edges of this region i.e., LEO and NRHO have been the main interest of research. The mission and operations are always the major concerns in a large-scale implementation of constellations. But with small satellites, this becomes much complex and a need to configure special strategic planning and operating mechanism is inevitable. The mission planning and operations aspects of the small satellite constellations are dealt differently using various techniques and creative approaches by researchers globally. An extensive literature review was done to form a solid basis for the proposed techniques for mission planning and matters relating to operations in this frame of work. This is to engage in the format and strategical research carried out globally for the universally acceptable solutions to the recent issues with constellations. Hence, a step-wise study and analyses were done to make sure that this research contributes to the problems which are risky and are robust after implementation through their lifecycles of operation. These need to planned at the systems engineering level to secure high output and enhanced quality data being continuously carried through one ground station to the other and make the job of an operator simple and effective. Here comes in the concept of autonomy and its systematic synergy with the satellites.

The constellations are studied for their feasibility in lower earth orbits specific to certain applications like hyperspectral imaging, SAR and similar ones. The variation in design and development of each constellation changes according to the configuration desired for a small satellite and its subsystem abilities aligning them and required applications. One such application was detailed in [9] which gives in sights on the architectures for proliferated LEO-based constellations. In the similar lines, the cost-effectivity is also a prominent factor to develop the constellations for majority of end-users which [10] determines and gives sustainable solutions for the same.

The coverage and the number of satellites is a common debate while designing and operating constellations using small satellites. In this context, [11] gives an insight on exact designing of partial coverage constellations considering the oblateness of the earth. This is well supported by another article [12] validating the needed of the hour for low-cost systems to perform on-board operations. This is important due to the fact the oblateness generates the perturbations mainly J2 and it effects the operation of the satellites in a constellation. The deployment of the satellites is discussed in [13,14] which paves away for using creative techniques for traditional and hybrid-type of constellations enabling advancement in technology and research effectively. The real-time applications are the major reason to develop and operate the constellations and [15,16] gives prominent examples in this direction respectively.

The above literature was studied to understanding the major reasoning in designing, developing, deploying and operating the constellations with small satellites. It was helpful to develop proper direction for the work, vision and direction to be followed for the research proposed in this paper. After going through this process, the background and foundation for the contribution for this paper was formed. The major issues and complications of any constellation design and development lies with the mission planning following by building a sustaining its operations for its life cycle. This paper will bring about and discuss key issues with planning and scheduling with two novel algorithms developed as optimal solutions using autonomy. This will be followed by demonstrating the autonomous system of operations named Controlled Deployment of Satellites (CODES) protecting crucial environment and astronomical data with reasonable number of deployed small satellites.

In this context, there have been numerous recent studies have been explored to reach out on what others are addressing with these real-time problems of planning, scheduling and operating a small satellite-based constellation. In the similar direction, [17] comes up with a novel scheduling solution for the formations and constellations which is less complex and reduces the burden of the scheduling by splitting it into smaller subsystems. In the new of the trends, [18] brings about the planning and scheduling algorithms for the COSMOS-SkyMed constellation in a simple but effective way. The low-cost factor within the mission planning is also considered in several missions as detailed by [19] as an imaging service using CONOPS. Whereas [20] gives a framework on the recent innovative methodologies for on-board scheduling technologies. For the operations, one aspiring work was presented by [21] which presents the optimal deployment of the satellites for a mega-constellation.

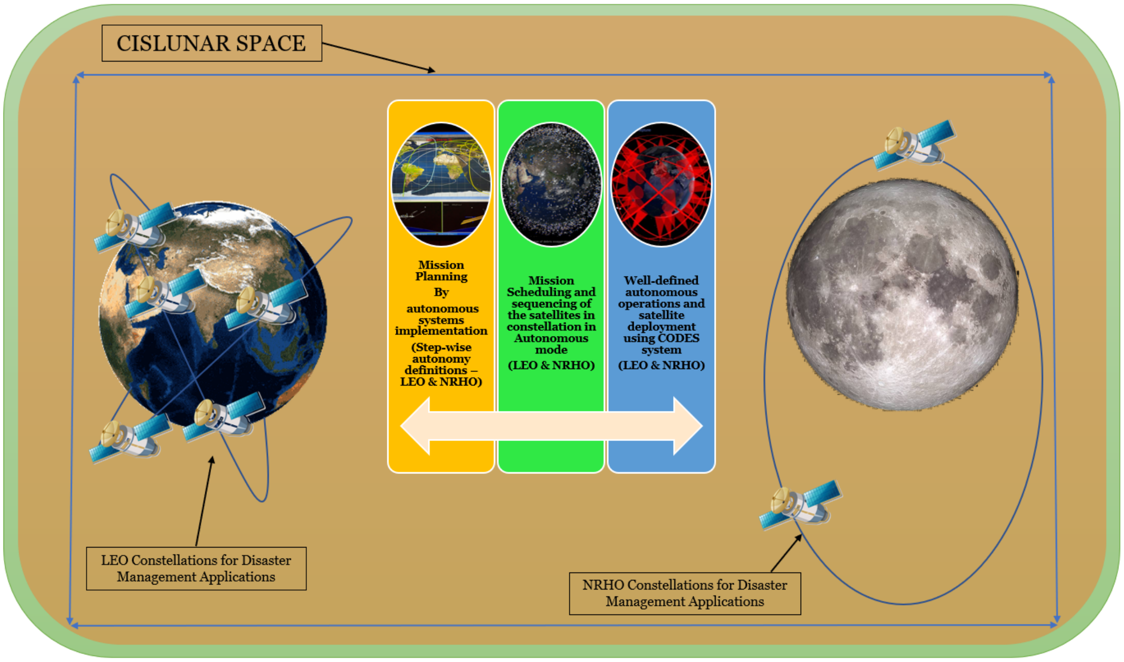


Fig. 8. Strategic problem definition and research ethos

1.2. Why Autonomy for Earth and Moon Applications?

The idea of having autonomy to be assigned for a particular task of a continuously operating satellite of a constellation always seems to be conditional and apprehending at the same time. But the idea here is not to have all the systems and operations of the satellites to function fully autonomously. The role of autonomy in constellations of small satellites will be an assist and wholesome support to the ground operators in synergy to ease their task of monitoring and updating their satellites' health and availability. This only applies to Earth-based constellations but also for the Cislunar-based NRHO as well. There will be concerns beyond particular recognition on orbit and anomalies of various sizes and scope for constellations to be operating in an ever growing and dynamic space environment. The major task in small satellite constellations is to monitor and report unknown anomalies and solve repetitive and known anomalies on orbit autonomously without the operator intervention. Hence, this will synergize the tasks among the operator and autonomy both for Earth and Moon operations.

This needs a dedicated planning and operations sequencing in a detail since the initial stages of the development of the constellations depending on the size and lifecycle of the operations. Hence, this paper will extend the synergy building among autonomous systems and the operator for an effective integration and a smooth operation for a longer duration mission. The conditions and implementation methods will be different for Earth-based and Moon-based missions as per their objectives and the operating conditions and respective environments. But the synergic application of autonomy comes with systematic alignment of the systems and controlled parameters involved with due consideration of the operational environments. In this direction, the literature was studied to know the recent trends in this area and found extensive work and interest is in progress globally. In particular, for the effective maintenance and deployment of the constellations (mostly small satellites).

For the distributed systems, [22] gives a strategic methodology with respect to trends, challenges and prospects forward to apply autonomy in a creative manner. Whereas [23] comes up with an autonomous scheduling of agile satellite constellations with a methodology for reactive imaging. On-broad mission re-planning concept using autonomy is introduced with [24] for satellites in constellation. To go a bit further, [25] makes a presentation of the autonomous satellite using on-board processing for a SAR application-based constellation. Not only for Earth and Moon based applications, [26] analyses the design and performance for a Martian environment with an autonomous navigation system for a small satellite constellation.

This paper will demonstrate the systems supporting the autonomous planning and operations of the small satellite constellations under a constrained configuration and severe respective space environments of Earth and Moon. In this research, LEO and NRHO are representing boundaries of the CisLunar space for an effective analysis covering major planning and operating techniques presented through this paper.

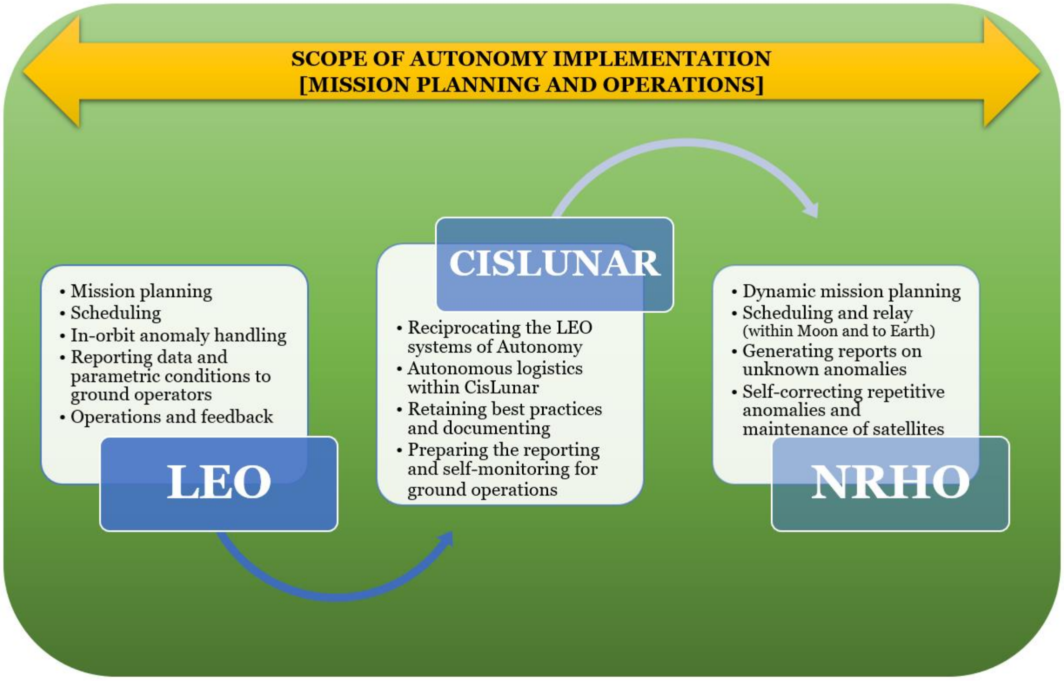


Fig. 9. Strategic autonomy implementation

2. Planning and Scheduling Dynamics (CisLunar Space – LEO & NRHO)

The mission planning and scheduling of a small satellite constellation needs a dedicated system to operate and coordinate events among the satellites and back to ground stations at various locations. The basic dynamics of mission planning and satellite scheduling for each satellite pass over a ground station is a sensitive parametric alignment. The reason for this is that the satellites in a constellation move in a dedicated pattern and needs to deliver the data at a nearest ground station at the quickest way possible (processed or unprocessed).

The most common and famous technique to do this is 'Heuristic' technique to align multi-satellite constellation for their planning and scheduling timely. This method has been extensively studied at first and results have been researched and analyzed for their determining the effectiveness and setbacks using the same. The dynamics involved in this technique is sorted in steps as below:

The planning and scheduling come in two different mathematical understanding and dynamics for the constellation scenarios. Hence, two different dynamics are discussed with same heuristic approach.

Mission Scheduling with Heuristic Method:

Scheduling with this method is common for the constellations and provided a detailed schedule and sequencing of the satellites in a constellation. In the same motive, [27] provides a set of scheduling equations satisfying basic problem formulations followed by the prioritizing and conflict-less heuristic approach divided into three major factors is defined below:

$$\Theta_i = \frac{\sum_{j\in R_i} d_{ij} + 2.t_j}{\sum_{j\in R_i}\sum_{1\le q\le|\Omega_{ij}|}((l_{ijq} - e_{ijq}) + 2.t_j)}, \forall i \in T_u \qquad (1)$$

This representation is not only for the sake of scheduling but also to be flexible in determining the available target at each pass of a satellite in a constellation.

$$\alpha_i = \lambda.\Theta_i + \mu.\bar{\varpi}_i, \forall i \in T_u \qquad (2)$$

$$\varphi_i = \frac{(\varepsilon_{ic} + 2.t_j)}{((l_{ijp} - e_{ijp}) + 2.t_j), \forall i \in \eta(c)} \qquad (3)$$

Hence, from these equations, the scheduling is devised with this heuristic approach.

Similarly, [28] represents the mission scheduling for a SAR constellation with heuristic method defining major parameters and results showing the conflicts and the stable solutions from this method. This reference indeed follows [27] as a basic mathematical foundation. But the interesting fact about the [28] is that it introduces the concept of need of the target evaluation using the contention equation as below:

$$\delta_i = \frac{\nu_i}{\nu_i * tw_i + \sum_{n=1}^{tw_i}\phi((i,n))} \qquad (4)$$

On the idea of optimizing the performances obtained by this approach, [29] gives a suitable detailing on the context of constellations used for remote sensing. It introduces the concept of the priority value for the distributed targets globally through an equation as given below:

$$\vartheta = \lambda.\partial + \Gamma.\mathrm{N} \qquad (5)$$

Mission Planning with Heuristic Method:

The mission planning using the heuristic approach is detailed on the similar lines by [30] and the mathematical modelling related to the image/data sequencing has been proposed. Here is the main difference with the

scheduling a satellite and how a mission itself could be planned. Both lie hand in hand for a design and configuring point of view. But the mission planning is where the autonomy of the satellite and a constellation overall can be aligned and set the parameters, constraints, operation flow and so on can be arranged and organized. Hence, this portion is extensively researched and literature has been studied significantly to understand the sequencing of the formulation and its capability to support autonomous operation. In this regard, [30] helped in gaining that aspect of planning is a deeper sense of understanding and implementation.
This is mainly to plan the sequential alignment of the satellites in a constellation without conflicting with other satellite's schedule within the given frame of time windows. Also, maneuver accordingly to match the planned sequence of reaching a ground station at the earliest as possible in synch with the constellation orientation. The confliction formulation and the methodology has been followed from [30] and some of the important extractions are given as below:

A confliction among the two targets is determined as:

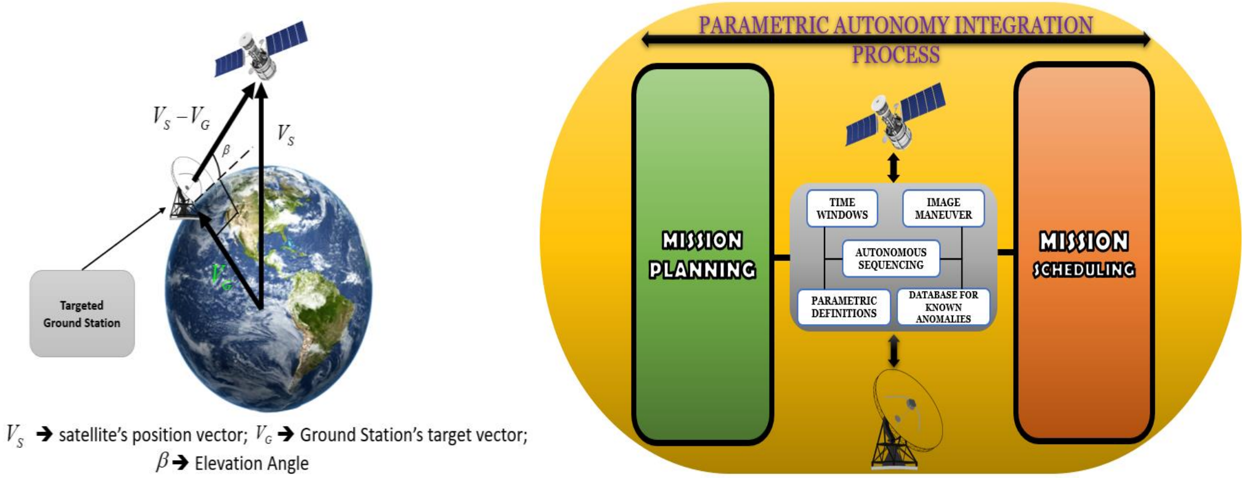
$$\varphi(i) = (Cw - Cw(i))\theta_{\max} + \sum_{n=1}^{N} \varphi(i,k) \qquad (6)$$

i, k are the two targets i.e., i is conflicting with other targets which includes k .

Also, the starting time of the imaging or data forwarding to the ground is important due to the fact it assists the sequencing in a dynamic manner without interfering into any other satellite's start time in the same slot. The equation governing the same for target n is given as Eq. 7 and the Fig. 10.(b) shows the vision of this paper as below:

$$T(i,\theta_i) = T(k,\theta_k) + t_{man}(i,k,\theta_i,\theta_k) + t_{imgperiod}(k) + t_s + t_{km\arg} \qquad (7)$$

θ_k is defined in $[-\theta_{\max}, \theta_{\max}]$ respectively.



(a) Orientation of satellite to targeted ground stations (b) Proposed autonomous mechanism

Fig. 10. Dynamics involving scheduling process with addition of autonomous capabilities

2.1 Set-up and Simulations to test the mission scheduling using Heuristic method (with autonomy into consideration)

Based on the study of the dynamics involved in the heuristic method, it was necessary to simulate it in the given real-time conditions. This also defines the configuration of the constellation for both LEO and NRHO orbits representing the edges of the CisLunar Space. Considering all the set of formulation mentioned in the Section 2., the following set-ups were designed and configured for the simulations as given below:

It is to be noted that these simulations are the planned to understand and propose improvements and novel algorithmic enhancements to the previous work done with Heuristic method.

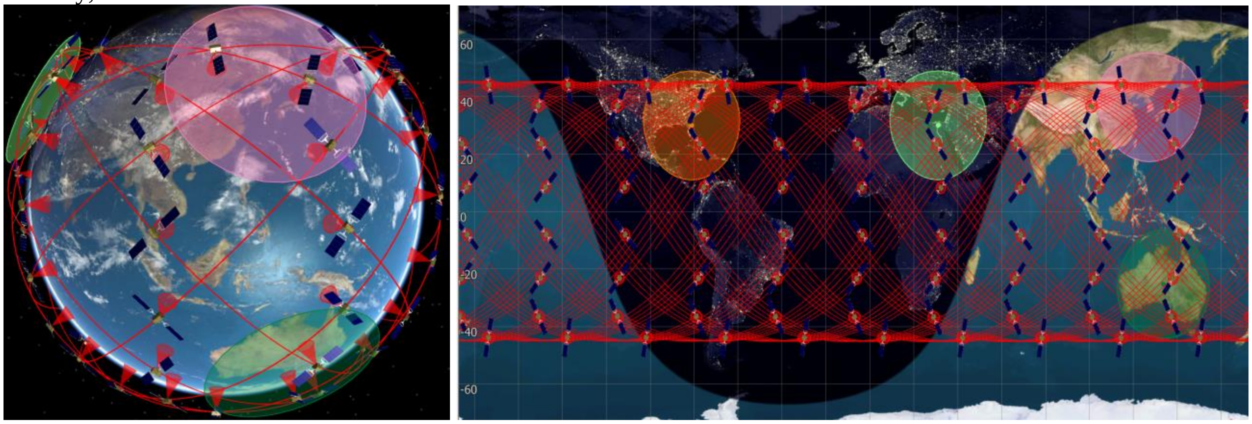
LEO-based small satellite configuration:

After a certain research and deeper understanding of the literature and related dynamics, the configuration of the desired constellation was devised and aligned to space environment in recent times. Major portion of LEO altitudes are of prime importance for future applications and solving persistent concerns through analyses has been considered as shown below:

Table 1. LEO-based small satellite constellation configuration (utilizing Heuristic method)

Parameter	Value
Number of Satellites	80
Semi-major Axis (Km)	7,000
Inclination (Deg.)	45
Number of planes	10
T (years)	5 years (lifetime)

Visually,



(a) 3D-Inerial Frame (b) 2D-Body Frame

Fig. 11. The visual depiction of the LEO constellation.

Near-rectilinear Halo Orbit (NRHO)-based small satellite configuration:

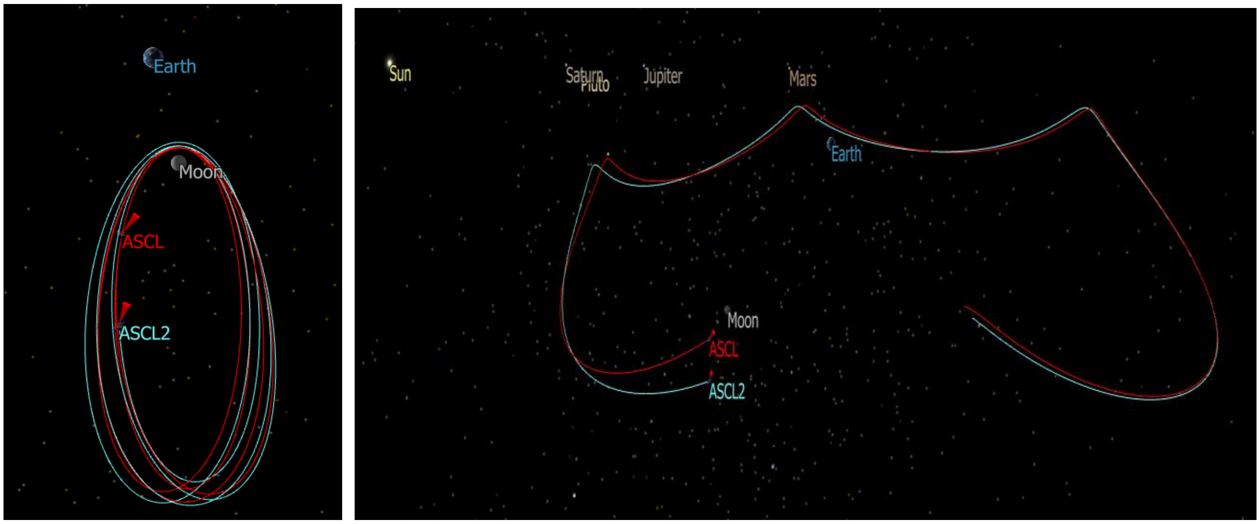
The motive of choosing the NRHO orbits for Moon for simulations is that they form a major portion and edge to the CisLunar region. They have prominent strategic value for the satellites to operate and position systems to propagate to the deep space with NRHO as favorable station. For this simulation, a basic propagation of NRHO with small satellites was done as it is understood that moderate number of satellites are enough to help the operations and data relay for the lunar conditions and environment.

Hence a basic configuration of one satellite is presented as shown below with the parameters specific to lunar orientation and propagation in NRHO respectively.

Table 2. NRHO-based small satellite constellation configuration (utilizing Heuristic method)

Parameter	Value
Number of Satellites	2 (initial test orbits)
Apogee (Km)	70,000
Perigee (Km)	3,000
Number of planes	2
Mass (Kg.)	85

Visually simulated as,



(a) 3D-Body Frame (b) 3D-Inertial Frame

Fig. 12. The visual depiction of the NRHO constellation.

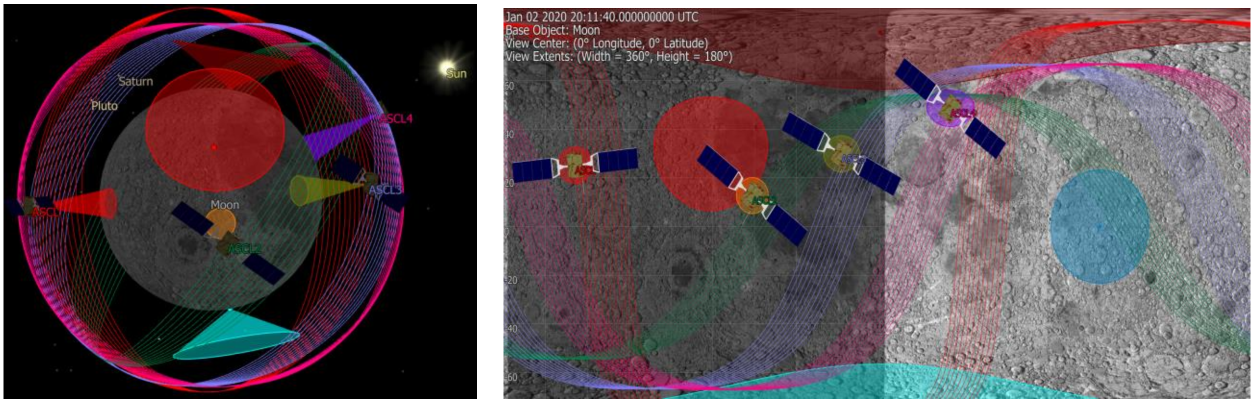
Soon after this propagation with a small satellite constellation, it was realized that the logical value of constellating the NRHO is low due to the fact that when the Gateway takes it position later in 2024 as mentioned by [31], there is a need for communication and data relay from Gateway to Moon and Moon to Earth and vice-versa. Hence, the strategy here was slightly changed to adapt the local conditions and possible extensive benefits to Artemis (Gateway) as a primary goal. This is of tremendous value to the entire mission and the strengthened architecture of communication and information transfer for the crewed and uncrewed missions in Artemis respectively.

Hence, the constellation was proposed to be circular with a semi-major axis of 3000 Km is termed as Medium Lunar Orbit (MLO) forming an important bridge between Gateway in NRHO, Moon's surface and back to Earth. Whereas, the Gateway's position remains to be same as 3000 Km at Perigee and 70,000 Km at the Apogee of the Moon respectively. This will cover even more region of the CisLunar Space and provide secure and diverse form of propagating small satellites in the given areas of operation.

To support this idea, the best example could be of the CAPSTONE mission from the industry which was a cubesat mission sent prior to Artemis-1 mission was set-up to track and examine the never explored region of NRHO. Soon after the CAPSTONE arrived at the designated NRHO and start performing the relevant designed operations, the Artemis-1 mission with Orion spacecraft with its designated trajectory was launched and it was accomplished well as per the given tasks and schedules which clears the way for Artemis-2 to be launched soon. Until, the Artemis-2 is ready for the launch with the GATEWAY space station in the NRHO, CAPSTONE will mostly be completing its allocated mission tasks and will be decayed for GATEWAY to take up its position and start its operations. Hence, the updated configuration and the basic representation visually were re-arranged and oriented as shown below:

Table 3. NRHO-based small satellite constellation configuration (utilizing Heuristic method)

Parameter	Value
Number of Satellites	4 (initial test orbits)
Orbit altitude (Km)	1,266 (Circular)
Eccentricity	0.001
Number of planes	4
Mass (Kg.)	85
Sensor Half Cone Angle (Deg.)	10 Deg.
Ground stations	Various possible landings (north and south poles included)
RAAN (Deg.)	50 ~ 200 (4 planes)
Inclination (Deg.)	3 planes at 45 and 1 plane at 110 (covering poles)
Step size (Sec.)	50
Frames	Body, Inertial



(a) 3D View (b) 2D View

Fig. 13. Re-arranged orientation of the small satellite constellation in MLO region of the CisLunar space

Now, as the arrangement of orbits at both Earth and Moon is completed, the mission scheduling algorithm made has been executed to test the Heuristic algorithm in the real-time conditions. The resulting parameters are the prioritized and scheduled passes of each satellite in the format presented as below:

Table 4. Resulting mission scheduling data

Priority	Target Index	Duration (Sec)	Number of Time Windows	Time Windows of satellite 1		
				Opening Time	Satellite Index	Roll Angle (Deg.)
5	1	22	32	2023/01/01 00:07:44	5	-12.5
3	2	15	25	2023/01/01 04:17:11	4	22.6
1	3	26	18	2023/01/01 06:06:25	3	13.4
2	4	11	14	2023/01/01 00:11:04	2	-4.2
4	5	21	17	2023/01/01 00:04:01	8	-17.6

3. Proposed Autonomous Planning and Scheduling Techniques- (CisLunar Space – LEO & NRHO)

The Heuristic method is executed in the section 2 and demonstrated the scheduling portion of this research through a simulation numerically and visually. There are pros and cons of the method that are observed and needs to be addressed which are briefly mentioned below:

Pros:

- The heuristic method is stable and is continuous.
- Quick and adaptive for a set of satellites.
- Cost-effective and less complex in implementation.
- Feedback as needed is available for analysis.
- Can be utilized with other methodologies.
- Can address issues and help take corrective actions.

Cons:

- Even though it is stable and continuous, it is quite limited to number of satellites that can use this technique due to complexity and nature of algorithm.
- Not optimal solution but reasonable solution. Does just as planned.
- Unknown anomalies not addressed. Only minor issues reported, major anomalies left out.
- Ground stations and related constraints not included to represent their scope of data reception problems.
- Scope for autonomous operation not observed or supported.
- Basic scheduling and indexing are possible and limited.
- Less output satellite parameters except only roll angle as satellite positioning parameter is known.
- Less scope for analyses. Just prioritizing and indexing is possible.
- Operator ease of data utilization seems complex and several important parameters are ignored.
- Requires an update and less robust for complex constellation operations.

The limitations with the Heuristic method can be supported with updated alternatives to be implemented and executed with complex constellations involving small satellites. This is due to their sensitive properties, operating and physical limitations for Earth and Moon under the respective space environments.

This paper demonstrates two novel algorithms to solve these issues significantly with robust autonomous operation available for an adaptable scheduling and planning of a complex small satellite constellation mission. These methods are crafted out of extensive research, testing and evaluation in the comprehensive real-time conditions for both LEO and NHRO respectively. The major outcomes of these algorithms are discussed and presented in this section as below:

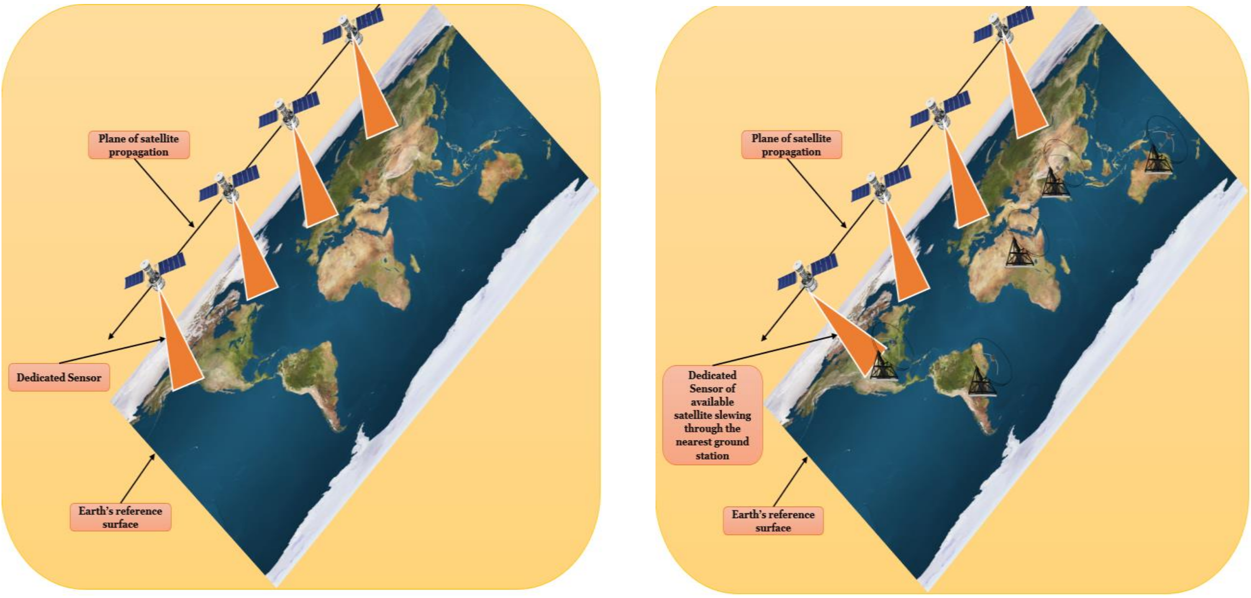
3.1 Script-based Slew-Maneuver Technique

The value of each spacecraft in a constellation is incredibly high considering the ever-growing number of near-earth objects, satellites and Debris. Hence, the number of satellites to be utilized and put into a constellation has to be a decisive part of the mission planning. Not only with the objects, the space environment at the LEO region has changed vastly over recent years and have been posing concerns of various dimensions to the satellite missions deployed for several applications. The understanding of the real-time consequences, durability and the frame of operation is of tremendous importance for a value-adding and purposeful mission respectively.

3.1.1 Concept

This technique is proposed is based on the concept of slewing. It refers to a spacecraft's attitude or movement with reference to Earth or Moon. So, the controlled movement of the satellite with a movement towards a location on Earth or Moon is highly valuable for a constellated satellite. A fully scripted algorithm was written to utilize this aspect of the slew maneuvering in the small satellite constellations. This is to align a satellite's propagation in a plane with respect to another to reach the nearest ground station scheduled for data reception autonomously as it approaches and maneuvers towards it delivering the captured data. Simultaneously, a report (both data and visuals) is generated continuously for the operator to observe which satellite in which plane is approaching which ground station.

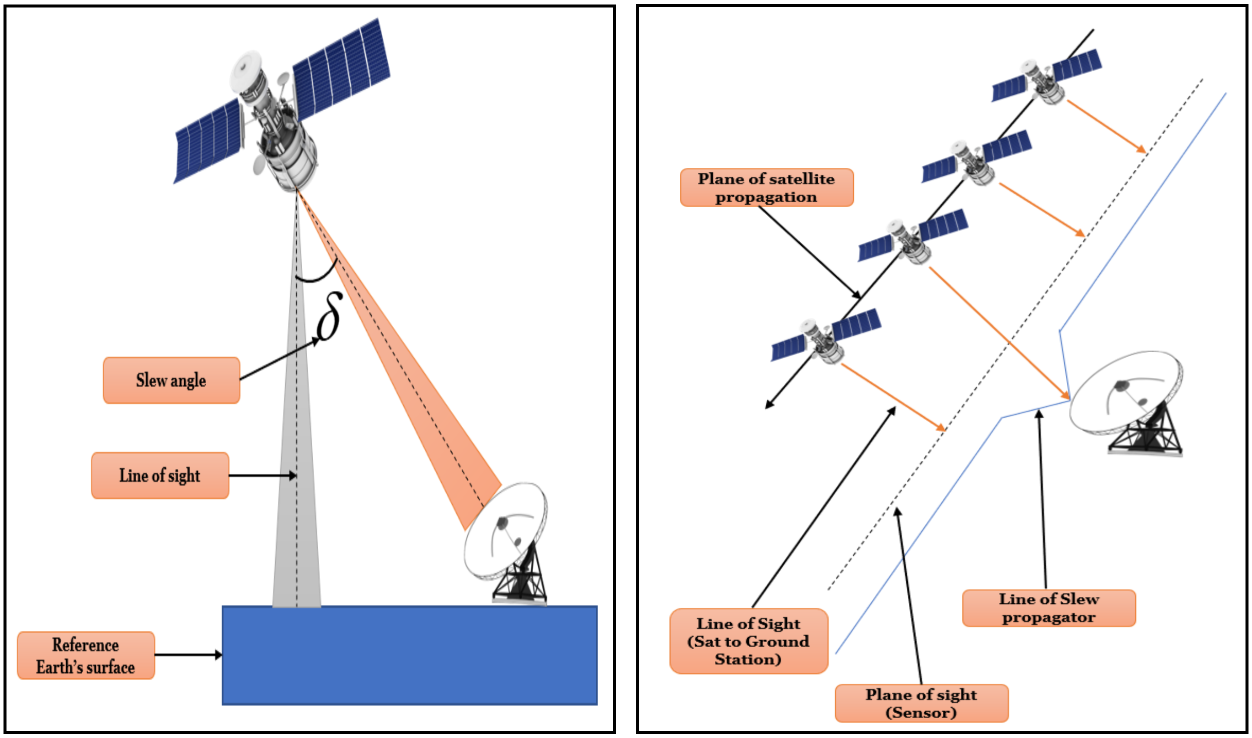
This is a counter solution to the traditional roll maneuvering in constellations (mostly adapted by SAR). The major issue of transition time of the roll maneuvering is solved to a major extent as it was a bigger constraint for the constellation scheduling in a long time using Heuristic methodology as mentioned in [28]. One available satellite in the plane, utilizing its sensor, determines the nearest approaching ground station and slews towards using a minor maneuver out of the plane and comes back to original position. The concept is pictorially depicted as below:



(a) Aligned without slew (b) Aligned with slew in action

Fig. 14. Concept of Slew Maneuvering for a small satellite constellation.

In the dynamics sense of view,



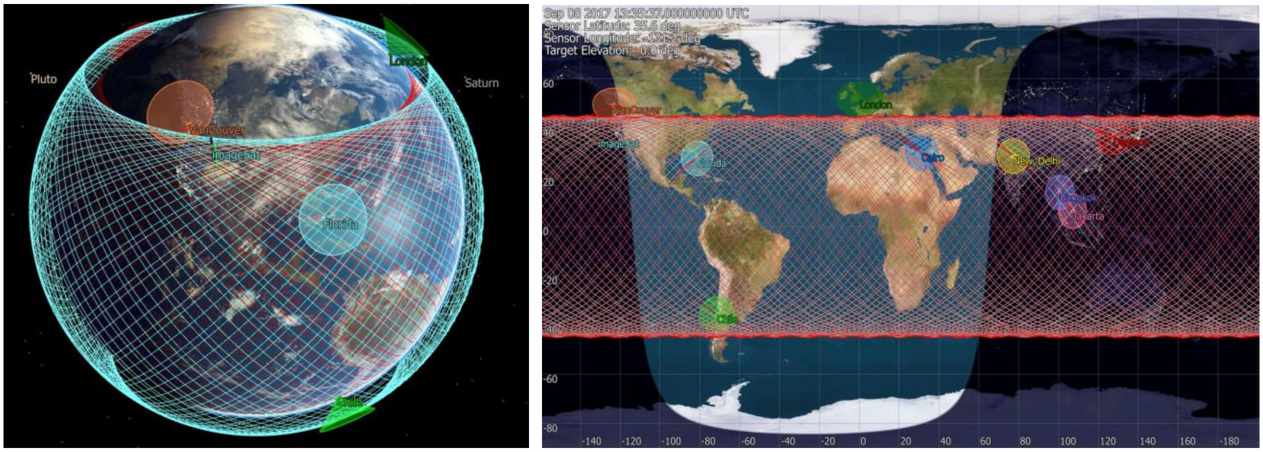
(a) Slew in progress (b) Slew dynamics

Fig. 15. Dynamic approach to slew maneuvering concept

This will certainly give a better hold on each parameter to be monitored and regulated by the operator without any intervention and schedule it manually. This concept even upgrades and enhances the heuristic method giving enough information to the operator to have a decision/judgement over a known or unknown anomaly if any. This will overcome a huge optimal solution issue with better control and in-orbit decision-making ability through autonomous operation.

3.1.2 Simulation for LEO-based small satellite constellation

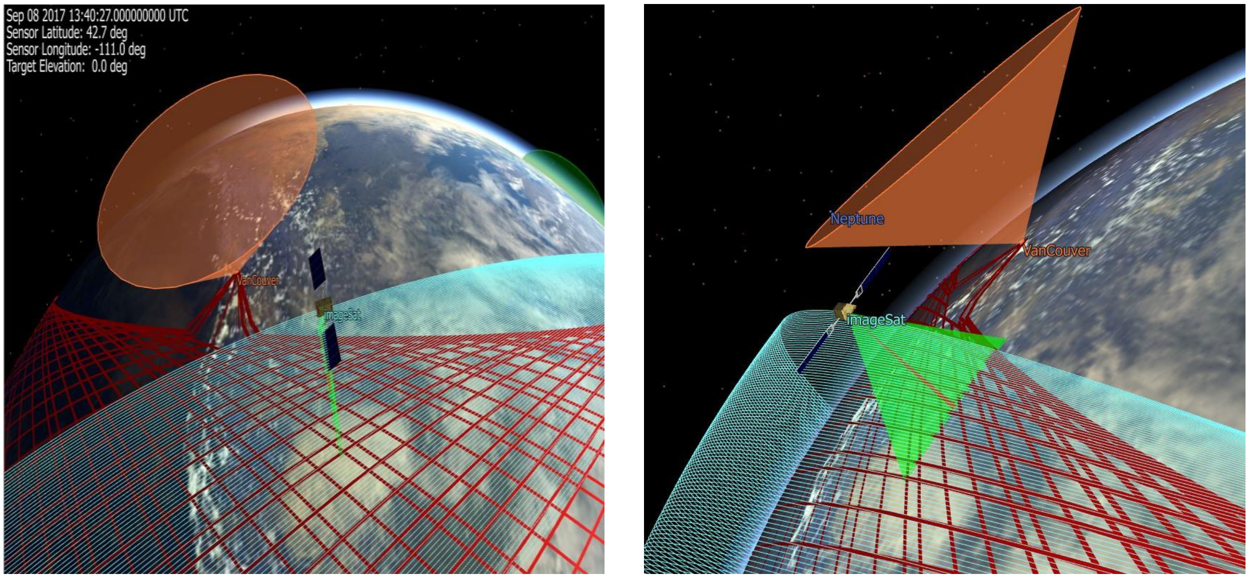
A detailed simulation was planned and executed to experience the designed algorithm in real-time conditions and visually demonstrated the concept as below for both Earth and Moon respectively:



(a) 3D-view (b) 2D-view

Fig. 16. Visual Demonstration of the set-up in LEO.

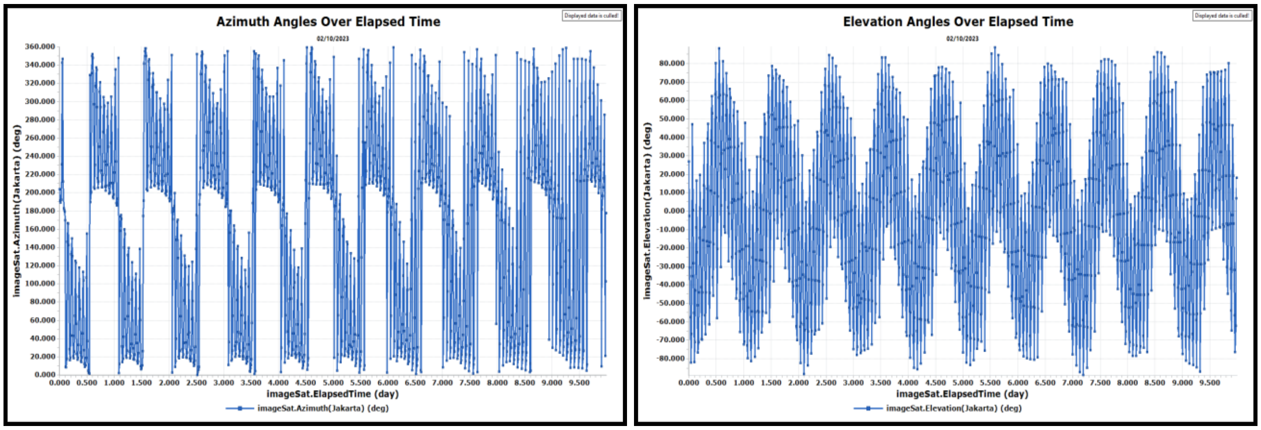
After the set-up was aligned, the constellation was propagated for 10 days and major results were plotted as below:



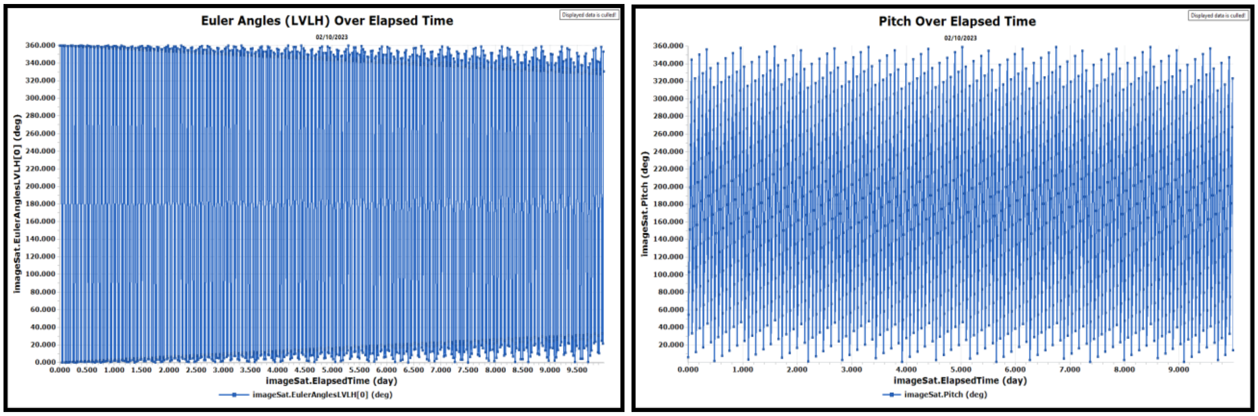
(a) Inertial view (b) Satellite sensor view

Fig. 17. Slew maneuvering in progress over a ground station.

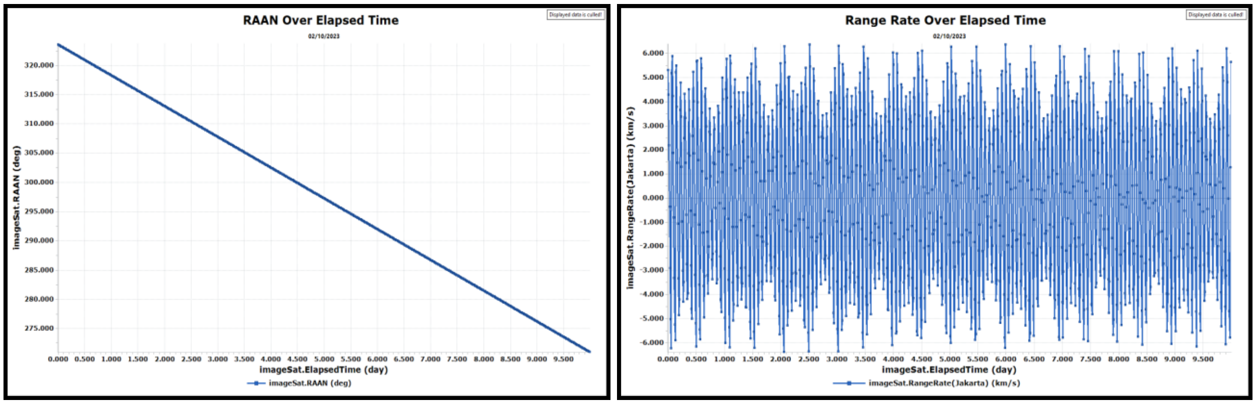
Crucial parametric orientation of the satellite as a resulting reference to the operator are as below:



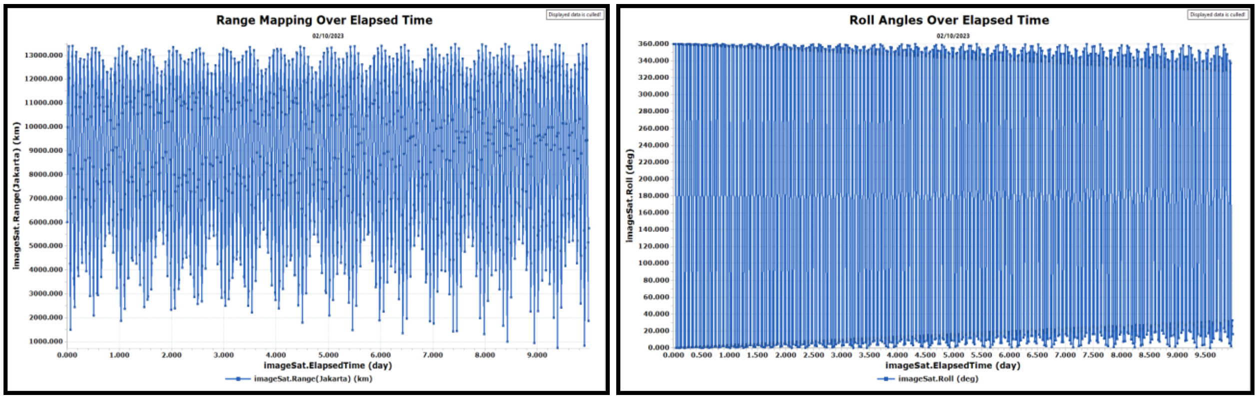
(a) Azimuth angle (Deg.) (b) Elevation angle (Deg.)



(c) Euler angles (LVLH – Deg.) (d) Pitch angle (Deg.)



(e) RAAN (Deg.) (f) Range rate (Deg./Sec.)

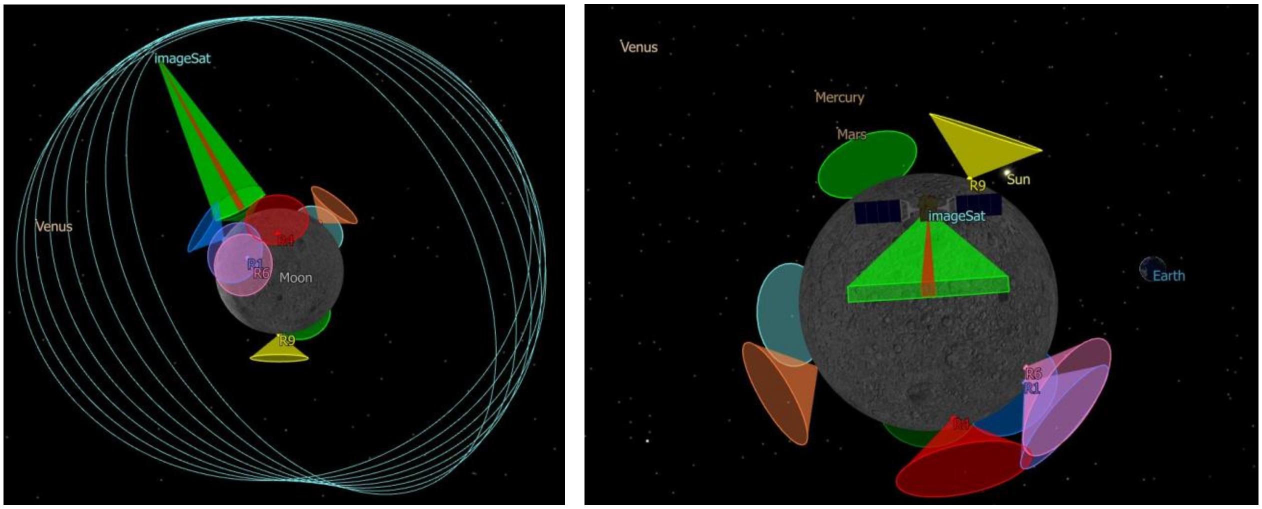


(g) Range (Km) (h) Roll angle (Deg.)

Fig. 18. Parametric analysis of the proposed concept of slew maneuvering Propagated for 10 days (LEO).

3.1.3 Simulation for MLO-based small satellite constellation

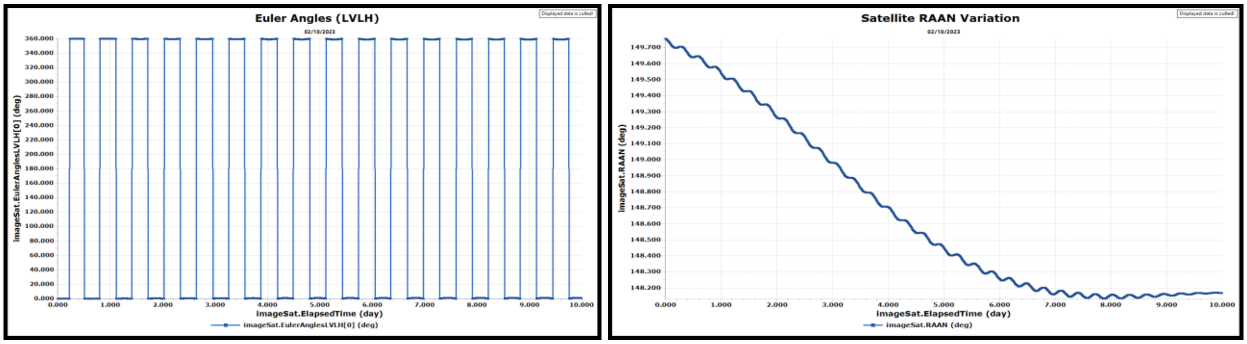
A similar approach was designed and demonstrated in complete consideration of the lunar environment and local conditions. The visual results and orientation of this concept on Moon is given as below:



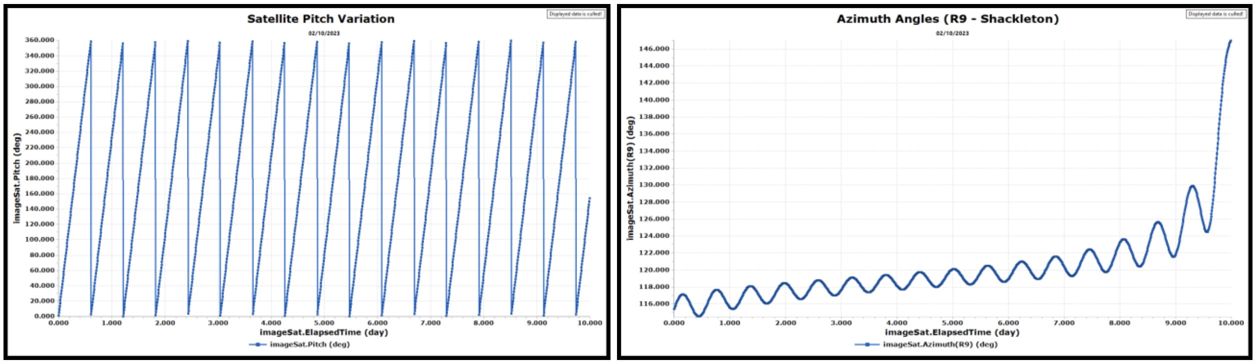
(a) Small satellite while in orbit (b) Satellite while slewing over designated ground stations

Fig. 19. Slew maneuvering mechanism – MLO.

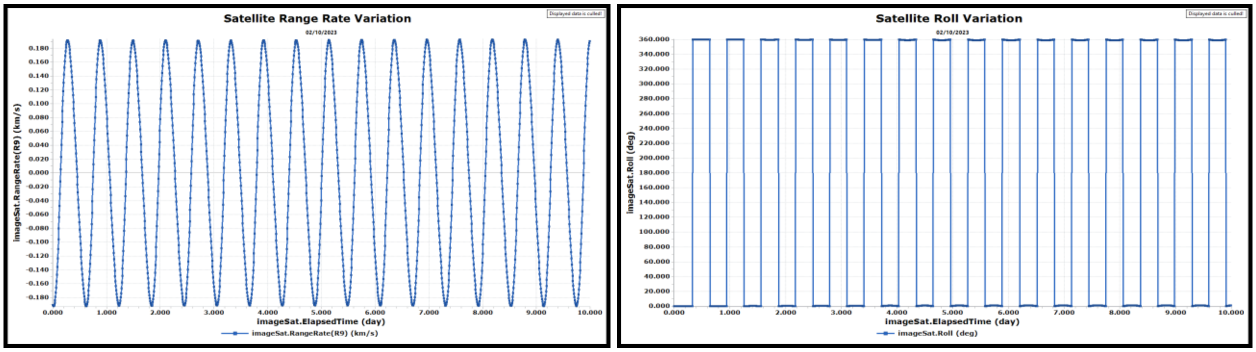
Crucial parametric orientation of the satellite as a resulting reference to the operator are as below:



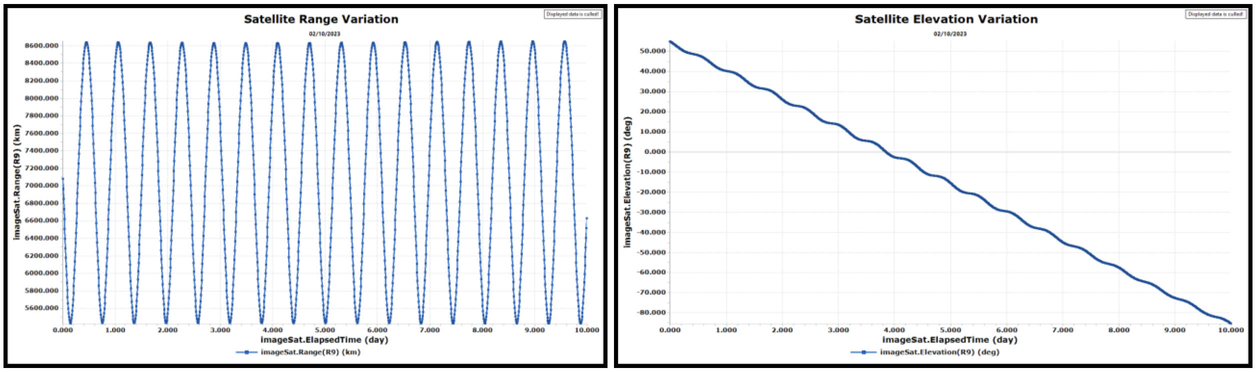
(a) Euler Angles (LVLH – Deg.) (b) RAAN (Deg.)



(c) Pitch angle (Deg.) (d) Azimuth angle (Deg.)



(e) Range rate (Km/sec.) (f) Roll angle (Deg.)



(g) Range (Km) (h) Elevation angle (Deg.)

Fig. 20. Parametric analysis of the proposed concept of slew maneuvering Propagated for 10 days (MLO).

Apart from the plots, the algorithm generates continuous reporting in a file or console format for ease of visually finding which satellite is slewing towards which ground station. A sample demonstration is given in the tables below for both LEO and MLO:

Table 5. Slew report (LEO)

Action	Ground Station (LEO)
Slewing towards	Daejeon
Slewing towards	Cairo
Slewing towards	Bangkok
Slewing towards	New Delhi
Slewing towards	Florida

Table 6. Slew report (MLO)

Action	Ground Station (MLO)
Slewing towards	R9
Slewing towards	R5
Slewing towards	R7
Slewing towards	R8
Slewing towards	R4

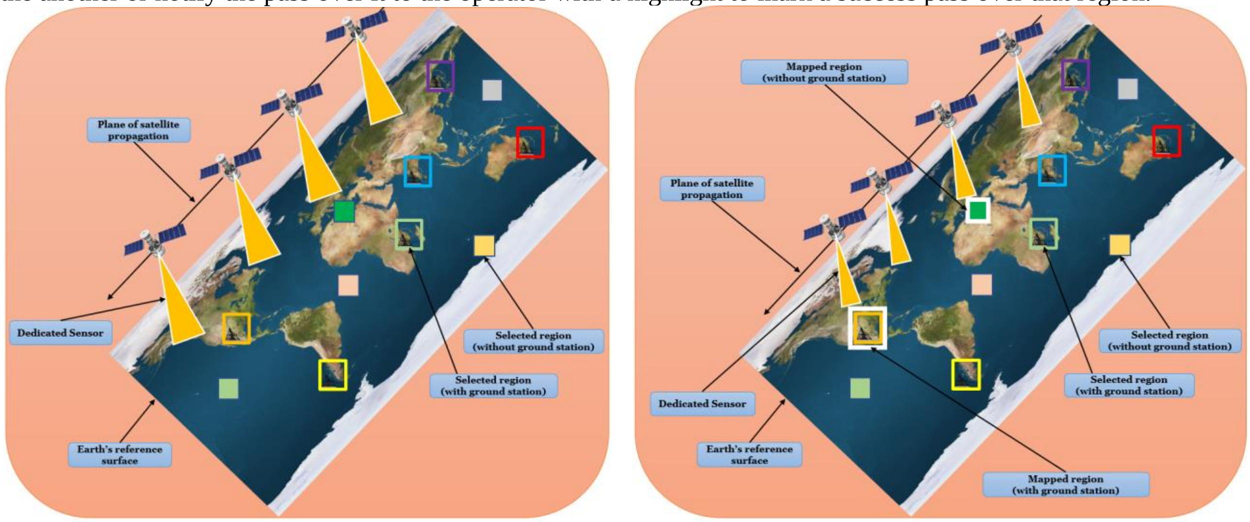
After the slewing action is completed, the timing (start and end) is also recorded and reported to the operator.

3.2 Script-based Adaptive-Mapping Technique

After the addition of the slew maneuver technique, there is a gap to be filled to determine certain remote regions on Earth and Moon irrespective of ground station placement and have difficult accessibility. There is an essential necessity for applications with this technique both on Earth and Moon. For Earth, the major application where robustness, confirmed and confined mapping is needed specifically for disaster management in the remote regions. Similarly, for Moon, the locations of important milestones like astronauts’ landing locations, systems operating at remote locations with the Artemis-2 mission will be of tremendous importance overall to support and strengthen the mission objective with contact and access effectively. This is a significant portion of the mission planning than the scheduling part of the small satellite constellation mission.

3.2.1 Concept

Based on the idea and its application mentioned above, a novel algorithm was planned to address the mapping of a selective region by the satellites in each plane in a constellation when required. The issue with Heuristic method for the planning for having reasonable or uncertain range of solutions and its accuracy [28, 30], can be successfully overcome by adding this new capability to the constellation reducing overall anomalies and uncertainties. The algorithm provides an autonomous mapping technique which can track and map any region under the given coverage of constellation and identify them as specific locations by highlighting them as needed by operator. Under this methodology, the satellites propagate in their own planes and track and highlight the locations of interest as they pass by. During this pass, they can either communicate and relay information one place/location to the another or notify the pass over it to the operator with a highlight to mark a success pass over that region.



(a) Selected regions for mapping (b) Mapped regions during the propagation

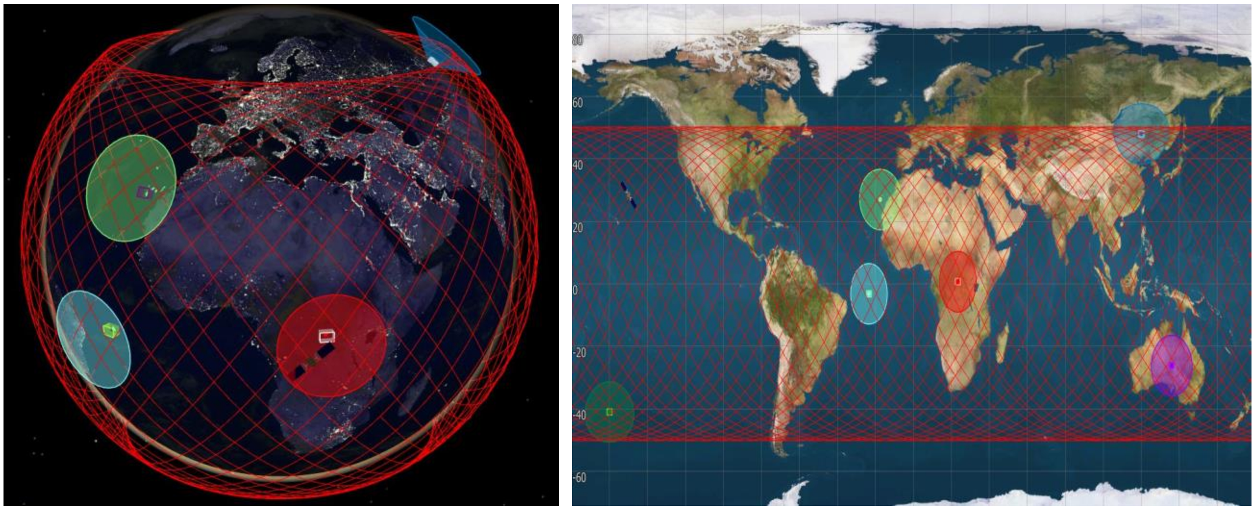
Fig. 21. Concept of adaptive mapping for a small satellite constellation

In both the cases, the information to the operator with this on Moon and Earth is of great importance and advances through the tracking and mapping issues overall with a constellation. These features are assumed to be in every satellite constellated and perform this operation for applications for Earth and Moon significantly adding robustness to the missions planned and operated respectively. The action of tracking and mapping is done by all or the most nearby and available satellite in the given plane. This technique will autonomously provide these mapped details to the operator for instantly providing the relief to the region for effective and quick disaster management on Earth. Like-wise, on Moon, when the Artemis – 2 mission kicks off, there will be huge need for smaller satellites to do the tracking and mapping autonomously one satellite to the other, to the gateway [31], to the systems on Moon and Earth. Several parameters can be tracked instantly and continuous results are available for the operator to make decisions. This is completely an adaptive-mapping technique to support and operate this algorithm autonomously.

The parametric and visual simulation and analysis of the same is presented for both LEO and MLO as below.

3.2.2 Simulations for the LEO-based Adaptive Mapping Technique

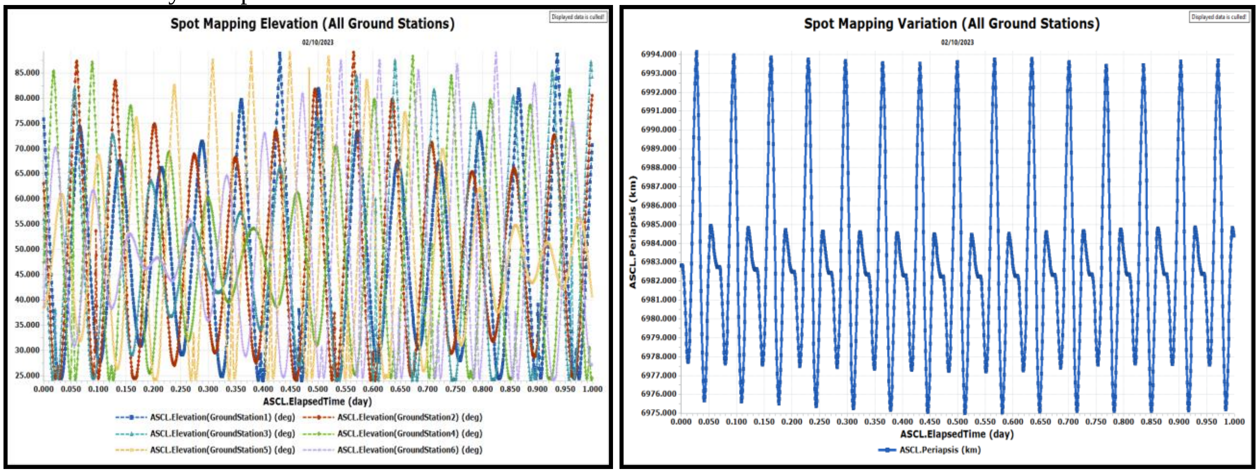
Considering all the local conditions of the small satellite constellation operating in LEO environment, the following real-time simulations have been carried out and results were plotted:



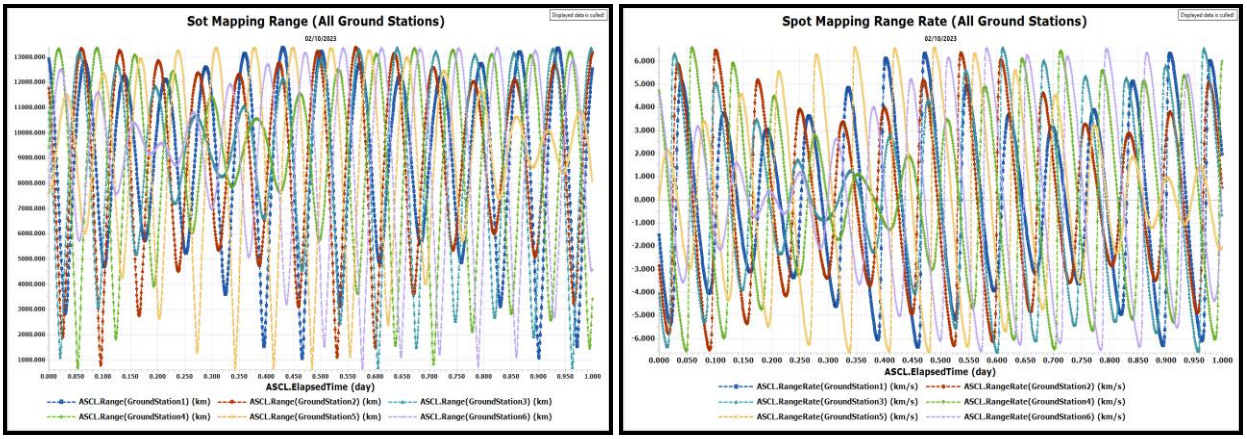
(a) 3D-View (b) 2D-View

Fig. 22. Visual demonstration of the adaptive mapping technique

Parametric analysis is presented as below:



(a) Spot mapping elevation at each GS (b) Satellite Periapsis

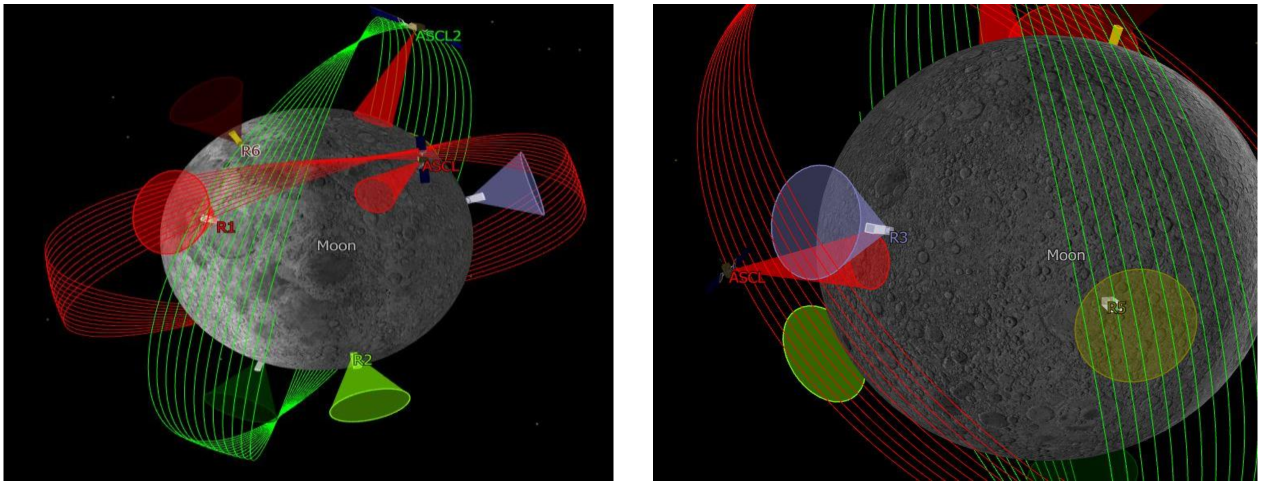


(c) Range (Km) (d) Range rate (Km/Sec.)

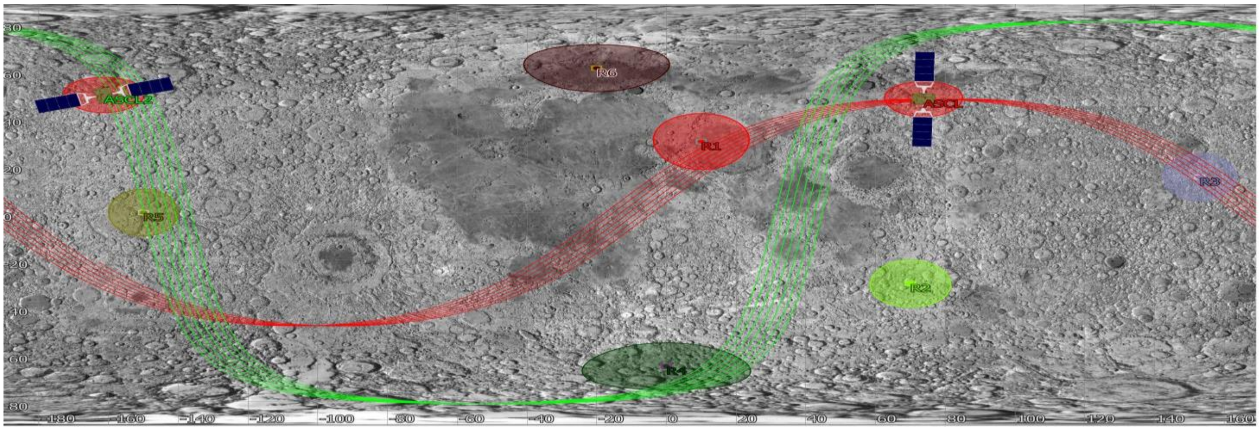
Fig. 23. Parametric analysis of the proposed mapping technique for LEO.

3.2.3 Simulations for the MLO-based Adaptive Mapping Technique

Considering all the local conditions of the small satellite constellation operating in lunar environment, the following real-time simulations have been carried out and results were plotted:



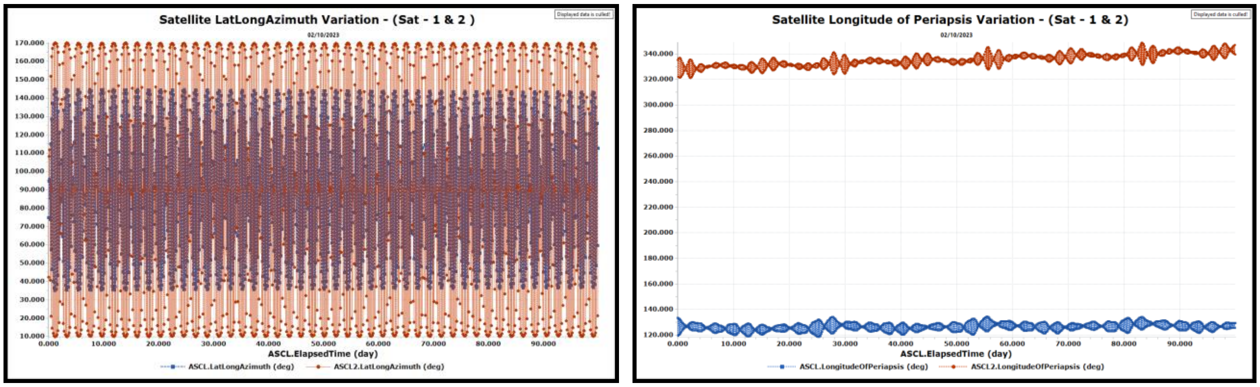
(a) Lunar mapping in 3D view (b) Lunar mapping – Close contact – 3D view



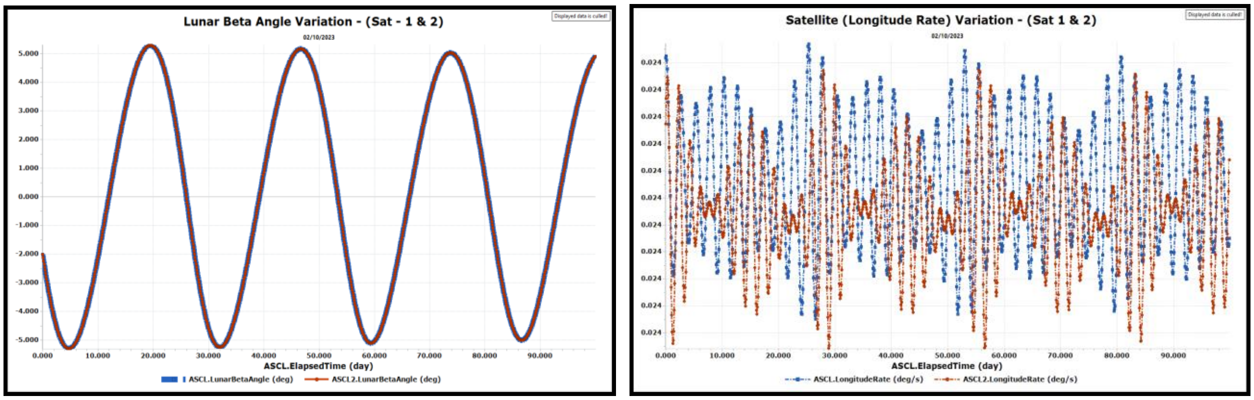
(c) Lunar mapping – 2D view

Fig. 24. Visual demonstration of the Lunar (MLO) mapping technique

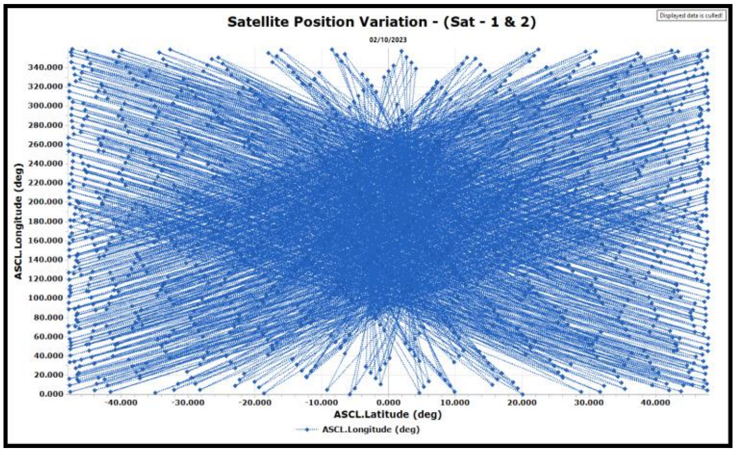
Crucial parametric orientation of the satellite as a resulting reference to the operator are as below:



(a) Satellite LatLongAzimuth (Deg.) (b) Satellite Longitude of Periapsis (Deg.)



(c) Lunar Beta Angle (Deg.) (d) Satellite Longitude Rate (Deg./sec)



(e) Latitude to Longitude – Satellite positioning (Deg.)

Fig. 25. Parametric analysis of the adaptive mapping technique – MLO.

Each parametric display above has a very specific significance while propagation of the satellites is in real-time and gives a valuable timely information to the constellation operator autonomously and reports the data and plots continuously and alerts the unknown anomalies regularly. The known and repetitive anomalies are self-corrective and are sorted on orbit at each satellite level or on the scale of the constellation in operation. Apart from the plots, the system also generates reports in a file or console format for the operator/user to watch out for the region being mapped and also after the action is completed, a detailed report on the sent out with duration of mapping as below:

Table 7. Mapping report (LEO)

Action	Ground Station (LEO)
Mapping towards	Target Region_4
Mapping towards	Target Region_2
Mapping towards	Target Region_1
Mapping towards	Target Region_6
Mapping towards	Target Region_7

Table 8. Mapping report (MLO)

Action	Ground Station (MLO)
Mapping towards	R9
Mapping towards	R5
Mapping towards	R7
Mapping towards	R8
Mapping towards	R4

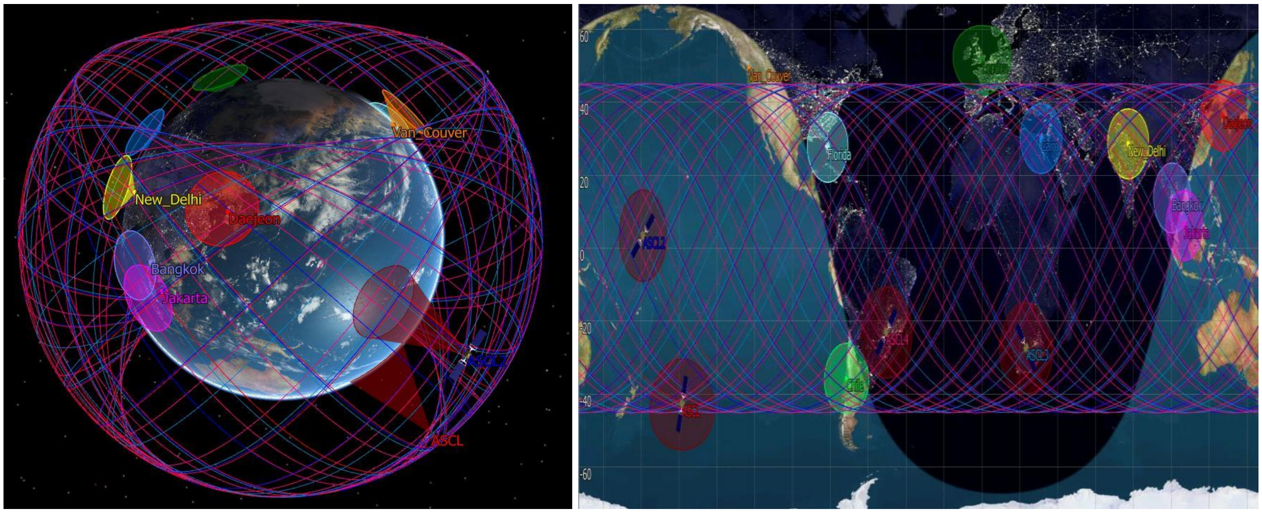
3.3 Ground Station – Prospect and Analysis

In the sections above, the proposed systems, dynamics and simulations were mainly focused from the prospect of on orbit satellites in a constellation, but the ground control also needs its portion of understanding of the satellite's orientation and its passes over time. So that the ground stations can effectively align themselves to the approaching satellites timely and autonomously without significant anomalies. This is an essential portion of the mission planning and scheduling for efficient operations which is often missed out on their considerations and critical parameters positioning and processing them. With the usual Heuristic method, this was never possible to consider the ground stations as an integral part of the mission planning and its autonomy in place.

The research in this paper has significantly studied, experimented and aligned simulations in due consideration of the real-time conditions. Crucial parameters involved in governing the ground stations designated to receive the constellation data and operate in synch with satellites autonomously have been planned and results have been noted. This was each analysed for LEO and MLO regions while the techniques where being implemented and tested for their feasibility and applicability in the given conditions. The reporting system was planned and executed in file or console format delivered autonomously for easy accessibility and comfort of use for the operator of the small satellite constellation. This is a continuous process and is simulated in complete synchronization of the methods discussed in Sections 3.1 and 3.2 respectively. This is considered and integrated to the autonomous mission planning of the proposed small satellite constellation configuration.

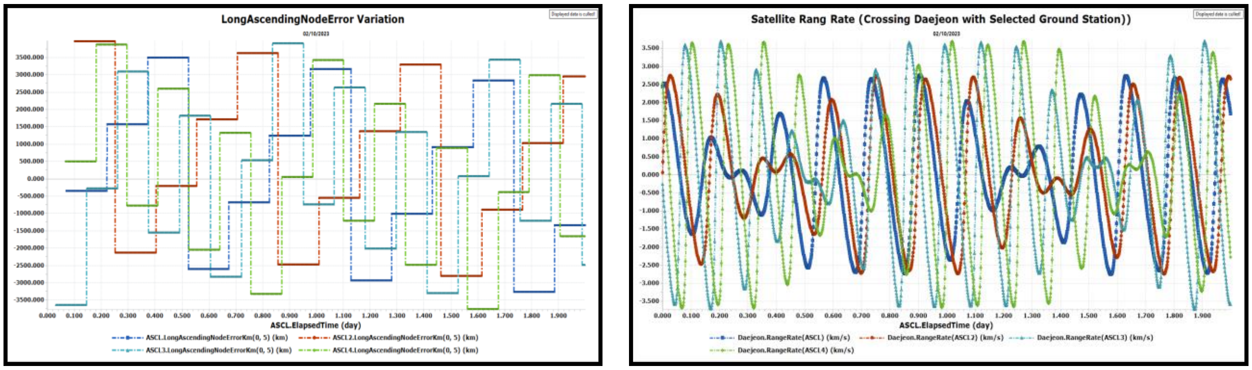
3.3.1 Ground Stations – LEO-based Simulations

For the purpose of the demonstration of the ground stations-based analyses, four satellites (ASCL, ASCL2, ASCL3, ASCL4) are considered operating in different planes with distinct orientation but similar configuration constituted as a constellation in LEO. The visual simulation demonstration is presented as below. This is followed by the reporting and plotting system demonstration which is for the ease and instant view of the constellation operator in simplified and continuous until its lifecycle providing invaluable data and information.

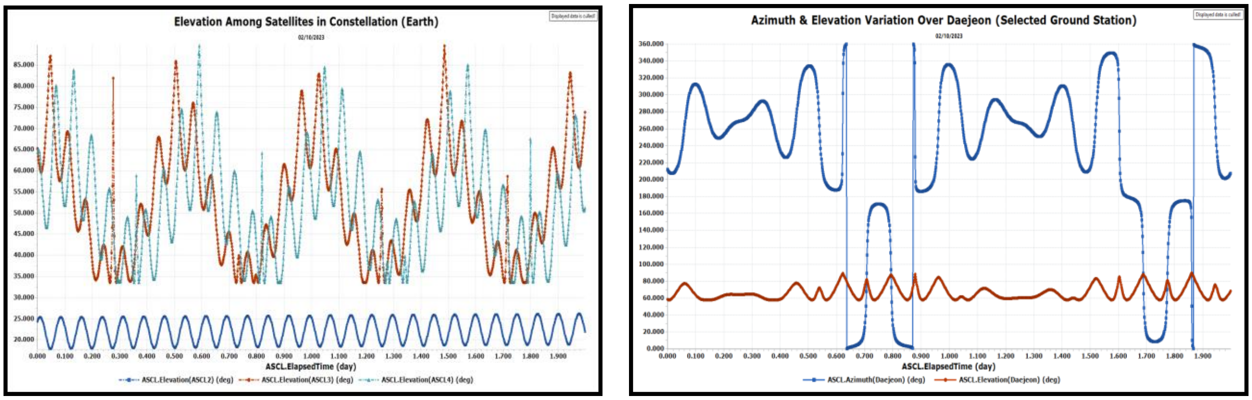


(a) Set-up – 3D view (b) Set-up – 2D view

Fig. 26. Visual demonstration of set-up for the ground station analysis – LEO.



(a) LongAscendingNodeError (Km) – all satellites (b) Range rate (Km/Sec) – all satellites



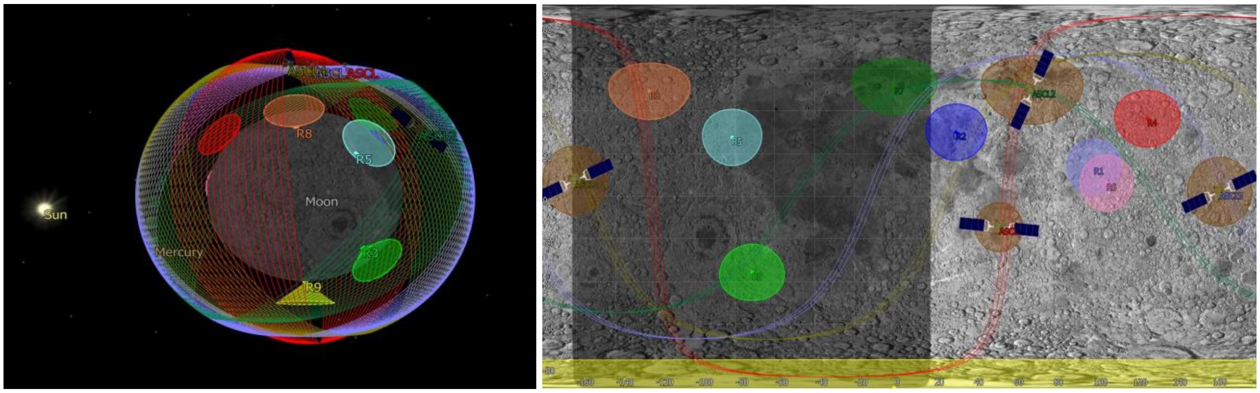
(c) Elevation among satellites in constellation (4 sats) (d) Elevation and Azimuth data in single frame (1 sat)

Fig. 27. Parametric analysis of the ground stations - LEO

3.3.2 Ground Station – MLO-based simulations

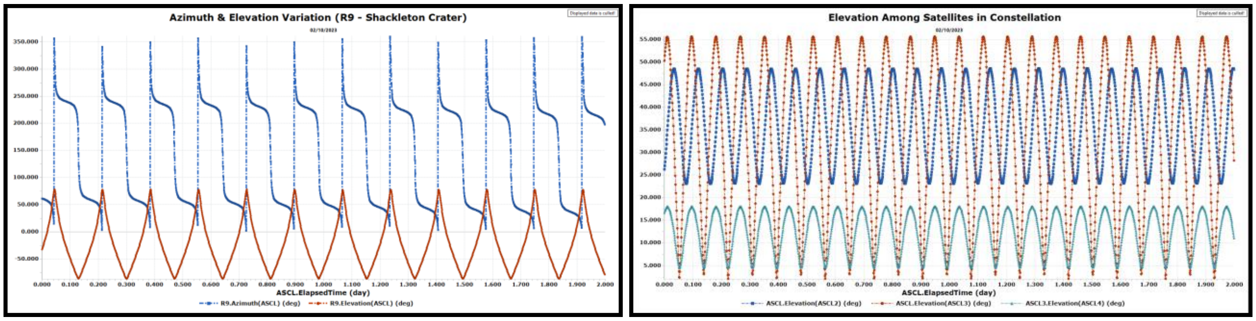
On the similar lines but different environmental conditions, the set up for the ground station analysis was made with MLO as an operation region for the constellation. All the regional and operating conditions were taken into consideration while designing and simulating this prospect of ground stations aligned with the given four satellites (ASCL1, ASCL 2, ASCL 3, ASCL 4). The reference ground station is taken as R9 (south pole -Shackleton Crater due to its scientific importance and possible landing of astronauts near it with the Artemis mission.

The visual demonstration and parametric analysis are presented as below. The necessary constraints were also studied and alignment was done to ensure the possible real-time scenarios for the lunar operations. Not only the communication and data relay among the satellites and systems near Moon but also to Earth is duly considered for the simulations and parameters of real value have been plotted and analysed for effective utilization during execution.

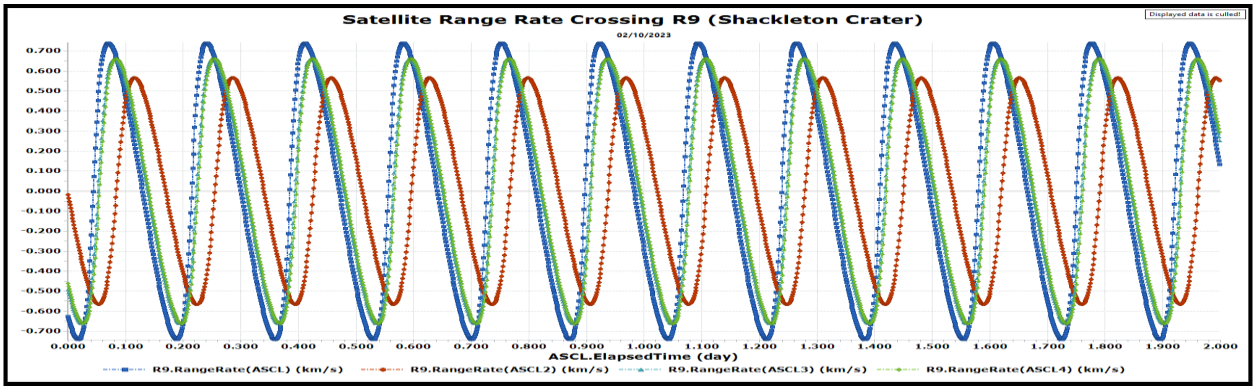


(a) Set up for MLO – 3D view (b) Set-up for MLO – 2D view

Fig. 28. Visual demonstration of the set-up of the Ground stations – MLO.



(a) Azimuth and Elevation (Deg. - R9) – (1 satellite)   (b) Elevation among satellites in a constellation (Deg.)



(c) Range rate (Km/Sec.) – all satellites (R9)

Fig. 29. Parametric analysis of the ground stations for the constellation – MLO.

Along with the plots, the reports are also generated continuously with the duration of the contacts and access of each satellite with each ground station during and after the action is completed. Each plot above has its own significance which is researched, tested and generated for the value on ground with an operator point of view.

4. Operations Dynamics – (CisLunar Space – LEO & MLO)

The operations in the CisLunar space are increasing and are going to be busy in this race to secure the posts on Moon from each competitive country and industry as a whole in this NewSpace age. The competence is not only for advanced technology demonstrations but also how fast and how safe the logistics, operations and planning could be to attain the given requirements of respective missions. Hence, the operations need to be sequential and optimal for safeguarding and maintaining the cislunar space environment and essential operating space in this region with due consideration to the ever-increasing debris of all sizes and shapes. There has been certain amount of studies which are contributing towards having reasonable and optimal deployment of the satellites forming small or mega constellations including the methodology mentioned in [21]. The following figure gives a general idea on the operations and fundamental need of the hour with the operations of the small satellite constellations.

Fig. 30. Operational alignment with dynamics and space environmental awareness for constellations

In the view of current state of the CisLunar space, the dynamics are built for operations based on the environmental conditions of both Earth and Moon separately. Firstly, considering the LEO environment with J2 perturbations, Solar Radiation Pressure (SRP – Mainly due to solar winds) and the Debris effects are deeply studied and considered during the operations planning and the propagation of each satellite in a constellation.

For Moon, though the environment is much stable due to weak gravity and no J2 perturbation but radiations from Sun play a vital role in the operations and planning portions of the mission. Hence, SRP is still prevalent for Moon orbits and entire CisLunar region as a whole. This comes along with the lunar space environment in local conditions and regions of operating the constellations over Moon. For this paper, Medium Lunar Orbit (MLO) as discussed in above sections is considered for studying dynamics and proposed system of operation respectively.

For LEO-based operations:

Along with the astrodynamics and mission design mentioned in each section above for the propagation of the satellites in a constellation [32,33], the satellites undergo harsh space environments and operations do get affected by the same. In early 2022, the 40 Starlink satellites were knocked out by a strong geomagnetic storm [34] and an evidence that the CisLunar space is not the same anymore with quickly changing activities of Sun. Hence, it is crucial to consider these changes in the form of solar radiation pressure (SRP), effects of J2 perturbations caused by earth's oblateness which have a greater effect on the constellations when operating, Atmospheric Drag and the space debris itself. The dynamics used to include these constraints in the satellites are briefly as follows:

J2 Perturbations:

The governing equation used for the J2 considerations [35] is given in a modified version as:

$$\frac{\partial\Omega}{\partial t}=\frac{-3}{2}*J_2*\left(\frac{R_E}{a(1-e^2)}\right)^2*\sqrt{\frac{\mu_E}{a^3}}*\cos(i) \qquad (8)$$

$\frac{\partial\Omega}{\partial t}$ is Nodal Precession; J_2 is Perturbation constant; R_E is the radius of Earth; a, e, i are semi-major axis, eccentricity and inclination; μ_E is standard gravitational parameter of earth.

Solar Radiation Pressure (SRP):

In the similar way, the SRP is defined as acceleration exerted on the satellites due to the solar radiation pressure [36] in the form of solar winds or geomagnetic storms is defined as:

$$\vec{a}_{SRP}=\frac{S*AU^2*C_R*A_{SRP}}{m*R^2*c}\vec{U}\,v \qquad (9)$$

S is Mean flux at 1AU; C_R is Coefficient of Reflectivity; A_{SRP} is SRP area; m is satellite mass; c is Speed of light; AU = Astronomical Unit in Kms; $\vec{U}$ is essential unit vector from Satellite to Sun; v is Eclipse factor.

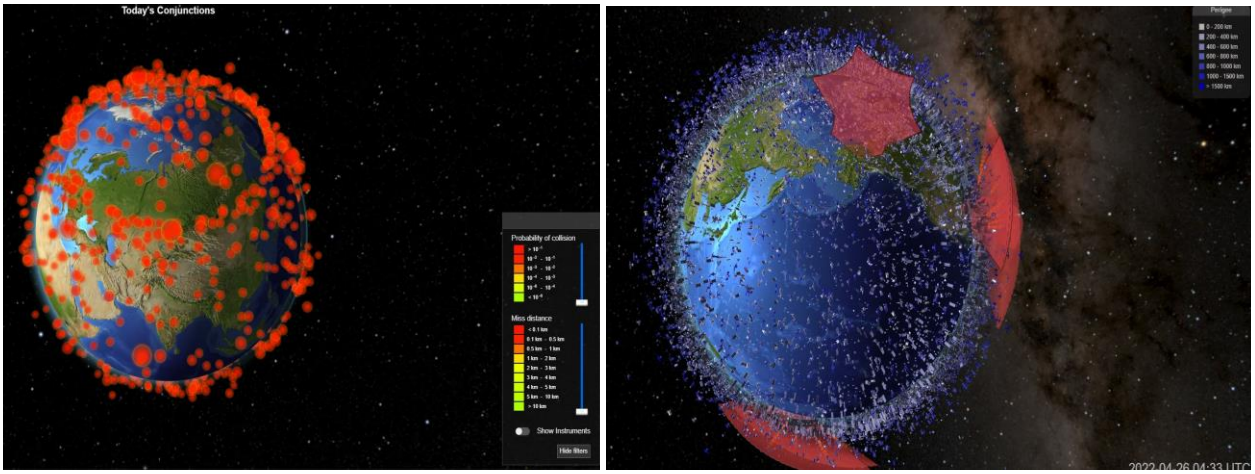
Debris dynamics:

The major aim to add this aspect to the dynamics is due to the face that as the number of missions are populating the LEO region, the debris keeps growing tens of times each year and has a serious impact on constellation operations. Several references were studied to incorporate space debris effect on the constellations while in orbit and [37] gives a thorough idea on the resonant orbital dynamics with only debris in focus in detail. The governing equation to find the resonant angle of the orbiting debris in LEO region is given as below:

$$\Phi_{ra}=\frac{2\Pi}{P_r} \qquad (10)$$

Φ_{ra} is the angle of resonance among the debris objects; P_r is the resonant period respectively.

A recent short-term collaboration with Leolabs Inc., has revealed a lot of insights about the current state of the LEO-based debris among the satellites in operations. Some glimpses of the same are captured as below:



(a) Collision scenarios of the LEO objects with Debris (b) LEO objects according to their Perigee heights

Fig. 31. Debris analysis – LEO.

For MLO-based operations:

With this NewSpace era, the moon's orbits will be busy and populated in no time [38]. Hence, there is a need to study and incorporate the environmental changes and requirements to build the constellations to support Artemis operations in real-time. As mentioned in the previous sections, the configurations will be same as discussed but with due considerations to local dynamics of operation including the effects of solar radiation pressure and the extreme temperatures adding to the satellites essential orbit maintenance and long-term operational requisites. Hence, these factors are duly considered for the operations point of view [39] and analyzed while developing simulations.

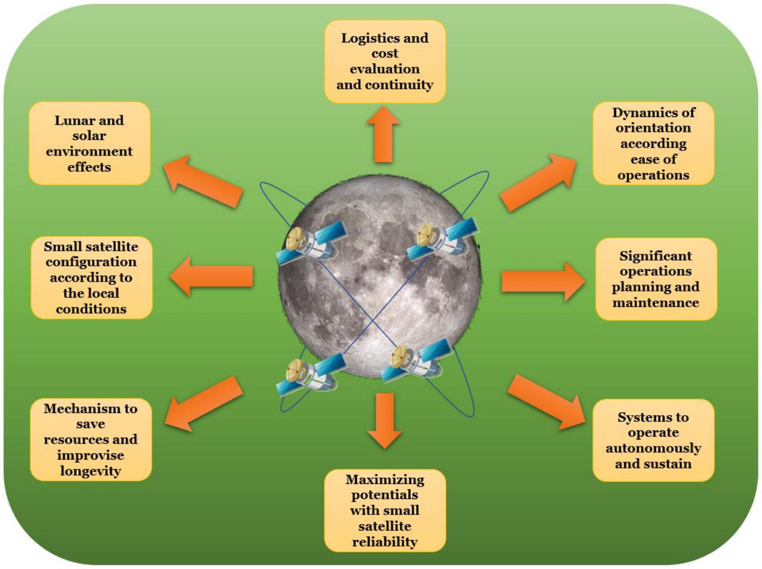


Fig. 32. Strategic operation and its elements – MLO.

This paper takes a leap to understand the underlying issues in operations, study the literature and dynamics involved in this CisLunar space in this new era of commercial and national space economies. The initial idea from this research was discussed in [32] and will be elaborated in this paper further on the implementation aspects of it and how the above concerns can be addressed thoroughly in a systematic manner in the later sections.

5. Proposed Operations System (CODES) – (CisLunar – LEO & MLO)

In order to address all the issues mentioned in the sections above, there is an urgent need for a dedicated system in place for aligning the future and current constellations. Specifically, with the small satellite market and its utility grows, the small satellite constellations are the rage of the next generation space exploration. Hence, this paper presents a dynamic and systematic approach with a system to align these constellations in CisLunar Space which is named as 'Controlled Deployment of Satellites (CODES)'.

5.1 Concept

The main objective here is to deployment of the small satellites in a systematic and optimal manner to ensure that they are deployed only when needed to align the constellations seamlessly and for a long term. Currently, the global scenario is to deploy the number of satellites in a constellation (including the mega-constellations) in large numbers to attain the end-user requirements in fastest manner possible to reach the targets and overall accessibility and economic goals in a given timeline [21,40]. But the CODES bring the concept of minimum satellites and higher reachability through optimal coverage [32,33] and utilizing autonomous system to reach the similar objectives as mega-constellations. This protects the space environment and utilize it effectively and purposefully with meaningful missions and give some relief to the astronomical experiments to be efficient and undistracted in CisLunar space. The concept for LEO and MLO based CODES concepts and mechanisms are detailed as below.

5.1.1 LEO-based CODES System

With already ever-growing LEO debris, there is a concern to minimize the number of satellites and make them optimally operational globally is a challenge beyond just mechanisms and launch facilities. The disaster management is a real-time application which needs sophisticated systems to work in sync to manage a productive and cost-effective constellation. CODES aim to address this issue and confine the scope to CisLunar operations to deploy and operate satellites as and only when required using autonomy. The pictorial concept is given as below:

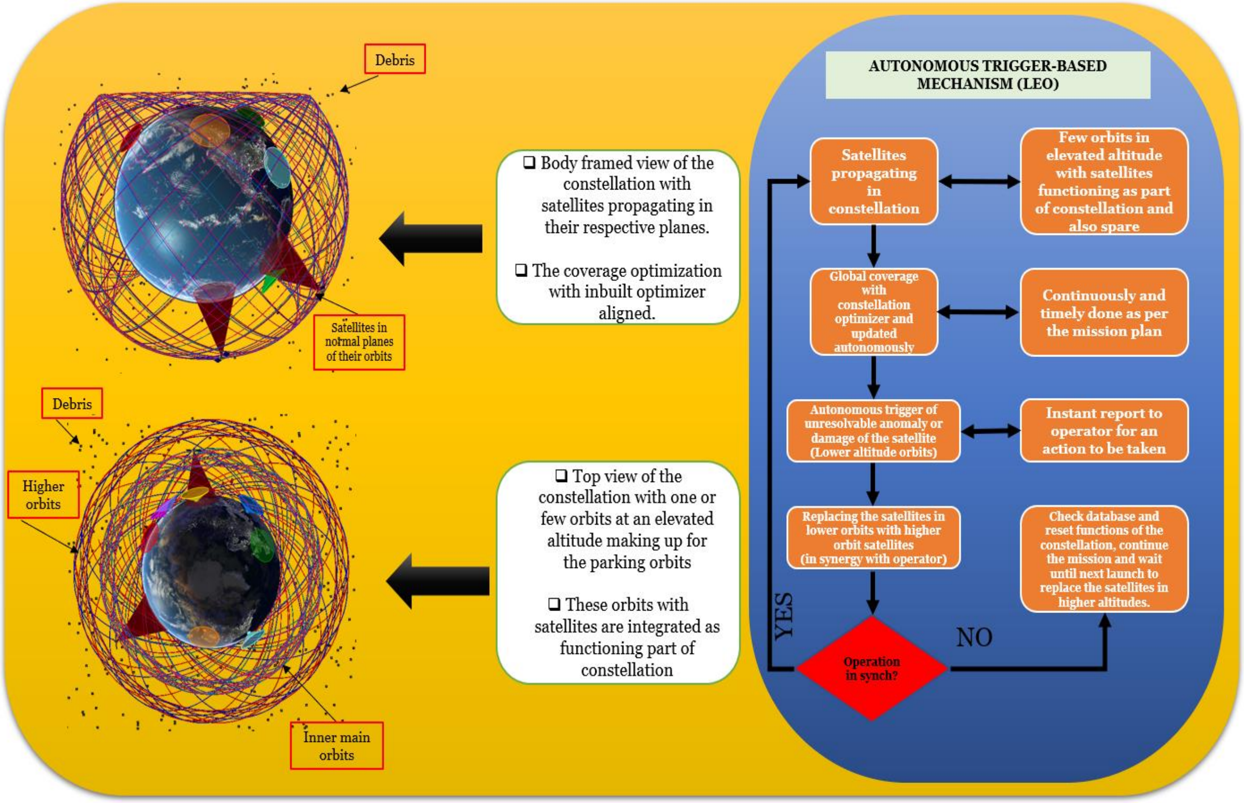
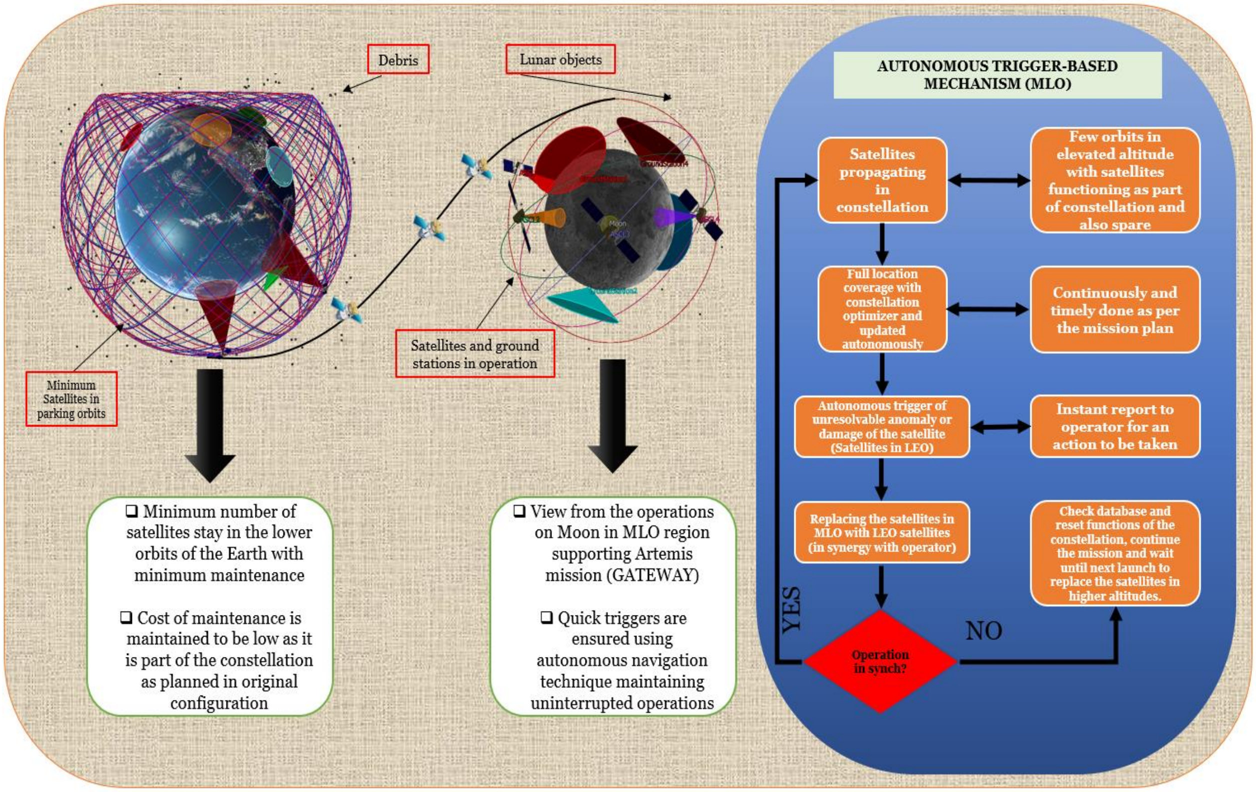


Fig. 33. CODES Concept – LEO.

Mechanism: The intent here is to utilize as minimum satellites as possible with great coverage and performance for a given lifecycle of the constellation. The coverage is taken care by the orbit optimizers in a constellation but the maintenance and sustaining through the rough space environment in LEO will remain crucial and essential for these missions. The overall maintenance in this concept is based on autonomous system implementation in the operations and build synergy with the operator for minimizing costs but with optimal approach. The figure above describes the concept pictorially that the parking orbits can be obsolete and have no functional requirement until a satellite is damaged and have operating costs involved. Hence, few orbits in a constellation can function at an altitudes and service both as parking orbit and also an integral part of the constellation. Whenever a satellite in lower orbits are damaged and have irreversible anomalies, the triggers are sent out to the operator autonomously and an action to replace those satellites with ones in higher altitudes until the next launch is available and vice-versa. This makes the operations to be continuous and uninterrupted with controlled number of satellites utilized for the mission which is usually accomplished by mega-constellation with satellites in thousands in number taking up crucial place in region.

5.1.2 MLO-BASED CODES System

The deployment of small-satellites to the MLO is a bigger challenge which many of the industry and professional are trying hard in this Artemis era to get it right the first time. The logistics and delta-v costs will add a significant lot to the mission apart from the competence of the satellites themselves as some part is mentioned through this research in [41]. The concept and mechanism of the same is presented as below:



- ☐ Minimum number of satellites stay in the lower orbits of the Earth with minimum maintenance
- ☐ Cost of maintenance is maintained to be low as it is part of the constellation as planned in original configuration

- ☐ View from the operations on Moon in MLO region supporting Artemis mission (GATEWAY)
- ☐ Quick triggers are ensured using autonomous navigation technique maintaining uninterrupted operations

Fig. 34. CODES Concept – MLO.

Mechanism: The concept and mechanism for the MLO-based region will remain the same as LEO but the mode of operation and scenarios will differ. But the main difference comes in with the fact that this region does not any way needs as many satellites as LEO does due to Moon's size and environment and other factors involved for Moon operations. These are well taken into consideration while planning the missions. With the optimization of the coverage, maximum number of tasks to be done with small satellite constellations in MLO are well achieved. But the catch here is the cost of losing a satellite in MLO is much higher than losing one in LEO with all the logistics and delta-v costs involved currently. This may improve over time as the rush to Moon's surface increase but until then finding the most feasible, adaptable and reasonably balanced solutions are only hope. Hence, the CODES way of operation and deployment slightly changes here. Instead of having set of spare satellites waiting at any parking orbits, a few satellites can function as LEO satellites in lower altitudes near Earth until an autonomous trigger is made to the operator of the defaults and damages in the MLO satellites. The deployment of the satellites can then start and depart to the given trajectory for MLO. This will save costs and significant continuity issues resolved for a long time. The satellites can also be deployed as per the local requirements at the Moon as needed by the mission to be attained. Hence, a structured form of controlled deployment can be ensured with seamless progression of mission operations.

5.2 Implementation Strategy

From the concept to the realization is a long journey of concept evaluation, initial simulations, costs analysis, feasibility tests and then practical implementation under quality standards. This needs a strategic approach and step-wise implementation process to systematically deliver the required goals in the given timelines. Mission planning is one stage where all these processes are aligned and processing for further development. CODES hold a special place in configuring and strategizing the CisLunar space in a comprehensive manner. The advancement of technology needs a blend of advanced techniques to implement them in an effective and resource-optimal direction as a vision rather than just a project. CODES gives a NewSpace system to resolve the on-orbit issues with due utilization of autonomy and optimization methodologies in complete synch with one another for an entire CisLunar space. This area which will soon be populated with concentrated and competitive missions, need a simple but effective implementation plan.

CODES as an autonomous system guided technique to solve the real-time issues of CisLunar space in NewSpace, is equipped with simple steps in a systematic order addressing critical issues in the process. Determining the correct configuration of the small satellites will be primary task to align and implement a constellation and its autonomy. In a quest to lower the cost and enhance the applicability, the use of commercially-off-the-shelf (COTS) is the most important portion of this entire vision and philosophy of autonomous operations. In this research, an extensive study was carried out to know-how and essential elements propelling the implementation of such demanding competence. Specially, the space environment today being difficult than ever with changing and unpredictable anomalies to solve instantly and effectively. Hence, to organize, integrate and device the small satellite constellations with substantial autonomous operations, this method of CODES is being developed and the strategic steps to determine this implementation is researched and emphasized as below:

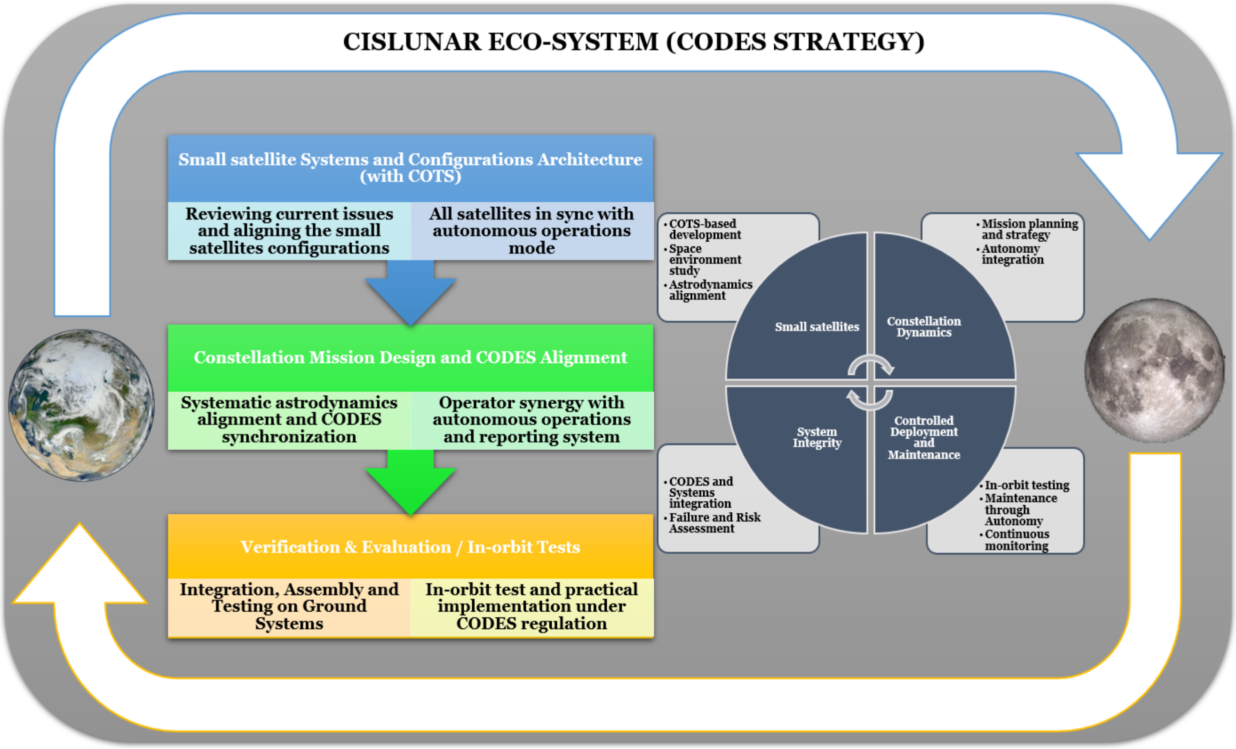


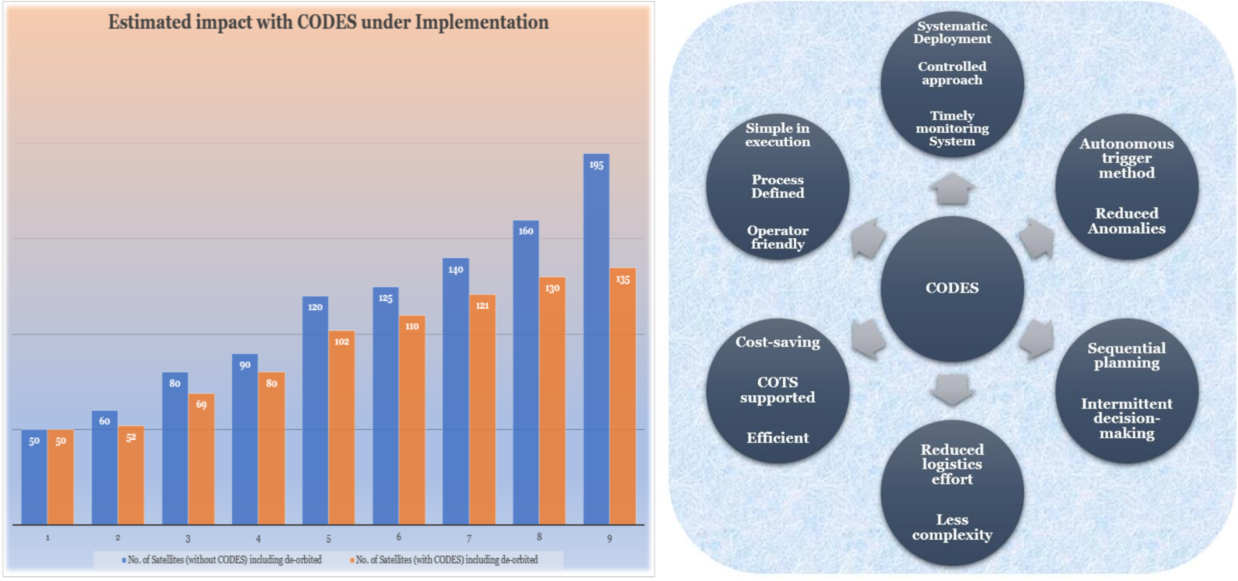
Fig. 35. CODES Implementation Strategy and Architecture Framework

5.3 Prospective results and notable benefits

Based on the concept and implementation strategy, finding the right alignment with the purpose and benefits from the proposed objectives of this method is inevitable. Hence, the favorable outcomes and paybacks of this approach has been broadly researched for long-term calculated planning and execution.

Notable benefits and observations:

- Autonomy reduces the liable costs significantly. It removes the extra burden of having the repetitive and known anomalies addressed.
- Unnecessary logistics costs are removed substantially by over 50 percent.
- Reduced Delta-v costs which actually relieves several other dependents and their costs as well.
- Optimized operational costs for a given lifecycle.
- Concept and costs with spare satellites in parking orbits completely removed with their associated maintenance costs.
- Number of satellites (operating and replacements) can be tremendously reduced and be regulated autonomously adding to much of the relief of the ground and operations team in fact reducing overall costs.



(a) Estimated trends with CODES (b) Possible edge with CODES in execution

Fig. 36. Notable benefits of CODES

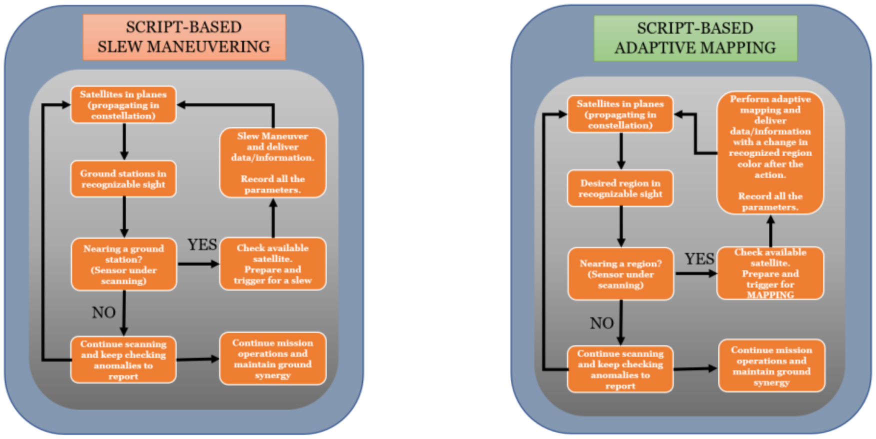
5.4 Long term goals – small satellite constellations for all and for good!

In these years, though the missions with small satellite constellation may not be functional up to 10 years as shown in the trends above, but the lifecycle can be prolonged with a controlled action plan as depicted in the sections above. The goal is to move towards sustainability and endurance in CisLunar space in this race of NewSpace age. Disaster management is a very essential need of the hour with utmost urgency for reliable long-term solutions for effective and quick availability of data as needed by the end user. Hence, developing purposeful systems with appropriate mission plan and operations can go a long way and attain longevity for small satellite constellations.

The precise and reasonable allocation of missions and their satellites can be resourceful and a contribution to even the under developed and developing countries for a cost-effective technology and data procurement. This is crucial for their survival and reduce losses due to natural catastrophes. This can make a balance as a whole for the global utilization of the right and efficient constellation services. The vision, techniques and strategies focused in this paper are aligned with this very cause for LEO-based implementations. But as the activities near Moon are increasing, the focus and goal is enlarged beyond LEO towards a productive and well-balanced CisLunar space with NRHO orbits forming the other edge of this region. This research is dedicated to utilize small satellites as a constellation for CisLunar space but specific to purpose of mission being disaster management through LEO and Artemis support through NRHO. Hence, the goal remains to be a sustainable and thriving CisLunar space for long term respectively.

6. Discussion / Critical Analysis

This paper is directed towards reforming and innovating the mission planning and operation techniques for specific applications in CisLunar space with LEO and MLO-NRHO forming the edges of the region. The initial portion presented the dynamics involved in the mission planning and its novel ideas demonstrated with simulations. The reason for executing the Heuristic method was to bring out the possible improvements and re-align it to be integrated with autonomy and various other enhancements required for a small satellite constellation planning and operations. Novel ‘Slew Maneuvering’ and ‘Adaptive-Mapping’ techniques were introduced and simulations were presented with visual demonstration for Earth and Moon cases respectively. The algorithms developed are completed script based and have been designed parameter-by-parameter for a fine control and execution of the algorithms. This plays a vital role in step-wise implementation of the autonomous operations with each satellite in proper alignment. The following figure gives an insight of the in-orbit operation using these techniques for an optimized propagation.



(a)Slew Maneuvering (b) Adaptive-mapping

Fig. 37. Schematic flow of autonomous operation of the proposed techniques.

For the portrayed parametric analysis for each of the methodology presented, a detailed analysis of set of parameters are of primary importance to the operator is thoroughly recognized, planned and simulated. Each of these have a specific understanding to understand the orientation of each satellite with respect to one another and to the ground station respectively. All the analytical paramters were propagated and observed for ten days to identify their behavior and response under the given conditions of harsh operating environment and executing given tasks as planned. The satisfactory aspect of all these results is that these are autonomous and available handy for operators for their decision-making of any unknown anomaly or situation. Usually for Heuristic method, the roll angle used to be of importance and an only satellite parameter reported and regulated. But from these proposed techniques, several parameters including the roll, elevation, pitch and many others are available with precise and autonomous scheduling. This complements a lot for building synergy between operator-based and autonomous algorithm-based planning and respective operations while managing a small satellite constellation of a reasonable size (less than 500 satellites).

Fig. 18. Shows the variation of different parameters in LEO constellation scenario while slew maneuvering algorithm is in operation. Interesting fact observed is that all parameters though stable, gives a confident and simple support of understanding to the operator with the information of the proposed plan and operation continuously. Fig. 18.(e), specifically shows how the impact of J2 and SRP can make a difference in propagation of an entire constellation with a full-scale re-orientation every few days giving a complete scenario through visual plots for analysis in case of anomalies in real-time. Like-wise, other parameters like Pitch, Euler angles, Range rate, Range, Roll, Elevation/azimuth angles, all have their significance in real-time operation and adds a tremendous essence to complete mission itself. On the other side, the MLO parametric analysis was done under the scenarios and conditions specific to lunar environment and necessities of a ground operator on Earth for a comprehensive monitoring. Fig. 20. Presents the overall essential parameters for MLO environment. Though most of the parameters remain same as LEO, the value and behaviour of each of them is completely different and gives a lot of significance of their operation in real-time and local conditions. For instance, the Fig. 20.(b), shows RAAN orientation in MLO, which keeps declining over a period of 10 days but it is not much concerning as the decline is less than kilometre until it is reconfigured by the operator if it continues to declining to the concerning levels. This will be of prime importance due to decision-making support it provides continuously for the ground team to take actions when necessary and to have uninterrupted operations.

In the similar approach, the adaptive-mapping technique was presented with an appropriate parametric analysis suitable to respective environments of LEO and MLO. Fig. 23. Presents the analysis for LEO-based small satellite constellation whereas, Fig. 25. gives the analysis for MLO. In Fig. 23.(a),(c),(d), though the data looks cumbersome to understand and recognize its significance, the plots are for 4 satellites together which is selectable by operator if a specific satellite data needs to be studied. These plots where to show their behaviour which are in absolute control under local conditions for a propagation of 10 days continuously. Same applies to the Fig. 25.(a), with the LongLatitudeAzimuth is the angle determined towards east in the plane perpendicular to the position vector, from the projection of the central body's inertial coordinate frame's z-axis onto this plane to the projection of the velocity vector onto this plane, Fig. 25.(b), with the Longitude of Periapsis is the angle measured between the vernal equinox and periapsis for the satellites in different planes. Fig. 25.(c), with the lunar beta angle is significant determination because it gives the declination information of the Earth-Moon vector with respect to Earth-Sun elliptic plane. Fig. 25.(d), gives the rate at which the longitude changes with respect to the orbit in the body frame of the satellites. Fig. 25.(e), which the satellite propagation from latitude to longitude is portrayed to determine satellite's positioning under uncertain anomalies. These parameters add tremendous essence to a planning and tracking capabilities of the constellation and an enhanced observation support to the operator instead of only relying on the roll angles.

Another addition to this research has been the inclusion of the ground station analysis with respect to the parameters to be monitored on ground and its related aspects. The simulations and analysis presented above have been with respect to the on-orbit operations of the satellites in constellations. Ground stations play a prominent role in the operations and planning in governing a constellation for a desired period of time. They have to be a significant portion of the planning and scheduling not only with respect to the satellites in-orbit, but also as ground systems operations on Earth or Moon. With this understanding in mind, the ground operations and analysis of the same was determined and executed with visual and parametric simulations as presented in the section 3.3. For LEO, the ground stations were aligned as multiple reception stations of the end-user data as strategized for the mission. Fig. 27 shows the parametric importance of the constellation with respect to ground stations graphically. Fig. 27.a gives the idea of the offset from a user-defined global reference repeating ground track grid determined at the Ascending Node. This has a great worth in constellations as the revisiting times of the satellites. Uniquely, Fig. 27.(c), gives the elevation of one satellite in operation in synchronization the other forming a constellation. This makes the autonomous tracking more efficient and adds to the synergy and ease of the operator in managing the constellation. Fig. 27.(d) presents the elevation and azimuth angles in one frame to avoid cumbersome detailing for an operator to understand specifics. Similar orientation and analyses are done for MLO based on local lunar conditions shown by Fig. 29.

7. Conclusion

This paper presents novel script-based ideas and their execution with simulations, visual demonstrations and parametric analysis of the mission planning, scheduling and operations of the small satellite constellations for CisLunar Space. As the applications for Earth is envisioned for comprehensive and cost-effective disaster management globally, the LEO-based constellations are significant for earth observation and efficient data relay. In similar lines, as this age of NewSpace is moving towards a compelling and ambitious mission like Artemis, the MLO region is proposed for a continuous and valuable support for it with small satellite constellations positioned in this portion of the lunar space and environment. As the planning and scheduling play a vital role in execution of these constellations to perform as desired, two novel upgrades to traditional Heuristic methodology has been proposed and presented named as 1. Slew Maneuvering 2. Adaptive Mapping which are both fully scripted for gaining autonomy over operations. Both the techniques add their respective value to LEO and MLO building cost-effective CisLunar economy for all irrespective to specific nations and entities taking the utmost lead and benefits for firm sustainability.

This research also recognizes the importance of operations along with mission planning and scheduling efforts. The Controlled Deployment of Satellites (CODES) is proposed with concept, execution strategy and its benefits to emphasize the need for not only building small-sized constellations with global and optimal coverage with small satellites but also to accentuate the serious issue of environmental and astronomical effects of growing satellites in CisLunar space. With space debris also in consideration, the consequences of the continuous filling up of the CisLunar region is cautioned for its setbacks and near future challenges. For future work, this research will be continued to study and develop several other unique concepts and algorithms extensively for CisLunar space. There a work in progress to develop a fully autonomous platform to monitor and small satellite constellations in both LEO and MLO regions with due consideration of managing and strategizing the CisLunar space. The above presented simulations and visual demonstrations form a prominent basis for the development of the platform with autonomy.

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