MULTIPLE NEAR-EARTH ASTEROID RENDEZVOUS MISSION: SOLAR-SAILING OPTIONS

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ABSTRACT

The scientific interest in near-Earth asteroids (NEAs) and the classification of some of those as potentially hazardous for the Earth stimulated the interest in their exploration. Close-up observations of these objects will drastically increase our knowledge about the overall NEA population. For this reason, a multiple NEA rendezvous mission through solar sailing is investigated, taking advantage of the propellantless nature of this propulsion technology. Considering a spacecraft based on the DLR/ESA Gossamer technology, this work focuses on a method for searching possible sequences of NEA encounters. The effectiveness of the approach is demonstrated through a number of fully-optimised trajectories. The results show that it is possible to visit five NEAs within 10 years with near-term solar-sail technology. Moreover, a study on a reduced NEA database demonstrates the reliability of the approach used, showing that 58% of the sequences found with an approximated trajectory model can be converted into real feasible solar-sail trajectories. Overall, the study shows the effectiveness of the proposed automatic optimisation algorithm, which is able to find solutions for a large number of mission scenarios without any input required from the user.

Keywords: Automatic trajectory design; Solar sail; Tree-search algorithm; Multiphase trajectory optimisation; Gossamer; Near-Earth asteroids; Multiple rendezvous

NOMENCLATURE

A	=	Sail area, m^2
$\mathbf{A}(\boldsymbol{x})$	=	Matrix of the dynamics
$\boldsymbol{a}$	=	Solar-sail acceleration, mm/s^2
a	=	Semi-major axis, AU
a_c	=	Solar-sail characteristic acceleration, mm/s^2
$\boldsymbol{b}(\boldsymbol{x})$	=	Vector of the dynamics
e	=	Eccentricity
f, g	=	In-plane modified equinoctial elements
g_0	=	Standard gravitational acceleration on Earth's surface, 9.81 m/s^2
H	=	Asteroid absolute magnitude
$\hat{\boldsymbol{h}}$	=	Orbital angular momentum unit vector

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I_{SP} = Specific impulse, s

j, k = Out-of-plane modified equinoctial elements

L = True longitude, rad

m_0 = Total mass, kg

m_{dry} = Spacecraft dry mass, kg

$\hat{\boldsymbol{N}}$ = Unit vector normal to the sail plane

$P_\oplus$ = Solar radiation pressure at Earth distance, 4.56 μN/m^2

p = Semi-latus rectum, AU

$\boldsymbol{r}$ = Sun-spacecraft position vector ($r := \|\boldsymbol{r}\|$), AU

$\ddot{\boldsymbol{r}}$ = Acceleration

$r_\oplus$ = Mean Sun-Earth distance, 1 AU

t = Time, s

t_0 = Departure date

U = Quality code

$\boldsymbol{x}$ = State vector in modified equinoctial elements

α = Sail cone angle, deg

Δv = Velocity increment, km/s

$\delta\varpi$ = Longitude of pericentre variation, rad

$\dot{\zeta}$ = Sail slew rate, deg/s

$\ddot{\zeta}$ = Sail angular acceleration, deg/s^2

θ = Angle between two angular momenta, rad

λ = Shaping parameter

μ = Gravitational parameter of the Sun, 1.3271×10^{11} km^3/s^2

φ = Phasing parameter, rad

ϖ = Longitude of pericentre, rad

Superscripts

T = Transpose

Subscripts

0 = Initial value

F = Boundary conditions at the final time

fg = In-plane modified equinoctial elements

I = Boundary conditions at the initial time

p = Semi-latus rectum

1. INTRODUCTION

In the last decades, near-Earth asteroids (NEAs) received considerable attention for planetary defence, science, human spaceflight and technology demonstration. From a technological point of view, NASA considers NEAs as a bridge toward the human exploration of Mars (Boden et al., 2015). A manned NEA mission offers similar challenges as a mission to the red planet (i.e. a relevant deep-space environment and a total mission duration similar to an Earth-Mars transit). On the other hand, the total mission duration and the required Δv (and, therefore, the launch costs) are below those needed for a full Mars return mission. As reported in Boden et al. (2015), however, for safety considerations, the asteroid selection for such a mission shall take into account several characteristics of the target objects (e.g. size, composition, rotation rate, etc.). Based on the observations taken from Earth, the characterisation of NEAs discovered to date often suffers from uncertainties in their physical, chemical and orbital properties. Moreover, some NEAs are defined as potentially hazardous asteroids (PHAs) and, especially for planetary defence scenarios, an accurate characterisation of their properties is needed (Sanchez et al., 2009). Sugimoto et al. (2013) underlined this need for deflection purposes. Even if methods exist to deal with NEA composition uncertainties (e.g. evidence theory), Sugimoto showed how some deflection methods – the ones that have a strong interaction with the target object (e.g. nuclear interceptor, solar sublimation or kinetic impactor) – are affected by uncertainties about asteroid composition (i.e. porosity, surface materials, precise shape, etc.) more than others. Furthermore, not only the chemical, physical and mineralogical composition but also the rotation of these objects can have an important role in the success of a mission, for both deflection and sample-return missions. Miller et al. (2015) gave an overview of the asteroid-characterisation priorities for planetary defence, pointing out the possible issues derived by a deflection mission to badly-characterised objects. Several survey and mitigation programs have been established for the purpose of a better knowledge of NEA characteristics (NEOWISE (Mainzer et al., 2012), JPL/NASA Near-Earth Object Program[*], and NEOShield (Harris et al., 2013) are just three examples) but most of them deal with ground-based observations. Specifically regarding Europe, Koschny and Drolshagen (2015) showed the ongoing activities to mitigate the potential threat posed by NEAs. To date, few missions to small bodies have been successfully completed (e.g. NEAR (Cheng et al., 1997), Deep Impact (Blume, 2005), Hayabusa (Fujiwara et al., 2004, Fujiwara et al., 2006), and Rosetta (Glassmeier et al., 2007, Pätzold et al., 2011)) and two spacecraft (OSIRIS-REx (Berry et al., 2013) and Hayabusa-2 (Tsuda et al., 2016)) are currently on their way to rendezvous two different NEAs (Bennu and 1999 JU_3, respectively). The Asteroid Impact and Deflection Assessment (AIDA) mission aims to demonstrate the kinetic-impact technique for asteroid deflection and consists of two spacecraft, the first of which is scheduled to be launched in late 2020 (Cheng et al., 2015). A further mission, the Asteroid Redirect Mission (ARM), is currently under study and is planned to capture and redirect a small NEA into an orbit accessible to a human crew (Gates et al., 2015). Nevertheless, a multiple NEA rendezvous mission can help the scientific community to improve our knowledge about these objects. A multiple-target mission is more desirable than a single-rendezvous mission due to the reduced cost of the single observation and the more extensive information returned. Moreover, within a multiple-target mission, it might be possible to change the targets in due course, if there is enough Δv available. This feature can be useful if new interesting objects are discovered after the launch. However, the large amount of possible sequences of objects that can be chosen to visit makes the optimal planning of such a mission very challenging. In fact, more than a billion of possible ordered sequences

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[*] https://cneos.jpl.nasa.gov/orbits/elements.html (cited 08 August 2015).

with three consecutive encounters exist, considering a database with more than 12,000 objects. Moreover, a trajectory-optimisation problem must be numerically solved to obtain feasible trajectories with the chosen propulsion system.

Regarding the propulsion system, a multiple NEA rendezvous mission can be very demanding in terms of total required Δv (Peloni et al., 2014). Solar sailing is an attractive way to perform such a challenging mission, because of its capability to deliver Δv without consuming propellant. Propelled only by the sunlight, a solar sail can be used for high-Δv interplanetary missions (Dachwald and Seboldt, 2005), as well as non-Keplerian orbits (Ceriotti and McInnes, 2011, McKay et al., 2011), and missions characterised by continuous thrusting (Bolle and Circi, 2011). Furthermore, because of the propellantless nature and the potentially-unlimited Δv available, a solar sail has a higher capability to perform a change of the target bodies than an electric propulsion system, even after the mission has started. Due to these advantages, several studies have been carried out on the application of the solar-sail technology for interplanetary missions, from an orbital dynamics point of view (Sullo et al., in press) as well as from a system-enginnering one (Grundmann et al., 2015, Peloni et al., 2015). The DLR/ESA Gossamer roadmap to solar sailing is one of those studies and it was divided into steps of increasing complexity (Geppert et al., 2011). Its aim was to push the boundaries of the current European solar-sailing technology by firstly testing the deployment of a small solar sail in a low-Earth orbit and then performing a multiple NEA rendezvous mission (Dachwald et al., 2014) as well as a sub-L_1 space weather mission (McInnes et al., 2014) and a solar polar mission (Macdonald et al., 2014) with a larger sail. A multiple NEA rendezvous mission is attractive for solar-sail technology demonstration as well as for improving our knowledge about NEAs.

To date, several studies have been carried out on multiple-object missions, mainly considering spacecraft propelled by electric thrusters. In the majority of the cases, the problem is divided into two sub-problems: firstly, potential sequences of encounters are found and, therefore, an optimisation strategy is used to refine and validate the sequences chosen among the ones found (Bertrand et al., 2009, Di Carlo and Vasile, 2016). Usually, the first sub-problem is the most challenging one due to the very large number of potential sequences to test. For this reason, two main approaches are used in literature to tackle this sub-problem. The first one is a tree-search algorithm with branching and stopping criteria based on heuristic rules (e.g. astrodynamical considerations, technological limitations, mission requirements) (Casalino and Pastrone, 2016, Izzo et al., 2016). A second approach is to use a heuristic optimisation algorithm such as the ant-colony optimiser (Ceriotti and Vasile, 2010, Stuart et al., 2016a, Stuart et al., 2016b) or an algorithm inspired by the behaviour of an amoeboid organism, the Physarum polycephalum (Di Carlo et al., 2017, Vasile et al., 2015). In any case, because of the large amount of trajectories to be computed, simplified trajectory models are used which require little computational effort (for instance, an approach using impulsive Lambert arcs is the one considered in Di Carlo and Vasile (2016)). Despite several studies have been found in the literature about multiple-object missions, very few of them deal with solar sails, such as the ENEAS+ mission study (Dachwald and Seboldt, 2005) and the DLR/ESA Gossamer roadmap technology reference study (Dachwald et al., 2014). Nevertheless, both of the aforementioned works do not investigate a systematic assessment of the potential sequences of objects to be visited. An NEA survey mission through solar sailing is investigated more in detail in Bando and Yamakawa (2011) which, however, considers only flybys of the objects in a two-dimensional dynamical model.

Starting from the mission requirements addressed by the reference study of Dachwald et al. (2014) as part of the DLR/ESA Gossamer roadmap to solar sailing (Geppert et al., 2011), the first aim of this paper is to present a method to select sequences of encounters for a multiple NEA rendezvous mission through solar sailing. A solar sail with a lower performance than the one in the reference paper is taken into account in this study. Although the Gossamer sail is already realistic for near-term solar-sailing missions, a decrease in the required performances further raises the mission-related technology readiness level (TRL) of the already available solar-sail technology.

Moreover, using the approaches proposed in Peloni et al. (2016a) for both the sequence search and the optimisation of solar-sail trajectories, the second aim of this paper is to study the reliability of these approaches on a database that contains targets more difficult to be reached, yet interesting from both the human and robotic exploration point of view. The reliability of the method will be studied in relation to the number of sequences found in the sequence-search phase for which the optimiser will be able to find a fully-optimised solution.

The paper is organised as follows. Sections 2 and 3 describe the sequence-search algorithm and the optimisation process used to test the sequences found, respectively. Section 4 describes in detail the Gossamer mission scenario. In sections 5 and 6, the results of the method described are shown for two databases taken into account. Lastly, section 7 presents our conclusions.

2. SEQUENCE SEARCH

Due to the large number of possible combinations of encounters, finding a sequence of NEAs for a multiple rendezvous mission is primarily a combinatorial problem. Moreover, an optimisation problem must be solved for each transfer leg in order to assess the existence of a trajectory feasible by a solar-sail. For these reasons, two subsets of the whole NEA database are introduced in section 2.1 to reduce the amount of objects to deal with. Therefore, the sequence-search algorithm, briefly described in section 2.2, is characterised by local prunings to further reduce the number of NEAs to test in each step of the tree-search algorithm, as detailed in section 2.2.1. Lastly, an approximated trajectory model has been used to have reliable results within a reasonable amount of time, as briefly discussed in section 2.2.2.

2.1 Asteroid database selection

Choosing the target asteroids to be visited in a mission is a difficult task because scientific interest, composition, orbital dynamics, and available launch windows shall be considered. The NASA Near Earth Object Program listed 12,840 NEAs on 8 August 2015[*] and this number is rapidly increasing. All those objects with an Earth minimum orbit intersection distance ≤ 0.05 AU and an absolute magnitude $H \leq 22$ (i.e. diameter $\gtrapprox 110-240$ m, depending on the albedo[†]) are classified as PHAs. The problem of finding a sequence of encounters is, first of all, a combinatorial problem. In fact, more than a billion of sequences of three objects can be found, if all the possible combinations with permutations are considered. Moreover, there seem to be no clear common priorities on the selection of NEAs in the scientific community. To reduce this huge amount of possible combinations, further classifications can be considered which take into account the interest from an exploration point of view. Barbee et al. (2010) introduced the Near-Earth Object Human Space Flight Accessible Target Study (NHATS) in which the objects are selected as those for which a low-thrust return mission can be found within a set of design parameters. A subset containing only PHAs and NHATS asteroids is, therefore, considered to be more usable and

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[*] https://cneos.jpl.nasa.gov/orbits/elements.html (cited 08 August 2015).

[†] http://www.minorplanetcenter.net/iau/lists/Sizes.html (cited 08 August 2015).

interesting. However, the list of NHATS asteroids is not univocally defined because the mission parameters for the trajectory computation can be set in several ways. The selection criteria used for the NHATS database considered in this paper are shown below. This database contains 1,801 objects, 1,607 of which are PHAs.

$$\text{NHATS criteria: } \begin{cases} \text{total } \Delta v \text{ required} \leq 8 \ \text{km/s} \\ \text{total mission duration} \leq 450 \text{ days} \\ \text{stay time at the object} \geq 8 \text{ days} \\ \text{launch}: 2015-2040 \\ H \leq 26 \text{ mag} \\ OCC \leq 7 \end{cases} \tag{1}$$

The term OCC in Eq. (1) is the Orbit Condition Code of an NEA's orbit, which refers to the accuracy of the orbit determination. For a complete explanation of the above criteria, the interested reader is referred to the JPL/NASA NHATS website*. In the following, this subset will be referred to as the PHA-NHATS database.

Boden et al. (2015) studied the target selection for manned NEA exploration and realised that the NEA accessibility to date is limited due to uncertainties in the objects' characterisation and the available technology. Nonetheless, they pointed out that 'there might be more targets within the currently known NEA population' for a NEA sample return mission. "One reason is that the actual rotation rates of most NEAs are unknown". A fast rotator, in fact, is not suitable for a sample return mission, either human or robotic. On the other hand, slow rotators can exist among those asteroids for which there currently is little knowledge about the rotation. Therefore, a second subset for a multiple NEA rendezvous mission can take into account those objects with a large uncertainty on the rotation rate to improve our knowledge for better planning a future exploration mission. The asteroid lightcurve database (LCDB) (Warner et al., 2009) is "a set of files generated from a database that includes information directly and indirectly obtained from observations made to determine the period and/or amplitude of asteroid lightcurves". The quality code U provides the assessment of the quality of the period solutions within the LCDB. For this reason, a second subset is taken into account in this study, which considers PHAs and those NEAs in the LCDB with $U \leq 2-$. That is, all those objects for which the given value of the rotation rate is not reliable for a statistical analysis. Such second database contains 1,813 objects, 271 of which are NEAs in the LCDB with $U \leq 2-$. Note that, as for the PHA-NHATS database, all the 1,607 known PHAs are also considered as part of this second database. In the following, this subset will be referred to as the PHA-LCDB database.

It is worth noting that the two subsets considered in this study are very different from each other. Despite the fact of having a similar number of objects and being made mostly of PHAs, the PHA-NHATS database contains NHATS asteroids that are, by definition, objects easy to be reached from the Earth. Therefore, their orbital elements do not differ much from those ones of the Earth. In contrast, there is not such constraint on the LCDB objects considered in the PHA-LCDB database. Therefore, finding feasible sequences of asteroids within this PHA-LCDB database is expected to be more difficult.

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* https://cneos.jpl.nasa.gov/nhats/intro.html (cited 08 August 2015).

2.2 Sequence search algorithm

Figure 1 shows the flowchart of the sequence search algorithm. First, the database is locally pruned by means of astrodynamical criteria, as detailed in section 2.2.1. This pruning allows the algorithm to consider fewer objects at a time so that no time is spent on those objects that would be difficult to reach. The shape-based approach described in section 2.2.2 is used to find approximated solar-sail trajectories to all the objects in the locally-pruned list. Therefore, the same iteration is carried out in a tree-search algorithm, the arrival object of each of the temporary sequences found so far being the departing object for the new iteration. When the total mission duration reaches the maximum allowed time (which is 10 years in this paper) or no feasible solar-sail trajectories are found, the algorithm stops. Note that this sequence search algorithm considers the sequence starting at Earth at a fixed time t_0.

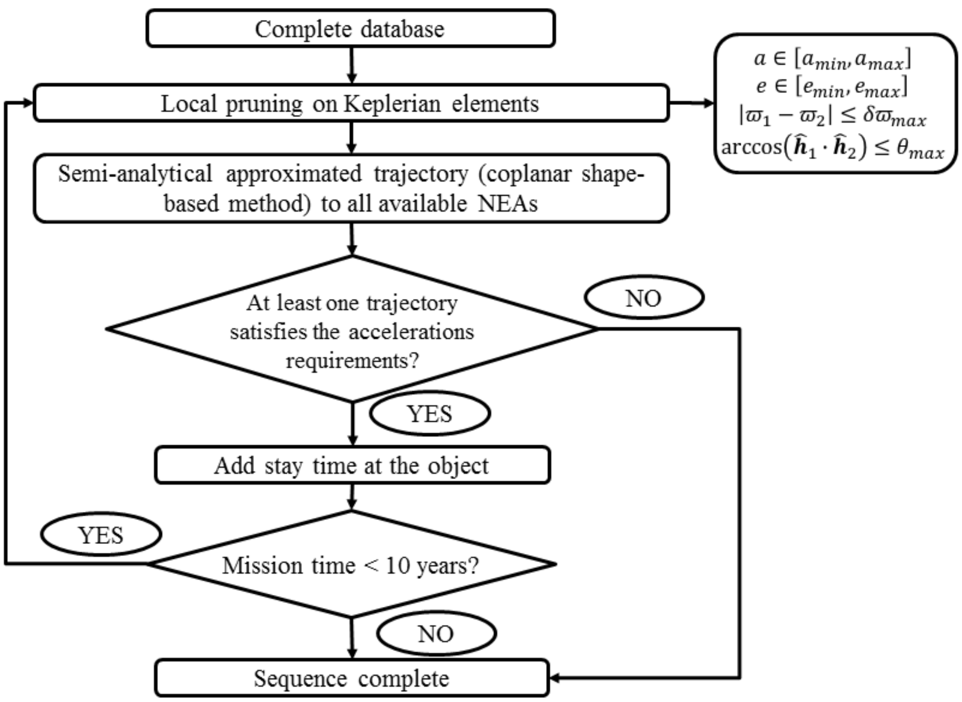

Fig. 1 Sequence-search flowchart.

2.2.1 Local pruning of the database

For each departing object at each leg, a local pruning on the available database is performed, to reduce the amount of objects tested at each leg and, therefore, speed up the overall sequence-search process. This is based on astrodynamical considerations. That is, target objects that are unlikely to be reached from the departure object with the considered sailcraft are discarded without a trajectory being computed.

Four conditions for the local pruning of the database are considered and briefly described below. For a complete description, the interested reader is invited to refer to Peloni et al. (2016a).

1) Semi-major axis: Boundaries on the semi-major axes for the target NEAs to be considered in the current leg are defined by propagating the current spacecraft state in an outward and inward spiral. The propagation is carried out by considering a control law that maximises the change in the semi-major axis (McInnes, 1999).

2) Eccentricity: Boundaries on the eccentricities for the target NEAs to be considered in the current leg are defined by propagating the current spacecraft state in an outward and inward spiral. The propagation is carried out by considering a control law that maximises the change in the eccentricity (McInnes, 1999).
3) Longitude of pericentre: A threshold on the maximum allowed variation of the longitude of pericentre has been considered for each object, as follows:

$$\delta\varpi_{\max} := \pi(1-e)^2 \tag{2}$$

That is, for each object, a region of candidate longitudes of pericentre can be defined which is centred in ϖ and has an amplitude equal to $\delta\varpi_{\max}$. Therefore, if an intersection does not exist between the regions of candidate longitudes of pericentre of departing and arrival objects, the arrival object is removed from the locally-pruned database. This condition can be mathematically represented as follows:

$$\begin{cases} \operatorname{mod}\left(\varpi_1 + \delta\varpi_{\max,1} + \pi,\ 2\pi\right) > \operatorname{mod}\left(\varpi_2 - \delta\varpi_{\max,2} + \pi,\ 2\pi\right) \\ \operatorname{mod}\left(\varpi_2 + \delta\varpi_{\max,2} + \pi,\ 2\pi\right) > \operatorname{mod}\left(\varpi_1 - \delta\varpi_{\max,1} + \pi,\ 2\pi\right) \end{cases} \tag{3}$$

4) Angular momentum: A threshold on the maximum allowed angle between the angular momenta of the departing and target orbits is defined. That is, al the objects, for which a change of the inclination and/or the longitude of the ascending node would be too large in the three-dimensional case, are not considered.

2.2.2 Shape-based approach for solar sailing

Describing the trajectory by means of modified equinoctial elements $\boldsymbol{x} = \left[p, f, g, j, k, L\right]^T$ (Walker et al., 1985), Peloni et al. (2016a) proposed a set of shaping functions for solar sailing in the coplanar case. The shaping functions that describe the coplanar trajectory of a solar sail are the following:

$$\begin{cases} p = p_I \exp\left[p_F\left(L - L_0\right)\right] + \lambda_p \sin\left(L + \varphi_p\right) \\ f = f_I + f_F\left(L - L_0\right) + \lambda_{fg} \sin\left(L + \varphi_{fg}\right) \\ g = g_I + g_F\left(L - L_0\right) - \lambda_{fg} \cos\left(L + \varphi_{fg}\right) \end{cases} \tag{4}$$

In the two-body problem approximation, the acceleration to follow a trajectory is retrieved by

$$\boldsymbol{a} = \ddot{\boldsymbol{r}} + \mu \frac{\boldsymbol{r}}{r^3} \tag{5}$$

Therefore, the acceleration needed to follow the trajectory given by Eq. (4) can be easily retrieved through Eq. (5). However, the acceleration given by a perfectly reflecting solar sail is

$$\boldsymbol{a} = a_c \left(\frac{r_\oplus}{r}\right)^2 \cos^2 \alpha \hat{\boldsymbol{N}} \tag{6}$$

In order to find the shape that best fits the solar-sail acceleration requirements given by Eq. (6), the shaping and phasing parameters $\left[\lambda_p, \lambda_{fg}, \varphi_p, \varphi_{fg}\right]$ are properly tuned.

3. SEQUENCE OPTIMISATION

Because an approximated two-dimensional trajectory model has been used to find sequences of NEAs to be visited, an optimisation problem must be solved to find high-fidelity, three-dimensional solar-sail trajectories.

The equations of the dynamics are defined by the following set of ordinary differential equations of motion:

$$\dot{\boldsymbol{x}}(t) = \mathbf{A}(\boldsymbol{x})\boldsymbol{a} + \boldsymbol{b}(\boldsymbol{x}) \tag{7}$$

in which $\mathbf{A}(\boldsymbol{x})$ and $\boldsymbol{b}(\boldsymbol{x})$ are, respectively, the matrix and vector of the dynamics, as described in (Betts, 2010). The propulsive acceleration $\boldsymbol{a}$ is the one shown in Eq. (6).

A direct transcription method (Patterson and Rao, 2014, Article 1) is used to find the optimal control vector that minimises the total mission duration while fulfilling the dynamics constraints of Eq. (7) at any time. The trajectory found through the coplanar shape-based approach is used as initial guess for the optimiser, which transforms it into a complete three-dimensional trajectory. The general-purpose optimal control software GPOPS-II (Patterson and Rao, 2014, Article 1), together with the nonlinear programming solver SNOPT (Gill et al., 2005), has been used in this work.

An automatic optimisation algorithm has been developed to find the optimal solar-sail trajectory in terms of total mission duration. This is schematically shown in Fig. 2, and discussed in detail in Peloni et al. (2016a).

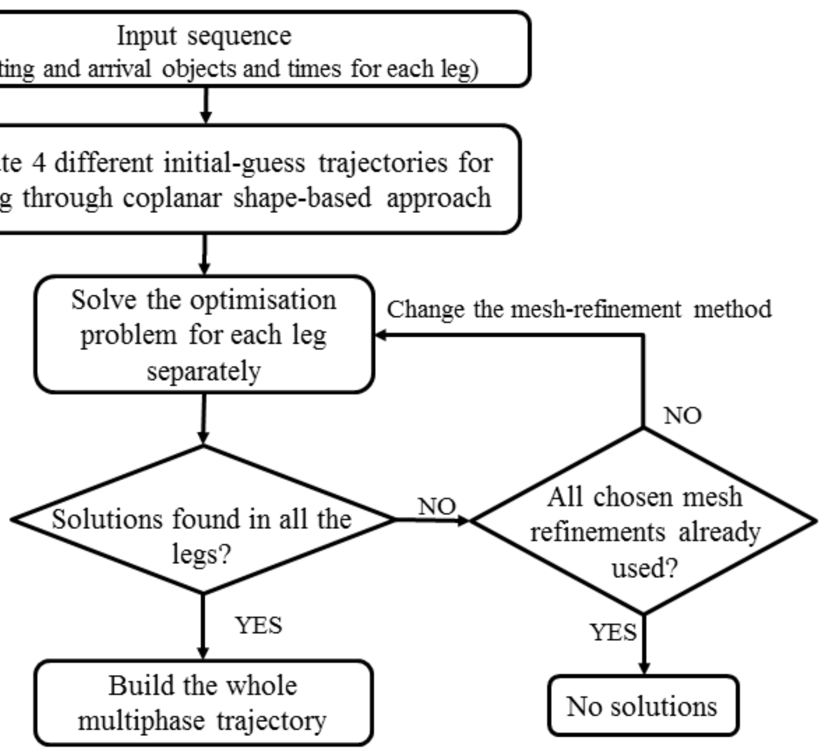

Fig. 2 Automatic optimisation algorithm.

4. APPLICATION TO GOSSAMER MISSION

The work of Dachwald et al. (2014) showed a 3-NEA rendezvous mission through solar sailing, considering a sailcraft with a characteristic acceleration $a_c = 0.3\ \mathrm{mm/s^2}$. The sequence of encounters, according to the DLR/ESA Gossamer roadmap to solar sailing (Dachwald et al., 2014), should respect the following criteria:

a) At least one object should be a PHA.

b) At least one object should be a potential target for future human exploration (i.e. should be part of the temporary NHATS database).

c) The last NEA should be a small object (i.e. $H \geq 25.5\ \mathrm{mag}$).

Because of the nature of the sequence-search method described in section 2, these criteria can only be verified *a posteriori*. Although there is no guarantee for meeting the above requirements, a large number of sequences are discovered. Therefore, the candidate sequences are chosen as those that best fit criteria a) – c) and that are made of the largest number of encounters.

Moreover, Dachwald et al. (2014) proposed three further steps to be investigated in future works for improving the technical feasibility and for increasing the support of the scientific and planetary defence communities:

i) Reduction of total mission duration.

ii) Reduction of required characteristic acceleration.

iii) Priority on PHAs within target selection.

A reduction in the total mission duration has not been taken into account in the current work, but sequences with more than 3 objects have been found, as presented in section 5.1.

A reduction of the required characteristic acceleration was addressed by considering a solar sail with a characteristic acceleration of $a_c = 0.2\ \mathrm{mm/s^2}$. It is worth to underline that, in the ideal case of a perfectly reflecting solar sail, the characteristic acceleration depends only on the area-to-mass ratio, as shown in the following.

$$a_c = 2P_\oplus \frac{A}{m_0} \tag{8}$$

Therefore, according to Eq. (8), such a reduction of the characteristic acceleration means a reduction of the area-to-mass ratio from $33\ \mathrm{m^2/kg}$ to $22\ \mathrm{m^2/kg}$. The latter implies the possibility of either carrying more payload on the same sail or using a smaller sail or a less-lightweight structure, with the result of lowering the technological challenges and thus increasing the mission-specific TRL of the available technology. According to the DLR/ESA Gossamer technology (Geppert et al., 2011), such a reduction in the characteristic acceleration implies reducing the sail size from about $(54\ \mathrm{m})^2$ - $(65\ \mathrm{m})^2$ to about $(39\ \mathrm{m})^2$ - $(48\ \mathrm{m})^2$. The interval of sail dimensions depends on the sailcraft bus adopted, as discussed in Dachwald et al. (2014).

Finally, the solutions with at least one PHA are preferred to the others.

5. RESULTS: PHA-NHATS DATABASE

In the following subsections, the results of the sequence search and selected fully-optimised sequences are presented. The PHA-NHATS database introduced in section 2.1 has been used. Therefore, the output sequences are very likely to fulfill the requirements a) – c) from the DLR/ESA Gossamer roadmap to solar sailing, as discussed in section 4.

5.1 Sequence search results

Starting from the departure date of the reference mission (which is $t_0 = 28$ November 2019), sequences have been searched on a set of departure dates $t_0 \in [28$ November 2019, 06 October 2029$]$, considering a step size of 90 days. This choice allows taking into account short and long-term variations in the phasing between the asteroids. Two consecutive legs are separated by a stay time of 100 days (Fig. 1).

More than 4,800 unique sequences have been found with at least five encounters, at least one of which is a PHA. It is important to underline that all the sequences found in this study contain only NHATS asteroids and sometimes a PHA. Figure 3 shows the number of unique sequences found for each departure date. More than 400 unique sequences with five encounters and at least one PHA have been found for a single departure date. If sequences with more than four encounters and at least one PHA are considered, more than 1,000 unique sequences have been found for a single departure date.

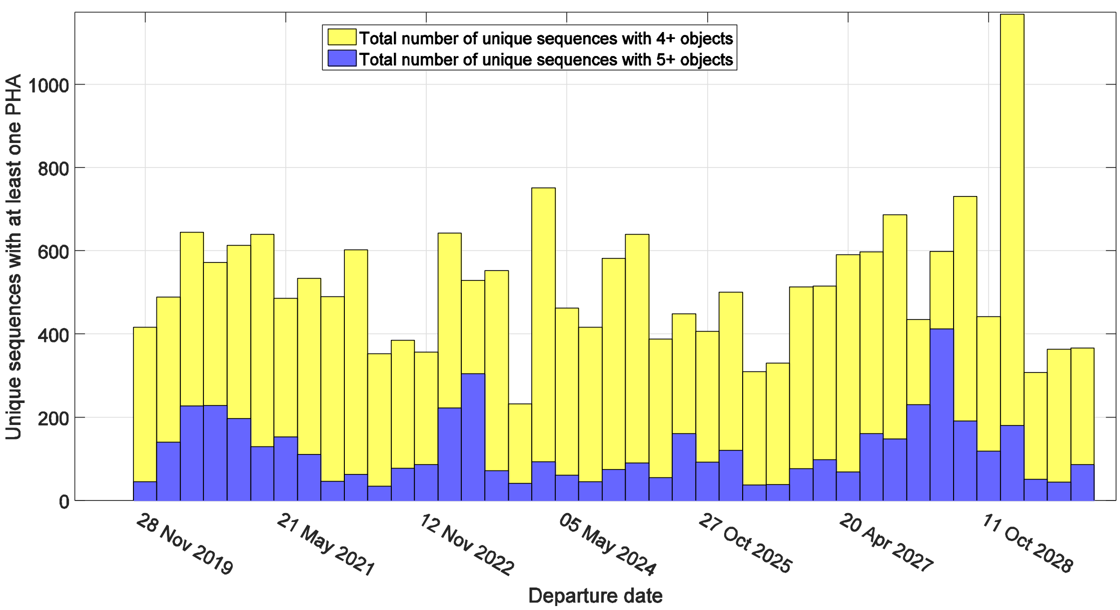

Fig. 3 Number of unique sequences with at least one PHA and four encounters as a function of the departure date. PHA-NHATS database.

Figure 4 shows an example of all the sequences with four NHATS asteroids and one PHA found for the departure date $t_0 = 14$ August 2022 . The typical tree-nature of the solution is clearly visible from the graph. If two sequences have a rendezvous with the same object and the arrival time differs by not more than 40 days, they are considered as a single sequence. For example, the second object in the two branches in the left – that is, 2011 CG_2 – is the same object in both cases, but the rendezvous times differ by about 51 days. Therefore, these are considered as two separate branches of the solution tree. The sequence characterised by the dashed red path (that is, the sequence Earth – 2012 BB_{14} – 2011 CG_2 – 2006 BZ_{147} – 2013 BS_{45} – 2014 YN) is the first fully-optimised sequence shown in section 5.2. Figure 4 shows how several sequences are partly repeated. This allows to easily changing the target asteroids, even after launch, if needed. Such a change is theoretically more feasible with a sailcraft than with a spacecraft propelled by an electric propulsion system, due to the propellantless characteristic of the solar-sail technology.

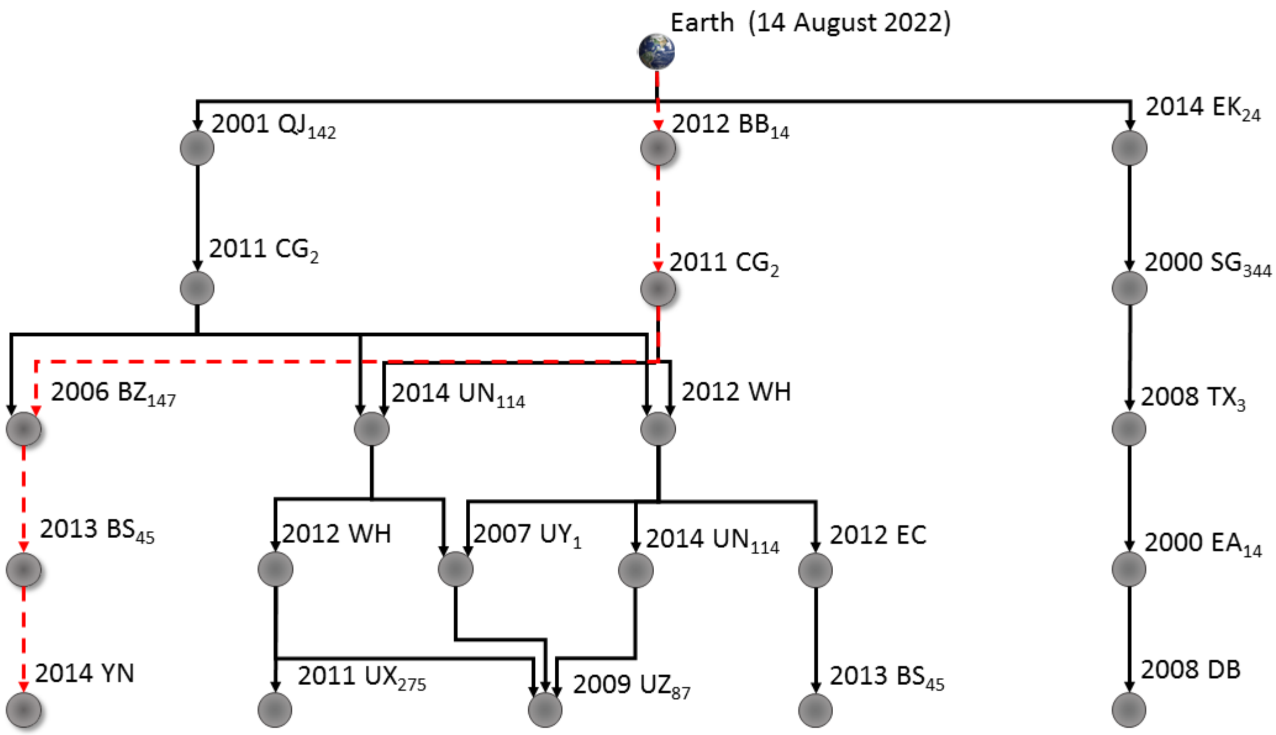

Fig. 4 Tree graph of all the sequences with five encounters found for the departure date t_0 = 14 August 2022. PHA-NHATS database.

5.2 Sequence optimisation results

Three sequences have been selected as samples and fully optimised by means of the automatic algorithm described in section 3. The first two sequences have been selected among all the sequences found with five encounters, of which one is a PHA and the last object is small, as from the mission requirements a) - c) described in section 4. On the other hand, the third sequence has been chosen because it is characterised by the presence of two PHAs, despite it has only four encounters.

Sequence 1. The first sequence presented here contains five objects. All encounters are part of the NHATS database and the last object, 2014 YN, is a very small asteroid. Moreover, the second encounter, 2011 CG_2, is classified as PHA.

A solar-sail multiphase trajectory has been found by following the optimisation steps described in section 3 and the mission is summarised in Table 1. The sail is injected directly into an interplanetary trajectory at Earth, with zero hyperbolic excess velocity. The sailcraft needs 3,521 days (9.6 years) to reach all asteroids in this first sequence, after spending more than four months in the proximity of each of those ones.

Table 1 Mission parameters for the first optimised sequence. PHA-NHATS database.

Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//	24 Aug 2022	18 Aug 2024	725
2012 BB_{14}	126	22 Dec 2024	03 Oct 2026	650
2011 CG_2	123	03 Feb 2027	21 Nov 2028	658
2006 BZ_{147}	166	07 May 2029	23 Jun 2030	412
2013 BS_{45}	188	28 Dec 2030	13 Apr 2032	473
2014 YN	//			

Figure 5 shows the two-dimensional projection of the complete trajectory of the first sequence. Control histories on each leg are plotted in Fig. 6. Plots of single-leg trajectories are not shown for the sake of brevity.

It is worth noting that the spikes visible in Fig. 6 are characterised by both slew rate and angular acceleration of the sail within the maximum values allowed by the current technology. This can be demonstrated by analysing the evolution of the sail control angle during the second leg of the mission (Peloni et al., 2016a). This leg is characterised by a sail slew rate $\dot{\zeta} \leq 10^{-4}$ deg/s and an angular acceleration of the sail $\ddot{\zeta} \leq 4\times10^{-10}$ $\mathrm{deg/s^2}$. Despite the second leg is the leg with the largest values of both slew rate and angular velocity among the whole mission, these values are still below some of the values found in the literature (Peloni et al., 2016a).

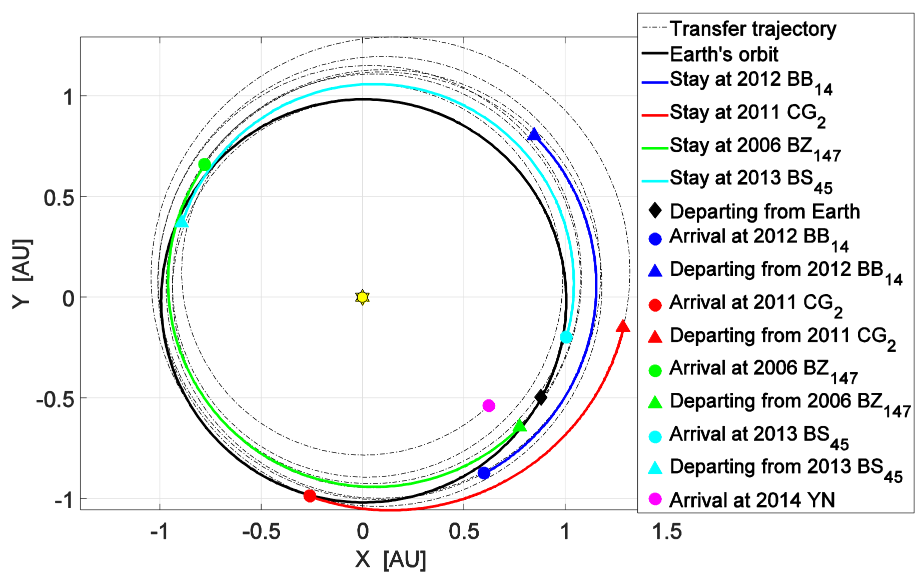

Fig. 5 Heliocentric two-dimensional view of complete three-dimensional trajectory of the first optimised sequence. PHA-NHATS database.

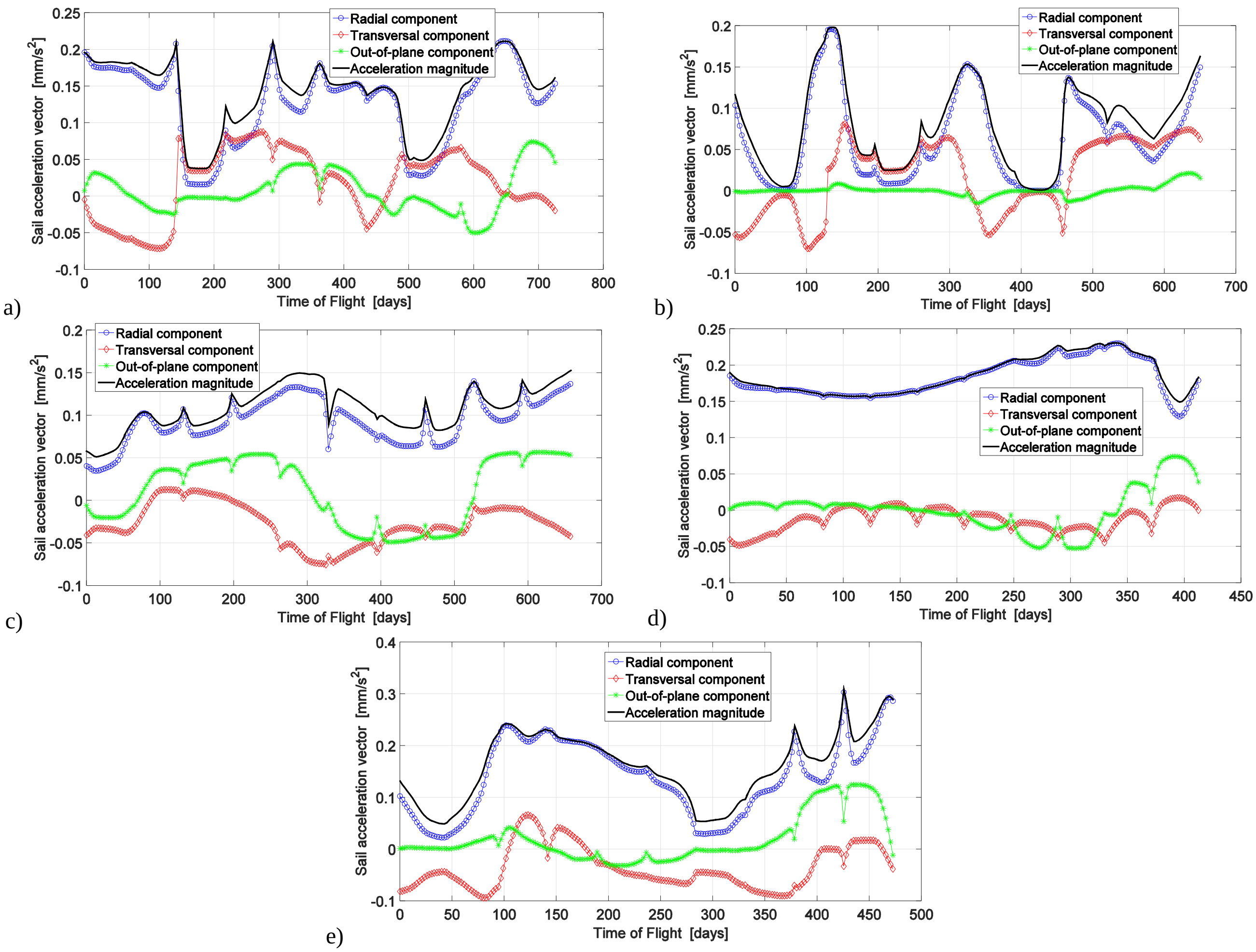

Fig. 6 Acceleration components history on each transfer leg of the first optimised sequence. PHA-NHATS database.

Sequence 2. The second sequence selected contains five objects. All but one of the encounters are part of the NHATS database and the last object, 2009 UZ_{87}, is a very small asteroid. The only object that is not part of the NHATS database is the fourth encounter, 2002 AW, which is classified as “only” a PHA.

A solar-sail multiphase trajectory has been found by following the optimisation steps described in section 3 and the mission is summarised in Table 2. The sailcraft needs 3,512 days (9.6 years) to reach all asteroids in this second sequence, after spending at least 1.5 months in the proximity of each.

Figure 7 shows the two-dimensional projection of the complete trajectory of the second sequence. Plots of single-leg trajectories and controls over time are again not shown for the sake of brevity.

Table 2 Mission parameters for the second optimised sequence. PHA-NHATS database.

Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//			
		18 Jul 2029	12 May 2031	663
2011 UX_{275}	114			
		03 Sep 2031	13 Sep 2033	742
2012 EC	115			
		07 Jan 2034	12 Jul 2035	552
2009 YF	51			
		02 Sep 2035	13 Jan 2037	499
2002 AW	208			
		09 Aug 2037	27 Feb 2039	568
2009 UZ_{87}	//			

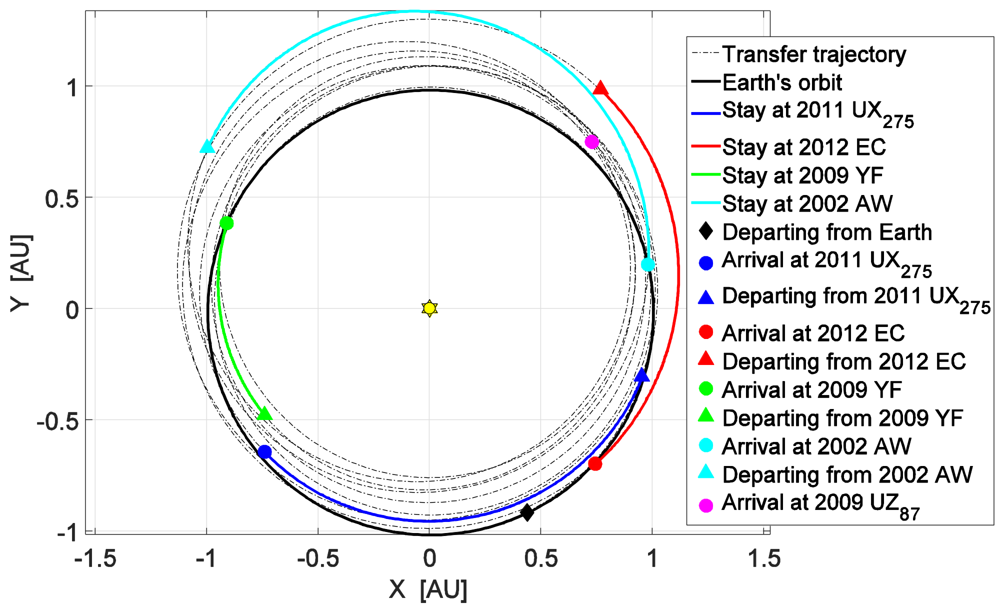

Fig. 7 Heliocentric two-dimensional view of complete three-dimensional trajectory of the second optimised sequence. PHA-NHATS database.

Sequence 3. The third sequence presented here contains only four objects. All but one of the encounters are part of the NHATS database. The only object that is not part of the NHATS database is the fourth encounter, 2015 JF_{11}, which is classified "only" as a PHA. This sequence is characterised by the presence of two PHAs, 2011 CG_2 and 2015 JF_{11}. Even if the last object is not a small one, this is a fully-optimised sequence containing four asteroids, three of which are part of the NHATS database and two are classified as PHAs.

A multiphase trajectory for the selected solar sail has been found by following the optimisation steps described in section 3 and the mission is summarised in Table 3. The sailcraft needs only 2,844 days (7.8 years) to reach all asteroids in this third sequence, after spending at least five months in the proximity of each.

Figure 8 shows the two-dimensional projection of the complete trajectory of the third sequence. Also here, plots of single-leg trajectories and controls over time are not shown for the sake of brevity.

Table 3 Mission parameters for the third optimised sequence. PHA-NHATS database.

Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//			
		19 Jan 2029	24 Sep 2030	614
2011 CG_2	176			
		20 Mar 2031	28 Nov 2032	620
2004 VJ_1	154			
		02 May 2033	11 Aug 2034	467
2005 TG_{50}	177			
		05 Feb 2035	02 Nov 2036	636
2015 JF_{11}	//			

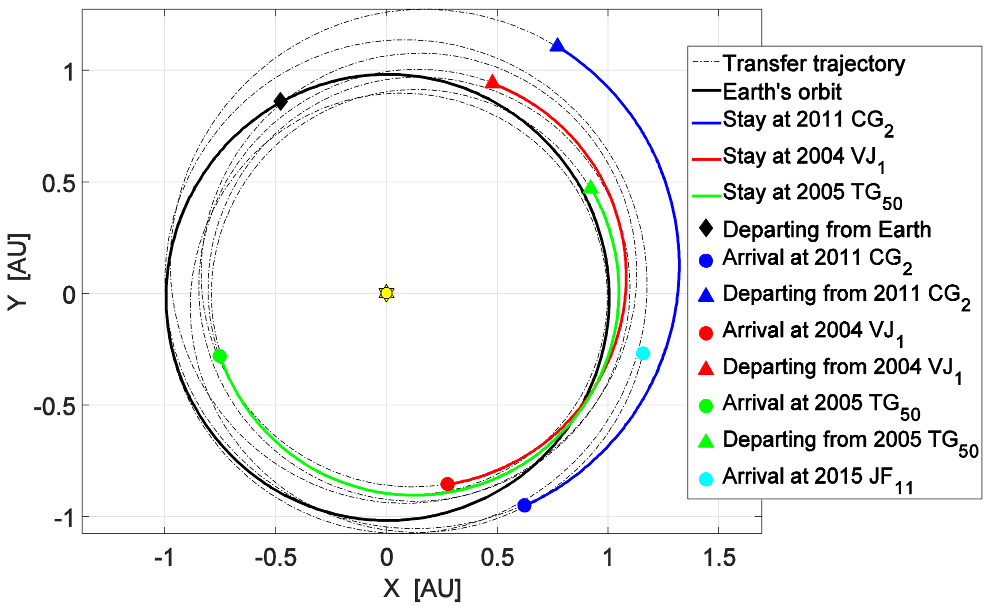

Fig. 8 Heliocentric two-dimensional view of complete three-dimensional trajectory of the third optimised sequence. PHA-NHATS database.

6. RESULTS: PHA-LCDB DATABASE

In this section, the results of the sequence search and the statistical results of the optimisation of all the sequences found are shown. The PHA-LCDB database introduced in section 2.1 and made of PHAs and asteroids in the LCDB with $U \leq 2-$ has been taken into account. This has been chosen to test the reliability of the proposed approach on a mission scenario more challenging than transfers mainly between NHATS asteroids. Because of the more challenging mission scenario, the number of sequences found by the sequence-search algorithm is significantly smaller than what found considering the PHA-NHATS database (section 6.1). Such a reduced number of sequences allows the possibility to test the automatic optimisation algorithm on the whole set of preliminary sequences found by means of the approximated shape-based approach. Section 6.2 shows the statistical results of this study.

6.1 Sequence search results

The same set of departure dates considered in the case of the PHA-NHATS database and discussed in section 5.1 is taken into account in this case. A stay time of 50 days has been considered between two consecutive legs within the sequence search algorithm. A maximum time of flight of 1,000 days for each leg was allowed in the sequence search with the PHA-NHATS database, whereas a maximum one-leg time of flight of 1,500 days was chosen for this study. This choice has been driven by the fact that the single transfers are more challenging in the case of the PHA-LCDB database. However, a maximum mission duration of 10 years is considered in this case as well, as in the previous case.

This search resulted in 589 unique sequences made of three encounters, of which at least one is a PHA. Figure 9 shows the number of unique sequences found for each departure date. Only those sequences with at least one PHA and at least three encounters are taken into account for the plot.

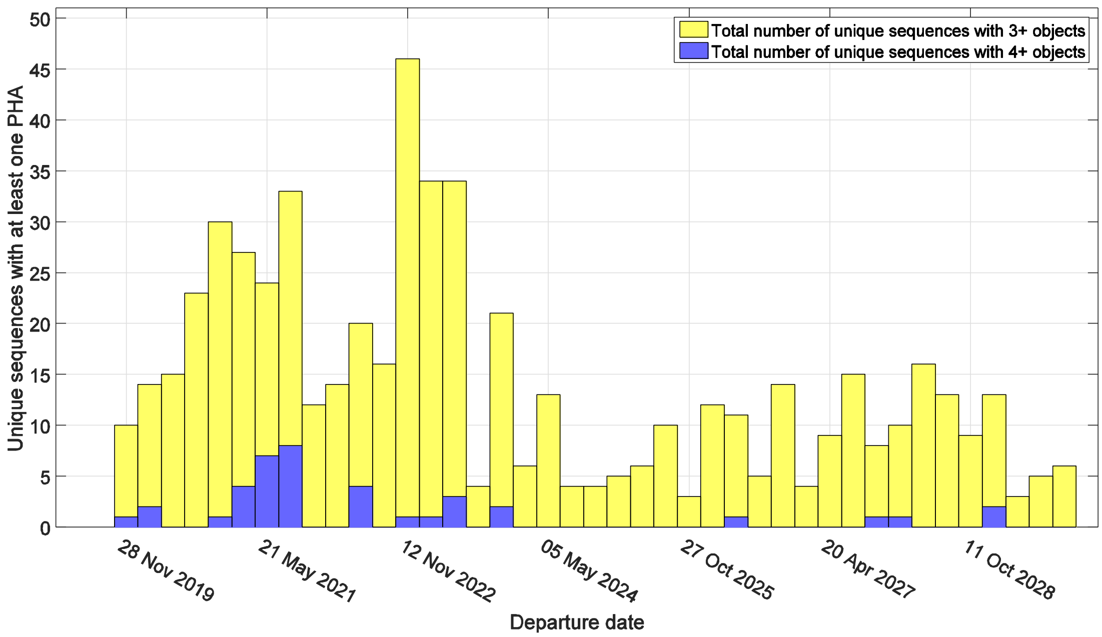

Fig. 9 Number of unique sequences with at least one PHA and three encounters as a function of the departure date. PHA-LCDB database.

6.2 Sequence optimisation results

All the 589 sequences found with at least three encounters and at least one PHA shown in Fig. 9 have been optimised to test the reliability of the trajectories returned by the sequence search algorithm. The automatic optimisation algorithm described in section 3 has been used without any additional user input. That is, no *ad hoc* parameters have been chosen for the optimisations of the solar-sail trajectories. The optimisation algorithm took less than 30 days looking for solutions to all the 589 sequences found, performing more than 20 optimisations per day on average.

The automatic optimisation algorithm has been able to find fully-optimised solar-sail trajectories for 343 sequences. That is, 58% of the preliminary sequences found by the sequence-search algorithm have been proven to be feasible mission scenarios for the chosen sailcraft. The optimised sequences are characterised by 84 unique NEAs. Among them, there are 59 PHAs, 11 NHATS asteroids and 27 NEAs which are part of the LCDB database with $U \leq 2-$.

One sequence has been selected to be discussed, which contains three objects. This sequence has been chosen among the others because it is characterised by the presence of two PHAs, 1989 UQ and 2002 RW_{25}. The third object, which is 2003 WT_{153}, is part of the LCDB database with with $U \leq 2-$. All the objects of the chosen sequence are Aten asteroids. That is, their semi-major axes are all less than one astronomical unit. Moreover, the orbits of the two PHAs in the sequence are significantly more eccentric than the one of the Earth, as shown in Table 4.

Table 4 Properties of the encounters of the chosen sequence. PHA-LCDB database.

Object	2003 WT_{153}	1989 UQ	2002 RW_{25}
Orbital type	Aten	Aten	Aten
Semi-major axis [AU]	0.894	0.915	0.825
Eccentricity	0.178	0.265	0.287
Inclination [deg]	0.371	1.299	1.327
Absolute magnitude	28	19.4	18.8
Estimated size [m]	7 – 15	330 – 740	420 – 940
PHA	no	yes	yes

A multiphase trajectory for the selected solar sail has been found by following the optimisation steps described in section 3 and the mission is summarised in Table 5. The sailcraft needs 3,541 days (9.7 years) to reach all asteroids in this sequence, after spending more than three months months in the proximity of each.

Figure 10 shows the two-dimensional projection of the complete trajectory of the chosen sequence. Also here, plots of single-leg trajectories and controls over time are not shown for the sake of brevity.

The total Δv needed for this mission is $\Delta v = 52.1$ km/s. To have a comparison with an electric propulsion system, let us consider the spacecraft taken into account in the 8th Global Trajectory Optimisation Competition (GTOC8) (Peloni et al., 2016b, Petropoulos, 2016). Such spacecraft is characterised by a total mass $m_0 = 4,000$ kg, a dry mass $m_{dry} = 1,890$ kg and a low-thrust engine with a specific impulse $I_{SP} = 5,000$ s. It is worth noting that both the specific impulse and the mass ratio $m_{dry}/m_0 = 0.47$ considered are very high performing and no spacecraft, to the best of the authors' knowledge, has similar performances to date. By using the Tsiolkovsky rocket equation, the maximum Δv available with such low-thrust system is $\Delta v = 37$ km/s. On the other hand, to reach a Δv as high as 52 km/s, a spacecraft with the electric propulsion system considered in the GTOC8 should be characterised by a mass ratio as low as $m_{dry}/m_0 = 0.35$, which is very low for the near-term electric-propulsion technology. For the above reasons, a multiple NEA rendezvous mission with a total $\Delta v = 52$ km/s is not feasible by an electric propelled spacecraft, even if a high-performing propulsion system is considered. A solar sail, on the other hand, enables high-Δv trajectories such as those found.

Table 5 Mission parameters for the chosen sequence. PHA-LCDB database.

Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//			
		24 Apr 2028	18 Jul 2031	1181
2003 WT_{153}	134			
		30 Nov 2031	29 Jun 2034	943
1989 UQ	110			
		18 Oct 2034	02 Jan 2038	1173
2002 RW_{25}	//			

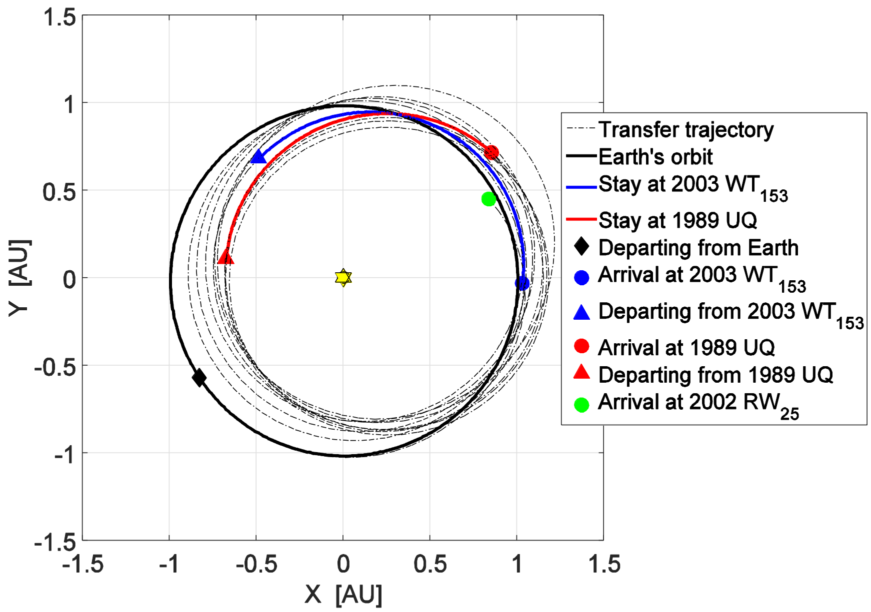

Fig. 10 Heliocentric two-dimensional view of complete three-dimensional trajectory of the optimised sequence. PHA-LCDB database.

7. SUMMARY AND CONCLUSIONS

This work presented an automatic method to find sequences of asteroids for a multiple near-Earth asteroid (NEA) rendezvous missions through solar sailing. A shape-based approach was used to find approximated solar-sail trajectories within the sequence-search phase and the subsequent optimisation phase. To reduce the computational time needed to find sequences of NEAs to be visited and to increase the possibility of finding objects of sufficient interest, two subsets of the whole database were considered in this study. One of them focuses on Near-Earth Object Human Space Flight Accessible Target Study (NHATS) asteroids, whereas the second one considers those asteroids with very uncertain data on their rotation rate. Both databases contain also potentially hazardous asteroids (PHAs).

The use of the PHA-NHATS database resulted in more than 4,800 unique sequences made of at least five asteroids (at least four NHATS asteroids and at least one PHA) within less than 10 years of total mission duration. Among all of those sequences, three were selected to be shown and fully optimised for the complete multiphase trajectory. Furthermore, a solar sail with a lower performance than the one considered in a previous reference study has been taken into account in this work. This means one step further in the Gossamer roadmap to solar sailing, as a lower characteristic acceleration implies a smaller or less-lightweight sail for the same spacecraft bus. As a consequence, this study showed that the mission-related technology readiness level for the available solar-sail technology is larger than it was previously thought and that such a mission can be performed with current or at least near-term solar sail technology. Moreover, it was shown that, at least for the PHA-NHATS database, a 5-NEA rendezvous is always possible within 10 years by means of a solar sail.

The use of the PHA-LCDB database demonstrated the possibility to use the approaches proposed for the sequence-search and the optimisation phases on several scenarios. In fact, this second study was more challenging than the previous one, which considered NHATS objects that, by definition, are targets easy to reach from the Earth. Moreover, the automatic optimiser was used to optimise all the sequences found using the PHA-LCDB database. This study demonstrated the reliability of the sequence-search algorithm results, the optimiser being able to find solutions for 58% of the 589 sequences found by the sequence search. These results have been found in a completely automatic way, without the need to tweak any parameter of the optimiser, which demonstrates also its capability to find several solutions in a completely automatic way.

Finally, this study showed a considerably large amount of possible mission scenarios for any of the launch dates tested. Therefore, it can be concluded that there are little to no constraints on the launch window for a multiple-NEA rendezvous mission, if a solar sail is involved.

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