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A Study of Cislunar-Based Small Satellite Constellations with Sustainable Autonomy

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Abstract: The Cislunar economy is thriving with innovative space systems and operation techniques to enhance and uplift the traditional approaches significantly. This paper brings about an approach for sustainable small satellite constellations to retain autonomy for long-term missions in the Cislunar space. The methodology presented is to align the hybrid model of the constellation for Earth and Moon as an integral portion of the Cislunar operations. These hybrid constellations can provide a breakthrough in optimally utilizing the Cislunar space to efficiently deploy prominent missions to be operated and avoid conjunction or collisions forming additional debris. Flower and walker constellation patterns have been combined to form a well-defined orientation for these small satellites to operate and deliver the tasks satisfying the mission objectives. The autonomous multi-parametric analysis for each constellation based in Earth and Moon's environment has been attained with due consideration to local environments. Specifically, the Solar Radiation Pressure (SRP) is a critical constraint in Cislunar operations and is observed during simulations. These are supported by conjunction analysis using the Monte Carlo technique and also the effect of the SRP on the operating small satellites in real-time scenarios. This is followed by the observed conclusions and the way forward in this fiercely competent Cislunar operation.

Keywords: small satellites; cislunar; conjunction; constellation; Solar Radiation Pressure (SRP)

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1. Introduction

The NewSpace era has opened up space competence to new heights, and the requirements to accomplish this are challenging due to space environment concerns. This is also exciting, as it created numerous possibilities and opportunities for the next-generation satellites to take a leap toward solving mainstream problems [1–3]. Small satellites [4] have been an important pillar of this new age of exploration and enhanced technology needs. They have contributed to the lower Earth orbits in the most dynamic ways for a variety of applications [5–7]. They are extensively useful if utilized as constellations [8–10] for both Earth and Moon missions as an integral part of the Cislunar space.

The Cislunar space is gaining interest globally due to its strategic value and economic influence in gaining access to the deeper space [11,12]. There is an urgent need to develop, evolve, and design the operations in this region to avoid severe concerns in the near future as the number of missions to the Earth and the Moon exponentially grows in the coming years. Several efforts in this direction are evident [13–15], and extensive efforts in this direction sincerely are being taken in terms of research and development as well as towards sustainability.

Figure 1 below gives the intense operations that depict the missions that are going to the Moon and also are serving the lower Earth orbits efficiently but have a critical load on managing and technically stabilizing the region as much as possible. This has to do with the safety and conformity of each mission planned for Cislunar space.

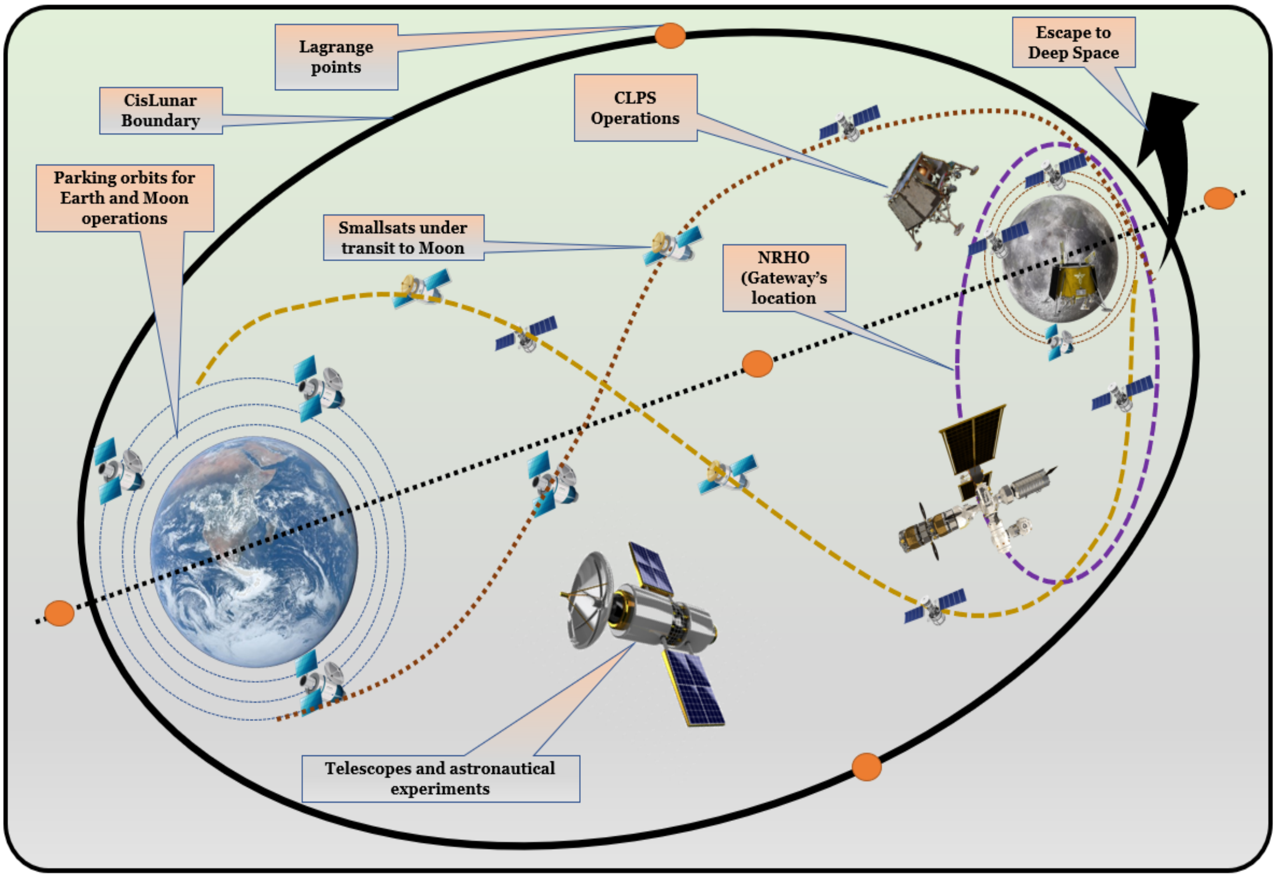


Figure 1. Cislunar space operations—current trends [16].

The target applications that are focused on through this research in the frame of the Cislunar space, which includes the Earth and Moon's orbital regions with specific values for defined forms of technology utilization, are precisely determined. For the Earth, disaster management is taken into consideration, which is at a critical stage at this node of global reforms [17,18]. Research in this direction is commendable [19,20], and a lot has to be done further in the span of the Cislunar space. For the Moon, it is for promoting, designing, and developing sustainable systems for effective communication relays and safe navigation. With Chandrayaan-3 [21,22], the stride towards the South Pole landing is intensifying, and this needs creatively unique methods to solve critical problems of tracking and environment perturbations.

Autonomy is an essential focus of this research. There is an immense need to do multiple tasks in a very particular situation that cannot be handled by ground control solely. This needs to be synergized with autonomous operations and systems governing the mission objectives thoroughly and with precision. This is the need of the hour in the Cislunar space, as developing ground for autonomy will enhance overall accessibility and sustainability in the long run. Several references have been studied to understand and develop strategies that will efficiently help develop autonomy in the Cislunar domain with focus on both Earth and Lunar operating environments [23–25].

This paper is an enhanced and extended version of [16], and sincere efforts have been made to definitively express the key outcomes of this research and its futuristic need. The sustenance of the Cislunar economy and its operations is only possible if there are well-defined, rigorously tested, and well-evaluated methodologies for the small satellite constellations. This will be of major importance in assisting and achieving major tasks in the form of applications. For Earth, it is mainly to assist disasters and reduce casualties as much as possible, as well as to assist missions like Artemis near the Moon. All these need to be achieved by surviving and analyzing the space environment significantly.

2. Problem Definition

After introducing the dynamic Cislunar space, there is a need to define the concerns and urgent needs of this significantly critical region. The main concern is the management of the Cislunar operations with due diligence and analyzing the space environment for both Earth and Moon orbits. For the Earth, the atmospheric drag, J_2, and Solar Radiation Pressure (SRP) will be of prime importance to be studied. For the Moon, the SRP is the main factor affecting the mission operations; hence, it needs to be addressed through real-time simulations. For this, the small satellite constellations will remain centroid for this paper with strategies to be developed for attaining synergic autonomy in the given region.

The autonomy defined will serve the Cislunar operations in the long term and will be crucial for all the missions to maintain safety and coordinate with other missions. The congestion and debris, which may cause in-orbit disasters with collisions and close proximities with debris and other missions, will be a primary problem in the coming years. This needs to be evaluated and extensively analyzed for collision and near-escape concerns in the orbit. There is a need for collectively addressing the space environment, and the congestion issues will be challenging but are highly needed for sustainable Cislunar operations in this NewSpace age. The balance of autonomy with small satellite constellation operations in these harsh and demanding space environments is the most challenging aspect at this point in time. This paper indicates these problems as the major cause of the Cislunar disaster in the near future if not addressed thoroughly both theoretically and practically. Figure 2 depicts this combination of the problems in a systematic approach, which is the ethos of this work that needs to find creative solutions.

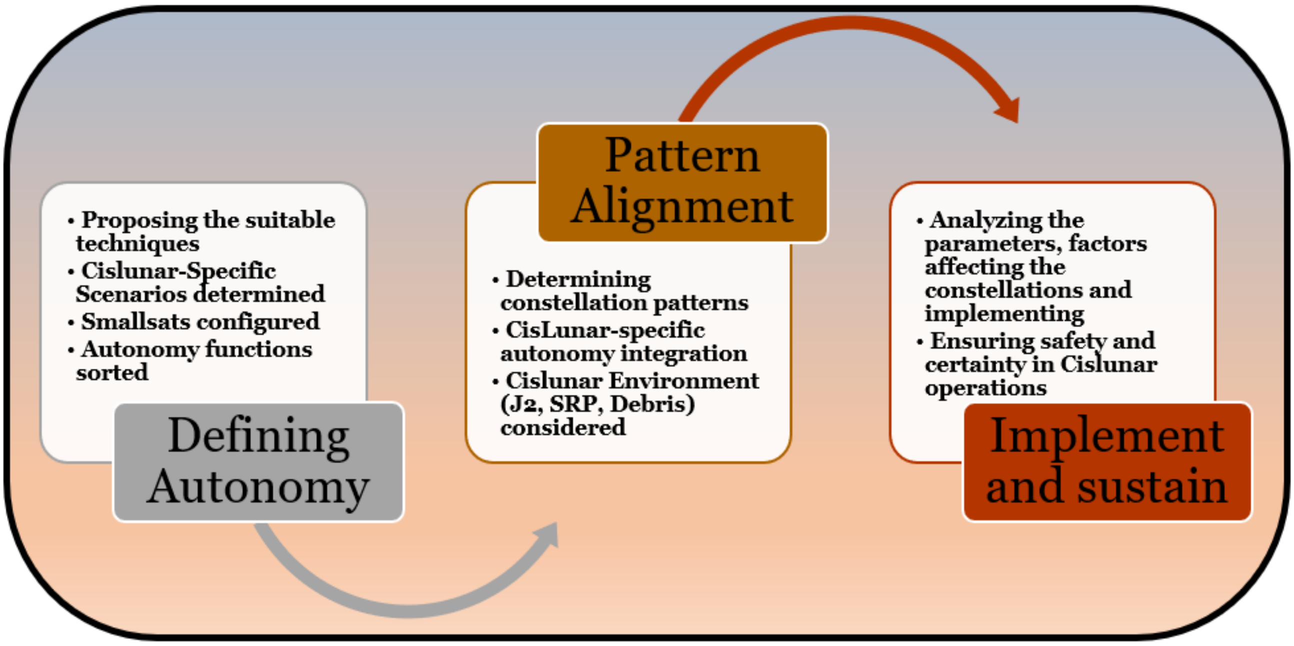


Figure 2. Cislunar-based process towards attaining autonomy [16].

The sections below will be dedicated to these concerns to be solved through various analyses and find continuity in those solutions. The way Cislunar space is growing each month and year, there is an urgent need for addressing these concerns and avoiding bigger concerns in the orbits of the Earth and the Moon. The global need for data is growing exponentially as the concerns on Earth increase day-to-day. The commercial and non-commercial missions take their trials to make possible solutions for this demand, but still, there is no sizeable and optimal solution to it. Even for the Moon, the exploration needs post Chandrayaan-3 mission is a new rage globally and has seen an upward trend in launches.

3. Proposed Approach

Considering the concerns above, a strategic plan is needed to navigate through these concerns and have a sustainable Cislunar space. This is only possible through enhanced technology, but to utilize them effectively for a long time, there needs to be methodologies governing them. For the strategies to develop autonomy in this region, Ref. [16] presents detailed and stepwise emphasis with creative techniques. This paper will focus on the results and the approach that was considered and designed for small satellite constellation operations in the Cislunar domain.

Utilizing the autonomous strategies mentioned in [16], the way forward is to have a dedicated analysis plan that includes the major elements of the space environment and the congestion factors in the Cislunar space. These two aspects have a disastrous impact if not designed and implemented with the due and optimal utility of autonomy. In fact, these factors influencing the small satellite constellations dynamically, theoretically, and practically need to be analyzed in a long-term sustainable propagation.

In consideration of these elements, a dedicated and detailed analysis has been proposed to study the impact of these elements on the small satellite constellations for both the Moon and the Earth, respectively. Research was carried out to make simulations in three stages: 1. Parametric numerical study, 2. Monte Carlo analysis of congestion (Debris and missions), and 3. Space environment analysis (impact on small satellites). Each of these three stages is interrelated and are highly impactful on the satellites to operate without halting their functions and daily tasks to attain their mission objectives in continuity.

Figure 3 below determines the ethos and the motivation of this proposed approach dedicated to both the Moon and the Earth's orbits. The essence of the autonomous operations is taken into consideration for the framework, simulations, and analytical results presented in this paper. Hence, sustainability is the major objective behind this designed method.

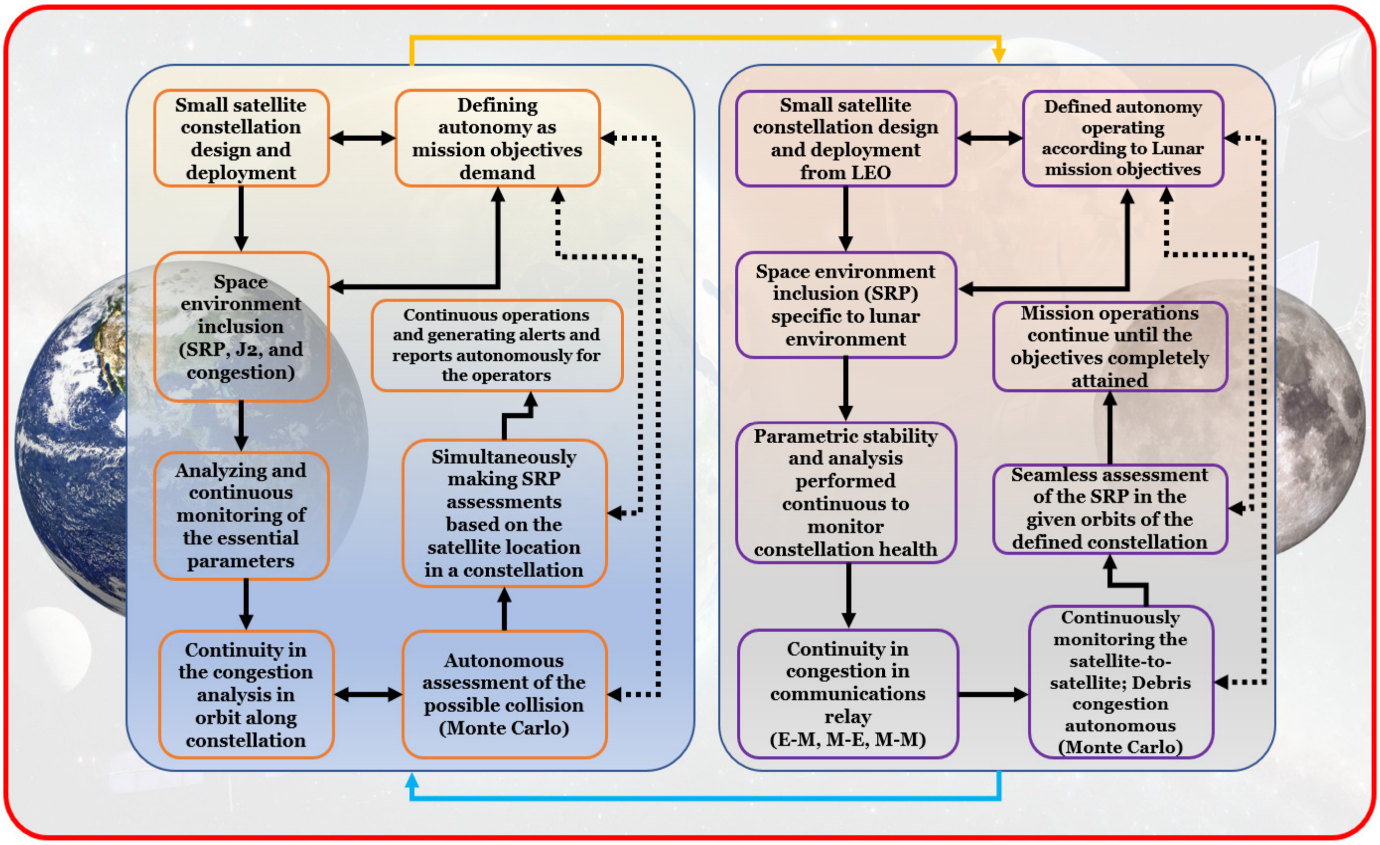


Figure 3. Proposed methodology for the continuity in autonomous operations (Cislunar).

4. Cislunar Dynamics (Constellation Scenario)

The dynamics of being aligned for the proposed method are the most critical parts of making operations feasible and adaptable for the cislunar space. The Earth and the Moon both have distinct environments, and their orientations are uniquely defined. The majority of the concerns have a root cause in the way their dynamics have been designed and incorporated into the small satellites. As this class of satellites are resource-constrained, it is usually difficult to make a clear balance of the dynamics proposed and designed to the real-time conditions. Hence, this paper makes a sincere effort to have a better interface of the proposed methodology to real-time operations.

Reference [26] is used as a defining input for the constellation building in the Cislunar with each small satellite as a three-body problem with reference to Earth and Moon and also with respect to the other satellites as chasers or followers with one reference body as Earth or Moon, respectively. The state vector is defined as:

$$x = [x, y, z, \dot{x}, \dot{y}, \dot{z}]^T \tag{1}$$

This vector for the satellite relative to the Earth and Moon center is organized in terms of rotating coordinates. The mass parameter is given as:

$$\mu = \frac{ms_1}{ms_1 + ms_2} \tag{2}$$

where ms_1 and ms_2 are the masses of the primary bodies of the Earth and the Moon. The first-order non-dimensional equation of motion is presented as:

$$\dot{x} = f(x) \tag{3}$$

with vector fields,

$$f(x) = [\dot{x}, \dot{y}, \dot{z}, 2n\dot{y} + U_x, -2n\dot{x} + U_y, U_z]^T \tag{4}$$

where n is the non-dimensional mean motion of the primary system and U is the pseudo-potential function of a three-body scenario in the Cislunar space. This is mainly for the circular orbits, but the variations over other orbital configurations can be planned with respective alternations in defining the governing equations.

The detailed derivations and the sequential alignment of the theories can be found in [26], respectively. This forms a fundamental background of the small satellite-based constellation design and simulation with the Earth-Moon Cislunar boundaries. New terminologies have been discussed in detail with the concept and the techniques proposed in this work.

4.1. Constellation Modelling

The constellations can be designed with a variety of mathematical models according to the mission objectives and the configurational capabilities of the satellites. In this research, a leap has been taken towards building the hybrid form of constellation designs to reduce the number of operational small satellites and enhance their performance and longevity. Similar to the Draim orbit concept defined in [27] from this research, the optimal hybrid constellation design is proposed, defined, designed, studied, and simulated for analysis for this paper. The main objective here is to develop a seamless, cost-effective, and safe environment for missions to operate and deliver the tasks as required utilizing the Cislunar region optimally for long-term sustenance.

Some portion of their dynamics with a combination of flower and walker constellation is given in the form of equations below.

4.1.1. Flower Constellations

There are several ways to model the flower-type constellations, but for this paper, Ref. [28] is followed to define and operate a flower constellation.

The Mean Anomaly and RAAN are termed as primary perturbative quantities, with J_2 considered given as:

$$\dot{\Omega} = -2\varphi n \cos i \approx \frac{-2\varphi\omega_{\otimes}[1 - A(\varphi)]\cos i}{\Gamma - 2\varphi\cos i} \tag{5}$$

where the i is the inclination of the orbit; and

$$\begin{gathered} A(\varphi) = \varphi[4 + 2\sqrt{1 - e^2} - (5 + 3\sqrt{1 - e^2}\sin^2 i)] \\ \varphi = \tfrac{3R_{\oplus}^2 J_2}{4p^2} \\ \dot{M}_0 = -\varphi n\sqrt{1 - e^2}(3\sin^2 i - 2) \\ \approx \tfrac{-\varphi\omega_{\otimes}[1 - A(\varphi)]\sqrt{1 - e^2}(3\ \sin^2 i - 2)}{\tau - 2\varphi\cos i} \end{gathered} \tag{6}$$

where $p = a(1 - e^2)$; J_2 = 1.08266269 × 10^{-3}; and $R_{\otimes} = 6378.1363$ Km which is equatorial Earth radius and n is the mean motion is expressed as

$$n = \frac{\omega_{\otimes}[1 + A(\varphi)]^{-1}}{\tau - 2\varphi[1 + A(\varphi)]^{-1}\cos i} \approx \frac{\omega_{\otimes}[1 - A(\varphi)]}{\tau - 2\varphi\cos i}$$

where $\tau = N_d/N_p$; N_d is the number sidereal days for ground repeats, and N_p is the number of petals; $\omega_{\otimes}$ = 7.2921158553 × 10^{-5} rad/s presents angular velocity of Earth.

4.1.2. Walker Constellations

In the other portion of the constellation, a well-defined mixed geometry walker pattern has been used as given in [29], and using the J_2 perturbation as defined by [9,30,31], the following equations for orbital elements under J_2 are rewritten as below:

$$\dot{\Omega} = \frac{r * P_h * \sin\theta}{h * \sin i} \tag{7}$$

$$\dot{\omega} = -\frac{\eta}{ane}\left\{P_r\cos f - P_s\left(1 + \frac{r}{p}\right)\sin f\right\} - \frac{r\cot i}{a^2 n\eta}P_h\sin\theta \tag{8}$$

$$\dot{M} = n + \frac{\eta}{ane}\left\{\begin{array}{l} P_r\left(\cos f - \frac{2re}{p}\right) - \\ P_s\left(1 + \frac{r}{p}\right)\sin f \end{array}\right\} \tag{9}$$

$$\begin{array}{l} n = \sqrt{\frac{\mu}{a^3}}; \eta = \sqrt{1 - e^2}; \\ p = a(1 - e^2); h = \sqrt{\mu p}; \\ r = \frac{p}{1 + e\cos f}; \end{array} \tag{10}$$

where a is the semi-major axis; e is the eccentricity of the orbit; μ is the Gravitational parameter of the Earth; f is the true anomaly; the magnitude of the position vector is $r = p/(1 + e\cos f)$; just to add, P_h, P_s, P_r are the components of the perturbation force.

4.2. Solar Radiation Pressure (SRP)

The in-depth understanding of the Solar Radiation Pressure (SRP) to be included in the simulation for the proposed constellation design [32] provides a clear and concise approach towards modelling the same as below:

The governing equation for SRP is given as:

$$a_{SRP} = -\frac{\phi}{c}\frac{A}{m}C_R\cos(\theta)\frac{1}{2}(C_{R_v} + C_{R_{IR}})\nu \tag{11}$$

where ϕ is the Solar Radiation Pressure; c is the speed of light; A is the area covering the satellite surface; m is the mass of the satellite; C_R is the scaling parameter which functions as a deficiency absorbent; θ is the angle between satellite surface normal and the incident radiation, C_{R_v} is the visible portion of the solar spectrum, $C_{R_{IR}}$ is the infrared part of the solar spectrum, and ν is the shadow spectrum.

The radiation pressure of the Sun in the vicinity of the Earth is

$$\phi = \left(\frac{1AU}{r_\odot}\right)^2 P_{\odot,1AU} \tag{12}$$

The reason for adding this expression is to determine and make the Sun's proximity to the Earth each time when the SRP is being calculated onboard each satellite of a constellation. The motive here to make sure that the alignment is correct while the operations are on.

The AU is the astronomical unit; $r_\odot$ is the instantaneous distance from the Sun to the satellite and the Sun position, and $P_{\odot,1AU}$ is the solar radiation pressure at 1AU. This leads to another important equation:

$$\phi_S = \left(\frac{1AU}{r_\oplus}\right)^2 * P_{\oplus,1AU}(t) \tag{13}$$

SRP remains crucial for both Earth and Moon orbits. Hence, utilizing the equations mentioned above, a detailed analysis of the SRP impact on both Earth and Moon orbits is done and will be elaborated in the sections below.

4.3. Cislunar Debris

The growing concerns with Cislunar debris have to be addressed through dedicated dynamic modeling and understanding of the possible debris model in the region. Various parameters have been studied and analyzed to be incorporated in the simulational scenarios on Earth and Moon constellations, respectively. Hence, the equations mentioned in [33] have been significantly useful in aligning the debris model as given below:

Debris model:

Given the kinetic energy of a particle is considered constant, then the particle speed is calculated as:

$$\partial = \sqrt{\frac{2}{m}\kappa} \tag{14}$$

where κ is the kinetic energy, and m is the particle mass.

The probability of the critical damage given an impact happening in orbit is determined by a vulnerability model based on the properties of the debris in the surroundings of the small satellite. Given this model, the probability of the damage is given as:

$$P_D = 1 - e^{-E*P_{K|H}} \tag{15}$$

$$E = \zeta * V_k \tag{16}$$

where $P_{K|H}$ is the instantaneous probability of spacecraft hazard, ζ is the debris number density, and V_k is the hazard zone volume.

When the total time of the damage from start to end is considered, the following expression is aligned: This expression redefines the difference in the initial timing of the disaster occurrence to the final time the impact was observed. The integral form of this variation can be observed with the Equation (17), which is the most dynamic part of operations.

$$\int_{t_0}^{t_f} P_D(t)dt \tag{17}$$

Referring back to [26], it mentions the surveillance factor for the selected orbits in the Cislunar space. This is to develop an optical sensor to monitor the vicinity of the spacecraft when needed and adjust its proximity as needed. The magnitude of a space object in the vicinity of this satellite is framed in an equation as:

$$\psi = \Psi_{sun} - 2.5 \log_{10}\left(\frac{I_S}{I_{Sun}}\right) \tag{18}$$

where Ψ_{sun} is the apparent reference magnitude of the Sun and I_S is the irradiance reflected from the spacecraft and Sun's reference irradiance.

Moving forward, this paper will add a unique dimension to the above-mentioned equations and debris-determining techniques by aligning a dedicated Monte Carlo simulation estimating the close approaches to each spacecraft in constellation using a well-designed Gaussian distribution over thousands of states of a satellite in a given scenario emphasizing the closest and farthest probability of collision. Hence, a detailed study to align the equations for the execution of this space situational awareness task with the proposed constellation designs and also during the transit scenario from Earth to the Moon is duly considered and analyzed. The equations for the Gaussian distribution are referred to from [34] as:

If X is the initial state of the satellite and has a Gaussian distribution with a mean μ and covariance matrix as Σ, then the distribution of the X for n trials is given by:

$$f_x(X) = \frac{1}{\sqrt{(2\Pi)^n |\Sigma|}} \exp\left\{-0.5(X-\mu)^T \Sigma^{-1} (X-\mu)\right\} \tag{19}$$

The total derivation and explanation are given in [34] significantly contributing towards SSA and its related uncertainties. This will add essence with thorough understanding and firm establishing of the work. The basis of this Monte Carlo analysis is to calculate and evaluate the number of close misses with a resulting probability of collision for thousands of random states, with the close approach close misses and grouped points, and with time of approach in a span of propagation and within a probable area of collision.

4.4. Orbital Formation

Apart from the Space Situational Awareness, the formation of each orbit remains an important part of this research. Though the major results on this subject will be published separately, the dynamics used in simulating the proposed constellation and autonomy design of this paper emphasize the importance of formation in each orbit. The referred article that followed for this part of formation assurance is demonstrated in [35], which is for a challenging starling mission for experimenting with an optical system.

Interestingly, it addresses the verification process of the optics alignment and formation conformity supporting the Monte Carlo trials which fit best for the constellation scenarios as well as if each orbit is considered to be a formation of a set of small satellites. For this paper, a similar relative and absolute spacecraft/orbit approach is taken into consideration. The equations governing this Monte Carlo simulation are detailed in [35] thoroughly. These formations also have to be autonomous due to various factors of environment and congestion in these NewSpace times. There needs to be self-navigating capabilities in orbit and to make certain and specific decisions to avoid sudden decay or misalignments in the constellation orientation. Reference [36] is one such article on this formation flying autonomy, which gives a detailed review, reasons, literature, dynamics, and requirements in the NewSpace that are elaborated extensively. The most important section presented is on collision-free formation flying. This will remain crucial for the Cislunar space with small satellite constellations with severe space environments and its relevance to the proposed methodology in this paper. The safety limit, defined as $d_{\min}$, depends on the separation among the satellites Along and Cross. This is critical when it is for a constellation, even though it is well-spaced with other missions and satellites among the same mission. One defined condition for the distances among the satellites is for the permitted and prohibited constellations depicted as an inequality as:

$$\begin{array}{c} \delta r_{nr}^{\min} \geq d_{\min}; safe \\ \delta r_{nr}^{\min} < d_{\min}; unsafe \end{array} \tag{20}$$

And J_2 is inclusive of these operations and expressed as a dependent factor as below:

$$\wp = \frac{J_2}{2}\left(\frac{R_E}{a}\right)^2 \frac{1}{\eta^4} \tag{21}$$

where η is eccentricity dependent factor, a is semi-major axis, and R_E is the radius of the Earth. Hence, the role of J_2 is critical in most of the operations in the Cislunar space as the missions from Earth move to the Moon from lower orbits. For the technique proposed, it forms one of the baselines for the space environment and its significance.

4.5. Maximum Coverage

Ultimately, full coverage with a minimum number of satellites will satisfy a major objective of this paper, which duly supports a seamless and robust development of autonomy for small satellite constellations for the Cislunar region. Hence, referring back to [29], the critical parameter to optimally organize and control will be the orbital velocity and period, which is optimally balanced with the orbital elements using the autonomous functions and arrangement of the given orbits. The equations for these parameters are given as:

$$v_o(h) \approx \sqrt{\frac{GM_E}{R_E + h}} \tag{22}$$

$$T_o(h) = \sqrt{\left(\frac{4\Pi^2}{GM_E}\right)(R_E + h)^3} \approx \frac{2\pi(R_E + h)}{v_o(h)} \tag{23}$$

where G is the universal gravitational constant, M_E and R_E are the mass and radius of Earth, and h is the altitude of deployment.

Also, referring to Figure 4 above, the three-body problem among the satellites (follower and target) is inspired by [37], which demonstrates the Rendezvous in the Cislunar space for elaborating the control and dynamics issue for NRHOs, which are the core positions for the missions to make a base at the Moon and sustain. These factors and essential dynamics are taken into thorough consideration while developing strategic autonomy and small satellite constellations in the Cislunar region of operations.

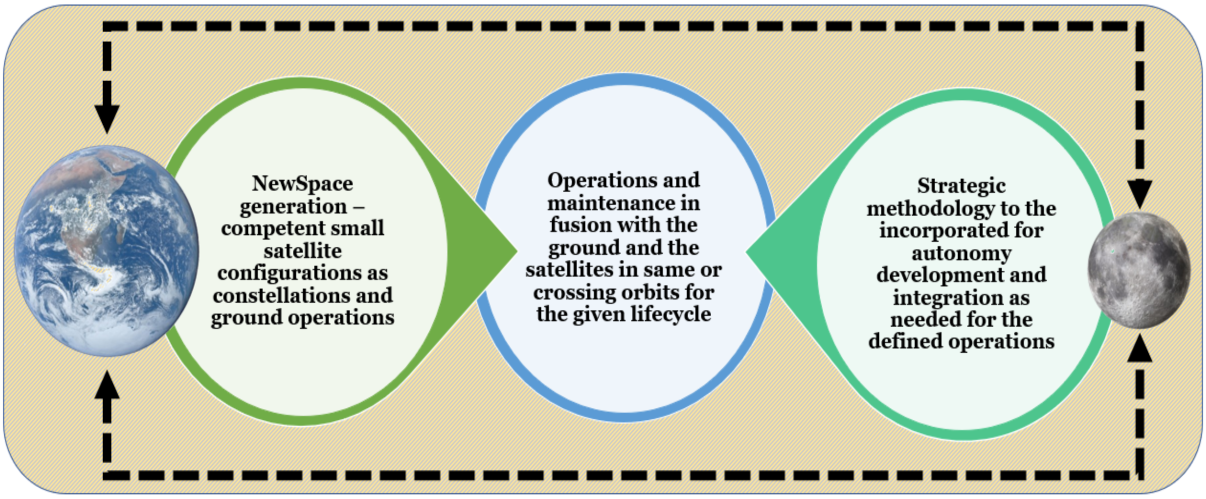


Figure 4. Approach defining the dynamics in the Cislunar operations [16].

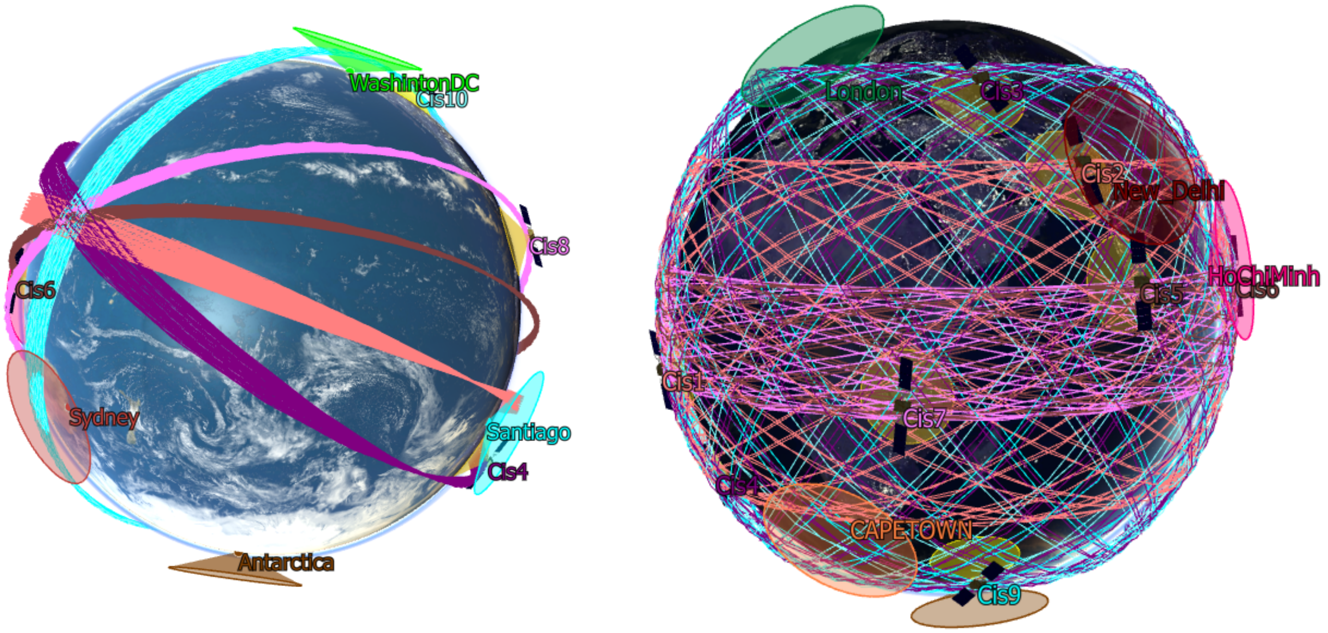
5. Visual Simulations and Analysis (Constellation Scenarios)

Based on the proposed methodology and the autonomous strategies to develop autonomy in the Cislunar space [16], the visual demonstrations are depicted through simulations that propagate the small satellite constellations for a defined period of time. These observations were significant with unique forms of designed constellations, which have different orientations for Earth and Moon as the operating environment that are unique on each side. But the most important aspect is that these fall under a single operating frame of Cislunar space, forming a center stage for deep space exploration. The Simulation configurations are presented in Table 1 for the Earth along with the visual representation in Figure 5.

The need for these simulations is that the major environmental issues need to be observed in real-time conditions and define the motive of Cislunar space appropriately. There are several concerns in this region that need to be thought of, designed, simulated, and implemented in due course for sustainable missions to be propagated in the near future. These simulations are propagated for the Moon and Earth separately while simultaneously aligning with the proposed methodology. The missions need to use the lower Earth orbits to maintain continuity for making the Moon's orbits operable and viable for movement into deeper space. Hence, these simulations have taken this into due consideration.

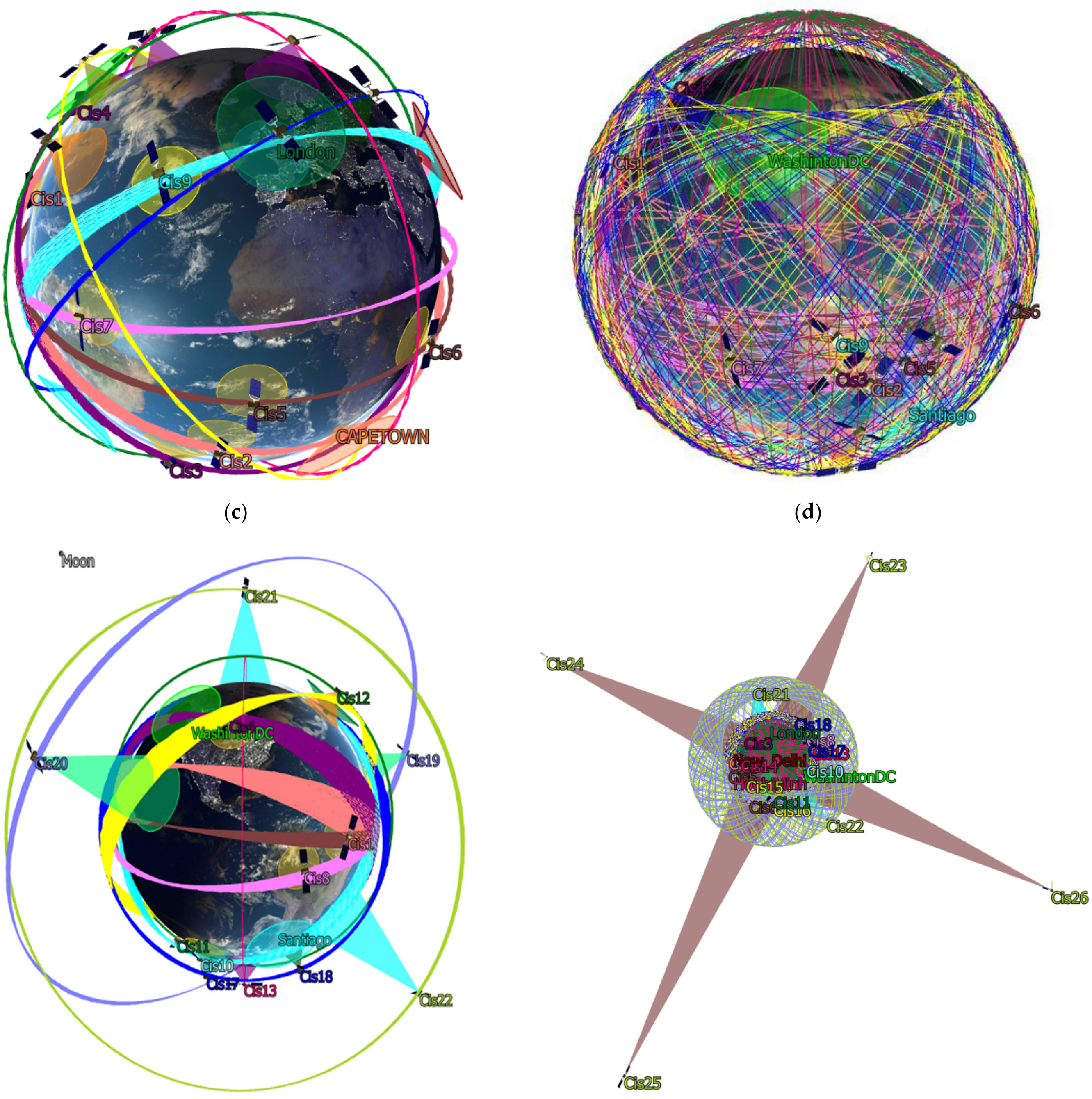
Table 1. Earth-based constellation configuration [16].

Parameter	Value/Comment
Orbits	Hybrid–Flower (5); Mixed walker (4); MEO—Inclined (2); GEO (1)
Eccentricity	0.001
No. of satellites	27
Sensors (FoV)	30 & 40 (Deg.)
Altitude	VLEO~GEO (Distributed)
SRP	Integrated module
Inclination	0~110 Deg. (varied)
Satellite Mass	85 (Kg)
Perturbations	J_2 and atm. Drag (included)



(**a**) (**b**)

Figure 5. *Cont.*



(**c**) (**d**)

(**e**) (**f**)

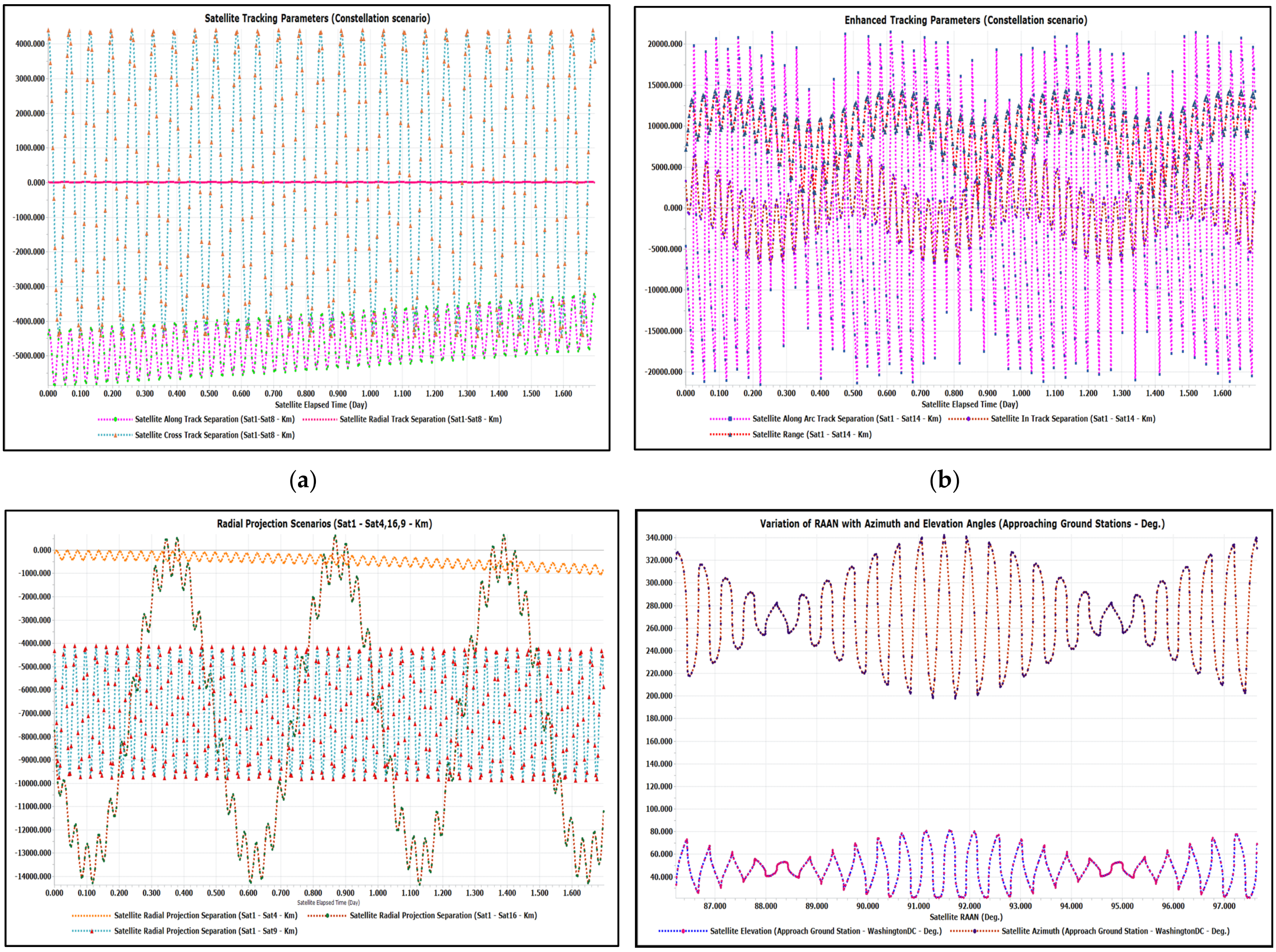
Figure 5. Visual demonstration of the Earth side of the Cislunar space (small satellite constellation) [16]. (**a**) Flower orientation (VLEO-inertial frame); (**b**) Flower orientation (VLEO—Body frame); (**c**) Hybrid orientation (LEO—Walker and Flower); (**d**) Hybrid orientation (LEO—Body frame); (**e**) Hybrid orientation (MEO orbits inclusion); (**f**) Comprehensive orientation (GEO inclusion—body frame).

5.1. Earth-Based Constellation Simulation

Several design considerations have been made to make sure that the desired objectives are attained and synchronize with the proposed methodology of this paper. The finalized small satellite constellation of a hybrid/non-uniform constellation has been selected after various trials along with the given operating environment and Solar Radiation Pressure (SRP) included during the propagation. The propagation cycles were planned to be continuous and in systematic orientation to observe the required parameters closely.

5.1.1. Autonomous Multi-Parametric Analysis (Earth's Side)

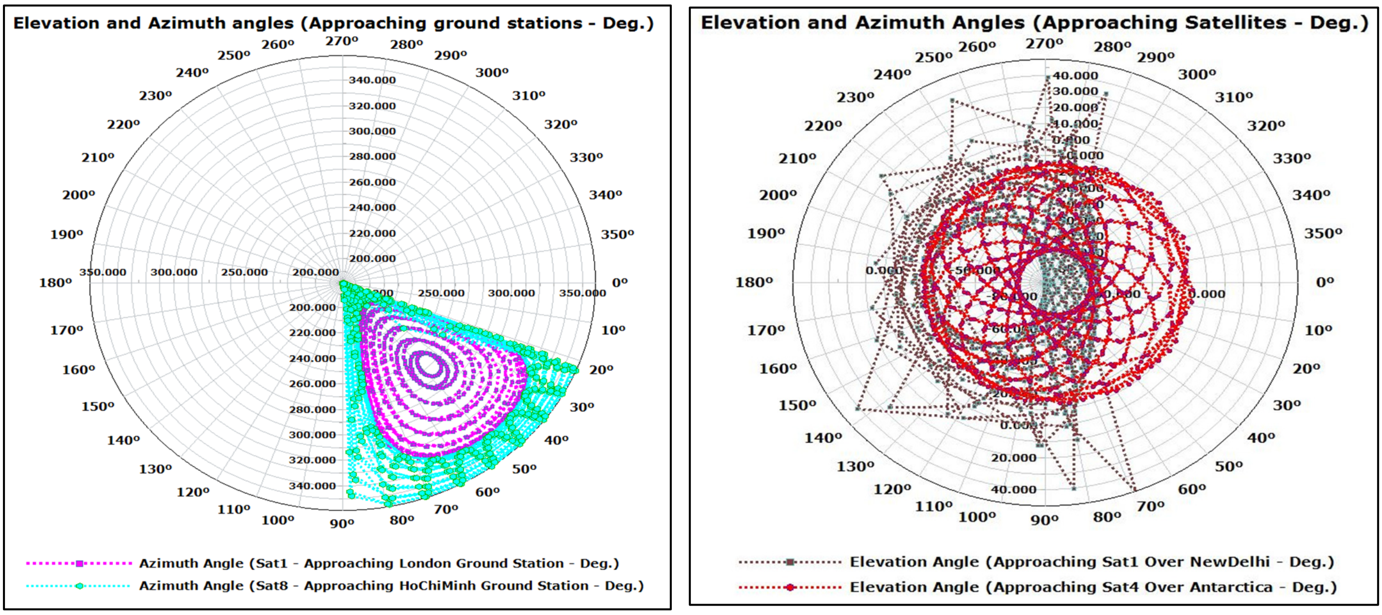
The parametric analysis needs to be generated autonomously while the small satellite constellation is delivering its daily operations attaining the required mission objectives and adding value towards the Cislunar sustainability. The major impact of each parameter was closely observed, studied, and plotted for their propagation cycles in the given operating environment. A systematic alignment to the proposed method and the Cislunar orientation was keenly taken into consideration to extract the importance of each of these parameters and their value in real-time operations. Though explanations for each of the plots are detailed in the discussions section, the significance of every parameter assisting the sustained form of propagation with autonomy is a view of assurance in each frame. Figure 6 shows this analysis visually obtained from the proposed constellation.



(**a**) (**b**)

(**c**) (**d**)

Figure 6. *Cont.*



(**e**) (**f**)

Figure 6. The parametric analysis of Earth's small satellite constellation (Cislunar) [16]. (**a**) Along, Cross, and Radial separations Sat-to-Sat (Km); (**b**) Along Arc Track, In-track, and Range variations (Km); (**c**) Satellites portraying the Radial projections (Km); (**d**) RAAN-Azimuth-Elevation variations (Deg.); (**e**) Azimuth angle variation with aligned satellites; (**f**) Elevation angle variation with the aligned satellite.

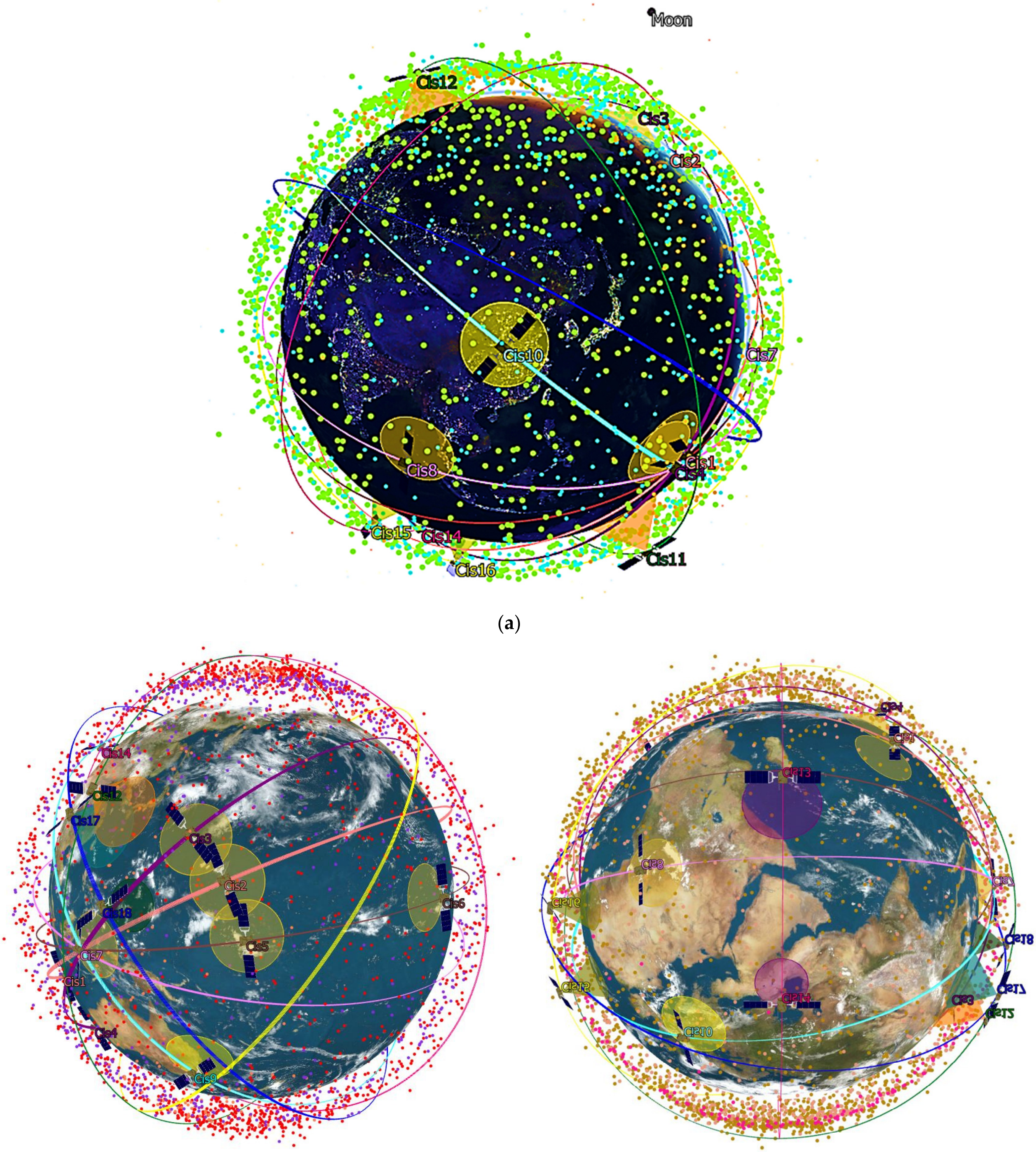
5.1.2. Monte Carlo Conjunction Tracking Analysis (Earth's Side of Cislunar Space)

Conjunction tracking is the next major element in the analysis onboard that needs to be aligned with the proposed method and be autonomous until the mission objectives are attained. This need to be done onboard, which will be presented in the later sections of this paper. Figures 7 and 8 below show the detailed analysis of the tracking conjunction using Monte Carlo. The word 'conjunction' is specifically mentioned in this paper due to the reason that two or more events are to be addressed in space at the same point in time. The debris and other missions operating and propagating together in multiple orientations, will make the situation risky some times when they all pass nearby each other and the chances of the collisions increase. Hence, the conjunction analysis is inevitable to ensure that the mission is safe and seamlessly operating specifically when it is a constellation of small satellite operating as one system.

The observations are provided in the Tables 2 and 3 below.

Table 2. Observations from Case-1 (Earth).

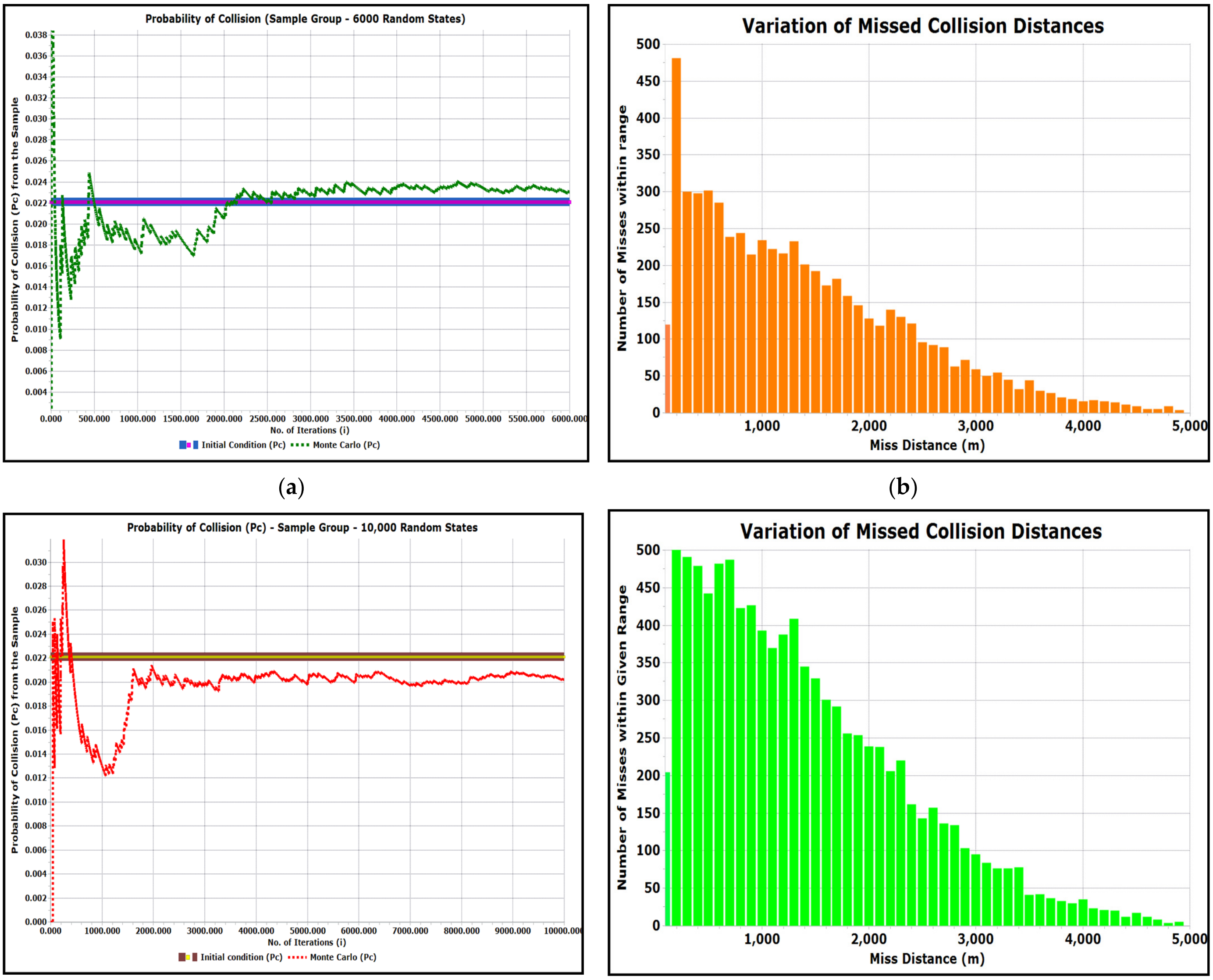
Parameter	Value
Probability of Collision (Pc)	0.022097
Probability of Collision (Pc)-with Monte Carlo	0.018540
The difference in TCAs	58 ms
Difference in Pc	−9.4902%
No. of potential hits	112
Closest Avg. Range	0.147045 Km
Closest Avg. Range-with Monte Carlo	1.331830 Km



(**a**)

(**b**) (**c**)

Figure 7. The debris (points) distribution over the constellation (Earth scenario). (**a**) Tracked debris in the safer zone with mission in progress [16]; (**b**) Constellation variation under intense debris movement; (**c**) Mission operations in medium-risk zone of Debris.



(**a**) (**b**)

(**c**) (**d**)

Figure 8. Autonomous collision assessment-Earth scenario (Monte Carlo) [16]. (**a**) Probability of collision (Pc-6000 random states); (**b**) State variations of missed collisions (6000 Distance-Km); (**c**) Probability of collision (Pc-10,000 random states); (**d**) State variations of missed collisions (10,000 Distance-Km).

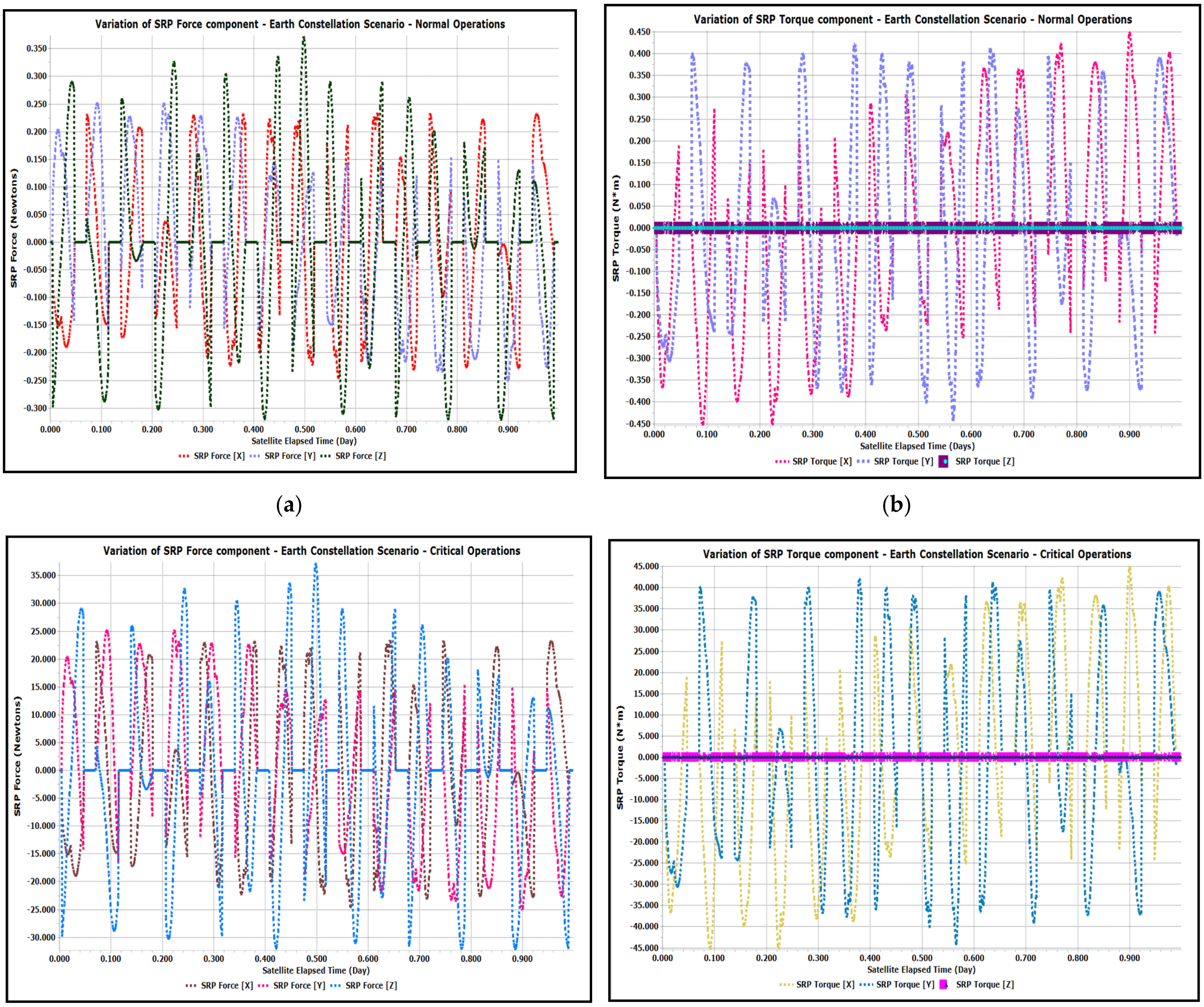
Table 3. Observations from Case-2 (Earth).

Parameter	Value
Probability of Collision (Pc)	0.022097
Probability of Collision (Pc)-with Monte Carlo	0.019147
The difference in TCAs	61 ms
Difference in Pc	−7.6800%
No. of potential hits	204
Closest Avg. Range	0.147045 Km
Closest Avg. Range-with Monte Carlo	1.315941 Km

The observations are in the real-time scenarios of Earth-based small satellite constellations. The space environment considerations are also made and are incorporated in the analysis that needs to be autonomous in every instance of the constellation operations.

5.1.3. Effect Observed on Small Satellites Due to SRP (Earth's Side)

This issue has been taken greater care of due to its critical significance and importance at this juncture of congested operations in lower Earth orbits. Two parameters are considered—1. SRP force and 2. SRP Torque—to observe their differences in critical (high influence of SRP) and normal conditions (minimum SRP). Figure 9 shows the variations in each of them.



(**a**) (**b**)

(**c**) (**d**)

Figure 9. SRP analysis for Earth orbits (Cislunar scenario) [16]. (**a**) SRP Force variation-Normal operations (Newtons); (**b**) SRP Torque variation-Normal operations (N·m); (**c**) SRP Force variation-Critical conditions (Newtons); (**d**) SRP Torque variation-Critical operations (N·m).

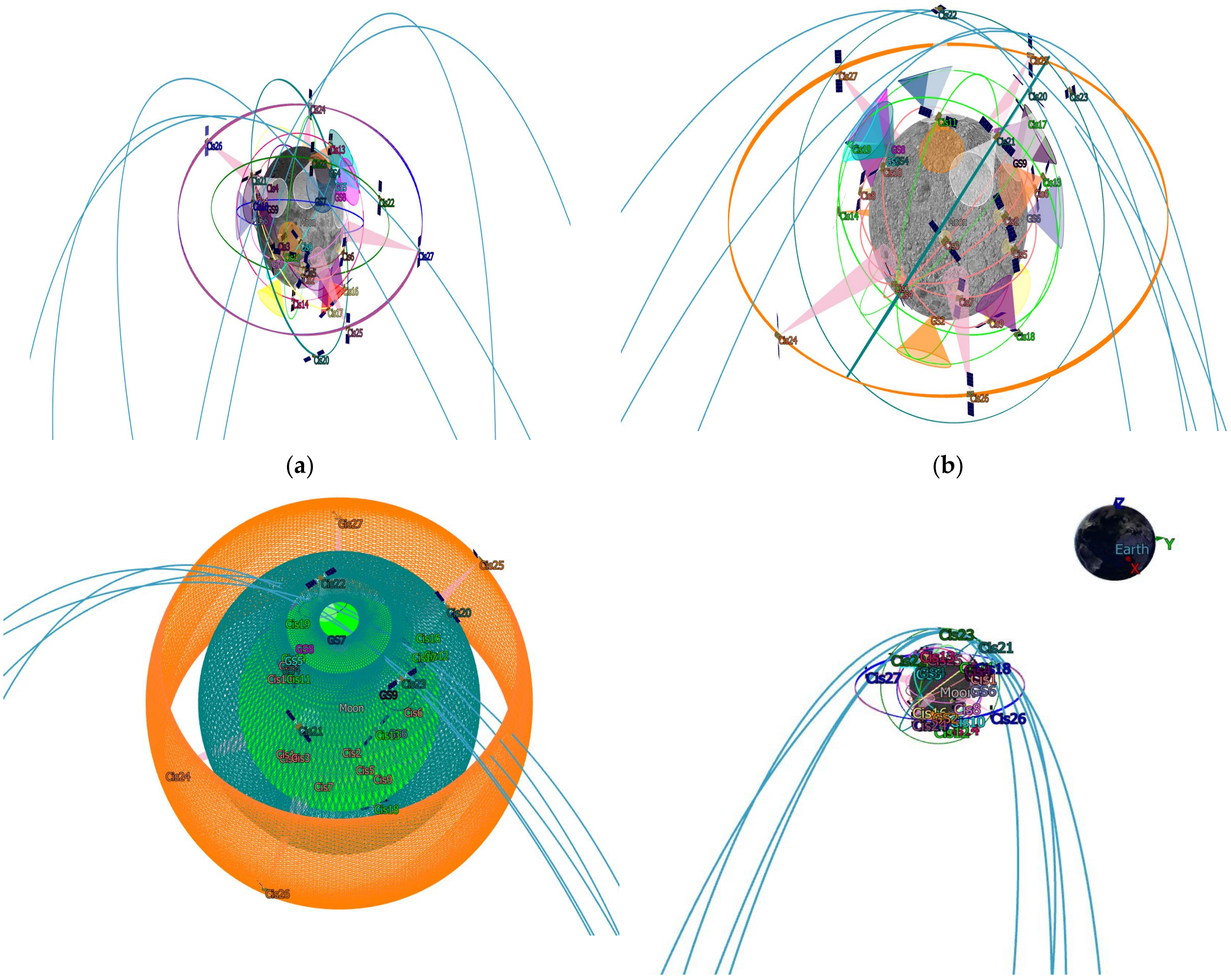
5.2. Moon-Based Constellation Simulation

The Moon's side of the Cislunar space, on the other hand, is the most critical area with strategic importance to reach deep space significantly in the near times. The Artemis missions are the most recent trials to retake humans to the Moon and make a habitation on it. The Artemis-2 will take the gateway to Near Rectilinear Halo Orbit (NRHO) and will need assistance to sustain for the long term.

This paper tries to utilize the small satellite constellations to assist gateway and other missions to organize and align the operations. It also aims to make the process of relays and ease the information sharing possible regularly and autonomously in a continuous loop of dedicated tasks to be attained daily. Hence, the simulations with local environmental conditions near the Moon have been considered, and with that, Figure 10 presents an insight into the real-time situations that are visually simulated and demonstrated. Table 4 gives the detailing on its configuration.

Table 4. Moon-based constellation configuration [16].

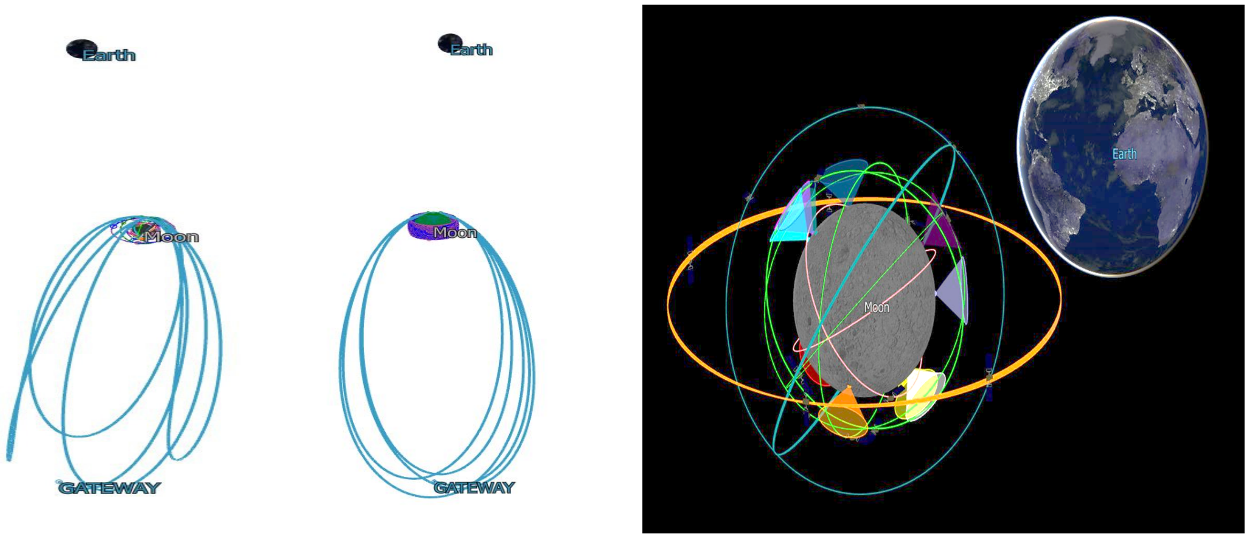
Parameter	**Value/Comment**
Orbits	hybrid–Flower (5); Mixed walker (4); MLO–Inclined (2); NRHO (1)
Eccentricity	0.001
No. of satellites	27
Sensors (FoV)	5~40 (Deg.)
Altitude	VLLO~NRHO (Distributed)
SRP	Integrated module
Inclination	0~110 Deg. (varied with NRHO in a different orientation)
Satellite Mass	85 (Kg)
Perturbations	Orbit to orbit relative disturbance



(**a**) (**b**)

(**c**) (**d**)

Figure 10. *Cont.*



(**e**) (**f**) (**g**)

Figure 10. Visual demonstration of the constellation (the Moon's side of the Cislunar space). (**a**) Complete orientation of constellation along NRHO; (**b**) varied orientation of constellation under perturbations; (**c**) The constellation variation with NRHO (Body frame); (**d**) Extended view with Earth coordinates (inertial); (**e**) Full-scale gateway propagation; (**f**) NRHO variation (inertial); (**g**) Dark-side view of the constellation in operations.

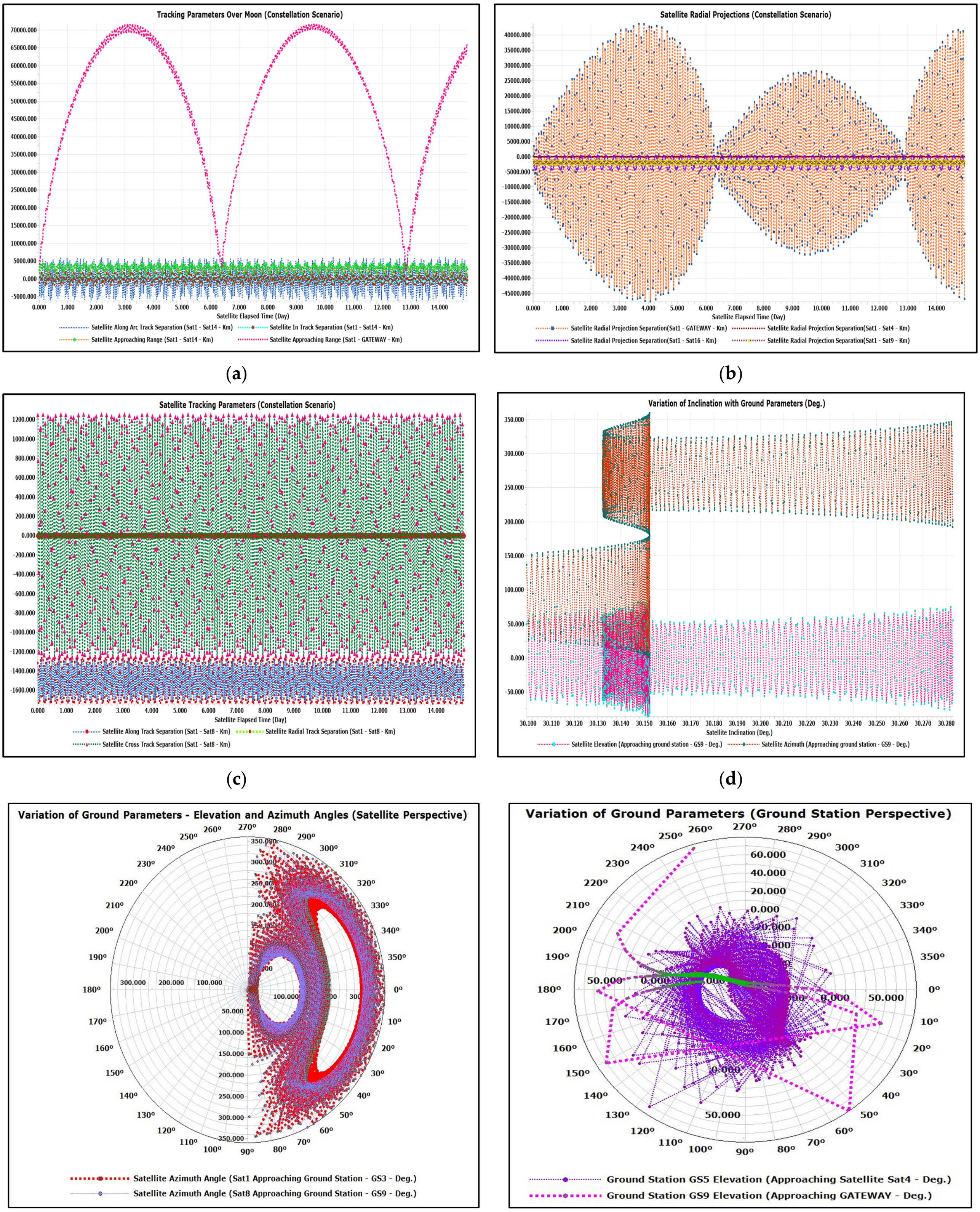
5.2.1. Autonomous Multi-Parametric Analysis (Moon's Side)

Even for Moon, the continuity in the parametric analysis needs to be autonomously generated and observed while the small satellite constellation performs its tasks with the lunar environment in consideration. Figure 11 below shows this analysis visually.

5.2.2. Monte Carlo Conjunction Tracking Analysis—Moon's Side of Cislunar Space

The Monte Carlo analysis was not actually part of the research until the Korean spacecraft had an important release of the issue near the Moon's orbital region. Continuous alerts were received by the satellite, warning of a possible collision [38]. Hence, this has provided significant evidence that there can be more such events in the near future, and with constellations building up, there is an extensive need for a Monte Carlo analysis with autonomous capabilities incorporated to avoid and overcome collisions efficiently.

The intensity of the debris or other missions' collision with the proposed constellation may not be as high as for the Earth's side of the Cislunar space, but the thing to understand here is that the planned and deployed missions towards the Moon are growing exponentially. This can be a reality that a post-Artemis crewed mission will reach the Moon's surface. The debris and missions' congestion may proportionally increase, and a systematic approach is needed to avoid conflicts and other issues in orbit and on Moon/Earth ground controls. Hence, a minimally congested scenario is considered for this simulation. The visual demonstration of lunar debris is not possible at the moment due to the lack of TLE release from the concerned organizations, but this can be a future work in progress. Tables 5 and 6 show the resulting solutions, and Figure 12 depicts the analysis pictorially for a detailed observation of the lunar mission's Monte Carlo collision probability over time.



(**a**) (**b**)

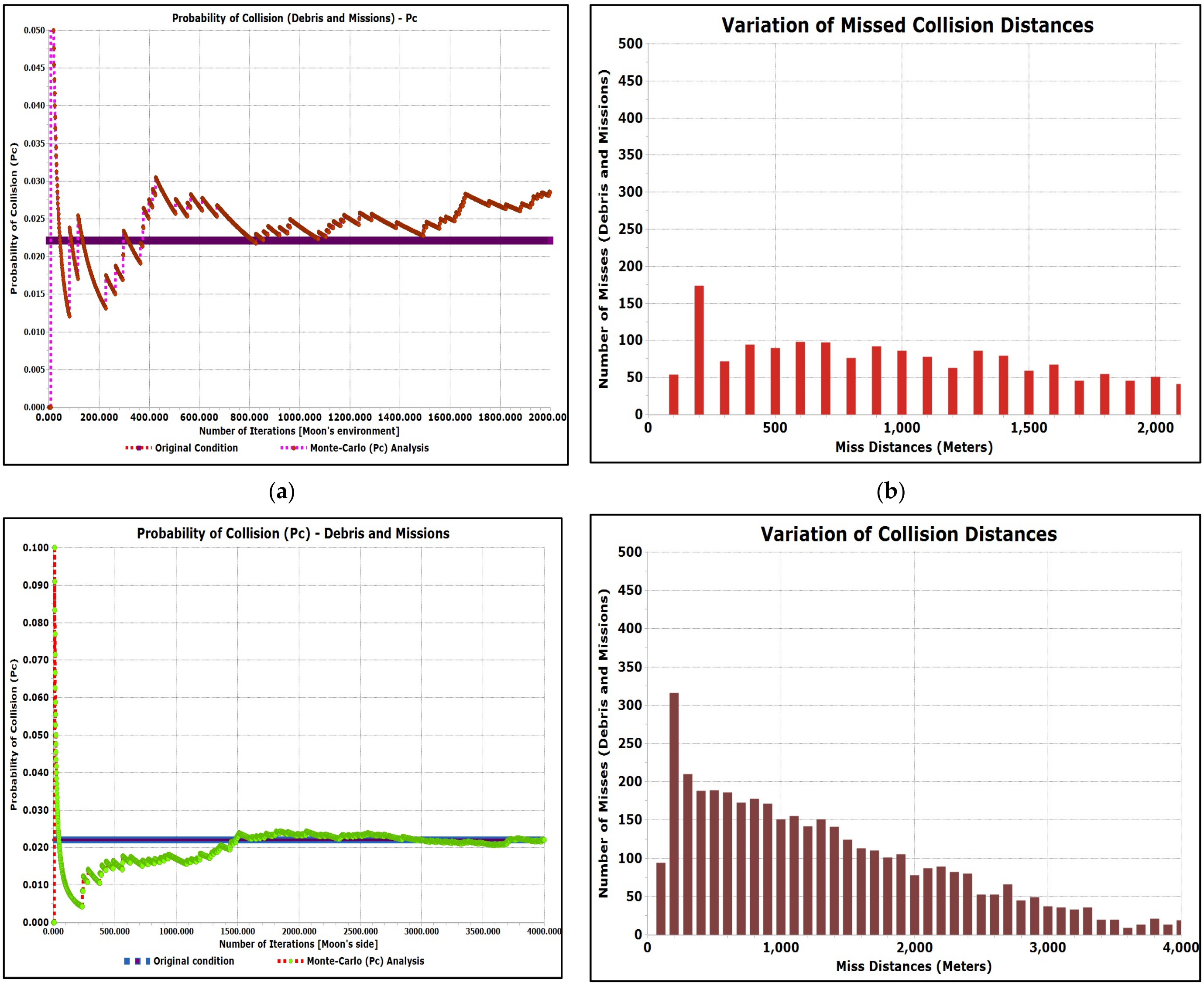
(**c**) (**d**)

(**e**) (**f**)

Figure 11. The autonomous parametric analysis (the Moon's side of the Cislunar space) [16]. (**a**) Along Arc, In-track, and range variations (sats-Km); (**b**) Radial projection separations among satellites (Km); (**c**) Along, Radial, and Cross track separations (Sats-Km); (**d**) Satellite Inclination variation with Az/El. (Deg.); (**e**) Ground parameter variations (Az./El.)-Satellites (Deg.); (**f**) Ground parameter variations (Az./El.)-GS (Deg.).

Table 5. Observations from Case—1 (Moon).

Parameter	Value
Probability of Collision (Pc)	0.032097
Probability of Collision (Pc)—with Monte Carlo	0.036820
The difference in TCAs	56 ms
Difference in Pc	+22.1883%
No. of potential hits	54
Closest Avg. Range	0.047045 Km
Closest Avg. Range—with Monte Carlo	1.295058 Km



(**a**) (**b**)

(**c**) (**d**)

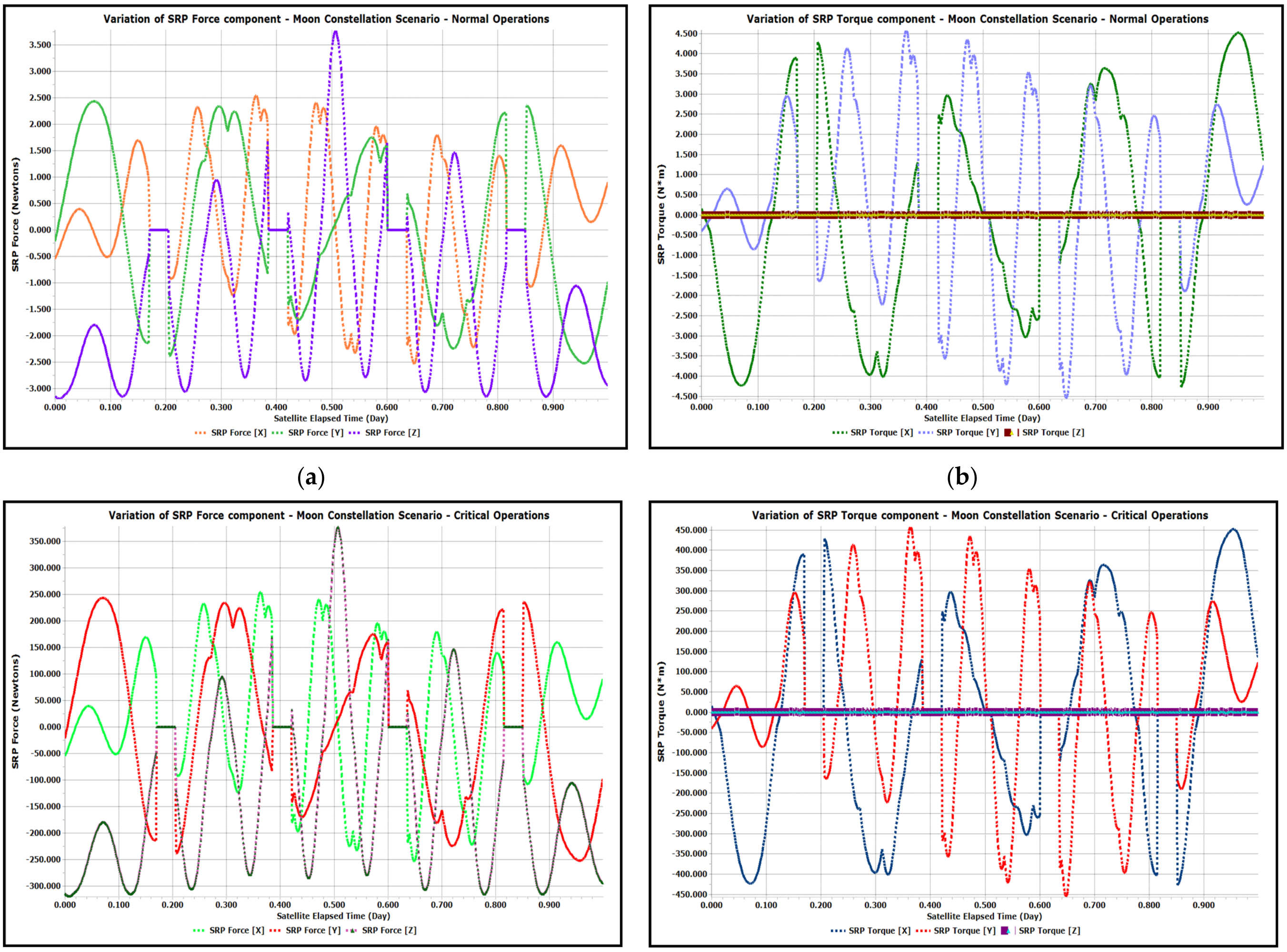
Figure 12. Variations in Probability of Collision Analysis (Moon's case). (**a**) Probability of Collision (Pc) (2k states); (**b**) Missed distances—2k states—Meters; (**c**) Probability of Collision (Pc)—(4k states); (**d**) Missed distances—4k states—Meters.

Table 6. Observations from Case—2 (Moon).

Parameter	Value
Probability of Collision (Pc)	0.032097
Probability of Collision (Pc)—with Monte Carlo	0.028883
The difference in TCAs	59 ms
Difference in Pc	+6.3491%
No. of potential hits	94
Closest Avg. Range	0.047099 Km
Closest Avg. Range—with Monte Carlo	1.209042 Km

5.2.3. Effect Observed on Small Satellites Due to SRP (Moon's Side)

The Solar Radiation Pressure is most influential on the satellites propagating the Moon's orbital environment. Severe issues were noticed several times in recent past missions [39,40]. Hence, it is important to analyze the intensity in terms of SRP force and torque on each satellite in a constellation. Figure 13 gives a thorough insight on its variations and determines the normal and worst possible scenarios.



(**a**) (**b**)

(**c**) (**d**)

Figure 13. Solar Radiation Pressure variations in different situations in operations [16]. (**a**) Variation of SRP force-Normal conditions (Newtons); (**b**) Variation of SRP torque—Normal conditions (N·m); (**c**) Variation of SRP force-Critical conditions (Newtons); (**d**) Variation of SRP torque-Critical conditions (N·m).

6. Discussions

NewSpace competence has taken a leap to move over the traditional approaches and define the path for creative and systematic changeover of space systems with unique methodologies. There are several ways in which space dynamics have changed and yet have to be evolved over time. The scope towards a sustainable Cislunar space and its optimal management is enormous and will redefine space like it has never been before. The economic factor of the Cislunar space will thrive, not only for the humans on Earth but also for deep space exploration in the true sense for a sustained period of time.

The direction provided by this paper is also towards sustainability of the operations in this major region of Cislunar space that binds Earth and Moon together as one system. Through literature, it has been observed that there is a need to find balance in the operations in the coming times. The intensity of mission growth and also debris alignment has been exponential and requires immediate attention to build a safe and reliable Cislunar space for a future that can be retained, maintained, and restored. This can only be done with precise but optimal use of technology with enhanced methodologies.

These times of Artemis missions are when humans will strive at the Moon with the purpose of moving into deeper space while using the Moon as an important station. The small satellite constellations are one supporting agent/tool for such ambitious missions. These satellites, though resource-constrained, will have greater capabilities to stand the space environment and deliver the best possible performance with their given objectives. These small satellites (<100 kg) have unmatchable capabilities and a capacity to attain objectives which were never thought of. This is both for the applications dedicated to the Earth and the Moon. These as constellations are the solutions to several longing issues in space and have proven their performance in near-Earth orbits and recently near the Moon as well.

Figure 3 demonstrates a proposed methodology that is the core portion of this research. The LEO region is the brain and centroid of the Cislunar space. It serves as a medium for orbiting the missions specific to the Earth applications and also as a parking station for the missions planned to be deployed to the Moon and beyond. Hence, this region acts as a major junction for all the Cislunar operations and beyond. Figure 3 comes forward with a strategy to use the LEO region efficiently by maintaining the small satellite constellations for Earth as well as holding the planned payloads and missions to be moved to the lunar orbits. Hence, the blocks represent the systematic schematic to deploy the small satellite constellations in the Cislunar space efficiently, utilizing the resources and saving costs as much as possible. This is also to sustain the missions for the long term for seamless development of the Cislunar economy and to support several major objectives for humanity to reach the Moon and beyond and explore the unknown.

The development of a sustainable autonomy in the Cislunar space is a major need for the moment. Hence, the proposed methodology has proven the seamless, robust, and reliable form of the system for small satellite constellations to maintain continuity in operations. The relevant dynamics associated with the Cislunar space will need to deliver sustained operations with due consideration to the space environment significantly different for the Moon and the Earth. This factor was taken care of while designing the proposed methodology and making a continuous streamline of operations in the Cislunar domain.

The dynamics of the Cislunar space, presented in Section 4, cover major elements of designing, maintaining, and retaining the constellations in the harsh Cislunar environment. The role of a satellite in the three-body system was deeply studied and emphasized the factors affecting their orientation as well. The Circular Restricted 3-Body Problem (CR3BP) is a common background of the proposed methodology and designed dynamics. The systematic approach was built to sustain the operations towards autonomous operations in the near future that are progressive and strong enough to sustain the competence in sustainability. These factors were closely observed and researched with relevant references to build the capacity over time and get resourceful benefits from the Cislunar space effectively and continuously. For this reason, the dynamics have extensively covered the hybrid constellation design, space debris, formation among the satellites, and majorly the impact of the space environment in the form of Solar Radiation Pressure, J_2 perturbations, and atmospheric drag, respectively. Also, the role of maximum coverage in the balance of defined autonomy is such an important aspect that the coverage is on full scale and has to be maintained in any given condition and scenario without any disruption of the operations of the aligned small satellite constellation. Hence, the chapter was separately given as Section 4.5. The other main reason is also that maintaining the maximum coverage will also allow the constellation to have a minimum number of satellites in utility of the creative methods in line with autonomy. Hence, a specific section is allocated to elaborate and highlight this objective, with developed autonomy having a bigger role to play with full-scale coverage to be deployed and sustained for the long term.

The visual simulations of the propagated constellation in Section 5 replicate the dynamics, and sufficient parameters are utilized to develop these algorithms to make the best possible situations and scenarios with the real-time environment simulated for the Earth and the Moon as an integral part of the Cislunar space. The significance of propagating the constellation in the respective environments of the Earth and the Moon gives an impactful observation of how the small satellites with their given configurations could react and sustain it while performing their operations daily. These were trialed in several ways, and parameters could be utilized efficiently to get the best balance of coverage, optimal resources, and operations to accomplish the mission objectives aptly. The major need for the analysis was unleashed once the propagation scenarios were fully understood and the proper benefits were observed.

As mentioned earlier, the analysis is divided into three different portions: 1. Parametric analysis, 2. Monte Carlo simulations for collisions, and 3. SRP variations under different conditions of the operations. Small satellite constellations have a distinct but situational emphasis on their behavior under varied conditions. This can be clearly seen in the results, which determine the operational stability that a constellation may have under different scenarios and the environment they are subjected to.

For Earth, starting from the parametric analysis, it is important to observe the variations closely as they perform their daily propagations as required by their mission objectives. Figure 6 brings about the parameters that define and orient the operations in the given orbits of a constellation. Figure 6a gives the alignment observation from satellite to satellite with respect to the Along, Cross, and Radial separations defining the actual position of each satellite in their respective orbits. Just thinking of the complexity of an entire constellation, things go way too much to handle with all these parameters intact and track each satellite independently. Hence, autonomy comes into the picture right away and takes control in the orbit, measuring the distances and maintaining a posed position and velocity as required for the proper functioning of a constellation overall.

In a similar line of action, Figure 6b gives a full-scale tracking with the Along Arc, In-track, and Range variations that defined the small satellite's nearest approximate location in the constellation. These variations will be so significant in the real-time operations that they will have ground control in complete trust that the constellation health is secured and in good shape altogether. Figure 6c,d will have the same impact but in a different parametric orientation. The Radial projections offered by Figure 6c will have an impact suggesting the major operation shifts, if any, when the anomalies in orbit show up. In the figure, it shows that there are slight variations from satellite to satellite but under a minor range of deviation. Hence, these changes are considered normal and can be highly varying in the case of unknown and critical anomalies.

Figure 6d shows the variation of the ground parameters (Azimuth and Elevation) with RAAN. This is crucial from the astrodynamics point of view, as RAAN is one orbital parameter that is impacted by the J_2 perturbations (which are included in the simulations), and it needs to be analyzed with the ground parameters of the approaching ground stations to be ready to deliver the data autonomously while aligning itself when needed.

On the ground side of the analysis, Figure 6e,f are the best forms of ground parameter observations. The reason is that these parameters influence the overall orientation and functioning of the constellation in a compact and resourceful manner. Figure 6e shows the Azimuth and Elevation angles of satellites one and eight approaching the ground stations. The confined pattern shown is the orientation of the satellites that signifies the major changes in their propagation with respect to the ground stations that are being targeted for data delivery. There can be some major differences in this orientation when the satellites are not perfectly aligned to deliver the data, and the ground control in synergy with the onboard autonomy can take action, if needed, to avoid disruption in the data missing out of delivery. The strategies mentioned in Reference [16] are one of the assets to determine and signify the utility of the autonomy in such situations efficiently.

Figure 6f is another aspect of the ground orientation with other ground stations in different locations. The pattern here is different as the orientation of those approaching satellites is different from the ground station locations. These are the parametric changes that impact the overall effectiveness of the constellation operations. This can be observed that New Delhi and Antarctica are poles apart, and the orientation of the satellites with respect to these ground stations can be seen in a single frame of operations in a defined pattern autonomously. This is one of the significant contributions of this multi-parametric autonomous analysis, which redefines the approach towards monitoring and utilizing the parameters precisely as needed. This can be more aptly observed through a determined approach in real time and maximize the potential of operations in the Cislunar space.

Section 5.1.2 includes the Monte Carlo analysis of collision avoidance with debris and the other missions in the vicinity. This is portrayed in Figure 7 in three different forms, density of debris, and a chance (probability) of collision. The first one, Figure 7a, is the most fairly distributed operation. Figure 7b gives intensively busy operations with an overall chance of a probable collision. Figure 7c comes through when operations are normal, but still, some areas of it define certain conflicts and near passes from one another or the debris. The constellations designed are shown in all these three scenarios and have adapted feasibility in all these three cases. The reason is that autonomous operations help the constellation navigate significantly out of the dangers when the nearest approaches are observed.

Monte Carlo analysis with two cases of 6000 and 10,000 states was performed to observe the changes from a number of state observations in a given instance and their precision in maintaining the true state. This needs to be done onboard to calculate the possible collision probability and the synergic action needed for the situation or the anomaly that is posed at the instance. It is important to know that the need for comparing the states (150 and 250) is due to observe the variation of the parameter values and their accuracy in that given condition and scenario (mostly for a critically close instance of collision), and to let the autonomy onboard determine the confidence in the solution and immediately iterate these points by checking the right Probability of Collision (Pc), and make critically serious decisions to navigate away from collision. This word “confidence” in solution is the main reason to deploy Monte Carlo and make quick decisions. It is not for choosing between the good decision and the bad one. All solutions are good, but the system needs to choose that one solution that inherits the best confidence in the critical situations where decisions need to be quick and instantaneous. Hence, this process had to be put forward as a major criterion for defined decision-making in near-miss collisions in real-time situations.

Several criteria were discussed and trialed, but the selected one for this research, which is presented in this paper, is the most prominently suitable for the situation of collision being the matter of concern, which could destroy the satellite and destabilize a constellation in seconds. Hence, robust, quick, and autonomous decision-making onboard will bring the situation under control thoroughly in case of emergency. Figure 8a shows the instance of calculating the probability of collision. It can be seen how at first the variations are intense until they stabilize, when the true state and a solution are addressed and navigated away from the danger with instant 6000 states iterated. On the other side, Figure 8b generates a histogram that defines the number of nearest misses in meters. Even in this case, it can be observed that the number of misses first starts rigorously high when the congestion happens, then slowly but steadily eases out and the misses reduce to the most minimal. This is the role of autonomy to safely and securely move away from the critical situations and maintain seamless operations.

Figure 8c brings about the variations with 10,000 states, and observations were made to see the changes from the probability of collision and the number of missions. Though the behavior of the curves and the histogram may be similar to one with 6000 states, the precision in the probability estimation is widely different. In this case, too, the variations initially are harsh as the congestion and the chance of a collision increase, and then it comes down slowly and stabilizes efficiently. The differences between 6000 and 10,000 states are shown in Tables 3 and 4, respectively.

Apart from the Probability of Collision differences as shown, the percentage differences are interesting to note. The negative percentage difference shows the change in probability when collision chances vary below zero but retain the operations with the best probability approximation calculated. Hence, these are actually normal, and the autonomous calculations in real time will be more precise and practical in many different ways. Monte Carlo is one such approach that can be operated accurately with small satellites in constellations autonomously. To help understand the computational process, the simulation adapts a methodology that syncs in two sets of calculations simultaneously propagated at the same time: 1. The theoretical collision simulation instance, where the system generates the Pc based on the initial conditions of the situation provided, and 2. The Monte Carlo simulation of the same set of points with a definitive algorithm. The comparison of these two outcomes is significant, and these sets of simulations gives the differences in Pc.

Solar Radiation Pressure (SRP) is the most critical element of destruction in space with many factors associated with it. The operations are widely impacted due to this environmental activity from the Sun. The SRP force and torque are two parameters that significantly affect the operations. Hence, these are to be calculated onboard and on the ground to continuously and autonomously monitor SRP for each satellite in a constellation. This can be seen in Figure 9, with a thorough comparison of normal to critical conditions.

This can be seen in the results from Figure 9a,c, showing that the normal and critical scenarios are so different from each other with regard to SRP forces. The variations from normal conditions to critical ones are so harsh that they can be as much as 10 times the force in the normal scenario, and this is the same for the SRP torque calculated for Figure 9b,d. This is the most difficult portion when critical situations occur due to the SRP on the satellites in the constellation. Hence, synergic and balanced use of autonomy can reduce this impact significantly, navigate satellites away from the dangers, and stabilize orbits for continued operations with as minimal losses as possible.

This also signifies that the Earth's lower orbits, which are essential for the scientific and technological observations needed for applications for Earth, have an impact on SRP, which needs immediate attention and to reduce the number of satellites in a constellation. This can be done with adequate design of the constellation with optimal coverage and proposed methodology. This aspect has been taken care of in this research as well, and the importance of SRP analysis is, hence, observed and portrayed.

For the Moon's side of the Cislunar space, the operations and the orientation of the small satellite constellation are quite unique with a significant inclusion of the Near Rectilinear Halo Orbits (NRHOs) for the long-term missions to establish habitation on the Moon's surface. Hence, the role of autonomous small satellite constellations will be of much importance, adding operational value to other bigger missions. This addition to the Cislunar space has been celebrated due to recent success in deep space, specifically in the NRHOs and lower lunar orbits.

Parametric analysis varies differently in the lunar orbits as the orientation and the orbital definitions are unique to the Moon's local environment and its positioning in the Cislunar space with respect to the Sun and the Earth. Figure 10 depicts a major outlook of the visual demonstrations of the simulations. As can be seen, several scenarios have been portrayed within the Moon's orbital area of the Cislunar space. Figure 10a,b differ in their scenario as they show a major change from perturbations and the SRP occurs in the orbital orientation of the constellation as a whole.

In Figure 10a, the colors can be observed that all are different defining operations from each satellite in the constellation. As soon as perturbations intensify, the colors change, notifying the operator on the ground that severe perturbations and SRP are being observed at that instance, as shown in Figure 10b. The orbital altitude-based coloring is shown due to observing the most impacted orbits in this scenario of criticality. This signifies the simple but effective observation autonomously that is evolutionary in itself and creates solutions that are impactful but simple in operation. These are observed in a variety of other observations both in inertial and body frames to give a sense of different scenes from the operations.

This is also done specific to Lunar orbits due to their distance from Earth and to get immediate or as early alerts as possible in case of a possible perturbation or a possible collision. Utmost efforts have been made to interface the real-time scenarios to the simulations aligned in this paper with NRHOs included, and its placement with respect to the Earth and the Moon is closely observed. The final simulations have been portrayed after several trials and with the study of the current trends and requirements in the Cislunar space.

Section 5.2.1 presents the parametric analysis for the Moon's side of Cislunar operations. These are the ones with the utmost critical operations, as the Moon's orbital region is still not fully known as well as how the parameters behave in their orbital space in these competent and highly demanding times. Missions will be growing significantly towards the Moon for strategic settlement on the surface as well as in the orbits. Two major orbital regions were explored in this paper: Lower Lunar Orbits (LLOs) and Medium Lunar Orbits (MLOs). These have high exploration value, as the Gateway will take its position in the NRHO for crewed landings at the South Pole and other missions aim at similar regions to land as well as explore with satellites as well as rovers in the near future.

Similar to Earth, the parameters of tracking remained the same but with due inclusion of the Gateway in NRHO. Figure 11a shows the Along arc, In-track, range among the satellites autonomously maintaining and managing operations. Figure 11c shows the significance of the Along, Radial, and Cross-track separations among the satellites to track them and maintain alignment strongly to seamlessly operate the constellation.

The small satellites are resource-constrained through cost-effective. Hence, a balance in autonomy in the proposed methodology is specified with respect to the Moon's orbital operations. This is because the operations over the Moon are significantly tougher to maintain for a longer duration of time. This is not only to perform the mission objectives but also to have robust communications with Earth in continuity along with the variations of the Gateway in NRHO. The significance of observing all these satellites and the Gateway in one frame of the plot is of high importance for regular operations monitoring on the ground.

Elaborating further, the main focus of this research is to support the missions like Artemis with dedicated small satellite constellations as a part of Cislunar operations. The Artemis-2 will get the Gateway station to the Near Rectilinear Halo Orbit (NRHO) over the Moon, and a large-scale operation will begin. This will extend the scope of the small satellite constellations to reach out and form a strategic alignment with Artemis and to support the day-to-day operations, regularly relaying data and information regarding the scientific and technological experiment. This is why the words "robust communications" are emphasized for these prominent communications that will be crucial for Artemis to have sustained operations with enhanced support and assistance from these constellations. Also, as the small satellites are resource constrained due to their smaller size and mass, there is a need to balance this deficit with a good balance of autonomy by extending their special supporting features and synergized methodology, which will help the constellations to thrive for a long period of time. This is a major ethos of this paper calling for sustained autonomy in the Cislunar space.

Figure 11b is a slight variation giving continuous Radial projection separations of each satellite in the constellation. It can be observed that they have a pattern of variation in the projections over the elapsed time of propagation. This is due to the orientation of the satellites with respect to the others during the constellation design and its configuration, as shown in Tables 1 and 2. The major significance of this pattern is to observe that satellites do not overlap one another's orbital positioning and retain their states as designed. These deflect when the perturbations occur, but they recover and come back to the original pattern of their orientation, which is satisfactory from the operations point of view.

The role of inclination sometimes gets overshadowed by the semi-major axis. But in the case of the Moon, this is absolutely critical to continuously monitor and assess the variations in inclination with other parameters. Figure 11d displays the variation of inclination of the constellation orbits with Azimuth and Elevation angles, respectively. This is as significant as monitoring RAAN for Earth due to perturbations. The SRP and in-orbit satellite-to-satellite lunar perturbations have a greater impact on the inclinations of the satellites in a constellation and can even change the orientation of an entire constellation. Hence, Figure 11d's variation with inclination and ground parameters signifies the variation of the satellites in healthy conditions over the lunar surface at the given altitudes. The fold shown in the plot is due to the turnaround of the satellite to re-take its position after moving over an approaching target ground station after the contact, moving away from it, retaining the orbit autonomously, and repeating the process.

Figure 11e,f is dedicated to the ground parameters' variations with the approaching satellites. Now, for the Moon, there is a slight difference from what is attained for Earth. The perspectives of the ground and satellite are crucial due to the placement of satellites in a hybrid form of constellation distant from the Earth's surface. For instance, Figure 11e shows the variation of the satellite's (Sat1 and Sat8) Azimuth and Elevation with respect to the approaching ground stations, whereas Figure 11f shows the variations of the Azimuth and Elevation angles of the ground station with respect to the approaching satellites (Sat4 and Gateway). This is important to differentiate the operating parameters and align them with respect to the given situation in orbit and on the ground (when the settlements happen on the Moon with a significant number of landings).

Figure 12 gives insights into the Monte Carlo analysis for the Moon's side of collision chances (probability) in its orbital space. The methodology remains the same with due consideration to the local environment. It can be closely observed that Figure 12a has a sharp variation with 2000 random states and the number of misses varies randomly, as shown in Figure 12b, with situations of Debris and Mission collisions included. These variations are much different from what is observed in this analysis of the Earth scenario. The major reason for this is obviously the intensity of congestion over the Earth and over the Moon are widely distinct. The reason is that the algorithm has a fewer number of random states to iterate and speed up the progression with iterations to find the solution sharply and tends to linearize as an optimal solution is found at the end of propagation. The fewer number of random states doesn't signify a less impactful form of analysis or prediction for a probable collision with respect to the method used. It only indicates that the number of probable collisions is less stable and needs to be balanced with appropriate autonomy to make the best solution for a particular situation during operations.

Figure 12c,d, on the other hand, gives more confidence in the solution and determines a much stronger and impactful prediction of a probable collision. These also need to be balanced and integrated into autonomy for synergizing decisions with ground control and navigating safely, avoiding any collision or near pass-by of another mission or debris. This is evident in Figure 12c, which shows impactful stability after a collision was predicted to its avoidance successfully in orbit. Figure 12d shows the strongest probable number of misses initially, and then the number reduces after the action was taken and the satellite continues its normal operations. Tables 5 and 6 show positive percentage changes in the probability of collision difference from nominal to Monte Carlo predictions. This indicates that the probability of collision iterations remains below zero at all times the instance of probable collision occurred. Hence, the change is observed and the possible danger is overcome with due coordination of the autonomy. These simulations emphasize the need for such calculations not only on the ground but also in orbit to synergize and solve issues with autonomy as precisely as possible. This can be done only with a proper methodology in implementation.

The impact of SRP over the Moon is a huge concern in these times. Hence, the observations and incorporation of the analysis of varying SRP force and Torque are of major importance and an element of prime inclusion in this research. Figure 13 portrays the variations of these SRP parameters on the satellites in the constellation. The reason for its inclusion is mentioned in Section 5.2.3 to contribute towards the growing issues with SRP over the Moon's side of the Cislunar space. Hence, a detailed analysis was carried out to know the scale of this impact on the small satellites and their performance. The result revealed staggering plots of how the SRP can be extremely critical for future missions to be operated as a constellation. Given the method to calculate these parameters remained the same as Earth, the impact observed is multiple times bigger on satellites than for the ones near Earth. The reason for emphasizing the SRP impact over the perturbations due to lunar gravity is due its extreme severity on the small satellites in a constellation in the recent past. Therefore, this paper is dedicated specifically towards analyzing the SRP impact on satellites in the Cislunar space with constellations operating over the Earth and the Moon, respectively. The impact of lunar gravity will be discussed and analyzed in future publications, which is also an important concern to be addressed but less severe than the impact of the SRP. Hence, it was prioritized and studied closely specific to autonomous small satellite constellations operating the limitations of the Cislunar space.

Figure 13a,b presents the SRP force and SRP torque's influence on the small satellites in constellation during normal operations. But the moment SRP impact intensifies, the parameters change significantly, as shown in Figure 13c,d. This can be catastrophic for the missions currently operating or planned to fly out to the Moon and operate in that environment for a longer duration. The difference is at least a hundred times showing intensive changes in the satellite's overall placement in a constellation. Hence, this needs to be analyzed and predicted in orbit in synergy with autonomy, and appropriate actions must be taken to avoid loss of or damage to any lunar mission. Though impact can't be reduced with the use of creative methodologies, they can be used to navigate out of danger if required by the given situation. Further research on this particular topic is ongoing and will be published in other articles in due course of time.

7. Conclusions and Future Work

This paper presented an important subject of strategically developing autonomy for the Cislunar space. This research aims to bring forth essential issues of today's space operations. The Cislunar economy will benefit humanity to an immeasurable extent if the resources and the methodologies governing them are well-defined and utilized precisely with optimal strategies. The NewSpace competence is highly dynamic and has several issues as well as opportunities to look forward to. The concerns to sustain the NewSpace environment with robust systems and the techniques to implement them will be a game-changer. The proposed methodology in this paper targets this main objective and designs a framework for sustainable space systems with synergic use of autonomy.

The impact that small satellite constellations create in the Cislunar space is remarkable in many ways. The combination approach of using small satellite constellations with the proposed methodology is unique and distinctive in the way it has been simulated. These simulations integrated into the space environment and generating real-time scenarios have been demonstrated for both the Moon and the Earth as an integral part of the Cislunar space. The role of autonomous operations in the given scenarios was deeply emphasized in various portions of this paper. It is going to be slow but steady to implement the strategies and methods proposed in this paper, but this is a vision towards much more sustainable space operations in the coming years.

The proposed methodology and its elements of analysis shown in this paper have several persuasive benefits for Cislunar operations, but they have a few limitations, too. The assertive gain from this approach is that a continuous loop of operations can be formed from Low-earth orbits to the Moon's orbits and to its surface specifically for small satellite constellations, but also in the long run, for the major missions with crew landings. The small satellite constellations will form essential tools for guiding, assisting, and devising the trajectories for these bigger missions and relay their tracking and mission data as required to the Moon as well as back to the Earth. Hence, a two-way benefit is seen when these miniature assets are utilized optimally with autonomy. Also, the robustness towards the space environment is also a major perk in these simulations through the proposed methodology. Addressing the SRP, Atmospheric drag, and also J_2-like perturbations is an important addition to the NewSpace efforts for sustainability in space. The debris and missions' congestion analysis with Monte Carlo also adds up to a comprehensive package of the operations in the Cislunar space in the near future.

The role of autonomy is significantly at a large scale in the Cislunar space. This is still underutilized and there is a lot to be done yet to enhance, spread, and evolve it over the traditional methodologies, but the work towards it is already in a focused direction and will be an asset for the Cislunar operations. This paper has bought forward the need for a sustainable form of autonomy in these times of aggressive Cislunar missions, especially towards building strategic positions and capturing the unique data of the Moon, which is of high quality and is adaptable in exploring the deeper space and knowing new facts about the Moon and later moving to Mars. This replicates in a different way for operations at the Earth's side of the Cislunar space. Applications such as disaster management, are of such critical importance for humanity and the preservation of the resources on Earth. The role of autonomy in such operations with small satellite constellations is exponentially valuable, and the need for further developing constellations just keeps growing. Overall, the autonomy of fairly and extensive size of implementation is critically needed for the dedicated and systematic operation of the Cislunar space. This paper makes a sincere effort towards that direction and forms a major foundation towards building autonomous systems and operations that are significantly contributing but also sustainable for a long term. This will bring synergy of various factors together and avoid unknown anomalies and conflicts in the Cislunar space, boosting its economy and allowing missions to be safe, intelligent, and organized while meeting their mission objectives as planned.

The limitations that are being worked on currently with this proposed methodology are the complexity of computations to be optimally reduced to a significantly lower level. It doesn't mean that it is not simple in computation now, but further efforts in this regard to reduce the complexity overall in a system of operations towards more precision in implementation will be desired. The computation time for each simulation (including the iterations of Monte Carlo) remained under 10 s, making the algorithms compact and significantly reliable. Even during several trials, the overall accuracy in the execution of the algorithms remained simple, compact, and accurate without any major anomalies detected. This can be further improved with upgraded accuracy and reduced computation efforts, as simple but effective systems are the key to the NewSpace challenges.

In the near future, these results will be studied further in various real-time operating scenarios. The space environment is dynamic and changes rapidly over time. Hence, more rigorous testing and evaluation of the proposed methodology will be aligned specifically to small satellites and their constellations. The Cislunar operations also will be the center of the focus to make its operations effective, safe, continuous, and enduring for a long period of time.

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