POLITECNICO DI TORINO

Master's Degree in Aerospace Engineering

Master's Degree Thesis

Sustainable missions to the Moon - Sustainability guidelines for lunar activities, a state-of-the-Art

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Summary

Lunar endeavors are set to experience a substantial increase in the coming years, and interest is growing for long duration human missions on the Moon, in-situ resources utilisation, and commercially-oriented missions. All these expected activities lead to cast a spotlight regarding environmental sustainability, to avoid the same problems faced nowadays with space debris in near Earth orbits, and address new challenges linked with regular activities on the surface of other celestial bodies than Earth. This work aims to inform on the current and lacking guidelines in lunar orbit and on its surface. By comparing them with those for Earth, it is possible to identify the key aspects to which future space actors will have to pay attention to and which they will undoubtedly have to address. In particular, the state-of-the-art study focuses on satellite disposal options to prevent orbital crowding, fragmentation potential and surface impacts, as well as lunar landing. The final purpose is to be able to understand what it means to behave sustainably when it comes to lunar missions, in compliance with the principles of transparency and coordination of international space law, raising awareness among stakeholders and proposing solutions whenever feasible.

Acknowledgements

My interest for space sustainability emerged during my last semester of Bachelor's Degree, sparked by the "Aerospace systems" course. It was there that I discovered the topic of space debris, which ultimately became the focus of my Bachelor's thesis.
Two years later, this Master's thesis opportunity presented to me. It was the beginning of a path that let me realize which areas I hope to engage during my future career.
The experience at eSpace was the first step in further exploring space sustainability, followed by seven months spent at the ESA Clean Space Office, in The Netherlands, where I dealt with Ecodesign and Life Cycle Assessment applied to space sector.
Looking back, I can't help but fondly remember the people, the teams, and the organisations I had the privilege to be a part of.
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Cordenons, October 2024

Table of Contents

List of Tables

List of Figures

Acronyms

ASAT Anti-satellite test

BCR4BP Bicircular Restricted Four-Body Problem

CAM Collision Avoidance Manoeuvre

CAPSTONE Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment

CDF Concurrent Design Facility

CLPS Commercial Lunar Payload Services

CNES Centre National d'Etudes Spatiales

CNSA China National Space Administration

COPUOS Committee on the Peaceful Uses of Outer Space

COSPAR Committee on Space Research

CR3BP Circular Restricted Three-Body Problem

CSSA Cis-lunar Space Situational Awareness

DLR Deutsches Zentrum für Luft-und Raumfahrt

DRACO Destructive Re-entry Assessment Container Object

DRO Distant Retrograde Orbit

EAGLE Effective and Adaptive Governance for a Lunar Ecosystem

ELFO Elliptical Lunar Frozen Orbit

EM Earth-Moon

EQUULEUS EQUilibriUm Lunar-Earth point 6U Spacecraft

ESA European Space Agency

GEO Geostationary Earth Orbit

GNC Guidance Navigation and Control

GRAIL Gravity Recovery and Interior Laboratory

GTO Geostationary Transfer Orbit

IADC Inter-Agency Space Debris Coordination Committee

ISO International Organization for Standardization

ISRO Indian Space Research Organization

ISRU In-Situ Resource Utilization

ISS International Space Station

JAXA Japan Aerospace Exploration Agency

JPL Jet Propulsion Laboratory

KPLO Korea Pathfinder Lunar Orbiter

LCROSS Lunar Crater Observation and Sensing Satellite

LEO Low Earth Orbit

LLO Low Lunar Orbit

LRO Lunar Reconnaissance Orbiter

LUMIO Lunar Meteoroid Impact Observer

LUMOS LUnar MOnitoring System

NAIF Navigation and Ancillary Information Facility

NASA National Aeronautics and Space Administration

NEO Near Earth Orbit

NRHO Near Rectilinear Halo Orbit

OST Outer Space Treaty

PSD Permanently Shadowed Region

S3VI Small Spacecraft Systems Virtual Institute's

SDMP Space Debris Mitigation Plan

SDMR Space Debris Mitigation Report

SE Sun-Earth

SEM Sun-Earth-Moon

SMART-1 Small Mission for Advanced Research in Technology

SOFIA Stratospheric Observatory for Infrared Astronomy

SOI sphere of influence

SSR Space Sustainability Rating

STSC Scientific and Technical Subcommittee

THEMIS Time History of Events and Macroscale Interactions during Substorms

UK United Kingdom

UN United Nations

UNOOSA United Nations Office for Outer Space Affairs

US United States

Chapter 1

Introduction

Since 17th August 1958, the launch date of Pioneer 0, the first mission planned to go beyond Earth's orbit, to the time of this report, there have been 138 attempts to reach the Moon or an orbit around it [1].

Between the 1950s and 1970s, during the Cold War, the United States (US) and Russia dominated the space scene, sparking what became known as the "space race".

The historical background of two of the most powerful nations in the world allowed mankind to develop extremely advanced technologies, stimulating each other in a two-way competition, such that they walked on the lunar surface and brought back mineral samples to Earth.

The vast resources invested returned significant results: the development of the Saturn V, the precursor of all modern launch vehicles, the creation of new materials suitable for re-entry into the Earth's atmosphere, and the capture of high-resolution images of the Moon, to name a few.

Scientific goals were an unprecedented success, also accompanied by the first (and so far, still only) collection of guidelines of international space law. Together with the United Kingdom (UK), active at that time in satellite research with the "Ariel" programme, Russia and US promulgated the Outer Space Treaty (OST) [2], in 1967. Currently, these are the only legally binding rules on extraterrestrial activities.

The 1980s marked a period for reassessing earlier achievements, initiating a second era of lunar exploration. This phase broke the Russian-American dominance, opening the door to Europe, several Asian nations, and even private companies.

What distinguishes the second era from the previous cycle is the awareness of reaching the Moon with the intention to staying. The objective is to establish a permanent human settlement, which will endure with the emergence of a circular economy in situ.

In this sense is emblematic the Artemis programme by National Aeronautics and Space Administration (NASA). With the second and third launches the mission

aims to set-up the human presence on Earth's satellite, culminating with the Lunar Gateway, the International Lunar Space Station.
The realisation of this utopian scenario, however, can only occur if the space actors behave in a responsible and sustainable way.

1.1 Why are we going to the Moon?

When referring to the Moon, it does not only involve satellites orbiting or landing on its surface. In the context of lunar missions, it is good to refer to a much larger space, called the cis-lunar space, which will be explored with more details in the next chapter.
Briefly, the cis-lunar domain is defined as that area of deep space under the gravitational influence of the Earth-Moon (EM) system [3].
The following discussion does not consider orbits that are strictly influenced by the Earth, such as Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO), but extends to the Lagrangian EM points, especially the first two collinear ones.
Missions to the Moon can be divided into several categories:

- Flyby: manoeuvre to bring the satellite closer to the lunar surface. It is often used to reach more remote destinations, as it uses the Moon's gravitational pull (the gravity assist) to increase the object's energy.
- Orbiter: the satellite is mainly under the influence of the Moon, and orbits more or less periodically around it, or around a Lagrangian point in the EM system. Due to the complexity of cis-lunar space, the trajectory is often unstable, behaviour that also depends on the object's distance from the main bodies.
- Impactor: mission category that creates a destructive crash of the satellite onto the lunar surface. As a result of the violent impact, a crater is formed and secondary debris are generated. In the past, the Indian Space Research Organization (ISRO) used this technique to analyse the composition under the lunar soil [4].
- Lander: unlike the impactor, the satellite lands on the Moon preserving its integrity and being able to continue its operational phase.
- Rover: linked to the landing, once the main body reaches the surface it deploys a specialised vehicle to survive and move through the hostile terrain, remotely controlled by an operator.
- Returner: return involves the re-entry to earth of all or part of the hardware sent to the Moon. Usually such missions are human or sample collection.

- Crewed landing: Apollo 17 was the last one, dating back to 11th December 1972. There have been no human missions other than NASA's Apollo programme.

To date, only the United States have successfully completed all seven mission categories, while Europe has yet to make a soft landing.
In fact, the only two European objects that touched the lunar soil have done so in a destructive manner: European Space Agency (ESA) on 3rd September 2006 with Small Mission for Advanced Research in Technology (SMART-1), and a Luxembourg company, LuxSpace, with its Manfred Memorial Moon Mission.
Therefore, the question is: what drives mankind to explore the Moon?
As has been mentioned, the first wave of American and Russian lunar missions, apart from the purpose of demonstrating their nation's technological power and knowledge, had scientific exploration as their goal.
Scientific exploration is the main driver of the missions of the new millennium as well, to which is added the search for materials that can be exploited and conditions that can be favourable for staying on its surface.
In this sense, NASA has worked together with American companies and ESA to launch, from 2024 onwards, commercial activities on the Moon, with the creation of the Commercial Lunar Payload Services (CLPS) programme. This initiative will enable the study of lunar resources using high-tech payloads, and will lay the foundation for future human settlement following Artemis III [5].
The first two missions of the programme were launched in the first quarter of 2024:

- Peregrine Mission One, developed by the American company Astrobotic, was unsuccessful due to a leak of the reaction‘s thrusters, and it decayed in the Earth‘s atmosphere after 10 days.

- IM-1 produced by Intuitive Machine has become the first private spacecraft to softly land on the surface of the Moon.

Over the next three years, dozens of landers and rovers belonging to the CLPS will be directed towards the lunar soil, most of them at the far side and South Pole.
Specifically, the latter site is of particular importance because it has numerous permanently shadowed areas, in which the presence of frozen water, hydrogen, and other volatiles of vital importance to humans has been detected.
For example, sophisticated payloads will perform ground mining, map study areas and their composition, and measure radio frequencies and radiation. All to succeed in future In-Situ Resource Utilization (ISRU) operations.
Additionally, the great revolution will be dictated by the actors in these activities: no longer just space agencies and governments, but also private industries.
In support of this thesis, a number of start-ups are springing up to investigate possible applications to support commercial activities directly on the Moon, and, above all, act in a sustainable manner.

Considering the current knowledge of the lunar environment and the quantities of the elements present [6], the most successful proposals currently focus on supplying essential resources (such as water, food, electricity, and solar energy) and constructing facilities to assist specific activities (such as landing, road transport, and living modules).
The synthesis of specific chemical compounds can be useful for the creation of lunar propellant by the use of hydrogen, oxygen and methane in situ. These are just a few proposed ideas; however, reducing reliance on Earth for these tasks lowers launch costs and creates the potential for utilizing the Moon as a refueling station for deep space missions.

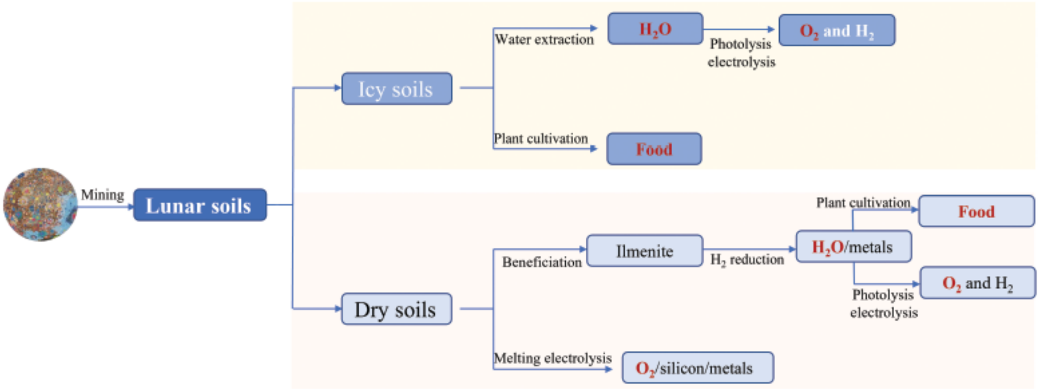


Figure 1.1: Example of a production chain for essential goods on the lunar surface, using ISRUs [6].

According to Ainardi et al. [7], activities on the Moon can be classified in five "end-goals":

- Scientific exploration;
- Resource utilization;
- Manufacturing;
- Construction;
- Tourism.

It is evident, therefore, that there is an increasing awareness of a non-scientific nature of the activities on the Moon, but rather aimed at the production of goods and the provision of services.
Parallel to the scientific community and industry, the legal field is also evolving.

On 13th October 2020, a coalition of eight states signed the Artemis Accords [8], and as time progresses, an increasing number of nations are joining this treaty, with the current count at 43.
This non-legally binding document lays down the principles for cooperation in the use of the Moon, Mars, comets and asteroids for peaceful purposes.
Above all, the Artemis Accords authorise the extraction of resources from the soil of these celestial bodies and the trade therein, in accordance with the OST.
In view of the above, and considering the announced intentions of the several space actors, hundreds of new objects - including satellites, deployable rovers, and human-transport capsules- are expected to enter cis-lunar space and the Moon's surface by the end of the 2020s.
To ensure a prosperous future for this environment, there is an urgent need to instill a sustainability mindset, both in technologies and in raising awareness for coordination and transparency among stakeholders.

1.2 Sustainability

The term "sustainability" in space can have different connotations depending on the context [9]. Usually, a commercial actor considers a mission "sustainable" if it is so from an economic point of view. On the other hand, a mission manager is concerned that the mission is programmatically repeatable.
The following discussion, however, focuses more on the meaning of environmental sustainability: this aims to prevent contamination of a celestial body or orbits to ensure they are not harmful in the long term.
Whenever something is launched into space, must be considered that it will remain there for a considerable period of time.
Several questions, then, need to be asked: what are the consequences of the object being in orbit? What reaction can other space actors have? What is launched today, can it have repercussions in the future?
These doubts are not directly related to the scientific purpose of the mission, but they are fundamental to ensure the continued viability of the space economy.
Unfortunately, Unfortunately, a supporting example is readily available: orbital pollution has been addressed too late, which has led to the current issue of space debris.

1.2.1 The space debris issue

Since 1957, when the space age began, almost 6640 rockets have been launched (excluding failures), placing more than 18,000 objects into Earth orbit [10].
The trend is steeply upward, especially in recent years: according to the Index of

Objects Launched into Outer Space [11], maintained by United Nations Office for Outer Space Affairs (UNOOSA), more than 2,700 satellites were launched in 2023 alone. The reasons for this exponential growth are the development of technologies and the rise of commercial launches, which has contributed to a drastic reduction in costs and the creation of the New Space Economy [12].

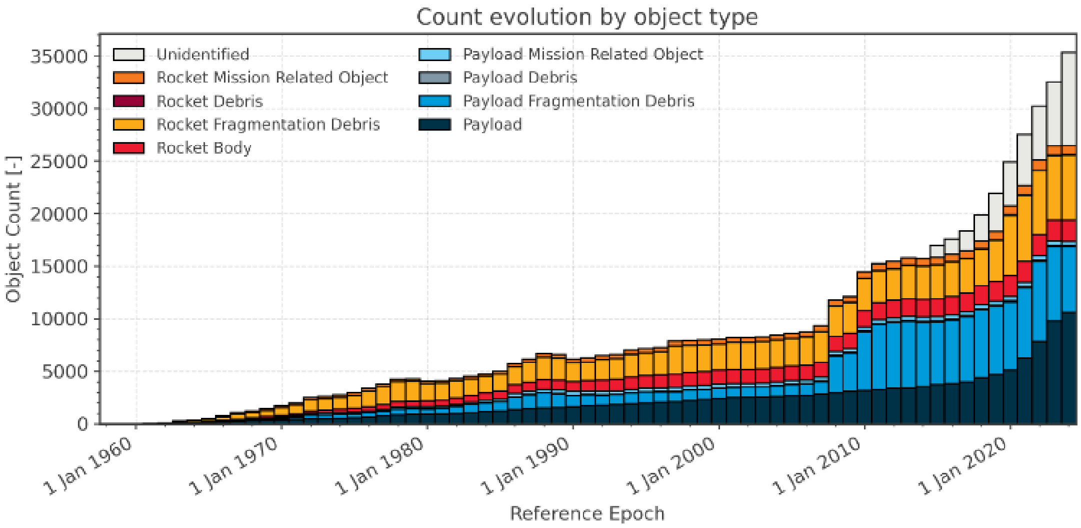


Figure 1.2: Evolution of the number of objects in space, (Image credit: ESA)

The most worrying fact, however, is that of the approximately 12,500 satellites in orbit at the moment, about 2,500 are non-operational [10], which is why they are space debris.

Numerous organisations, both European and global, such as ESA [13], International Organization for Standardization (ISO) [14] and Inter-Agency Space Debris Coordination Committee (IADC) [15], define space debris as "all non-functional, artificial objects, including fragments and elements thereof, in Earth orbit or re-entering Earth's atmosphere".

Depending on the size of space debris, collisions with a satellite or another space object can have catastrophic results for a mission, and a single event can fuel the proliferation of fragmentation, the Kessler Syndrome [16].

To confirm this, there are already certain orbits between 800 and 1,000 km in height that attest to a growing debris population without any launching of objects from Earth.

Current observation and tracking technologies generally allow knowledge of the detection and cataloguing of objects larger than 10 cm, which can be avoided thanks to Collision Avoidance Manoeuvres (CAMs). On the other hand, there is no ability to identify the 130 millions debris between 1 mm and 1 cm.

The most dangerous fragments, however, are the 10 millions objects between 1 and 10 cm in diameter, which can be detected but not tracked, and their energy is sufficient to take out a satellite.
It is clear that this phenomenon is easy to propagate and at the same time seriously threatens the future integrity of the space economy.
In particular, the most vulnerable orbits are those that have the highest number of applications: this is why the LEO and GEO have been declared protected regions [15].
These two portions of space are considerably crowded because of their special location, thanks to which they can offer various services:

- LEO: from the Earth's surface up to 2000 km. Due to their low height and cost of access, they are used for telecommunications and observation purposes. In addition, the International Space Station (ISS) and constellations of thousands of satellites reside in LEO environment. Their low altitude create extremely high impact velocities;
- GEO: circular orbits 35786 km above the Earth, which have a near equatorial inclination. This precise distance and set of inclinations give the satellite an orbital period equal to the period of the Earth's rotation, resulting in constant coverage of a specific area. GEOs are used for communication, navigation and meteorology.

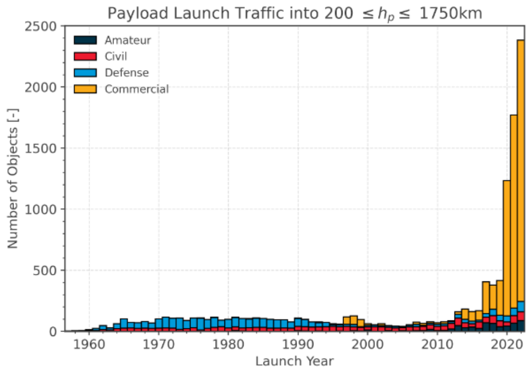


Figure 1.3: Evolution of the number of objects in LEO, (Image credit: ESA)

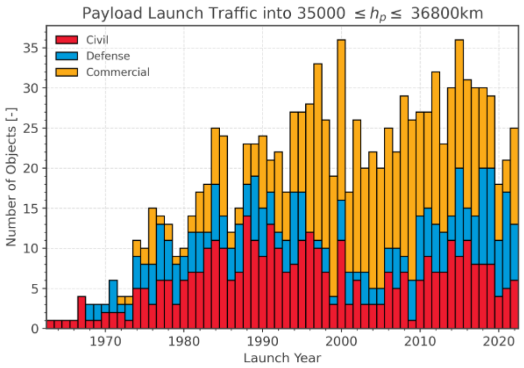


Figure 1.4: Evolution of the number of objects in GEO,(Image credit: ESA)

Numerous space actors, including agencies, governments, non-profit organisations and private companies are cooperating to limit the problem. In recent years, their efforts have led to the creation of several guidelines, handbooks and standards not legally binding, which instruct on how to act sustainably in this field.

Among the instructions, there are effective risk reduction mechanisms, some of which must be considered when designing the mission:

- passivation: act of permanently depleting, irreversibly deactivating, or making safe all on-board sources of stored energy capable of causing an accidental break-up [17];
- shielding and coating: solution that allows the external structure of the object to be more resistant to random impacts and light phenomena;
- redundancies: lowering the probability to create a debris in case a spacecraft fails;
- post-mission disposal: provide a strategy to decommission the satellite or the rocket body at the end of its life. It may consists of re-entry into the atmosphere or parking in a graveyard orbit. In chapter 4 post-mission disposal techniques will be debated;
- collision-avoidance maneuvers: planning and execution of strategies to mitigate the risks associated with on-orbit conjunctions [17];
- active debris removal: missions dedicated to the removal of debris in orbit. One example is the ESA project ClearSpace-1 by the German large system integrator OHB and the private Swiss company ClearSpace SA, which will remove an ESA spacecraft, PROBA-1, in low orbit by atmospheric re-entry [18].

It is also surprising to note how a single event can have catastrophic results.
For instance, in January 2007, China conducted an Anti-satellite test (ASAT), launching a rocket from the ground towards a low-orbit satellite. The consequences were fatal, as more than 3300 trackable objects were added, increasing the debris population at the time by 25% [19].
Moreover, in February 2009, two communication satellites, the American Iridium 33 and the defunct Russian Kosmos 2251, accidentally collided into each other at a relative speed of almost 12 km/s, creating more than 2,000 large pieces of debris [20].
This is why, in addition to the development of new technologies to reduce risk and the awareness of the need to limit launches into orbit, the proliferation of debris in orbit requires coordination and transparency between all states, and more generally, actors in space.

1.2.2 Space Sustainability Rating

With sustainability in mind, future missions not only have a duty to comply with these guidelines, but have the possibility to share this publicly.

This is the aim of Space Sustainability Rating (SSR) [21] : encourage space actors to design and implement sustainable space missions and operations.
On a voluntary basis, stakeholders have the opportunity to demonstrate their commitment to reducing the risk of space debris, in-orbit break-ups and inappropriate orbit operations by submitting their actions to scrutiny by SSR operators.

Figure 1.5: SSR rating badges

Thanks to various parameters, the sustainable decisions of the operators will be quantified and measured, in order to obtain a final score and, depending on the result, a "badge".
The modules on which the evaluation is conducted are:

- Mission index: quantifies the level of risk and physical interference that the mission creates throughout its duration.
- Collision avoidance capabilities: concerns the steps taken to reduce the risk of collision with debris in an active manner.
- Data sharing: assesses the amount of relevant information an operator shares to different stakeholders.
- Detectability, Identification and Trackability: module to encourage satellite operators to consider how the physical attributes of their satellite design and their operational approach during launch, operations and disposal affect the level of difficulty for observers to detect, identify, and track the satellite.
- Application of design and operations standards: rates the level of commitment on the adoption of internationally endorsed standards in the space domain .
- External services: innovations in the field of preparation for removal, in case of a failure.

It is noticeable that in parallel to an evaluation of the mitigation techniques considered, equal importance is given to the sharing of information and data.
Near Earth Orbits (NEOs) have also suffered and are suffering from a lack of transparency, which is why this value should be promoted from the dawn of the new cis-lunar economy.

1.3 Sustainability on and around the Moon

The growth of interest in the Moon will result in a growth of activity towards the Moon, and on its surface.
The greater the number of different actors involved, the higher the likelihood of disputes arising regarding the use of the celestial body.
For this reason, unanimously agreed regulations are needed to deal with the grey areas. In other words, there is the need to draft the behaviour to be adopted for certain actions and phenomena for which there is still unclearness.
By shedding light on grey areas, future stakeholders will, at least, have the possibility to act in a sustainable and responsible way.
According to the Lunar Policy Handbook [9] and the Effective and Adaptive Governance for a Lunar Ecosystem (EAGLE) report [22], there are several issues that deserve more attention, such as the registration of space objects: a rigorous up-to-date list of spacecraft directed towards cis-lunar space and the Moon's surface is needed to enable all actors to monitor this environment. This commitment is closely related to responsibility; when a state registers an object it is also responsible for it.
Responsibility should also apply both during the operational phase and at the end of life, and appropriate actions are needed to prevent the proliferation of space debris and to preserve certain lunar sites.
In this regard, it is urgent to protect either the lunar cultural heritages, such as the remains of the Apollo missions, and certain areas of the lunar surface of significance, called safety zones. Within the Artemis Accords the safety zones are defined as "area in which nominal operations of a relevant activity or an anomalous event could reasonably cause harmful interference".
Safety zones may enclose important mining activities, landing areas or even pressurised habitation modules.
Regulating the flow of entrants into safety zones allows on one hand to avoid contaminating valuable resources, but on the other opens up the debate concerning the limitation of a space that, according to the OST, must be open-access.
Furthermore, the extracted resources may be subject to trade, which adds to the uncertainty surrounding how this business can be managed and by whom.
The issues and the grey areas in relation to the Moon and its environment are

numerous and complex. This is why international cooperation and coordination are needed to solve them, seeking to reduce the risk of conflict and supporting peaceful purposes in the lunar context.
Taking into account the aforementioned variables, the following discussion aims to investigate the end-of-life management of missions to the Moon, especially orbital ones, by drawing up guidelines on recommended disposal techniques and risk mitigation strategies to prevent pollution in cis-lunar space.
Starting from a study on the state-of-the-art of lunar knowledge and regulations, the final aim is to identify the key aspects to which future stakeholders will have to address, proposing solutions for sustainable behaviour when feasible, to avoid the same problems faced nowadays with space debris in near Earth orbits.
The debate will also consider the consequences of an impact and landing on the lunar surface and highlight the need for transparency and data sharing to enhance the Cis-lunar Space Situational Awareness (CSSA).

Chapter 2

The lunar environment

In view of the many applications it can offer, the Moon is attracting increasing interest.

Its surface is characterised by numerous craters, caused by a steady rain of asteroid and meteorite impacts, which cannot be shielded by its very thin atmosphere [23]. The atmosphere is so weak that even meteorological phenomena such as wind or erosion do not occur, leaving the lunar mantle intact for years.

Figure 2.1 illustrates that among the human legacies on this celestial body, the enduring boot prints of the first astronauts remain visible even after decades.

In addition, billions of years of collisions created a soil layer of fine detrital rocky dust, called lunar regolith. Because of its composition and fineness, lunar regolith is one of the many obstacles complicating future colonisation of the Moon. Since it is electrically charged, it adheres to walls (and humans themselves) if lifted, causing degradation of material properties and infiltrating the astronauts' respiratory system.

Missions like Lunar Prospector, Lunar Crater Observation and Sensing Satellite (LCROSS), and Lunar Reconnaissance Orbiter (LRO) provided crucial insights into lunar soil composition, highlighting not just rocky surfaces but also substantial concentrations of water ice within the permanently shadowed regions at the South Pole.

Additionally, the recent discovery facilitated by NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) mission revealed the presence of water molecules even in sunlit areas of the Moon [24].

These findings have catalyzed an emphasis on studying both the lunar body, for future activities of ISRU, and its surrounding environment.

Compared to Earth, the Moon gravitational field exhibits a greater level of complexity and instability, prompting intensified research efforts aimed at unraveling its unique characteristics and dynamics.

Figure 2.1: Buzz Aldrin's bootprint on lunar soil

To define the lunar environment, it is appropriate to refer to the term cis-lunar space. The region contains the Earth-Moon system, including the Moon's orbits and those of the Earth.
It is possible to estimate a sphere of influence (SOI) of the EM system, which helps to understand the limits and magnitude of space, calculated as:

$$R_{SOI} \approx a \left(\frac{m_E + m_M}{m_S} \right)^{\frac{2}{5}} = 929\,182 \ km \tag{2.1}$$

considering $a = 149\,598\,261 \ km$ the distance between the Earth and the Sun, $m_E = 5.97236526 \times 10^{24} \ kg$ mass of the Earth, $m_M = 7.34603131 \times 10^{22} kg$ mass of the Moon and $m_S = 1.988475415 \times 10^{30} \ kg$ mass of the Sun.
Beyond the SOI, the Sun's gravitational force is predominant, which is why there is no longer any reference to cis-lunar space [25].
This environment includes orbits around the Lagrangian Points of the EM system, i.e. the five equilibrium points of the Circular Restricted Three-Body Problem (CR3BP), where the gravitational influences of the two primary bodies and the virtual rotational forces cancel each other out.
Moreover, the following discussion recognises that the cis-lunar region also includes terrestrial orbits, but they will be explicitly named if necessary.

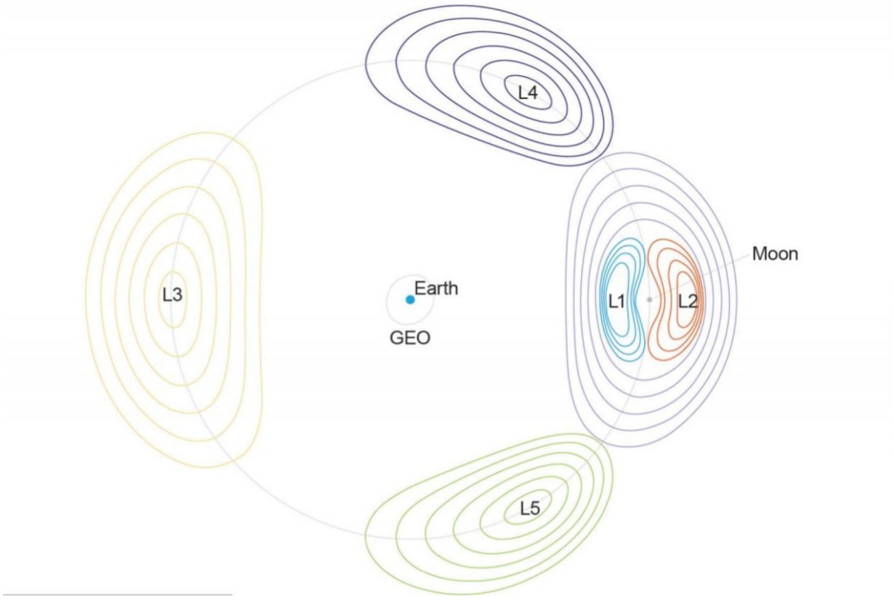


Figure 2.2: Cis-lunar space (Image credit: Jonathan Aziz, Center for Space Policy and Strategy)

2.1 The Circular Restricted Three-Body Problem model (CR3BP)

The dynamics of a satellite low orbiting around the Earth is well approximated by the two-body problem.
In this region, the minor body is mainly affected by the Earth's mass. Without disturbances like atmospheric drag, solar radiation pressure, or the influence of a third body, it follows Keplerian orbits defined by six orbital elements.
The further away from the Earth's surface, the greater the attraction felt by external bodies. Therefore, to simulate the dynamics of a satellite within cis-lunar space, it is possible to fall back on the CR3BP. This hypothesis offers a good compromise between reliability of the equations and computational simplicity.
In this model, the motion of a spacecraft with negligible mass is simulated to be under the influence of only two bodies, approximated as point masses. Further explanations can be retrieved in [26].
The treatment can be extended to any pair of main bodies, which in this case are the Earth and the Moon.
The problem is developed according to the following assumptions:

- the spacecraft, or minor body, has negligible mass;
- the primary mass m_1 and secondary mass m_2, Earth and Moon respectively,

perform a circular motion around their common centre of mass;

- $m_1 \geq m_2$.

By convention, the quantities are dimensionless, so that the characteristic length is equal to the distance between the Earth and the Moon, the characteristic mass is $m_1 + m_2$ and the characteristic time is such that the universal gravitation constant is unitary (i.e. G=1).
The only parameter of the system is the mass parameter, defined as $\mu = \frac{m_2}{m_1+m_2}$, and under these assumptions $\mu = 1.215 \times 10^{-2}$.
In order to derive the equations of motion, it is appropriate to go back to a rotating reference frame called x-y-z, with origin in the centre of mass of m_1 and m_2 and where the x-y plane is the orbital plane of the primary bodies.
Furthermore, the x-axis lies on the conjunction of the two masses, the y-axis is perpendicular to it and the z-axis completes the triad, as shown in Figure 2.3.
This reference system rotates with respect to the inertial reference system with an angular velocity equal to the mean motion of each mass.

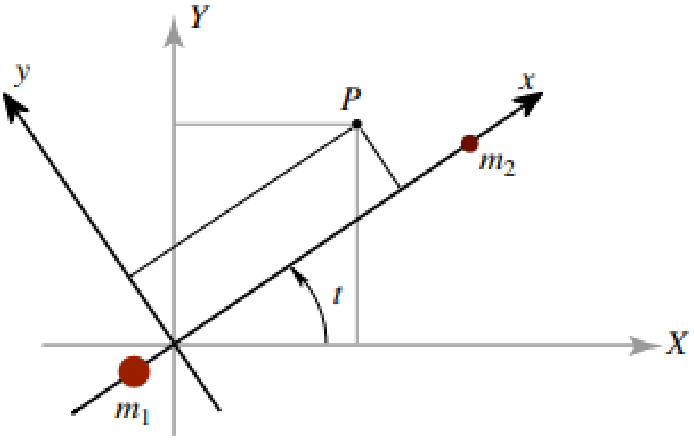


Figure 2.3: Inertial and rotating frames for CR3BP

In this way, in the rotating reference frame the mass m_1 is positioned in co-ordinates $(-\mu, 0, 0)$, while the mass m_2 in position $(1-\mu, 0, 0)$.
The gravitational potential that the spacecraft experiences due to the two major bodies is

$$U(x, y, z) = -\frac{\mu_1}{r_1} - \frac{\mu_2}{r_2} - \frac{1}{2}\mu_1\mu_2 \tag{2.2}$$

with r_1 and r_2 the distances between P and the respective masses, while $\mu_1 = 1 - \mu$ and $\mu_2 = \mu$.
The equations of motion can be derived using various approaches, such as Newtonian,

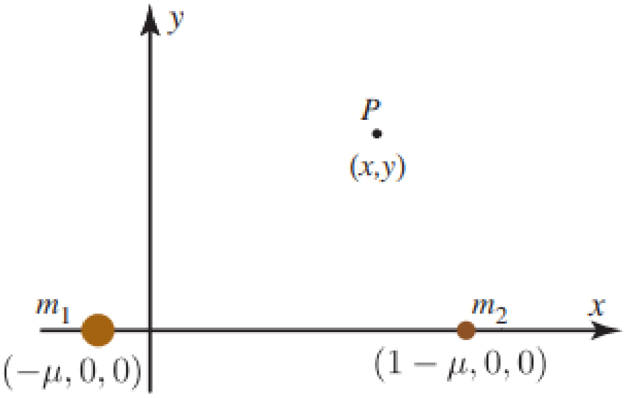


Figure 2.4: Rotating reference frame for CR3BP

Lagrangian or Hamiltonian.
After some simplifications, it is obtained

$$\begin{cases} \ddot{x} - 2\dot{y} = -\bar{U}_x \\ \ddot{y} + 2\dot{x} = -\bar{U}_y \\ \ddot{z} = -\bar{U}_z \end{cases} \tag{2.3}$$

where

$$\bar{U}(x,y) = -\frac{1}{2}(x^2+y^2) + U(x,y,z) \tag{2.4}$$

is the augmented potential.
The equations of motion (Equation 2.3) are time invariant and admit an energy integral of motion, a function of position and velocity, which can be expressed as

$$E(x,y,\dot{x},\dot{y},\dot{z}) = \frac{1}{2}(\dot{x}^2+\dot{y}^2+\dot{z}^2) + \bar{U}(x,y,z) \tag{2.5}$$

At this point, a quantity linking augmented potential to velocity is introduced, called the Jacobi integral, which can be expressed as

$$C = -V^2 - 2\bar{U} \tag{2.6}$$

where V is the velocity of the spacecraft in the rotating reference system.
This equation defines the space where motion is feasible, in particular, if $V^2 > 0$, and therefore $C > 2\bar{U}$.
It is possible to have a simplified visualisation by representing motion in a plane $\bar{U} - V^2$: knowing both position and velocity, a series of lines represent all the

motions that can be realised by varying the constant C.
The special case in which $2\bar{U} - C = 0$ defines the surfaces of zero velocity, also called Hill surfaces, limit regions in which the velocity of the spacecraft is zero.
Zero velocity surfaces can also be visualised as closed lines formed by the intersection with the horizontal plane, as in Figure 2.6.

2.1.1 Lagrangian points

Remanelling the Equation 2.3 to first order, and considering them in planar form (with z=0):

$$\begin{cases} \dot{x} = v_x \\ \dot{y} = v_y \\ \dot{v}_x = 2v_y - \bar{U}_x \\ \dot{v}_y = -2v_x - \bar{U}_y \end{cases} \tag{2.7}$$

it is possible to impose them equal to zero to find the equilibrium points of the problem.
The CR3BP, under these assumptions, admits five equilibrium points, also called Lagrange points, shown in Figure 2.5.
These five points are the precise locations where the gravitational influences of the primaries and the virtual rotational forces are balanced.
In particular, the first three L_1, L_2 and L_3 are called collinear, while L_4 and L_5

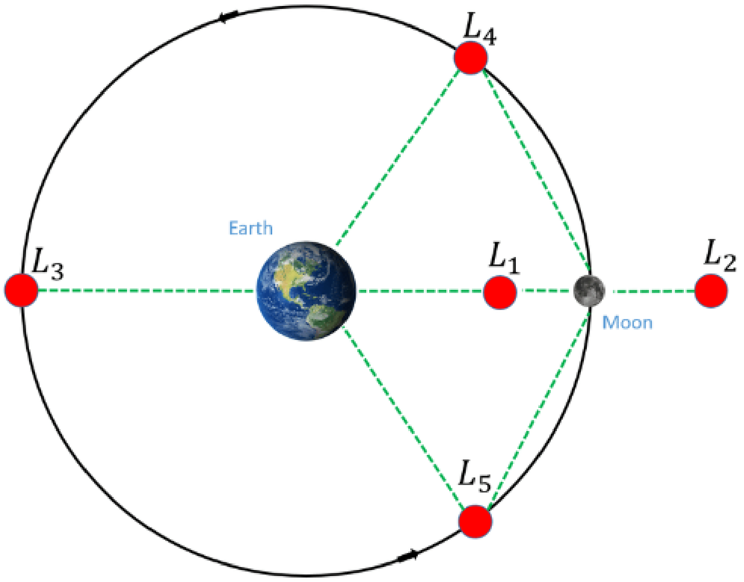


Figure 2.5: Lagrangian points for Earth-Moon system [27]

are called equilateral.
The collinear points lie on the x-axis of the rotating reference system in Figure 2.3. Therefore, all the three points have ordinates equal to zero. The abscissae, instead, can be obtained by computing the maxima of the function $\bar{U}\,(x{,}0)$, solving the quintic as a function of γ_1, γ_2 and γ_3.
In the EM system, γ_1 is the adimensional distance between L_1 and the Moon, γ_2 is the adimensional distance between L_2 and the Moon, and γ_3 is the adimensional distance between L_3 and the Earth.
To find equilateral points, on the other hand, solutions are sought which do not lie on the conjunction between the primary bodies, i.e. $y \neq 0$.
These two points are at the vertex of an equilateral triangle whose base is on the conjunction just mentioned: L_4 is in the upper half plane, while L_5 is in the lower half plane.
Table 2.1 shows the dimensionless positions of the five Lagrangian points in the planar CR3BP, with their value of Jacobi constant.

Lagrangian point	**x**	**y**	**C**
L_1	$1 - \mu - \gamma_1$	0	3.1885
L_2	$1 - \mu + \gamma_2$	0	3.1723
L_3	$-\mu - \gamma_3$	0	3.0122
L_4	$\mu - \frac{1}{2}$	$+\frac{\sqrt{3}}{2}$	2.9880
L_5	$\mu - \frac{1}{2}$	$-\frac{\sqrt{3}}{2}$	2.9880

Table 2.1: Dimensionless positions of Lagrangian points in the planar CR3BP and their value of Jacobi constant

Imagining a spacecraft at a precise point in space, with $\bar{U}$ and C fixed, it is possible to make considerations on the zones of possible motion, with reference to the Figure 2.6:

- when $C > C_{L_1}$ the spacecraft can only move around the body it is orbiting, and cannot reach the grey regions (case a);
- if C decreases the zone of motion expands, until $C = C_{L_1}$. In this situation the satellite can reach the first Lagrangian point, but it will have zero velocity;
- if $C < C_{L_1}$, as in case b, the spacecraft is able to move in the area between the Earth and the Moon;
- if $C < C_{L_2}$ (case c) the spacecraft manages to escape the EM system from "behind" the Moon;

- if $C < C_{L_3}$ the spacecraft can move freely in space, with the exception of the areas near the last two Lagrangian points.

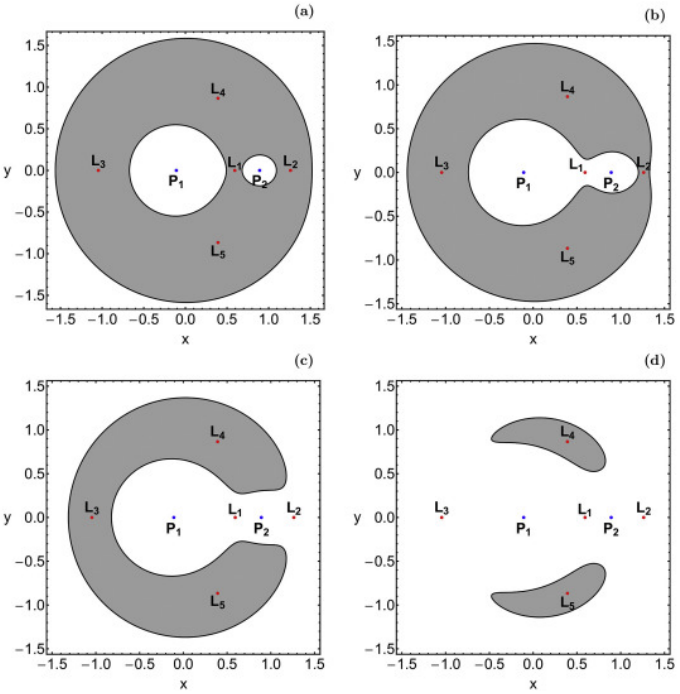


Figure 2.6: Zero velocity curves for some C values in Earth-Moon system [28]

2.1.2 Bicircular Restricted Four-Body Problem (BCR4BP)

The CR3BP considers the influence of only two bodies on a third, namely the Earth and the Moon. This approximation is acceptable for bodies in the vicinity of the lunar surface, but the higher the altitude of the spacecraft from the lunar ground, the greater the attraction of a fourth body, the Sun.
This is why it is appropriate to refer to the Bicircular Restricted Four-Body Problem (BCR4BP), which can also be used to compute trajectories to reach cis-lunar space from Earth.
Only the relevant equations and results will be presented, as there are already researches on the subject [26], [29].
The problem is developed according to the following assumptions:

- The spacecraft, or minor body, has negligible mass;
- The Earth and Moon perform circular orbits around their centres of mass;

- The centre of mass of the EM system performs a circular orbit around the centre of mass of the Sun-Earth-Moon (SEM) system;
- The orbits of all bodies are on the same plane;
- It is defined P_1 the Earth, P_2 the Moon, P_3 the spacecraft and P_4 the Sun.

To develop the problem, a two-dimension rotating synodic system is used with respect to the EM system.

The origin is positioned in the centre of mass of the EM system, the x-axis connects the Earth and the Moon, and the y-axis is such that it is orthogonal to x.

In this non-inertial reference system, the Earth and Moon have fixed positions, while the Sun is rotating clockwise around the origin.

In Figure 2.7, the positions of the four bodies can be seen: in particular, a mass of $1-\mu$ has been assigned to the Earth and μ to the Moon, with $\mu = 1.215 \times 10^{-2}$ as in the previous case, in order to obtain a unitary value of the Gravitational constant G.

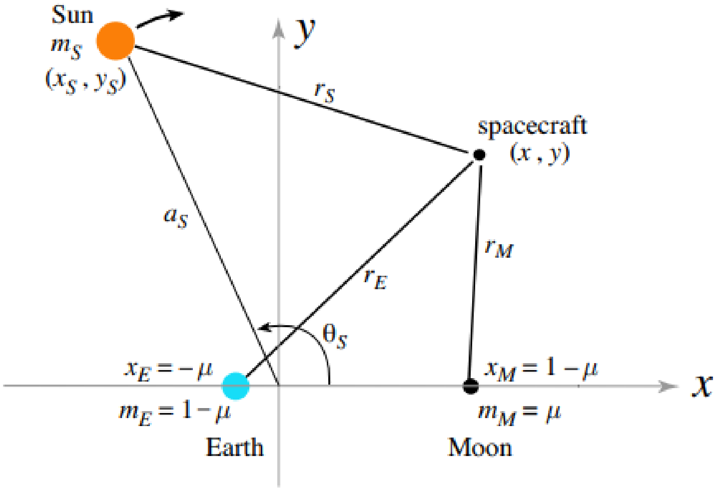


Figure 2.7: Rotating coordinate frame in the BCR4BP approximation

The equations describing the motion of a satellite in the system of Figure 2.7 are given by:

$$\begin{cases} \ddot{x} = 2\dot{y} + \frac{\partial \Psi}{\partial x} \\ \ddot{y} = -2\dot{x} + \frac{\partial \Psi}{\partial y} \\ \ddot{z} = \frac{\partial \Psi}{\partial z} \end{cases} \tag{2.8}$$

with Ψ *pseudo-potential* in the BCR4BP defined as:

$$\psi = \frac{1-\mu}{r_{13}} + \frac{\mu}{r_{23}} + \frac{x^2+y^2}{2} + \epsilon \left(\frac{m_4}{r_{43}} - \frac{m_4}{a_s^3}(x_s x + y_s y + z_s z) \right) \tag{2.9}$$

where r_{ij} is the position magnitude of P_i relative to P_j, m_4 is the non-dimensional mass of the Sun $m_4 = \frac{m_s}{m_E+m_M}$ and a_s is the semi-major axis of the circular orbit reflecting the motion of the Sun around the center of mass of the EM system [29]. The term ϵ is a scaling parameter for the Sun mass, so $\epsilon = 0$ reflects the EM CR3BP with no solar gravity, $\epsilon = 1$ for the BCR4BP.

The BCR4BP does not possess any integrals of the motion, but it is possible to derive a quantity similar to the energy used to study transfers in the lunar environment, defined as:

$$H = 2\psi - v^2 \tag{2.10}$$

with v velocity of the spacecraft, in the reference system of Figure 2.7.

2.1.3 Higher fidelity models

The BCR4BP improves the representation of the dynamical forces acting on a satellite by also considering the influence of the Sun. Despite this, to have a complete understanding of the gravitational forces acting on a mass it is appropriate to consider the influence of N-1 celestial bodies, studying the N-body problem.

In this formulation, the motion of a satellite is subject to the gravitational attraction of N-1 celestial bodies, to which the periodically updated ephemeris state is incorporated. The positions and velocities of the interpolated N-1 bodies are extracted from the Navigation and Ancillary Information Facility (NAIF) server at the Jet Propulsion Laboratory (JPL).

The equations of motion are formulated as

$$\ddot{\bar{r}}_{c,s} = -\frac{Gm_c}{r_{c,s}^3}\bar{r}_{c,s} - G\sum_{i=1}^{p} m_i \left(\frac{\bar{r}_{c,i}}{r_{c,i}^3} - \frac{\bar{r}_{s,i}}{r_{s,i}^3}\right) \tag{2.11}$$

where $\bar{r}_{c,s}$ is the position vector from the central body, c, to the spacecraft s (assumed, as the previous cases, massless), G is the universal gravitational constant, m_i is the mass of the i^{th} perturbing body, m_c is the mass of the central body, $\bar{r}_{c,i}$ is the position vector from the central body to the i^{th} perturbing body, and $\bar{r}_{s,i}$ is the position vector from the spacecraft to the i^{th} perturbing body, where there are a total of p perturbing bodies.

As can be seen from the structure of the formula, the computational cost to derive the forces at play on a satellite is very high, reflecting the complexity of the space surrounding the Moon.

Furthermore, the ideally periodic orbits that a spacecraft would travel, around a Lagrangian point or around the Moon, are actually to be corrected by exploiting the influence of N-bodies and the irregularity of the lunar gravitational field.

For these reasons, this work is not presenting the demonstration of this model.

2.2 Significant orbits in cis-lunar space

Orbital mechanics around the Earth is characterised, as discussed in the previous section, by Keplerian orbits. The assumptions of the two-body problem cause satellites to travel orbits with known geometric shapes: circular, elliptical, parabolic and hyperbolic.
In cis-lunar space, however, it is not possible to describe the motion of a satellite using Keplerian assumptions, and trajectories in this environment are highly perturbed.
Considering the simplest hypothesis dealt with, the CR3BP, the following differences with Keplerian orbits can be highlighted, with the exception of special cases [30]:

- trajectories no longer repeat themselves;
- trajectories are no longer planar;
- trajectories can no longer be described as simple geometric functions.

In the context of the above assumptions, as anticipated, there are exceptional orbits that repeat their path after a given period of time.
Examples of periodic orbits in the cis-lunar space can be Halo or Lyapunov orbits around Lagrangian points and Distant Retrograde Orbits (DROs).
Other special orbits are the Low Lunar Orbits (LLOs), where a satellite travels on a closed trajectory around the Moon, very near its surface.
Unfortunately, the attractions of other celestial bodies adversely affect periodic paths, and the presence of N-bodies makes them almost periodic enough to remain in the vicinity of the initial points.
One of the biggest issues with these orbits, however, is their instability. Several reasons lead a satellite to drift quickly, including the attraction of other bodies, the solar radiation pressure and the irregularity of the lunar gravitational field (especially for Low Lunar Orbits (LLOs)).
The latter, is due to the presence of concentrations of masses, or mascons, on the surface, which greatly increase the force of gravity at that particular site, causing an uncontrolled satellite impact in months or years.
The following subsections will investigate in more detail the orbits that are and will be used most in the future in cis-lunar space.

2.2.1 Orbits around the Moon

Low lunar orbits

Among the orbits with the Moon as main body, the most historically used are certainly the LLO.

Usually, LLOs are defined as circular or elliptical trajectories in the region of space below 750 km height from the Moon. With this conditions, the Earth's attraction is negligible, in favour of dynamics governed by the highly non-spherical lunar gravity field [31]. However, unlike the Earth, the lunar atmosphere is very thin and does not influence the path of a satellite.

For this reason, it is possible to exploit trajectories that are much closer to the lunar ground than Low Earth Orbits (LEOs), which is why most applications for LLOs use orbits up to 200 km high.

Until now, Low Lunar Orbits (LLOs) have been used with the scope to observe the lunar surface or to study its gravitational field, for instance during NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission.

They have also been, and will continue to be, employed as staging orbits for access to the lunar surface, as demonstrated with the three ISRO Chandrayaan missions and the China National Space Administration (CNSA) Chang'E programme.

However, due to the instability of the environment, a spacecraft in a LLO needs frequent station-keeping in order not to impact the soil in a short time.

The closer to the lunar surface, the greater the effect of the mascons, which cause orbits to decay in periods of less than a year [32].

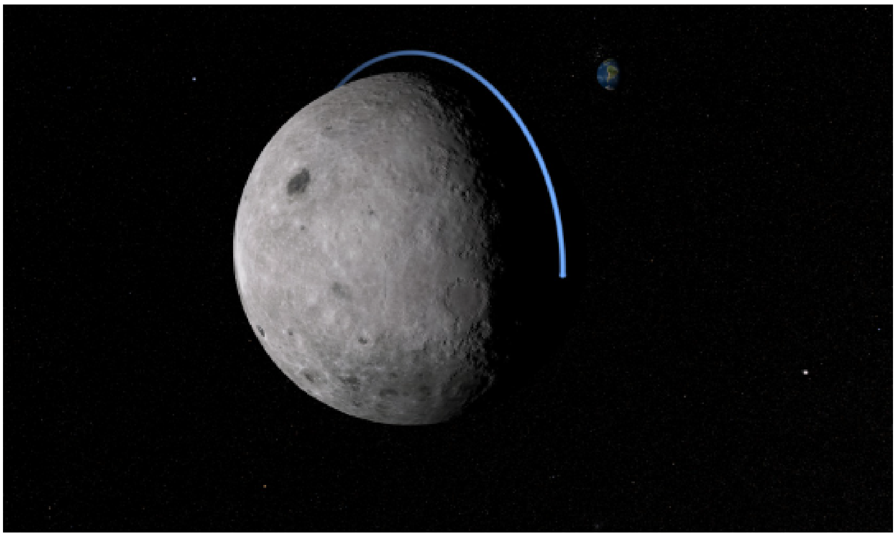


Figure 2.8: Lunar Reconnaissance Orbiter orbit, (Image credit: NASA)

Lunar frozen orbits

Despite this instability, there is a small set of trajectories around the Moon that are characterized by maintaining a nearly constant eccentricity on average, with a fixed argument of periapsis.

These are called Lunar Frozen Orbits and exist for certain combinations of eccentricity, inclination and energy.
They are closed circular or elliptical paths, and according to Elipe A. and Lara M. [33] two particular families have been identified:

- S_0: it starts at the equator with low eccentricities and it continues up to an inclination of 90° with progressively larger eccentricities. This family presents two dips in eccentricity at inclinations around 27° and 53°.

- S_1: the family starts with I=86°.46 and e=0.153 and ends with an inclination I=73°.89 and e=0.146. There is a dip at I=78°.26 with a minimum of e=0.0002.

Intuitively, due to their excellent stability (and thus low propellant requirement for correction), they are very desirable for long duration missions for scientific and reconnaissance purposes, and range over different altitudes.
The NASA's LRO travelled through a quasi-frozen orbit during a commissioning phase, before entering a circular polar orbit 50 km above the lunar ground.
A peculiar sub-class of the frozen orbits are the Elliptical Lunar Frozen Orbits (ELFOs), deeply analysed in [34]. They gained more attention in recent years, as constellations of a few spacecraft in the Elliptical Lunar Frozen Orbits (ELFOs) would provide total coverage of the lunar surface for telecommunication systems.
The orbits are elliptical with their line of apsides librating in the polar region, and exhibit lifetimes in excess of ten years.
Numerous space actors designed and are designing future missions to populate the Elliptical Lunar Frozen Orbits (ELFOs): CNSA launched on 20th of March 2024 the Queqiao-2 relay-satellite, a 1,200 kg spacecraft with an antenna larger than 4 metres in diameter, which will support communication with the new Chinese Chang'e landers throughout the 2020s.
On the 2nd of April 2024 Queqiao-2 entered in an elliptical frozen orbit of 200 km × 16,000 km with an inclination of 62.4°, where it is expected to operate for the coming years [35].
ESA as well is working to shape the service provision and infrastructure to grant sustainable commercial Lunar data-relay services for communication and navigation around the Moon, within the Moonlight project.
A constellation of interconnected lunar orbiters will enable surface missions operating on the far side of the Moon, without direct to Earth line of sight, to keep constant contact with Earth.
It will also provide lunar navigation signals to support critical mission phases, such as precision landing of scientific equipment and the operation of rovers.
The first spacecraft of the program will be the Lunar Pathfinder, with the launch currently scheduled for 2025, offering communication services to any lunar asset,

both on the surface and in orbit [36].
The Pathfinder will be placed in an ELFO that will provide long duration coverage over the Lunar South Pole and long accesses to Earth. The orbit has an inclination of almost 55°, an eccentricity of 0.58 and a periselene altitude of 673 km.

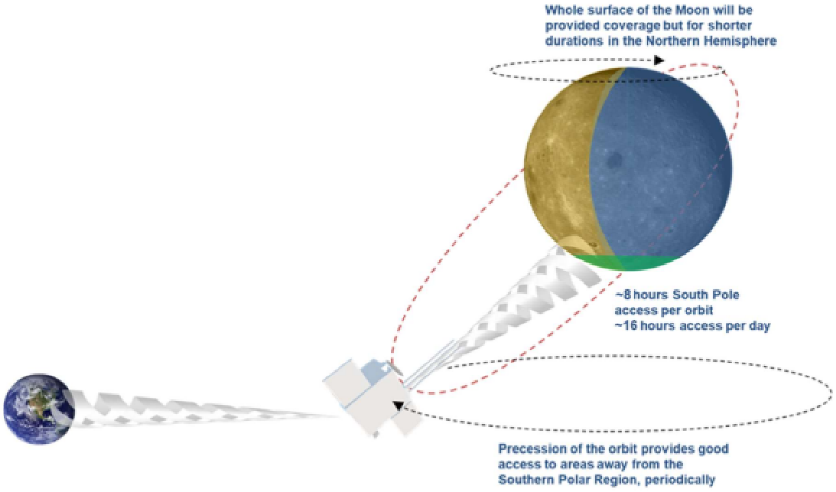


Figure 2.9: Lunar Pathfinder ELFO [36]

Distant retrograde orbits

An additional family of trajectories around the Moon with growing interest are the Distant Retrograde Orbits (DROs).
These orbits are known to be stable solutions of the CR3BP: as early as the late 1960s, studies demonstrated the existence of certain regions of stable orbits under these assumptions [37].
In particular, in the EM system, the motion of a satellite in a DRO is opposite to the direction of the Moon around the Earth, at a height of the order of tens of thousands of kilometres from the surface of the Moon.
Due to their unique characteristic, Distant Retrograde Orbits (DROs) can have several applications: L. Jannin et al. [38] propose them as future parking orbits in cis-lunar space, G. L. Condon and J. Williams [39] speculate them as a graveyard for captured meteorites, and finally M. Stramacchia et al. [40] as an environment in which to position satellites for space-based observation purposes.
The stability of these trajectories is also reflected in high-fidelity models: thanks to an analysis conducted following spacecraft break-up events [41], Distant Retrograde Orbits (DROs) show significant secondary fragmentation permanence.
In spite of this, however, the orbits have a high access cost, also from cis-lunar

space [42] [43], and the number of objects that have travelled them is very limited:

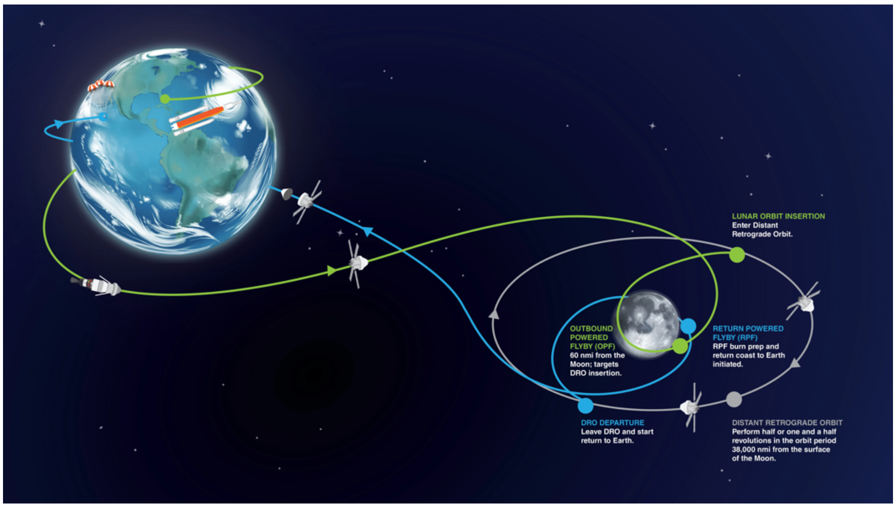


Figure 2.10: Concept of Operations of Artemis 1, with Orion immission into a DRO, (Image credit: NASA)

- The Chang'e 5 orbiter was the first satellite to enter this environment, at the end of 2021 [44]. The spacecraft, previously around the first Earth-Sun Lagrangian point, returned to cis-lunar space, with no official announcement from the CNSA.
  In 2022, several amateur observers recognised it [45].
- On 25th November 2022, the Orion capsule, part of the Artemis 1 mission, entered a DRO, about 70,000 km from the Moon's surface, and remained there for six days [46].
- On 13th of March 2024 the Chinese media announced that two spacecraft had not been inserted accurately into their designated orbit by the rocket's Yuanzheng-1S upper stage.
  These satellites were supposed to be DRO-A and DRO-B, and were designed to be inserted in a DRO, to communicate with another satellite, named DRO-L, in LEO [47].

2.2.2 Orbits around the Lagrangian Points

As anticipated, a satellite in cis-lunar space can also orbit around stability points, the Lagrangian points of the EM system.
Among these trajectories, analysed with high-fidelity models, only few of them repeat naturally, and sometimes have their period shortened or extended by a few

days in a month.
Except in rare cases, these orbits are characterised by instability, which is why a spacecraft travelling there needs propellant for station-keeping.
Within this set, there are different types of trajectories.
The first are closed and remain in the plane of the EM system, called Lyapunov orbits. The second are closed and include out-of-plane components of the EM system, controlled so that the in-plane and out-of-plane frequencies to be connected, called Halo orbits [48].
Most missions with interest in the Moon are directed towards the first (EML_1) or second (EML_2) Lagrangian point, since they are the closest to the lunar surface. Moreover, the cost of station-keeping in this environment is moderate, on the order of tens of m/s per year [49].
Other advantages of an orbit around EML_1 and EML_2 include [3]:

- to avoid interaction problems with the lunar surface (e.g. lunar dust);
- do not be affected by gravity perturbations of Earth and Moon;
- as of 2024, there is no high danger of collision with man-made and/or natural space debris;
- the lunar soil is accessible;
- especially for EML_2, there is a long period of viewing the far-side of the Moon.

Several satellites travelled or are currently travelling a Halo orbit around the first and second stability points, and more are planned for the future.
For example, Queqiao, a relay spacecraft for the CNSA's Chang'e 4 mission, travels a Halo EML_2 since 2018. Furthermore, EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS) is a cubesat developed by Japan Aerospace Exploration Agency (JAXA) and deployed by Orion, en route to another EML_2 Halo.
In contrast to the first two collinear points, the equilateral Lagrangian points offer better stability: a spacecraft orbiting EML_4 or EML_5 may require less station-keeping propellant [50].
Due to their peculiar solidity and position about halfway between Earth and Moon, these orbits are the subject of discussion for possible constellations of space-based observing satellites [48], especially for the observation of cis-lunar space.
Another reason they are currently being studied is the presence of dust clouds, known as Kordylewski dust clouds, whose magnetic and electrical characteristics are not yet fully understood.
Discovered by Kazimierz Kordylewski in 1961, recent mission proposals to observe these dust clouds using space-based methods have been emerging [51], as they are difficult to capture from Earth's surface.

A subset of the Halo orbits expected to be of future use are the Near Rectilinear Halo Orbits (NRHOs), particularly around the EML_2 point. These special trajectories are characterized by very close passes over the lunar poles and show considerable stability.
A NRHO around EML_2 has been chosen for the future Lunar Gateway: in particular, it has a resonance of 9:2 with reference to the lunar synodic period, which allows to avoid long periods of eclipse caused by the Earth's shadow [52].
In addition, it has a perilunium of a few thousand kilometres, granting an easy access to the Moon's surface, and an apolunium of over 70,000 km.
Thus, a spacecraft operating in the NRHO of the Gateway completes a highly elliptical orbit in a reference system centered on the Moon, constantly oriented towards Earth, and requiring about 10 m/s per year for station-keeping.
To test the feasibility of the Lunar Gateway's trajectory, NASA launched a 12-unit cubesat, Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE), into the same NRHO in 2022. In May 2023, the spacecraft completed its primary mission, extending its operations to demonstrate the stability of this orbit [53].

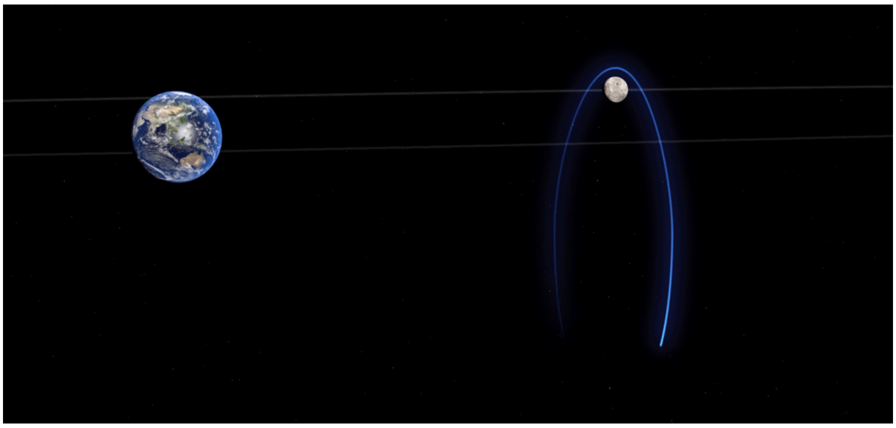


Figure 2.11: Gateway's near-rectilinear halo orbit, or NRHO, around the Moon, (Image credit: NASA)

The six satellites orbiting in the vicinity of the Moon as 2023 are shown in Figure 2.12:

- CAPSTONE is in a NRHO around EML_2;
- the Chandrayaan-2 orbiter, the LRO and the Korea Pathfinder Lunar Orbiter (KPLO) travel through Low Lunar Orbits (LLOs);
- Time History of Events and Macroscale Interactions during Substorms (THEMIS)-B and THEMIS-C are in two elliptical orbits around the Moon.

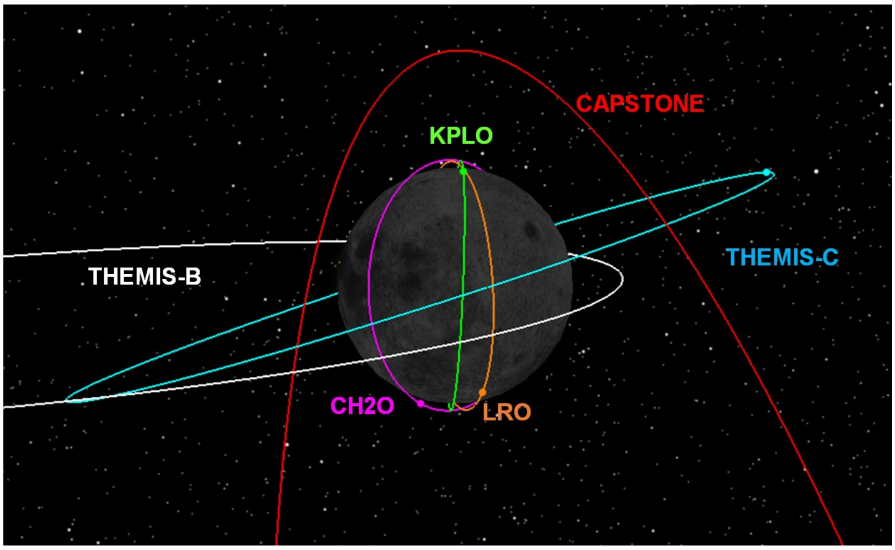


Figure 2.12: Current space situation around the Moon, (Image credit: ISRO)

On top of those, there are three more satellites launched in March 2024 from the CNSA into a large elliptical frozen orbit around the Moon: Queqiao-2 and the pair of spacecraft Tiandu, which will perform lunar navigation and communication [54]. Additionally, several satellites are either already in Halo orbits or are on trajectories to reach them. Further, the orbiter from the Chang'e 5 mission is believed to be in a Distant Retrograde Orbit (DRO), though official confirmation is still pending.
Over 70 objects are expected to be launched into cis-lunar space during this decade, a region that, as debated along this chapter, requires meticulous management due to its instability and the limited knowledge of its dynamics.
A break-up event, collision or release of debris in lunar orbits can have catastrophic consequences, with a much greater chance of fragmentation proliferation than in terrestrial orbits.
For this reason, in order for the twenties to be called the Roaring '20s of the Moon, there is an urgent need to act in a sustainable and responsible way, sharing the conduct with the space community.

Chapter 3

A state-of-the-art for policies of the space sector

As mentioned in chapter 1, space research and exploration are progressing, and consequently space law must also advance.
Regulating human activities in this environment is crucial, as it fosters the development of coordination and transparency necessary to ensure prosperous growth and peaceful uses in this field.
The first official document, and among the few legally binding ones, dealing with principles to govern the activities of states in space is the Outer Space Treaty, promulgated on the 27th January 1967 [2].
The OST also concerns the Moon and other celestial bodies, and covers high-level topics, including:

- Free exploration by all States and the prohibition of appropriation;
- The promulgation of cooperation and transparency for purely peaceful purposes, and the prohibition on the use of nuclear weapons in orbit;
- The responsibility of States for their own actions and objects.

The OST was supported during the 1960s and 1970s by other international legislative documents, disseminated by the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS), such as the Liability Convention [55], the Moon Agreement [56], the Astronaut Rescue and Return Agreement [57] and the Registration Convention [58].
However, the themes addressed by the above-mentioned regulations are of a general nature, and do not take into account various current issues, such as the space debris.
In this regard, a number of documents of a non-legally binding nature have been

promulgated in recent years, which attempt to fill the gaps in the older treaties. Above all, they provide guidelines that raise awareness on how to behave in outer and Earth-bounded space.
A very important branch of space law is certainly sustainability: in the section 1.2 three definitions of the term were given, and as already announced, the discussion focuses on environmental sustainability, in particular on the space debris issue.

3.1 Policies for Earth orbits sustainability

When relating Earth orbits sustainability to space activities, it often refers to ESA Clean Space Office's branches interest areas [59]: EcoDesign, thus addressing the Earth's environmental impact (understood as the atmosphere, the water and the soil) coming from the life-cycle of a space mission; End-of-life Management, to minimise the creation and proliferation of space debris with regulations and technologies; and In-Orbit Servicing, to design specific missions and services which provide maintenance to spacecraft directly in orbit during operations, and possibly remove the deceased ones.
The problem of space debris and the overcrowding of orbits was presented in the subsection 1.2.1, along with the measures that can be implemented to limit it.
Literature on this subject is expanding, and several organisations at international and national level have been working on policies that are entirely dedicated, or take in consideration, space debris and the mitigation of them:

- The UN issued the United Nations Space Debris Mitigation Guidelines, a non-legally binding document [60];

- At international level there are standards issued by ISO, and also the IADC guidelines [15].
  The latter, subscribed to by numerous states, provide guidance on minimising potential on-orbit break-ups, limiting the release of debris during normal operations and on post-mission disposal;

- National policies promulgated by space agencies, with mandatory value for government programmes, such as NASA, ESA, Centre National d'Etudes Spatiales (CNES) and Deutsches Zentrum für Luft-und Raumfahrt (DLR).
  Among these, the ESA Space Debris Mitigation Requirements [17] present both a Space Debris Mitigation Plan (SDMP) (i.e. a plan for the implementation and verification of the requirements), and a Space Debris Mitigation Report (SDMR), which contains verification methods, reports and close-outs;

- Finally, industry is also joining forces to create documents containing best practices for mitigating terrestrial space debris.

> The Zero Debris Charter [61], an initiative facilitated by ESA and created and written by more than 40 space actors, stands as a model, with the target of achieving Zero Debris by 2030.

The problem of space debris in Earth orbit was raised more than 20 years ago, when in February 1999 the Scientific and Technical Subcommittee (STSC) of the UN COPUOS first adopted a "Technical Report on Space Debris".
This report, debated in the 3rd European Conference on Space Debris [62], did not stipulate the establishment of a space debris order on the UN COPUOS agenda, nor did it mention any legal aspect on this issue.
In spite of this, it was a fundamental pillar for the elaboration of a number of starting points on which to begin work, including mitigation techniques.
For this reason, it is clear that the issue of sustainability on the Moon and in its orbits needs to be raised as soon as possible. Despite the relatively extensive literature on space debris around Earth, which has existed for several decades, the problem has continued to grow.
Most space actors "opened their eyes" only when such measures became necessary, such as performing Collision Avoidance Manoeuvres (CAMs) or launching dedicated missions to remove space debris.
It is not premature to start discussing techniques for debris mitigation in cis-lunar space: in the coming years, people will continue to launch objects into this unstable and restricted environment, increasing the possibility of precluding certain orbits.
Mindful of what happened (and still happens) to Earth, it is at least possible to try to prevent lunar orbital pollution.

3.2 Policies for lunar sustainability

As mentioned above, while regulations are growing for sustainability of Earth, the literature on this subject for the Moon is still very scarce. Only recently, especially in the current decade, States and industries began to mobilise.

Following the last century's treaties promulgated by the UN, such as the OST and the Moon Agreement (in which the Moon was mentioned along with the other celestial bodies), both lunar missions and related policies slowed down for about 30 years.

During the Apollo program, not only the operators, but also the astronauts juggled without having a solid legislative basis on how to behave, especially considering a sustainability mindset.

In May 2019, NASA announced the Artemis Programme, which will culminate in the first human moon landing in the new millennium.

From that moment on, the international space community began its efforts to establish a legal framework that could guide proper actions on this celestial body, which is expected to see an exponential increase in both orbital and surface activity in the coming years.

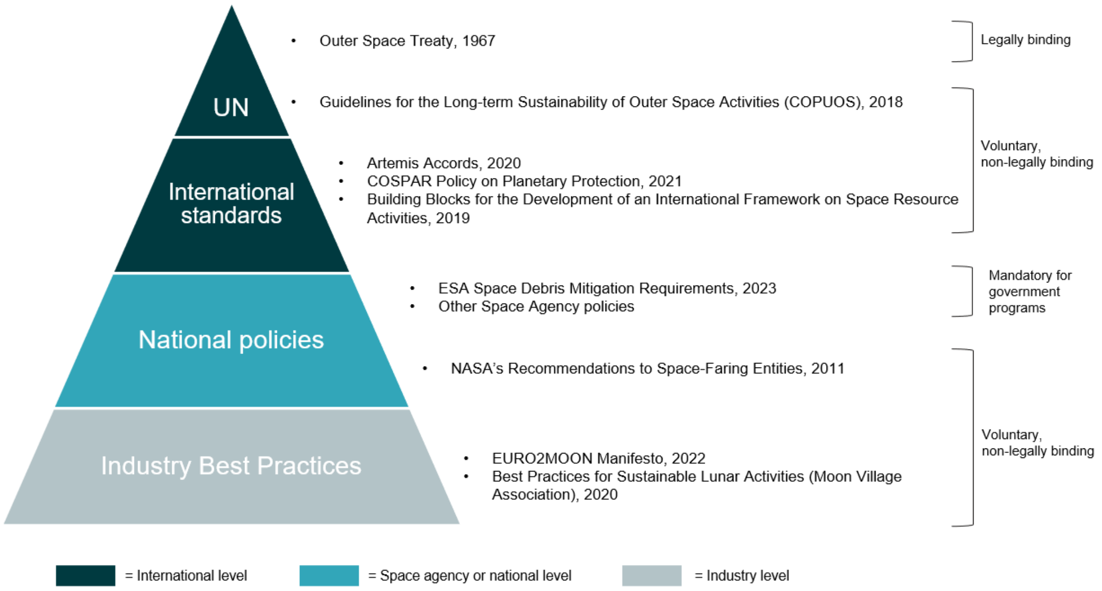


Figure 3.1: Framework of policies for lunar sustainability, adapted from ClearSpace presentation at Clean Space Industry Days 2023

In Figure 3.1 there is a panoramic of the most important documents dealing

with or mentioning lunar sustainability, categorised according to jurisdiction level.
In addition to the aforementioned OST, one of the only legally binding, the most revolutionary document in the recent history of space exploration is undoubtedly the Artemis Accords [8], signed on 13 October 2020 by then eight states.
For one of the first time, the subject of safety on the Moon is addressed, with principles that aim to "increase the safety of operations, reduce uncertainty, and promote the sustainable and beneficial use of space for all humankind".
Further, the Artemis Accords have raised much clamour among the scientific community: in fact, the extraction and trade of space resources is authorised. This results in the creation of safety zones, which would restrict access to certain areas on the surface, like heritage artefacts from Apollo program.
On the other hand, the accords states are committed to find solutions to mitigate the creation and proliferation of space debris in outer space, including through efficient post-mission disposal.
Another relevant policy at international level is the Policy on Planetary Protection [63], promulgated by the Committee on Space Research (COSPAR).
In the text, to each celestial body is assigned a category, from 1 to 5, depending on the level of restrictions to be applied in order not to contaminate it with human and non-human missions.
For flyby, orbiter and lander missions to the Moon, Category 2 has been declared, and in particular the following restrictions should be applied:

- orbiters and fly-by missions must submit a planetary protection plan, and reports on each mission phase;

- landers, in addition to the precautions of orbiters, must ensure that they do not contaminate the lunar environment with elements released by the propulsion system.
  Moreover, if their target are the poles or the Permanently Shadowed Regions (PSDs), a complete inventory of all organic materials on board is required.

From this, it follows that the impact on the lunar surface is permitted, and is not regulated in any way yet.
As with the terrestrial environment, in cis-lunar space industries join efforts to provide best practices on topics of interest including lunar exploration and the use of space resources in an efficient and sustainable manner.
Among them, the association EURO2MOON [64], a consortium founded by AirLiquid, Airbus Defence & Space and ispace Europe, in its Manifesto proposes four objectives in order to create a strong industrial ecosystem, developing an ambitious and sustainable ISRU implementation plan:

- representing the industrial members of the space and non-space domain;

- creating a platform for discussion and for the provision of recommendations, based on interoperability and standardization;
- advocating to European stakeholders to define dedicated investments;
- fostering a European industrial ecosystem dedicated to the sustainable exploration of lunar resources.

Enriching the literature on lunar sustainability is crucial.
However, space actors also need precise guidelines to know how to behave according to the type of mission.
In the Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts [65], NASA took the first steps towards drafting technical advice for soft and hard landing missions. Among other recommendations, it is asserted that the point of impact of an object should be no closer than 2 km from a cultural heritage, intended as previous impact or landing sites.
Regardless, the ESA Space Debris Mitigation Requirements [17] mark an important milestone in the definition of lunar sustainability, especially in the topic of space debris.
This document contains a section entirely dedicated to lunar orbits, specifically mentioning the avoidance of debris in this habitat, and also dealing with space traffic coordination.
In addition, for the first time the disposal options of an object in this environment are debated and proposed.
In the requirements, disposal is intended as "actions performed by a spacecraft or launch vehicle orbital stage to permanently reduce its chance of accidental break-up and to achieve its needed long-term clearance of the protected regions".
ESA indicates four different techniques: lunar impact, injection in a heliocentric orbit, injection in a lunar graveyard orbit and Earth re-entry.
The pros and cons of each will be discussed in detail in the chapter 4.
What is required by the experts, above all, is a justification of the choices made, with orbit propagation analysis, assessment of the impact point on lunar soil and probability of re-entry to Earth, contained in a clear SDMP.
The compulsory sharing of this type of documentation allows space actors to be aware of the actions of their colleagues, with a twofold benefit: on one hand, knowing the actions and positions of objects in an unstable environment, and on the other hand, increasing knowledge of an habitat still mysterious.

3.3 Sustainability in contemporary space missions

The section 3.2 showed that the literature on lunar sustainability is in its infancy. While the problem has been identified, there are few practical demonstrations of viable solutions.

Even though the number of guidelines for this environment is limited, missions to the Moon are increasing: since 2020, almost 30 objects - including orbiters, landers and flybys- reached cis-lunar space.

The lack of specific regulations and comprehensive knowledge resulted in less attention being given to the end-of-life phase of spacecraft in this habitat.

Addressing this issue requires enhancing transparency among stakeholders. Improved coordination would help prevent the creation of unwanted space debris and contribute to a prosperous lunar space economy.

While lunar sustainability is still in its early stages, examples of end-of-life phases for lunar missions provide cases that highlight the need for more structured guidelines. Despite this, it is evident that space actors are going towards this direction.

In November 2019, the camera of NASA's LRO [66] captured an image of a crater on the Moon's surface, caused by the impact of China's Longjiang-2 satellite.

Launched in 2018 alongside the Queqiao satellite as part of a communication relay mission to the Moon, Longjiang-2 was designed to operate for one year in an elliptical lunar orbit.

As its mission neared completion, the CNSA decided to lower its periaxis by about 500 km. This reduction in altitude allowed gravitational forces to naturally bring the satellite to a collision with the lunar surface in half an hour [67] [68].

The manoeuvre resulted in a crater nearly 5 meters in diameter and 10 meters deep [69], discovered through amateur observations and imagery from the LRO's camera.

A further example involves the Chang'e 5 service module and its associated manoeuvres.

As announced, the Chang'e 5 mission included four modules -a service module, a lander, an ascent vehicle and an Earth return module- with the aim of returning a lunar sample to Earth.

After achieving its main goal, the service module entered an orbit around the first Lagrange point (L_1) of the Sun-Earth (SE) system [70].

Later, the module executed a maneuver placing it in a DRO around the Moon, a development observed by several amateur astronomers [45]. This made China the first nation to utilize this type of trajectory.

The rationale behind this maneuver by CNSA has not been officially disclosed. However, experts believe that the service module may be conducting tests in preparation for future lunar missions [44], as part of the ongoing development of the Chang'e program.

In July 2023, the ISRO launched Chandrayaan-3, a mission to demonstrate the ability to safely land on the lunar surface.

The spacecraft consisted of three components, a lander, the propulsion module and a rover [71]. The mission was a success, and in August 2023, India became the fourth country to achieve a soft landing on the Moon.

While the lander and the rover touched down, the propulsion module remained in a circular polar LLO 100 km above the lunar surface [71], in an environment that, as explained in subsection 2.2.1, is known to be unstable.

On 30th October 2023, three months after the launch, ISRO officially announced that the propulsion module was equipped with two radioisotope heating units [72].

On 4th December 2023, ISRO revealed that the propulsion module successfully performed a return maneuver in October and is now in a parking orbit 154,000 km from Earth, as shown in Figure 3.2. According to Indian press reports, this action was taken to "avoid uncontrolled crashing of the propulsion module on the Moon's surface at the end of its life, thereby meeting the requirement to prevent the creation of space debris" [73].

On the other hand, the end-of-life management of CAPSTONE, is already re-

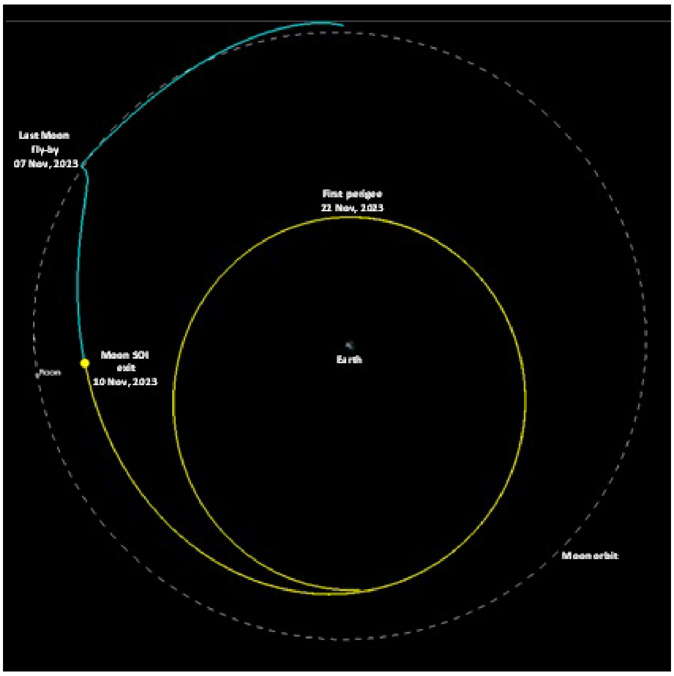


Figure 3.2: Chandrayaan-3 Propulsion Module Earth arrival trajectory, (Image credit: ISRO)

vealed.
Launched by NASA in June 2022, this cubesat was designed to test the feasibility of a Near Rectilinear Halo Orbit (NRHO) around the Moon, an orbit planned for the future Lunar Gateway. Over two years later, the mission remains operational in this orbit.
In addition to this, NASA in the monthly webinar Small Spacecraft Systems Virtual Institute's (S3VI), in March 2023, held a presentation entitled "An Overview and Status of the CAPSTONE Mission" [74]. During this speak, it has been said that the satellite will impact on the lunar surface, along with other details presented in Table 3.1, such as the amount of propellant required, the point of impact and the velocity.

Manoeuvre magnitude and direction	**Impact coordinates**	**Impact velocity**	**Impact angle**
[-5,0,0] m/s	81.89421° N 15.22779° E	2.349 km/s	6.63°

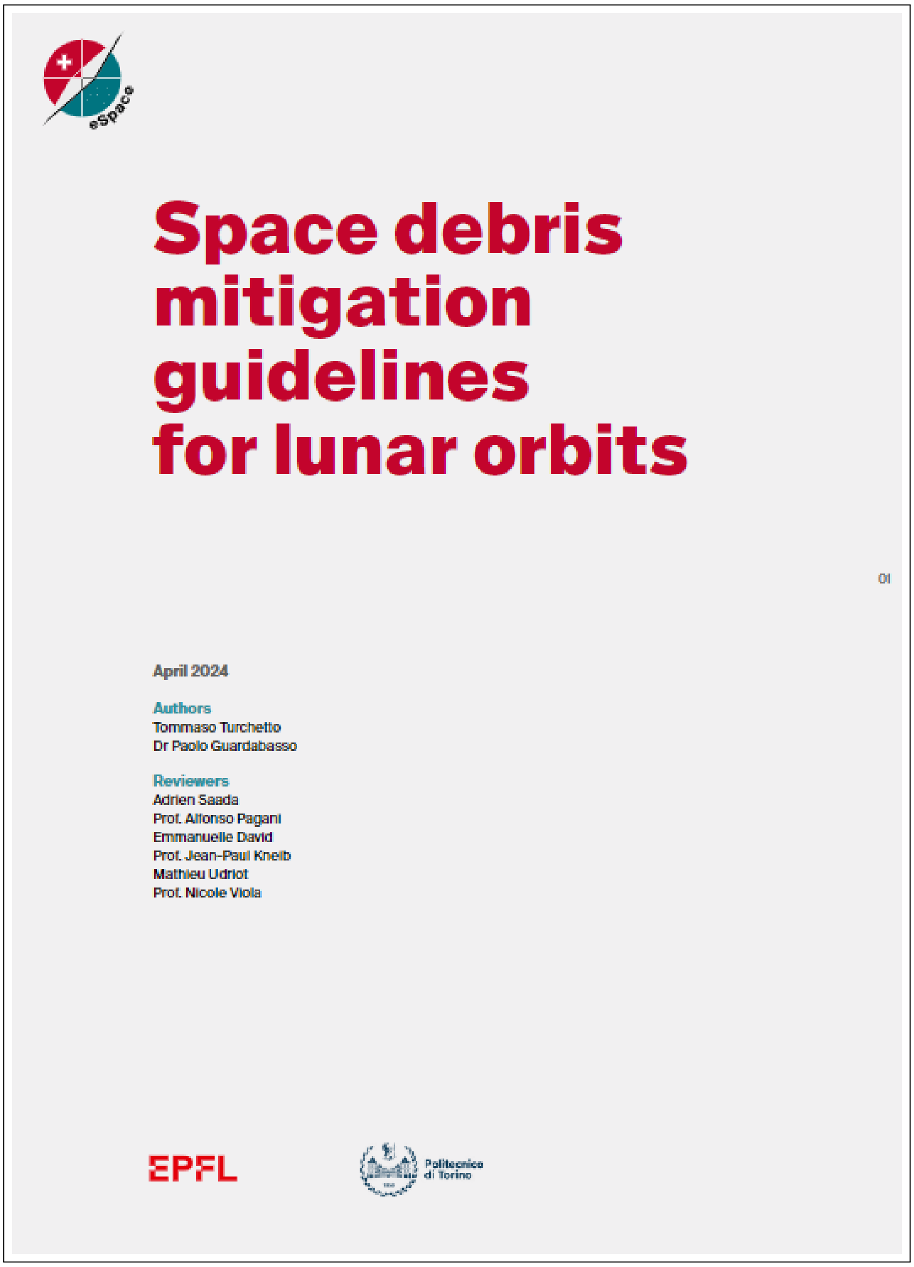
Table 3.1: NASA's CAPSTONE decommissioning datas

Furthermore, at the end of the session, it was expressed that "items like planetary protection, orbital debris, range safety requirements for launch, and transport requirements for an overseas launch are not well understood by most space systems development teams and require significant oversight by project management" [74].
Most recently, an additional example came from the private company Astrobotic, that publicly shared information on the progress of Peregrine mission.
Peregrine Mission One was a lunar lander, part of CLPS, launched on 8th January 2024, which was supposed to land on the surface of the Moon and subsequently deploy two rovers.
A few hours later, Astrobotic disclosed a propulsion system issue, which affected the mission's primary objective.
In spite of this, the spacecraft continued on its trajectory, updated daily with press releases. On 14th January 2024, in accordance with NASA, Astrobotic decided to burn the entire hardware by performing an atmospheric re-entry, following an evaluation of how "safely end the spacecraft's mission to protect satellites in Earth orbit as well as ensure we do not create debris in cislunar space" [75].
On 19th January, the return manoeuvre was successful.
The varied approaches observed in the missions described underscore the importance of advancing literature on lunar space sustainability. Specifically for this report,

there is a need to enhance understanding and practices related to spacecraft end-of-life management and the mitigation of space debris.
In addition to the on-orbit demonstrations, policies mentioned in the section 3.2 also require documents such as the ESA Space Debris Mitigation Requirements for the lunar environment: for instance, the Artemis Accords [8], the Lunar Policy Handbook [9] and the report of the Lunar Policy Platform, entitled Lunar Policy Priorities - For safe and sustainable lunar development [76].
In the latter, in particular, a Lunar Policy Decalogue is discussed, a proposal of ten necessary elements (in agreement with relevant stakeholders) for safe and sustainable lunar development, including:

- Lunar transparency standards;
- Lunar landing and proximity studies and procedures;
- Luna debris and disposal guidelines;
- Lunar cooperation policies and coordination norms, and others.

Given the above considerations, there is a growing recognition of the importance of creating a document entirely devoted to lunar sustainability. This report includes a step further, which will be debated in chapter 5. The outcome is entitled "Space Debris Mitigation Guidelines for Lunar Orbits" [77].
Its main scope is to reduce the generation and proliferation of space debris in lunar orbits, covering the environmental impact of missions.
In particular, it focuses on limiting the release of orbital debris during operations, and those created following an impact on the Moon's surface.
It also discusses the minimisation of potential in-orbit break-ups and end-of-life management, delving into post-mission disposal techniques according to the operational orbit.
International collaboration and shared commitment to these guidelines would be an aid to ensuring the long-term sustainability of lunar missions.



Space debris mitigation guidelines for lunar orbits

01

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Figure 3.3: Space debris mitigation guidelines for lunar orbits

Chapter 4

Disposal strategies and end-of-life management

In the subsection 1.2.1 it has been said that space debris are not only fragments or elements of satellites, but also entire spacecraft that are no longer functional and have reached the end of their life cycle [13].

To mitigate the risk of collision with an uncontrolled object in orbit, which could lead to mission failure and contribute to the growing debris population, it is essential to plan and execute either active or passive disposal strategies.

Intuitively, space operators must show a high likelihood of successfully disposing of their spacecraft by thoroughly analyzing all potential factors that could lead to failure and the resulting consequences.

Consequently, missions should be designed to offer multiple options for end-of-life management, not only if the primary objective is met but also, and particularly, in the case of unforeseen circumstances. Therefore, removing satellites also decreases the need to perform Collision Avoidance Manoeuvres (CAMs), as the population density in orbit is reduced.

ESA, in the Space Debris Mitigation Requirements, considers that the minimum probability of successful disposal of a spacecraft on a mission should be kept above 90%, calculated in accordance with ECSS regulations.

In the case of orbital stages or operations in protected regions, the threshold can approach 100%.

While Earth techniques for removing satellites from operational orbits are preciser and frequently applied, cis-lunar space, due to the limited number of applications and restricted knowledge of the environment, needs studies and empirical verification.

Until now, end-of-life management has not always been taken into account, and when it has been considered, it has typically relied on experiences from past and

similar missions [25], rather than involving predictive calculations.
Despite there currently being only six objects orbiting in the vicinity of the Moon (Figure 2.12), there have already been frequent conjunctions involving the LRO, KPLO, and the Chandrayaan-2 orbiter. This situation led the ISRO to conduct three Collision Avoidance Manoeuvres (CAMs) over the last three years [78], [79]. Given the numerous objects expected to reach trajectories around the Moon in the coming years, the need for studies on tailored disposal plans becomes increasingly urgent.

4.1 Disposal techniques for Earth orbit clearance

Post-mission disposal is unanimously recognised as one of the most effective means of mitigating space debris in Earth orbit.
Numerous organisations, both in Europe and overseas, mention it in their documents [15], [80], [17] and provide guidelines on which option to adopt and how to do it. The techniques can be divided into three categories, and their use depends on the operational orbit of the spacecraft and on the type of the mission:

- immediate atmospheric re-entry to Earth, controlled, uncontrolled or semi-controlled;
- positioning in an orbit with a natural decay in limited time;
- positioning in a parking orbit (or graveyard).

It is evident that a significant feature of Earth, namely its atmosphere, is utilized for this purpose.
A satellite re-entering Earth from space has a very high velocity, in the order of tens of thousands of kilometres per hour [81].
As shown in Figure 4.1, interaction with the dense low atmosphere triggers flames that burn materials. This follows to complete destruction, if not adequately protected by heat shields or if they were designed with materials supposed to be demisable.
The measure allows space operators to leave no trace of small sized spacecraft, removing the risk in orbit, although the possible contamination of the atmosphere and its impact it is not yet clear.
With this purpose, ESA has planned to launch the Destructive Re-entry Assessment Container Object (DRACO) mission, whose main goal is to measure the representative break-up of a spacecraft in the space environment with a small platform and demonstrate prototyped re-entry safety applications [82].
On the other hand, however, larger objects often fail to disintegrate completely, releasing debris into the Earth's environment. In this case, it is necessary to perform

controlled re-entry in order to direct the debris to a specific area, which usually coincides with the South Pacific Ocean Uninhabited Area.
This technique makes it possible to create satellite "landfills" and to reduce the on-ground casualty risk, but it is expensive, as it requires large amounts of propellant. While for large objects the expense is justified, for medium-sized ones affordable solutions are being sought, such as semi-controlled re-entry [83].
The technology of this system allows for much lower costs (since the first and last part of the re-entry will be uncontrolled) but is still much safer, as the central phase of the manoeuvre is carefully guided.

Figure 4.1: Uncontrolled re-entry of Long March 3B rocket (Image credit: Steve Cullen Photography)

The use of propellant for atmospheric re-entry considerably shortens the timeframe; in fact, the manoeuvre is completed in a few days, instead of years in the natural, free, uncontrolled case.
It is understandable that this strategy is most widely used for satellites in the LEO protected region. In the latest version of the Space Debris Mitigation Requirements [17], ESA stipulates a maximum lifetime of five years (under certain conditions) in this habitat, within which the object must be removed from space.
In cases where the trajectory is not particularly close to the Earth's atmosphere, but, for example, the spacecraft is in a GEO, it is envisaged to place it into a graveyard orbit.
According to IADC [15], these orbits for geostationary missions must have a

minimum increase of the perigee altitude of the GEO equal to:

$$\Delta H = 235\,km + \left(1000 \times C_R \times \frac{A}{m}\right) km \tag{4.1}$$

where C_R is the solar radiation pressure coefficient, $\frac{A}{m}$ is the aspect area to dry mass ratio $\frac{m^2}{kg}$ and 235 km is the sum of the upper altitude of the GEO protected region (200 km) and the maximum descent of a reorbited spacecraft due to luni-solar and geopotential perturbations (35 km).
In addition, the eccentricity must be less than or equal to 0.003.
Operators must verify through appropriate simulations that long-term perturbative forces will not cause the satellite to drift into a graveyard orbit and interfere with protected regions or known constellations for at least one hundred years.
Given these considerations, it is important for the end-of-life phase to be factored into mission design from the outset. This is because a specific amount of propellant is necessary to execute the disposal maneuver, and additional assessments of trajectories can significantly alter the system requirements.

4.2 Disposal techniques for Lunar orbit clearance

While many LEO missions can count on "free and permanent disposal aid" thanks to the atmosphere, the situation around the Moon is different.
As discussed in chapter 2, the lunar atmosphere is extremely thin, lacking the capacity to produce atmospheric phenomena such as wind and erosion. Consequently, it is not capable of destroying objects that enter it, even at high speeds.
For this reason, scientists wondered (and still speculate) how a spacecraft could safely end its life in the cis-lunar environment, leaving no trace in populated orbits, trying not to damage celestial bodies and other space-assets.
The difficulty increases considering habitat instability and distance from ground stations, which could cause communication delays or blackouts and affect the final outcome of the manoeuvre.
A number of policies that alert to the importance of post-mission disposal in cis-lunar space have been mentioned in the section 3.2, and the scientific community has identified four different disposal strategies for this environment [84], [25], [17], each presenting specific constraints, advantages and drawbacks:

- lunar surface impact;
- Earth re-entry (destructive or not destructive);
- injection into heliocentric orbit;
- injection into a cis-lunar graveyard orbit.

Similar to Earth, each option appears to be more suitable for specific mission types, depending on factors such as the operational orbit, the technological capabilities of the spacecraft, and its size and mass. However, definitive certainties or precise evaluation criteria for these considerations have not yet been established.

In addition to the four strategies presented, a fifth one should be considered, the landing.

Intuitively, for a mission aiming at a soft touchdown on the lunar surface, the post-mission disposal will coincide with the landing, while the remaining ones are more suitable for orbiters and propulsion modules.

All five will be presented and analysed individually in the following sections.

4.2.1 Lunar surface impact

One of the most historically used disposal strategies is the destructive impact on the lunar soil of the spacecraft [43].

From the point of view of occupying the orbit, it is certainly the most effective method. Naturally, or thanks to an impulsive manoeuvre, the object is diverted towards the surface of the Moon, impacting violently on the rocky ground and breaking up, with the certainty of removing it from an unstable environment.

At the same time, depending on the trajectory of operation, the technique requires modest or none amounts of propellant, and therefore low or free cost.

In the event of a satellite in a LLO, its path is strongly perturbed by the Moon's unstable gravitational field, caused mainly by mascons: the height of an object in this environment can vary drastically if not properly controlled.

Very low polar orbits, such as those at 50 km altitude, can experience rapid decay. Orbits situated further from the lunar surface, instead, such as those around 100 km, tend to have significantly longer impact periods, extending to over a year. [32], [85], as shown in Figure 4.2.

Even when considering departure from more distant orbits, such as certain types of large EML_2 Halo or EML_2 southern NRHO, in which it is necessary to impart a ΔV to the spacecraft, simulations indicate that the cost of maneuvering is reasonable, ranging from one m/s up to a few tens [25].

For smaller satellites, the size of a cubesat, the amount of propellant to impact the Moon's soil from cis-lunar space could be even less. For example, the 12U cubesat Lunar Meteoroid Impact Observer (LUMIO), a mission to a EML_2 Halo orbit planned for 2026, has a ΔV of 2 m/s to perform the lunar impact disposal manoeuvre [86].

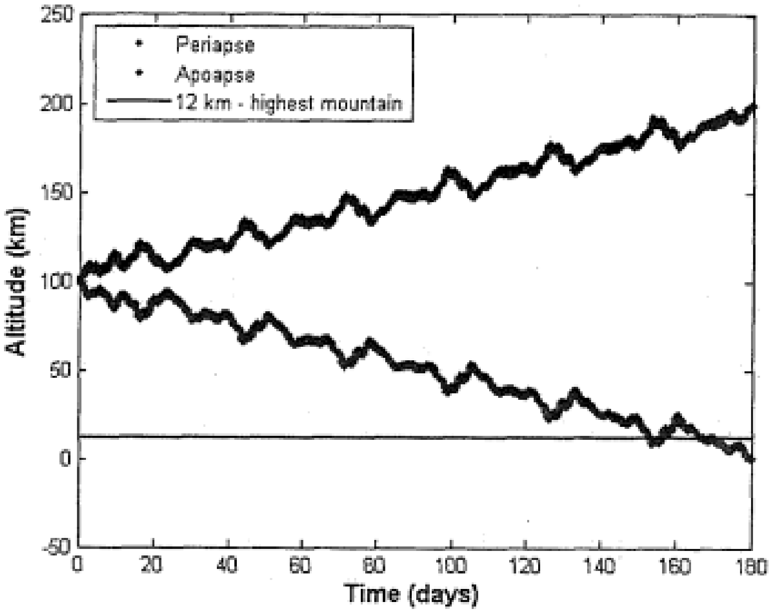

Figure 4.2: Altitude variation for 100 km circular polar orbit around the Moon [85]

In addition, the lunar crash makes it possible to exploit some of the materials previously used, particularly metals, to build new structures and facilitate the enhancing of lunar circular economy.
Several ideas in recent years are emerging in this regard, such as the mission of Orbit Recycling [87]. The start-up proposes to divert large debris, such as upper stages of launchers, directly from the Geostationary Transfer Orbits (GTOs) to the surface of the Moon, recycling its aluminium.
In the future, the material may be exploited for various applications, such as the construction of walls, tanks and heat storage systems.
The need to recycle resources on the Moon has crucial importance: relying solely on supplies transported from Earth is impractical and would incur exorbitant costs. Additionally, the availability of in-situ elements may be limited.
While this disposal strategy is convenient from an economic and orbit clearance point of view, it raises questions regarding the preservation of certain areas of scientific interest or heritage sites [65], [8], as well as on the assessment of possible ejecta released as a result of the event.
A spacecraft [88] or a debris [41] colliding with the lunar surface has a very high velocity, usually varying between 2 and 2.5 km/s (considering that lunar escape velocity is 2.4 km/s).
An impact at such a regime occurs at different angles, and can create craters of

conspicuous size, with radii up to tens of metres [25] [88].
The final volume of the crater depends on several quantities, including how large the object is, its velocity and the type of target. The literature on this subject is well-established [89], [90], and includes studies on the mass of ejecta generated downstream from the phenomenon [91].
Many doubts remain, however, in quantifying the distances reached by the ejecta, and especially how dangerous they may be for future lunar activities and safety zones.
Due to the Moon's extremely weak atmosphere and lower gravitational force compared to Earth, fragments ejected as debris can travel several kilometers without atmospheric drag. This situation raises an important question regarding the disposal technique: how far from a protected area can a spacecraft impact without risking damage from the impact itself or the ejecta?
This doubt is debated by many scientists, and simulations report variable results.

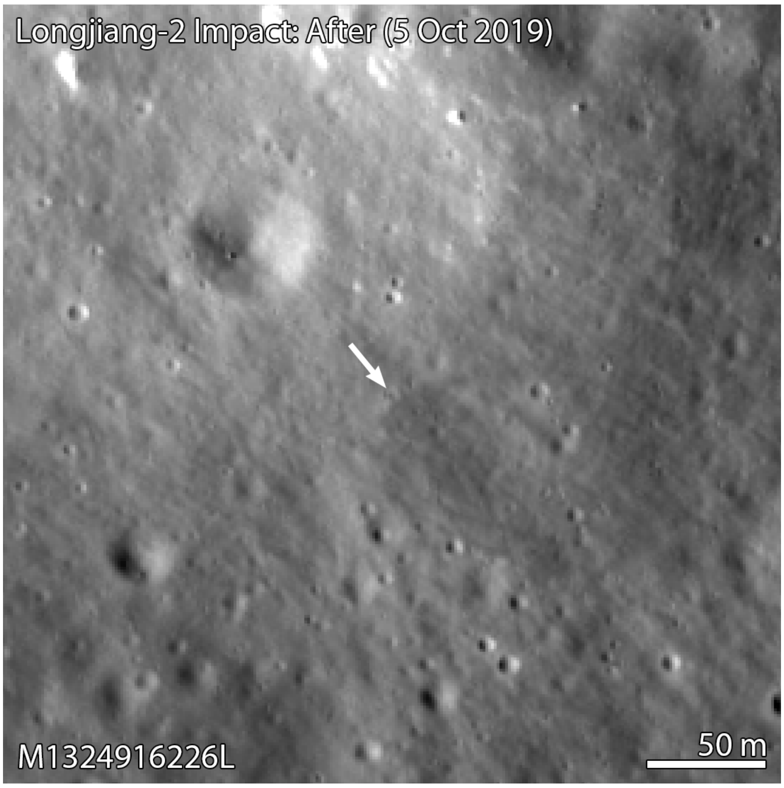

Figure 4.3: Crater created by the impact of 45 kg spacecraft Longjiang-2. Crater is 4 meters by 5 meters in diameter, seen from the LRO [69].

In any case, it is rare for ejecta to travel trajectories greater than 10 km [25], although they have velocities in the order of km/s [92].

According to Frank Koch, founder of Orbit Recycling [87], analyses conducted on Ariane 5 upper stages impacting at about 1 km/s on the lunar surface would create fragments that scatter up to 300 metres from the crater.

What certainly influences the distance of the ejecta is the mass of the object, and consequently the impact energy of the satellite ($E_i = \frac{1}{2}mv^2$). A cubesat at a modest speed will generate a smaller crater, and therefore less debris, than a multi-ton orbiter.

Currently, the only organisation that has spoken out to define a safe distance is NASA [65], recommending impact at least 2 km from a lunar asset.

The threshold would be more accurately defined if assessments were conducted using specialized simulators that account for the lunar terrain's configuration, the dynamics of the cis-lunar environment, and the specific characteristics of the impacting spacecraft.

Following an analysis of the trajectories of ejecta generated by a crash, a distance limit could be established to ensure that a high percentage of the fragment mass does not lead to contamination.

In addition, it is certainly necessary to identify and agree on what the lunar points of interest are, so that operators can have a clear map of where not to dispose the object during simulations.

To preserve a "history of man on the Moon" [9] Apollo landing sites must remain uncontaminated, as well as areas of current scientific interest at the lunar south pole, key assets on the far side, and future critical activities such as habitation modules, extraction sites, and landing platforms.

The simulations described above serve as a method to assess whether the spacecraft can land on the lunar surface without the need for corrective maneuvers, by leveraging the instability of the gravitational field while considering potential time constraints. Alternatively, they can indicate whether an impulse is necessary to facilitate a controlled landing.

Moreover, engineers while taking the crash site into account, can combine the assessments with the exploitation of natural terrain barriers [65] [25], such as hills, crater rims and ridges, which allow for cost-free containment of secondary ejecta.

Increased awareness of impacts on the Moon and their consequences may lead to the creation of lunar landfills. They can be defined as places where post-mission disposal is most suitable and where these events can be concentrated, away from lunar points of interest.

Excluding areas of high scientific interest and those potentially containing valuable minerals, researchers are hypothesizing that lunar landfills could be established in the southern part of the far side (within the blue boundaries shown in Figure 4.4) [93], where space debris could be directed for disposal.

In an imaginary future, materials from defunct satellites in these areas could be recycled to give them a second life.

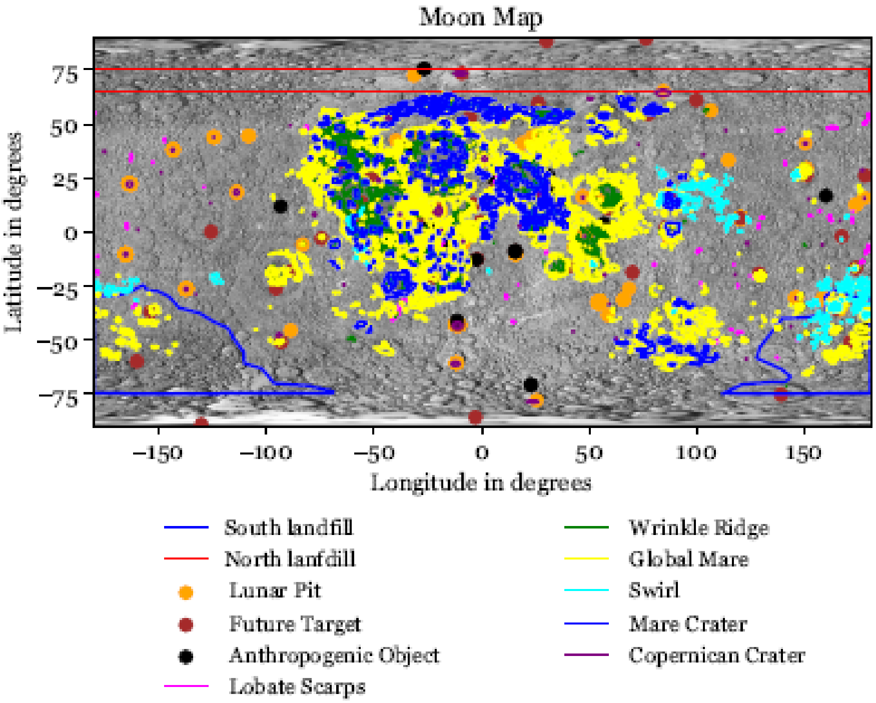

Figure 4.4: Moon map with areas to avoid and potential landfills [93]

Pros and cons of the lunar surface impact strategy are summarised in Table 4.1.

Pros	Cons
Affordable in ΔV Orbit clearance Recovery of materials	Protection of lunar surface sites Secondary ejecta

Table 4.1: Pros and cons for lunar surface impact disposal strategy

4.2.2 Earth re-entry

While numerous spacecraft in cis-lunar space were predicted to crash on the Moon, the human lunar landings of the last century certainly could not afford it.
Among all the missions, more than 40 spacecraft have planned a return manoeuvre to Earth: in addition to the Apollo programme, several sample return demonstrations have made use of this strategy, including the recent Chang'e 5 module and the Orion vehicle, part of Artemis 1.
Although this technique is necessary in specific situations, it is certainly not a convenient disposal when it comes to un-manned orbiters, especially when compared

to others.
A strength lies in orbit clearance: an object in cis-lunar space returning to Earth is planned to leave no trace in orbit, and therefore the risk of contamination by space debris around the Moon is reduced.
In any case, it cannot be ruled out that the satellite will not return under the lunar influence or some other celestial body, since the interplanetary return transfer can be very complex.
Adding to the complexity is the significant amount of propellant required for such maneuvers. For instance, the major burn of the Orion capsule to leave the DRO and return to Earth required approximately 290 m/s [94], which translates into a substantial economic cost, considerably higher if compared to other disposal options.
Once the spacecraft reaches the vicinity of the atmosphere, the disposal phase can end as discussed in the section 4.1, performing a destructive manoeuvre or, if the modules are manned or sample-return, a non-destructive one, recover or not the materials used.
Finally, an object that is re-entering to the Earth may interfer with the protected regions LEO and GEO, being a possible target for other functioning satellites and/or space debris, increasing the risk of particle proliferation and the probability of collision and mission failure.
Based on the above findings, Earth re-entry presents economic challenges and potential risks to the Earth's orbital environment. As a result, it may be appropriate for missions that specifically require it, but is generally not recommended for missions orbiting near the Moon's surface.

Pros	**Cons**	**To be assessed**
Orbit clearance	Interfering protected regions Expensive in ΔV Complex manoeuvre Long transfer time	Recovery of materials SOI of other bodies

Table 4.2: Pros and cons for Earth re-entry disposal strategy

4.2.3 Injection into heliocentric orbit

In addition to techniques involving a celestial body's surface or atmosphere, scientists are exploring other strategies for post-mission disposal in cis-lunar space: parking the object in a stable orbit. This approach aims to make the disposal permanent without compromising the preservation of any surrounding ecosystem.

As dealt with in the subsection 4.2.2, the cost and complexity to escape from lunar environment to the Near Earth Orbits (NEOs) can be high.

Simulations have shown that, with the right adjustments, a habitat that could grant reliability is the heliocentric one.

The following discussion does not set out to analyse the trajectories of this environment, nor those necessary to reach it, and detailed studies have already presented results in this regard [95], [52].

Generally, the manoeuvre for solar escape categorized into two types: direct and indirect. A direct maneuver involves an immediate transition from cis-lunar space to the heliocentric environment, while an indirect maneuver entails performing additional revolutions around the Earth-Moon system's barycenter before completing the transfer.

One of the strengths of the strategy is the modest amount of propellant required, and thus the low cost, since the centrifugal effect is exploited.

Previous studies demonstrated that the departure from the future orbit of the Lunar Gateway, a 9:2 NRHO, for a heliocentric disposal was successful with a ΔV of 15 m/s, while no solution was satisfied using an input of a ΔV of just 1 m/s [52]. In any case, even for certain large EML_2 Halo orbits, the ΔV required is of the same order of magnitude [25].

For example, EQUULEUS, already mentioned in subsection 2.2.2,is a 6U cubesat developed by the University of Tokyo and JAXA, en route to a EML_2 Halo.

As can be seen from its ΔV budget, a total of 99 m/s was planned [96], after the deployment from the Orion vehicle to the end-of-life.

The exact amount of propellant required for post-mission disposal is not indicated, but it is explicitly stated that "before completion of the onboard ΔV, the spacecraft will be disposed into an Earth-escape orbit for space debris compliance" [96].

Considering from its ΔV budget that almost 91 m/s are required for the various positioning and station-keeping manoeuvres, it can be deduced that the ΔV for heliocentric injection is within the above predictions.

However, this option is accompanied by a number of uncertainties and weaknesses.

Firstly, it is a manoeuvre which assumes quite long transfer times compared to those of a lunar impact at the same orbit of departure [25], especially if multiple lunar fly-bys are required.

The longer the flight time, the greater the cost of ground operations, and, from a sustainability point of view, the occupation of cis-lunar space by the object.

Furthermore, although orbits in the heliocentric habitat have long periods and are stable, they are difficult to predict, since they are influenced by all the celestial bodies within the solar system.

For this reason, while impacting the Moon's surface ensures that the spacecraft will no longer pose a threat to protected regions, the risk of a satellite in a heliocentric orbit eventually returning and impacting the Earth cannot be entirely ruled out.

Due to the prohibitive distances from the ground segment, performing maneuvers or corrective actions to avoid space assets or debris would be challenging, especially for smaller spacecraft. Therefore, it is recommended to passivate the object once its operational life has ended.

According to the IADC definition [15], passivation is the elimination of all stored energy on a spacecraft or orbital stages to reduce the chance of break-up.

The action is irreversible: the batteries are discharged, excess propellant is expelled and other components are depleted. The satellite then is no longer controllable, decreasing the likelihood of unwanted internal damage, and thus the creation of space debris.

While passivation can be debated in the context of lunar impacts (for instance, CAPSTONE does not passivate to "navigate all the way to impact" [74]), since the manoeuvring time would be short and the risk of on-orbit break-up is relatively low, spacecraft intended for heliocentric environments should be designed to ensure passivation. This is crucial because a break-up event in such a complex environment could cause fragments to scatter unpredictably, posing risks to other space assets.

To enhance knowledge of an object's position and support reliable simulations of its trajectory, features that improve the satellite's detectability could be utilized.

In this context, detectability is defined as the likelihood that a spacecraft in a given orbit can be detected by surveillance users with optical telescopes or radars.

The development of these features, which could coincide with additions external to the object, should go hand in hand with the improvement of space observations, both from the ground and, especially for this environment, with space-based hardwares.

ESA, to contribute on this aspect, in the first quarter of 2024 carried out a Concurrent Design Facility (CDF) study named LUnar MOnitoring System (LUMOS). With the concurrent engineering approach, consisting in an interactive and faster method to design a space mission, having at the same time all the systems and subsystems engineers in the same room, ESA designed a mission and spacecraft for the identification, detection, and tracking of artificial objects and fragmentation debris in the cislunar domain [97].

The uncertainty of heliocentric space presents several challenges, including concerns about the potential for an object to re-enter Earth's trajectory and its protected regions. Additionally, there are questions regarding the feasibility of recovering materials in the future, as parking them in heliocentric space maintains their integrity.

Therefore, this disposal technique can be preferable for objects in Halo orbits, particularly around EML_2, rather than for spacecraft in LLOs, which can save on propellant by directing towards the lunar surface.

In addition, due to the remote environment, the cost of the mission could be higher, either for the disposal manoeuvre, which requires more propellant than an impact on the Moon, and for the computational cost of simulations, which must verify the stability of the spacecraft for tens of years.

Pros	Cons	To be assessed
Affordable in ΔV	Long transfer time (in case of fly-by)	Recovery of materials SOI of other bodies Interfering protected regions Orbit clearance Detectability with spacecraft

Table 4.3: Pros and cons for injection into heliocentric orbit disposal strategy

4.2.4 Injection into a cis-lunar graveyard orbit

The latest disposal technique analysed is the parking in a cis-lunar space orbit, but as of 2024, there are still no uses of this strategy [43].
The chapter 2 dealt with the lunar environment and its relevant orbits around both the Moon and the EM Lagrangian points, and in particular the instability of the habitat was emphasised.
For this reason, in most trajectories a spacecraft needs frequent corrections so that its path is not deflected, and orbits that guarantee stability over a long period are very rare.
Among these, one set of solutions that are stable under the assumptions of the CR3BP are the Distant Retrograde Orbits (DROs), already analysed in the subsection 2.2.1, and their linear stability is also reflected in high-fidelity models.
Various researches have indicated DROs as potential parking orbits in cis-lunar space [38], [25], [42], although only few objects have travelled them so far.
Other trajectories possess characteristics of high stability in this environment, such as frozen orbits. However, the discussion does not consider them since they exist for heights in the order of LLOs, and their path could interfere with that of other orbiters in their operational state.
Despite the advantage of having stable dynamics makes them particularly suitable for graveyard orbit function, DROs, as their name suggests, are very far from the lunar surface, which results in a high cost of access, especially from LLOs.
The ΔV required for the transfer is in the order of hundreds of m/s even for several NRHOs [42], making it almost unsuitable for small spacecraft, which do not support subsystems capable of performing such manoeuvres.
It could be, however, a reasonable strategy for missions already operating in high DROs, as they may have graveyard orbits at an easily reachable distance.
In addition, larger satellites could have the technologies and resources to perform

this disposal as well from more complex regions. It is no coincidence that NASA tested with Orion the insertion into a DRO. The future Lunar Gateway has as a system requirement the ability to perform a transfer to a DRO and return to its operational habitat (a NRHO) within 11 months [98].

Considering the limited use of the above-mentioned environment, precautions are necessary, in particular on the actual stability over a long period of time.

Operators must be able to demonstrate by predictive calculations that a spacecraft in a graveyard can remain for several tens of years without intervention from the ground, and above all that it does not interfere with protected regions or celestial bodies.

Furthermore, as with heliocentric orbits, the question remains as to whether or not the spacecraft's materials can be recycled at the end of their primary purpose.

If future missions confirm their distinctiveness, this family of trajectories would have the potential to develop the growth of the cis-lunar economy in a sustainable way, offering both scientific applications that should not require station-keeping and a strategy for a safe end-of-life of the satellite.

Pros	**Cons**	**To be assessed**
Stability	High access cost Few data	Recovery of materials SOI of other bodies Interfering protected regions Orbit clearance

Table 4.4: Pros and cons for injection into cis-lunar graveyard orbit disposal strategy

4.2.5 Landing

While landing on the lunar surface is primarily a mission objective rather than a disposal strategy, it is presented in the work as a fifth option for removing a spacecraft from its operational orbit.

The following discussion will present the landing as it is another way to manage the end-of-life, but it is not considered as an option to dispose an orbiter around the Moon.

A lunar landing refers to the process of safely and softly bringing a spacecraft down from lunar orbit to the Moon's surface. Usually, this technique is used in missions aimed at exploring the surface, collecting samples, or establishing a human or robotic presence on its soil.

Historically, the first successful lunar landing was achieved by NASA's Apollo 11 mission on 20th July 1969, when astronauts Neil Armstrong and Buzz Aldrin became the first humans to set foot on the Moon. After that event, dozens of spacecraft landed on the lunar surface.

Given that high accuracy is essential for accessing a specific site, and considering that achieving a nondestructive maneuver requires the relative velocity between the module and the Moon to approach zero, the technological challenges become evident.

A successful soft-landing process is made of several phases:

- The injection into a Low Lunar Orbit, where the spacecraft transitions from its operative environment into an almost circular orbit closer to the lunar soil, usually around 100 km.
- The descent initiation, a maneuver that slows down the spacecraft reducing the altitude to almost 10 km.
- The powered descent and braking phases, during which the main engines of the lander are activated to decrease the velocity. At this stage, a careful evaluation has to be carried, to ensure that the amount of propellant permits to complete the landing, and at the same time the velocity is reduced enough.
- The terminal descent is the last stage: the spacecraft is vertical and it is performing the final adjustments to ensure a precise touchdown. This phase is critical, as the lunar soil is irregular and presents numerous ridges and craters. The on-board sensors, lasers and cameras feed the navigation algorithms to enable last-second adjustments, until the touch-down is completed, with an approximated relative velocity of 1 m/s.

Figure 4.5 shows the final landing phases of IM-1, the first commercial successful lander from Intuitive Machine that on the 23rd of February 2024 softly touched the surface of the Moon.

Once on the lunar soil, the lander begins its operational phase, deploying rovers if it has any, and starting to collecting data.

A current limit for the landing missions is represented by the lunar night.

A lunar day lasts approximately two weeks, which are followed by two weeks of lunar night. During this time, the conditions on the lunar surface are extremely harsh with temperatures falling to -170°, when sunlight does not warm the surface. Usually, a lander is operative few days for this reason.

To realize long-term missions, new technology and systems are required to survive the cryogenic environment of lunar night, as the Japanese private company ispace is developing joining the forces with the University of Leicester [100].

The consortium is working on radioisotope power systems to provide heat to spacecraft, or converted to electricity to power key subsystems, in order to extend the life of the objects over the lunar nights too.

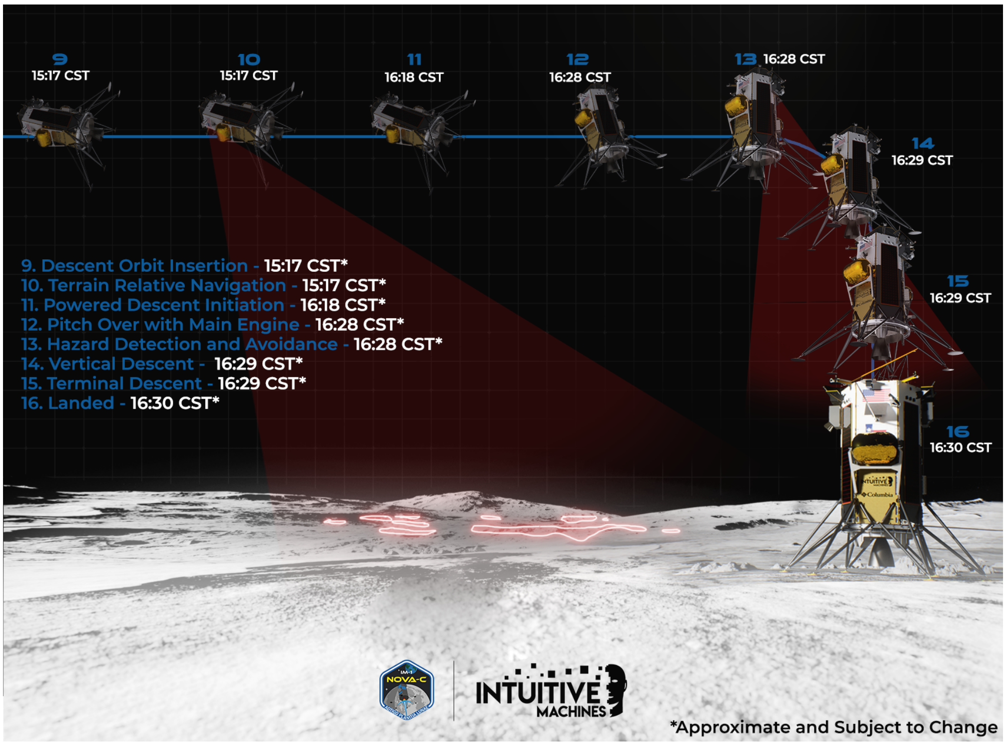

Figure 4.5: Landing trajectory of IM-1 lander [99]

As previously mentioned, since landing is the primary objective of these specific missions, it falls outside the scope of this discussion to evaluate the advantages and drawbacks of this process. Such systems require significant amounts of propellant, advanced autonomous Guidance Navigation and Control (GNC) capabilities, and, crucially, crush core legs to absorb the energy upon touchdown.

4.2.6 Overall of the disposal techniques

In the previous subsections each disposal strategy has been evaluated, providing an assessment of the possible advantages and drawbacks, highlighting as well the peculiarities and what needs further evaluation.

To keep track of all the post-mission disposal techniques, the report also relies on the Lunar Mission Database (moonDB) [43], developed by Dr. Paolo Guardabasso during his PhD work [25].

This database contains past and present spacecraft in the cislunar space, and it is compiled through publicly available sources. It was designed to better understand the rationale behind missions, focusing on their final results, current status, funding agencies and nations. Particular attention has also been given to the surface of the Moon, where landing sites have been identified.

According to this source, and updating it to December 2023 with other online available information, 195 objects launched towards the cis-lunar space were taken in analysis, and in particular:

- 61 crashed on the lunar soil;
- 41 re-entered to the Earth SOI;
- 10 were injected in an heliocentric orbit;
- no object is yet disposed in a lunar graveyard orbit;
- 61 landed softly on the surface of the Moon;
- 22 objects had or have an unknown end-of-life management.

The data collected are clearly showing that there is a trend to dispose the objects on the lunar surface, either with a crash or a soft manoeuvre.

As previously reported, the lunar graveyard orbits, and more precisely the Distant Retrograde Orbits (DROs) are not exploited yet, despite few objects already explored them.

What needs to be addressed, however, is that 22 objects were not providing specific indications on their disposal techniques or end-of-life management, and the majority of them belong to very recent missions.

As remarked along the several chapters, stepping stones to fuel the literature on the sustainability for the lunar orbits could be means to improve these lacks. The following section will tackle the already announced guidelines, extracted from this report, and will go in details one by one.

Chapter 5

Space debris mitigation guidelines for lunar orbits

Within chapter 3 and chapter 4 a document entirely devoted to lunar sustainability was presented. In particular, in chapter 4 the four (plus landing) disposal techniques were discussed, with the possible drawbacks and advantages.
In this section, the Space debris mitigation guidelines for lunar orbits [77] are provided, and the rationales on the statements are debated as notes.

5.1 Scope

The goal of these guidelines is to limit the generation of debris in the Earth-Moon system. The guidelines cover the environmental impact of missions in space, with a focus on the following:

1. limitation of debris released during normal operations;
2. limitation of debris created after a lunar impact;
3. minimisation of the risk of on-orbit break-ups;
4. post-mission disposal strategies.

They apply to the entire life phases of spacecraft and orbital stages that will be injected into lunar orbit.
Organizations and industries are encouraged to employ these guidelines in identifying standards for future Lunar spacecraft and orbital stages when establishing mission requirements.
Operators of existing spacecraft and orbital stages are strongly encouraged to consider these guidelines to the fullest extent possible, as they assist in minimising

potential adverse impacts and ensuring responsible conduct during their current activities.

5.2 General guidelines

To prevent the proliferation of space debris in lunar orbits, it is strongly recommended that a Space Debris Mitigation Plan is established and documented for each orbital lunar mission, along the lines of [17], and considering the following.
A plan for disposal of the spacecraft and/or orbital stages and the management of the end-of-life should be assessed from the mission requirement analysis and definition phases.
Choices and selections should be justified, especially for the disposal option.
The disposal should be a trade-off which considers many factors, such as the cost, complexity, and feasibility of manoeuvres (*e.g.* propellant required, navigation, propulsion technology), the probability of collision with lunar points of interest and space assets, and the risk of uncontrolled atmospheric re-entry on Earth.

5.3 Mitigation measures

5.3.1 Avoiding the creation of space debris

The spacecraft or launch vehicle orbital stage shall be designed not to release or create space debris into the Earth-Moon space during normal operations.
This includes the possibility of generating space debris following an impact on the lunar surface. An assessment of the dispersion of subsequent ejecta should be performed.

Minimise the risk of accidental on-orbit break-up

In lunar orbit, the risk of accidental break-up of a spacecraft or launch vehicle orbital stage shall be assessed and minimised.
According to ESA Space Debris Mitigation Requirements [17], the accidental internal break-up probability of a spacecraft or launch vehicle orbital stage in lunar orbits shall be less than 10^{-3} until its end-of-life.
Note: a fragmentation in lunar orbits can have repercussions on the entire Earth-Moon system, and precautions shall be kept even after end-of-life [25].

Rationale As presented in chapter 2, the cis-lunar space is a very unstable environment.
The scattering of space debris following an orbit break-up could result in an

unpredictable outcome.
The threshold for the internal break-up probability of Earth orbits is here proposed, but a further assessment is needed, with the aid of numerical simulations.

Avoid any intentional on-orbit break-up

In lunar orbit, intentional break-up of a spacecraft or launch vehicle orbital stage shall be avoided.

5.3.2 Passivation

A spacecraft or launch vehicle orbital stage operating in lunar orbit shall be designed to guarantee successful passivation after the end of the mission.
Successful passivation entails the elimination of all stored energy on board to reduce the chance of break-up.

Lunar impacts

A spacecraft or launch vehicle orbital stage operating in lunar orbit that intends to impact the lunar surface as a means of disposal shall be passivated after the last manoeuvre targeting the impact location.
In the case of an uncertain orbital propagation, or a spacecraft impact in the vicinity of a lunar point of interest or its protected zone, a trade-off should be done between the passivation moment and the navigation aid.

Rationale The trade-off is proposed since the duration a spacecraft spends on a trajectory towards the Moon's surface can be relatively short.
Therefore, the probability that an internal accident might occur would be limited. However, maintaining navigation capabilities until the impact, like will demonstrate CAPSTONE, could enhance the precision of the manoeuvre, thereby improving the likelihood of a successful post-mission disposal.

5.3.3 Post mission disposal options

Spacecraft in lunar orbits have four main disposal options, as debated in chapter 4:

- **Lunar impact**
- **Earth atmospheric re-entry**
- **Heliocentric graveyard orbit**
- **Earth-Moon graveyard orbit**

The choice of each strategy depends on multiple factors.
Its starting location, the operational orbit, plays a significant role in the availability and relative cost of each solution.
Other aspects, such as the spacecraft size, manoeuvrability and level of autonomy, drive the trade-off.

General precautions: trajectories should have short transit times through the LEO (Low Earth Orbit) and GEO (Geostationary Orbit) protected regions, as defined by IADC [15].
Additionally, features shall be required to increase the satellite's detectability.

Lunar impact: in case of an impact trajectory, simulations should verify the spacecraft's natural decay time and impact location.
Controlled disposal should always be the reference in case impact is selected.
The impact effect shall be assessed to ensure ejecta and fragments of spacecraft remain outside of protected zones.
This may be combined with the exploitation of natural terrain barriers (such as hills, crater rims, and ridges) and an evaluation of the angle of impact.
Moreover, according to COSPAR Policy on Planetary Protection [63], measures for contamination control are required.

Rationale Due to the uneven gravitational field of the Moon, especially in proximity of the lunar soil, a controlled manoeuvre would increase the chances of successful post-mission disposal.
An option that could be explored around the Moon, along the lines of the Earth orbits, would be the semi-controlled re-entry.

Heliocentric graveyard: disposal in a heliocentric orbit shall be supported by orbital propagation to minimise the probability of interference with Earth and lunar spacecraft for 100 years, as per ESA guidelines [17].

Probability of successful disposal

The overall probability of successful disposal of a spacecraft or launch vehicle orbital stage in lunar orbit should be kept above 90% through to the end of life, for all the considered disposal options.

Rationale The threshold for the probability of successful disposal of Earth orbits is here proposed, but a further assessment is needed.

Nuclear energy source

A spacecraft carrying a nuclear energy source shall avoid impacting on the Moon or re-enter the Earth.
The disposal of a spacecraft carrying a nuclear energy source should include one of the following means, in order of preference:

1. Heliocentric orbit
2. Lunar graveyard orbit

Note: the selected graveyard orbit must not pose any risk of interference with other orbiting spacecraft until the predicted depletion of the nuclear energy source, if above the 100-year threshold.

Rationale Nuclear energy sources are expected to increase in the coming years on the surface of the Moon, especially for granting extended life to landers during lunar nights [100].
Regulating the presence of this contaminants from orbiters and propulsion modules could be beneficial for planetary protection purposes.
One potential strategy is to position spacecraft with nuclear energy sources into a parking orbit. This would allow radioactive compounds to decay away from other celestial bodies.
However, simulations are needed to confirm that this approach would not interfere with other orbiting spacecraft.
Currently, heliocentric orbits are given priority due to their more extensive exploration compared to lunar graveyard orbits.
As debated in subsection 4.2.3 and subsection 4.2.4, depending on the starting orbit the propellant required might be less, like the computational cost to design such manoeuvre.

Example of disposal application

Here are the suggested procedures for disposing of missions after completion in three specific orbits: Low Lunar Orbits (well established for lunar missions) and two three-body orbits (Halo orbits and DROs) which are anticipated to attract future interest [25]. Other lunar orbits of relevance are also mentioned in 5.3.3.

Low Lunar Orbits Spacecraft that have terminated their mission shall be disposed from LLO so as not to cause interference with spacecraft or orbital stages still in LLOs and the Earth-Moon space.
The disposal of a spacecraft in these orbits should include one of the following means, in order of preference:

1. Lunar impact or heliocentric orbit
2. Lunar graveyard orbit or Earth re-entry

Rationale In subsection 2.2.1 and subsection 4.2.1 the features of the Low Lunar Orbits (LLOs) were analyzed. These trajectories, depending on the altitude, can be very unstable, and spacecraft in some of them decade quickly [32] [85].
Intuitively, the uneven gravitational field could be exploited to drift the object on the soil as a low-cost solution.
For this reason, the order of preference of the strategies foresees the lunar impact as a more feasible choice.
In parallel, the crash site of the object shall be evaluated, as well with the ejecta created afterwards. Therefore, the heliocentric injection is proposed as an alternative.
With the growing interest in lunar exploration and related activities, directing all satellites to the Moon would be unsustainable.
Considerations should be made regarding several factors, including the size of the orbiter (as larger objects can produce more debris upon impact), its ability to maneuver and be detected in a heliocentric environment, and the altitude of the LLO.

L_2 **Halo Orbit** Spacecraft that have terminated their mission should be disposed from L_2 Halo Orbits so as not to cause interference with spacecraft or orbital stages in this orbit family.
The disposal of a spacecraft in these orbits should include one of the following means, in order of preference:

1. Lunar impact or heliocentric orbit
2. Lunar graveyard orbit or Earth re-entry

Rationale In subsection 2.2.2 the peculiarities of the Halo orbits were analyzed. More specifically, the advantages of the Halo orbits around the second Lagrangian point were presented.
Several researches [43], [86] reported that for specific sets of L_2 Halo orbits a lunar impact disposal would be a possible solution in terms of propellant.
For this reason, the order of preference of the strategies foresees the lunar impact as a more feasible choice.
On the other hand, the time of flight of the object to impact the Moon would be longer than from a LLO, along with the complexity of the manoeuvre.
In parallel, the potential crash site of the object shall be evaluated, as well with the ejecta created afterwards. Therefore, the heliocentric injection is proposed as

an alternative.
Considerations on the heliocentric injection from a L_2 Halo orbit were provided in subsection 4.2.3. The injection manoeuvre cost is on the same order of magnitude of the lunar soil disposal.
This technique allows to send the object in a slow-dynamic environment, but further assessment need to verify the detectability of the spacecraft and the stability oft eh trajectory.

Near Rectilinear Halo Orbits The above guidelines also apply to the Halo subset, the Near Rectilinear Halo Orbits.
In this case, the disposal for specific operations with sufficient propellant for end-of-life can be a Lunar graveyard orbit.

Rationale Considerations for L_2 Halo orbits apply.
Satellites with adequate technologies and resources may exploit the injection into a Lunar graveyard orbit. For instance, the Lunar Gateway has a system requirement which implies the ability to perform such transfer [98].

Distant Retrograde Orbits Spacecraft that have terminated their mission should be disposed from DRO so as not to cause interference with spacecraft or orbital stages still in DROs.
The disposal of a spacecraft in these orbits should include one of the following means, in order of preference:

1. Lunar graveyard orbit
2. Heliocentric orbit
3. Lunar impact or Earth re-entry

Rationale In subsection 2.2.1 the features of the Distant Retrograde Orbits (DROs) were discussed. This set of trajectories seems promising for its stability, but still they are not explored enough.
The distance from the surface of the Moon, and in general from the low lunar environment, makes the transfers complex. Therefore, lunar impact is considered as last option, together with Earth re-entry.
However, DROs can coincide with lunar graveyard orbits. For this reason, the order of preference of the strategies foresees the lunar graveyard orbit as a more feasible choice.
Further simulations and experiments need to confirm the feasibility of this statement.

Other valuable orbits Spacecraft or orbital stages can operate, partially or completely, in bounded lunar orbits other than LLO, L_2 Halo orbits and DRO, including orbits which at a certain time can interfere with LLO, L_2 Halo orbits and DRO, *e.g.* due to natural forces.
These can also include orbits of future interest and which currently have no applications, such as:

1. Lunar Frozen Orbits, which are LLOs that provide long-term stability, contrasting the irregularities of the Moon's gravitational field [34].
   There is a class of them named Elliptical Lunar Frozen Orbits (ELFOs) for only certain combinations of inclination, eccentricity and energy. These orbits are valid for their stability and visibility of Earth, for telecommunications applications. One of them is chosen for the Lunar Pathfinder, part of ESA Moonlight vision.

2. Earth-Moon L_1 L_4 L_5 Halo orbits. L_4 and L_5 orbits are deemed valid for the observation of the lunar orbits.

3. Elliptical Lunar Orbits (ELO), which can have a lower cost access from Earth while maintaining a low perilune. NASA ARTEMIS-P1 and ARTEMIS-P2 travel two different ELOs.

4. Prograde Circular Orbits (PCO), circular orbits of various sizes that rotate in the prograde direction and are highly stable, with an altitude range from 3.000 to 5.000 kilometres.

These orbits are considered part of lunar orbits, therefore, the same guidelines to prevent debris and planetary contamination are applicable. Disposal options from these orbits require case-by-case assessments.

5.3.4 Examples of applicability

The following subsection is providing several examples of current spacecraft in lunar orbits or in development phase to which the "Space debris mitigation guidelines for lunar orbits" can be applied.
As this report is being prepared, some of the proposed missions lack information on disposal techniques. Providing these indications could be beneficial in raising awareness among operators and guiding future practices.

Korea Pathfinder Lunar Orbiter - Danuri

KPLO, better known as Danuri, is a 550 kg spacecraft launched in August 2022 with a Falcon 9, inserted in December 2022 in a low lunar orbit [101].

At the moment, the satellite is orbiting a 100 km circular orbit around the Moon, monitoring the lunar surface and producing a topographic map to select future landing sites and to survey any type of lunar resources.

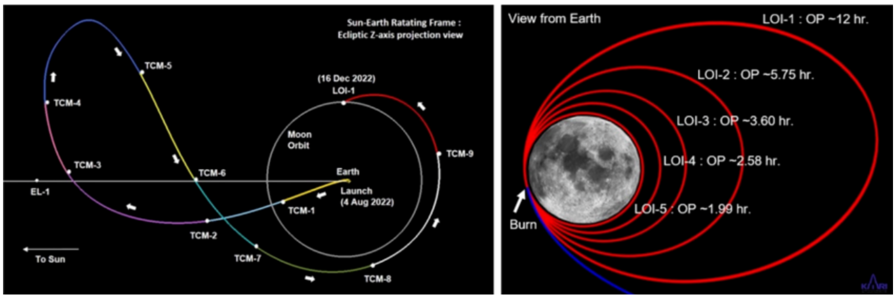

Figure 5.1: Korea Pathfinder Lunar Orbiter trajectory view. Launch case (a) and lunar orbit acquisition phase (b) [102]

Currently, there is no information available regarding the disposal techniques that will be used for this spacecraft.

Since the satellite is operating in a lunar low orbit, options such as a lunar impact or an injection into a heliocentric orbit should be considered. Additionally, an assessment of the potential impact location and details on the amount of onboard propellant are needed to evaluate the possible maneuvers that can be performed.

Queqiao

Queqiao is a 325 kg satellite from CNSA, operating in a Halo orbit around L_2 EM Lagrangian point [103] since January 2019, and communicating with the Chang'e 4 rover.

Currently, there is no information available regarding the disposal techniques that will be used for this spacecraft.

Since the satellite is operating in a Halo orbit around L_2, options such as a lunar impact or an injection into a heliocentric orbit should be evaluated. This decision should be made through a system-level trade-off, taking into account factors such as the available propellant, the spacecraft's detection capabilities, and the potential impact location if a lunar disposal is chosen.

CAPSTONE

CAPSTONE spacecraft was already discussed in section 3.3.

The NASA's cubesat is operating in a NRHO around L_2. NASA shared information about its end-of-life, saying that it will impact on the surface of the Moon, in a safe zone.

Further assessment is needed regarding the passivation of the spacecraft. NASA has indicated that the spacecraft will not be passivated to retain navigation capabilities until the lunar impact. The advantages of maintaining navigation capabilities may outweigh the risks of potential internal malfunctions during the disposal process, considering the time of flight to impact on the lunar surface.

Lunar Trailblazer

Lunar Trailblazer is a planned NASA mission that will provide new insights into the lunar water cycle and geology. The spacecraft will map the distributions and abundances of different forms of water on the surface of the Moon.
The satellite will weight 210 kg and will be launched in a Falcon 9 ride-share mission alongside the second lander of Intuitive Machine IM-2.
Once inserted into the operational orbit, it will be in a polar LLO, at a height of approximately 100 km above the surface [104].
For its low mass and trajectory a lunar impact disposal can be considered.
An assessment of the potential impact location is needed to evaluate the possible maneuvers that can be performed. Additionally, NASA disclosed the amount of ΔV available during the operations [105]. Further calculations are needed to estimate the quantity of propellant allocated to end-of-life.

Figure 5.2: Illustration of the Lunar Trailblazer mission (Image credit: Lockheed Martin)

Chapter 6

Conclusions

Lunar missions are increasing, and so is the need for sustainable practices in this environment.

Dozens of orbiters and landers are being directed to the Moon and its orbits. In the near future, humanity will establish its first space station in this habitat, the Gateway.

In recent years, nations, space agencies and industries have begun addressing the sustainability of lunar activities through frameworks such as the Artemis Accords and the COSPAR Policy on Planetary Protection.

In section 1.3 an overview of the key areas of study concerning Moon' sustainability was provided.

This work specifically aimed to tackle one of the several aspects of sustainability: the space debris issue. However, it is also essential to consider surface activities in future research and investigations.

In-situ resources utilization operations are expected to come to the forefront in the coming years. Therefore, alongside the technologies developed to succeed on the extraction and utilisation of materials on the Moon, efforts should be put to regulate those. Their performances should follow a sustainable behaviour, including the protection of safety zones and acting with transparency and coordination among operators. Currently, academic research on the definition of sustainability in the In-Situ Resource Utilization (ISRU) value chain—from extraction, transport, and transformation to storage—is being conducted at eSpace, part of the EPFL Space Center [106].

As more stakeholders prioritize sustainability in their lunar activities, alignment between their efforts becomes crucial.

For this reason, work to reinforce the literature on this topic is vital to ensure a prosperous future for the Moon.

The lunar environment was presented in chapter 2. Here, the dynamics of the cis-lunar space were discussed, together with the relevant orbits around the Moon

and around the Lagrangian points of the EM system.
In chapter 3 a state-of-the-art of the policies that mention sustainability around the Earth and around the Moon was provided. Additionally, section 3.3 explored numerous end-of-life management strategies applied to contemporary space missions.
A summary of the disposal techniques in Earth orbits and lunar orbits was analyzed in chapter 4. For lunar orbits, four strategies were debated, with their advantages, drawbacks and demonstrations on operative spacecraft.
Lastly, chapter 5 provided the outcome of the work: the "Space debris mitigation guidelines for lunar orbits". This document is intended as a first-step to raise the awareness among the space actors, encouraging them to behave in the lunar environment in a responsible way. It considers measures to reduce the potential creation of space debris in the orbits around the Moon and around the Lagrangian points of the EM system.

6.1 Future work

The space debris mitigation strategies in lunar orbits will evolve alongside upcoming missions. With more satellites deployed into cis-lunar space, an increasing number of actors will need to consider disposal techniques, passivation measures, and collision avoidance capabilities for their spacecraft, supported by numerical simulations.
As discussed in chapter 4, the knowledge and experience of the disposal strategies must be enriched, as several aspects require further assessments.
Up to December 2023, only 112 objects exploited the four measures analyzed [43], the lunar impact, the injection into heliocentric orbit, the re-enter to Earth SOI and the injection into a lunar graveyard orbit.
Additionally, 22 objects had or have an unknown end-of-life management.
Launching more satellites to the lunar environment with sustainability in mind, and with defined space debris mitigation plans, will improve future disposal manoeuvres. For instance, science missions with the objective to explore the lunar graveyard orbits, such as the DROs, can confirm the feasibility of this technique, along its stability.
Special attention should be given to the lunar impacts. With the growing interest on the activities on the surface of the Moon, more areas will require protection.
Therefore, it is important to expand the knowledge on the consequent ejecta after a collision on the soil, their range and the energy they carry.
Furthermore, the possibility to create landfills on the Moon could create several sustainable market solutions. These zones, discussed by D. Andrievskaia et al. [93], might concentrate the impact events far from potential human and commercial operations.

Once the deceased satellites lie on the landfills, the aluminium and other metals and materials could be recycled in-situ to build, for instance, infrastructure.
Finally, research is needed to improve the space situational awareness in the cis-lunar environment.
One of the biggest current challenges for the cis-lunar habitat is the lack of means to observe it from Earth.
Enhancing observability will help create a catalog of the debris population, enabling the identification of debris sizes and the necessary mitigation techniques.
Missions specifically designed to monitor and track space debris will contribute to a better space situational awareness, as proposed by the LUMOS, one of the last ESA concurrent design facility study, mentioned in subsection 4.2.3.
A potential development of the work performed during this master thesis would be to support the guidelines with numerical simulations. Thereby, preciser definitions on the orbits in the lunar environment, as well as thresholds on the post-mission disposal strategies could be provided.
In conclusion, while research on lunar sustainability and debris is still in its infancy, the growing awareness among the space community highlight a shift towards considering responsible practices in lunar exploration. As missions to the Moon increase, the importance of sustainable approaches becomes more critical. Stakeholders are called to actively explore strategies that will protect lunar resources and environments for the future of the cis-lunar economy.

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