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Characterization of Orbits in Cislunar Space for Space Traffic Management

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Abstract

Over the last decade, there has been a rise in the number of missions aimed at lunar exploration. Several international and private agencies have landed on the surface of the Moon to understand the secrets of the universe and how to utilise the potential of the Moon as a future space settlement for mankind. Most future deep-space manned missions are conceptualised to have a stopover at the Moon, before embarking on the longer journey through the solar system. Projections have shown that there will be a rise in the number of spacecraft in cislunar space over the next few decades. Without a necessary framework for traffic management, operations in the cislunar space will be challenging. Characterization of orbits is a potential solution to this problem. We may define set orbits for particular use cases of space mission operations, and observe the behaviour of such traffic management frameworks over the long term. We can also define specific orbits to house the defunct satellites and orbits for on-orbit servicing. Assignment of orbits for specific Lunar missions will be decided based on the requirement of Lunar access. We aim to study the feasibility of characterization of orbits, and its pros and cons in the big picture of cislunar space. To do so, we have selected several use case scenarios such as formation flying communication relays and Lunar Orbital space stations, which will be using the different periodic and quasiperiodic orbits. We will also look at the positioning of Space Situational Awareness (SSA) systems to ensure that all systems are in coordination with each other.

Keywords: Space Situational Awareness (SSA) , Space Traffic Management (STM) , Cislunar Space, Libration Points , Periodic Orbits

Nomenclature

μ	Mass Ratio	-
r_1	Distance between m_1 and P	LU
r_2	Distance between m_2 and P	LU
U	Pseudo-potential	-
C_J	Jacobi Constant	-
A	Jacobian Matrix	-
λ	Eigenvalues	-

Acronyms/Abbreviations

SSA	Space Situational Awareness
STM	Space Traffic Management
CR3BP	Circular Restricted Three-Body Problem
IVP	Initial Value Problem
LEO	Low Earth Orbits
MEO	Medium Earth Orbits
GEO	Geostationary Orbits- GEO
CSTM	Cislunar Space Traffic Management

1. Introduction

Since the successful launch of the Sputnik I, mankind has never turned back launching spacecraft into orbit for several purposes. Estimates show that there are nearly 17000 satellites that have been launched into space since the beginning of the space age, out of which 15500 of them have been registered with the United Nations Office of Outer Space Affairs (UNOOSA) [1]. Due to lack of end-of-life planning, a lot of these satellites who have completed their missions remain in stray orbits, posing risks to other active satellites in the form of the Kessler syndrome [2]. Rising challenges in orbit gave rise to this new subject area referred to as Space Situational Awareness (SSA).

The main aim of SSA is to predict the trajectory of uncontrolled spacecraft and warn operators about potential conjunctions of dead satellites or space debris with active satellites.

Having successfully completed several interplanetary missions in the past few decades, space agencies are now shifting their focus towards manned missions to the Moon, and then to Mars in the near future. Due to this, projections estimate a rise in traffic in the cislunar space, which refers to the region surrounding the Earth and Moon, where a spacecraft would be under the influence of both the bodies. The Cislunar Infrastructure market is projected to increase from 3.62 billion USD in 2022 to over 9.17 billion USD by 2031. It is estimated that the majority of these costs may be towards the development of constellations which may be used as a communication relay for future manned space missions, and for space stations.

The dynamics within this region cannot be described using the usual two-body problem, since the spacecraft is considered to be the third body. Thus, the dynamics in this region is described using the Three-Body problem. Unlike the two-body problem, they do not have analytical solutions since they are nonlinear and heavily dependent on the initial conditions. Getting an accurate model of the cislunar space is a computationally intensive task, and hence a simplified model is used, referred to as the Circular Restricted Three-Body Problem (CR3BP).

The rising traffic in the cislunar space poses a challenge for operators since it is hard to predict the trajectories of satellites in the cislunar space without knowing the right initial conditions given the chaotic nature of the system. Furthermore, there is a strong limitation on the measurement accuracy of ground based optical systems. This paper aims to understand the most feasible locations for possible future sensor locations based on illumination conditions and visibility constraints, and the power constraints for radar systems. We first look at the dynamical model of the CR3BP and the potential types of orbits which may be used for the placement of sensors and how they behave based on the previously mentioned constraints.

1.1 Objectives

The main objectives of the study is:

1. To review existing traffic management strategies.
2. To understand the implementation of operational zones.
3. To characterise orbits based on their respective operational zones.
4. To recommend traffic control strategies.

2. The Dynamical Model

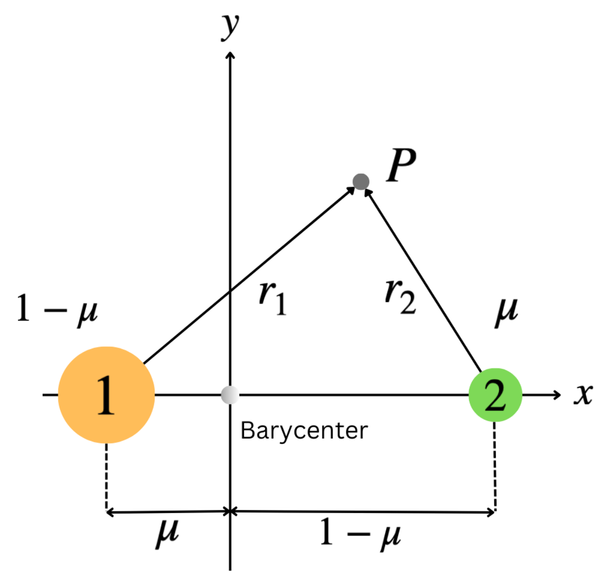

Fig. 1. CR3BP Model

As stated earlier in section 1, the nonlinear nature of the multi-body problem makes it chaotic and challenging to simulate. The easy fix to the same is to simplify the problem by assuming the following:

1. The primary and the secondary bodies revolve around the barycenter of the system in a circular orbit.
2. The third body is considered to be a point mass such that it has no effect on the primary and secondary bodies.

We may observe the assumed model as shown in figure 1. The primary body is represented by 1, secondary by 2, and the third body is represented by P. The system is non-dimensionalized to ensure that the system is scalable and can be used to represent any three-body system. μ represents the mass ratio given by:

$$\mu = \frac{m_2}{m_1 + m_2} \tag{1}$$

$$r_1{}^2 = (x+\mu)^2 + y^2 + z^2 \tag{2}$$

$$r_2{}^2 = (x+(1-\mu))^2 + y^2 + z^2 \tag{3}$$

where m_1 represents the mass of the primary body and m_2 represents the mass of the secondary body, and $\mu = 0.01215$ for the Earth-Moon system. We may write the equations of motion as:

$$\ddot{x} - 2\dot{y} = \frac{\partial U^*}{\partial x} \tag{4}$$

$$\ddot{y} + 2\dot{x} = \frac{\partial U^*}{\partial y} \tag{5}$$

$$\ddot{z} = \frac{\partial U^*}{\partial z} \tag{6}$$

where, U is given by:

$$U = \left(\frac{x^2 + y^2 + z^2}{2}\right) + \left(\frac{1-\mu}{r_1}\right) + \frac{\mu}{r_2} \tag{7}$$

Since the above equations do not have any closed form solutions, numerical methods are used to compute the solutions. They are studied in depth from the next section.

We may also introduce the term *Jacobi's constant*, which is given by:

$$C_J = -2U \tag{8}$$

This term is used to determine the realms of possible motion and the forbidden regions in the Earth-Moon system.

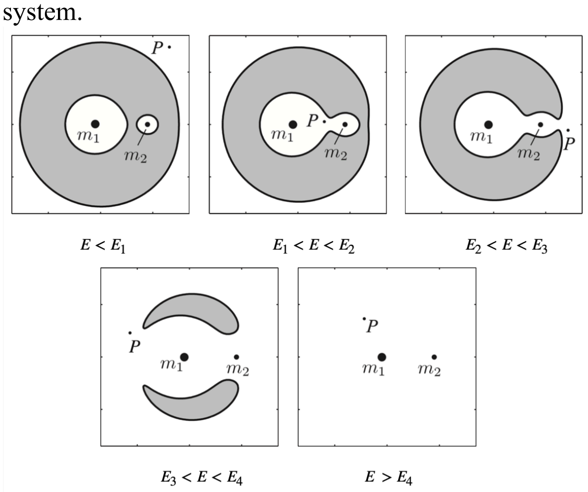

Fig. 2. Realms of Possible Motion for Different Jacobi Constant Values (Adapted from [4])

2.2 Libration Points

The CR3BP provides a variety of specific solutions. The system's set of equilibrium points is also a particular kind of solution. Equilibrium points are points in space where products of velocity and acceleration vectors are both 0.

For the conditions, the velocity and acceleration vectors to be zero, the conditions for a solution that tends to an equilibrium point are:

$$\frac{\partial U}{\partial x} = 0 \quad \frac{\partial U}{\partial y} = 0 \quad \frac{\partial U}{\partial z} = 0 \tag{9}$$

The equilibrium points in the CR3BP are locations where the pseudo-potential, a function representing the combined gravitational and centrifugal forces acting on the third body, remains constant. To find these points, we calculate the partial derivatives of the pseudo-potential with respect to the configuration space variables, which gives us the equilibrium points or the libration points as shown in figure 2.

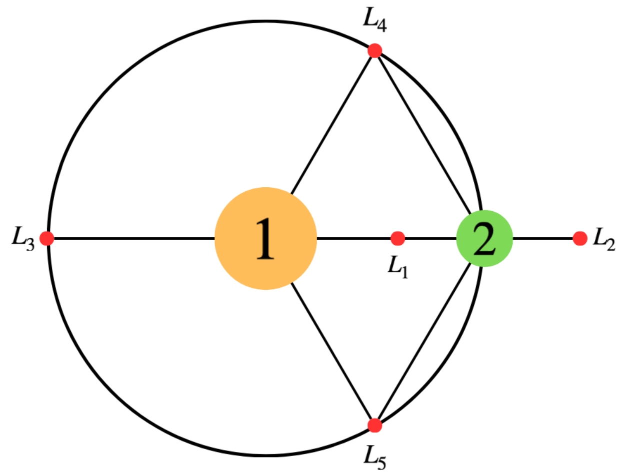

Fig. 3. Libration Points

Solving the partial derivative with respect to the z-coordinate shows that all equilibrium points in the CR3BP must lie within the orbital plane of the primary bodies. Solving the equations of motion leads to five distinct equilibrium points: three aligned along the x-axis, known as the collinear points, and two positioned off the y-axis, forming equilateral triangles with the primary bodies. Each coincidentally forms the vertex of an equilateral triangle, its base being the line joining the two primary. These five equilibrium points are called Lagrange points or libration points. The three collinear points are called L1, L2, and L3, whereas the triangular points are denoted as L4 and L5.

In the Earth-Moon synodic frame: L2 and L3 are on the x-axis and are separated from the origin by the second and first primaries, respectively, whereas L1 is on the x-axis between the two primaries. Triangular equilibrium points with positive y coordinates are L4 and L5, respectively, and negative y coordinates are L5.

2.3 Stability of the Libration Points

The Study on analysing the Lagrange points' stability provides important insight into how trajectories behave near the equilibrium points. Representation of small deviations from a nominal state, (x*,y*,z*), associated with a Lagrange point, new variables are represented as:

$$\xi = x - x^* \quad \eta = y - y^* \quad \zeta = z - z^* \tag{10}$$

The perturbed equations of motion, grouped by nominal components ()* and perturbation terms (), are given by:

$$\ddot{x} - 2\dot{y} = (\ddot{x^*} - 2\dot{y^*}) + (\ddot{\xi} - 2\dot{\eta}) = \frac{\partial U^*}{\partial x}$$
$$\ddot{y} + 2\dot{x} = (\ddot{y^*} + 2\dot{x^*}) + (\ddot{\eta} + 2\dot{\xi}) = \frac{\partial U^*}{\partial y} \quad (11)$$
$$\ddot{z} = \ddot{z^*} + \ddot{\zeta} = \frac{\partial U^*}{\partial z}$$

A first order Taylor expansion of the pseudo-potential around the nominal points is carried out, which yields:

$$U = U^* + \frac{\partial U}{\partial x}|_* \xi + \frac{\partial U}{\partial y}|_* \eta + \frac{\partial U}{\partial z}|_* \zeta \quad (12)$$

The nominal components of each equation, the initial grouped terms on the left-hand side, are identical to the nominal partial derivatives on the right-hand side. This leads to their cancellation, leaving a system of differential equations exclusively in the perturbation variables. We arrive at the final equation by representing this system as a set of first-order ordinary differential equations in a matrix which is given below.

$$\dot{X} = A\,X \quad (13)$$

A = Jacobian matrix, given by:

$$A = \begin{bmatrix} \frac{\partial x}{\partial x_0} & \frac{\partial x}{\partial y_0} & \frac{\partial x}{\partial z_0} & \frac{\partial x}{\partial \dot{x}_0} & \frac{\partial x}{\partial \dot{y}_0} & \frac{\partial x}{\partial \dot{z}_0} \\ \frac{\partial y}{\partial x_0} & \frac{\partial y}{\partial y_0} & \frac{\partial y}{\partial z_0} & \frac{\partial y}{\partial \dot{x}_0} & \frac{\partial y}{\partial \dot{y}_0} & \frac{\partial y}{\partial \dot{z}_0} \\ \frac{\partial z}{\partial x_0} & \frac{\partial z}{\partial y_0} & \frac{\partial z}{\partial z_0} & \frac{\partial z}{\partial \dot{x}_0} & \frac{\partial z}{\partial \dot{y}_0} & \frac{\partial z}{\partial \dot{z}_0} \\ \frac{\partial \dot{x}}{\partial x_0} & \frac{\partial \dot{x}}{\partial y_0} & \frac{\partial \dot{x}}{\partial z_0} & \frac{\partial \dot{x}}{\partial \dot{x}_0} & \frac{\partial \dot{x}}{\partial \dot{y}_0} & \frac{\partial \dot{x}}{\partial \dot{z}_0} \\ \frac{\partial \dot{y}}{\partial x_0} & \frac{\partial \dot{y}}{\partial y_0} & \frac{\partial \dot{y}}{\partial z_0} & \frac{\partial \dot{y}}{\partial \dot{x}_0} & \frac{\partial \dot{y}}{\partial \dot{y}_0} & \frac{\partial \dot{y}}{\partial \dot{z}_0} \\ \frac{\partial \dot{z}}{\partial x_0} & \frac{\partial \dot{z}}{\partial y_0} & \frac{\partial \dot{z}}{\partial z_0} & \frac{\partial \dot{z}}{\partial \dot{x}_0} & \frac{\partial \dot{z}}{\partial \dot{y}_0} & \frac{\partial \dot{z}}{\partial \dot{z}_0} \end{bmatrix}$$

The characteristic equation is given by:

$$\det(A - \lambda I_6) = 0 \quad (14)$$

We find positive eigenvalues for the collinear points, while negative for the triangular points. Thus, we can confirm that the libration points L_1, L_2, L_3 are the unstable points, while L_4, L_5 are the stable points.

2.5 Periodic Orbits

Integrating these equations and applying the differential correction gives us the position and velocity of the third body for the time period for which it was integrated, which in turn gives the trajectory of the third body. The system of equations may be solved as an Initial Value Problem (IVP). Given the nonlinear nature of the system, they behave chaotically and hence depend heavily on the initial conditions. In fact, different initial conditions give rise to several different families of periodic orbits. To name a few,

1. Lyapunov orbits
2. Halo orbits
3. Vertical orbits
4. Axial orbits
5. Vertical orbits
6. Resonant orbits
7. Distant Retrograde orbits
8. Distant Prograde orbits
9. Short Period orbits
10. Long Period orbits

The location and the orbital period of these orbits are dependent on the initial conditions as discussed earlier. It has been studied in depth in the next section.

3. Space Traffic Management in Cislunar Space

Having understood the dynamics of the cislunar space from the previous sections, let us now look at the strategies that may be used for traffic management.

On ground, air traffic controllers approach the problem of traffic management by using well established protocols and infrastructure to ensure smooth operations of aircraft. They ensure that all aircraft have planned flight paths and schedules, such that their movements are coordinated. Communications and navigation services are broken down into simpler components to ensure no mix up occurs. For instance, airports usually employ multiple levels of radio communications such as having a dedicated controller for approach, tower and ground operations respectively. This helps with breaking down the operations fundamentally and ensuring seamless traffic flow.

The number of variables, however, significantly increases in the case of space traffic management. For instance, the dynamical system is different from that of air traffic control. Moreover, no existing infrastructure is available to cater to the needs of future cislunar operations. Moreover, communication challenges due to the farther distance poses a challenge to the operations since it is hard to predict conjunctions unlike in the case of Earth orbits. Moreover, due to the chaotic nature of the system, traditional end-of-life solutions may not be feasible.

In 2002, the upper stage of the Saturn V rocket launched during the Apollo 12 mission in 1969 mysteriously reappeared around the Earth orbit. It was in fact assumed to be an asteroid, and was only found to be a part of the Saturn V rocket after further investigations [6]. NASA used to use a Trailing side flyby of the moon to ensure that the third stage of the Saturn V would enter a heliocentric orbit. However, during Apollo 12, the third stage was said to have been faster than it should have been, which would make it pull a Leading side flyby, which was not desirable. To correct the same, the third stage was slowed down beyond the necessary speed which made it enter a highly elliptical orbit around Earth. Amidst this, it crossed the L_1 points of the Earth-Sun system, and thus it ended up in an obscure orbit around the Sun before entering Earth orbit again in 2002. The third stage is predicted to visit Earth once again in the 2040s. All of this is due to the dynamics of the cislunar space, which is chaotic and unpredictable. This case sets a precedent of what is to come in the future. Active and inactive spacecraft, both pose a threat to each other and hence having the necessary infrastructure and protocols are paramount for ensuring safe operations in space.

3.1 Classification of Operational Zones

Establishment of operational zones helps with demarcating the region into several zones based on their utility or location. This is analogous to air traffic control systems, where a different controller is designated for different phases of the flight as mentioned earlier.

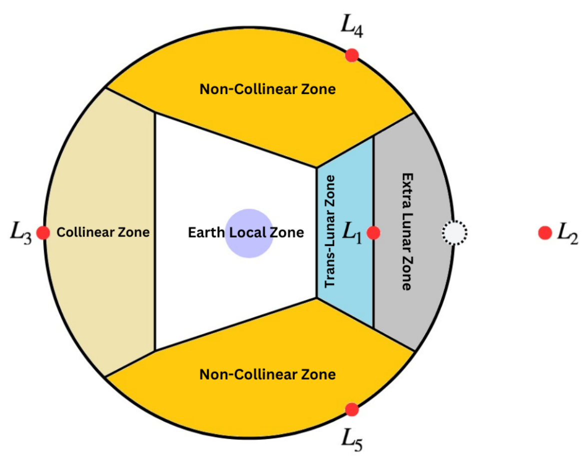

Fig. 4. Operational Zones in Cislunar Space (Adapted from [3])

As presented by Cunio et. al. (2021) [3], we may divide the cislunar space as per shown in figure x. The figure is not to scale, and is just a representation of the idea conveyed.

3.2 Characterization of Orbits based on Operational Zones

3.2.1 Earth Local Zone

The Earth Local Zone is characterised by the two-body orbits. It mainly consists of the following orbits;

1. Low Earth Orbits
2. Medium Earth Orbits
3. Geostationary Orbits
4. Geosynchronous Orbits
5. Sun-Synchronous Orbits

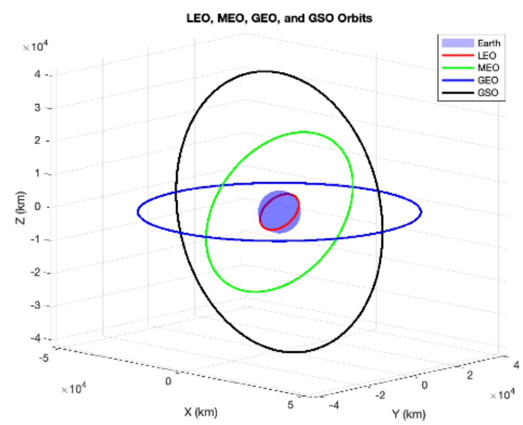

Fig. 5. Earth Local Zone Orbits

This zone has been the centre of over 95% of the space missions launched till date. The main applications of these orbits include Earth observation, Communications, Navigation, Weather prediction, Environment monitoring, and scientific research such as space stations and space telescopes.

3.2.2 L_3 Collinear Zone Orbits

The L_3 libration point is a collinear point, and hence dynamics around this point is similar to that around L_1 and L_2. Thus we observe the following orbits:

1. Halo Orbits
2. Lyapunov Orbits
3. Vertical Orbits
4. Axial Orbits

The L_3 Libration point orbits can be used for maintaining solar observations, space weather monitoring, deep space communication and navigation systems, and for scientific research purposes.

3.2.3 L_4 and L_5 Non-Collinear Zone Orbits

The L_4 and L_5 Libration point orbits are the stable points. The types of orbits in this region vary from that of the collinear point orbits. They include:

1. Vertical Orbits
2. Axial Orbits
3. Short Period Orbits
4. Long Period Orbits

As L_4 and L_5 Libration point orbits are the most stable libration points in cislunar space they can be utilized by various space observatory missions as it does not have any interferences with earth's orbits, they are ideal locations in space for orbit parking and also makes them well-suited for communication satellites, particularly for regions with limited terrestrial coverage. due to their high stability.

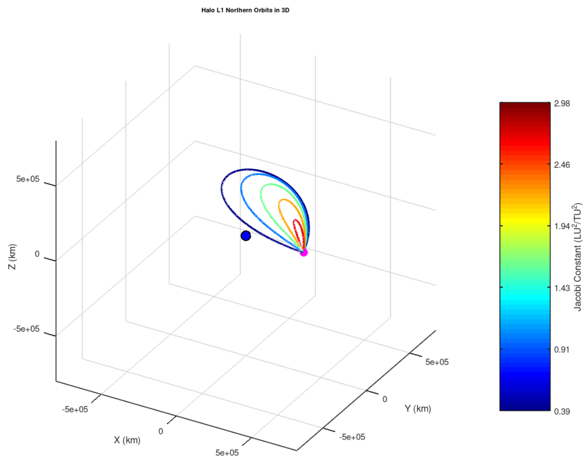

Fig. 6. L_1 Northern Halo Orbits

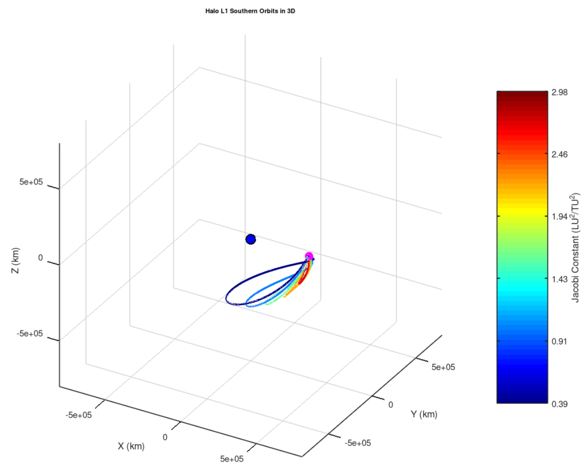

Fig. 7. L_1 Southern Halo Orbits

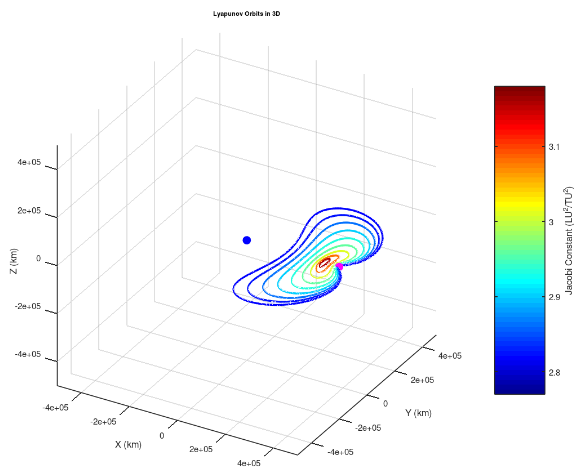

Fig. 8. L_1 Lyapunov Orbits

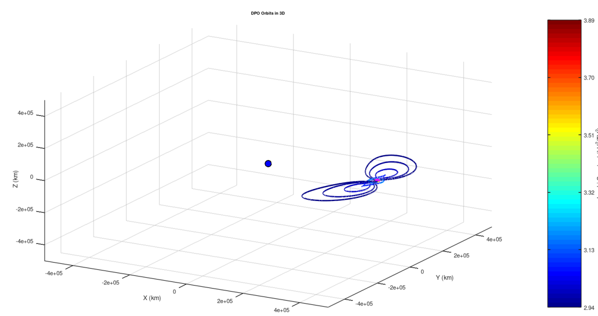

Fig. 9. L_1 Distant Prograde Orbits

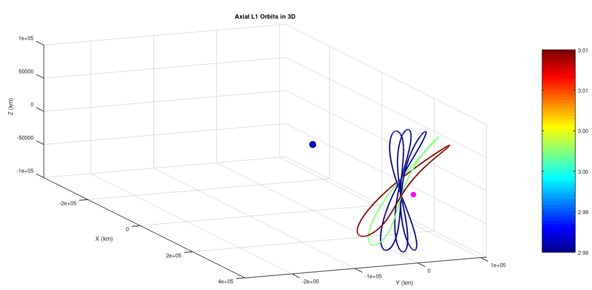

Fig. 10. L_1 Axial Orbits

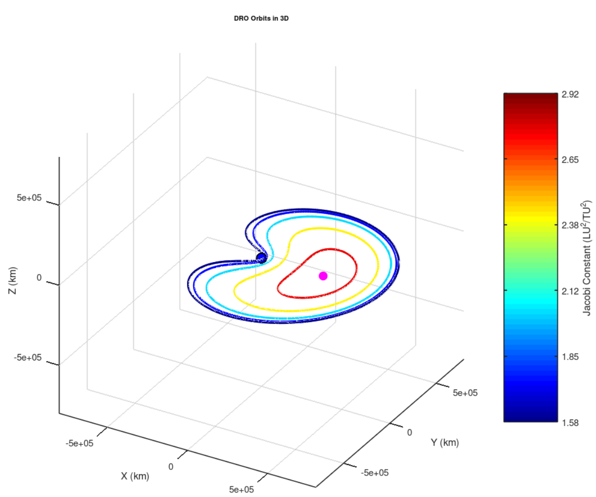

Fig. 11. L_1 Distant Retrograde Orbits

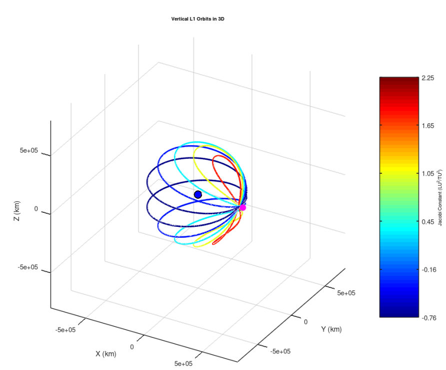

Fig. 12. L_1 Vertical Orbits

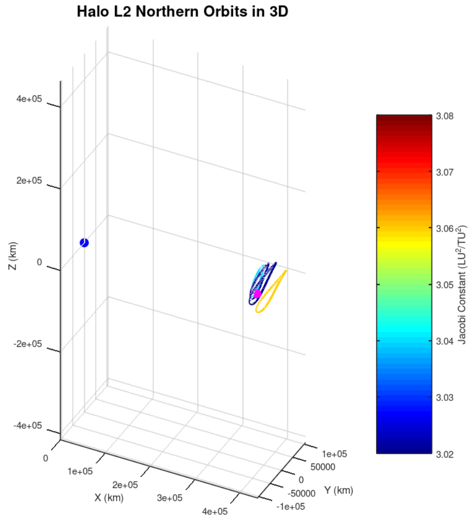

Fig. 13. L_2 Northern Halo Orbits

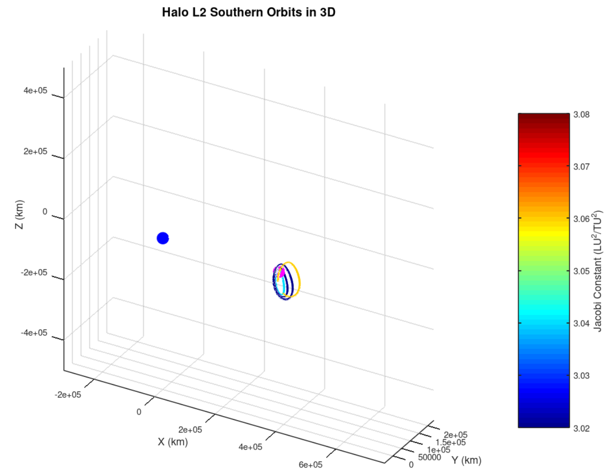

Fig. 14. L_2 Southern Halo Orbits

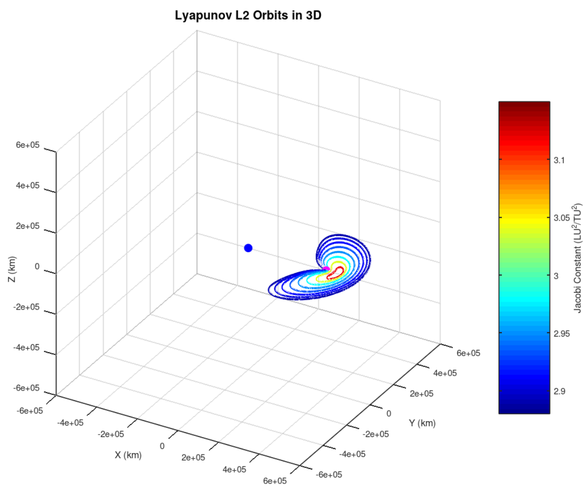

Fig. 15. L_2 Lyapunov Orbits

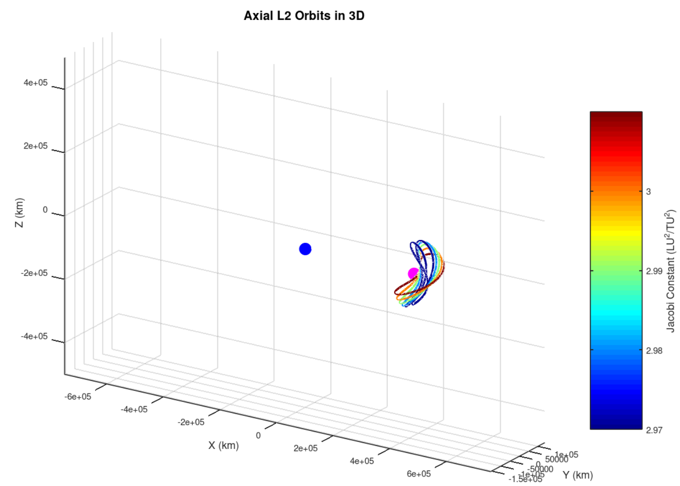

Fig. 16. L_2 Axial Orbits

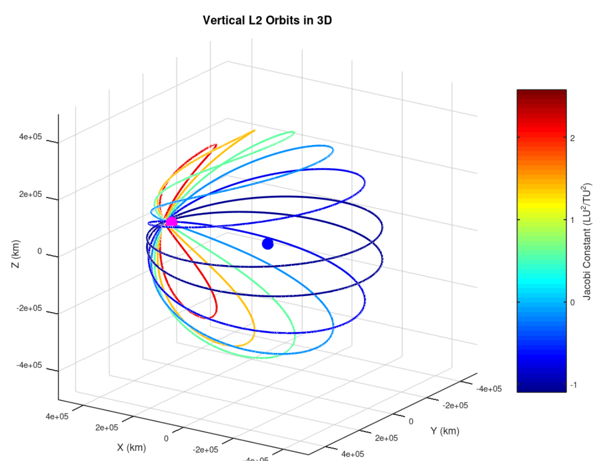

Fig. 17. L_2 Vertical Orbits

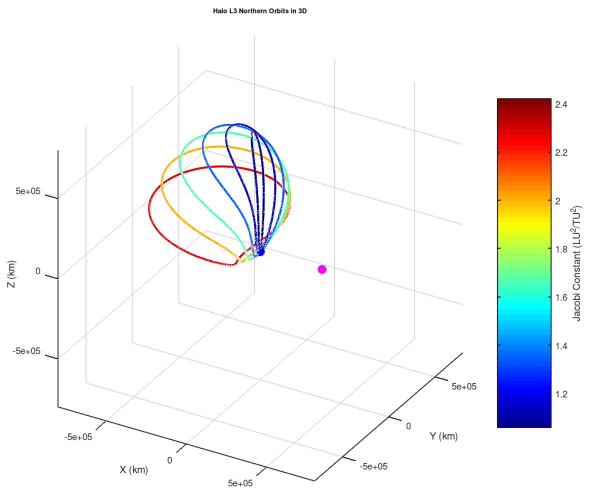

Fig. 18. L_3 Northern Halo Orbits

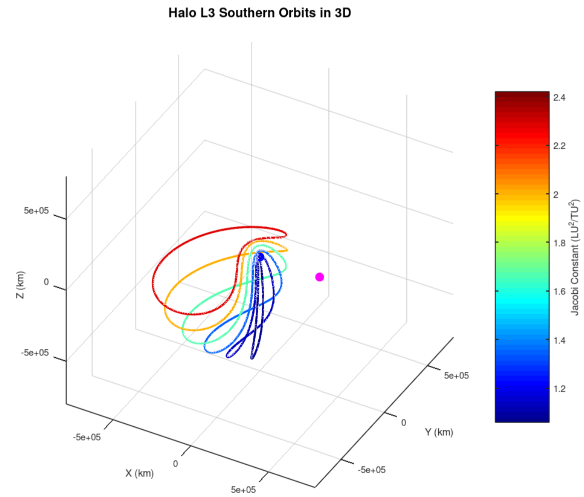

Fig. 19. L_3 Southern Halo Orbits

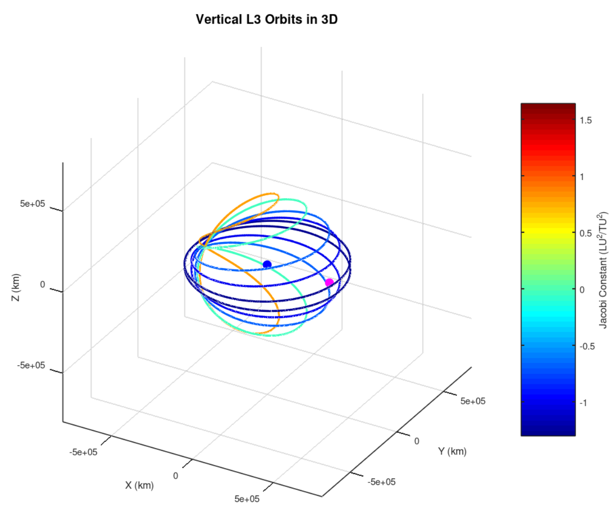

Fig. 20. L_3 Vertical Orbits

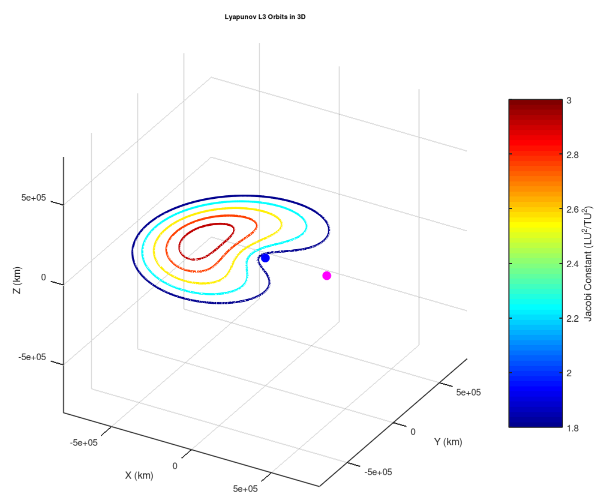

Fig. 21. L_3 Lyapunov Orbits

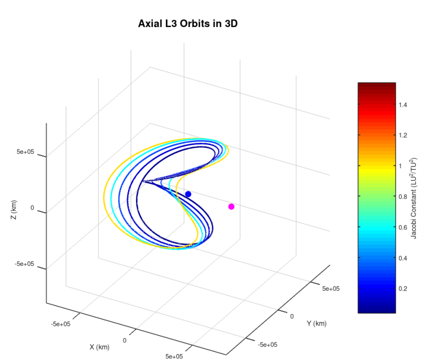

Fig. 22. L_3 Axial Orbits

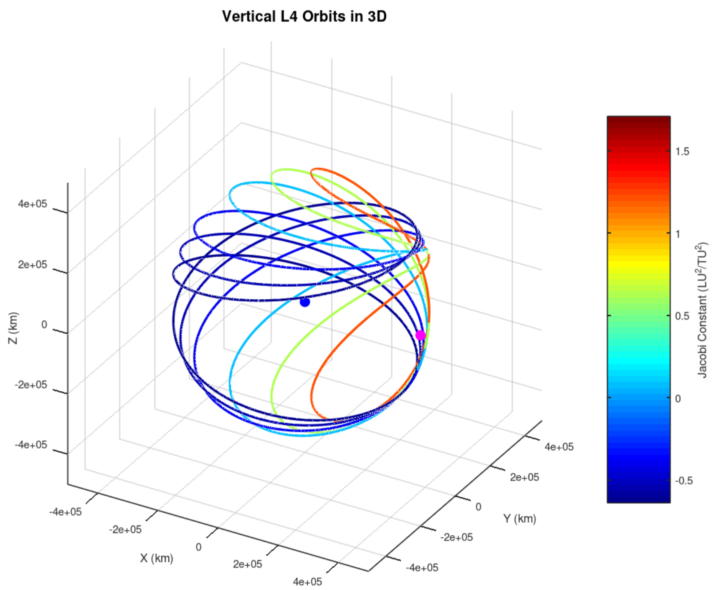

Fig. 23. L_4 Vertical Orbits

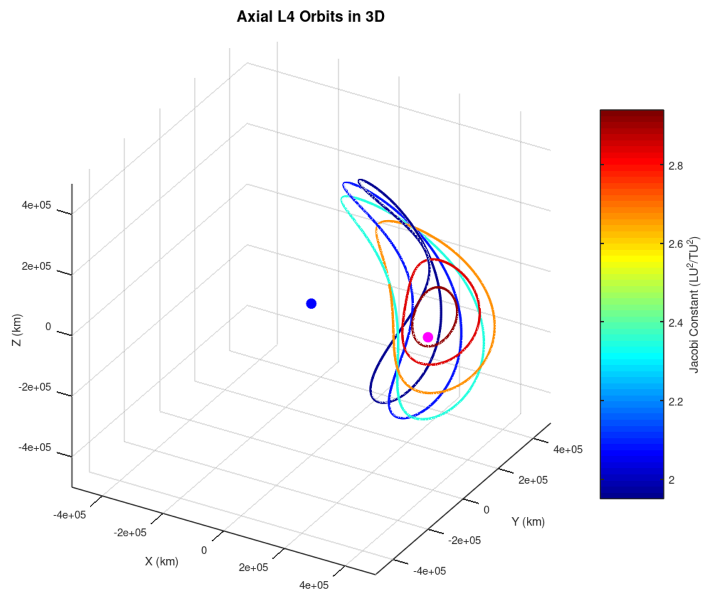

Fig. 24. L_4 Axial Orbits

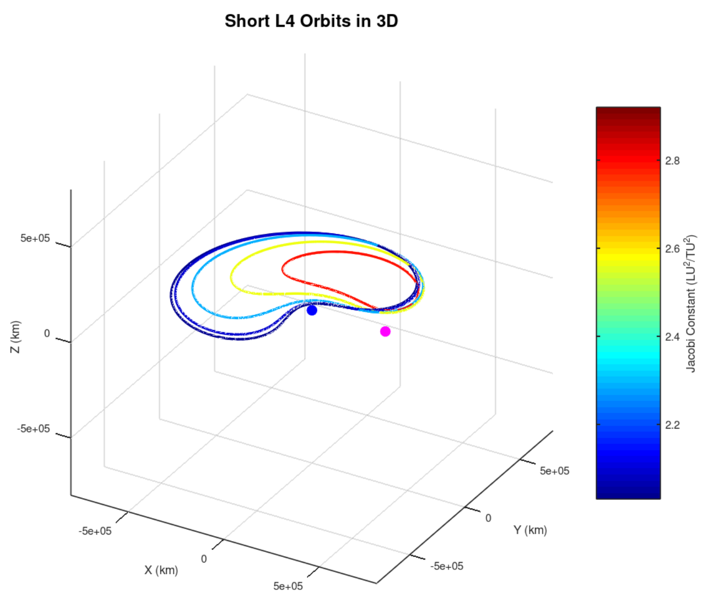

Fig. 25. L_4 Short Period Orbits

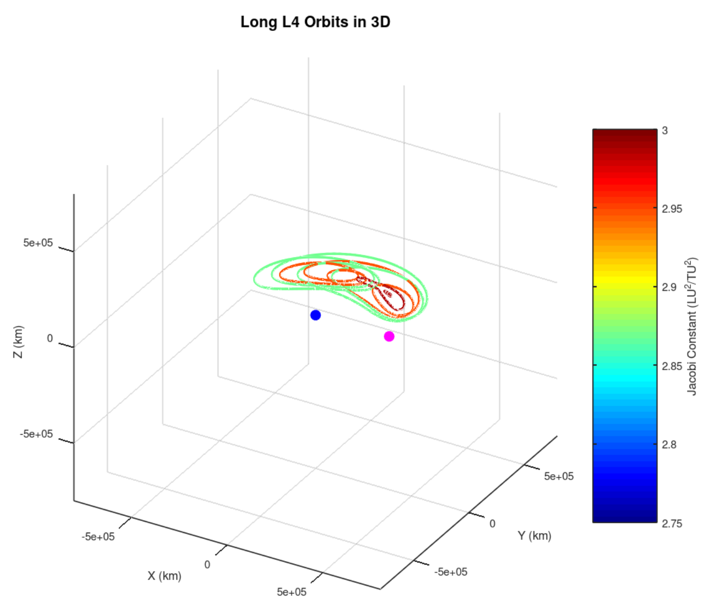

Fig. 26. L_4 Long Period Orbits

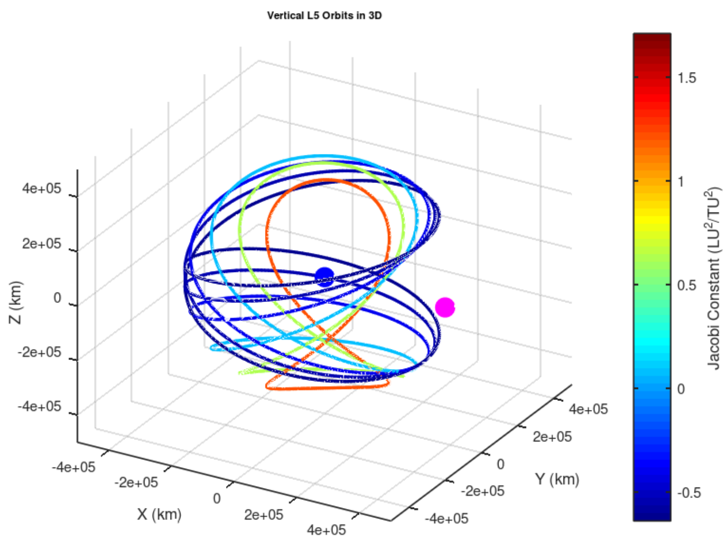

Fig. 27. L_5 Vertical Orbits

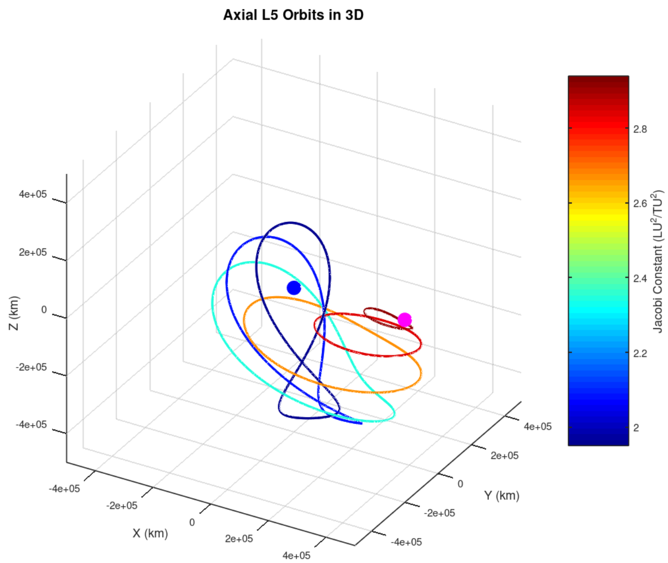

Fig. 28. L_5 Axial Orbits

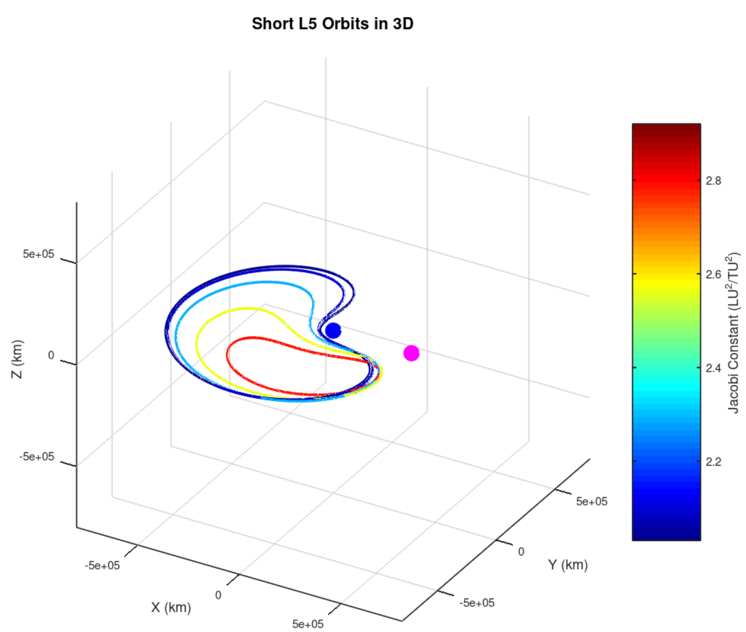

Fig. 29. L_5 Short Period Orbits

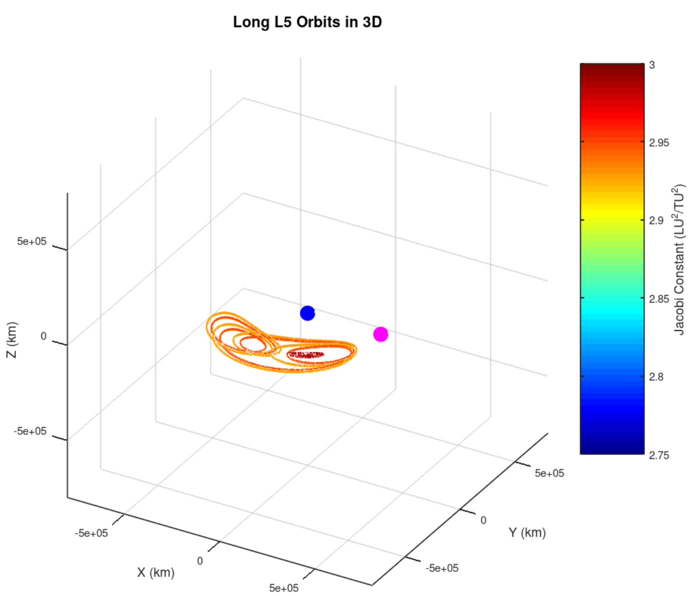

Fig. 30. L_5 Long Period Orbits

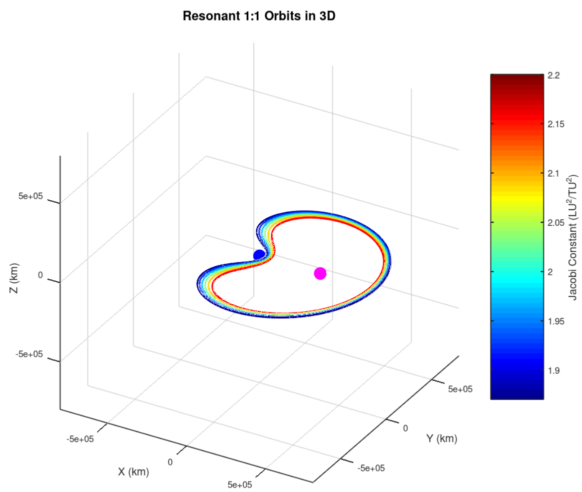

Fig. 31. 1:1 Resonant Orbits

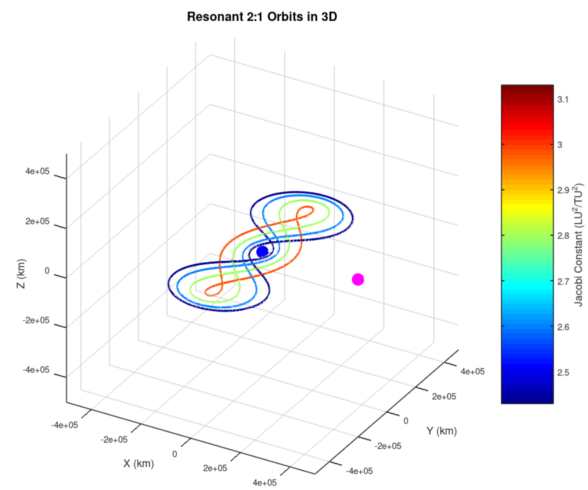

Fig. 32. 2:1 Resonant Orbits

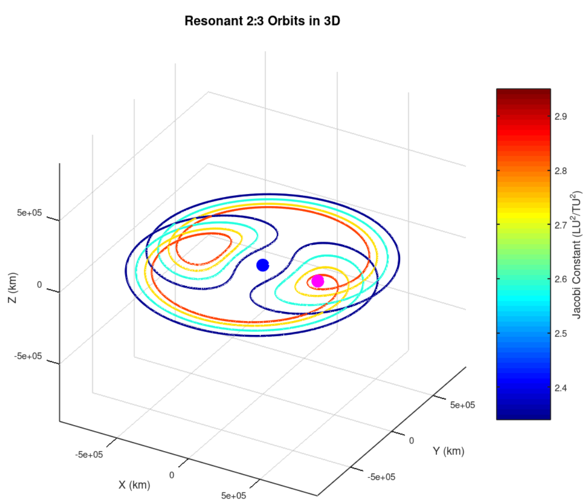

Fig. 33. 2:3 Resonant Orbits

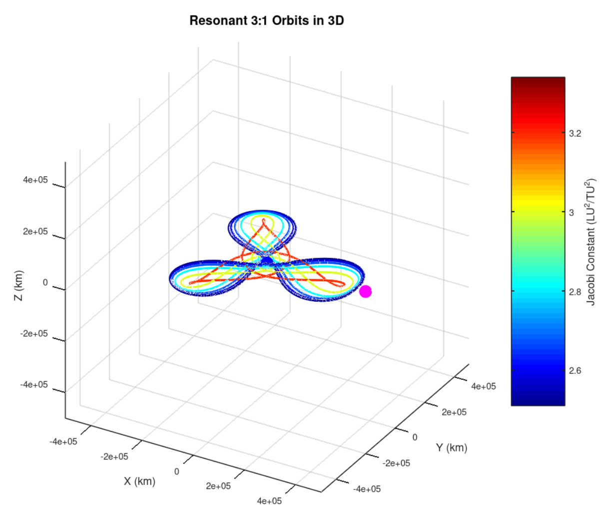

Fig. 34. 3:1 Resonant Orbits

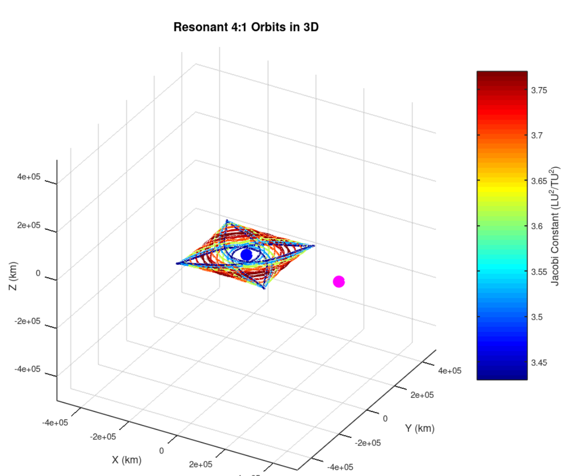

Fig. 35. 4:1 Resonant Orbits

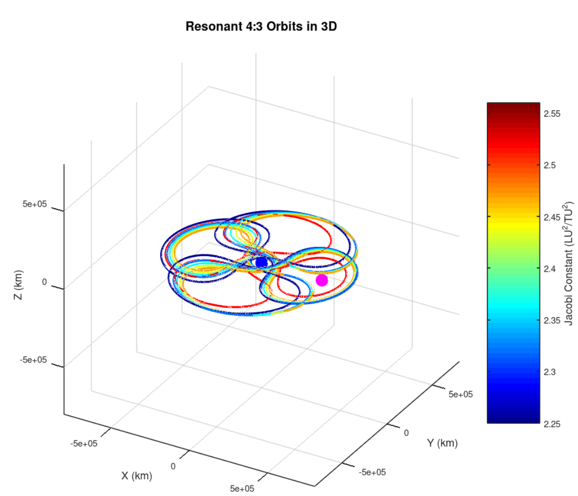

Fig. 36. 4:3 Resonant Orbits

The L_4 and L_5 Libration point orbits are the stable points. The types of orbits in this region vary from that of the collinear point orbits. They include:

1. Vertical Orbits
2. Axial Orbits
3. Short Period Orbits
4. Long Period Orbits

As L_4 and L_5 Libration point orbits are the most stable libration points in cislunar space they can be utilized by various space observatory missions as it does not have any interferences with earth's orbits, they are ideal locations in space for orbit parking and also makes them well-suited for communication satellites, particularly for regions with limited terrestrial coverage. due to their high stability.

3.2.4 Trans and Extra Lunar Zone Orbits

Trans and Extra Lunar Zone Orbits are located near the L_1 and L_2 Libration points. This region is widely utilised by various cislunar missions due to its proximity to the Moon.

1. Halo Orbits
2. Lyapunov Orbits
3. Distant Prograde Orbits
4. Distant Retrograde Orbits
5. Vertical Orbits
6. Axial Orbits

Trans and Extra Lunar Zone Orbits are among the most frequently used cislunar orbits due to their proximity to the Moon. These orbits are critical for many lunar missions, such as the Lunar Gateway and the Lunar Constellation for communication satellites. Even the Apollo 11 mission utilised this zone. Additionally, these orbits can be employed for orbital transfers and manned missions, as they offer low radiation levels. They are also ideal for lunar exploration and observation missions.

3.3 Cislunar Surveillance Orbits

Surveillance in the cislunar space is necessary to:

1. Prevent collisions between spacecraft
2. Manage traffic flow

A surveillance system may be placed in a resonant orbit in the cislunar space. Resonant orbits are those whose orbital period is a fraction of that of the Moon's orbital period. For instance, a p:q mean motion resonance with the moon means that the spacecraft makes p revolutions around the Earth in the same time the Moon makes q revolutions around the Earth. It may be expressed as:

$$\frac{p}{q} = \frac{\frac{1}{T_p}}{\frac{1}{T_q}} = \frac{T_q}{T_p} \tag{15}$$

Resonant orbits are a better choice for surveillance orbits because they can cover a broader area swept by unique orbital geometries as seen earlier.

The following resonant orbital families exist:

1. 1:1, 1:2, 1:3, 1:4
2. 2:1, 2:3
3. 3:1, 3:2, 3:4
4. 4:1, 4:3

4. Traffic Management System

Having studied the different operational zones, it is now paramount to understand how to set up a traffic management system in space.

The basic objectives of such systems include:

1. Minimising risk of damage during operations
2. Minimise any sort of interference, either electromagnetic or optical
3. Optimising operations
4. Generate alerts related to space weather events
5. Protection of all equipment in the region.

4.1 Steps to Create a Traffic Management System

Steps to create a traffic management system include:

1. Selecting an appropriate surveillance orbit. This step is important because a good orbit can ensure maximum coverage. As studied in the previous section, resonant orbits provide the optimal coverage of the cislunar space.
2. Design of a constellation of surveillance spacecraft. Despite the periodic nature of resonant orbits, they may be unable to survey the entire region at the same time. A formation of multiple satellites may be beneficial to sweep the entire region at the same time.
3. Data fusion. Data obtained from the constellation may be fused together to create a real-time map of the cislunar space. This map may be used for initial orbit determination.
4. Creation of a Centralised Database. This database can be used to store the real-time state vectors of all spacecraft in cislunar space. As explored in earlier sections, the dynamics of a body in the three-body system is unpredictable without the initial conditions. This database can be used to keep track of the orbits of all bodies, and hence can also be used to determine real time events such as conjunction analysis, space weather or debris related events.
5. Establishing Communication Protocols for Cooperation. Since there exist several space agencies and corporations looking to make gains from the cislunar space, it is necessary to ensure that well defined standards and protocols are set in place for operations. International agreements, safety standards and a regulatory framework are necessary to ensure

safe and coordinated operations as in the case of air traffic. A central authority analogous to the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO) must be established to create the necessary regulations, standards and protocols. These bodies have been responsible for making regulations related to air traffic on earth.

6. Development of Decision Support Systems. Modern tools must be developed to simulate various scenarios and assess potential risks. The entire process may also be automated using algorithms, simplifying the process while also making informed choices regarding operations.

4.2 Services

The model proposed by Cukurtepe et. at. (2009) [5] consists of services and an executive committee with subcommittees for legal consultancy, international coordination, and observation. The executive committee is tasked with the administration of the traffic management system. They are responsible for introduction of safety regulations, protocols, definition of SoPs, and many more functions. Services, however, build up the basic building blocks of the system. There are various types of services that may be implemented in this model as listed below:

1. Monitoring and Tracking services.
2. Data Management services. This service is responsible for maintenance of the data collected from the surveillance systems to create the earlier mentioned real-time map of the region. They are also responsible for maintaining four main databases, which include
    a. RF Database. This is a database of all communication between ground and the spacecraft, and also between multiple spacecraft.
    b. Spacecraft Database. This database lists out all spacecraft in the cislunar region.
    c. Space Weather Database. This database provides real-time data on space weather related events such as Coronal Mass Ejections (CMEs), solar storms, and so on.
    d. Space Debris Database. This database keeps track of all inactive spacecraft and other smaller debris which may pose challenges to operations of spacecraft.
3. Operations services. This service is a consultant service to help clients with the following.
    a. Launch phase. The service determines necessary launch windows and the availability of orbits during this phase. It lists out specific time intervals suitable for the launch while also ensuring that there is sufficient clearance from other spacecraft in the region.
    b. Operations phase. The service coordinates with the other operators to ensure that the spacecraft operations proceed seamlessly. They keep track of potential conjunctions with other spacecraft, and electromagnetic and optical interferences. They also help with planning mission manoeuvres and collision avoidance manoeuvres.
4. Warning services. They warn operators about predicted conjunctions or interferences.
5. Conflict Management services. This service deals more with the legal authorities.

4.3 Cis-Lunar Disposal of Debris for Traffic Management

Cis-Lunar missions have additional challenges due to the presence of debris in orbit. Despite the absence of spacecraft debris clouds in the Cis-Lunar regime, spacecrafts may still face threats from natural and artificial debris.

The Kordylewski clouds, consisting of micrometeoroids and natural debris, exist between the Earth and Moon at L4 and L5. The stability of the L4 and L5 points make it an ideal location for scientific research, long-duration human crews, and Space Situational Awareness (SDA) missions. The L4 and L5 points have modest stationkeeping requirements, making them suitable for Positioning, Navigation, and Timing (PNT) systems and alternate options for geospatial applications [7].

An examination of debris in 5 Cis-Lunar periodic orbits revealed little collision risk, perhaps due to the broad operational zone [8]. Lunar orbits pose a larger risk of manmade debris. A 30-day simulation of a spacecraft battery explosion in polar lunar orbit showed a greatly increased danger of collision. The study found that a spacecraft in a circular 100-km polar lunar orbit has a hazard probability of $1.472 \times 10{-}3\%$ during a one-month period. This hazard can continue for a long time, posing a risk to both orbital and surface missions [9].

Missions in the Cis-Lunar domain include spacecraft crossing numerous orbital regimes to reach their final orbit. Spacecraft go from LEO to MEO, GEO, and beyond. The end-of-life protocol for each spacecraft is unique to its mission and orbital parameters. The following scenarios will be crucial in mitigating the debris scenario in cis-lunar space:

1. Graveyard Orbit Disposal

A graveyard orbit, also known as a disposal orbit or garbage orbit is a space zone used to securely "retire" defunct or end-of-life spacecraft, keeping them out of active orbital regions to avoid collisions or interference with working satellites.
Heliocentric disposal is the technique of launching a dead spacecraft or satellite into an orbit around the Sun, essentially removing it from Earth's orbital environment and preventing it from becoming space trash. This technology is commonly employed for satellites or probes in high-energy orbits. Heliocentric disposal requires that the spacecraft is not within the radius of the L1 point. A successful escape trajectory is one that lasts more than 365 days and does not return to Earth. To avoid a 1:1 resonance with Earth's orbit, satellites must use more delta-v to adjust the spacecraft's orbital energy through secondary burns [7].

2. Lunar impact disposal
Lunar impact disposal refers to intentionally crashing a defunct spacecraft or satellite onto the surface of the Moon, which was the oldest and most convenient approach for ending Lunar missions.
To dispose of a spacecraft on the lunar surface, the "United Nations Treaties and Principles on Outer Space, UNOOSA, 2002" and "NASA's Recommendation to Space Fairing Entities" guidelines are to be complied. These standards aim to save old hardware, experiments, artificial impact sites, and historical evidence, including astronaut footprints and rovers [7].
3. On-orbit satellite servicing
On-orbit satellite servicing entails executing maintenance, repair, refuelling, or upgrade operations on spacecraft orbiting. This proposal applies the concept of on-orbit servicing, which has previously been used in low Earth orbit (LEO), to a bigger and more remote realm of cislunar space. As human and robotic missions venture to the Moon and beyond, the capacity to service and maintain satellites in this region will become increasingly critical for maintaining long-duration missions and enabling a more resilient space infrastructure.

5. Discussion

In this study, we have explored various families of orbits and examined their characteristics across different regions of cislunar space. Our analysis begins with an overview of the dynamical model, specifically the three-body problem, and the associated families of orbits, as discussed in Section 2. In Section 3, we delve deeper into the specific orbital families and their respective regions within cislunar space, providing a comprehensive understanding of their behavior and dynamics.

A key focus of our research has been to highlight the significance of space traffic management (STM) in the context of both current and future space missions. As human activity in cislunar space increases, effective STM will be critical for ensuring the safety and success of operations. We discuss how the growing complexity of space missions necessitates a more sophisticated approach to managing orbital paths, reducing the risk of collisions, and optimising mission planning.

Furthermore, we emphasise the practical implications of our study for future space missions. By analysing and categorising orbital families in cislunar space, our research provides valuable insights that could enhance mission efficiency, safety, and cost-effectiveness. This knowledge is particularly relevant as space agencies and private entities alike plan to expand their operations beyond low Earth orbit, with cislunar space becoming a key focus for exploration, satellite deployment, and other activities.

Overall, this study contributes to the broader understanding of orbital mechanics in the Cislunar region and offers critical insights into how space traffic management will play an increasingly vital role in the future of space exploration. Our findings lay the groundwork for more successful and sustainable space missions, making space traffic management an integral component of mission design and execution.

6. Conclusions

Cis-lunar space is soon to be a busy part of space with space programs all over the world targeting lunar exploration. The spotlight is back on the moon with projects such as NASA's Lunar Gateway and Artemis programs. This increase in activity will require developing a sustainable space traffic management system.

In this paper, we have explored the necessity behind implementing space traffic management (STM), particularly within the context of the Cislunar region. We have identified how these orbits can be strategically utilized for future space missions by examining and comparing the characteristics of different orbital families. The intricate dynamics of the cislunar environment, governed by the complexities of the three-body problem, pose substantial challenges to spacecraft navigation and trajectory prediction. To address these challenges, we proposed a classification of cislunar space into distinct operational zones, each characterised by specific orbital attributes. This classification serves as a fundamental framework for managing space traffic in this region. Furthermore, we emphasised the need for a centralised database, standardised communication protocols, and decision support systems to facilitate the coordination and management of spacecraft operations in cislunar space.

Mitigating the issue of space debris is also paramount to ensuring the long-term sustainability of the Cislunar environment. We discussed key debris mitigation strategies, such as the use of graveyard orbits, heliocentric disposal, and on-orbit servicing, all of which are essential to preserving the safety and accessibility of this region. Additionally, we underscored the importance of international collaboration and establishing regulatory frameworks, given the global implications of cislunar space traffic management (CSTM). This Paper underscores the critical importance of CSTM as a cornerstone for the future of space exploration. By proactively addressing the challenges associated with cislunar space and implementing robust management solutions, this region has the potential to evolve into a sustainable and thriving hub for both human activity and scientific discovery.

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