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Parametric Assessment to Fully Deploy Autonomous Small Satellite Constellations for Cislunar Space

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ABSTRACT

In this new age of cislunar competition for attaining the optimal solutions for Earth and the Moon, NewSpace stakeholders have leaned toward sustainable operations. Both industry and academia play major roles in this era of challenging space survival with the growing number of missions and debris. This paper focuses on scaling and optimizing small satellite (<500 kilograms) constellations and utilizing them in cislunar space by evaluating earth observation missions' constellations for support in Artemis-2-like missions for Lunar orbits. From an astrodynamics point of view, a significant amount of scaling of constellations is done by identifying the parameters affecting the performance, which are mission-specific to their environments with fewer satellites. A detailed parametric analysis of medium-sized constellations, operable in cislunar space, for critical applications like communication (Lunar region) and disaster management (Earth region) is presented. Literature, related dynamics, discussions of the possible futuristic scenarios, discussions, and conclusions are explored.

INTRODUCTION

The cislunar economy is raging towards building sustainable and meaningful space missions focused towards applications critical to humankind on various fronts of exploration and solving sensitive Earth issues. Small satellites can play a major part in the cislunar economy for applications like disaster management for Earth and the communication relay in missions like Artemis-2 for the Moon. The small satellites as constellations function as a close-knot system to deliver the necessary data to Earth and Moon as required by the end-user. Once said, the concerns and adaptation to the space environment are a challenge bigger than ever before in this NewSpace competence. Hence, there is a need for creative and purposeful implementation of the limited number of satellites in a constellation. The constellations must be managed optimally to save important resources and avoid unnecessary blockage to other crucial missions significant for the Earth and Moon applications for long-term sustainability. To assure long-term sustainability, autonomy must be used to balance mission operations and align to the ground segment in complete synchronization to reach desired goals in orbit and on the ground for the given mission lifecycle. NewSpace competence in resource utility constraints and adapting to challenging space environmental factors have a huge scope for research and developing systems for small satellites and their payloads. The use of these small satellites in scaled constellations must be considered to maximize performance with minimal resources.

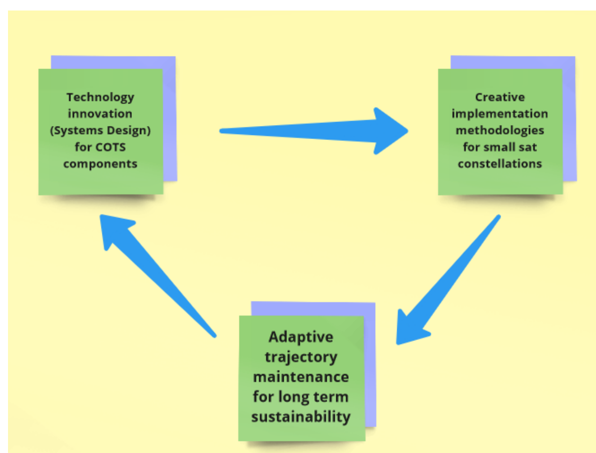


Figure 1: NewSpace systems development strategy

Balancing all these constraints is a painstaking effort for the developers and systems engineers. Hence, a calculative risk is needed in full conformity with the dynamics involved in the constellation design, development, and deployment in a single framework, along with systematic mission planning and operations for a given mission lifecycle. Fig. 2 addresses this balance in a closely-knot design and operation of the parameters supporting the constellation development and full deployment in Cislunar space.

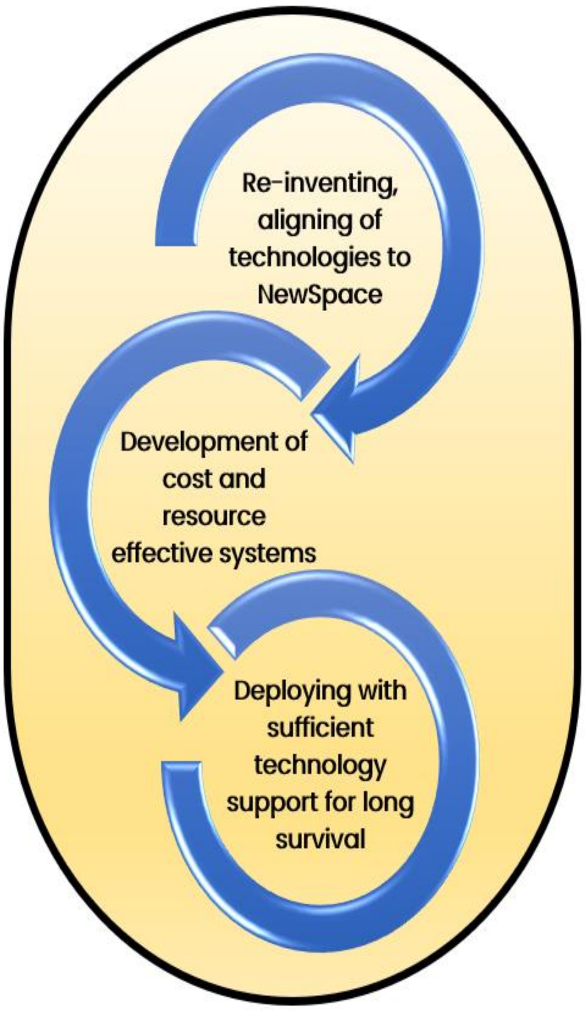


Figure 2: Process alignment in constellation designing

It is also concerning that most of the Cislunar space still needs to be explored fully with present satellite technology. Consequently, it poses more threats and uncertainties to try new technologies and communicate, especially with the Moon's region of Cislunar operation. These challenges became evident through the missions like FLASHLIGHT and CAPSTONE [1,2], but several such attempts are aligned globally to reach and even land on the surface of the Moon in this decade, including the most anticipated Artemis-2 mission slated for launch in 2023. The parametric balance with resource constraints and system performance is depicted in Fig. 3 below.

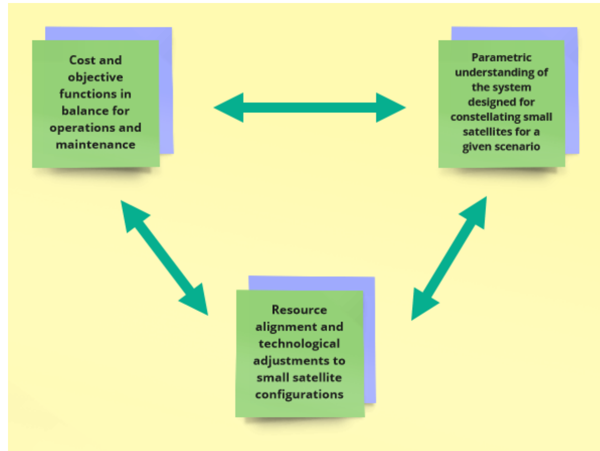


Figure 3: Balancing factors in deploying small satellite constellations

Therefore, with all these factors in focus, this research analyzes the major and critical parameters affecting the small satellite operations in the Cislunar region. Significant research is being carried out globally at various levels of constellation design and implementation for numerous applications. The sudden shift in paradigm with NewSpace initiatives and standards in place has caused the constellations to operate in a much more challenging and unpredictable environment than ever before. With small satellites, this difficulty is doubled with various constraints to incorporate resources and payloads to operate precisely in the given dimensional boundaries.

The reference [3] brings about the recent changes in the satellite constellations from existing to emerging ones is an eye-opener in this NewSpace era. Similarly, the [4] gives an important outlook of the large constellations using small satellites. On the application side of it, SAR constellations are catching up globally as an important portion of space utilization strategy. This has been practically implemented and maintained by several commercial companies globally. However, the reachability to Asian countries still has a large void because of the cost constraint, as the data is expensive and needs moderation soon to adapt to this region's applications fully.

In this regard, [5] presents a mini SAR constellation from the European Space Agency and details the ongoing and futuristic missions in the next few years for Moon. This is presented in comparison with the global missions, which are taking a major leap towards gaining access to cislunar space and operating missions which are meaningful to humankind in the long term. In the case of coverage assurance, [6,7] determines a technique to fully utilize the small satellites as constellations for the application of surveillance, which is termed as a 'lightweight' constellation mission for continuous and stable coverage of a particular region for a given mission duration. The decentralization of the constellations on a large scale is demonstrated by [8], an important aspect of today's constellation scenarios with large constellations. On assessing the reliability of the arbitrary constellations, [9] presents a method for a wide range of application-based concepts as the constellations are taking a significant amount of space near Earth and soon to be near Moon.

For autonomous operations, several researchers have come forward to use autonomy for a sustainable constellation in this ever-changing Cislunar space environment. The research presented by [10,11] directs this motive towards a seamless autonomous operation in the Cislunar domain. It is to be supported, the role of legal aspects is also to be closely monitored, and research is intensifying on the same ground. With research articles like [12,13], the Cislunar space is moving towards a controlled and adaptive environment of operations which is dully important for safety and equal-opportunity for all the space-enthusiast countries. This will also regulate and define the Cislunar economic boundaries.

This paper will primarily focus on the systems engineering aspects of the small satellite constellation deployment using autonomy. A detailed parametric analysis is presented covering the Cislunar region and its real-time scenarios of operation and scaling them optimally for efficient use of space in this region, as depicted in Fig. 4. This will align a direction of the futuristic use of this region in a controlled manner avoiding critical cases of collision and adaptive use of the technologies to use resources responsibly. Several layers of these crucial elements will be discussed in this paper for an effective small satellite utilization for the constellations in the Cislunar domain.

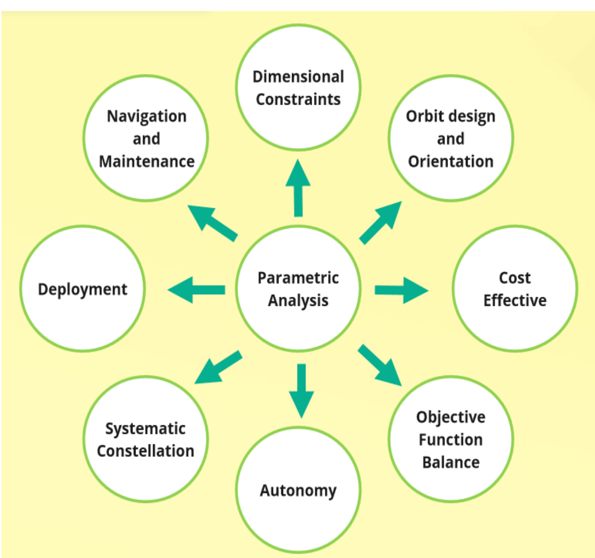


Figure 4: Elements of parametric scaling of constellations

TARGET APPLICATIONS AND WHY?

Cislunar space is growing and getting intense, with several countries participating in the NewSpace initiatives for missions to Moon, constellations, and enhanced technology demonstration in the Low-Earth orbits. This has much to do with valuable applications with each mission with commercial and national interests. The target applications for Earth and Moon are distinct but equally important in their respective environments. The classification and their essence are presented below specifically.

Earth

The climate change and global warming terms are real and need an immediate focus on various fronts in the global scenarios of industrialization and calamities caused due to its impact on Earth's environment and ecosystem. Utilizing space effectively with the Earth's orbits is a challenge, but several missions recently have been trialed to get the most out of enhanced technological advancements to provide instant relief for disaster management. According to a United Nations report [14], in 2022 alone, more than 270 billion USD has been lost in infrastructure and other losses, along with about 30,000 lives lost. This number is expected to be much higher in the coming times, and it needs serious strategizing on the actions to be taken over a while to suppress these statistics in coming years. Small satellites have been prominent in delivering much-needed data individually and in the constellation for a few decades. Their application for disaster management is significant in constellations with even hourly data possible to be acquired as per their mission objectives. But the challenges of balancing the cost, resources, and lifecycle longevity still leave a huge scope for research and development to fulfill the global requirement for such data. Thus, this research will take this as an opportunity to optimize small satellite constellations and reduce the constraints in its overall applicability for Earth orbits as a part of the cislunar region detailed in Fig.5.

Figure 5: Process alignment for disaster management application

The applications and innovation in small satellites are still difficult to maintain their performance and align all the operations and individual functions for long-term sustenance and enduring space environment.

Moon

Lunar missions are being experimented on more frequently than ever before. The HAKUTO-R [15] mission has opened commercial doors for private companies to actively participate in the NewSpace lunar activities as the Artemis-2 gears up for a station at Near-rectilinear Halo Orbits (NRHO) and also land astronauts in 2023 [16]. This region, part of the cislunar space, will get populated sooner and need scientific and technological assistance to regulate, operate and maintain satellites effectively.

This research aims at supporting Artemis and similar missions, providing insight and support with systems engineering and related dynamics, analyzing possible scenarios under a lunar environment, and determining meaningful data and information that can sustain the deep space for the betterment of humankind in the long run. Several initiatives are under progress globally with Moon to Mars missions and ideas to solidify the significant role of cislunar space in the coming years.

This paper will contribute towards the communications and parametric scaling of small satellite constellations for the case of the Moon and determine the results and framework of the proposed concept and mission architecture accordingly. Small satellites tremendously assist Artemis missions, with CAPSTONE taking place before Artemis-2 departs later this year. These satellites as constellations will be an asset for the Moon and cislunar space.

Therefore, there is an urgent need to plan, test, and execute these satellites strategically for a given assignment for Moon. If implemented in a well-defined methodology and unique systems design and operations alignment, these constellations will provide data to Moon and Earth with much less latency and accuracy for regular communication and information sharing with Earth's ground control and Moon's landing sites. A balance of all these parameters will scale down the constellations to be used efficiently and optimally for a longer duration and sustain uncertainties. The process is depicted in Fig. 6.

CONSTELLATION DYNAMICS (CISLUNAR)

The constellation design widely depends on the dynamics used and the parameters used for aligning the satellites systematically. It remains a significantly pivotal element of the small satellite constellations in the cislunar region. The parameters are determined, correlated, analyzed, and evaluated in each mission to make the most out of each in uniformly affecting the mission. This is also most significant in terms of scaling the constellation size, reducing the number of satellites, and optimally managing the constellation under all known constraints with small satellites.

This paper will present the important parameters integrated through the constellation-based dynamics in the Cislunar environment. Designing, aligning, and maintaining these parameters under the influence of several disturbances and unknown anomalies have never been as challenging as these days. Accordingly, detailed, and dedicated research on the effective scaling of constellations has been carried out with due consideration to the small satellites and their modes of operation in this given region.

The dynamics utilized for detailed parametric analysis are determined below.

In the current scenarios of the orbits operating in a close-knot resource constraint and a severe space environment, the [17] presents a set of relative motion equations in a plan of the constellation with chief and deputy satellites and without perturbations as:

$$x = \frac{r_f}{2}[(1+\cos i_R)\cos(\Delta\alpha^- + \beta_{xy}^-) + (1-\cos i_R)\cos(\Delta\alpha^+ + \beta_{xy}^+)] - r_m \quad (1)$$

$$y = \frac{r_f}{2}[(1+\cos i_R)\cos(\Delta\alpha^- + \beta_{xy}^-) + (1-\cos i_R)\cos(\Delta\alpha^+ + \beta_{xy}^+)] \quad (2)$$

$$z = r_f \sin i_R \sin(v_f + \beta_z) \quad (3)$$

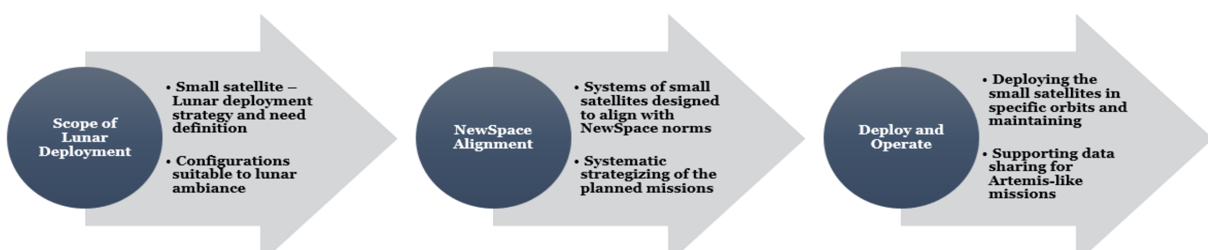


Figure 6: Process alignment for Moon-based applications

Where α and β are the angular and phase angles. These equations are relevant for the Moon's parametric propagation as well but with due consideration of its own operating ambiance. For Earth, J2 is the most dominant perturbation in lower Earth orbits but with significance to the solar radiation pressure and other major perturbations.

As the defined orbits are usually circular in propagation, the phasing rule of the master satellite defined by [17] in this case is given by individual orbital elements as below:

$$\Omega_l = \Omega_1 + \theta_\Omega (l-1), l = 1,2,3......N \tag{4}$$

$$i_l = \cos^{-1}\left(\frac{\cos i_R}{\sqrt{1-\sin^2 i_c \sin^2 \Delta\Omega_l}}\right) + \tan^{-1}(\tan i_c \cos \Delta\Omega_l) \tag{5}$$

$$\omega_l = \Phi_l + \omega_R, \omega_R = \omega_1 - \Phi_1 \tag{6}$$

$$M_{l0} = \bar{M}_{10} + \Psi(M_{c0} - \Phi_{c(l)}) - \omega_R \tag{7}$$

$$\Delta\Omega = \Omega_f - \Omega_m \tag{8}$$

Where 'f' represents a follower satellite and 'm' is a master satellite in a plane of a constellation.

J2 being a major perturbation in the lower Earth orbits and drifts due to these disturbances are common in this region affecting the overall constellation. But at the parametric level, each orbit element has its own deviation from the designed configuration under these severe drifting conditions. The most affected elements are shown in the equations below [17]:

$$\dot{\Omega} = -\frac{3}{2} J_2 n \left(\frac{R_e}{p}\right)^2 \cos i \tag{9}$$

$$\dot{\omega} = \frac{3}{4} J_2 n \left(\frac{R_e}{p}\right)^2 (5\cos^2 i - 1) \tag{10}$$

$$\dot{M} = n + \frac{3}{4} J_2 n \left(\frac{R_e}{p}\right)^2 \sqrt{1-e^2}(3\cos^2 i - 1) \tag{11}$$

Where $p = a(1-e^2)$

Therefore, as this can be noticed that the parameters are such a crucial part of the constellation orientation under various scenarios and environments. This paper will have orbits with different environments for the Earth side of applications and this is highly essential for analysis for scaling these constellations precisely for a given mission and its parameters governing it.

A much-detailed impact of the J2 perturbation is presented in [18] with simulations based on Earth's oblateness and gives significant results with analysis. This paper utilizes the J2 perturbation partially as it includes lower Earth orbits but also the other disturbances in higher orbits (MEO and GEO) are also analyzed as an integrated part of the proposed concept. Fig. 7 depicts an overview of the Earth-based constellation dynamics with due consideration of orbital parameters in operation.

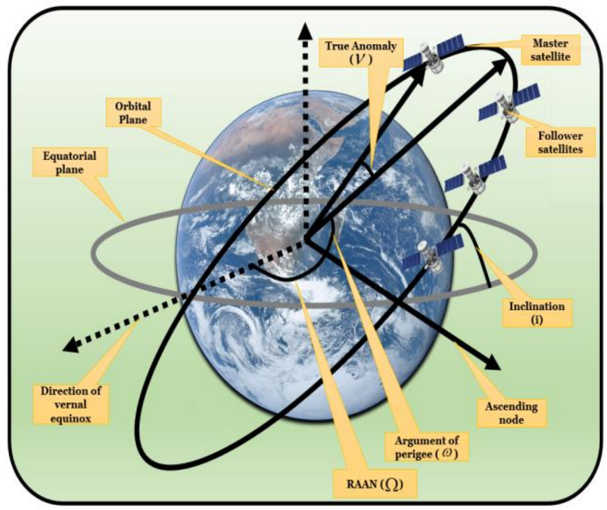


Figure 7: Parametric essence of an orbit in a constellation with multiple satellites (Earth)

Apart from the system and constellation design, the coverage geometry is followed with [19] with a clear understanding of the orbital coverage per plane in a constellation. The equation is depicted below.

$$\cos(\theta + \varepsilon) = \frac{\cos\varepsilon}{1 + \frac{h}{r_e}} \tag{12}$$

Where θ is the angle from the center of the Earth to the satellite; ε is the elevation angle from the ground; h is the height of the satellite from the center of the Earth; r_e is the radius of the Earth.

This is the core reason to utilize this concept in this paper for optimal constellations for a scaled number of satellites using 'Draim' orbits and circular orbits for better and effective coverage and longevity of the trajectories within their given planes in a constellation. These orbits are symmetrical, elliptical, and circular, operating with common functions and executing daily tasks in orbit in synchronization with the defined ground stations. This concept is seldom utilized in the real world, but it is high time ideas like these came into existence to optimize and scale the constellations for better utilization of the cislunar space.

In the case of a Moon's constellation, the dynamics are different due to contributing anomaly elements to the satellite propagation unique to the lunar ambiance. The major disturbances come from solar radiation pressure and gravitational variations. These dynamics are followed by [20], which describes the constellation orientation in a specific unique way to maintain the orbits in the given scenarios of the harsh lunar environment. The relative position vector is computed as:

$$\Delta r = r_a - r_b \tag{13}$$

Where r is the position of the respective satellites a and b. Based on this approach, the respective angles to govern the positions of one satellite to the other are determined as shown below:

$$\alpha_{ij}(t) = \arccos\left(\frac{r_a(t) \bullet r_b(t)}{\|r_a(t)\|\|r_b(t)\|}\right)$$
$$\alpha_t(t) = \arccos\left(\frac{R_m}{\|r_a(t)\|}\right) \tag{14}$$
$$\alpha_t(t) = \arccos\left(\frac{R_m}{\|r_b(t)\|}\right)$$

Fig. 8 presents a pictorial overview of the lunar module of dynamics as shown below:

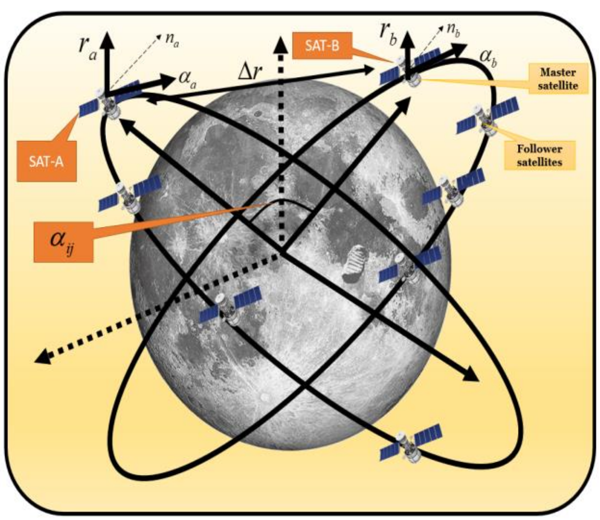


Figure 8: Parametric essence of an orbit in a constellation with multiple satellites (Moon)

The effects of the gravitational uncertainties and solar radiation pressure are presented with the equations below:

The gravitational potential used is given as:

$$U_G = \frac{\mu}{r} + \frac{\mu}{r}\sum_{n=2}^{N}\sum_{m=0}^{n}\left(\frac{R_0}{r}\right)^n \left[C_{nm}\cos(m\varphi) + S_{nm}\sin(m\varphi)\right]P_{nm}(\cos\theta) \tag{15}$$

where μ is the gravitational parameter of the central body, r the distance to the center of mass of the body, φ the longitude, θ as co-latitude, R_0 is a reference radius, $P_{nm}(x)$ are Associated Legendre Functions, while C_{nm} and S_{nm} are Stokes coefficients.

The Solar radiation pressure is defined with an equation given below:

$$a_{SRP} = \frac{\chi_S}{c} * \frac{(1AU)^2}{d_S^2} * c_R * \frac{A_S}{m} \tag{16}$$

χ_S is 1367 Wm^-2 is the Sun mean flux at 1AU, c = 299792458 ms^-1 is the speed of light, d_S is the current Sun-body distance, c_R is the reflectivity, and A_S is the cross-sectional area of the body exposed to the radiation. The remaining values are set according to the configuration selected for the satellites. As this is for a small satellite weighing under 500 kg, the generic values are determined and inputted for analysis in the later sections of this paper.

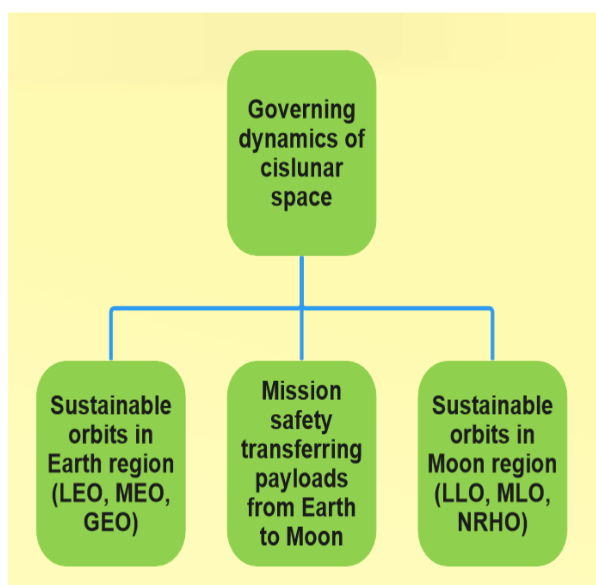


Figure 9: Cislunar dynamics alignment

CISLUNAR AUTONOMOUS OPERATIONS – ROLE AND SIGNIFICANCE

After aligning the constellation dynamics, it is essential to define the portions of integrating the autonomous logic and the operations in consideration and synchronization with the ground operations and the mission objectives. Small satellites (ranging from 1 to 500 Kilograms) are the need of the hour with several applications that are aspired with the cislunar orbits, including deep space utilizing the Moon orbits to explore Mars and beyond. Hence, strategically the cislunar space becomes the most pivotal region for space exploration and solving real-time issues on Earth for coming generations.

Accordingly, this aspect of autonomy in small satellite constellations needs to be planned, organized, designed, deployed, and operated until the mission objectives are fully attained. Attempts are being made globally to progress towards stable and adequate results from these constellations allowing creative competence in the region for sustainability in long-term resource management. The article [21] brings out the essence of the LEO-based nanosatellite constellations to assess the capacity of transmission based on the orbits selected and the associated attitude control needed. This gives a sense of understanding about how important it gets to manage the constellations optimally with better configurations and adaptability to the shared ambiance. In similar content, [22] briefly details the constellation and network architectures and technologies associated with small satellites but comes up with innovative ideas to deal with issues for applications like maritime surveillance. With this being application-focused, [23] further defines the decision-making and optimization framework for a new generation of constellations. These articles imply the significance of research in technological enhancement as a major necessity in the coming times for evolving and utilizing small satellites as constellations more effectively than they are currently in the cislunar scenario.

Defining and implementing autonomous operations for fully deploying these small satellite constellations comes with several difficulties due to the dynamic and diverse space environment in this NewSpace era. Hence, several considerations, calculations, and analyses must be considered, tested, and implemented as adaptable to the given Cislunar ambiance. This needs a specific and strategic implementation process to fully deploy constellations autonomously and operate them until the given life cycle and bring them back to Earth without contributing to cislunar debris in coming times as the mission grows in the region. This can be witnessed by the recent ongoing research for attaining autonomy in certain small satellite constellation operations sections. One such reference is given through [24] for validating the design of an autonomous orbit determination system for a small satellite constellation. Whereas [25] uses autonomy for developing the safety-guided system for mega-constellations of satellites surrounding Earth.

These references are discussed to understand the global push for integrating autonomous functions into the operations in cislunar space to safeguard the missions and get the intended solutions and results from the defined target objectives. The research presented through this paper will emphasize scaling the constellations using appropriate autonomous functions and logic to utilize the cislunar space optimally as per the defined goals saving cost and resources valuable for Earth and its existence as presented in Fig. 10 as a set of factors significant with autonomy.

Figure 10: The Significance of utilizing autonomy in small satellite constellations

This paper makes a combined effort to integrate autonomy into the operations of the small satellite constellations specific to cislunar space. This is to emphasize the utilization of the autonomous functions to fully deploy the 'Draim' constellation and substantially scale them to fewer satellites for Earth and Moon. It is understood that it is not always about designing and deploying small satellites with a better configuration for higher performance in given orbits but also about optimizing the constellations' size to enhance the missions' overall value. This implies utilizing the cislunar space with better coverage, simultaneously attaining targeted mission objectives under limited resources, cost, and physical constraints about small satellites. This is portrayed in Fig. 11 below.

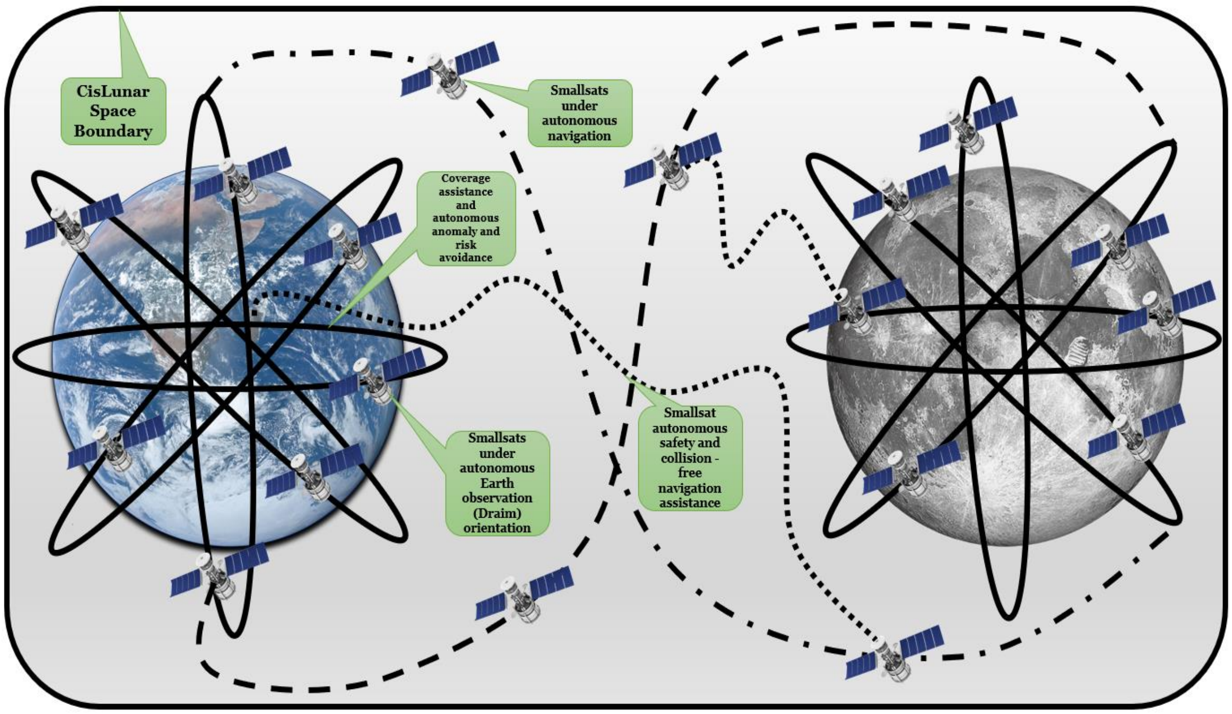


Figure 11: Concept of autonomous operations integrated with small satellite 'Draim' constellation

PROPOSED FRAMEWORK

After presenting the constellation dynamics and role/significance of autonomous operations in cislunar space, the proposed conceptual framework focused on in this paper is required to be discussed, evaluated, and presented with due consideration to the severe cislunar environment and operational constraints. A detailed study of the framework design of the proposed concept of parametric scaling of the constellation is attained and discussed in this paper.

The core vision of this research is to scale the constellation of autonomy-integrated small satellites through a tight-knot parametric design of the configuration with a well-defined 'Draim' concept utilization in Cislunar (Earth and Moon orbits) with fewer satellites fully deployed with enhanced coverage. The constellation is proposed to be operated autonomously in synergy with the ground operators and the stations to deliver the acquired data with minimum latency and loss to achieve their daily tasks appropriately. For this, parameters at both ground and in-orbit operations play the most pivotal role in governing and orienting the enhanced operations in the defined mission. Therefore, the parametric analysis is divided into specific portions as constellation-based (in-orbit perspective) parametric analysis. With this in focus, the framework of the proposed constellation design and its parametric analysis is detailed and elaborated. The fundamental ethos of this framework is defined in Fig. 12.

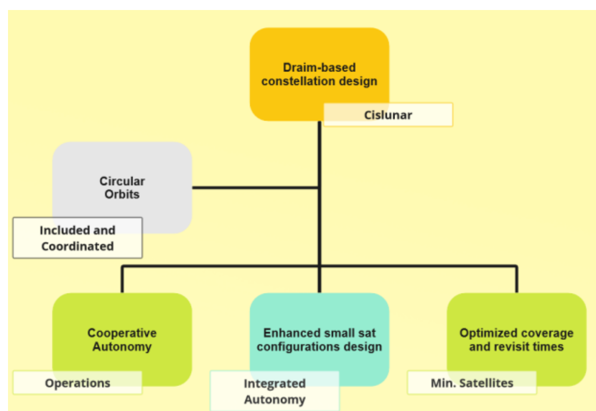


Figure 12: Essence of the proposed framework

As shown in Fig. 12, the circular orbits are also a core part of the constellation proposed. This is because there is significant operational value with circular orbits if utilized in lower earth orbits with optimally designed orbit elements specifically for disaster management type of Earth observation. These orbits are coordinated with other Draim orbits to form a distributed constellation near the Earth or the Moon within the given boundaries of the cislunar region. Recalling the value of Eq. (12), this proposed concept fully justifies using 'Draim' orbits in complete synchronization with one another as a constellation. Hence, utilizing the abovementioned concept, a detailed framework is outlined, organized, and prepared for testing through simulations and thoroughly analyzing the associated parameters. Fig. 13 shows a dedicated framework in progress for designing this concept for a cislunar-compatible constellation. This design will be used for parametric simulations and analysis and practical synthesis in futuristic research and deployment of autonomous constellations.

ANALYSIS SET-UP (VISUAL DEMONSTRATION OF CONSTELLATIONS)

The parametric analysis has been set with due consideration to dynamics, framework, and the core purpose of this research mentioned in the section above. The constellation design with distributed orbits is difficult to align and deliver the right data at a defined location. But this can be sorted by adapting creative methodology to ease the coordination of the satellites in orbit in the same or different planes. The main focus remains on scaling down the constellation size and getting maximum outcomes from it, as it is usually with a medium or large constellation utilizing better coverage capabilities for applications described in the previous sections. These satellites are designed and moderated autonomously for their defined mission objectives. Several trials were made before these set-ups presented in this paper were finalized and analyzed parameter by parameter significantly important to their respective environments (Earth and Moon). The set-ups are defined as detailed below.

Simulation Set-up Design

The set-up design for simulation has been kept common for Earth and Moon with due consideration to their operating environment and the radii of Earth and Moon, respectively.

Earth

Lower earth orbits have been highly contributing to applications like disaster management. With the given framework, a design of the constellation was made, and the elements were set as specific to the framework of the concept defined. These variations will be capitalized for various applications supporting disaster management with the data attained for instant relief provided with the given constellation coverage.

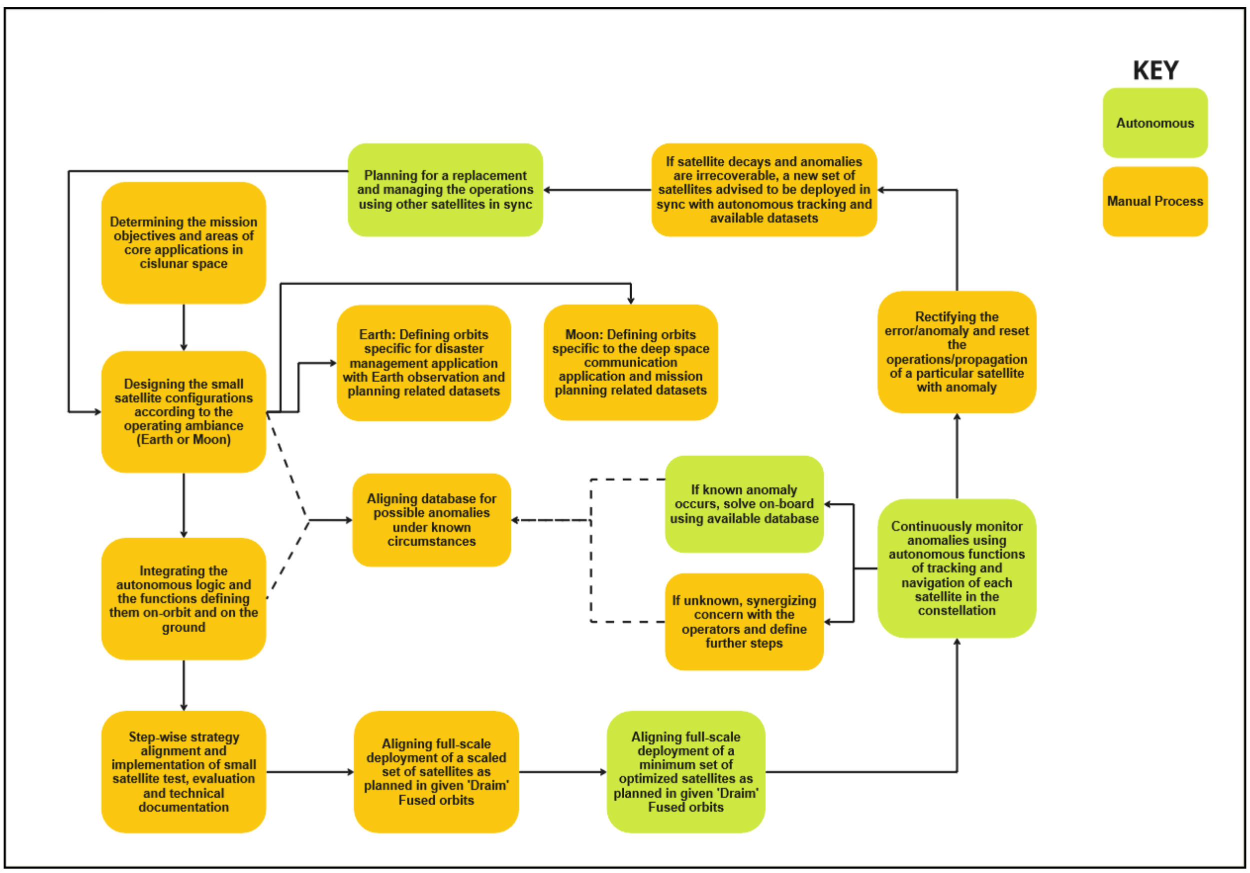


Figure 13: Common framework and strategy for scaled deployment of small satellite constellation

Moon

For Moon, the major application is the communication and data relay to the Moon's surface, inter-satellite exchange, and then back to Earth with minimum latency with this defined distributed set-up and sustain the lunar ambiance for a long duration supporting Artemis and other missions substantially.

Table 1 below shows the common set-up alignment for the constellation for the Cislunar region (common constellation strategy for Earth and Moon).

Table 1: Set-up parameters of the designed constellation

Parameters	Value
No. of Orbits	7
No. of Satellites	14
No. of Ground stations (Global)	10
Inclination (Deg.)	45 (Circular) 110 (Elliptical) 0 (Symmetrical)
RAAN (Deg.)	Equi-distant in each class of orbits
Sensor Focus (Deg.)	5~45 (Depending on satellite position in Earth or Moon orbit)
Satellite Mass (Kilograms)	100
Orbit Altitudes	550~8000 (Earth) 1200~8000 (Moon)

VISUAL DEMONSTRATION OF THE PROPOSED CONSTELLATION

The visual representation of the constellation proposed and designed is to be demonstrated to understand the setup and the orientation of the small satellites within the defined boundaries. The Earth and Moon orbits are arranged and shown below.

Earth and Moon (Collective CisLunar faring efforts)

The scenarios concerning the Earth orbits were deeply studied and aligned specific to an idea which aims to facilitate the CisLunar operations but keeping the applications solving the concerns on Earth. This is mostly specific to rigorously developing Earth Imaging aspects to enhance the disaster management not only to provide data to the end-user quickly but also meaningfully uplifting the application in relief provision and utility factor overall. This is not targeted only for getting this done for only space fairing countries but also make it affordable and reachable to the other developing or under-developed countries who are keen to enhance these capabilities. Same goes with the Moon operations as the crew lands with Artemis mission, the cost and objective functions along with each parametric observation plays a vital role.

Hence, the visualization plays a key role in developing the small satellite constellations to optimize the critical factors and resources in orbit and on ground. The figures from Fig. 14 through Fig. 19 demonstrate the conceptualized constellation for both Earth and Moon.

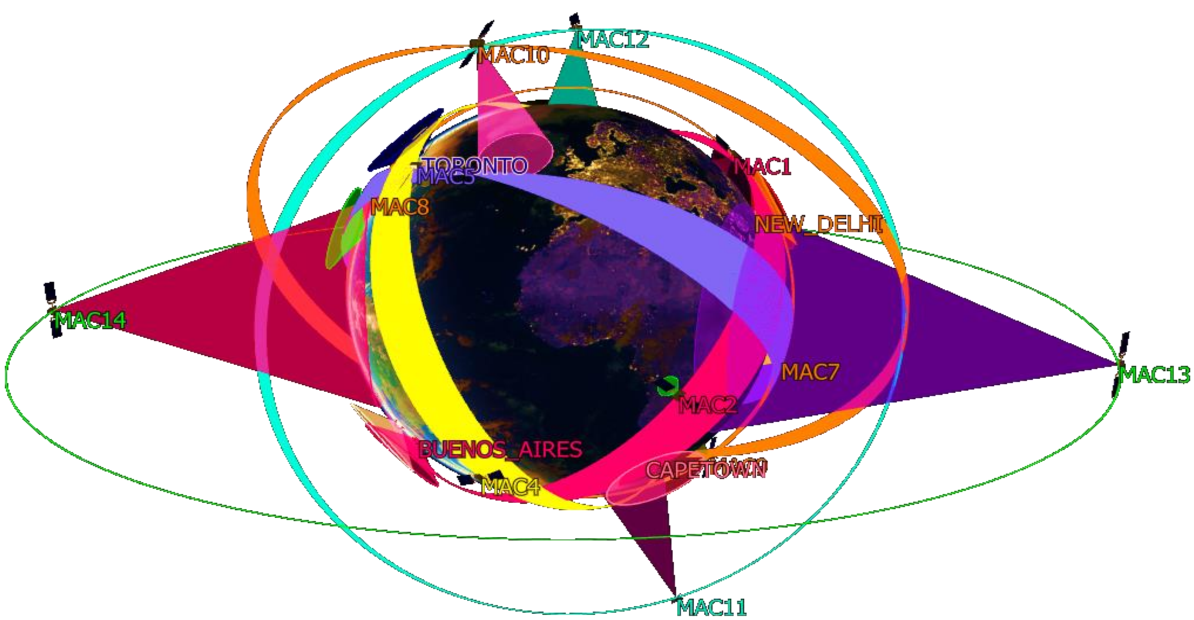


Figure 14: Inertial framed constellation demonstration (Earth) – Expanded view

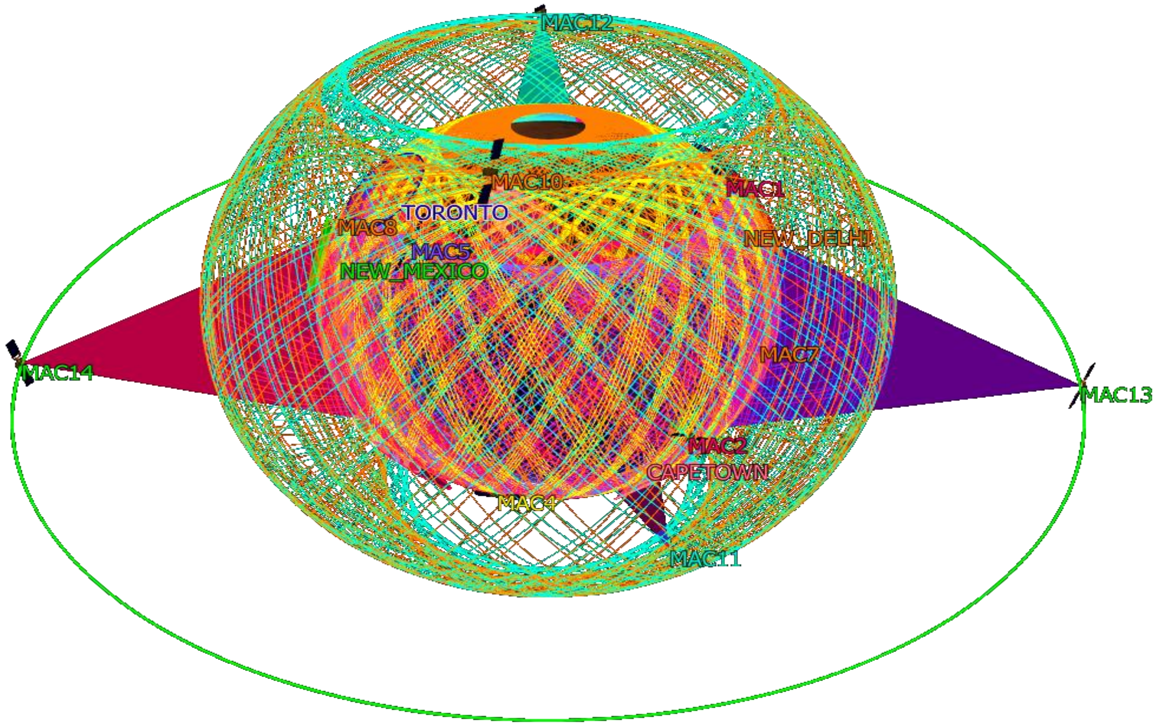


Figure 15: Body frame of the constellation under demonstration (Earth) – Scaled View

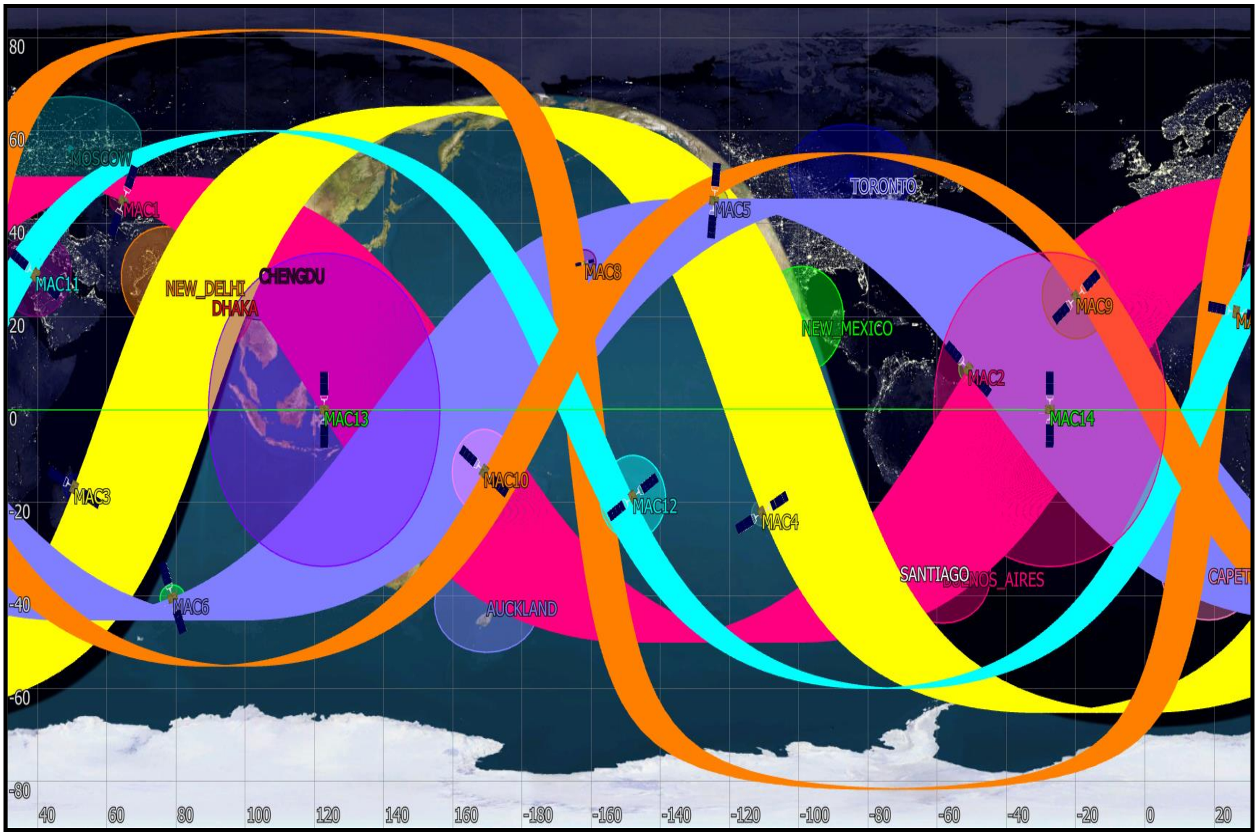
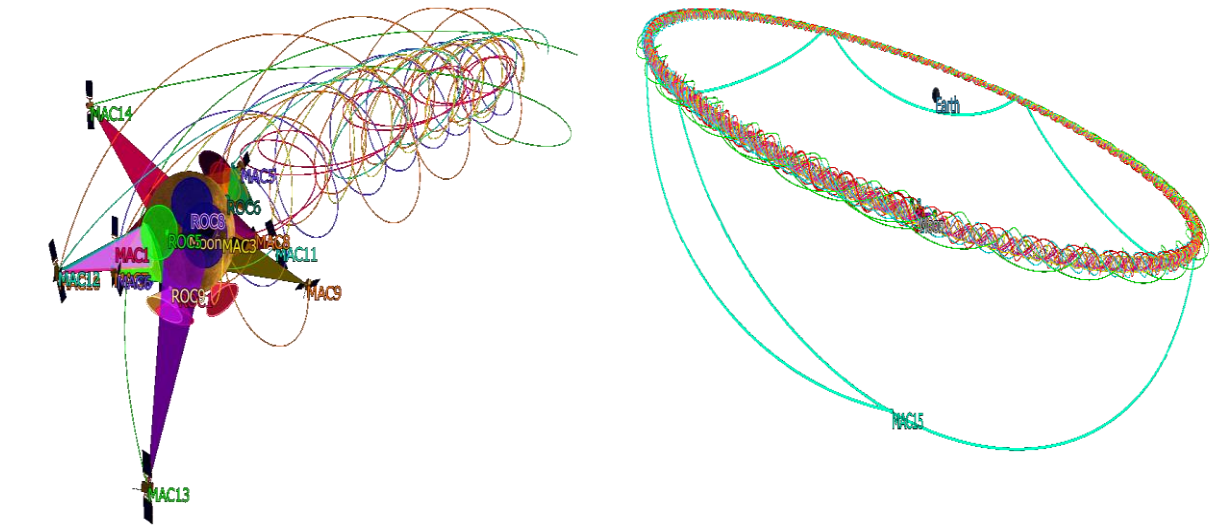


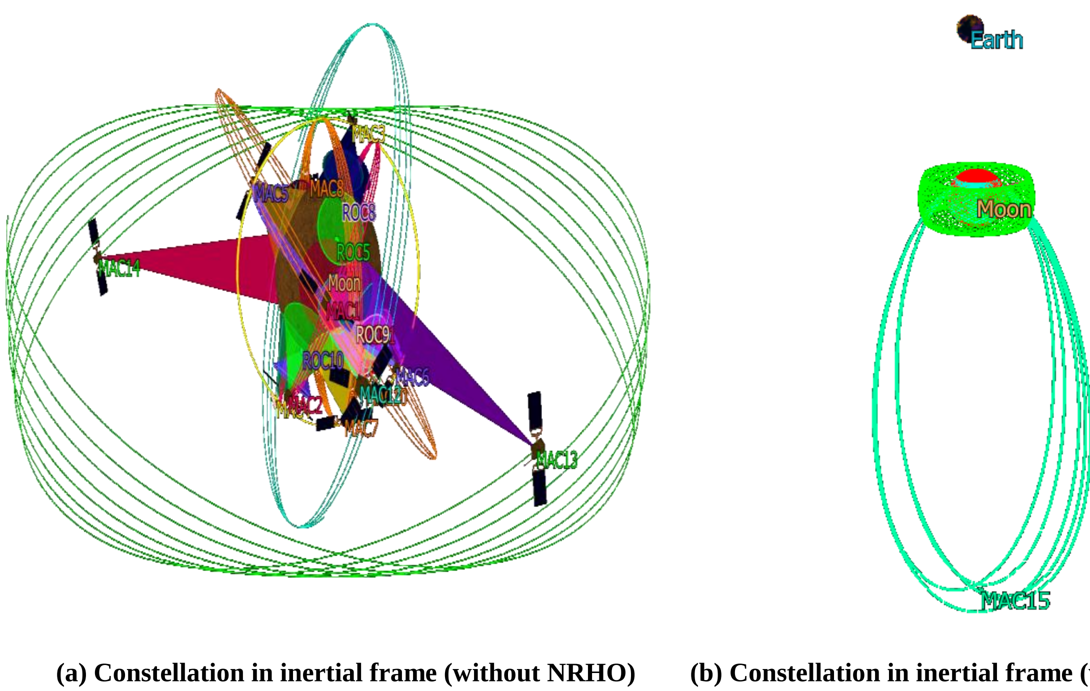
Figure 16: Inertial frame (2D) view of the constellation under demonstration (Earth) – Day/Night Scenario

Moon



(a) Constellation in inertial frame (without NRHO) **(b) Constellation in inertial frame (with NRHO)**

Figure 17: Inertial frame propagation of the constellation under demonstration (Moon) – Expanded view



(a) Constellation in inertial frame (without NRHO) **(b) Constellation in inertial frame (with NRHO)**

Figure 18: Body framed propagation of the constellation under demonstration (Moon) – Scaled view

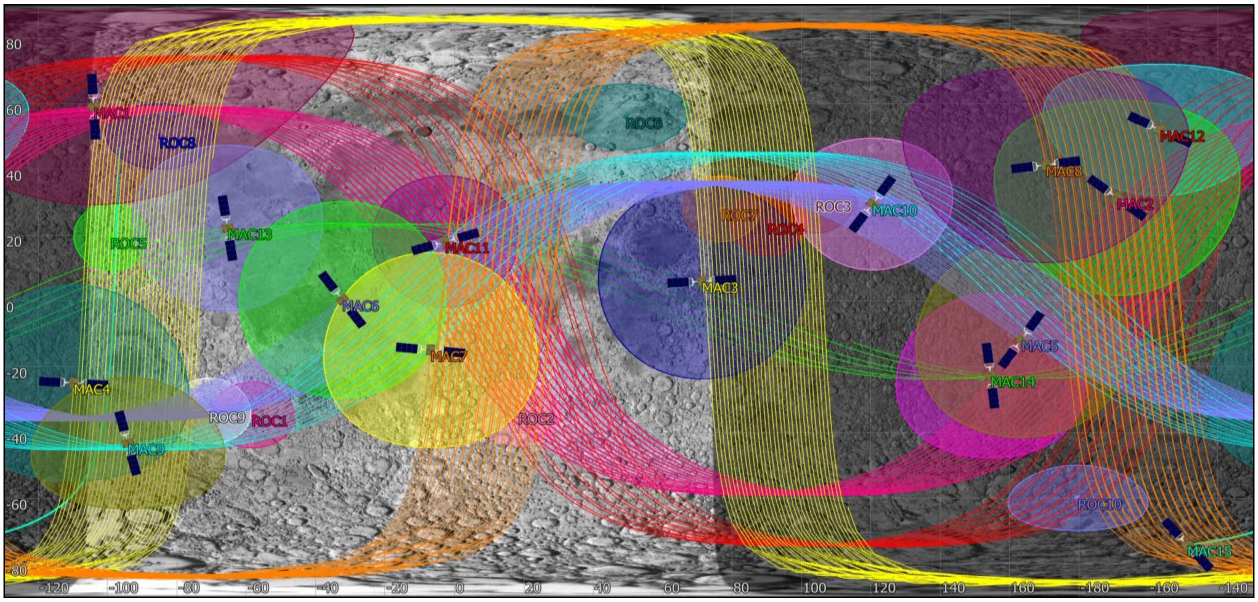


Figure 19: Body frame (2D) view of the constellation under demonstration (Moon) – Day/Night Scenario

RESULTS

The results for Constellation-based parametric analysis (in-orbit and ground scenarios) are presented for Earth and Moon below.

Constellation parametric analysis

Earth

The scaling of the iterations was performed to ensure that the points plotted are clear and have a continuous propagation over their execution. The analysis includes the orbital elements varying under severe space environment consideration (Solar radiation pressure and J2 perturbations) and significant impact being observed during the satellite propagation in a constellation for a given mission operation. The results are shown from Fig. 20 through Fig. 27.

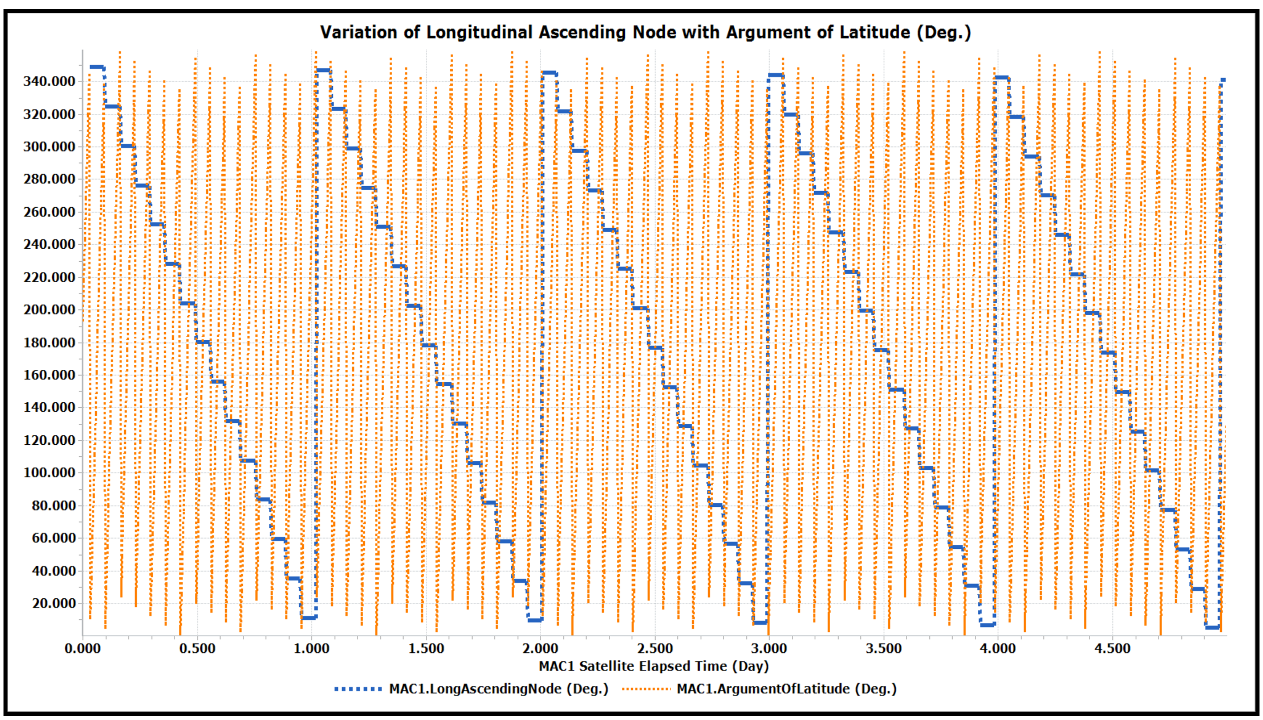


Figure 20: Variation of Longitudinal Ascending Node with Argument of Latitude (Deg.)

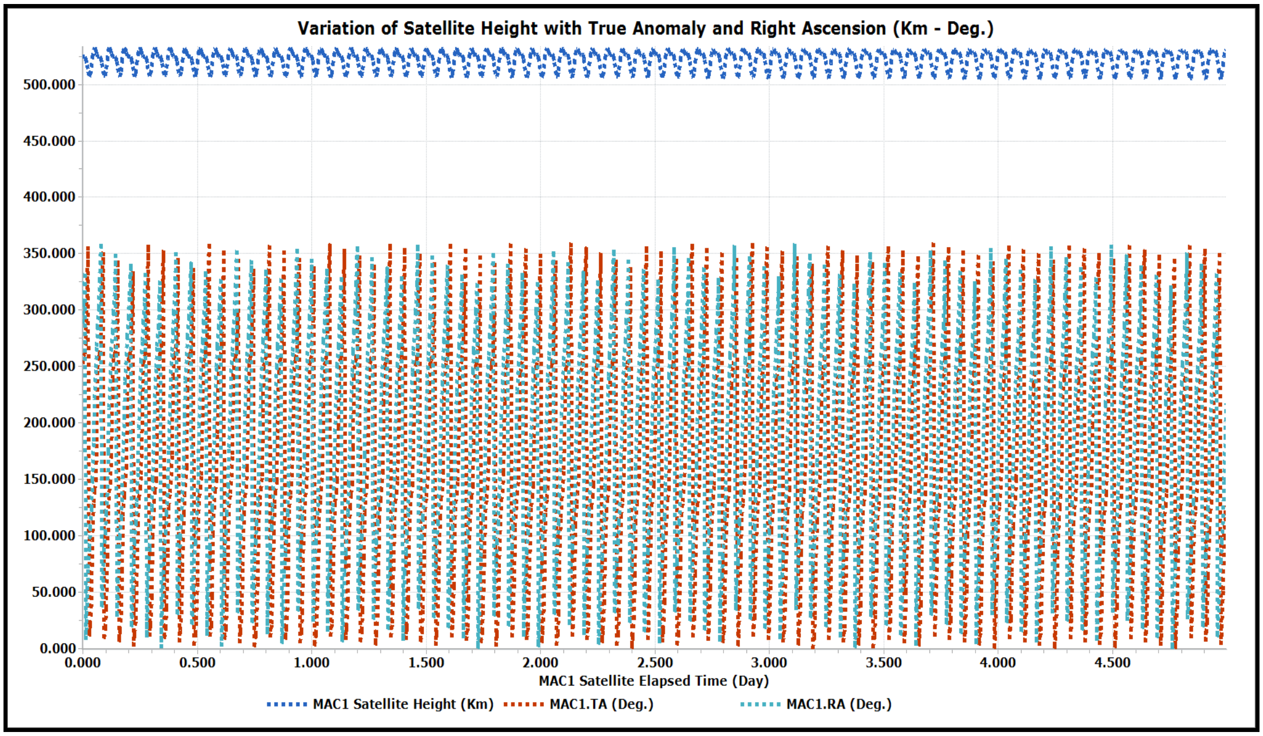


Figure 21: Variation of the satellite parameters (Height, True Anomaly and Right Ascension) over a period of propagation

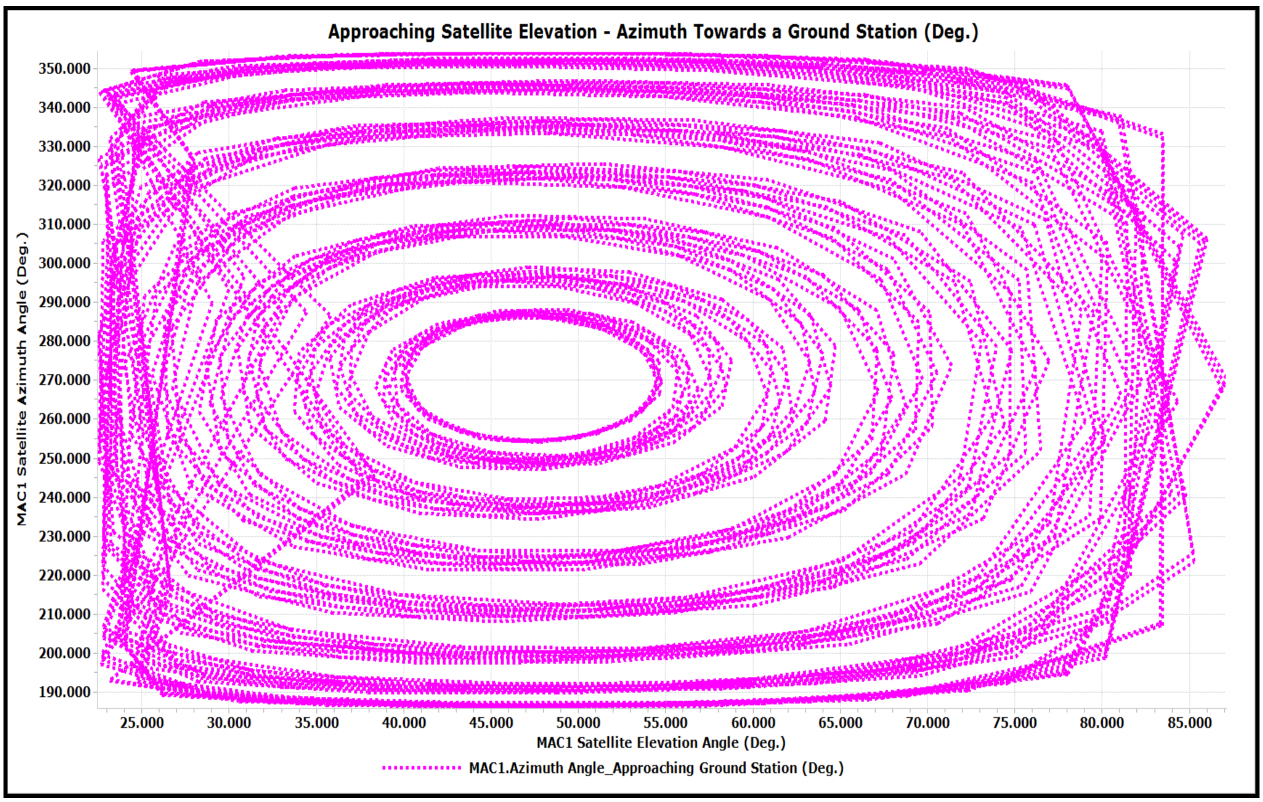


Figure 22: Variation of Elevation and Azimuth Angles of a ground station for an approaching satellite

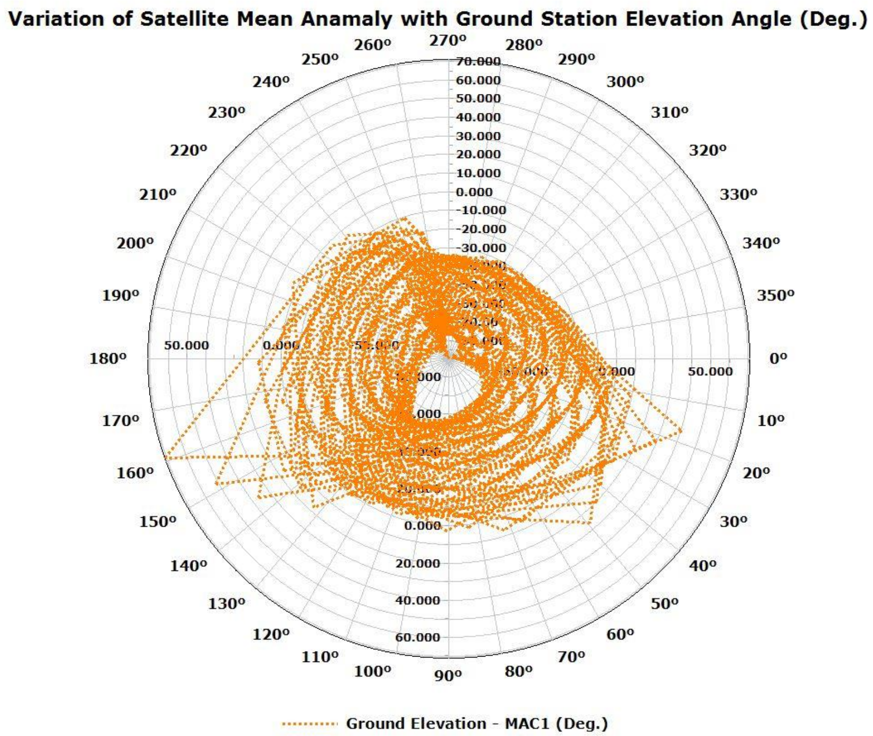


Figure 23: Variation of Mean Anomaly of the satellite with elevation angle of the approaching ground station

Moon

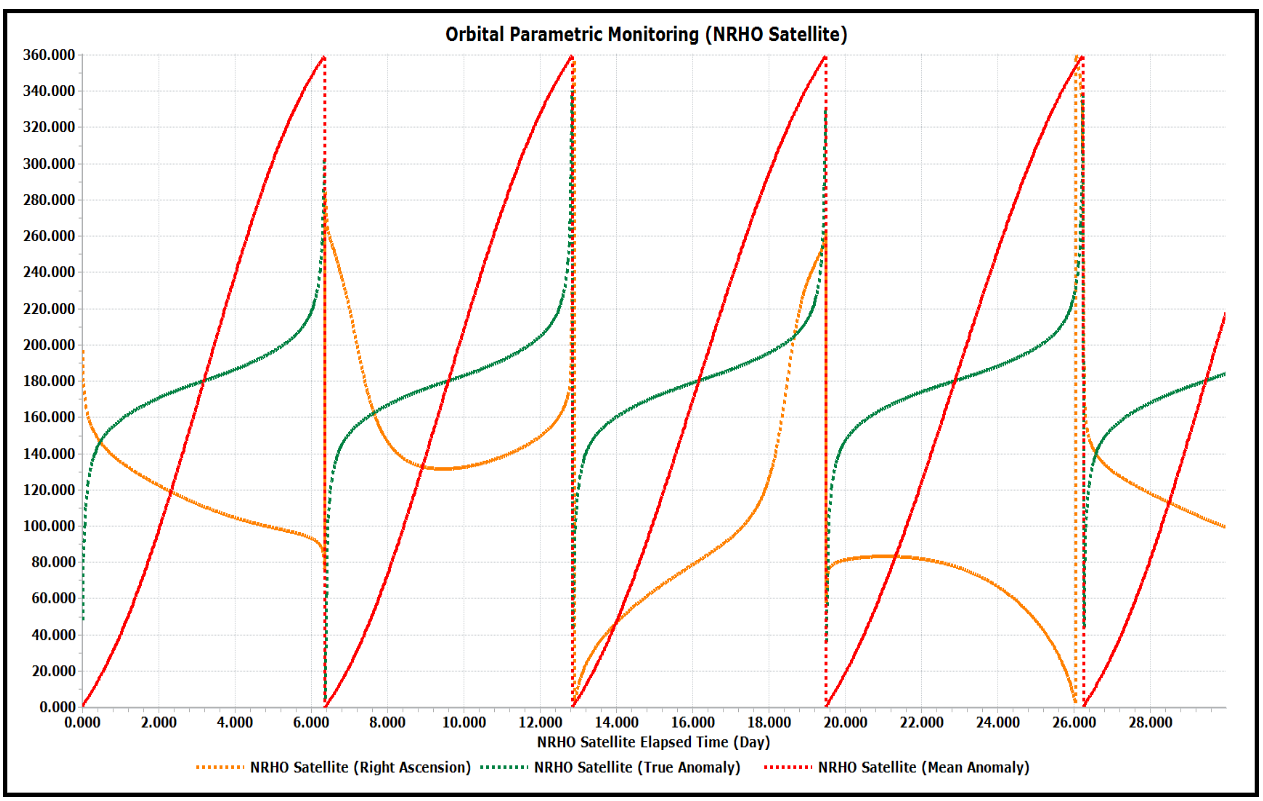


Figure 24: Variation of orbital elements of the NRHO constellated Satellite – (TA, MA and RA)

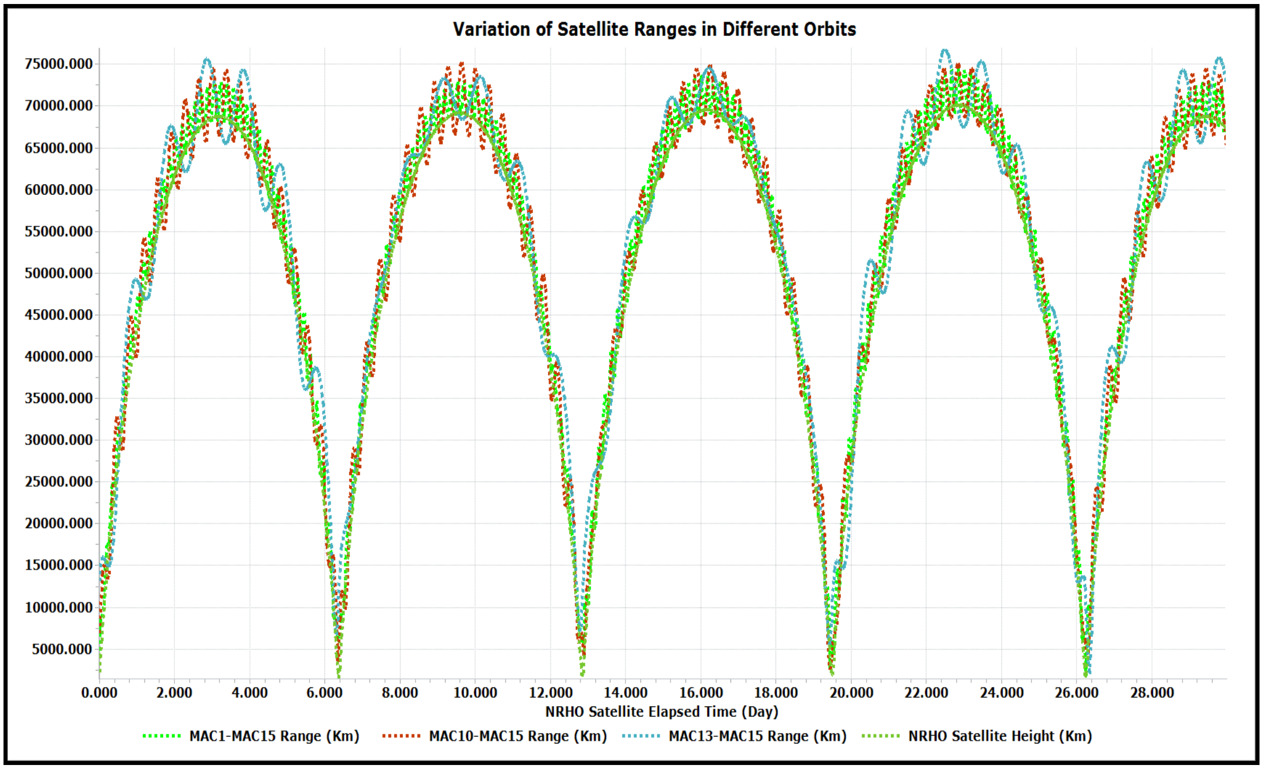


Figure 25: Range variation from satellite to satellite in constellation (with reference to NRHO)

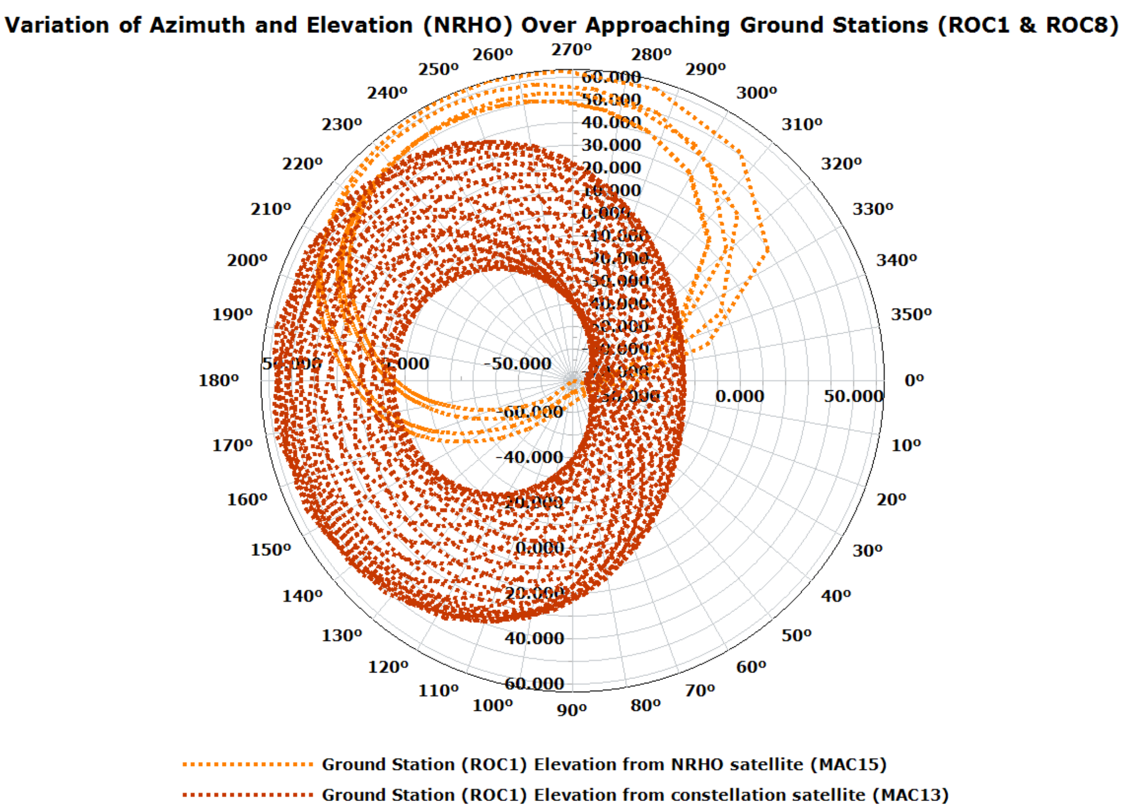


Figure 26: Ground elevation and Azimuth variation of the approaching satellites (MAC 15 and MAC13)

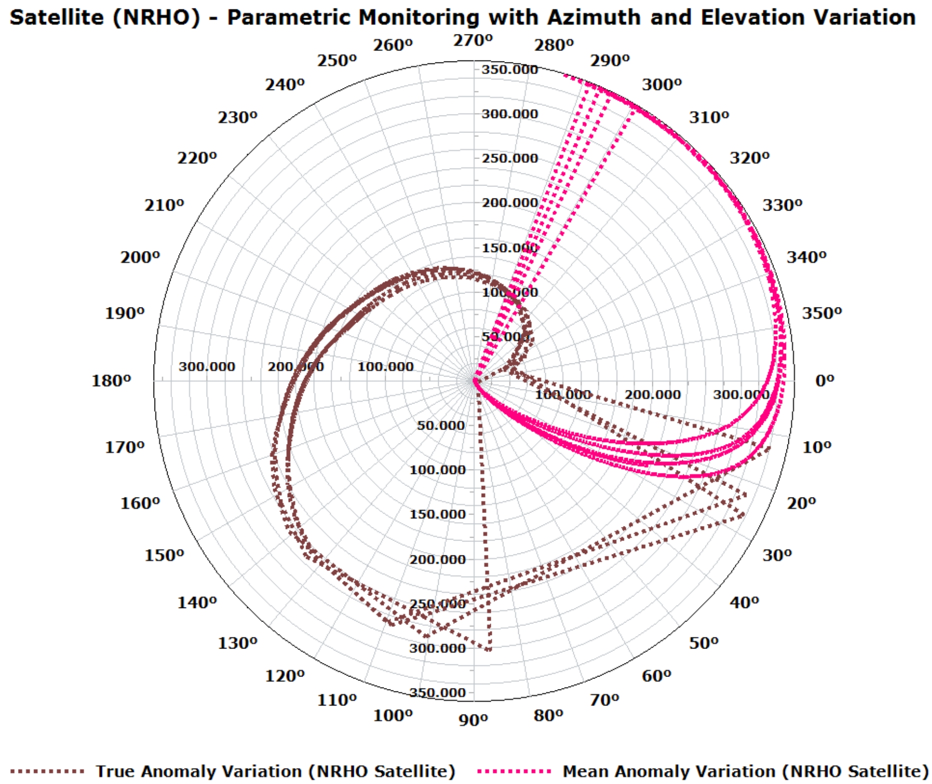


Figure 27: Ground azimuth and elevation variation with NRHO satellite's orbital parameters (TA and MA)

DISCUSSIONS

This paper highlights the importance of scaling the small satellite constellations specific to Cislunar space. As the competence and growth in several missions are substantially higher, the need for innovation and strategic changes is inevitable. The vision to develop systems and methodologies to survive such a space environment will be a critical challenge to look for in the coming times. Small satellites are highly capable and can take advantage of their cost-effectivity, dynamic configuration, and durability in Earth orbits and recently in deep space, proving immense scope to utilize this technology efficiently and for a long-term application in this Cislunar space.

The small satellites as constellations have recently been adapted to deliver data for applications like Earth Observation (EO) to support disaster management, climate monitoring, ocean surveillance, and many more. These come as a pivotal addition to space utilization when resources are a constraint in this rush to attain global solutions for commercial and national purposes. These constellations can add a highly paced data relay for Earth and Moon if utilized with specific unique techniques in their implementation. Hence, this paper makes an effort toward this direction and envisions developing compact and well-scaled constellations shortly.

Several attempts have been made to design and align the techniques to utilize the small satellites effectively in a better manner, saving resources and costs significantly. After several trials and understanding of the orientation of the small satellites (<500 Kilograms) and knowing their specific constraints in constellations, the proposed framework was worked out with autonomy as a major element in designing and developing 'Draim' orbits-based constellations. The capabilities of these types of constellations are under-utilized until now and need to be part of the Cislunar region for their potential to perform optimally using fewer resources and better coverage for Earth and Moon efficiently.

Several trials were made to check the limitations and their applicability in the Cislunar environment before finalizing the setup for the Earth and Moon orbits. For Earth, all the 'Draim' orbits were thoroughly utilized, along with the capabilities of the circular orbits. These are placed in layers to best utilize them for strategically better coverage and optimal use of the given region across Earth's space environment. On the other side, the only inclusion to the Moon's constellation is the addition of the Near-rectilinear Halo Orbits (NRHOs), one orbital region that will also station the Artemis-2 mission as ‘Gateway.’ This leads to systematically aligned constellations. With the set-ups designed, the results were organized based on the major satellite parameters and the ground stations, as mentioned in Table 1. The combination was selected for the specific use of the operator to monitor the autonomous operations and keep a closer look at the constellations in which critical situations occur and the need to solve unknown anomalies. Also, one more consideration here is that the role and significance of all the small satellites in a constellation are equally and predominantly crucial for the constellation to function as a system. Every satellite can have a priority or better utility than the other. With this in consideration, the constellation orientation is designed and scaled accordingly with precise coverage concerning the end-user locations globally.

The plots are selected precisely based on their applicability in real-time and situations over the mission life cycle. Constellations under the autonomous framework can be a breakthrough in the coming times for their efficient and faster data transmissions. For Earth-based constellation simulation, Fig. 20 shows the variation of the longitudinal ascending node and argument of latitude, which play a crucial role in determining the position of a satellite crossing the equator from south to north, respectively. Fig. 21 brings major parameters together over a satellite’s propagation for some time. The true anomaly, right ascension, and height give a significant outlook of a satellite’s performance in orbit from a system engineering point of view during a critical situation or a daily planned check. For the ground station perspective, Fig. 22 and Fig. 23 show the variations of the ground parameters concerning the approaching satellite for Earth-based constellation. Fig. 22 shows the propagating satellite’s complete cycle orientation with variations in Azimuth and Elevation angles in prime focus. Fig. 23 gives a unique perspective of the variation of the true anomaly of a satellite with the changing elevation angle of the approaching ground station. These parameters are crucial to monitor the satellite’s approach in delivering the data autonomously and keep this process consistent and regular to complete the given tasks daily or hourly. This will be more efficient with enhanced coverage utilizing the proposed framework.

The Moon simulations are carried out with due regard to the lunar environment with various altitudes as the orbits are differently planned and implemented, as discussed above. The experience with the Moon set-up is quite different and unique when compared to the one in the Earth-based set-up with several different variations needed to be considered in this given lunar scenario along with an added NRHO orbital space which has a greater significance with CAPSTONE still operating, and GATEWAY to be on its way in this year. The results are then organized by selecting the critical parameters essential to be monitored in the lunar ambiance and supporting the Artemis mission adequately.

Fig. 24 gives an overview of the orbital parameters (True Anomaly, Right Ascension, and Mean Anomaly), which are propagated over 30 days in an NRHO orbit. This is to get an essence of a satellite orientation in a constellation. This data is of specific importance to an operator to monitor and make a critical decision in a given operation scenario. This is to be synchronized with autonomy. Whereas Fig. 25 provides a thorough understanding of the range of the small satellites from one another and specifically with the NRHO orbit satellite, which is also significant when the GATEWAY takes its place in the same orbit. The height of the NRHO satellite is also included to analyze the variations in the base height of the NRHO under a given lunar environment (solar radiation pressure and other gravitational effects).The ground segment remains the essential portion of the lunar missions by far, with all the previous missions observed, and some of them failed to communicate back to Earth with an appropriate set of data. Hence, this has been taken duly into consideration, and the set-up has been analyzed with crucial parameters of satellites and the ground in fusion to give tremendous support to the control and operations at the ground stations globally. Fig. 26 shows this aspect clearly with the elevation and azimuth angle variations to different ground stations located distant from each other on the lunar surface. The NRHO and circular orbits’ small satellite orientations have been utilized for analyzing the same. On the other hand, the orbital elements (True and Mean anomaly) vary with the azimuth and elevation angles over the propagation of 30 days. The significance of these parameters is essential to monitor and scale the constellations precisely and consistently. This will support the optimal use of resources and enhance the possible longevity of the missions soon.

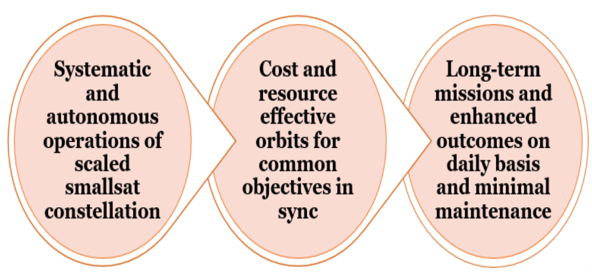


Figure 28: Impact of scaled smallsat constellations

CONCLUDING REMARKS

NewSpace initiatives are in full swing globally and have triggered the need for intense innovation in technology, systems, and methodologies in space research and commercial product development. For a few decades, small satellites have been responsible for delivering the tasks traditional satellites have been doing since their inception. This change has bought up a thought process to save resources and move towards cost-effective strategies to make space feasible and adaptable for all, specifically for Cislunar operations.

This paper is envisioned towards the same thought process, and the research presented through it aligns the efforts towards it. The small satellite constellations are the future of the space industry, with several real-time applications as solutions to the major crisis on Earth and for deep space exploration. This is the time to make the best utility of these assets and provide solutions that are cost-effective and have reachability to all enthusiastic about learning and contributing to space.

The work presented in this paper capsules the major requirement to scale these constellations optimally without obstructing the space environment and other major science exploration through effective methodologies and efficient use of available technologies. The conceptual framework, simulations, and analyses presented are towards this direction and form a platform for constellation operators to see this as a futuristic mission plan specific to small satellite constellations and its applications for Earth and Moon as a common platform for the Cislunar region.

An attempt is made towards distributed multi-layer constellation design concept using small satellites, and the relevant results with discussions have been presented in the focus of the Cislunar region and its operations. In the future, several creative methodologies will be investigated for adaptive and sustained technology usage to effectively transition into the NewSpace agenda for the long-term sustainability of the designed missions. A full-scale deployment of the autonomous constellations is only possible with optimal scaling of these constellations as per the mission requirements and minimal use of resources under given constraints of configurations and severe space environment. Adding the Artemis-2 mission to the NewSpace initiatives gives ample reason to support and build a cooperative environment across the Cislunar region and help solve issues for humankind in the coming years. Several such missions are anticipated and are bound to impact and contribute to the space community greatly.

Acknowledgments

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Notes

The research is original and bought about with real-time scenarios in the current cislunar environment. Further work on this topic is in consideration and in progress which will be published soon.

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