LUNAR ORBITAL DEBRIS MITIGATION: CHARACTERISATION OF THE ENVIRONMENT AND IDENTIFICATION OF DISPOSAL STRATEGIES

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ABSTRACT

There is a clear, increasing interest towards the Moon, with the idea of establishing permanent human settlements on its surface and in orbit, assembling and operating a cislunar orbital laboratory, the Lunar Orbital Platform - Gateway (LOP-G), in a L_2 Near Rectilinear Halo Orbit (NRHO). This new scenario will involve multiple actors, including national agencies and private companies, which will insert and operate a high number of spacecraft in the cislunar space. A subject that still remains open and generally unregulated is the end of mission: the majority of past missions have been commanded to impact on the lunar surface, but this option might not be a sustainable long-term solution. In this work, the Circular Restricted 3-Body Problem (CR3BP) is used to study the dynamics of the Earth-Moon system, and several families of periodic orbits are identified and their main dynamical characteristics and behaviours described, with the final aim of creating a cartography of the cislunar space. This review of CR3BP orbits could prove useful both for identifying optimal matches with future applications and provide an estimation of the cislunar space utilisation and debris environment. Particular focus is given to NRHOs since, in the coming decades, they are likely to become the most targeted orbits for lunar spacecraft and therefore the origin of most artificial debris. Furthermore, disposal strategies available in the cislunar space, such as lunar impact and ejection towards a graveyard orbit, are reviewed and evaluated. To provide a preliminary trade-off for the disposal of planned missions, several scenarios are simulated to assess the optimal mission design ensuring feasibility of the chosen strategy with respect to mission requirements and its sustainability with respect to national and international guidelines.

Keywords: Lunar exploration, Debris, Cislunar space, Disposal.

1. INTRODUCTION

Lunar exploration is once again, after the last Apollo mission in 1972, in the spotlight. National agencies as well as private actors are expressing their interest in visiting the Earth's moon, with the aim of exploring its surface, exploiting its resources and establishing there a permanent presence of humankind. The coming years will likely see an increase of missions, with a large variety of targets, masses and volumes. In particular, plans for an orbiting station are now well established. The strongest candidate for its location is not a classical, keplerian orbit, but rather a three-dimensional, periodical trajectory defined in the frame of the Earth-Moon "Three-Body Problem" [16]. The cislunar space, defined as the region between the Earth and the Moon, is in fact dominated by the gravitational influences of the two celestial bodies, which have a comparable effect on the motion of a spacecraft. This results in a complex dynamical environment which can present both chaotic and periodical motion. Each three-body system admits in fact five equilibrium "libration" points L_i), around which periodical solutions, called Libration Point Orbits (LPOs), can be found [11].

To abide to present regulations and avoid the pollution of the cislunar space, future missions will require to limit their generation of debris and properly plan the disposal of the spacecraft involved. In fact, cislunar debris represent a risk for future lunar assets, both on orbit and on the lunar surface, as well as for Earth's protected orbital regions and surface. Hence, knowledge of the dynamical environment and of the available strategies for disposal is of paramount importance to mitigate the generation of lunar debris, towards sustainable space exploration missions.

After an introduction on the context of the present research and a review of available disposal strategies for lunar spacecraft, this paper focuses on the analysis of disposal manoeuvres from cislunar orbits. In Section 2, the dynamical framework used in this analysis is presented. The main characteristics of the cislunar environment are reported, with attention to the Circular Restricted 3-Body Problem (CR3BP) model and its governing equations. Moreover, Halo orbits are briefly discussed and the orbits chosen for the case studies are presented. The proposed methodology to analyse disposal of lunar spacecraft is then illustrated in Section 3. Section 3.2 presents an example of application of this methodology for two case studies. In Section 4, the conclusions of this research are drawn.

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1.1. Disposal strategies

Several studies have addressed the problem of disposal for Sun-Earth LPOs missions, because of their interest for astrophysics and solar observation missions [5, 1, 12]. In the Earth-Moon system, the available literature mainly discusses disposal strategies for spacecraft on Near Rectilinear Halo Orbits (NRHOs), with special emphasis on the L_2 southern NRHO with a 9:2 resonance with Moon's synodic period [2, 6, 7]. Some works consider also other Halo family members [3, 4].

Based on the available literature and on the history of past missions, a cislunar spacecraft at the End Of Life (EOL) has three main options for its disposal: impact on the lunar surface, transfer to a stable graveyard orbit or perform an Earth atmospheric re-entry.

The majority of past missions towards the Moon have been either directly commanded to impact the lunar surface in a short time, or have been left in low lunar orbits, the instability of which eventually produced an impact. Nevertheless, any falling spacecraft could damage historical sites [10], and it might also pose a risk for future lunar "safety zones", as defined in the recent Artemis accords [14]. Moreover, if used indiscriminately, impacts can potentially pollute areas relevant for scientific research [13] with heavy materials and chemicals. Hence, it might not be a sustainable option in a long-term scenario.

From the cislunar space, it is possible to reach heliocentric space by performing a single-impulse manoeuvre and exploiting multi-body dynamics of the Earth, Moon and Sun [3]. Nevertheless, to avoid a 1:1 resonance with Earth's orbit, a second manoeuvre can be performed to raise (or lower) the orbital energy and avoid re-entries [1], although this possibility requires maintaining control of the spacecraft until the second manoeuvre. Other potential graveyard orbits in the cislunar space, around the Earth or the Moon or on stable Earth-Moon LPOs, could have the advantage of keeping the space debris at a reachable distance, in case a future space economy is able to profit from the material left in orbit.

The other possibility to dispose of lunar spacecraft is to inject into a trajectory to re-enter Earth's atmosphere. This possibility has not been applied in past missions, except in the case of crew vehicles or robotic sample containers returned to Earth. Current directives impose for the risk of casualty on ground to be lower than 1 in 10000 [8]. If this number cannot be achieved, a controlled re-entry is necessary, targeting specific low-risk areas. In addition, an atmospheric re-entry implies the crossing of protected Low Earth Orbit (LEO) and Geostationary Orbit (GEO) regions, which poses a risk of collision for assets orbiting the Earth.

2. DYNAMICAL MODELS

2.1. The Circular Restricted 3-Body Problem model

The CR3BP studies the motion of a particle in the combined gravitational field of two massive bodies [11]. With respect to the more general three body problem, the CR3BP model is based on two simplifications: the two spherical massive bodies, denoted as "primaries", have *circular* keplerian orbits around their common centre of mass; the third body in the dynamical system, e.g. a spacecraft, has a negligible mass with respect to the primaries, and can't affect the motion of the primaries, which makes the problem *restricted.*

The CR3BP allows for a good understanding of the dynamical behaviour of a spacecraft travelling in the Earth-Moon region, and avoids the complexity and computational effort associated with higher fidelity models. For this reason, it has been used to perform the preliminary analyses discussed in this research.

The CR3BP dynamical system is conveniently described using a rotating reference frame (often referred to as "synodic" frame) centred in the primaries' common barycenter, with the axis x pointing towards the smaller primary, the axis z aligned with the angular momentum vector of the orbiting primaries and y that completes the right-handed frame. The resulting equations of motion, opportunely normalised with a set of characteristic quantities [11], are:

$$\begin{aligned} \ddot{x} - 2\dot{y} &= -\frac{\partial \tilde{U}}{\partial x} \\ \ddot{y} + 2\dot{x} &= -\frac{\partial \tilde{U}}{\partial y} \\ \ddot{z} &= -\frac{\partial \tilde{U}}{\partial z} \end{aligned} \tag{1}$$

where $\tilde{U}$ is an "effective" potential, taking into account for gravitational and centrifugal influences, defined as:

$$\tilde{U} = -\frac{1}{2}\left[(1-\mu){r_1}^2 + \mu {r_2}^2\right] - \frac{1-\mu}{r_1} - \frac{\mu}{r_2} \tag{2}$$

where $r_1 = |\mathbf{r}_1|$ and $r_2 = |\mathbf{r}_2|$ are the position vectors of the spacecraft with respect to the Earth and the Moon, and $\mu = m_2/(m_1 + m_2)$ is the mass parameter, where m_1 and m_2 are the masses of the primaries.

Under the above mentioned hypotheses, the CR3BP is a conservative, time-invariant system, and it admits only one integral of motion:

$$E = \frac{1}{2}(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) + \tilde{U} = -\frac{C_J}{2} \tag{3}$$

where $C_J = -2E$, called Jacobi constant, is often used to differentiate between energy levels of orbits and trajectories.

Table 1: Relevant parameters for the two L_2 *southern Halo orbits considered in this work.*

Type	T [days]	Az [km]	C_J [-]	ν_i [-]	Ref.
L_2 NRHO	6.56	69958	3.06	93.2429	(a)
L_2 Halo	13.79	58245	3.08	0.6845	(b)

2.2. Halo orbit families

In the frame of the CR3BP model, five equilibrium points can be defined (indicated with L_i), often called "libration" points, around which several families of periodic orbits can be found [11]. Among these families, Halo orbits have been already used for past mission and are a potential candidate target for future applications. In particular, NRHOs, which exists at the extremity of the family close to the Moon, are currently the baseline for a future orbital station.

To compute halo orbits, first a third-order approximation is used to provide an initial guess of the initial state [15]. This guess is then refined through an opportunely defined differential correction routine until a periodic solution is found. The entirety of the family is then computed through the process defined as continuation. There exists Halo orbits for collinear points L_1, L_2 and L_3, and for each libration point, two families can be defined, symmetrical with respect to the orbital Earth-Moon plane. These are defined as "southern" and "nothern" families.

Along a family, it is possible to evaluate several parameters: the vertical extension A_z, which corresponds to the maximum value of the z component, the Jacobi constant C_J, defined in Equation (3), and the stability index ν, defined as [9]:

$$\nu_i = \frac{1}{2}\left(\lambda_u + \frac{1}{\lambda_s}\right) \tag{4}$$

where λ_u and λ_s are respectively the unstable (maximum in modulus) and stable (minimum in modulus) eigenvalues of the "monodromy" matrix of the orbit, which is the State Transition Matrix (STM) after one orbital period.

In the present study, two example orbits are considered: a "large" L_2 southern Halo orbit and L_2 southern NRHO with a 9:2 resonance with the Moon's synodic period. Relevant parameters on the two orbits are reported in Table 1, with a reference for Figures 3 and 4. These values are also shown in Figure 1 along the entire family parameters, plotted with respect to the orbital period T. In Figure 2, a graphical representation of the family in the Earth-Moon system is reported, with the two case study orbits highlighted.

3. DISPOSAL ANALYSIS

A methodology is here outlined to study the disposal of spacecraft from CR3BP orbits. A single, impulsive manoeuvre is applied to several initial states along a chosen orbit to perform a scan of the possible final destinations. The aim is to correlate initial conditions of a spacecraft, such as the starting position on the orbit and the initial manoeuvre's direction and magnitude, to its final state. This will contribute in creating a dynamical cartography of the cislunar space. In the following, methods used to initialise, perturb and propagate trajectories are discussed, and preliminary results are presented.

3.1. Investigation methods

First, to identify specific points on an orbit, a period fraction parameter θ is defined as:

$$\theta = \frac{t - t_0}{T} \tag{5}$$

where t_0 is the time of passage at the periapsis (defined as the minimum distance from the Moon), and T is the orbital period. This equal-time sampling strategy has been used to obtain the results presented. Considering $t_0 = 0$, it follows that $\theta \in [0, 1[$, where $\theta = 0$ corresponds to the periapsis and $\theta = 0.5$ to the apoapsis of the orbit.

Once an initial state $\mathbf{p}_0 = (\mathbf{x}_0, \mathbf{v}_0) = (x_0, y_0, z_0, \dot{x}_0, \dot{y}_0, \dot{z}_0)$ is identified unequivocally with a value of θ, an instantaneous change in velocity $\Delta\mathbf{v}$ is applied so that:

$$\mathbf{p}_0^+ = (\mathbf{x}_0, \mathbf{v}_0 + \Delta\mathbf{v}) \tag{6}$$

Then, propagation is performed integrating the dynamics provided in Equation (1) using a variable step solver.

The integration is automatically stopped in case the trajectory intersects the Moon, modelled as a sphere of radius $R_M = 1737$ km, exits from Earth's Sphere Of Influence (SOI) of radius $R_{SOI_E} \simeq 0.929 \times 10^6$ km, or passes behind the Earth, *i.e.* the x component of the trajectory's state vector crosses x_E, the position of the Earth on the x axis.

To assess the disposal options for cislunar orbits in the CR3BP, a large scan of trajectories is initialised, perturbed and propagated until an event occurs or the total propagation time is reached. In the frame of this research, the initial state is perturbed in the velocity and anti-velocity directions, *i.e.* along the unit vector $\hat{\mathbf{u}}_V = \mathbf{v}_0/|\mathbf{v}_0|$ with a varying magnitude $\Delta\mathrm{V}$, resulting in a manoeuvre:

$$\Delta\mathbf{v} = \pm\Delta V\,\hat{\mathbf{u}}_V \tag{7}$$

This analysis, although limited to the velocity tangential direction, allows to link each starting point θ_i and each

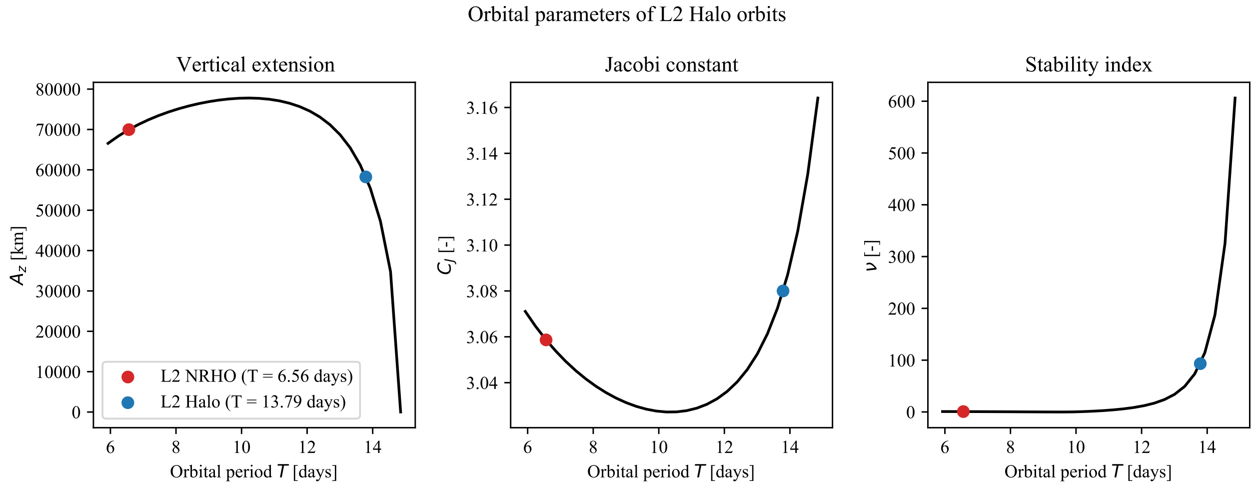

Figure 1: Main parameters for the L$_2$ *Southern Halo orbit family, plotted with respect to the orbital period* T*. The orbits considered in this study are highlighted with round coloured markers.*

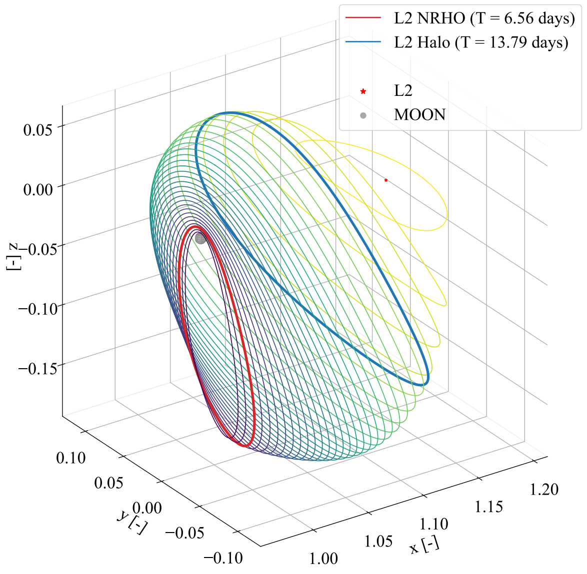

Figure 2: Three-dimensional representation of the L$_2$ *Southern Halo orbit family in the rotating reference frame, with adimensionalised units. The orbits considered in this study are highlighted.*

manoeuvre magnitude ΔV_j to a final outcome. There is also the possibility that none of these conditions is met during the propagated time, which results in an unknown outcome. As it will be seen in section Section 3.2, this rarely occurs with the propagation times considered.

From such an analysis, it is possible to identify "clusters" of trajectories with the same outcome, as well as zones, in terms of θ and ΔV, with chaotic behaviour. The elapsed time of propagation before the occurrence of an event can also be considered to judge disposal options, especially in the frame of a cluster. Moreover, probabilities of the propagation outcomes can be extrapolated for each value of θ or ΔV, and an overall outcome probability can be computed for each orbit.

Nevertheless, it is not possible to draw precise conclusions on the impact latitudes and longitudes due to the Moon's rotation axis obliquity, which is not modelled in the CR3BP. Some solutions exist to partially overcome this issue [7], but they are not implemented in the present research, and only the occurrence of a lunar impact is studied.

3.2. Case study analysis

In the frame of this research, an example analysis is run to evaluate the methodology developed and identify future directions of research.

Trajectories are initialised on each of the two orbits presented in Section 2.2 through 500 equally spaced values of $\theta \in [0, 1[$. They are then perturbed with 400 different values of $\Delta V \in [-20, 20]$ m/s with a step of 0.1 m/s (negative ΔVs result in manoeuvres in the anti-velocity direction). This results in $2 \times 500 \times 400 = 400'000$ trajectories, which are then propagated in parallel for 200 days, or until one of the stopping events is met.

Once an outcome is computed for each trajectory, a map can be constructed to link them, for each orbit, to values of starting θ and manoeuvre ΔV magnitudes. An example of this analysis for the orbits considered in Section 2.2 is presented in Figure 3. Several areas of similar behaviour can be identified, were small variations in θ and ΔV don't change the final result. Areas where points are more scattered, changing outcomes with small variations of parameters, identify probable chaotic behaviour. For the NRHO, reported in Figure 3a, such chaotic areas are observed for small values of ΔV, except for the group

Table 2: Probability of each outcome for 200 days propagation for two example Halo orbits. In unknown cases, propagation was not interrupted by an event.

Orbit	Outcome			
	Lunar impact	Exit SOI	Around Earth	Unknown
L_2 NRHO	4.9%	15.0%	80.1%	<0.001%
L_2 Halo	11.7%	13.7%	74.6%	<0.01%

of impacting trajectories around the periapsis, and some bands of trajectories exiting the SOI. The results in terms of probability of each outcome are reported in Table 2.

In Figure 4, the detail of the propagation time for the case of lunar impact is shown. Here, it is possible to observe how areas that seemed belonging to the same group in Figure 3, are in fact part of distinct clusters of trajectories. For example, in Figure 4a, of the impact cluster right after the periapsis, defined for $\theta \in [0.0, 0.12]$ and $\Delta V \in [-20, -5]$ m/s, is actually composed of two distinct clusters, where the time to impact doubles. This underlines the need for a cluster-level analysis, searching for trajectories with both outcome and transfer time robust to variation of input parameters.

4. CONCLUSIONS

This paper presented a review of available disposal strategies for cislunar spacecraft, briefly discussing their feasibility and main constraints. Then, the CR3BP model has been used to study the dynamics in the Earth-Moon system, as a two-body, keplerian motion fails to properly describe the gravitational environment generated by the two celestial bodies. The process to find periodical solutions in the CR3BP has been introduced, bringing the example of Halo orbits around the libration point L_2. Among this family, two orbits have been chosen as case study: a ”large” Halo orbit and an Near Rectilinear Halo Orbit.

The methodology introduced aims at linking orbits in the CR3BP to the available disposal options, creating a dynamical cartography of the cislunar space. For the two cases considered, several single-manoeuvre disposal trajectories have been initialised and propagated starting from different points along the orbit, through a grid search approach for varying manoeuvre magnitude ΔV in the velocity and anti-velocity directions. This resulted in the creation of “outcome” maps, where the propagation stopping event is highlighted for each propagated trajectory (identified by a starting position and a value of ΔV).

These results represent a subset of the potential analyses that can be carried out with this type of approach. First of all, a deeper analysis of each trajectory can be performed, to better distinguish different clusters with similar shapes. Sampling several orbits along CR3BP families can be considered as well. Moreover, different directions of the disposal manoeuvre can be envisaged, expressed in the form of pitch and yaw angles in a Velocity Normal Bi-Normal (VNB) frame. The use of higher fidelity models will allow to create a more realistic cartography, in comparison with the results obtained with the CR3BP. This would also allow for a better identification and characterisation of impact locations, the coordinates of which cannot be precisely determined by the CR3BP. More advanced research could focus on a multiple-manoeuvre or continuous low-thrust disposal transfers, studying the use of graveyard orbits, both in cislunar space and around the Sun.

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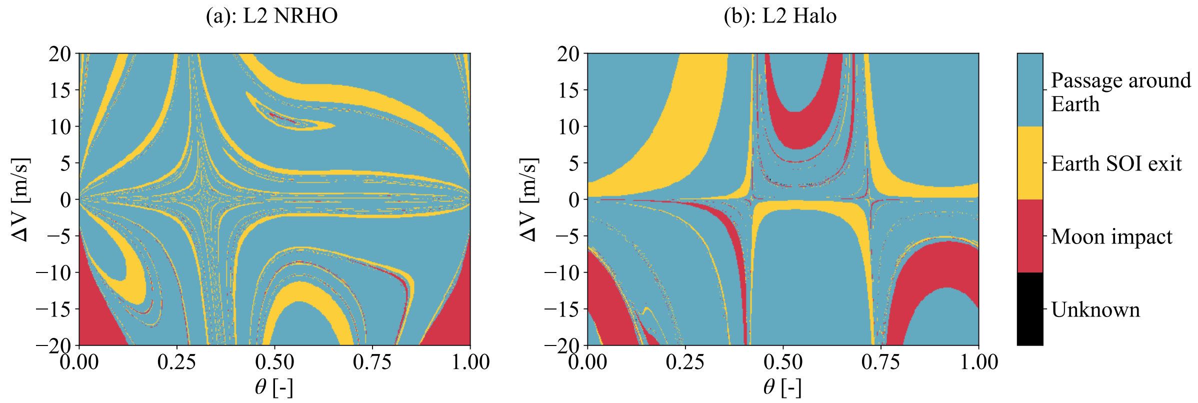

Figure 3: Outcome of propagation for the two L$_2$ *southern Halo orbits.*

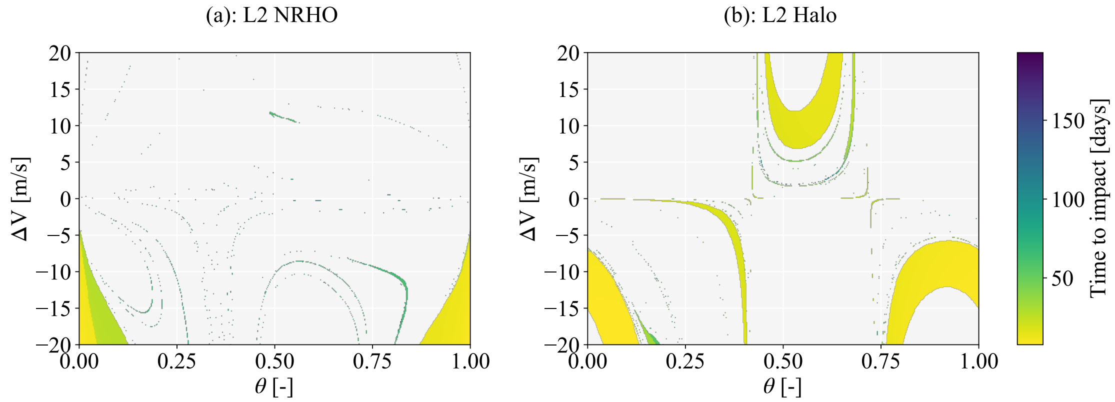

Figure 4: Time to impact for the two L$_2$ *southern Halo orbits.*

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