SAILING AT THE BRINK – THE NO-LIMITS OF NEAR-/NOW-TERM-TECHNOLOGY SOLAR SAILS AND SEP SPACECRAFT IN (MULTIPLE) NEO RENDEZVOUS

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Abstract

Near-Earth object (NEO) in-situ exploration can provide invaluable information for science, possible future deflection actions and resource utilisation. This is only possible with space missions which approach the asteroid from its vicinity, i.e. rendezvous. This paper explores the use of solar sailing as means of propulsion for NEO rendezvous missions. Given the current state of sail technology, we search for multiple rendezvous missions of up to ten years and characteristic acceleration of up to 0.10 mm/s². Using a tree-search technique and subsequent trajectory optimisation, we find numerous options of up to three NEO encounters in the launch window 2019-2027. In addition, we explore steerable and throttleable low-thrust (e.g. solar-electric) rendezvous to a particular group of NEOs, the Taurid swarm. We show that an acceleration of 0.23 mm/s^2 would suffice for a rendezvous in approximately 2000 days, while shorter transfers are available as the acceleration increases. Finally, we show low-thrust options (0.3 mm/s^2) to the fictitious asteroid 2019 PDC, as part of an asteroid deflection exercise.

Keywords

Solar sail; asteroid; near-Earth object; Taurid; low thrust.

1. Introduction

Near-Earth objects (NEOs), mainly asteroids, are being regarded as one of the most interesting targets in the solar system: it is believed that they have significantly contributed to the geological and biological formation of planet Earth, and yet their composition and properties are still largely unknown to date. Of all NEOs, those with an Earth Minimum Orbit Intersection Distance (EMOID) lower than 0.05 AU and estimated diameter greater than 150 m, are classified as potentially hazardous objects (PHO), because they might pose a potential threat to the Earth in case of impact (Lissauer and De Parter, 2013). Both science and planetary defence (PD), the protection of planet Earth from hazardous impacts, will benefit from in-situ characterisation of NEOs, only enabled by rendezvous missions. Given the large variability in the characteristics of NEO, multiple NEO rendezvous (MNR) missions are preferred, allowing characterisation of multiple targets with a single launch. In addition to a scientific return, such characterisation of multiple NEOs will be key to understanding the scale and distribution of useful asteroid resources such as accessible water and metals, to underpin future large-scale space ventures.

The targets must be selected carefully, both for their potential scientific return, but also for accessibility in terms of orbital energy, inclination and phasing, all of which affect the Δv needed. Low-thrust propulsion provides a small, but continuous acceleration, enabling the spacecraft to slowly change the orbit over a prolonged amount of time. While gravity losses, and hence Δv, are usually higher, this is more than compensated with the fact that the specific impulse of solar-electric propulsion is generally one order of magnitude higher than conventional chemical, impulsive propulsion (Goebel and Katz, 2008).

Note that the sample-return missions like solar-electric propelled HAYABUSA's and OSIRIS-REX are effectively a single NEO rendezvous (SNR) plus fly-by's including Earth itself as a fly-by "target" when the sample capsule is delivered. The solar-electric propelled DAWN mission achieved rendezvous and orbit of 2 large main-belt asteroids (MBA), (1) Ceres and (4) Vesta. An extended mission fly-by of a 3rd target was considered for this mission at least at some point in time[1]. The total Δv capability of the HAYABUSA's design is around 3.5 to 4 km/s if the full Xenon load is carried, that of DAWN is around 13 km/s. Solar-electric MNR missions have been studied, e.g. SESAME (Maiwald and Marchand, 2013), which required a total Δv of 16.6 km/s to rendezvous with 5 NEOs selected solely on the basis of trajectory optimization. The 1571 kg SESAME design, only slightly larger than DAWN, would have carried 55 kg of science payload including 5 small, 4.3 kg landers.

At the upper end of the specific impulse spectrum, solar sailing offers the highest specific impulse, as no propellant is needed, but instead the acceleration is provided by the momentum carried by photons from the Sun, being absorbed and reflected by the sail membrane (McInnes, 1999). It should be noted that the effective specific impulse of a solar sail is not infinite, although it does not require reaction mass, since the lifetime of the sail in the space environment is limited as is the total impulse delivered. However, solar sails will in principle offer significant advantages for long-

[1] https://spacenews.com/nasa-reviews-options-for-dawn-extended-mission/ (cited 29/08/2020).

duration and/or multiple target missions if sail coatings are available which degrade only slowly under the action of solar radiation (McInnes, 2014).

NASA has been designing the first solar sail mission to fly-by an asteroid, NEA SCOUT, and at the time of writing it is due for launch as secondary payload on NASA's Artemis I[2] in November 2021 (Pezent et al., 2019). In 2019, The Planetary Society demonstrated orbital energy increase using an attitude-controlled solar sail performing period slew manoeuvres while in low Earth orbit, with the LIGHTSAIL 2 mission (Nye, 2019), showing that solar sailing can be also used in low-cost nanosatellites around the Earth. Solar sailing was also proposed in the literature as a means to deliver an asteroid kinetic energy impactor (Dachwald and Wie, 2007, McInnes, 2004) or for comet fly-by and/or rendezvous (Hughes and McInnes, 2004).

The idea of using solar sailing for reaching one or multiple asteroids is appealing for the flexibility that this technology offers, in terms of (potentially) unlimited amount of Δv, which allows to theoretically reach numerous targets, as well as redirect the mission to different targets, depending on contingency (for example, a new NEO is discovered after mission launch).

For these reasons, MNR was among the three mission types selected for extensive studies in the framework of the DLR-ESTEC GOSSAMER Roadmap to Solar Sailing (Geppert et al., 2011) from those identified as uniquely feasible with solar sail propulsion. Next to MNR (Dachwald et al., 2014), forward-deployed solar storm warning by a probe on a solar sail supported heliocentric orbit ahead of the Sun-Earth Langrange point L_1, the so-called Displaced L_1 (DL1) orbit (McInnes et al., 2014), and exploration of the Sun's high-latitude regions by a Solar Polar Orbiter (SPO) in two variations (Macdonald et al., 2014), were studied by the respective Gossamer Roadmap Science Working Groups. All these mission types had been studied intensely before by the solar sailing community (Fu et al., 2016). These studies have been continued since. A natural focus was on trajectories because very few solar sail projects with the intent of building flight hardware have ever been started, among them IKAROS (Mori et al., 2009), GOSSAMER-1 (Seefeldt, 2017, Seefeldt et al., 2017), NEA SCOUT (Johnson et al., 2017, McNutt et al., 2014) and OKEANOS (Mori et al., 2019). There are more mission types which are uniquely feasible with or would benefit exceedingly from solar sail propulsion. For example, next to sail deployment and control technology development, the ODISSEE study combined observations of the Earth and Moon with a meticulous 550-day traverse of the Earth–Moon system from launch to

[2] https://www.nasa.gov/content/nea-scout (cited 29/08/2020)

lunar fly-by or orbit capture (Leipold et al., 1999); the GEOSAIL mission study used its modest solar sail to precess the line of apsides to keep the orientation of an otherwise inertial high Earth orbit aligned to the geomagnetic tail throughout the year (McInnes et al., 2001); precession of the line of apsides is also possible for heliocentric orbits to have their aphelion follow Earth in its orbit for solar activity monitoring missions (Heiligers and McInnes, 2014); and pole-sitter solar sails have been proposed for a whole host of Earth surface, climate, atmospheric, weather and magnetospheric observation missions (Ceriotti et al., 2014, Ceriotti et al., 2011). Many of these mission types only become feasible because solar sails are not limited by reaction mass, although the sail lifetime is limited in the space environment, and so for much of this subset this already unleashes their full potential. However, because of the inherent limitations on the direction of magnitude of thrust (Spencer and Carroll, 2014), some mission types can benefit for specific requirements or target objects from hybridization with solar-electric propulsion (SEP) (Baig and McInnes, 2008). Examples of sail-SEP hybrid propulsion are high viewing angle pole sitters or the JAXA mission OKEANOS to rendezvous with a Jupiter Trojan asteroid. It is worth noting that many of the mission types described above address science topics and monitoring tasks that have in recent years been consolidated under the space situational awareness (SSA) activities of the major space agencies. Space debris, also of particular interest to large membrane-based spacecraft, can be mapped on orbital traverses of the Earth–Moon system on the way to the Moon, DL1 or pole sitter operation. Space weather warnings would benefit from operation at DL1 and support from the more science focused magnetospheric, heliospheric and solar studies missions including SPO. The threat of impacting asteroids, the in geocentric terms most distant field of SSA activities, is addressed by MNR missions and opposition surveys conducted in cruise to search for asteroids passing outside the sailcraft. The related activities at DLR have progressed from asteroid survey studies (Findlay et al., 2013), comet and asteroid landers (Biele et al., 2015, Ho et al., 2017) and the solar sail developments leading to the GOSSAMER Roadmap, towards a combination of solar sail and small asteroid landers which range from optional SNR in extended mission of a technology development mission re-using a nanolander spare as a monitoring instrument package to investigate sail membrane ageing (Grundmann et al., 2015) to 5-NEA MNR with sample return from each target by a shuttling microlander (Dachwald and Seboldt, 2005, Grundmann et al., 2019a, Grundmann et al., 2019b).

Bearing in mind the sinuous history of solar sailing, it is not unlikely that the next step towards full-scale solar sailing may not be a fully optimized development leading to a large and performant sail rather directly but could be made in small steps and on the basis of re-use of as many existing developments as possible, and towards an intermediate size accepting limited performance. Identification of the useful steps along this ladder of increasing sail size and performance is key to ensuring the long-term development of the technology.

In part and in a way, GOSSAMER-1 and NEA SCOUT (Johnson et al., 2017, McNutt et al., 2014) already followed this concept. In most subsystems they are based on CubeSat technology which was developed independently in the past two decades. For GOSSAMER-1 this was limited to the avionics re-using the DLR's CLAVIS concept (Dittus and Spröwitz, 2010) of more flexible integration of diverse CubeSat avionics in the Central Sailcraft Control Unit (CSCU) and simple PC104 stacks in the Boom Sail Deployment Units (BSDU) design (Seefeldt, 2017, Seefeldt et al., 2017, Seefeldt et al., 2019b). NEA SCOUT also uses CubeSat structures. GOSSAMER-1 was built in a limited size, $(5\ m)^2$, although all sail and deployment related elements were already designed for GOSSAMER-2's $(20\ m)^2$ size. This allowed the projects to focus their externally or programmatically constrained development efforts and resources on the new and untested items such as booms and the membrane and their deployment mechanism. Dedicated development with optimization for the purpose of solar sailing thus happens but is at the same time constrained mainly or exclusively to these mechanisms and structural elements.

Accepting this constrained environment and taking it one step further is possible at least when it comes to finally achieving an initial form and sustained if slow development of solar sailing. By also reusing other spacecraft structures and units, non-disposable mechanisms and booms designed to deploy different and therefore heavier membranes for other purposes, the development effort for 'the new' can be further restricted to the membrane as well as the attitude control methods for solar sailing, which do not rely on a combination of CubeSat thrusters and reaction wheels.

The question then is whether such a non-optimized, relatively heavy and small solar sail can still do anything useful to demonstrate the unique capabilities of, and the missions uniquely feasible with, solar sailing.

This paper builds upon the work previously done by the authors, combining a methodology for solar sail trajectory design for multiple targets (Peloni et al., 2016), the requirements of a near-term solar sail based on DLR's GOSSAMER roadmap and the experience gained on asteroid missions through the MASCOT nanolander which successfully completed its mission on the PHA (162173) Ryugu on October 3rd, 2018 (Krause et al., 2019).

This work will discuss the trajectory design process and resulting options for single and multiple rendezvous missions, using a low-acceleration sail and steerable and throttleable low thrust, such as the one provided by SEP. The latter can then be used as an initial guess for solar sail options, as it is known that solar sail trajectories can be generated converting low-thrust trajectories appropriately (Sullo et al., 2017, Viavattene and Ceriotti, 2019). Sullo et al. (2017)

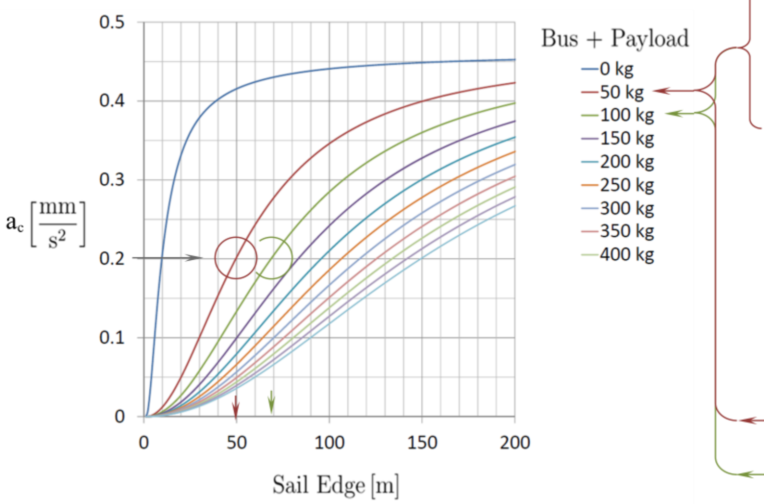
showed that a continuation method can be used to incrementally convert a low-thrust trajectory (with an acceleration of arbitrary direction and limited magnitude) to a solar-sail trajectory with the same maximum acceleration. The process relies on iteratively changing a homotopy parameter and optimising the trajectory based using the solution of the previous iteration.

In this work, two scenarios and transfer options will be discussed. The first is MNR with a low-characteristic-acceleration solar sail, assessing the maximum number of NEOs, and their sequences, that can be rendezvoused in a timeframe of ten years; the second is a rendezvous missions to NEOs within the Taurid swarm (TS), looking for low-thrust transfers with low maximum acceleration required (and thus potential candidates for a solar sail transfer).

2. Multiple NEO Rendezvous with low-characteristic-acceleration solar sail

2.1. Going slowly still goes

We investigated the MNR performance of 'slow' sails with a characteristic acceleration a_c < 0.2 mm/s² (the acceleration of the sail when directly facing the sun at 1 AU). Using such low characteristic acceleration models both for fully optimized (but small) solar sail spacecraft, as well as larger sailcraft made from re-used or re-purposed units, not optimized for solar sailing.



Bus (Gos-1 + X-Band)	≈30 kg
Mother Spacecraft Science Instruments	≈10 kg

Lander	
PHILAE	98 kg
SPS Lander	100kg
1 MASCOT	10 kg
5 MASCOTs	50 kg

Figure 1. Payload performance of near-term solar sails based on Gossamer-1 technology, and approximate size at a_c = 0.2 mm/s² in relation to micro- and nanolander payloads for near-term missions. From (Grundmann et al., 2017) by methods described in (Seefeldt et al., under review). The 0 kg trace refers to the sail and booms, only, without bus and payload, after separation of deployment units. Note that a larger set of MASCOT-like nanolanders requires a dedicated carrier structure of approx. 10 kg (not accounted for in the tables) while one nanolander can be accommodated on an existing structural panel using a flat MASCOT2-style Mechanical Electrical Support System (MESS) of < 1 kg (Lange et al., 2018).

Recalling Figure 1, it is noteworthy that the sail control technology demonstrator GOSSAMER-2, at (20~25 m)² size, could already have achieved a characteristic acceleration in the range of a_c = 0.05~0.075 mm/s² (best estimate) when built modestly optimized for mass, i.e., not exclusively for low cost. A fully optimized GOSSAMER-2 would have had a mass of approx. 55 to 85 kg after separation of the Boom Sail Deployment Units (BSDU), although this was not a design goal. The only mass requirement was to stay within the limits of secondary payload platforms in the launch configuration with BSDUs attached. The performance range remains similar when alternative deployer technology solutions from other membrane based spacecraft applications are used, such as those studied by Seefeldt et al. (2019a). The effects of different deployer concepts on sail performance and the respective scaling law are studied in detail by Seefeldt et al. (under review), including the model used to calculate Figure 1. The added mass is considered as sail payload which adds to the mass of the sail and booms and residual deployer elements, if any. This added mass also includes the spacecraft bus in addition to a science payload. The parameters here applied are based on the deployment concept and main elements used in the GOSSAMER-1 Engineering Qualification Model (EQM), i.e., the Boom Sail Deployment Units are separated and do not contribute to sailcraft mass (Seefeldt et al., 2017, Seefeldt et al., 2019b, Spietz et al., under review). The membrane consists of Upilex-S with a thickness of t_{sail} = 7.5 µm aluminized on both sides with a 100 nm layer resulting in a density of ρ = 1350 kg/m^3 and an efficiency of μ = 0.9. To assemble the membrane, 3M Tape 966 with adhesive type 100 of 1.27 cm width and ~0.6 g/m linear density is applied in fold-parallel joints at a distance corresponding to the foil roll width of w = 1.016 m. Coilable tubular CFRP booms of a lenticular cross-section scaling with sail size and a buckling safety factor of k_{FS} = 3 are assumed. For sails beyond a few-10's m side length this assumption is conservative because other boom technologies would be used which become more efficient for very large sails at the system level (Hillebrandt, 2020). The sail area scaling law considers only the membrane by applying inside the circumscribed square scaled gaps along the booms and for the Central Sailcraft Unit (CSCU) bus and avionics module where the outer corners of the membrane quadrants touch at the boom tips and the inner corners at the centre of each side of a square of a constant side length of k = 0.34 m representing the CSCU cross-section in the membrane plane.

Any path towards sail development would most likely have a similar intermediate size, technology-experiment-oriented step in the middle, likely of (20~30 m)^2 size, because of the need to demonstrate useful acceleration and the need to operate attitude control experiments in the dynamic environment of a very large thin membrane. Just as likely, these "middle step" prototype sailcraft would be designed for low-cost rideshare launch which inherently limits their mass, most likely ≤ 181~200 kg to fit the ESPA or/and ASAP platform standards. Thus, unlike IKAROS (Mori et al., 2009), they will likely achieve a characteristic acceleration in the range of a_c = 0.05~0.1 mm/s^2 even though that may not be strictly required for their mission.

Based on the performance achieved by GOSSAMER-1 EQM technology (Seefeldt et al., 2017), this estimate assumes that the sail attitude control experiments of GOSSAMER-2 add about the same mass to the sail itself as the 30 kg bus including deep-space communication equipment. A further 10 kg are allocated to science or/and experiment documentation instruments, and 10 kg for one MASCOT nanolander. These create the sailcraft configuration behind the 50 kg bus + payload trace of the figure above in 2017 for an optimized entry-level MNR sailcraft.

The same range of characteristic acceleration could be achieved by a larger sail, re-using non-sail deployment technologies even under the most pessimistic of assumptions, for as-is technology re-use penalties: at 150 kg mass of bus + payload, a (35~50 m)^2 sail achieves a_c = 0.05~0.10 mm/s^2. That is, we consider a mass penalty of 100 kg added solely for the not-sail-optimized *overhead* to the 50 kg bus + payload of our one-MASCOT MNR sailcraft (Grundmann et al., 2019a). To achieve a_c = 0.2 mm/s^2, and thus the same performance as baselined by Grundmann et al. (2017) and the trajectory optimization by Peloni et al. (2018b) it was based on, it would have to grow to (85 m)², merely the limit of the GOSSAMER technology 'comfort zone'.

We shall stress that the delivery of a MASCOT-like lander in the same fashion as HAYABUSA2 would require hovering at a very low altitude from the asteroid (Jaumann et al., 2019), posing a challenge for a sailcraft. It is assumed that landers are separated from the carrying sailcraft in the same way as MASCOT from HAYABUSA2 (Ho et al., 2017), using a pre-set spring force. The solar sail trajectory is modified such for lander separation that the initial state vector relative to the asteroid ensures that the separated lander hits its mark, similar to MASCOT2 and AIM (Grundmann et al., 2019a). The sail may be in very slow fly-by, or in a stable solar-radiation-pressure displaced orbit or station-keeping. Further, there is a self-transfer option in the MASCOT portfolio which has recently been studied by Chand (2020). This study was started as a lesson learned from the changes that turned the closely approaching AIM into the Hera mission which will observe (65803) Didymos only after the DART impact from a distance (Cheng et al., 2016). Current research by the authors is investigating strategies for delivery of payload to the surface of the asteroid from a solar sail, however in this work we assume this is performed in the stay time at the asteroid without substantial change of the heliocentric trajectory. A detailed analysis of the proximal motion of the sail to the asteroid is likely not to change the results presented here, due to the extremely weak gravity field of the asteroid.

2.2. Feasible sequences of asteroids

The design of MNR missions is a complex global optimisation problem, which can be split into two different levels: a discrete combinatorial part (the selection of the asteroid sequence from a finite and discrete set of known NEOs), and a continuous part (solution of the optimal control problem from the initial to the final conditions) (Viavattene and Ceriotti, 2019). The size of the search space grows factorially with the number of asteroids (Mereta and Izzo, 2018), and this is an issue because more than ten thousand NEOs are known to date.

We performed a search for "slow" sail NEO rendezvous sequences with launch dates within 2019-2027 (the fictitious timeframe of the Planetary Defense Conference (PDC) 2019 tabletop exercise (Grundmann et al., 2019c)) to find SNR/MNR trajectories. (In the context of the exercise, these trajectories pose as "nominal" trajectories of a fictitious scientific sail mission which is then re-targeted towards the fictitious exercise target asteroid, "2019 PDC"[3], see Table 4). The search was performed in a way similar to Peloni et al. (2018a), which we also describe in (Grundmann

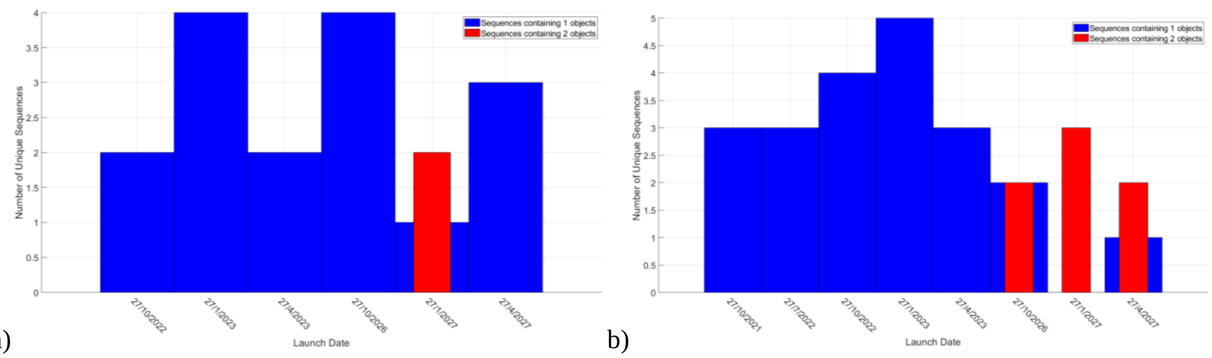
[3] P. Chodas et al., Hypothetical Impact Scenarios, https://cneos.jpl.nasa.gov/pd/cs/ (cited 30 March 2020)

et al., 2019a), but in the performance range $a_c \leq 0.10$ mm/s². The stay time of each asteroid rendezvous is set to 100 days.

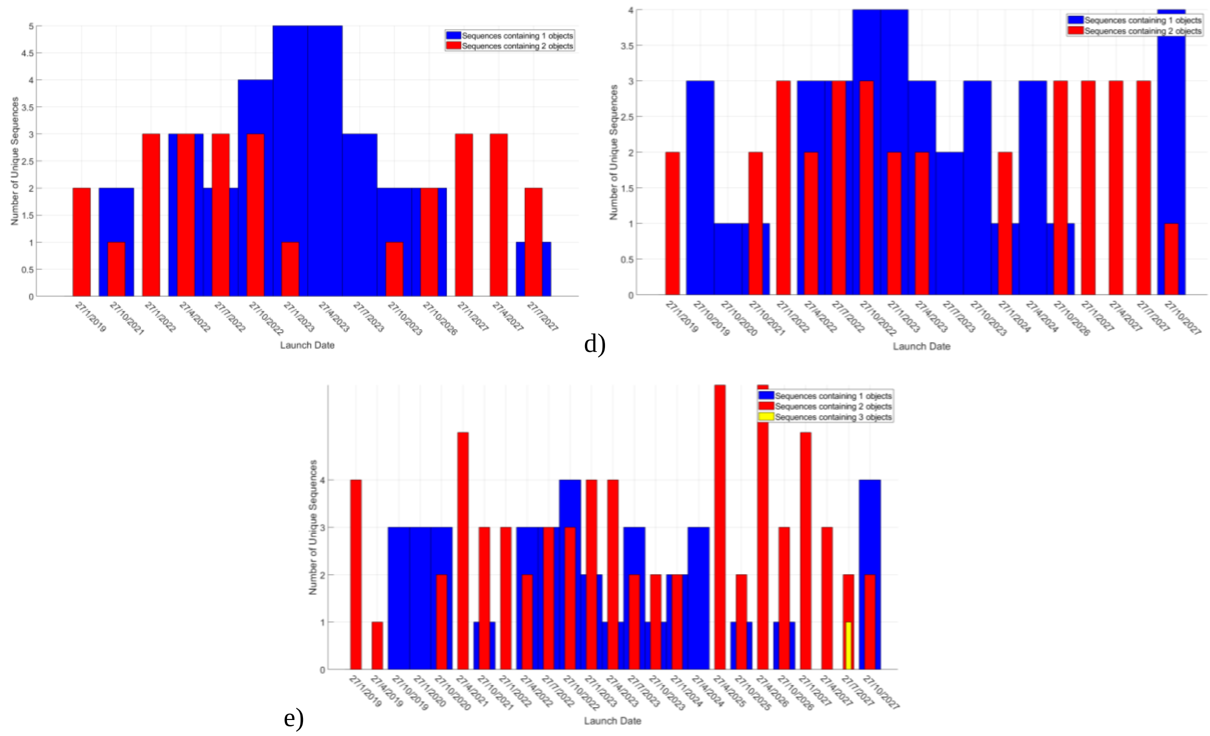
We found single rendezvous trajectories for all launch dates in the 2019 to 2027 timeframe given for the tabletop exercise at the PDC 2019. At the low end of a_c, some of the early part of this period did not yield trajectories, but already at $a_c = 0.06$ mm/s², 2 to 3 SNR targets per launch date appear continuously throughout the later 2/3 of this period, and two 2-target MNR trajectories within one period of 4 months were found. At $a_c \geq 0.08$ mm/s², the entire 2019 to 2027 timeframe offers at least 2 trajectories to choose from at any point in time, with about the same number of SNR and 2-target MNR trajectories in most time blocks. At $a_c = 0.1$ mm/s², the first 3-target and thus genuine MNR trajectory appears.

Sails of $a_c > 0.1$~0.2 mm/s² have been considered "first-generation" sails in the related studies previously mentioned, including those in which some of us participated. Thus, it appears that a "0th-generation" sail of a performance similar to that envisaged for GOSSAMER-2 sail control technologies demonstrator can already compete with the state of the art of SEP NEO rendezvous missions.

Following the visual pattern established by Peloni et al. (2016), Figure 2 shows the temporal distribution of the unique sequences of solar sail NEO rendezvous trajectories for "slow" sails in the timeframe 2019-2027. Note that 2-object sequences always imply a first leg that can be flown as a 1-object mission (SNR).



a) b)



c) d) e)

Figure 2. Unique SNR/MNR sequences in the period 2019-2027. Solar sail characteristic acceleration of: a) a_c = 0.06 mm/s²; b) a_c = 0.07 mm/s²; c) a_c = 0.08 mm/s²; d) a_c = 0.09 mm/s²; e) a_c = 0.10 mm/s².

Once the specific targets accessible to these 0th-generation or/and re-use-based a_c = 0.06~0.10 mm/s² sails at the specific launch dates are factored in, it also becomes possible to draw a ‘family tree’ diagram of the unique sequences, such as in Figure 3. Table 1 lists the number of unique sequences for number of encounters and characteristic acceleration.

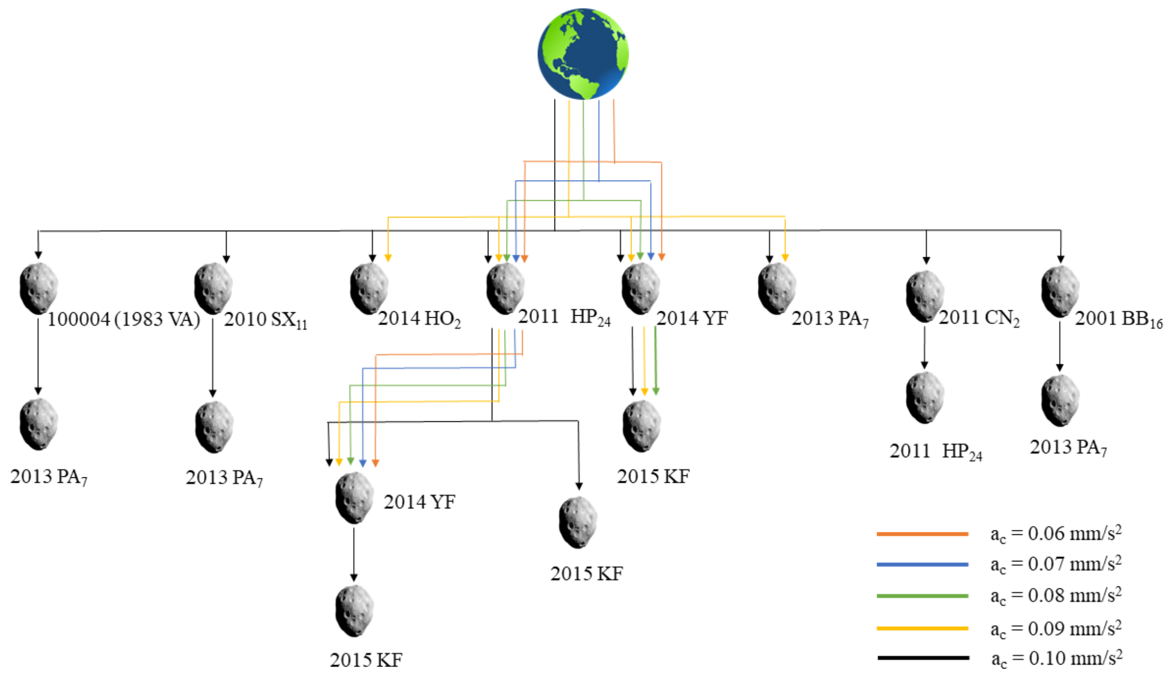


Figure 3. Unique sequences and their respective target NEOs for a_c = 0.06~0.10 mm/s² sails in the period 2019-2027

Table 1. Number of unique sequences and target NEOs for a_c = 0.06~0.10 mm/s² sails in the period 2019-2027

Characteristic acceleration a_c, mm/s²	0.06	0.07	0.08	0.09	0.10
Unique SNR	1	1		2	4
Unique 2-target sequences	1	1	2	2	8
Unique 3-target sequences					1
Number of different targets	2	2	3	5	9

As may be expected, the number of unique sequences rises quickly with sail performance. On the one hand, this generates an increasing independence of the launch date if the requirement is to visit >1 NEO. On the other hand, a closer look at the targets shows that some 1st targets re-appear as 2nd targets, and one 2nd target as the single 3rd target of the unique sequences found. Thus, at a given launch date, the post-launch target flexibility uniquely feasible by solar sail propulsion already develops in this a_c range, just slightly beyond the fundamental SNR feasibility threshold. For example, Figure 3 shows that, at $a_c \geq 0.06$ mm/s², the mission designer may choose to visit 2014 YF first or after 2011 HP_{24}. If it is intended to visit 2015 KF for whatever reason, it can be visited after 2014 YF by all $a_c \geq 0.08$ mm/s² sails, or at $a_c \geq 0.1$ mm/s² in three unique sequences involving 2014 YF or/and 2011 HP_{24}. Figure 4 provides a target-oriented representation of the unique sequences shown above.

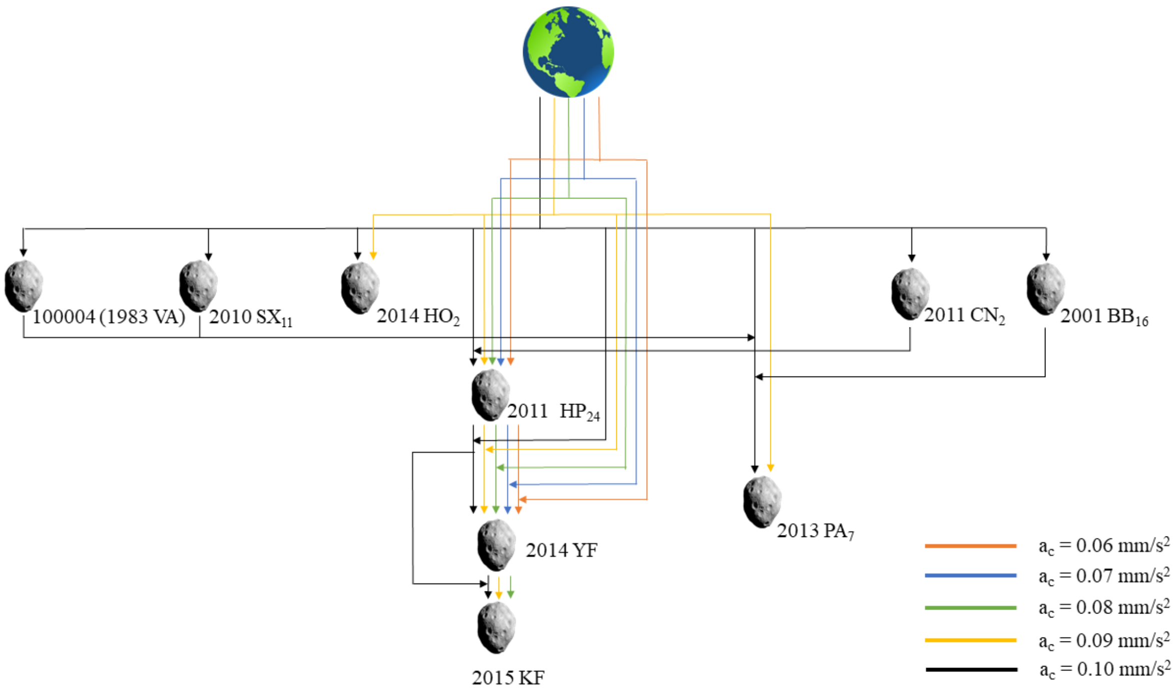


Figure 4. NEO targets in the unique sequences for a_c = 0.06~0.10 mm/s^2 sails in the period 2019-2027. Note that the sequence via 2011 CN_2 ends at 2011 HP_{24}

Table 2. Orbital parameters, classification and absolute magnitude of the rendezvoused objects.

Object (class)	Semimajor axis, AU	Eccentricity	Inclination, deg	Abs. magnitude (H)
1983 VA (Apollo)	2.59	0.703	15.8	16.3
2001 BB_{16} (Aten)	0.85	0.172	2.02	23.2
2010 SX_{11} (Apollo)	1.15	0.249	5.15	24.8
2011 HP_{24} (Amor)	1.18	0.109	3.06	25.8
2011 CN_2 (Apollo)	2.23	0.619	19.6	18.6
2013 PA_7 (Amor)	1.15	0.087	3.47	22.5
2014 YF (Aten)	0.91	0.151	5.86	22.7
2014 HO_2 (Apollo)	1.19	0.280	0.58	26.0
2015 KF (Aten)	0.98	0.145	7.47	25.1

3. Low-thrust options: Responsive trails to challenging targets

3.1. Taurids resonant swarm

The Taurid meteor shower is highly unusual, with its long duration (∼6 months), dispersed radiant, and presence of relatively large particles (Clark et al., 2019). Clube and Napier (1984) suggested that some NEOs are related to a giant comet breakup in the inner solar system, which produced a number of fragments, including 2P/Encke, and are now related to the Taurid complex; Asher and Clube (1993) further inferred that these NEOs, named Taurid Resonant Swarm (TS), are now orbiting in the 7:2 mean-motion resonance (MMR) with Jupiter. A hypothesis, although not universally accepted, exists that some large NEO impacts on Earth might be related to Taurids.

In addition, in 2019 the Earth approached the centre of the Taurid resonant swarm within 5 degrees of mean anomaly, its closest post-perihelion encounter with Earth since 1975 (Clark et al., 2019), in good conditions for observation and tracking.

If the predicted locations and trajectories are confirmed, the Taurid swarm will come much closer to Earth in the early 2030's – so close that objects might have possible trajectories that impact the Earth in 2031 to 2036. Visible objects will be Tunguska-sized or larger, and in fact it is hypothesized that the Tunguska object itself was probably a Taurid object, too (Clark et al., 2019).

The typical Taurid orbit is between the limits of current technologies that would be used to build near-term solar sails as well as SEP spacecraft. At the typical Taurid perihelion of ≈ 0.3 AU, the heat flux from the Sun is about the thermal limit for the membrane (glue) as well as for photovoltaic power generation which drop in efficiency with increasing temperature. At the typical Taurid aphelion of ≈ 4 AU, the flux is near the limit for photovoltaics of a reasonable array area to generate a useful amount of power for SEP (further out, it becomes more like a solar power sail without engines) or to operate small landers, respectively, despite increasing photovoltaic cell efficiency at cold temperatures.

We therefore envisage that a mission to further study one or more of these objects may be useful. This can be in the form of a slow fly-by or rendezvous (for estimation of body properties, imaging and precision orbit determination). Characterisation of properties is also extremely important in view of a possible future deflection action. In this section, we study the accessibility of the Taurid swarm and the feasibility of a rendezvous mission with NEOs in the Taurid swarm using a low-thrust (SEP) system.

3.2. *Low-thrust transfers to Taurids*

The search was performed on a number of NEO which are currently deemed to belong to the Taurid complex. The list, which was provided by Dr Auriane Egal (University of Western Ontario, Canada), comprises 55 objects, whose elements vary in semimajor axis from 1.09 to 2.55 AU, eccentricity from 0.54 to 0.88, and inclination from 1.94 to 14.65 deg. The orbital parameters of the Taurid objects are detailed in Table 6. in Appendix A.

We investigated transfers exploiting a low-thrust propulsion system, with steerable and throttleable thrust vector, iteratively decreasing the maximum acceleration available, in the attempt to find its minimum value that enables a transfer. This relatively low value is affordable by current SEP technology, and in addition, could be achieved by near- to mid-term solar sails. The search was performed considering a launch window in the period 01/01/2020 and 30/12/2030. The maximum acceleration allowed was set to 0.3 mm/s^2. The time of flight of the transfer was limited to a maximum of 2500 days. The trajectories are computed using a shape-based method (De Pascale and Vasile, 2006).

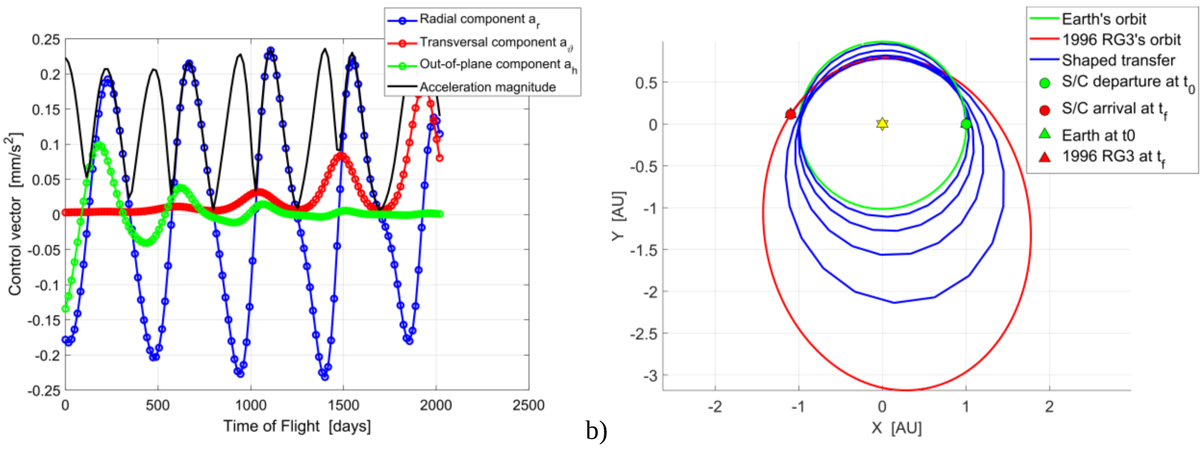
For each candidate target asteroid, the shape-based method defines the shape of the transfer departing from Earth and retrieves the control history necessary to perform the obtained transfer. A genetic algorithm is employed to search for the optimal shaping parameters for the transfer with minimum time of flight. The control history is changed by changing the shape, thus the shaping parameters, so that the acceleration constraint is satisfied. For each object, the maximum acceleration is firstly set equal to 0.2 mm/s^2. If no feasible transfer is found, the maximum acceleration is slightly increased in an iterative manner until a transfer is found. When the maximum acceleration allowed is reached and the method cannot still find a solution, then the transfer to that object is considered unfeasible for the given near- to mid-term solar sail capabilities.

Feasible trajectories were found for 1996 RG$_3$ and 1989 DA, whose orbital elements are in Table 3.

Table 3. Orbital parameters of the feasible TS objects.

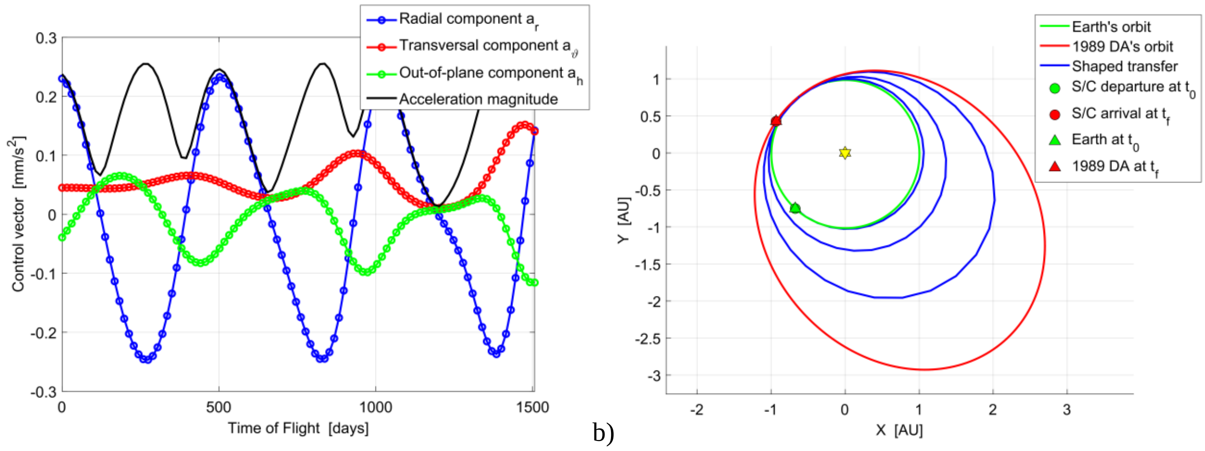
Parameter	1996 RG$_3$	1989 DA
Semimajor axis, AU	1.20	2.16
Eccentricity	0.61	0.54
Inclination, deg	3.57	6.49
Longitude of the ascending node, deg	158.20	349.13
Argument of perigee, deg	300.08	139.81
Mean anomaly, deg	320.96	182.91

The following transfer options are intended to show the lowest value of the maximum acceleration necessary for transfers. For example, a transfer to 1996 RG_3 can be achieved with a maximum acceleration as low as 0.23 mm/s^2 in approximately 2000 days (departure date: 23/09/2022), and this solution is shown in Figure 5. Instead, 1989 DA can only be reached with a slightly higher maximum acceleration of 0.25 mm/s^2; however, this is compensated by a much shorter transfer time, of about 1500 days. It is also worthwhile noting that faster transfers were found for 1996 RG_3 for higher acceleration, as expected.



a) b)

Figure 5. Low-thrust acceleration profile over time (a) and trajectory (b) for the transfer to 1996 RG_3.



a) b)

Figure 6. Low-thrust acceleration profile over time (a) and trajectory (b)for the transfer to 1989 DA.

4. When the target selects you

The bi-annual Planetary Defense Conference (PDC) offers a unique opportunity for active community participation, a week-long table-top exercise connecting all stakeholders and domains in the fields of asteroid surveys and studies, exploration spacecraft design and construction, mission analysis and planning, civil defence, and public outreach. The task is to deflect a fictitious incoming asteroid which in the scenario was discovered at around the date of the respective conference. Data on the target asteroid are released to the public and the planetary defence (PD) community a few months before the conference starts, so that studies and conference papers can be prepared to support the exercise. Adding to the realism of the real effort behind a fictitious threat are fictitious press releases and other colourful injects prepared by the game masters. For the PDC 2019, two fictitious impactors were unleashed by the exercise team, a NEA for the table-top exercise and a near-parabolic comet for extended studies (orbital parameters detailed in Table 4). To accommodate the scenario within one week, approximate launch windows for typical deflection campaign spacecraft mostly based on conventional designs are provided in the briefings. The scenario is tight on purpose, and by intervention of the game masters, the deflection must at least partially fail – if only to ensure that the civil defence experts can do their part. Thus, sight was duly lost of the fictitious impactor shortly after a partially successful deflection attempt because of the loss of all monitoring spacecraft in the upheaval of an unintended fragmentation, and as may be expected, a large fragment was still headed for North America, Earth, and would only become visible again 2 weeks prior to its fictitious impact just after midnight, 27th April 2027. We set out to recover it much earlier.

Table 4. Orbital parameters of the two 2019 PDC fictitious impactors. Reference epoch for the mean anomaly is 01/01/2019.

Object	a, AU	e	i, deg	Ω, deg	ω, deg	M, deg	P, yrs
Asteroid 2019 PDC	1.919	0.534	17.997	38.398	226.713	300.15	2.658
Comet c2019 PDC	236.471	0.996	128.713	339.876	211.021	359.78	3642.736

Data from: https://cneos.jpl.nasa.gov/nda/nda.html

First, we found a launch window for a fast fly-by at 2019 PDC on 3rd January 2025, more than 2 years before the fictitious impact. It required a high Earth departure velocity, $c_3 \approx 56.25$ km²/s² which nearly matches the 500 kg payload to $c_3 = 56$ km²/s² option for a stripped-down computational model of the Ariane 5 ECA, presented by Grundmann et al. (2019a). Within this payload limit, one spacecraft nearly of the size of HAYABUSA2 or two to three micro-spacecraft on a customized dispenser could be launched at the same time on the same trajectory. However, it turned out there was no significant benefit if any of these were solar sails and launch would be required barely 14 months after the discovery of “2019 PDC” (Grundmann et al., 2019c).

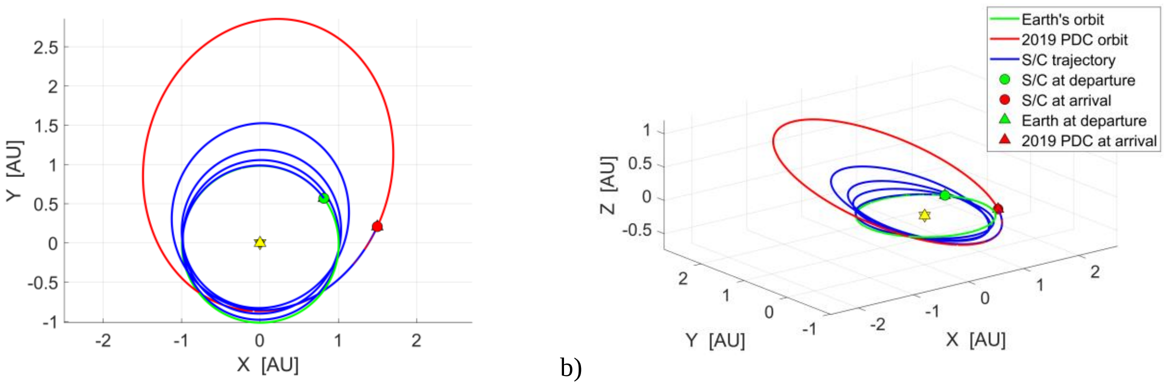
4.1. Low-thrust transfer to "2019 PDC"

To obtain possible solar sail rendezvous trajectories to the fictitious impactor "2019 PDC", we started with a low thrust trajectory only limited to a maximum acceleration of a_{max} = 0.3 mm/s² which at 1 AU and full illumination of the sail is the maximum characteristic acceleration $a_c \leq 0.3$ mm/s² we consider as a realistic upper limit for an optimized first-generation sailcraft. For these pathfinder trajectories, also to save computation time, the direction of acceleration (i.e., thrust) is unconstrained. In a second step, starting with the trajectories thus found, acceleration is then modulated with the directional dependence of a real solar sail membrane (similar to the "pseudo-solar sail" of Sullo et al. (2016)), where the magnitude of the sail acceleration is now depending on the cone angle to the Sun, while the cone angle remains unconstrained for simplicity. We have not found trajectories for solar sail rendezvous of an optimized sail launched after the fictitious discovery of "2019 PDC" and arriving before its fictitious impact in 2027. However, we found a low-thrust trajectory with a maximum acceleration of a_{max} = 0.3 mm/s² departing 19 months after the discovery of "2019 PDC" that achieves rendezvous on 22nd January 2025. It requires some periods with thrust components radially inward to the Sun which a sail cannot provide because of its operating principle but a SEP spacecraft can. The trajectory search yielded a successful SEP rendezvous with the parameters in Table 5..

Table 5. Parameters of a low-thrust rendezvous mission to fictitious impactor "2019 PDC".

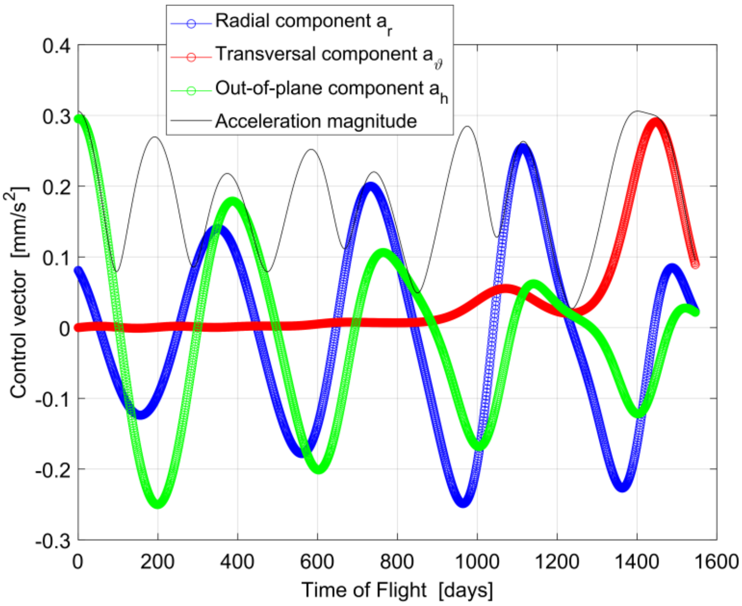
Parameter	Value
Maximum acceleration, a_{max}	0.3 mm/s²
Departure (launch) date	2020-Oct-27
Earth departure velocity, v_∞	0
Arrival date	2025-Jan-22
Total time of flight	1546 days (4.23 years)
Relative distance at arrival	< 1000 km
Relative velocity at arrival	0
Specific impulse	3000 s (29420 m/s)
Propellant mass ratio	0.342 (< 0.4)

In comparison to the (effectively) ballistic orbit of the "kick-started" fly-bys, the SEP trajectory presented in Figure 7 and Figure 8 appears highly dynamic. During the first three revolutions, the SEP trajectory mainly increases inclination (i) and then eccentricity (e) while the semi-major axis (a) and thus the orbital period at first remains nearly constant. The spacecraft thus stays relatively close to Earth early on. Only during the last revolution, acceleration becomes mainly transversal and it catches up with "2019 PDC" in a late dash. In a slightly longer running exercise scenario or from a suitable MNR orbit already passing at NEAs of e.g. a similar inclination and orbital plane orientation as “2019 PDC”’s fictitious orbit, it is likely that a rendezvous could also have been achieved by a solar sail, i.e., without direct inward acceleration, and at near-term performance levels in the range of a_c = 0.2~0.3 mm/s². However, SEP technology well established by missions such as DAWN and the HAYABUSAs and the close technological relation of solar sail membrane deployers such as GOSSAMER-1’s and large photovoltaic membrane deployers such as GOSOLAR (Seefeldt et al., 2019c, Sproewitz et al., 2019) enables responsive adaptation to such scenarios, real as well as fictitious, according to their requirements.

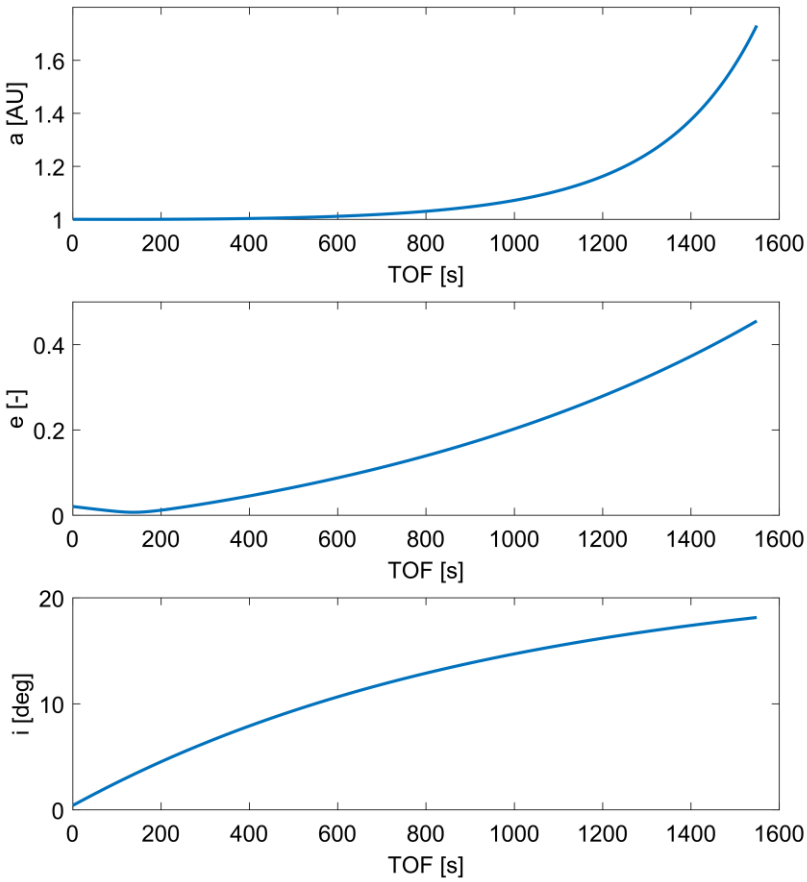


a) b)

Figure 7. Low-thrust rendezvous trajectory to fictitious impactor “2019 PDC”, a_{max} = 0.3 mm/s². (a) Ecliptic plane view; (b) Oblique view.



a)



b)

Figure 8. Control (a) and orbital parameter (b) history of the low-thrust rendezvous trajectory to fictitious impactor "2019 PDC", a_{max} = 0.3 mm/s².

It may be said that both trajectories we found pose an unrealistic launch date requirement to begin with, within 14 to 19 months of the discovery of “2019 PDC”, that can barely be met even by an all-out crash programme. However, there are examples of extremely fast-paced space programmes which made it to the launch pad that fast at a point in time in history (Day et al., 1998, McDonald, 1997, Peebles, 1997) and there are also examples that at least came close under less pressing circumstances more recently regarding the responsive production of flight hardware after extensive preceding studies, e.g. (Grimm et al., 2019). At the other end, either one of these flights of fancy we created would have, in the fictitious scenario of the PDC 2019 exercise, extended the time in which the location of the coming asteroid impact was precisely known from barely 2 weeks to well over two years, and would have given that much more time to the complete evacuation of New York City and the surrounding metropolitan areas from New Jersey to Long Island and Connecticut. This is a game changer.

5. Conclusions

In this paper, we showed that a near-term solar sail, with characteristic acceleration of up to 0.1~0.2 mm/s^2, enables realistic single and multiple near-Earth object (NEO) rendezvous missions. The authors’ previous work on deployable technology was used to inform on realistic values for near-term or now-term of characteristic acceleration. Then, tree search and trajectory optimisation were applied to an extended launch window, and a mission time of ten years, in search of multiple NEO rendezvouses. We found a feasible sequence with 2 unique NEO with characteristic acceleration as low as 0.06 mm/s^2, and 8 sequences with two NEO and 1 with 3 NEO increasing the characteristic acceleration to 0.10 mm/s^2.

We have also performed a preliminary investigation of rendezvous to a specific sub-set of NEOs, belonging to the Taurid swarm, due to their interesting properties. This investigation was initially conducted using a shape-based trajectory that uses a continuous acceleration, under the assumption that it can be converted into solar sailing with existing techniques in a future work. We found feasible transfers to two Taurids, 1996 RG3 and 1989 DA, with maximum accelerations of 0.23 and 0.25 mm/s^2 respectively, with direct transfer times from Earth of 2000~1500 days. The higher acceleration compared to the earlier results can be explained in the fact that NEOs in the Taurid swarm have very high eccentricity. The capability to rendezvous quickly with such challenging targets was demonstrated in the course of a planetary defence exercise where the unique capabilities of near-term low-thrust spacecraft greatly enhanced the options to address the imminent threat within a fictitious asteroid impact scenario.

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Appendix A

Table 6. Orbital parameters of the Taurid complex members. Reference epoch for the mean anomaly is 27/04/2019.

Taurid Complex	a, AU	e	i, deg	Ω, deg	ω, deg	M, deg
2201 Oljato (1947 XC)	2.17	0.71	2.52	74.99	98.26	80.08
4183 Cuno (1959 LM)	1.98	0.63	6.70	294.87	236.36	190.14
4197 Morpheus (1982 TA)	2.30	0.77	12.58	7.13	122.43	149.86
4341 Poseidon (1987 KF)	1.84	0.68	11.85	108.10	15.64	331.14
5143 Heracles (1991 VL)	1.83	0.77	9.03	309.49	227.80	331.91
5731 Zeus (1988 VP4)	2.26	0.65	11.42	281.67	217.02	309.65
6063 Jason (1984 KB)	2.21	0.77	4.92	169.40	337.15	223.25
8201 (1994 AH2)	2.54	0.71	9.55	164.11	25.13	71.76
16960 (1998 QS52)	2.20	0.86	17.55	260.46	242.95	64.93
69230 Hermes (1937 UB)	1.66	0.62	6.07	34.22	92.75	73.58
162195 (1999 RK45)	1.60	0.77	5.89	120.02	4.09	223.37
168318 (1989 DA)	2.16	0.54	6.49	349.13	139.81	182.91
217628 Lugh (1990 HA)	2.55	0.70	4.02	183.12	310.23	35.44
269690 (1996 RG3)	1.20	0.61	3.57	158.20	300.08	320.96
297274 (1996 SK)	2.43	0.79	1.96	197.41	284.34	317.09
306367 Nut (5025 P-L)	2.53	0.74	3.77	346.23	152.81	243.78
380455 (2003 UL3)	2.24	0.80	14.65	153.14	13.02	186.90
405212 (2003 QC10)	1.37	0.73	5.04	0.09	120.73	233.15
408752 (1991 TB2)	2.05	0.79	7.94	291.93	199.36	124.09
452639 (2005 UY6)	2.26	0.87	12.15	343.61	180.78	324.89
496901 (2001 HB)	1.31	0.69	9.29	195.91	237.89	31.43
503941 (2003 UV11)	1.45	0.76	5.92	31.93	124.77	279.26
1991 BA	2.19	0.67	1.94	118.88	70.69	346.82
1991 GO	1.93	0.65	9.55	24.09	89.62	197.32
1993 KA2	2.22	0.77	3.18	239.63	261.30	14.09
1995 FF	2.32	0.71	0.56	177.40	291.01	13.18

1999 VR6	2.19	0.76	8.52	212.90	294.17	341.70
1999 VK12	2.24	0.78	9.51	48.96	102.73	345.29
2001 QJ96	1.59	0.80	5.86	338.66	121.73	262.52
2002 MX	2.51	0.80	1.96	284.30	237.58	13.74
2002 XM35	2.33	0.84	3.06	229.96	312.64	347.02
2003 SF	2.16	0.78	5.74	77.68	31.77	342.48
2003 WP21	2.30	0.79	4.32	38.08	123.65	344.31
2004 TG10	2.23	0.86	4.18	205.09	317.37	95.19
2005 NX39	2.44	0.88	14.15	121.75	38.15	12.91
2005 TF50	2.27	0.87	10.69	0.69	159.88	319.41
2005 UR	2.25	0.88	6.93	20.03	140.48	346.61
2006 SO198	1.93	0.86	9.77	10.39	125.37	344.21
2007 RU17	2.04	0.83	9.08	17.48	129.82	314.31
2007 UL12	1.97	0.81	4.19	67.11	95.64	42.50
2015 TX24	2.27	0.87	6.04	33.01	127.01	357.10
2010 TU149	2.20	0.83	1.97	59.72	91.71	203.00
2011 TC4	1.49	0.72	3.13	200.98	309.06	2.12
2011 TX8	0.91	0.71	5.97	207.93	313.27	174.32
2012 UR158	2.24	0.86	3.22	287.66	238.17	322.33
2014 NK52	2.20	0.84	2.54	256.28	268.63	189.98
2015 VH66	2.28	0.85	7.36	329.70	195.42	340.18
2016 TP18	1.09	0.69	4.63	210.95	295.49	312.01
2001 UX4	1.72	0.75	8.94	182.45	333.82	246.36
2016 VK	1.79	0.78	5.98	210.97	315.31	334.20
2005 TB15	1.81	0.76	7.29	9.52	139.11	148.21
2013 GL8	2.43	0.84	8.52	331.56	47.56	228.18
2015 TX24	2.27	0.87	6.04	33.01	127.01	357.10
2012 ES10	1.89	0.76	6.82	346.57	72.93	24.99
2016 CM246	1.94	0.78	6.26	325.95	43.89	39.22

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