

SOLAR SAILCRAFT OF THE FIRST GENERATION

MISSION APPLICATIONS TO NEAR-EARTH ASTEROIDS

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ABSTRACT

Utilizing solely the freely available solar radiation pressure for propulsion, solar sails provide a wide range of opportunities for low-cost deep space missions, many of which are of great scientific relevance and – due to their large ΔV -requirements – difficult or even impossible to accomplish with any other type of conventional propulsion system. But very advanced solar sails that are very large and lightweight are required to perform those missions. Taking the current state-of-the-art in engineering of ultra-lightweight structures into account, solar sails of the first generation will be of relatively moderate performance. It will be shown in this paper that even with such moderate performance solar sailcraft of the first generation, challenging scientific missions are feasible at relatively low cost. Near-Earth asteroids with moderate inclinations are a promising category of target bodies for those solar sailcraft, since they can be accessed relatively easily and since they are of great scientific relevance. Some proposed missions to near-Earth asteroids will be analyzed.

INTRODUCTION

Being propelled solely by the freely available solar radiation pressure, solar sailcraft provide a wide range of opportunities for low-cost missions, many of which are – due to their large ΔV -requirement – difficult or impossible for any other type of conventional spacecraft. Many of those high-energy missions are of great scientific relevance, such as missions to near-Earth objects (NEOs, asteroids and short period comets) with highly inclined or retrograde

orbits.¹ Such missions can be performed with solar sails, but a demanding sail performance (low specific weight) is required to keep mission durations within moderate limits. Taking, however, the current state-of-the-art in engineering of ultra-lightweight structures into account, solar sailcraft of the first generation will be of relatively moderate performance, if assessed w.r.t. flight duration alone, even inferior to already state-of-the-art electric propulsion systems (although solar sailcraft might have an advantage in launch mass). Nevertheless, on the way to more advanced solar sailcraft, they are an indispensable first stepping stone. Near-Earth asteroids (NEAs) with a moderate inclination are a promising category of target bodies for near-term solar sailcraft, since they can be accessed relatively easily. Therefore, in August 2000, a dedicated mission for the exploration of NEAs with solar sailcraft (ENEAS) was proposed by DLR in cooperation with the Westfälische Wilhelms-Universität at Münster (Germany) as a candidate within the German small satellite program for space sciences. Using a $(50\text{ m})^2$ square sail with a specific weight of about 30 g/m^2 , ENEAS was intended to rendezvous a NEA (1996FG₃) with a total payload of about 75 kg (incl. spacecraft bus and 5 kg scientific payload) within less than 5 years [1, 2]. Based on our experience gained during the successful ground deployment of a $(20\text{ m})^2$ solar sail structure [2, 3, 4], we consider a $(70\text{ m})^2$ solar sail with a specific weight of about 20 g/m^2 to be a realistic, however still ambitious, near-term development goal.

¹more than 55% of the NEO population has inclinations larger than 10° , more than 30% has inclinations larger than 20°

Within this paper, it will be demonstrated that even with moderate-performance solar sails of the first generation, challenging scientific missions, like a sample return mission (ENEAS-SR) or a multiple rendezvous mission (ENEAS+) to near-Earth asteroids, are feasible at relatively low cost. It will be shown that, using a $(70\text{ m})^2$ solar sail with a specific weight of 23 g/m^2 , ENEAS-SR would be able to return a sample from the C type NEA 1996FG₃ to Earth within 10 years from launch. The payload (the total system except the sail assembly) for this mission is about 300 kg, including a lander and a sample return capsule. With a 75 kg-payload, a solar sail of the same size and weight would also be able to rendezvous three NEAs (2000AG₆, 1989UQ, and 1999AO₁₀) subsequently within 7.6 years from launch (with about 200 days of operations at each NEA). A larger solar sail of about $(140\text{ m})^2$ would even be capable to transport the ENEAS-SR payload to the three ENEAS+ target bodies and sample all of them. The samples could be returned to Earth within about 10 years from launch.

The future technical development steps that are required to realize the missions described within this paper, are detailed in a paper entitled "Solar Sailcraft of the First Generation: Technology Development", submitted in parallel to the 54th IAC 2003 [5], including a technical development roadmap.

SOLAR SAILCRAFT

For the optical characteristics of a solar sail, different assumptions can be made, which result in different models for the magnitude and the direction of the **solar radiation pressure** (SRP) force acting on the sail. Simple models assume an ideally reflecting sail surface or model its non-ideal reflectivity by introducing an overall **sail efficiency factor**. It is shown in [6] that those SRP force models should *not* be used except for *very* preliminary mission feasibility analyses, since they misrepresent the direction of the real SRP force. Within this paper, a more realistic SRP force model is used for

trajectory simulation and optimization, which considers the optical characteristics of the real sail film, which is aluminum-coated on the front side² and chromium-coated on the back side³.

The orbital dynamics of solar sailcraft is in many respects similar to the orbital dynamics of other low-thrust spacecraft. However, as Figure 1 shows, other low-thrust spacecraft may orient its thrust vector into any desired direction, whereas the thrust vector of solar sailcraft is constrained to lie on the surface of a "bubble" that is always directed away from the Sun. Nevertheless, by controlling the sail orientation relative to the Sun, solar sailcraft can gain orbital angular momentum and spiral outwards – away from the Sun – or lose orbital angular momentum and spiral inwards – towards the Sun.

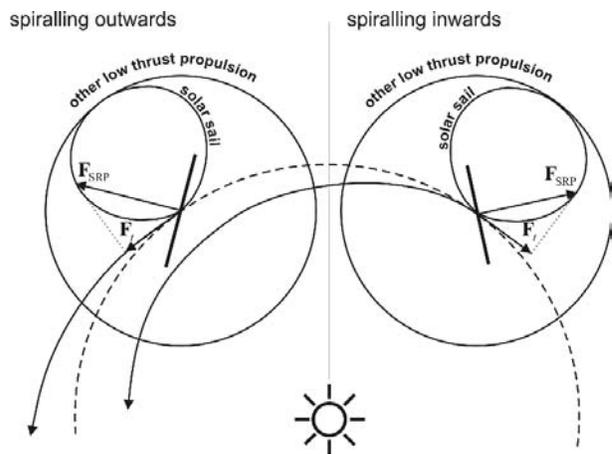


Figure 1: Spiralling towards and away from the Sun

Below, the commonly used performance parameters to compare different solar sail designs and different solar sailcraft will be introduced. The **sail assembly loading**, defined as the mass of the sail assembly (the sail film and the required structure for storing, deploying and tensioning the sail, index "SA") per unit area, is the key parameter for the efficiency of the solar sail's structural design:

$$\sigma_{SA} = \frac{m_{SA}}{A} \quad (1)$$

²for high reflectivity

³for high emissivity

The **sailcraft loading** is defined accordingly as the specific mass of the sailcraft including the payload (index "PL"), where the term payload stands for the total sailcraft except the solar sail assembly (i.e. except the propulsion system):

$$\sigma = \frac{m}{A} = \frac{m_{\text{SA}} + m_{\text{PL}}}{A} = \sigma_{\text{SA}} + \frac{m_{\text{PL}}}{A} \quad (2)$$

Especially for trajectory analyses, it is convenient to express the performance of solar sailcraft in terms of the **characteristic acceleration** a_c , which is defined as the SRP acceleration acting on a solar sail that is oriented perpendicular to the Sun-line at Sun-Earth distance, where the effective SRP on the aluminumized sail film is $8.288 \mu\text{N}/\text{m}^2$:

$$a_c = \frac{8.288 \mu\text{N}/\text{m}^2}{\sigma} = \frac{8.288 \mu\text{N}/\text{m}^2}{\sigma_{\text{SA}} + \frac{m_{\text{PL}}}{A}} \quad (3)$$

At DLR, a $(20\text{ m})^2$ solar sail was successfully deployed in December 1999 on-ground in a simulated gravity-free environment and ambient environmental conditions (Figure 2) [2, 3]. The DLR solar sail baseline design is a square



Figure 2: Deployed $(20\text{ m})^2$ solar sail and CFRP boom at DLR

sail that consists of four CFRP (Carbon Fiber Reinforced Plastics) booms and of four triangular sail segments. The booms are made of two CFRP shells that are bonded at the edges to form a tubular shape, so that they can be pressed flat and rolled up in a central deployment module. During deployment, they unfold

automatically and return to their tubular shape with high bending and buckling strength. Subsequently, the four sail segments are deployed by ropes.

OBJECTIVES FOR NEA MISSIONS

Comets and most of the asteroids are in some sense the fossils of the solar system [7]. They vary highly in size, surface properties, composition, and probably origin. Especially the undifferentiated primitive carbonaceous (C type) asteroids are expected to hold key information for understanding the origin of the solar system and the formation of the planets, since they are – unlike the planets – primitive bodies that have undergone little physical and chemical alteration, and thus represent most closely the properties of the primordial solar nebula. Therefore, they have a very high exploration priority [1]. C type asteroids are the largest taxonomic class ($\sim 40\%$), but most of them are located in the outer asteroid belt beyond 2.7 AU , where they are not easily accessible [8].

Although a large amount of asteroid samples exists on Earth as meteorites, many questions are yet unresolved. One of the most important unresolved questions is the linkage between asteroid classes and meteorite classes. Many asteroid classes have reflectance spectra that are similar to those of meteorites. For example, C type asteroids are supposed to be linked to chondritic meteorites due to their similar spectra, indicating carbon-rich material. However, some asteroid types have no meteoritic analogue in their spectra, like the P and D type asteroids, which are supposed to be even more primitive than the C type asteroids and to carry organic compounds [8]. It is also curious that no large asteroid class seems to match the meteorite spectra of ordinary chondrites, the most common meteoritic samples [8].

Near-Earth objects (NEOs) are asteroids (NEAs) and short-period comets with orbits that intersect or pass near the orbit of Earth. About 665 NEOs with diameters $\gtrsim 1\text{ km}$ are currently (Sep03) known [9], but the entire population contains perhaps more than 1000

objects of this size [7]. They pose a significant hazard to human civilization and to life on Earth. It is today widely accepted that NEO impacts have caused at least one mass extinction (65 million years ago at the Cretaceous/Tertiary boundary), and they are suspected to have caused several global catastrophes before [10]. Even NEOs that do not intersect the orbit of Earth may evolve into Earth-crossers, since their orbits are chaotic, having a relatively short dynamical lifetime ($\sim 10^7$ years) [11][8]. One day, it might become necessary to prevent a specific object from impacting the Earth by nudging it out of its orbit. To be able to do this, the bulk properties of NEOs (material strengths, composition, structure, moments of inertia, etc.) should be determined as soon as possible [12].

Since NEAs are probably fragments of main belt asteroids, they are believed to be a representative sample of them [1]. Unlike their parent bodies, some NEOs are the most readily accessible extraterrestrial bodies. The energy requirement to rendezvous with some of them is less than to land on the Moon’s surface [7]. Since relatively short transfer times to such bodies are expected even for solar sails with very moderate performance, they are ideal targets for a first technical demonstration of solar sail propulsion, although the true potential and advantage of solar sails over other propulsion systems is expected to become evident only for high- ΔV -missions.

NEA RENDEZVOUS MISSION (ENEAS)

ENEAS was intended to transport a scientific payload of 5 kg (CCD camera + IR spectrometer + magnetometer) to a NEA within less than five years (Table 1 summarizes the ENEAS parameters).

1996FG₃ had been chosen as the target body for the ENEAS mission, since it has orbital elements not too different from that of Earth and since it is an object of exceptional scientific relevance. Observations [13, 14] indicate that 1996FG₃ is a binary C type asteroid, consisting of a primary body with a rotation period of

Sail area	A	$(50 \text{ m})^2$
Sail assembly mass	m_{SA}	73 kg
Sail assembly loading	σ_{SA}	29.2 g/m ²
Payload mass (incl. spacecraft bus)	m_{PL}	75 kg
Total sailcraft mass	m	148 kg
Sailcraft loading	σ	59.2 g/m ²
Char. acceleration	a_c	0.140 mm/s ²
Char. SRP force	F_c	20.7 mN

Table 1: ENEAS

about 3.6 hours and a secondary body with an orbital period of about 16 hours. Based on the typical C type albedo of 0.06, the primary body has an estimated diameter of about 1.4 km and the secondary body an estimated diameter of about 0.4 km. The separation of the two bodies is about 1.7 times the diameter of the primary body. The determined average bulk density is $1.4 \pm 0.3 \text{ g/cm}^3$, which is highly suggestive of a "rubble pile" structure. ENEAS was intended to determine the morphological properties and the compositional properties of the 1996FG₃ system via remote sensing [1]. Trajectory optimization using InTrance, an evolutionary neurocontrol based global trajectory optimization method recently developed at DLR [15, 16, 17], yields an optimal transfer time of 4.18 years for $C_3 = 0 \text{ km}^2/\text{s}^2$ (Figure 3) and 2.74 years for $C_3 = 4 \text{ km}^2/\text{s}^2$ (Figure 4). Figure 5 shows the dependence of transfer time on hyperbolic excess energy. As it can be seen, it would be very beneficial, if the launcher could provide some hyperbolic excess energy for interplanetary injection, but this is not absolutely necessary to accomplish the mission.

For a first solar sail technology demonstration mission in deep space, a target object might be required that is still easier accessible than 1996FG₃, to keep operation costs low and to provide as quickly as possible feedback for the tested technologies. Despite its small dimension, the NEA 1999AO₁₀ might be a potential target object for such a technology demonstration mission. With $C_3 = 0 \text{ km}^2/\text{s}^2$ and $a_c = 0.14 \text{ mm/s}^2$, as InTrance-optimization

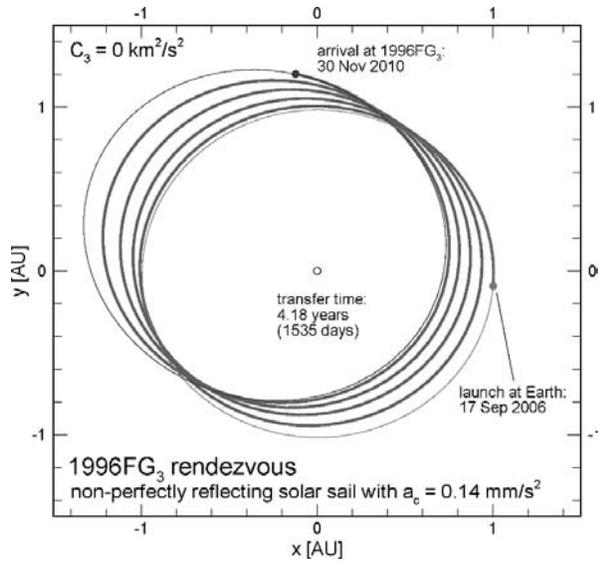


Figure 3: ENEAS trajectory option for $C_3 = 0 \text{ km}^2/\text{s}^2$

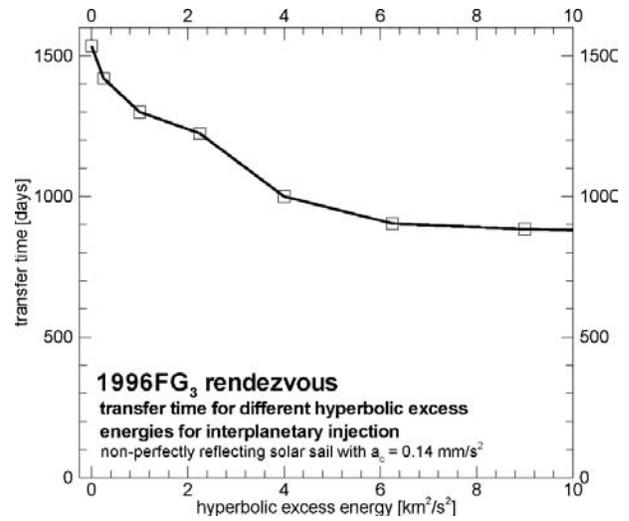


Figure 5: Influence of C_3 on ENEAS transfer time

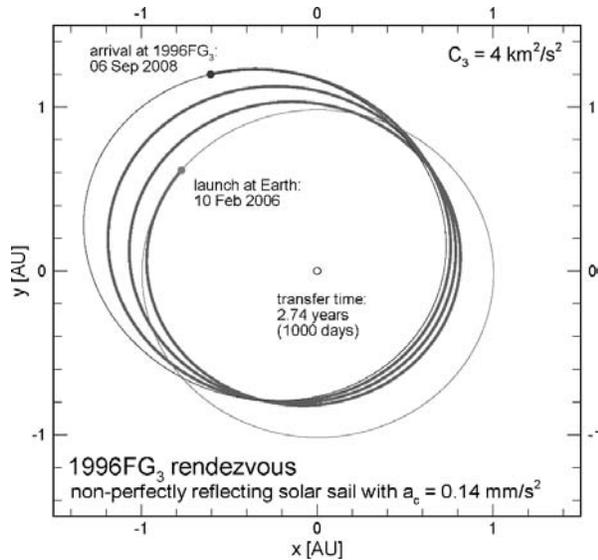


Figure 4: ENEAS trajectory option for $C_3 = 4 \text{ km}^2/\text{s}^2$

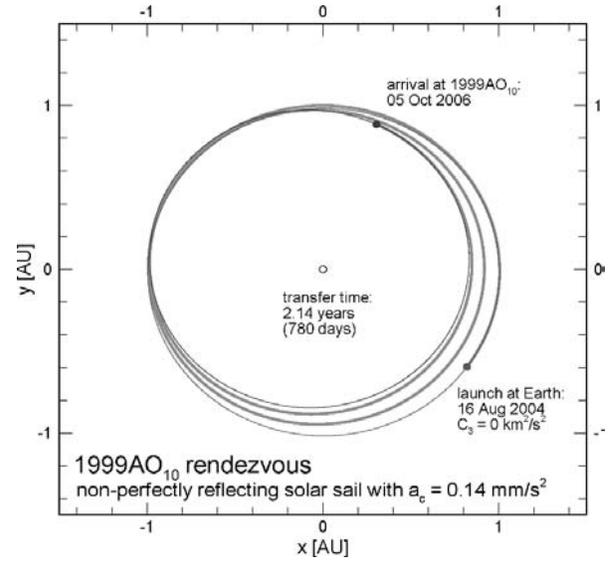


Figure 6: ENEAS trajectory option to 1999AO₁₀

NEA SAMPLE RETURN MISSION (ENEAS-SR)

shows, it could be reached with the ENEAS sailcraft within nearly half of the time (2.14 years / 780 days) that is required for 1996FG₃ (Figure 6). During the transfer and at the asteroid, critical technologies (attitude control, autonomy, sail aging due to the erosive effects of the space environment, close proximity operations at the asteroid, etc.) could be tested for relatively low cost.

To study the 1996FG₃ system in detail, it would be necessary to place a lander on the surface of the asteroid (e.g. for mass spectrometry and/or alpha-proton spectrometry). Some investigations (e.g. micro-structure and isotope analysis) to determine the age and the evolution of 1996FG₃ could probably only be accomplished by taking samples of the asteroid back to Earth.

Solar sailcraft are – due to their high ΔV -capability – supposed to be especially capable to perform such a mission. However, compared to the ENEAS rendezvous mission, the payload has to be extended considerably, including a lander and a sample return capsule.

To derive the required *minimum* solar sailcraft performance for this mission, the maximal mission duration was set to 10 years, since we consider a longer mission duration to be not acceptable.⁴ Trajectory optimization using InTrance shows that the ENEAS-SR mission to 1996FG₃ can be achieved even with a low characteristic acceleration of 0.10 mm/s² in exactly 10 years, including a rendezvous trajectory of 6.7 years (Figure 7), 117.5 days of operations at the asteroid, and an Earth return trajectory of 3.0 years (Figure 8). The Earth return leg is much shorter than the outward leg, since no rendezvous is required at Earth.

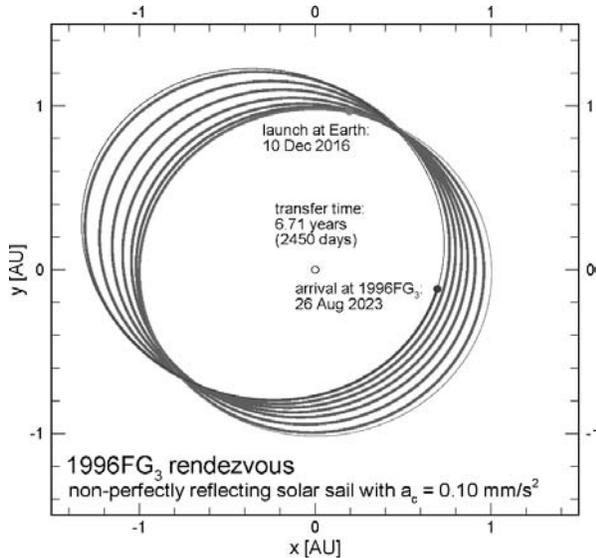


Figure 7: ENEAS-SR outward trajectory option

Looking at equation (3), one can see that the solar sailcraft performance depends on three design parameters, the sail assembly loading σ_{SA} , the payload mass m_{PL} , and the side length s (or area $A = s^2$) of the solar sail, defining a three-dimensional solar sailcraft design

⁴Looking at the Rosetta-mission, about 10 years seem to be the scarcely acceptable maximum duration for a mission with an exceptional scientific return.

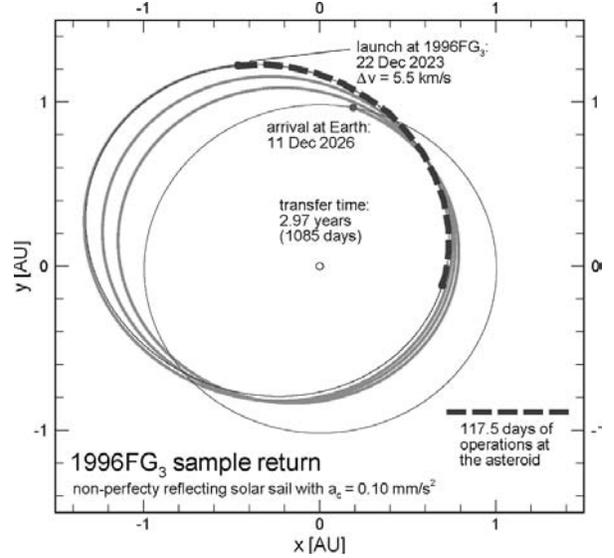


Figure 8: ENEAS-SR return trajectory option

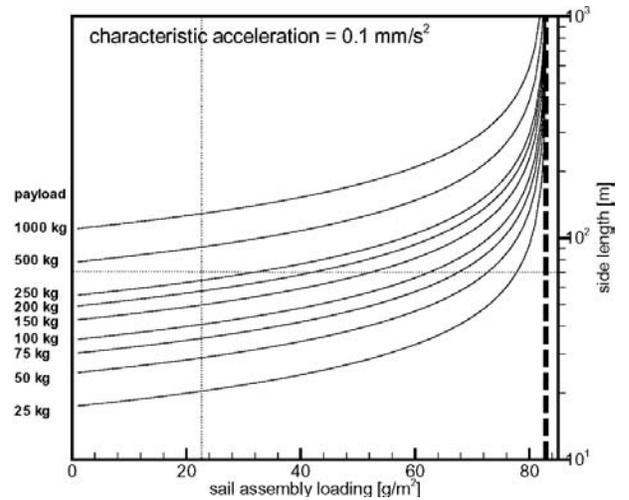


Figure 9: The side length s of the solar sail that is required to achieve a characteristic acceleration of 0.10 mm/s² as a function of σ_{SA} and m_{PL}

space. Figure 9 shows the required sail size for different sail assembly loadings and payload masses, to obtain a characteristic acceleration of 0.10 mm/s². Based on our experiences with the ground-based solar sail technology demonstration, a maximum sail size of (70 m)² with a sail assembly mass of 111 kg ($\sigma_{SA} = 22.7$ g/m², sail film + booms + deployment module) is considered as a realistic – however still challenging – baseline for the ENEAS-SR mission [18].

This yields a payload mass of 295 kg. The realization of a spacecraft within the specified mass budget, including a lander of about 150 kg and a sample return capsule of about 50 kg, appears to be feasible but requires further investigation. Table 2 summarizes the ENEAS-SR parameters.

Sail area	A	$(70 \text{ m})^2$
Sail assembly mass	m_{SA}	111 kg
Sail assembly loading	σ_{SA}	22.7 g/m ²
Payload mass (incl. spacecraft bus)	m_{PL}	295 kg
Total sailcraft mass	m	406 kg
Sailcraft loading	σ	82.9 g/m ²
Char. acceleration	a_c	0.100 mm/s ²
Char. SRP force	F_c	40.6 mN

Table 2: ENEAS-SR

Since for solar sailcraft of moderate performance it is difficult and time consuming to gain orbital energy in the Earth’s gravitational field, the launcher inserts the ENEAS-SR sailcraft directly into an interplanetary trajectory. After injection and deployment, the sail is oriented to follow the pre-calculated attitude profile that leads to an optimal interplanetary transfer trajectory. During the transfer, the ENEAS-SR sailcraft runs almost autonomously, so that ground monitoring is carried out on a weekly basis only [2]. At the end of the transfer trajectory, the solar sailcraft makes a rendezvous with 1996FG₃ within its gravitational sphere of influence (Hill-sphere) of between 70 and 150 km radius (at 1996FG₃’s perihelion and aphelion respectively).

Even in the near-field of the asteroid, the SRP acceleration of between 0.05 and 0.21 mm/s² (at aphelion and perihelion respectively) is larger than the asteroid’s gravitational acceleration (0.01 to 0.00005 mm/s² in a distance ranging from 5 to 50 km), so that the sailcraft is able to hover on artificial equilibrium surfaces in the hemisphere that is opposite to the Sun (Figure 10). Those quasi-stationary hovering positions are unstable but can be stabilized using a feedback control loop [19].

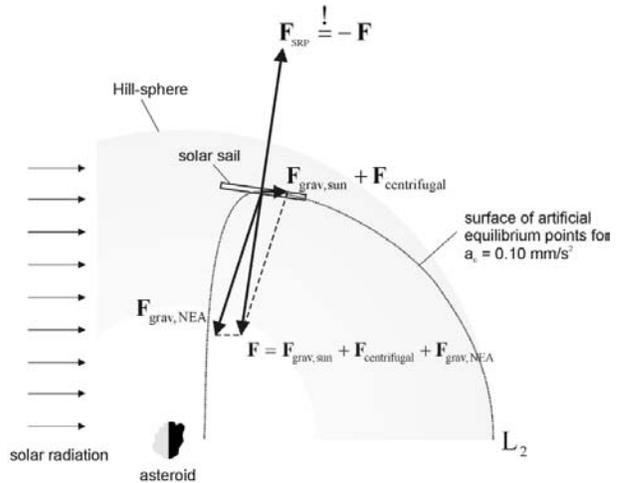


Figure 10: Hovering at the asteroid

Hovering near the asteroid, the (likely complex) gravitational field is studied, so that a coarse gravitational field model can be determined. Thereafter, the lander with the integrated Earth return capsule is separated from the solar sail to go into closer orbit around the asteroid. While measuring the asteroid’s gravitational field with increasing accuracy, the orbit of the lander is continuously lowered until a safe landing trajectory can be computed (some or all of those extensive computations may be performed on Earth) and landing can be performed. Once landed, the sample is fed directly into the Earth return capsule. After all sampling operations are finished, the lander brings the samples back to the hovering sailcraft. In this mission phase, the sailcraft is waiting edge-on (so that no SRP force is acting on the sail) at the L₂ Lagrange point to assist the rendezvous between the lander and the solar sail. Since 1996FG₃ is a binary system, it would be interesting to land and extract samples from both bodies, to investigate the origin and the collisional evolution of the 1996FG₃ system. Since the gravitational acceleration is very low near the asteroid and the required ΔV for the lander less than 10 m/s, a cold gas system with a propellant mass of less than 4 kg is sufficient to perform all lander operations.

After rendezvous with the hovering sailcraft, the re-docked ENEAS-SR solar sailcraft returns

the sample to Earth. Finally, some hours before the arrival at Earth, the lander with the return capsule is separated from the sail, the capsule is spun-up to maintain the required entry attitude, and injected into an Earth reentry trajectory, where it is decelerated by atmospheric friction and breaking parachutes. The return trajectory is much faster than the transfer trajectory to 1996FG₃ since no rendezvous is required at Earth. Thus, the sailcraft may arrive with a relatively large hyperbolic excess velocity of about 5.5 km/s. The gravitational acceleration of Earth adds another 11.2 km/s, so that the Earth entry velocity may reach about $\sqrt{5.5^2 + 11.2^2}$ km/s = 12.5 km/s. This is slightly less than the entry velocity of NASA’s Stardust capsule, which has the highest entry velocity of any Earth-returning mission up to date (12.9 km/s) [20, 21].

To assess the capability of solar sail propulsion for the ENEAS-SR mission, comparative mission analyses have been performed for two SEP systems, using NASA’s NSTAR ion thruster and using a cluster of three NSTAR thrusters respectively [15]. With a single thruster, the mission could be performed within a total mission duration of 3.5 years. About 180 kg of Xenon would be required as propellant. The launch mass would, however, be 50% larger than for the solar sail option, requiring eventually a more expensive launch. Using a cluster of three thrusters, the total mission duration would be further reduced to 1.9 years (this would not only require a larger thrust but also about 20% more propellant). In this case, the launch mass would be about twice that of the solar sail option. Therefore, if only the flight duration is considered, the solar sail option is clearly outperformed by the SEP option, whereas, if only the launch costs are considered, the solar sail might be the favorable option. Thus, if the longer arising ground operation costs are lower than the savings in launch costs, and if the mission duration plays a subordinate role with respect to cost, the solar sail might be the better propulsion option for this mission.

MULTIPLE NEA RENDEZVOUS AND SAMPLE RETURN MISSIONS (ENEAS+, ENEAS+SR)

For ENEAS-SR, a (70 m)² solar sail with a mass of 111 kg was presumed to accomplish a characteristic acceleration of 0.10 mm/s² with a 295 kg payload. Within this section, it is investigated, whether – using the same solar sail – a multiple NEA rendezvous mission can be performed with the small ENEAS payload of 75 kg. This multiple NEA rendezvous mission is termed ENEAS+. Table 3 summarizes the ENEAS+ parameters.

Sail area	A	(70 m) ²
Sail assembly mass	m_{SA}	111 kg
Sail assembly loading	σ_{SA}	22.7 g/m ²
Payload mass (incl. spacecraft bus)	m_{PL}	75 kg
Total sailcraft mass	m	186 kg
Sailcraft loading	σ	38.0 g/m ²
Char. acceleration	a_c	0.218 mm/s ²
Char. SRP force	F_c	40.6 mN

Table 3: ENEAS+

For the given solar sail and the given payload, the characteristic acceleration of the ENEAS+ solar sailcraft is 0.218 mm/s². To compare the solar sail option with the SEP option, the target objects of the Hera-mission, a proposed multiple NEA sample return mission⁵ that employs a spacecraft with a cluster of three NSTAR thrusters to return samples from three different NEAs to Earth within a mission duration of about 4.8 years (676 kg dry mass; 1102 kg total mass), have been adopted [22]. InTrance has been used to calculate the transfer times between the targets for various launch dates to find the optimal target sequence. The best found sequence is illustrated in Figures 11 to 13.

The optional trajectory from 1999AO₁₀ to Earth, shown in Figure 14, is not part of the actual ENEAS+ mission. Never-

⁵mission proposal to NASA under the lead of the Arkansas-Oklahoma Center for Space and Planetary Science

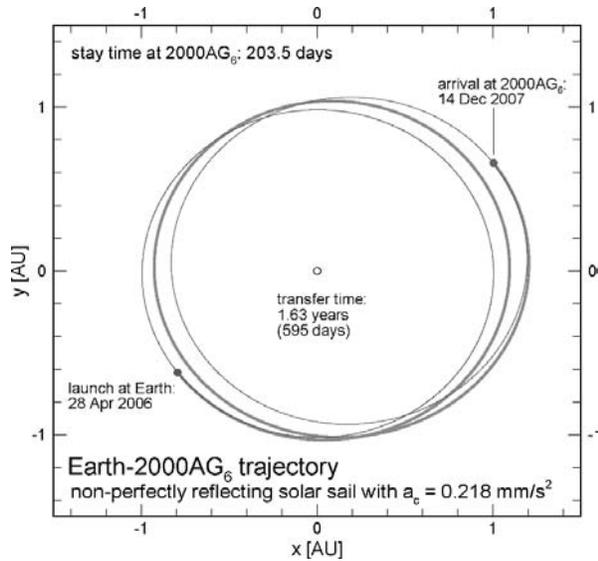


Figure 11: ENEAS+ trajectory option for Earth-2000AG₆-leg

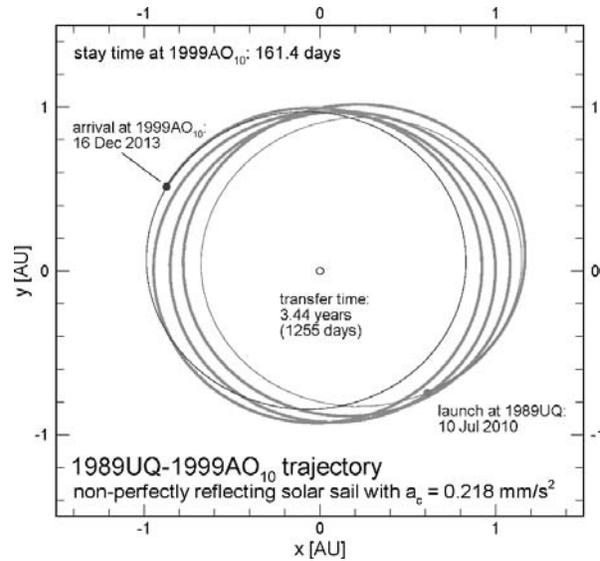


Figure 13: ENEAS+ trajectory option for 1989UQ-1999AO₁₀-leg

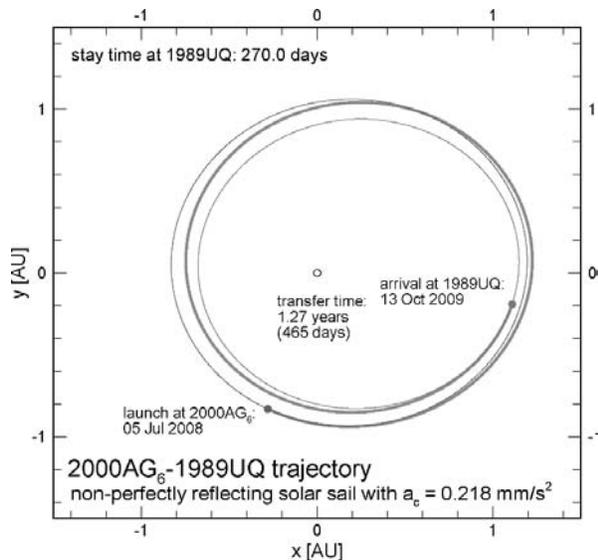


Figure 12: ENEAS+ trajectory option for 2000AG₆-1989UQ-leg

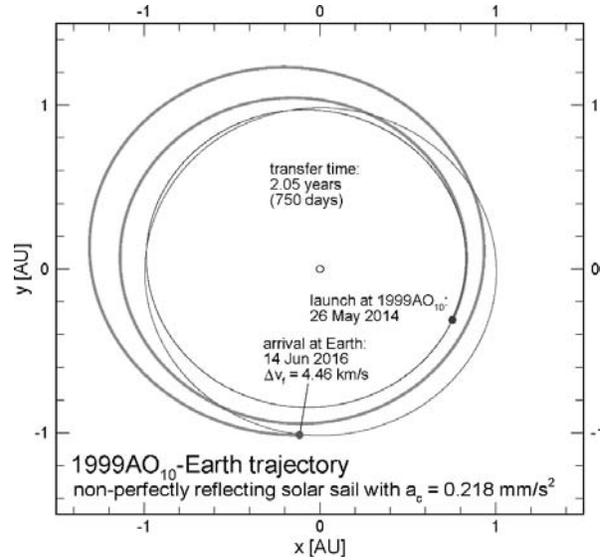


Figure 14: ENEAS+SR trajectory option for 1999AO₁₀-Earth-leg

theless, the trajectories are valid for any solar sailcraft that accomplishes a characteristic acceleration of 0.218 mm/s^2 . Using a larger solar sail ($s = 139 \text{ m}$), this mission might be also performed with the ENEAS-SR payload. With such a solar sailcraft, all three visited NEAs could be sampled, and the samples could be returned to Earth within 10.1 years (this mission might be termed ENEAS+SR). Regarding the

question, whether solar sail propulsion or SEP is superior for such a mission, the same conclusions as in the previous section can be drawn.

SUMMARY AND CONCLUSIONS

It was shown that even with moderate-performance solar sails of the first generation, challenging scientific missions, like a sample re-

turn mission or a multiple rendezvous mission to near-Earth asteroids, are feasible at relatively low cost. It was shown that a $(70\text{ m})^2$ solar sail with a specific weight of about 23 g/m^2 is able to transport a 300 kg-spacecraft (incl. a lander and a sample return capsule) to a near-Earth asteroid and to return a sample to Earth within 10 years. With the same solar sail, a triple NEA rendezvous mission with a 75 kg-payload is feasible within 7.6 years, spending about 200 days at each asteroid.

The obtained results demonstrate that near-term solar sailcraft are outperformed by the SEP option, if only the flight duration is considered, whereas, if only the launch costs are considered, the solar sail might be the favorable option. Thus, if the longer arising ground operation costs are lower than the savings in launch costs, and if the mission duration plays a subordinate role with respect to cost, the solar sail might be the better propulsion option for the missions considered within this paper. Nevertheless, on the way to more advanced solar sailcraft, as they are required for high- ΔV missions, the development of solar sails with moderate performance is an indispensable first stepping stone.

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