# A Primer on Cislunar Space

M. J. Holzinger[1], C. C. Chow[2], P. Garretson[3]

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[1] Associate Professor, H. J. Smead Faculty Fellow, Ann & H. J. Smead Aerospace Engineering Sciences Department, University of Colorado Boulder

[2] Founder & CEO, Cloudstone Innovations LLC

[3] Space Vehicles Directorate, Air Force Research Laboratory, USSF

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# 1 Introduction

## 1.1 Purpose

This primer aims to familiarize the reader with "cislunar[4] space." It is targeted at military space professionals who will answer the call to develop plans, capabilities, expertise, and operational concepts. Cislunar space has recently become prominent in the space community and warrants attention, as reflected in the recent Memorandum of Understanding (MOU) between the National Aeronautics and Space Administration and the United States Space Force states:

> When established in December 2019, USSF was tasked with defending and protecting U.S. interests in space. *Until now, the limits of that mission have been in near Earth, out to approximately geostationary range* (22,236 miles). *With new U.S. public and private sector operations extending into cislunar space, the reach of USSF's sphere of interest will extend to 272,000 miles and beyond - more than a tenfold increase in range and 1,000-fold expansion in service volume. USSF now has an even greater surveillance task for space domain awareness (SDA) in that region*, but its current capabilities and architecture are limited by technologies and an architecture designed for a legacy mission… As NASA's human presence extends beyond ISS to the lunar surface, cislunar, and interplanetary destinations, and *as USSF organizes, trains, and equips to provide the resources necessary to protect and defend vital U.S. interests in and beyond Earth-orbit*, new collaborations will be key to operating safely and securely on these distant frontiers. [emphasis added] [1]

This MOU reflects the increasing importance of cislunar space, as articulated in national level guidance, including the National Space Council's *A New Era for Deep Space Exploration and Development* [2], the *Future of Space 2060 & Implications for U.S. Strategy* [3], *State of the Space Industrial Base 2020* [4], and *Spacepower: Doctrine for Space Forces* [5]. To realize the ambitious roles and missions outlined in *Spacepower*, the activities articulated in *A New Era for Deep Space Exploration and Development*[5], and the NASA-USSF MOU,[6] a better understanding of this complex domain is required.

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[4] Spelling variation: Cislunar or Cis-lunar. Capitalization is used here for emphasis only; it is not a proper noun.

[5] "This vision begins with a *campaign to utilize Earth's orbital environment, the surface of the Moon, and cislunar space* to develop the critical technologies, operational capabilities, and *commercial space economy necessary for a sustainable human presence on the Moon, Mars, and beyond*…The United States Space Force (USSF) does not have a direct role in the civil exploration and development of space per se – its responsibilities focus on organizing, training, and equipping the forces needed to support combatant commands and *ensure unfettered access to and the use of space by the United States and its allies and partners*. However, *activities such as space transportation and logistics, power, communication, navigation, and space domain awareness, are of dual-use value to all space sectors* – civil, national security, and commercial."

[6] The MOU lays out an ambitious list of areas for U.S. Space Force cooperation: Deep space survey and tracking technologies to support extended *SDA and NEO detection beyond geosynchronous orbit*; Capabilities and practices enabling *safe, sustained near-Earth and cislunar operations such as communications; navigation; space structure servicing, assembly, and manufacturing*; and interoperability among those capabilities to *support resilience for functions in this remote region*; *Search, rescue, and recovery operations for human spaceflight*; *Space logistical supply* and support; *Ride shares and hosted payloads beyond Earth orbit*; Establishing standards and best practices for safely operating in space, to include conjunction assessment, space situational awareness sharing, orbital debris

In this article, we build a fundamental understanding of this complicated environment and provide foundational terminology. The article aims to provide an overview for educational purposes and is not intended to be an exhaustive literature study; some omissions are made in the interest of brevity and clarity.

### 1.2 Scope

This article describes cislunar space and provides speculative insights to assist forward progress for operations within cislunar space. Specifically, we include an overview of the dynamics, list challenges in observation, and highlight nuances in spacecraft operations.

## 2 Overview of the Dynamics

### 2.1 A matter of scale – distances and time

The volume of space influenced by the Earth and/or Moon, here called cislunar space, is vast. Our usual yardstick for distance, the geosynchronous orbit radius (from the center of the Earth, 42,164 km = 1 GEO), is a small fraction of the distance between the Earth and Moon (384,402 km = 1 LD = 9.12 GEO, on average). With the region about the Moon being 9 times more distant than GEO and repeating orbit periods on the order of weeks or months, our intuition and sense of distance and time must adapt. However, we must further expand the volume of space we consider when discussing cislunar topics. Some transfers between Earth and cislunar space extend well beyond the Moon, to distances in excess of 1.5M km (35 GEO; GRAIL[7], THEMIS/ARTEMIS[8]) in their multi-year transfer trajectories.

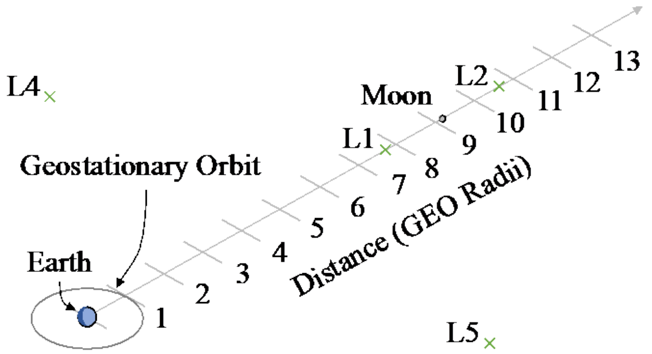

*Figure 1. Spatial scale in cislunar space.*

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mitigation, and space systems protection; Interoperable spacecraft communications networks for Earth orbit and beyond; Fundamental scientific research and technology development cooperation; Developing and sharing a talent pool of premier space professionals and expertise, and an open call to investigate opportunities for potential collaboration in these and other areas of mutual interest.

[7] https://www.nasa.gov/mission_pages/grail/main/index.html

[8] https://www.nasa.gov/themis-and-artemis

Figure 1 helps to visualize these differences in scale. While these measures are in terms of linear distance, it is important that we recognize that cislunar space is a 3-dimensional volume that dwarfs the volume of space encompassed by GEO. Even if we only consider the volume of space out to 12 GEO (just beyond L2, which is insufficient – see §4.3), cislunar space is 1,728 times larger than the volume of space within 1 GEO.

## 2.2 How are trajectories different from classical motion?

When we are first taught orbital mechanics (a.k.a., astrodynamics) we make three key assumptions: 1) there are two 'bodies' (i.e., the Earth and a spacecraft), 2) the mass of the spacecraft is so small relative to Earth that it can be safely ignored, and 3) both the Earth and the spacecraft can be treated as point masses. We call a system satisfying these assumptions a Keplerian (i.e., 2-body or classical) system [6]. These assumptions lead to four different types of trajectories: circular, elliptical, parabolic, and hyperbolic. In fact, the geometric shape and orientation of each of these trajectories is encoded in the classical orbital elements: semi-major axis, eccentricity, inclination, right ascension of the ascending node (RAAN), argument of periapsis, and the true anomaly. These classical orbital elements have well known transformations to and from position and velocity vectors.

For good reason these classical orbital elements have been used as the basis for Two-Line Elements (TLEs) for decades, which we use to share locations of objects in their orbits. Of course, there are propagation approaches that can handle minor deviations from Keplerian motion, even allowing for more general perturbations (e.g., lunar, solar, non-spherical, atmospheric) that produce accurate future state predictions [7]. These approaches, however, begin to degrade or even fail if the three assumptions of Keplerian motion are heavily violated. The boundaries in which these assumptions are valid are defined by the intended application – no single rule applies. However, the common theme is that differences between nearly Keplerian and highly perturbed trajectories will diverge over time, causing the intended application of any analysis to dominate only the timeframe over which such approximations are sufficient.

To understand how trajectories[9] evolve when we add gravitational effects from the Moon to our system, we must violate the key assumption of Keplerian motion – there are now three bodies. The most striking difference between Keplerian motion and 3-body problem (3BP) is that nearly all of our cherished, intuition-building notions are null and void. In particular, the following differences between the 2BP and the 3BP are critical to internalize:

- Trajectories are no longer circular, elliptical, etc. While in some cases they may bear superficial resemblance, only very special trajectories (see §2.6) repeat; most don't repeat.
- Trajectories are no longer planar. Outside of special cases, there is no fixed orbit plane.
- Trajectories are no longer easy to geometrically describe. Because they are no longer planar and don't have easy to define shapes like circles and ellipses; 3BP trajectories are not described using these tools.

We also face basic challenges in visualizing how trajectories in the 3BP evolve over time. There are two main options: 1) we visualize 3BP trajectories in the inertial frame (a non-rotating,

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[9] Orbits are a special subset of trajectories that repeat in the inertial from or a rotating frame, such as the rotating frame in the CR3BP.

non-accelerating origin and coordinates, as we currently do for Earth-centered orbits), or 2) we construct a rotating (non-inertial) frame that moves with the Earth and Moon as they rotate about one another (similar to ground tracks).

The most common visualization leverages simplified 3BP dynamics in a rotating frame and is called the Circular Restricted 3-Body Problem (CR3BP). The CR3BP system makes several assumptions of its own: 1) there are three bodies, 2) the mass of the spacecraft is small relative to the other two bodies, 3) the Earth, Moon, and spacecraft are point masses, and 4) the Earth and Moon orbit about their common center of mass in a perfect, planar circle with a constant angular rate [6]. Figure 2 shows the rotating frame fixed to the common center of mass, with the *x-axis* lying on the line connecting the Earth and Moon, the *z-axis* being perpendicular to the Earth and Moon's mutual orbit plane (parallel to the joint angular momentum of the Earth and Moon), and the *y-axis* being perpendicular to both the *x-* and *z-axes*.

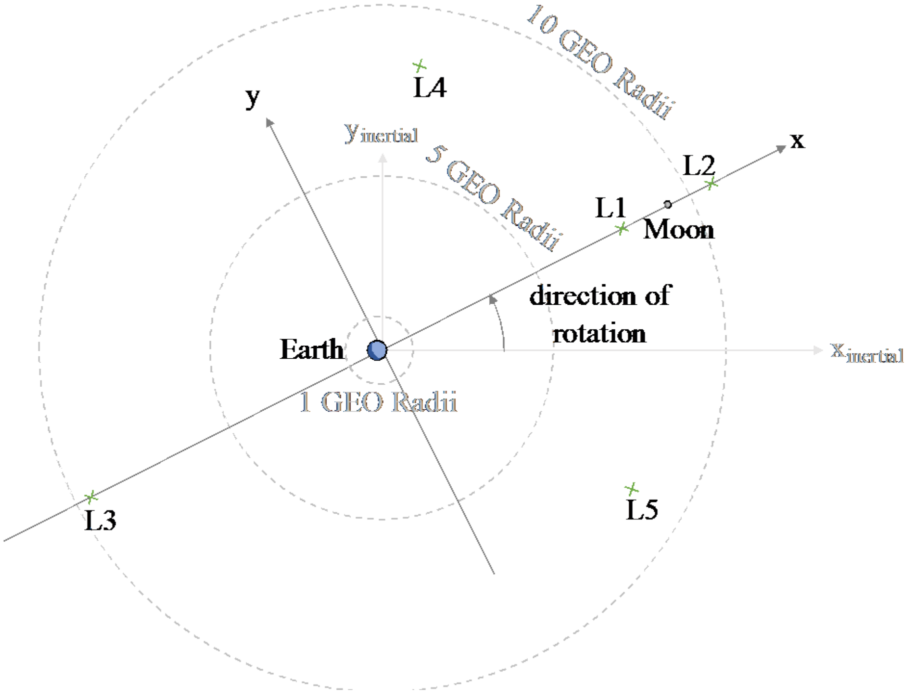

*Figure 2. Geometric and coordinate representation for the CR3BP. The z-axis is up and out of the page.*

Astute readers will note that the Moon's orbit about Earth is not strictly circular and neither the Earth nor the Moon can actually be treated as point masses. While the CR3BP system and corresponding visualization does not exactly match reality (much like Keplerian systems), it is close enough to reality to allow us to build geometric intuition regarding motion in the 3BP.

## 2.3 TLEs are no longer useful

Today's operational Space Domain Awareness (SDA) and trajectory planning systems are optimized for conditions where Keplerian assumptions hold – GEO and below – and so are designed to use TLEs.

Hopefully at this point we all agree that when orbits are far enough from the Earth to be influenced substantially by the Moon, classical orbital elements and by extension, TLEs, do not help us describe trajectories. In these regimes it is best practice to numerically propagate trajectories in an inertial frame and to visualize these trajectories in inertial and/or rotating frames. While we *can* convert a position and velocity vector at some time (epoch) to an instantaneous classical orbital element set, that *pseudo-TLE will only be accurate for a very short period of time before another conversion must be made*. Another principal problem with TLEs is that they lack the numerical precision to accurately transform to position and velocity vectors and propagate with any accuracy in cislunar space (see §2.7). Consequently, we must understand that TLEs are not a useful mechanism to keep catalogs, share trajectories, or task sensors in cislunar space.

Because of these differences between 2BP and 3BP, when sharing trajectories, it is best practice to share instantaneous position and velocity vectors in an agreed-upon inertial frame at some known time (i.e., epoch), rather than TLEs or orbital elements.

## 2.4 Special locations in the Earth/Moon and Sun/Earth systems

The CR3BP gives us a system that we can analyze for special properties. When talking about trajectories, a very special kind of trajectory is one that is *stationary in the rotating frame*. These points are special because, in the CR3BP, if an object is placed exactly at one of these points, it will remain there indefinitely. Joseph-Louis Lagrange was the first individual to recognize and study these special points, which is why we call them Lagrange points [8]. There are five such equilibrium points (L1, L2, L3, L4, and L5) with locations identified in Figure 2. It should be noted that such orbits are not stationary in the inertial frame – they are only stationary in the relative geometry between the Earth and Moon. In the inertial frame they rotate at the same rate as the Earth and Moon, tracing out circular orbits about the Earth-Moon common center of mass.

The Lagrange points L1 and L2 are in the immediate vicinity of the Moon, and as such have received significant attention in 3BP and CR3BP literature[10].

## 2.5 Zones in the Earth/Moon and Sun/Earth systems

In our discussion of cislunar space, we have introduced the idea that the volume of space under consideration is very large, however we have not yet formally defined different regions or zones. A commonly used approach to defining zones is by which body (or bodies) are principally affecting a given point in space. Naturally, objects close to Earth are principally affected by Earth's gravity and can view the gravitational effects of other bodies (solar, lunar) as distant perturbations. In fact, this very idea is the basis of the concept of 'spheres of influence.' This Earth-centered neighborhood is where SDA activities have largely focused in the past. Studies [9] have categorized different zones of cislunar space in just this manner – according to which bodies (Sun, Earth, Moon) dominate the dynamics in a particular region. These partitions also have a loose relationship to orbit energy in the CR3BP, called the Jacobi Constant (which accounts for the centrifugal potential, gravitational potential, and kinetic energies in the rotating reference frame).

Figure 3 shows how such zones may be divided. There is a region immediately about the Earth, a region dominated by both the Earth and Moon, as well as a region governed by the Earth, Sun, and Moon, amongst several others. It should be emphasized that this description of regions in cislunar space is really more to the benefit of discussion, intuition building, and some feature classification applications – actual propagations of objects should use detailed models including

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[10] There are more than a thousand papers published over the past 100 years relevant to the 3BP, CR3BP, etc.

each of these principal bodies. Further, as one approaches the Earth or the Moon, non-spherical gravity effects of those bodies should be modeled as well.

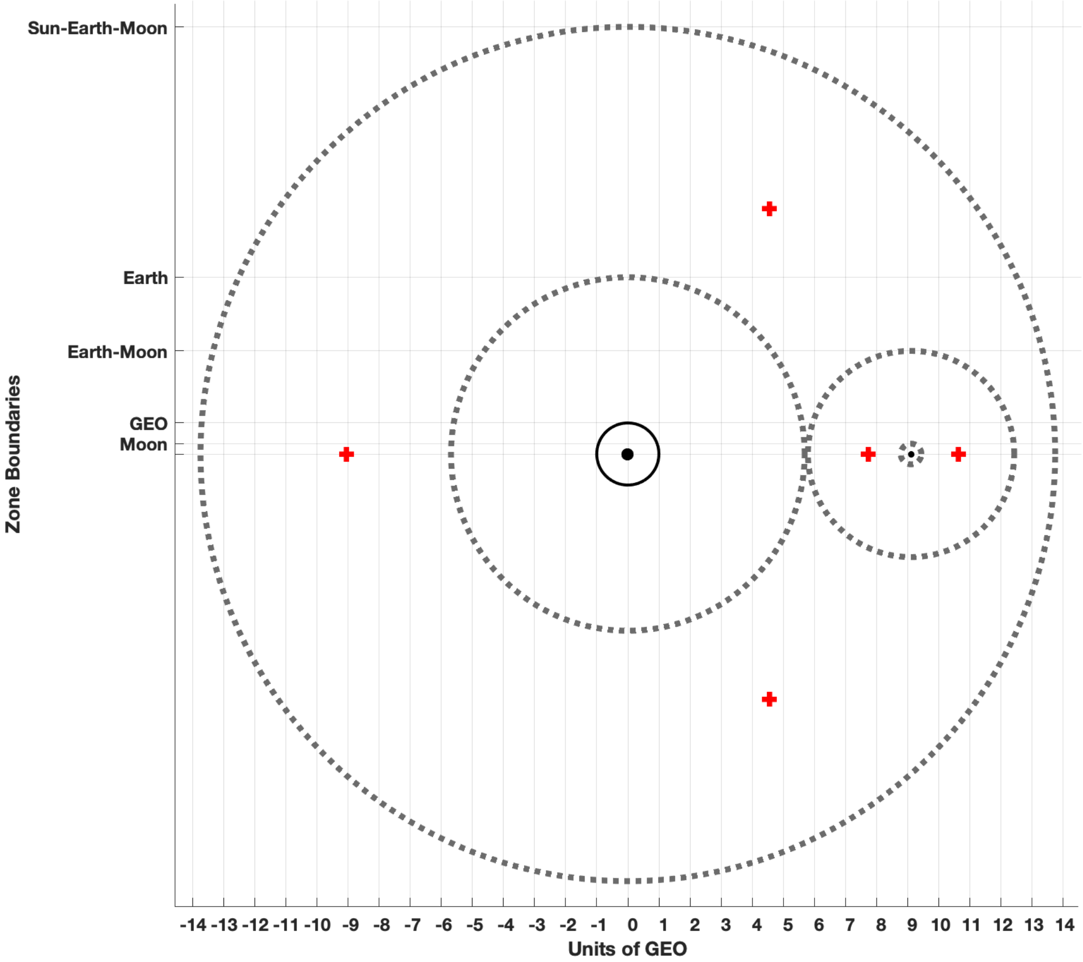
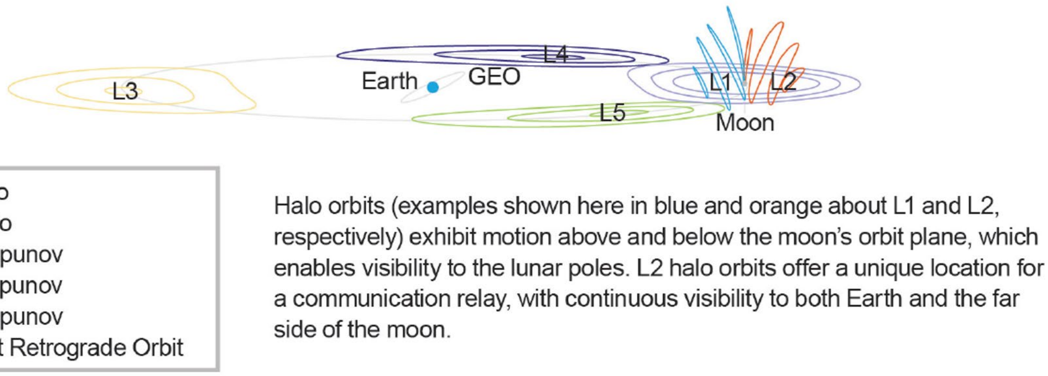


*Figure 3. 2D projection of 3D spherical Zones in the CR3BP, composing cislunar space. Earth is at the center, Moon is at about 9 GEO, and the Lagrange points are shown as red crosses. Everything outside of the Sun-Earth-Moon Zone is considered the Sun-Earth Zone.*

## 2.6 Repeating natural orbits

Lagrange points are not the only trajectories of interest in the CR3BP. There are a variety of trajectories in the vicinity of the Moon and Lagrange points that have a very special property: they repeat themselves in the rotating frame of the CR3BP. Orbits that repeat their trajectory within a fixed time period are called repeating natural orbits or sometimes simply periodic orbits and can have periods as short as a few days or in excess of one month. As a note, one could view the Lagrange points as repeating natural orbits for any time period we choose, since they're stationary.



Halo orbits (examples shown here in blue and orange about L1 and L2, respectively) exhibit motion above and below the moon's orbit plane, which enables visibility to the lunar poles. L2 halo orbits offer a unique location for a communication relay, with continuous visibility to both Earth and the far side of the moon.

*Figure 4. A sampling of repeating natural orbit families in the Earth-Moon system with GEO included for scale (courtesy of Aerospace Corporation).*

There are a wide variety of families of these orbits (e.g., L1/L2 Halo, L1/L2 Lyapunov, distant retrograde) [10], some of which are illustrated in Figure 4. Each of these families boasts a continuum of individual repeating natural orbits. Said differently, there are infinite repeating natural orbits, all grouped into sets of families. Further, for each individual repeating natural orbit in a family, there are infinite neighboring quasi-periodic orbits (QPOs) that have bounded motion (i.e., they stay within the neighborhood) but never exactly repeat their trajectories. Figure 5 visualizes a subset of these orbit families. Repeating natural orbits that take multiple revolutions before they repeat also exist [11][12]. We refer the reader to 3BP literature (e.g., [10][11]) for more exhaustive lists of possible families.

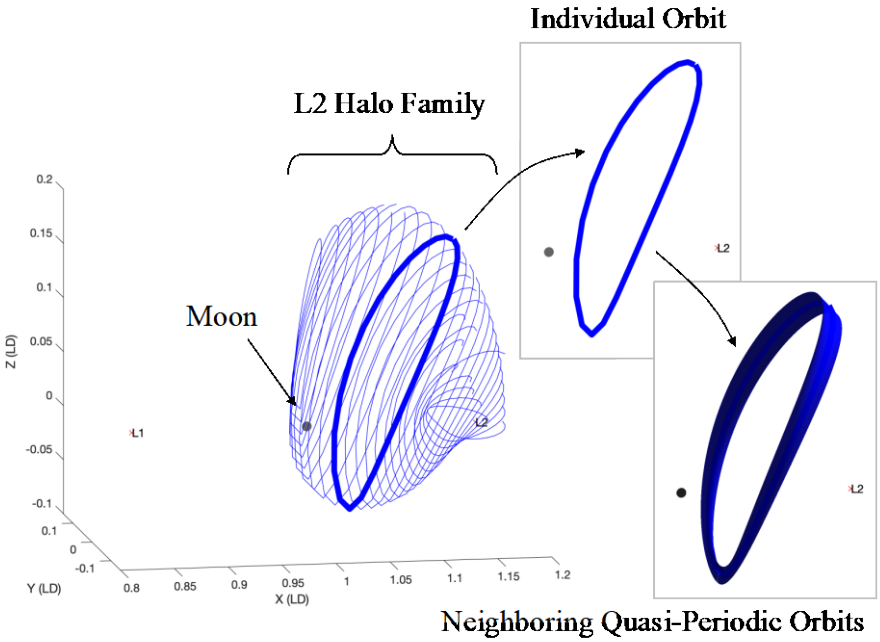


*Figure 5. Repeating natural orbit families and their relations to one another.*

Repeating natural orbits possess great utility in cislunar space. They are currently featured in NASA's Lunar Gateway design (an L2 northern near-rectilinear halo orbit – NRHO; also a member of the family shown in Figure 5) [13], orbiters to survey the Moon's polar ice caps [14], cislunar communications relay constellations [15], vehicle staging [16], as well as cislunar SDA studies [17][18]. Cycler and horseshoe orbits are also possible and have been proposed for supply and other missions (see Figure 6) [19]. It should be noted that, while we have focused on the Earth/Moon Lagrange points and repeating natural orbits, analogous Lagrange points exist for the Sun/Earth system, albeit greater distances from Earth than those in the Earth/Moon system.

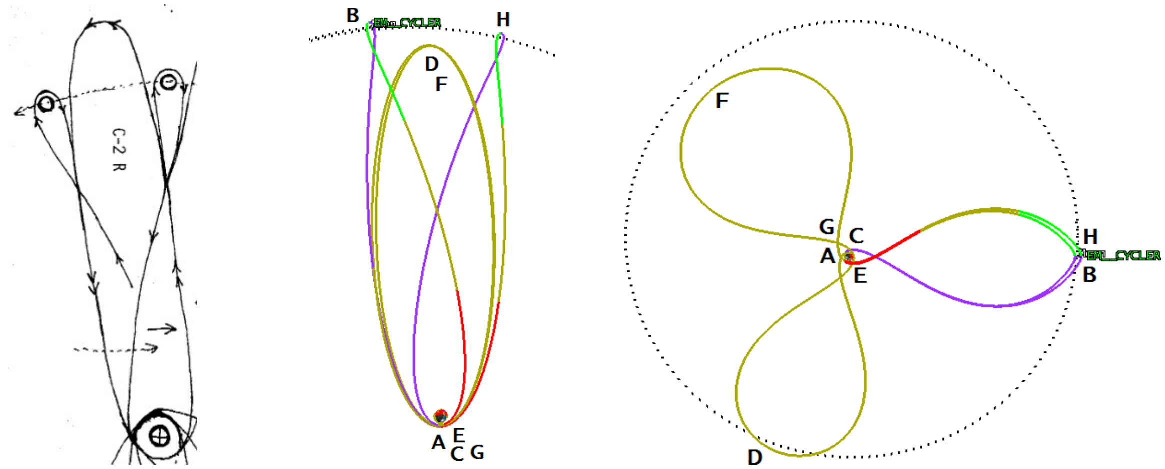


*Figure 6. Shamrock Earth-Moon Cycler Orbit shown in Earth inertial (left & center) and Earth- Moon rotating (right) frames. One complete cycle is shown, with two complete sub-lunar phasing orbits connecting consecutive free-return "figure-8" orbits. Aldrin's theorized cycler (C-2-R) is shown for a side-to-side comparison (left).*

## 2.7 Motion in the Earth/Moon and Sun/Earth Systems is unstable

It would be elegant if all the Lagrange points, repeating natural orbits, and quasi-periodic orbits were stable, i.e., an object placed in such a trajectory would stay there forever. Sadly, with few exceptions, L1, L2, L3, and most repeating natural trajectories and quasi-periodic orbits are unstable. In fact, astrodynamicists quantify differing levels of instability using a stability index, varying from 1 to arbitrarily high values [10]. A stability index value of 1 is the best we can hope for and indicates oscillatory motion about the repeating natural orbit. Stability index values above 1 mean the satellite will drift away from its repeating natural orbit exponentially; it may start out slow but can diverge quickly[11]. While this inherent instability is frustrating for keeping spacecraft in repeating natural orbits and often drives operational cadence and fuel costs (see §4.1), it can be useful for very low thrust transfers to other repeating natural trajectories (see §4.2, in particular Figure 12).

The lone exceptions to this rule in the Earth/Moon (and Earth/Sun) systems are small volumes of space about L4 and L5. Objects located in these very special areas are stable for long durations and are called Trojan objects [8]. In fact, in 2010 an asteroid was located in the Sun / Earth L4 region[12]. There are also dust clouds in these areas, however this dust is highly perturbed by solar radiation pressure (e.g., a non-gravitational force) and behaves somewhat differently. These objects are analogous to the Trojan asteroids in the L4 / L5 locations of the Sun / Jupiter system.

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[11] The stability index is a characteristic for each individual repeating natural trajectory. Initial divergence is exponential, followed by chaotic motion about the Earth-Moon system.

[12] https://www.nasa.gov/mission_pages/WISE/news/wise20110727.html

An outcome of this fundamental instability is that motion in cislunar space is highly chaotic. By chaotic, we mean that even the slightest deviation in the object's current position or velocity could cause very large differences in its future propagated position and velocity (a la, the cliché Butterfly Effect) [20]. This consequence is independent of any finite numerical precision, even if we had perfect state estimates with no uncertainty (which we do not). For non-maneuvering objects, once custody is lost, the object's trajectory can quickly diverge from its predicted path, often quite substantially. Over longer time scales all we can say about a lost object is that, because of conservation of energy, we can bound the possible regions of space of where the object might be. In fact, even around the Moon, only a few select orbits are stable [21].

### 2.8 Key takeaways

- The volume of space under consideration is huge and extends at least to ~2M km.
- Unless very close to Earth, trajectories are not circular, elliptical, or even planar.
- TLEs are not sufficient for identifying or sharing trajectory information; alternate representations will be used.
- Several special points in Earth/Moon and Sun/Earth systems are nearly stationary in those frames.
- There are several zones in the Earth/Moon and Sun/Earth systems that are summarily defined by what dominant force(s) are acting.
- Analogous to orbits near Earth, infinite 'closed' orbits exist, organized into families. Neighboring exotic quasi-periodic orbits and multi-revolution also exist.
- All trajectories in this domain are unstable; some trajectories and repeating natural orbits are more unstable than others (butterfly effect / chaos).

## 3 Challenges in Observation

### 3.1 Sensor types

Several types of sensor phenomenologies have utility for observing cislunar space. They can be grouped into two categories with two sub-categories:

- Electro-Optical (EO)
    - Passive (e.g., telescope)
    - Active (e.g., laser ranging)
- Radio-Frequency (RF)
    - Passive (e.g., antenna)
    - Active (e.g., radar)

All phenomenologies stand some chance of successfully observing objects in cislunar space, but some are more well-suited to the task than others. For example, both passive systems (EO and RF) can have substantial utility since there is no dependence on "pinging" the object; passive sensing can leverage reflected sunlight and transmissions from objects. With the huge distances at play, not to mention the rapidly changing geometries, the pinging necessary for any active system (EO or RF) would likely require prohibitive levels of power to be effective.

Collected data from sensors are often called observations. A single image from a telescope with several spacecraft in the field of view can contain several observations – one for each spacecraft. Observations can be raw, in the case of an image directly taken from a sensor or can be processed and refined into data that can be directly used in initial orbit determination and orbit update algorithms.

## 3.2 Sensor locations

Observations are unique and give us glimpses of what is occurring in the space domain. SDA is naturally improved by obtaining as many observations of as many objects as possible. The relative arrangement of the sensor and the object over time is fundamental to the value and information content of a given observation. Since time is an independent variable and the objects are generally unknown quantities, a principal strategic decision that we control is where to place sensors.

There is no single sensor location that can observe all cislunar space. The motion of the Sun relative to the rotating Earth/Moon system and the physical locations of the Earth and Moon will always cause gaps in coverage for both EO and RF systems. This fact motivates the need for a collaborative network of sensors. Many factors are involved in selecting sensor locations, but generally speaking, a wide diversity of perspective will have the best coverage, see the largest number of objects, and offer the best quality of information for cislunar SDA. This section reviews several sensor location groups (Earth ground-/space-based, Moon space-based, and a few examples in between) and highlights some challenges for each group when applied to observing cislunar space.

### 3.2.1 Earth ground-based sensors

By far the most common and inexpensive location for sensors is on the ground … on Earth. For observing GEO, ground-based sensors are locked to the motion of the Earth and are thus naturally in sync with GEO (an orbital regime that rotates at the same rate as the Earth revolves around its axis). At the GEO distance, the average brightness of solar-illuminated objects fits well within the optical sensitivity range of most sensors (at night), and telemetry signals can be routinely transmitted directly from the spacecraft to the ground without the need for intermediate relay satellites. In short, if a sensor placed on the ground can effectively stare at one spot in the GEO belt, it will likely see the same GEO object in its field of view indefinitely (plus or minus some small variations due to the eccentricity and inclination of the actual orbits).

*Figure 7. Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), developed and operated by the Institute for Astronomy at the University of Hawaii (image courtesy of University of Hawaii).*

A similar summary of a sensor's collection strategy for cislunar space objects, however, cannot be as simply stated as with the GEO case. The difficulty lies in the fact that cislunar space cannot be characterized in the same manner as GEO – it is not just a larger version of GEO. The Lagrange points (§2.4) and repeating natural orbits in the 3BP (§2.6) move with that system as it rotates, and from the Earth's perspective (on the ground), is certainly not fixed in the sky like objects in GEO. As discussed in the previous section, the intricacies of the dynamics lead to a wide variety of behaviors that consequently require as many types of responses.

*Detection*. Perhaps the most intuitive challenge to understand is that the enormous distances of cislunar space make object detection difficult. As the objects get farther from the observer, they will naturally get fainter (both for EO as well as RF sensors) and thus will put a strain on remote sensing capabilities to the point of potentially being undetectable entirely. Also, cislunar objects will generally have much longer orbital periods than GEO, thereby creating the need for more observations to cover significant fractions of orbits. One further challenge, specific to near-Earth EO sensors, is not being able to look near the Moon due to its reflection of sunlight (i.e., albedo).

*Tracking*. Opposite from the LEO case where the Earth is revolving slower than a LEO object, the Earth is now revolving faster than a cislunar object (GEO is the inflection point where the rotations match). The difference in relative motion between the sensor and the object means that a single sensor will almost never be able to maintain continuous coverage of a single object. For EO sensors, the additional apparent motion of the Sun with respect to the Earth/Moon system mean that even if a region of interest in cislunar space is geometrically accessible, it may be poorly illuminated by the Sun (note, for ground-based sensors, this sometimes means the objects appear near the Sun and only give line-of-sight access during the day). Even with a network of sensors, an asynchronous collection strategy is necessary to track a cislunar object. Impacts to tasking and scheduling are highly dependent on the object in question and whether the hand-off between one sensor and the next is successful. These challenges are present either for rate-tracking a object/star or staring at a fixed point in the sky.

An additional problem Earth ground-based sensors face is that they do not regularly see the same volume in cislunar space. As an example, consider an orbit near the Moon. There are periods of time when the Moon and surrounding volume are in the sky every night and the solar lighting conditions are excellent (i.e., a full moon). However, the phasing of the Moon's motion about Earth and the rotation of the Earth itself conspire to cause periods of time when the Moon is not visible at night from a given ground location.

### 3.2.2 Earth-orbiting space-based sensors

The next logical location is to consider sensors in orbits near Earth. Space-based sensors share most of the difficulties experienced by their ground-based counterparts, plus some. Additional problems with being in space include limited accessibility and size, weight, and power constraints. For sensing equipment in particular, there is also a tradeoff decision to be made between on-board processing capability and transmission bandwidth (either the raw data is processed on-board or it is sent directly down to Earth). With all that said, a potentially offsetting benefit of being in space is the lack of atmosphere (e.g., no light scattering). Without the atmosphere the sensors will only have three EO exclusion zones or "blind spots", one for the Sun, Earth, and the Moon, rather than typically being constrained to operate only at night.

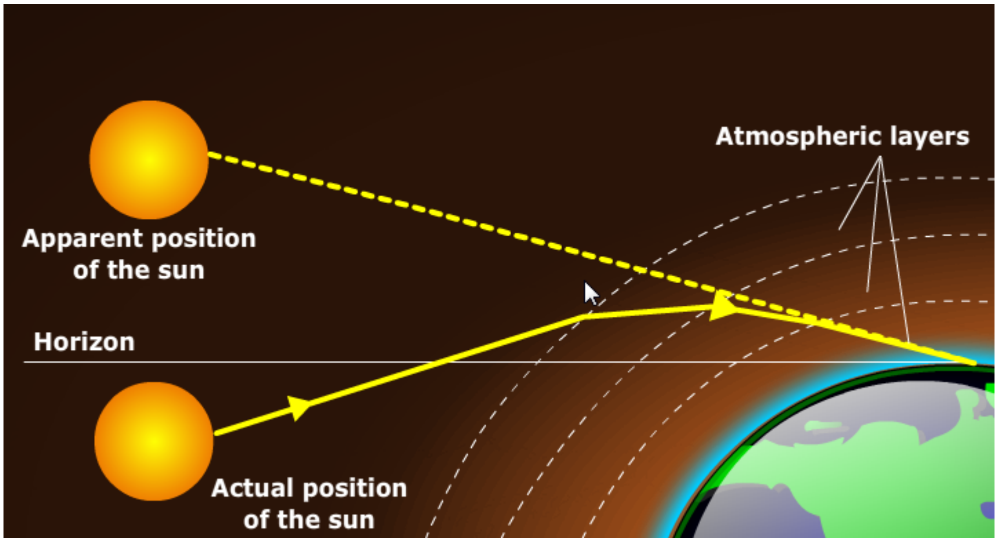

*Figure 8. Sensors on Earth experience light scattering and refraction due to the Earth's atmosphere. Sensors in space do not experience this phenomenon if looking away from the Earth (image courtesy of Physics Stack Exchange).*

*Figure 9. Artist's rendering of the Space-Based Space Surveillance (SBSS) system (image courtesy of Boeing).*

An existing operational example is the DoD's Space-Based Space Surveillance (SBSS) system[13], whose mission is to detect and track space objects in orbit around the Earth. Earth space-based EO sensors suffer from the same periodic lighting conditions as Earth ground-based sensors as the Sun progresses in its apparent motion about the Earth / Moon system.

### 3.2.3 Moon-orbiting space-based sensors

Moon space-based sensors are constrained here to mean only those that are dominantly affected by the Moon's gravity. This region thus includes only basic Keplerian orbits (circles and ellipses) centered on the Moon. Being closer to the Moon, it is true that these sensors would also offer a closer view of many of the repeating natural orbits, but also due to the proximity to the Moon, most of these orbits move very fast (like LEOs), completing entire revolutions in a matter of hours. This rapid rate of motion makes them less ideal for use as sensing platforms for observing other orbits because they would likely need to be frequently reoriented to see their objects. An additional challenge of Lunar orbiters is that the gravity field of the Moon is very uneven and only a few orbits are stable for any extended period of time [21]. However, lunar orbiters are quite useful to observe the Moon itself, as exemplified by NASA's Lunar Reconnaissance Orbiter (LRO)[14], whose mission is to map the surface of the Moon.

### 3.2.4 Cislunar space-based sensors

So far, we have covered Earth ground-/space-based and Moon space-based sensor locations. Everything in between and beyond we will consider to be "cislunar space-based." Since this space

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[13] https://www.afspc.af.mil/About-Us/Fact-Sheets/Article/249017/space-based-space-surveillance-sbss/

[14] https://lunar.gsfc.nasa.gov/

is quite vast, we will narrow it down to discuss only the repeating natural orbits present in this environment.

An intuitive choice for an orbiting sensor is to put it in an orbit that is bound (i.e., naturally repeating). The problem here is that these repeating natural cislunar orbits are all unstable (§2.7). Granted, there are varying degrees of instability across these orbits, but there is still a common hurdle to overcome in designing lasting missions using these orbits: compensation for stationkeeping. Stationkeeping costs translate directly to a fuel budget, therefore, the more unstable the orbit is, the more fuel will be required to maintain its orbit, which in turn may influence the possible size of the spacecraft. This relationship is discussed more in §4.1.

One interesting feature of using cislunar orbits as observing platforms is that they have a unique ranging signature with other cislunar orbits. To say it differently, the differences in positions (i.e., ranges) as measured from one cislunar spacecraft to another cislunar spacecraft as they move through their orbits is uniquely attributed to exactly this pair (barring reflectively symmetric pairs). In fact, this phenomenon is the basis of a novel navigation strategy called LiAISON [22] that is leveraged in the upcoming cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission[15] that will explore the usage of CubeSats for cislunar missions.

Starting at the most basic cislunar locations, the Lagrange points (L1-L5) themselves are equilibrium points for the Earth-Moon 3BP much like GEO is for Earth's 2BP. They are unique in that they are orbits in inertial space that are locked to the motion of the Earth-Moon line. Most of the repeating natural orbits are described in relation to or are considered emanating from these Lagrange points. As such, sensors located at Lagrange points have useful geometries for observing cislunar space.

Unlike with near-Earth or near-Moon sensors, cislunar orbiting sensors are not necessarily constrained to a local neighborhood; some orbits can span many different regions in cislunar space. For example, members of the W4W5 family transit between the L4 and L5 Lagrange points while dipping in close to the Moon at certain times in their orbits (see Figure 10).

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[15] https://www.nasa.gov/directorates/spacetech/small_spacecraft/capstone

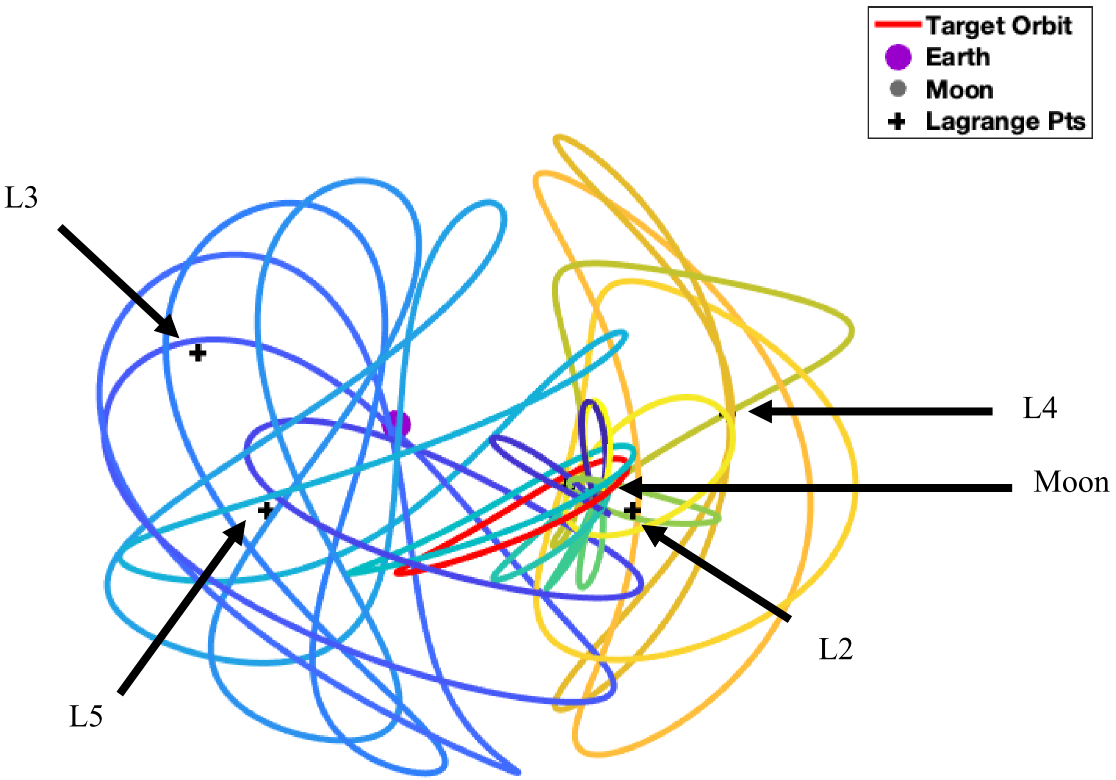

*Figure 10. A sparse discrete sampling of orbits from the continuous W4W5 periodic orbit family in the rotating frame of the CR3BP. A sample object orbit is shown in red to highlight an individual orbit amongst the family (as represented by 20 orbits, each with a different color).*

Now, despite the unique perspectives offered by these exotic orbits, they could pose quite challenging from a CONOPS standpoint due to them being almost constantly at lunar distances relative to Earth and, at times, at lunar distances from their object.

Among the more well-behaved repeating natural orbits are the families of Halo orbits about the L1 and L2 Lagrange points. These families have Moon-orbiting-like behaviors but are still 3BP orbits. Their orbital periods span from several days to several weeks, making them much more suitable for sustainable missions; in fact, these very orbits are considered hosts for NASA's Lunar Gateway concept [12]. Furthermore, a recent experiment is being championed at AFRL called the Cislunar Highway Patrol System (CHPS)[16], whereby spacecraft are to be deployed as remote sensing platforms to monitor the region about the Moon.

EO sensors in repeating natural orbits in cislunar space must still contend with the apparent motion of the Sun. One solution to this problem is to find repeating natural orbits that are resonant with apparent solar motion (i.e., a period of one synodic month – 29.5 days). When phased with the Sun correctly, synodic-resonant orbits offer spacecraft advantageous solar illumination of the observation object more often than other orbits [17][18]. Figure 11 identifies several useful orbits, in particular the 1:1 synodic-resonant L1/L2 Lyapunov and distant retrograde orbits (DROs).

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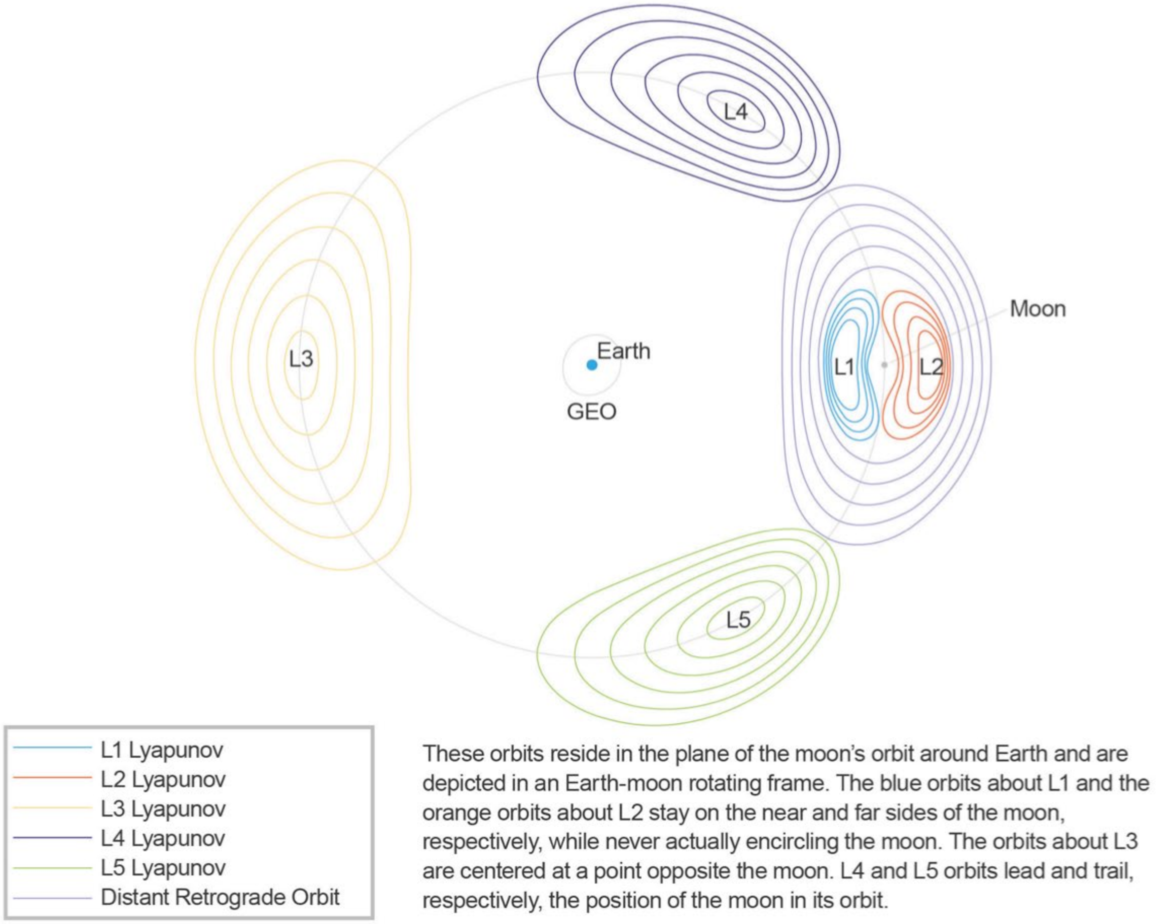
[16] https://spacenews.com/air-force-research-laboratory-announces-new-space-experiments/



These orbits reside in the plane of the moon's orbit around Earth and are depicted in an Earth-moon rotating frame. The blue orbits about L1 and the orange orbits about L2 stay on the near and far sides of the moon, respectively, while never actually encircling the moon. The orbits about L3 are centered at a point opposite the moon. L4 and L5 orbits lead and trail, respectively, the position of the moon in its orbit.

*Figure 11. Several planar repeating natural orbits in the Earth-Moon system (courtesy of Aerospace Corporation).*

## 3.3 Key takeaways

- Detection is more difficult
  - Objects are fainter; longer distances will stress remote sensing capabilities.
  - Objects are slower; longer time scales mean more observations are required to see significant fractions of orbits.
  - EO systems have difficulty observing near the Moon due to its albedo.
  - Apparent motion of the Sun with respect to the Earth/Moon system causes EO systems to have periodic difficulty observing portions of cislunar space; it is easier to escape detection in these cases.
- Tracking is harder
  - Objects are not stationary, vis-à-vis GEO objects.
  - The Earth is rotating faster than cislunar repeating natural orbits; a single ground-based sensor cannot maintain continuous coverage.
  - Sensor networks will require asynchronous data collection strategies, impacting tasking and scheduling.

- Extending the sensing architecture
    - Special repeating natural orbits offer different vantage points unattainable by ground or near-Earth orbiting sensors.
    - Lagrange points are locked relative to the Earth-Moon alignment (analogous to the GEO belt) and could provide unique sensing perspectives.
    - Passive EO systems in repeating natural orbits that are resonant with the Earth / Moon synodic period can offer commanding views of nearby space.
    - Due to the perturbation of the Moon, there are very few repeating natural orbits; limited "real estate" available to place orbiting sensors.
- Types of sensors
    - Passive EO systems (e.g., telescopes) can have substantial utility, if the object is sufficiently illuminated.
    - Active EO systems (e.g., laser ranging) may not be as useful, because they are extremely sensitive to minor pointing errors and their beams rapidly lose strength at long distances.
    - Passive RF systems (e.g., antenna) can have substantial utility, if the object is transmitting directly towards a receiver.
    - Active RF systems (e.g., radar) may not be as useful, because they require tremendous power to be effective outside of short distances.

# 4 Spacecraft Operations in Cislunar Space

## 4.1 Staying on a trajectory

As discussed in §2.7, trajectories in cislunar space are unstable (with the sole exception of trajectories in the vicinity of L4 and L5). This instability causes trajectories to drift away from their planned trajectories, which in turn requires regular maneuvers. The size and frequency of maintenance maneuvers in cislunar space (particularly around the Moon) depends greatly on the degree of instability the trajectory possesses. Smaller stability indices (those close to 1) may only need to maneuver once every few days. The trajectory maintenance plan for NASA's Lunar Gateway is an excellent example of this cadence [12]. Spacecraft on trajectories with larger stability indices diverge from their trajectories quicker, requiring more regular maneuvers – perhaps daily or multiple maneuvers each day. Navigation uncertainty can also drive maneuver frequency, potentially motivating cislunar precision navigation & timing solutions.

The dynamical environment about the Moon is highly sensitive to perturbations, which also means that, generally, only small maneuvers are required to stay on trajectories. In most cases, maintenance maneuvers are very small and often in the mm/s range (<u>orders of magnitude lower than most GEO stationkeeping maneuvers</u>). This consequence leads to our central observation regarding staying on trajectories: <u>in cislunar space, trajectory maintenance maneuvers are very small and can occur more often than in LEO or GEO regimes, potentially motivating autonomous maneuver implementations</u>. The size and frequency of these maneuvers can be particularly challenging for remote sensors to detect but are excellent pieces of information in determining the operational cadence of spacecraft. Frequency of maneuvers can be reduced in exchange for larger maneuvers, but for a variety of reasons, this trade is not typically done. The small size of the maneuvers also means that spacecraft propulsions systems are often either electric (i.e., low-thrust systems) or have very small minimum impulse bits (in the case of hydrazine or AFRL Green Fuel[17] systems).

## 4.2 Transferring between trajectories

The very same instability in trajectories paradoxically makes transfers between different orbits (most commonly from one repeating natural orbit to another) easier. A spacecraft can leverage the unstable motion about its trajectory to, after some time and with perhaps a small maneuver or two, take it to a different trajectory or repeating natural orbit substantially different from the initial trajectory. The variety of such transfers, fuel costs, and transfer durations are infinite. Naturally, this increases the difficulty of maintaining quality SDA. However, such low energy transfers tend not to change the orbit energy substantially, making object association and identification of possible object trajectories easier based on energy conservation methods. Said differently, we might only need to look in the vicinity of other repeating natural orbits with similar energies to recover a lost object. An example of a transfer from one repeating natural orbit to another is shown below in Figure 12. In this transfer a spacecraft departs an L1 Lyapunov repeating natural orbit (12.2 day period) on an unstable manifold, executes a small mid-transfer maneuver, and arrives in a L2 Lyapunov repeating natural orbit (14.5 day period) with a total 20.35-day transfer time. As with other topics in the 3BP, there is substantial literature and ongoing research in identifying transfer trajectories that trade fuel cost against transfer time (e.g., [11]). We should be careful to remember that much larger maneuvers that do not attempt to heavily leverage dynamics to trade fuel for transfer time are always possible.

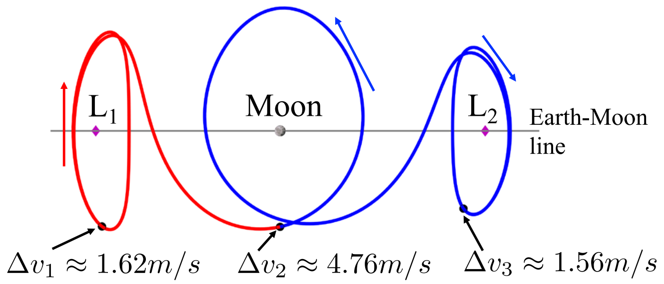


*Figure 12. An un-optimized Low-energy transfer between two repeating natural orbits [courtesy Prof. Natasha Bosanac, CU Boulder].*

When observing active spacecraft in cislunar space, one potentially difficult problem is identifying whether a spacecraft is initiating a maneuver to transfer to another trajectory. Because the maintenance maneuvers are so small, it can be days after the transfer has begun that real observable differences manifest. This motivates continuing research in improving the sensitivity of maneuver detection algorithms.

## 4.3 Types of Earth / Moon transfers and previous missions

A brief description of some common Earth/Moon transfer trajectories is given below. Emphatically, this list is not meant to be exhaustive, merely instructional. There is an extensive

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[17] https://www.wpafb.af.mil/News/Article-Display/Article/1883658/green-propellant-infusion-mission-to-test-afrl-developed-green-propellant/

literature and continuing research in the field of 3BP trajectory design. The transfers below are selected for discussion because they span interesting design points in fuel cost, transfer time, and distance from the Earth.

Direct Transfers involve boosting directly from LEO and targeting the Moon with a leading trajectory. As the spacecraft approaches the leading side of the Moon, the increasing acceleration from the Moon pulls the spacecraft back and around the Moon. The Apollo[18] and Chang'e[19] missions are excellent examples of direct transfers. Historically, these transfers have been used for missions taking place on the Moon. They can, however, be modified to inject objects into cislunar space and with additional maneuvers target other trajectories, such as repeating natural orbits or transfers back to exotic Earth-centered orbits (e.g., reverse GEO, large inclination changes). This transfer is amongst the quickest, taking several days.

Low-Energy L1 Transfers are sometimes used by low-thrust spacecraft, in which the apogee is successively raised until it approaches Earth/Moon distances. Then, the phasing of the orbit's apogee is timed to coincide with when the L1 point passes in the inertial frame, executing a transfer to cislunar space, called a Translunar Injection. This type of transfer can be initiated from LEO, GEO, and other orbits. In fact, from GEO, the additional fuel costs to execute a Low-Energy L1 transfer is quite modest (only a few km/s). Chandrayaan 2[20] is an example of an Indian mission that used this transfer from LEO. Transfer durations can be as short as a week or may be months.

Some transfers go well beyond the Moon's orbit into regions of space that are influenced by the Earth, Moon, and Sun. Such transfers are called 4-Body Transfers (i.e., CAPSTONE[21], THEMIS-ARTEMIS[22], and GRAIL[23] missions). These 4-Body Transfers are characterized by their very low fuel costs, very long transfer times (months to years), and extreme distances from Earth (>1.5M km). Because 4-Body transfers spend much of their time beyond the Moon's orbit, they are the most difficult transfer to track with sensors and can be designed to enter the region about the Moon from most directions.

## 4.4 Key takeaways

- Frequent small maneuvers are required to stay on an orbit or trajectory.
- Maneuvers present very differently in cislunar space as compared to LEO or GEO.
- Maneuvers can be difficult to discriminate from perturbations.
- Because the dynamics are so sensitive, small maneuvers can create large trajectory changes.
- There are some well-known direct transfer high-energy approaches (e.g., Apollo).
- There are a wide variety of transfers with low-energy and long-duration (e.g., GRAIL).

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[18] https://www.nasa.gov/mission_pages/apollo/missions/index.html

[19] https://www.planetary.org/space-missions/change-4

[20] https://www.planetary.org/space-missions/chandrayaan-2

[21] https://www.nasa.gov/directorates/spacetech/small_spacecraft/capstone

[22] https://www.nasa.gov/mission_pages/themis/mission/index.html

[23] https://www.nasa.gov/mission_pages/grail/main/index.html

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