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Past, present, and future of solar sailing

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Прошлое, настоящее и будущее солнечных парусов

Солнечные паруса – это технология, которая недавно была фантастикой, а сегодня уже является реальностью. С помощью солнечных парусов, теоретически, можно управлять движением космических аппаратов совершенно без затрат топлива, так как топливом для солнечных парусов являются фотоны света, которые излучает Солнце. Более того, солнечные паруса порой открывают возможности, которые практически недостижимы при применении классических реактивных двигателей. Тем не менее, несмотря на большой потенциал солнечных парусов, и на то, что уже было запущено несколько демонстрационных миссий с солнечными парусами, технология солнечных парусов вызывает также и обоснованный скептицизм, а некоторые о ней даже и не слышали. *Текущая работа* носит обзорный характер и нацелена на то, чтобы без углубления в технические детали дать представление о том, чем на самом деле сегодня является солнечный парус, как развивалась технология, из каких компонент она состоит, и чего можно ожидать от неё в будущем. Для этого приводится подробный исторический обзор пути становления технологии солнечных парусов и осуществлённых миссий, приводятся потенциальные направления применения парусов, а также обсуждаются те технологические и научные вызовы, что возникают при проектировании миссий с солнечными парусами. В конце автор даёт оценку текущему состоянию развития технологии солнечного паруса и её перспектив.

Ключевые слова: солнечный парус, обзор, история, миссия, технологии, вызовы, перспективы

Denis Glebovich Perepukhov

Past, present, and future of solar sailing

Solar sailing is a technology that has transitioned from science fiction to reality. Solar sails theoretically allow one to control a spacecraft without propellant expenditure, as it utilizes photons emitted by the Sun as fuel. Moreover, solar sails also unlock specific destinations that are unattainable with conventional rocket engines. Despite their significant potential and the successful launch of several demonstrator missions, solar sails also face justified skepticism, and some have not even heard of it. *The purpose of this review* is to provide a comprehensive view on the current state and prospects of solar sailing, as well as on its historical development and key technological components, without diving into technical details. For this a detailed historical overview is provided of how the idea of solar sailing has evolved and of what missions have been launched. The overview is complemented with a discussion of potential application areas and technological & scientific challenges of solar sails. In conclusion, the author offers an assessment of the current developmental status and future potential of solar sail technology.

Keywords: solar sail, review, history, mission, technology, challenges, prospects

Introduction

Solar sailing is an actively developing area in the field of space exploration, which transitioned from the realm of science fiction into the domain of real technology at the turn of the XX and XXI centuries. Today, most scientists involved in space exploration have heard of solar sails, however, attitudes toward this technology vary widely. Some hold extremely optimistic views, at times bordering on science fiction. Others are overly skeptical, considering solar sails unrealistic. Those engaged in the development and construction of solar sails hold more realistic and moderate expectations for this technology. And some are simply aware that such technology exists. However, when it comes to actual development, missions, and investments, it is essential to have a realistic understanding of solar sailing technology in order to form an objective opinion and make decisions.

The aim of this work is to provide insights into what solar sail technology actually represents today, how it has evolved, what components it comprises, what has (and has not) been achieved in its development, and what can be expected from it in the future. Emphasis is made on a historical review of solar sailing missions, which provides a view on how the technology has been evolving, and perspectives of using solar sails in space exploration. Specific technical aspects are also discussed (deployment mechanisms, fabrication of reflective membranes, control methods, etc.), as they are important for forming a comprehensive view of solar sail technology. All of this is presented without delving into intricate technical details or calculations and can be comprehended by a broad audience.

Over the past century, plenty of works on solar sailing have been published, including review articles. Monographs [9, 61] are considered classics and serve as textbooks on solar sailing. Works [18, 69, 83, 39] provide detailed information and comprehensive analyses of various aspects of solar sail development and applications. Review [18] is devoted not only to solar sails but to space sails in general (solar sails, laser-drive sails, drag sails, magnetic sails, electric sails, etc.), discussing historical aspects, the current state of the art, synergies between different types of sails, and providing an overview of existing space agency plans regarding space sails. Work [69] focuses on solar sails and covers nearly all aspects of solar sailing; this work is the closest to the present study. Reviews [83, 39] give attention to specific technical aspects of solar sail missions. In [83] authors discuss solar sails geometry, sail packaging methods, operational conditions, ground testing infrastructure, and required technology developments. In [39] mathematical aspects of solar sailing are discussed, including trajectory design, non‑Keplerian orbits, attitude control, and structural dynamics.

In this review the author attempts to combine historical and technical perspectives in order to form a comprehensive view on solar sailing technology. Compared to the monographs, this work differs: first, in its scope; second, in the absence of detailed mathematical derivations; third, in the inclusion of new information that has appeared since those monographs were written.

The structure of this paper is such that each section can be read independently of the others. The only exception is Section I, which describes the operating principles of solar sailing and introduces the concept of *characteristic acceleration*, which is used in other sections. Section II outlines the history and evolution of the solar sail concept: from science fiction to the first serious scientific studies. Section III provides information on all solar sail missions to date. Section IV discusses areas of space exploration where solar sails may prove useful or even irreplaceable. Section V offers a comprehensive overview of technical and mathematical challenges intrinsic to solar sail missions. Section VI presents the author's view on the present and future of solar sailing. The conclusion briefly summarizes the paper.

I. Solar sailing basic principles

A conventional sail on a sea ship generates thrust by interacting with the incoming air. A solar sail operates in a similar manner, but instead of a continuous flow of air, it uses a “molecular” flow of photons emitted by the Sun. For this reason, solar sails are usually constructed from highly reflective and lightweight materials. Essentially, a modern solar sail is a large thin foil film that is somehow stretched and attached to the spacecraft. In practice, of course, materials that are more suitable for space are used, aluminized Kapton for example.

To determine the force generated by a solar sail, let us consider a simplified model (see Fig. 1). The sail is assumed to be flat, perfectly reflective, with surface area A, and the total mass of the apparatus, including the sail, m. One side of the sail is reflective (working) and specularly reflects all incoming photons, while the other side is radiative (cooling) and must always remain in shadow. The orientation of the sail is determined by a unit vector $\mathbf{n}$ that is perpendicular to the radiative side of the sail. Since the distance between the Sun and the sail is much greater than the size of them both, we assume that all photons incident on the sail travel in the direction defined by the vector $\mathbf{e}_1 \coloneqq \mathbf{r}/r$, where $\mathbf{r}$ is the sail's radius vector relative to the Sun. The symbol $\alpha_\mathbf{n}$ denotes the angle between $\mathbf{n}$ and $\mathbf{e}_1$. Strictly speaking, incident photons can be reflected specularly, reflected diffusely, and absorbed. However, in this paper we will limit ourselves to the simplest model that accounts only for the specular reflection.

The energy W that is transferred per unit time by photons passing through a unit area oriented orthogonally to $\mathbf{e}_1$, depends on the distance to the Sun. Treating the Sun as a point source of light, we can write

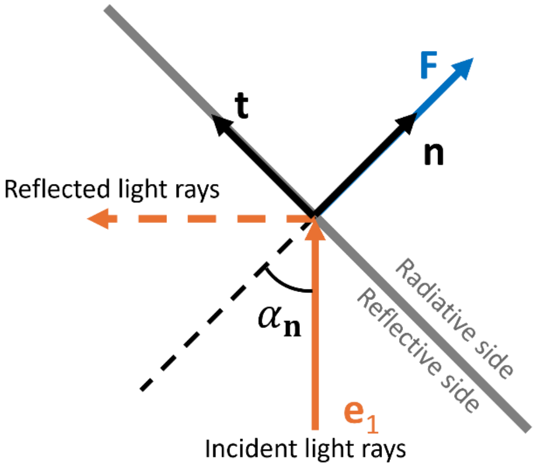

Fig. 1. The scheme of a flat mirror solar sail. The sail itself is shown in gray, and the direction of propagation of the light rays $\mathbf{e}_1$ is shown in orange; black corresponds to the unit vector $\mathbf{n}$ and to the unit vector $\mathbf{t}$; blue denotes the net force **F**.

$$W(r) = W(1\ AU) \cdot \left(\frac{1\ \mathrm{AU}}{r}\right)^2$$

where $W(1\ \mathrm{AU})$ is the same energy at one astronomical unit (*AU*) from the Sun, i.e. in Earth's orbit. The quantity $W(1\ AU)$ is known as the solar constant, based on experiments, it is equal 1360 W/m^2 (the entire spectrum of solar radiation is integrated over). Knowing $W(r)$, it is possible to calculate the momentum transferred by photons per unit time through unit area orthogonal to $\mathbf{e}_1$:

$$P(r) = \frac{W(r)}{c} = P(1\ \mathrm{AU}) \cdot \left(\frac{1\ \mathrm{AU}}{r}\right)^2$$

here c – is the speed of light and $P(1\ \mathrm{AU}) \approx 4.5$ µN/m^2.

Using all the values presented above, and taking into account the specular nature of photon reflection, the total force of light pressure acting on the sail is expressed as

$$\mathbf{F}(r, \mathbf{e}_1, \mathbf{n}) = 2P(r)A\cos^2\alpha_{\boldsymbol{n}}\,\mathbf{n} = 2P(r)A(\mathbf{e}_1 \cdot \mathbf{n})^2\mathbf{n}\,.$$

This formulae contains $\cos\alpha_{\mathbf{n}}$ in the second degree, because the cosine it is responsible both for projecting the photon momentum onto the direction given by $\mathbf{n}$, and for projecting the sail area onto a plane orthogonal to $\mathbf{e}_1$ (the effective area is $A\cos\alpha_{\mathbf{n}}$).

In the language of accelerations, the acceleration of the center of mass of the entire spacecraft caused by the solar sail is

$$\mathbf{a}(r, \mathbf{e}_1, \mathbf{n}) = 2P(r)\frac{A}{m}\cos^2\alpha_{\boldsymbol{n}}\,\mathbf{n} = \frac{2P(r)}{\sigma}\cos^2\alpha_{\boldsymbol{n}}\,\mathbf{n} \qquad (1)$$

The quantity $\sigma \coloneqq m/A$, which is measured in g/m^2, is referred to as the solar sail loading and is a key engineering parameter that determines the efficiency of a solar sailing spacecraft: the lower the load, the greater acceleration the sail can provide. Mind that the mass m in the definition of solar sail loading is the mass of the entire spacecraft, not just the sail.

To abstract away from engineering parameters, the *characteristic acceleration* of a solar sailing spacecraft is introduced, it is usually denoted as a_c. The characteristic acceleration of a sailcraft is defined as the maximum magnitude of acceleration that the sail can provide at one astronomical unit from the Sun. In the case of the flat mirror, the specific acceleration can be calculated using the formulae

$$a_c = 2\frac{P(1\ \mathrm{AU})}{\sigma}$$

The characteristic acceleration is measured in mm/s^2. For the convenience of mapping the characteristic acceleration and the solar sail loading, Fig. 2 is presented. Currently, all launched sailcrafts have had characteristic accelerations of less than 0.06 mm/s^2.

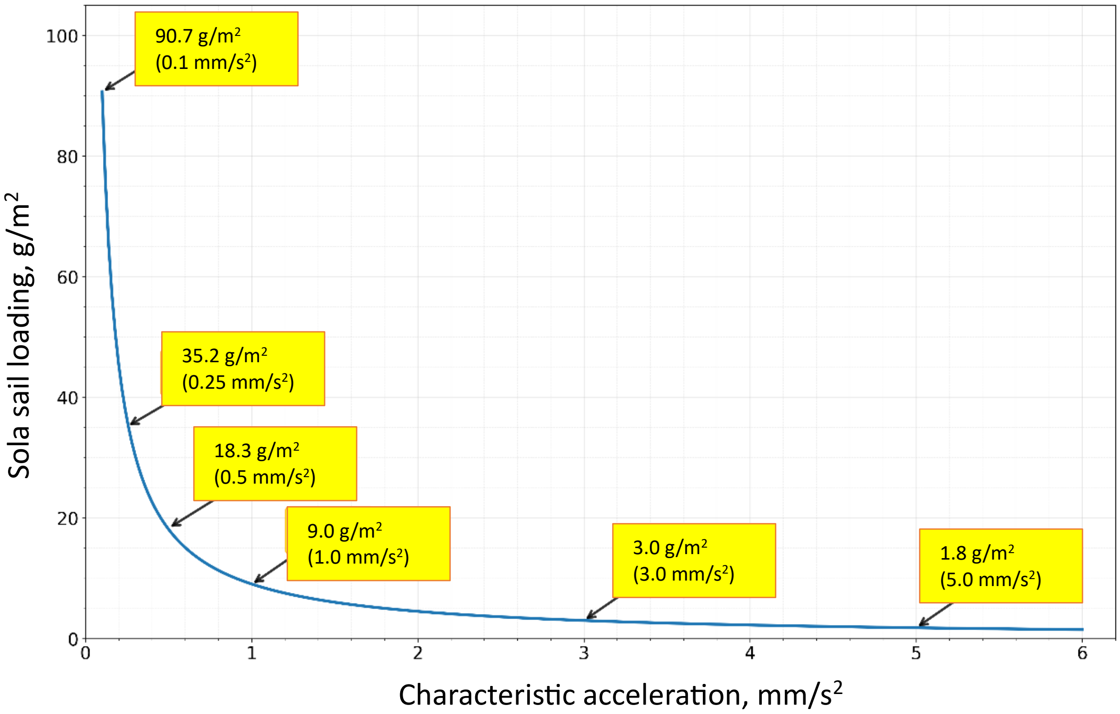

Fig. 2. Solar sail loading as a function of the characteristic acceleration (model of a flat specularly reflecting sail)

For comparison[1], the gravitational acceleration from the Sun at 1 AU is approximately 6 mm/s^2. Using the characteristic acceleration, formula (1) can be rewritten as

$$\mathbf{a} = a_c \left(\frac{1\ \mathrm{AU}}{r}\right)^2 \cos^2 \alpha_{\boldsymbol{n}}\, \mathbf{n}$$

With the concept of characteristic acceleration, it is possible to evaluate capabilities of a sailcraft without considering its actual design, mass, and sizes. This is quite convenient at the preliminary mission design phase. In this text, it is the characteristic acceleration that is used to quantify the effectiveness of solar sailing spacecrafts.

The information provided in this section should be sufficient to understand the idea of solar sailing, as well as to navigate the terms that are used throughout the text. It is worth noting, however, that real sails are neither flat nor specularly reflecting, and the Sun is not a point source. To more accurately describe how solar sails work more complex models are needed, one can acquaint with them in [61, 77, 52].

II. History of the solar sailing concept

Birth of the idea

The hypothesis that sunlight exerts pressure on bodies was first proposed in 1619 by the German scientist Johannes Kepler. While observing comets, he noted that their tails always point away from the Sun, leading him to suggest the existence of a certain “force”

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[1] Quantity $\beta = a_c \,/\, (6\ \mathrm{mm/s^2})$ is usually referred to as the *lightness number* of a sailcraft.

that pushes comets' tails away [49]. More than two centuries later, in 1873, the Scottish scientist James Clerk Maxwell, based on his theory, concluded that light carries momentum and exerts pressure on any surface with which it interacts [60]. Experimental confirmation that light exerts pressure on solid bodies was obtained in 1900 by the Russian scientist Pyotr Lebedev [53], who conducted a torsion balance experiment in a vacuum chamber and gained worldwide recognition for this achievement (he later also demonstrated that light exerts pressure on gases, thereby confirming Kepler's hypothesis).

The first ideas regarding the practical use of light pressure for exploring space originated in science fiction, as usual. As early as 1856, Jules Verne mentioned a concept of a spacecraft propelled by light rays in his novel «From the Earth to the Moon» (originally *De la Terre à la Lune*) [48, ch. 19]: "Is it not evident, then, I ask you, that there will someday appear velocities far greater than these, of which light or electricity will probably be the mechanical agent?". Another notable work anticipating solar sail technology is an adventure novel «Around the Sun» (part of the series «Les aventures extraordinaires d'un savant russe»), written in 1889 by Georges Le Faure and Henri de Graffigny. There they described spacecraft propelled by the reflection of light [7, ch. 5]: «Извольте, я выскажусь яснее. Свет есть ничто иное, как колебание эфира. Так? Прекрасно. Теперь предположим, что значительное количество таких колебаний отражено при помощи огромного зеркала, прямо по направлению к Венере, что тогда выйдет? Конечно, световые волны со страшной скоростью понесутся в пространстве и достигнут Венеры. Обитатели Луны пользуются этим, чтобы передавать звуки своего голоса, а мы воспользуемся, чтобы перенестись самим»[2].

The first more or less realistic ideas of using solar sails are commonly attributed to a student of Tsiolkovsky, a prominent Russian and Soviet pioneer of rocket technology Friedrich Zander. In his 1924 work [14], he proposed a concept of a "space airplane" for interplanetary travel. The "space airplane" would ascend through the dense layers of Earth's atmosphere like an aircraft, then be brought into space by a rocket engine, and finally maneuver in space using mirrors (or dust particles) reflecting sunlight: "Если солнечный свет упадет на зеркало, экран или пылинки, он произведет на них определенное давление. При огромных расстояниях, с которыми мы имеем дело в межпланетных пространствах, малые силы дают сравнительно большие скорости полета"[3]. However, constructing such a vehicle was impossible due to technological limitations (and it remains a challenging task even today), and Zander's idea has not been realized. Nevertheless, it is worth noting that his concept—excluding the use of dust particles and the atmospheric flight phase—corresponds, in its essence, to the modern concept of a solar sail.

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[2] Translation: Let me make this clearer. Light is nothing more than vibrations of the ether. Right? Excellent. Now suppose a significant number of these vibrations were reflected by a huge mirror, directly toward Venus. What would happen then? Of course, the light waves would travel through space at incredible speed and reach Venus. The inhabitants of the Moon use this to transmit sounds of their voices, and we will use it to transport ourselves.

[3] Translation: If sunlight hits a mirror, film, or dust particles, it will exert a certain amount of pressure on them. Given the vast distances we encounter in interplanetary space, small forces result in relatively high cruise speeds.

Development of the idea

After the initial surge of interest, global attention to solar sails declined until approximately 1950, when the concept appeared in American science fiction literature. The first American author to propose using light pressure for space propulsion was Carl Wiley (used the pseudonym Russel Saunders). In 1951, he published an article in Astounding Science Fiction [81], where he discussed the design of a realistic solar sail with great amount of technical details. Independently of Wiley, in 1958, an IBM engineer Richard Garwin published a scientific paper [38] in which he assessed—quite optimistically—capabilities of solar sails. According to his estimates, using a “relatively primitive” solar sail it would be possible to made a round-trip from Earth to Venus in less than a year. In the same work, Garwin also introduced the term “solar sail” for the first time.

A major contribution to the popularization of the solar sailing concept was made by a British writer Arthur C. Clarke, who in 1964 published a short science fiction story «Sunjammer» (also known as «The Wind from the Sun») [26]. In this story, the protagonist participates in a regatta of solar sailing “space yachts” towards to the Moon. Well received by the audience, the story was included in the anthology «World's Best Science Fiction: 1966», and eventually became a classic. For many people, it served as a first introduction to the idea of solar sailing. The story inspired scientists and engineers and sparked renewed interest in the concept.

The first project in which the application of solar sails was considered seriously was a mission to Halley's Comet, investigated at NASA in the 1970s. Its history is described in detail in [61]; here it is sufficient to say that a concept of a solar sailing spacecraft competed with a spacecraft design based on electric propulsion, leading to the formation of two “opposing” groups within NASA. The main advantage of the solar sailing concept was that, theoretically, it would allow reaching Halley’s Comet in just four years, whereas the electric propulsion would require 7–8 years (the encounter was planned near perihelion), which had a direct impact on mission development timelines. However, the solar sail project was ultimately not realized: in September 1977, NASA abandoned the idea in favor of funding the electric propulsion concept, citing a higher probability of mission success. However, shortly thereafter the electric propulsion project was also canceled due to increasing cost estimates[4].

The work on the solar sail concept for a Halley’s Comet mission stimulated worldwide interest in solar sailing. One of the most important outcomes was the establishment of the World Space Foundation in California, USA, in 1979, and the Union pour la Promotion de la Propulsion Photonique (U3P) in Toulouse, France, in 1981. Both organizations remain active to this day. Joined by the Solar Sail Union of Japan (SSUJ), founded in 1982, these organizations worked actively for many years to promote and advance the concept of solar sailing.

The next major project involving solar sails was the race to the Mars [61, 8, 3]. Marking the upcoming 500th anniversary of Christopher Columbus’s discovery of America,

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[4] Despite the cancellation of NASA's plans to rendezvous with Halley's Comet, it was nevertheless intercepted by spacecraft from the USSR («Vega-1» and «Vega-2»), Japan («Suisei» and «Sakigake»), and the European Union («Giotto»); these five spacecraft are often referred to as the "Halley armada."

the anniversary committee of the United States Congress in 1989 announced an international competition to develop solar sailing spacecrafts that would race to the Mars. The race was scheduled to begin in 1992 and was expected to last approximately 500 days. Teams from China, Japan, Italy, the United Kingdom, Canada, the United States, and the Soviet Union announced their participation. The Soviet Union was represented by a specially established consortium «Space Regatta» composed of specialists from NPO «Energia» and the «Dolgoprudny Design Bureau of Automation». Its first general director was a Corresponding Member of the Russian Academy of Sciences Vladimir Syromyatnikov, who came up with the idea of participating in the race [3]. As time passed, teams withdrew one by one due to various technical and economic challenges. One of the few teams to carry the project through to completion was the Soviet Union team. Moreover, the Soviet solar sail concept was recognized as the best among all submitted designs and received the highest score from the jury. However, the race never took place, as the organizers failed to secure funding. A hypothesis is that the expected duration of the race exceeded the time span during which a broad audience would remain engaged, thereby limiting sponsorship opportunities [61].

Despite the fact that the race did not take place, it significantly stimulated the scientific and engineering communities, driving the development of solar sails. Furthermore, the technological groundwork developed in the Soviet Union was not lost and was later used in the Russian mission «Znamya-2».

III. Maturation of solar sails: missions' historical review

Znamya-2 (1993)

A precursor to solar sails and the first project in which a large-area thin-film structure was deployed in space was the Russian experiment «Znamya-2». As part of the experiment, on February 4, 1993, a 20-meter (in diameter) thin-film structure (Fig. 3) was deployed using centrifugal forces aboard the cargo spacecraft «Progress M-15». The structure consisted of eight blades and had a total area of about 300 m² [69]. The experiment was a practical implementation of the solar sail concept previously developed by the «Space Regatta» \for the Mars race. The objectives of the experiment were [12]: validation of the overall system concept, investigation of stability and determination of system characteristics, testing of control methods for flexible structures in space, and conducting the «New Light» experiment aimed at illuminating the Earth at night.

It is important to note that although this thin-film structure was a solar sail by design, the experiment was not intended to demonstrate thrust generation via light reflection. Its primary goal was to test the feasibility of illuminating the night side of the Earth from space; that is, the deployed structure functioned as a large reflector rather than a solar sail. Nadezhda Tatarnikova, former chief designer of the «Dolgoprudny Design Bureau of Automation», commented on this [3]: «Деньги мы получили именно на разработку солнечного зайчика. Это одна и та же разработка [что и парус], просто под солнечный зайчик давали деньги, а под парус нет»[5].

The experiment was successful: the thin-film structure was deployed as planned, and for the first time in history artificial illumination of the Earth from space was achieved [12]. At dawn, a light spot of approximately 5 km in diameter passed over Western Europe at a speed of about 8 km/s; it remained visible for around 6 minutes (observations were conducted by cosmonauts aboard the «Mir» station). Despite cloudy weather conditions, numerous observers from different countries (France, Germany, Poland, Czechoslovakia) reported seeing a flash of light from space. Meteorologists at an Alpine station measured the apparent brightness of the reflector and found it to be comparable to that of the full Moon. After the experiment, the blades of the thin-film structure were detached from the «Progress» spacecraft and subsequently burned up in the atmosphere.

In 1999, an attempt was made to conduct a follow-up experiment, «Znamya-2.5», which also involved deploying a space reflector, but with a modified design and larger dimensions (25 meters in diameter). However, due to a technical error, the reflector membrane became entangled with an antenna during deployment and tore, resulting in mission failure. After this failure, funding for the program was discontinued, and no further experiments in the «Znamya» series were carried out. It has been noted, however, that the deployment system for the thin-film structure was preserved, and that experiments can potentially be resumed if there is funding [12].

Although it is not entirely accurate to describe «Znamya-2» (and «Znamya-2.5») as solar sailing demonstration experiment—it was a reflector rather than propulsion system—

Fig. 3. A photo of the unfolded thin-film structure of the «Znamya-2» experiment from the «Mir» space station. Source: S.P. Korolev Rocket and Space Corporation "Energia".

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[5] Translation: We received the money specifically for the development of the sunbeam. It's the same development [as the sail], it's just that they gave money for the sunbeam, but not for the sail.

it represents an important milestone in the development of solar sails, as it demonstrated the practical feasibility of deploying large-area thin-film structures in space.

It is also worth noting that in May 1996, the United States conducted the «Inflatable Antenna Experiment», in which a 14-meter inflatable radio antenna was successfully (though only partially) deployed in space [61]. While this project was not directly related to solar sails, inflatable structure technology was later applied in solar sail missions, making this experiment conceptually similar to the «Znamya» project.

Cosmos-1 (2005)

The first attempt to deploy an actual solar sail in space was the American–Russian project «Cosmos-1». The goal of the project was to demonstrate the feasibility of using a solar sail to control the motion of a spacecraft. In particular, it was planned to increase the semi-major axis of the spacecraft's orbit using only the solar sail. The project was initiated by the The Planetary Society, with co-funding from the American organizations Cosmos Studios and A&E Network. The spacecraft itself was developed in Russia, where it was designed and assembled by specialists from the Space Research Institute of the Russian Academy of Sciences (SRI RAN) in collaboration with the Babakin Scientific and Testing Center [37].

A small spacecraft with a mass of 98 kg was developed, of which 44 kg corresponded to the orbital platform and 54 kg to the sail system. The sail system, with a total area of 600 m², consisted of eight blades. Each blade included an inflatable tube which, when filled with gas, stretched a thin sail membrane made of aluminized Mylar with a thickness of 5 micrometers [37, 74]. Fig. 4 shows the overall sail system and a photograph of one of the blades during testing. The spacecraft was intended to be placed into a near-circular geocentric orbit with an inclination of 78° and a perigee altitude of 832 km (high enough to avoid the atmospheric drag).

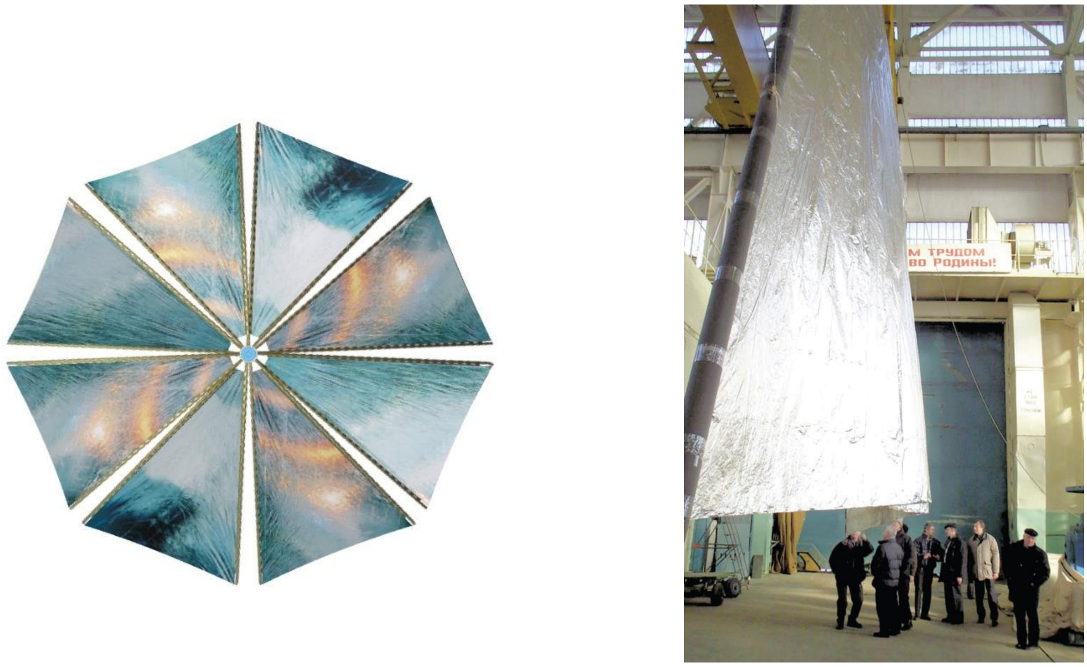

Fig. 4. A general view of the «Cosmos-1» spacecraft (left) and a photograph of one of the blades during testing (right). Source: [37, 74].

The first launch attempt of a prototype equipped with only two blades took place on July 20, 2001, from the Russian nuclear submarine «Borisoglebsk» using the «Volna» launch vehicle. However, the spacecraft failed to properly separate from the rocket, and both subsequently sank in the ocean. Despite this initial failure, a second launch attempt was made on June 21, 2005, this time with the fully assembled spacecraft and using the same «Volna» launch vehicle. Unfortunately, this launch was also unsuccessful due to an unplanned shutdown of the rocket's first stage. The second failure brought the project to an end, and no further spacecraft of this type were developed or launched.

IKAROS (2010)

The first successful mission demonstrating the capabilities of a solar sails was the renowned interplanetary mission «IKAROS» of the Japan Aerospace Exploration Agency (JAXA). The objectives of the mission were: demonstration of solar sail deployment in space, verification of generation of thrust from the solar sail, demonstration of navigation and attitude control methods for a solar sailing spacecraft, and demonstration of electricity generation using solar cells integrated into the sail [93].

Mission comprised of a small spacecraft with a mass of 310, of which 20 kg corresponded to propellant and 15 kg to the solar sail system. The sail system (Fig. 5) was a square sail with an area of 200 m² equipped with integrated photovoltaic elements (solar panels) and devices for controlling reflectivity of individual sail segments. Deployment and stabilization of the sail were achieved using centrifugal forces, with special masses attached to the sail tips. The spacecraft was launched on May 21, 2010, as a piggyback launch with the «AKATSUKI» spacecraft (also known as «Planet-C»), which served as the primary payload and was intended to enter orbit around Venus to study its atmosphere. Both spacecraft were successfully injected into a heliocentric trajectory toward Venus. After separation from the upper stage, the checkout and sail deployment phase began.

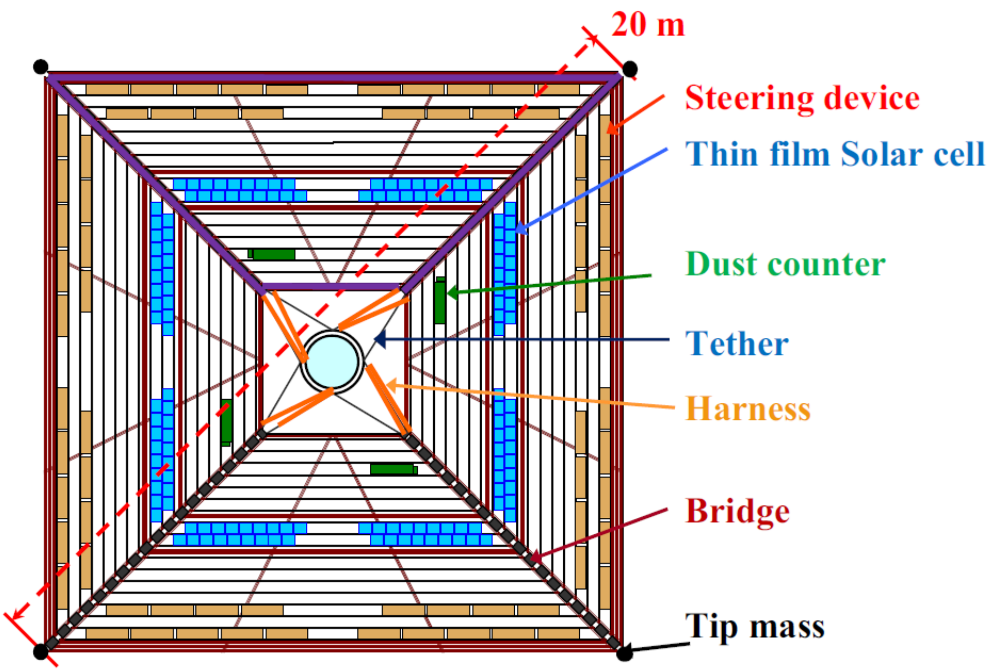

Fig. 5. IKAROS solar sail scheme. Source: [93].

Following the deployment of the sail, images of the fully deployed sail were obtained, and electricity generation by the integrated photovoltaic elements was confirmed. This was followed by a series of experiments aimed at verifying sail performance and demonstrating control capabilities [93, 64]. All tests were successfully completed—navigation data showed for the first time that the spacecraft experienced acceleration that could not be explained without accounting for light pressure. Attitude control was achieved by adjusting the reflectivity of special sail segments. The solar sail was also used to modify the spacecraft's Venus flyby conditions: while the primary spacecraft «AKATSUKI» performed a flyby over the dayside, «IKAROS», initially following a similar trajectory, passed over the nightside at a distance of 80 800 km.

At this stage, all primary objectives had been achieved, and the mission was declared a complete success; it was subsequently extended to conduct additional experiments. These included changing the direction of spacecraft rotation (to study sail dynamics under such maneuvers), as well as placing the spacecraft into hibernation mode and later recovering it. The hibernation experiment yielded particularly notable results. The transition to hibernation was forced, as due to the natural dynamics of the solar sail the spacecraft gradually turned away from the Sun, preventing its solar panels from generating sufficient power. As a result, the spacecraft was placed into hibernation for approximately six months (from December 2011 to July 2012), and communication with it was lost for about nine months (until September 2012). Despite the absence of navigation data during this period, communication was successfully re-established based solely on theoretical predictions of the spacecraft's position and attitude. This experiment demonstrated the practical accuracy of the applied dynamical models for solar sail spacecraft, both in terms of orbital motion and attitude dynamics.

The IKAROS mission was a milestone in the field of solar sailing. It demonstrated the fundamental feasibility of solar sail propulsion and showed that the behavior of solar sails of the IKAROS type (flat, spinning) can be accurately described by existing theoretical models. In addition to confirming these fundamental principles, the mission also tested innovative technological solutions that paved the way for subsequent solar sail missions.

LightSail-1 & 2 (2015, 2019)

As a continuation of the unsuccessful «Cosmos-1» project, The Planetary Society initiated a new project called «LightSail». The goal of the project remained the same—to demonstrate capabilities of a solar sail in Earth orbit. However, this time it was decided to limit the mission to a 3U CubeSat with a mass of about 5 kg. The project began in 2009 and was funded primarily through public support: a Kickstarter campaign was launched, with contributions coming from community members and space enthusiasts.

In 2015, after a prolonged period of delays and launch arrangements, the first test spacecraft «LightSail-1» (originally «LightSail-A») was launched into orbit as a secondary payload. Despite the overall success of the mission, the spacecraft did not demonstrate solar sail propulsion, as it was placed into a low Earth orbit (perigee 356 km, apogee 705 km, inclination 55°). At such altitudes, the effect of solar radiation pressure on the sail was negligible compared to atmospheric drag. Nevertheless, the mission enabled testing of all key technologies, including sail deployment, and provided valuable operational experience. The knowledge gained was later used in preparation for the next mission [75].

The second spacecraft, «LightSail-2», was launched as a secondary payload on June 25, 2019, into a near-circular orbit at an altitude of approximately 720 km with an inclination of 24°. After orbital insertion and system checkout, a solar sail with an area of 32 m² (Fig. 6) was successfully deployed. The next step was to demonstrate controlled orbital motion using the solar sail—the spacecraft was expected to increase the apogee of its orbit using solar radiation pressure.

To achieve this, the following sail control strategy was employed: near perigee, the sail was oriented toward the Sun to maximize acceleration along the velocity vector, while near apogee it was turned away from the Sun to minimize acceleration opposing the motion. Under this control law, the evolution of perigee and apogee altitudes followed the trend shown in Fig. 7, confirming that the solar sail was indeed modifying the orbit in the desired manner. At this point, the primary objective of the mission was achieved, and the mission was declared successful. No further solar sail spacecraft have been developed by The Planetary Society since then.

NEA Scout (2022)

The first, albeit unsuccessful, attempt to use a solar sail for scientific research rather than purely for technology demonstration was the «NEA Scout» (Near-Earth Asteroid Scout) mission developed by NASA. The primary objective of the mission was to demonstrate the feasibility of using small, low-cost spacecraft for asteroid exploration with a solar sail as the main propulsion system. From a scientific perspective, the mission aimed to address

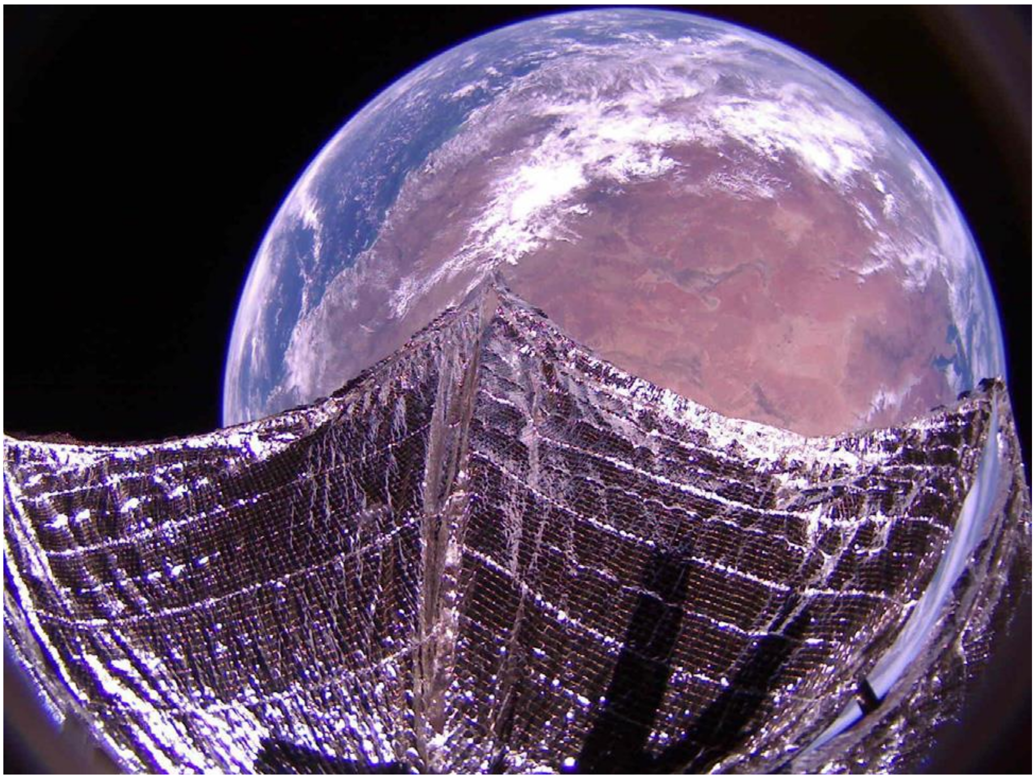

Fig. 6. Deployed solar sail of the «LightSail-2». Source: [84].

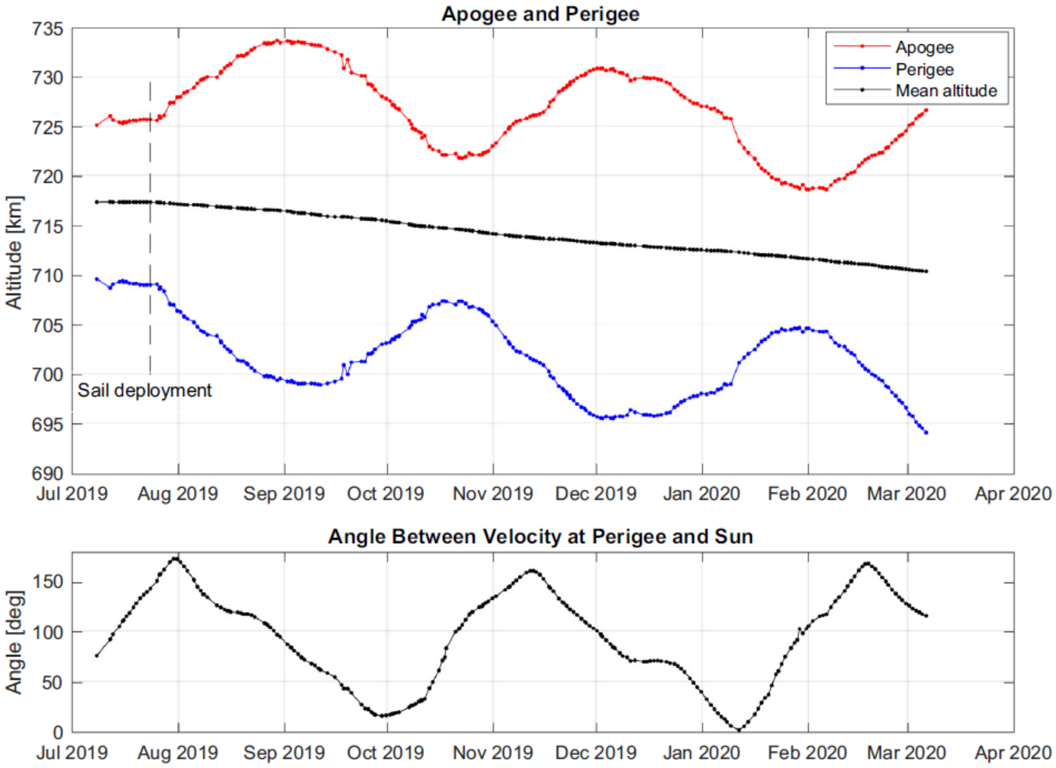

Fig. 7. Evolution of periapsis, apoapsis, and the angle between the velocity at periapsis and the direction of the Sun for the «LightSail-2». Source: [84].

gaps in knowledge about small near-Earth asteroids by imaging the surface of one of them during a flyby at a sufficiently low relative velocity (< 20 m/s). In particular, for asteroid 2020 GE—the primary target of the mission—the following parameters were to be determined or refined: orbit, size, mass and density, rotation rate, surface morphology, and characteristics of the surrounding environment (e.g., dust near the asteroid). The mission was intended to contribute both to the accumulation of scientific knowledge about asteroids, necessary for future missions, and to the development of small spacecraft technologies for asteroid exploration, including solar sail technology.

For the mission, a 6U CubeSat with a mass of about 14 kg was developed. It was equipped with a miniature camera (with a mass of about 400 g) intended for imaging the asteroid surface during the flyby, as well as for navigation during the approach phase. To provide propulsion and control of the spacecraft’s center-of-mass motion, a solar sail with a total mass of about 2 kg and an area of 86 m² was used [56]. Notably, in its stowed configuration, the sail together with its deployment system occupied only about two liters of volume (Fig. 8).

It is worth noting that the decision to use a solar sail was not merely driven by the desire to implement this technology: due to the limited volume of the spacecraft and other constraints, alternative propulsion systems were not feasible [56, p. 30]. Thus, this mission was to become the first in which a solar sail would be used not for demonstration purposes, but as the primary propulsion system enabling scientific research.

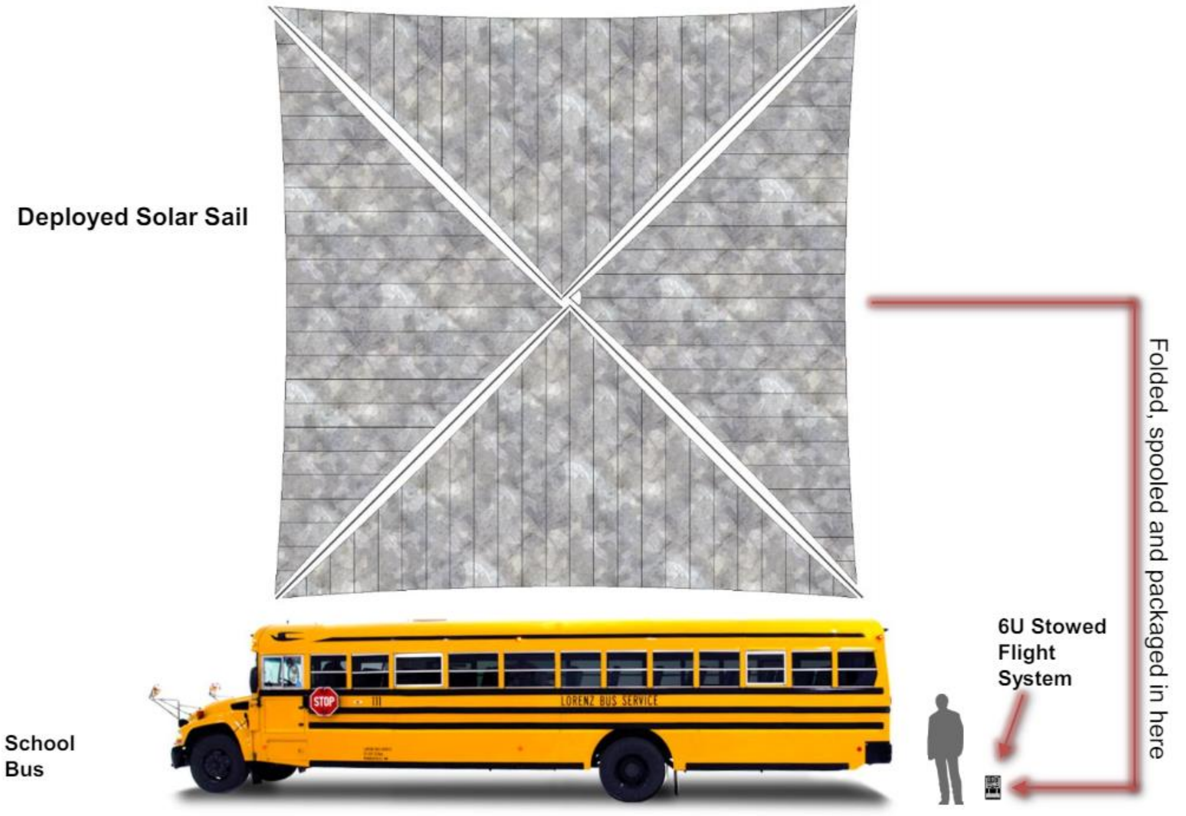

Fig. 8. NEA Scout's solar sail compared to other objects. Source: [56].

The spacecraft was launched on November 16, 2022, as a secondary payload of the Artemis I mission. According to the plan, it was to separate from the upper stage and proceed toward a rendezvous with the near-Earth asteroid 2020 GE. However, after separation, communication with the spacecraft was not established; currently the mission is considered lost [32].

ACS3 (2024)

The most recent mission involving a solar sail is the «Advanced Composite Solar Sail System» (ACS3), in which NASA, in partnership with other organizations, developed and launched a 12U CubeSat of the same name equipped with a solar sail. The primary objective of the mission was to demonstrate and investigate a solar sail deployment technology based on deployable composite booms. In addition, the mission aimed to demonstrate the capability to raise and lower the spacecraft's orbit using a solar sail, as well as to study the dynamic behavior and oscillations of the sail. The mission was considered a precursor to the future «Deployable Composite Booms» (DCB) mission, in which it is planned to deploy a sail with an area of several hundred square meters [102].

The ACS3 spacecraft is a 12U CubeSat with a mass of approximately 16 kg, of which about 7.7 kg corresponds to the sail system (membrane, booms, and deployment mechanism). The sail area is 80 m², and the membrane has a thickness of 2.115 micrometers, consisting of aluminized and chromium-coated PEN film [101]. The spacecraft was launched on April 23, 2024 [80] into an orbit at an altitude of about 1000 km [2]. Later, in October 2024, images were released confirming successful deployment of the sail. However, since the spacecraft's attitude control system was turned off during deployment, the spacecraft began to rotate slowly, and further experiments were postponed until full attitude control could be restored [36]. As of March 2026, no official updates on the spacecraft status or its experimental results have been published. Therefore, it remains unclear whether the spacecraft has been successfully stabilized and whether orbital changes using solar radiation pressure have been achieved; results of conducted experiments have also not been disclosed.

Related missions

The missions discussed above include only those that demonstrated or were intended to demonstrate control of the spacecraft's center-of-mass motion using solar radiation pressure (with the exception of «Znamya-2» and «LightSail-1»). However, there are also missions in which large thin-film structures are used for atmospheric braking. Although such systems are not, strictly speaking, solar sails—more appropriately to call them «drag sails»—the underlying technologies are essentially the same as those used in solar sails. For this reason, the development of solar sails is closely linked to the development of drag sails. The latter, however, has significantly broader commercial applications, which makes it more attractive for private companies. Due to the large number of such missions, they are not listed here; however, a presumably comprehensive list of drag sail missions can be found in [18, table 12].

IV. Solar sails applications

Solar sails have a wide range of potential space exploration applications. In some areas, they compete with chemical and electric propulsion systems, while in others they clearly outperform them, representing the most promising solution. Naturally, regardless of mission objectives, the use of a solar sail generally implies a relatively small spacecraft, as the acceleration produced by a sail strongly depends on the spacecraft mass.

Below, the currently known potential applications of solar sails are briefly reviewed; for further details, the reader is referred to the cited literature. For reference, the highest characteristic acceleration achieved to date by a launched solar sail is about 0.06 mm/s^2 (NEA Scout); more detailed information on characteristic accelerations of various spacecraft can be found in [83].

Earth orbits

Solar sails can be used for orbital transfer, orbit maintenance, and deorbiting. However, in this domain, they face strong competition from conventional chemical and electric propulsion systems.

First of all, at a distance of 1 AU from the Sun, solar sails typically provide lower thrust levels than electric propulsion systems, which results in longer maneuver times. For example, a 50 kg spacecraft equipped with an SPD-50M thruster with a thrust of up to 18 mN [1] (corresponds to an acceleration of approximately 0.36 mm/s^2) can transfer from a circular low Earth orbit at 650 km altitude to a circular orbit at 1300 km altitude in about 10.4 days, consuming 1.3 kg of xenon (assessments were performed using formulae from [86]). In contrast, performing a similar transfer using a solar sail with a characteristic acceleration of 0.36 mm/s² would take about 22 days [63], roughly twice as long (atmospheric drag neglected). This is due to the fact that the thrust generated by a solar sail depends on its orientation, resulting in an average thrust being significantly lower than its maximum value, whereas electric propulsion systems do not exhibit this limitation.

Second, at low Earth orbits, solar (drag) sails can be used effectively primarily for deorbiting, since atmospheric drag significantly exceeds solar radiation pressure. The minimum altitude at which solar radiation pressure can overcome atmospheric drag depends on solar activity and typically lies between 600 and 1000 km [63].

Nevertheless, the above does not imply that solar sails are useless in near-Earth space. They have already proven useful for deorbiting applications [95] and can also be used for maintaining high-altitude orbits [25]. Solar sails enable unique mission concepts such as “pole-sitter” missions, which require continuous thrust to maintain non-Keplerian orbits [22]. In addition, solar sails may be the only viable option for missions where spacecraft size constraints prevent the use of conventional propulsion systems with sufficient propellant storage, as was the case for «NEA Scout».

Cislunar space

In cislunar space, solar sails become more competitive with conventional propulsion systems. Compared to near-Earth operations, the required accelerations for maneuvers are generally lower, longer maneuver durations are acceptable, and atmospheric effects are essentially negligible.

Using a solar sail, a small spacecraft can be transferred from a high Earth orbit to an arbitrary lunar or libration orbit within the Earth–Moon system using virtually no propellant (aside from minor usage for attitude control). Naturally, this “propellant-free” transfer comes at the cost of time. For example, transferring from a geostationary transfer orbit to a lunar orbit with a solar sail providing a characteristic acceleration of 0.58 mm/s² would take on the order of 300 days [67], whereas a spacecraft equipped with an electric propulsion system of comparable thrust could complete the transfer in less than 200 days. The transfer duration depends not only on the characteristic acceleration, but also on the control strategy and the initial and final orbits.

Solar sails can also be used to create and maintain lunar and libration orbits within the Earth–Moon system, as well as to transfer between them. For instance, it has been shown that even with relatively low characteristic acceleration (on the order of 0.05 mm/s²), a solar sail spacecraft can maintain low polar lunar orbits [24]. There is also a substantial body of research on maintaining libration orbits [45] and transferring between them [40].

Importantly, solar sails enable not only the maintenance of trajectories that exist within the classical circular restricted three-body problem (Earth–Moon–spacecraft), but also the creation of entirely new, non-Keplerian trajectories that arise only when continuous forces such as solar radiation pressure are taken into account. In the classical formulation of the circular restricted three-body problem (whether Earth–Sun–spacecraft or Earth–Moon–spacecraft), only five equilibrium (libration) points exist. However, when solar radiation pressure is included, entire continuous surfaces emerge on which a solar sail spacecraft can “hover” (for the Earth–Moon system, these surfaces depend on the Sun’s phase) [62]. Points on these surfaces are often referred to as *artificial libration points*.

Similarly, solar sails enable so-called artificial orbits [42, 15], some resembling classical libration orbits and others differing significantly. A notable special case is the class of orbits known as «pole-sitter» orbits, in which a spacecraft remains continuously above the north or south pole of a celestial body (e.g., the Moon), enabling continuous observation and communication with that region. Such orbits do not exist in either the two-body or three-body problem and require continuous thrust, which can be provided by a solar sail [67].

Near-Earth deep space

Continuing the previous discussion, solar sails can be effectively used for “nearby” missions beyond Earth’s gravitational sphere of influence, such as missions to Sun–Earth libration points, near-Earth asteroids, and similar targets.

As in the case of cislunar missions, a solar sail can be employed to transfer a spacecraft from a high Earth orbit beyond Earth’s gravitational sphere of influence [58]. Once there, the sail can be used to create and maintain libration point orbits [20, 17, 35], as well as heliocentric trajectories such as Earth-following (or Earth-trailing) orbits [43, 71]. One important application of such “artificial” orbits and libration points is solar observation missions aimed at early detection of solar flares and geomagnetic storms [46, 43]. Solar sails are also widely considered promising propulsion systems for missions to near-Earth asteroids [68]; in particular, the NEA Scout mission discussed earlier was specifically designed for this purpose. A separate and more speculative application is the concept of a SunShield, intended to reduce the flux of solar radiation reaching Earth in order to mitigate global warming caused by the greenhouse effect [59, 27].

Interplanetary missions

A large body of work exists on solar sailing missions to asteroids, as well as to Mars, Venus, Mercury [29, 54, 103, 13, 85, 11, 4], and even to the Sun itself [57]. It is in this domain that solar sails truly reveal their potential and begin to significantly outperform both chemical and electric propulsion systems.

Their advantage arises from the fact that solar radiation pressure inversely depends on square of the distance from the Sun. As a result, the acceleration produced by a solar sail increases substantially as the spacecraft approaches the Sun. For example, for a sail with a characteristic acceleration of 1 mm/s^2, the maximum acceleration near Mercury’s orbit would be approximately 6.7 mm/s^2. Thus, solar sails become more effective closer to the Sun, whereas electric propulsion systems do not exhibit such behavior. Consequently, solar sails can, in principle, enable faster transfers to inner planets such as Mercury and Venus compared to conventional propulsion. For instance, a heliocentric Earth–Mercury transfer using a solar sail with a characteristic acceleration of 0.2 mm/s^2 would take on the order of 4 years [29], whereas the estimated transfer time of the BepiColombo mission, which relies on electric propulsion and multiple gravity assists, is about 8 years [34].

However, it should be noted that this advantage diminishes for missions to Mars and beyond. As heliocentric distance increases, solar radiation pressure decreases, making solar sails comparable to—in some cases even less efficient than—electric and chemical propulsion systems in terms of transfer time [61].

Outer Solar System and interstellar space

Despite seeming counterintuitive, solar sails also open pathways to missions in the outer Solar System and even beyond. The key concept underlying such missions is the use of *Sundiver* trajectories. These trajectories enable spacecraft to enter hyperbolic escape paths, allowing rapid travel to large heliocentric distances. The defining feature of a Sundiver trajectory is a close solar flyby–ranging from a few solar radii to approximately 0.2 AU, –during which a solar sail spacecraft can significantly increase its heliocentric orbital energy by combining the Oberth effect with intense solar radiation pressure.

As a result of such a maneuver, a solar sail with a characteristic acceleration of, for example, 1 mm/s^2 can achieve hyperbolic excess velocities of up to 20 AU/year for a perihelion distance of about 10 solar radii, and about 5 AU/year for a perihelion distance of around 50 solar radii [70, fig. 4]. At such velocities, a spacecraft could reach a distance of 100 AU in less than 5 or 20 years, respectively.

Proposed applications of such trajectories include: rapid flyby missions to distant Solar System objects, interception of interstellar objects (such as 1I/'Oumuamua or 3I/ATLAS), deflection of potentially hazardous asteroids, exploration of the heliosphere and nearby interstellar space, reaching the focal region of the Sun's gravitational lens, testing general relativity, and conducting other advanced scientific experiments [94, 31].

Although this direction is undoubtedly the most futuristic, it has been studied in considerable detail from the view of practical feasibility. These studies suggest that such missions could be realized using current state-of-the-art technologies and those under active development [44].

V. Technologies of solar sailing

A spacecraft equipped with a solar sail is aquite complex technological system comprising numerous subsystems. This section outlines the key technological and scientific areas whose development is essential for enabling solar sailing mission

Engineering aspects

Sail membrane

The sail membrane must be lightweight, exhibit high reflectivity on one side and high emissivity on the other, and be resistant to various forms of damage and degradation. The overall efficiency of a solar sail spacecraft is primarily determined by its (effective) areal density: as follows from Eq. (1), the characteristic acceleration depends on the ratio of sail area to total spacecraft mass.

The total mass consists of the sail membrane mass (proportional to the square of the characteristic sail size), the mass of the supporting structure (proportional to the first power of the characteristic size), and the mass of the payload and all other spacecraft components. Denoting the characteristic sail size by l, the areal density of the sail membrane by σ_{mem}, the linear density of the structural elements (spars and rigging[6]) by ρ_{rig}, and the payload plus bus mass by m_{pl}, one obtains the following expression for the area-to-mass ratio A/m:

$$\frac{A}{m} = \frac{l^2}{\sigma_{mem}\, l^2 + \rho_{rig}\, l + m_{pl}} < \frac{1}{\sigma_{mem}} = \lim_{l \to +\infty} \frac{A}{m}.$$

Thus, even if the sail size were increased indefinitely (in theory), the area-to-mass ratio would remain bounded, and consequently, the characteristic acceleration cannot grow unlimitedly. The upper bound for a_c is determined by the level of available technology: the thinner and lighter the sail membrane, the higher the achievable acceleration (in the limit). At present, typical values of sail areal density range from 2 to 20 g/m^2. A more detailed discussion of achievable values and materials can be found in [39], while scalability study is presented in [92].

It is also worth noting the growing interest in so-called *diffractive solar sails* [91, 87, 88, 28]. Such sails employ surfaces analogous to diffraction gratings, generating thrust not through reflection but via diffraction and interference of light. This enables more effective generation of transverse thrust compared to conventional reflective sails. For example, when a flat reflective sail is oriented directly toward the Sun, it produces thrust purely along the Sun–spacecraft line. In contrast, a diffractive surface can generate an additional component in the transverse direction. In practice, this can be advantageous for missions requiring transverse thrust, such as orbital phasing, orbit raising in low Earth orbit (where diffractive sails may operate effectively at lower altitudes than reflective sails), or formation flying [91, 33, 73].

Sail stowage and packaging

While the sail must have a very large area in its deployed configuration, it must be compactly stowed during launch and transport. A demonstrative example is the NEA Scout mission (fig. 8): its sail had a characteristic size of over 9 meters when deployed, yet in its stowed configuration it occupied a volume of only about two liters (including the deployment system) [56].

The method of folding the sail affects not only its stowed dimensions but also its mechanical properties [69]. During long-term storage, the material may adhere along fold lines and become damaged during deployment. The folding pattern influences stress distribution during deployment, as well as the formation of wrinkles in the deployed membrane, which in turn affects the thrust produced by the sail. Therefore, the folding strategy has a significant impact on the sail's in-orbit performance and must be carefully designed. To date, a wide variety of folding schemes have been proposed, including approaches inspired by origami. A concise overview of these methods can be found in [69].

Sail deployment system

Solar sail deployment is typically accomplished using one of two classical approaches. The first method relies on centrifugal forces. Technically, this is a relatively simple approach: small masses are attached to the sail tips, the spacecraft is spun about a designated axis, and

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[6] On sailing vessels, spars are the general name for the above-deck structures used for setting and carrying sails; rigging is the general name for all tackle (ropes, cables, etc.) on a vessel used for securing and controlling sails and spars.

the sail deploys under the action of centrifugal force. This method was used, for example, in the IKAROS mission. An obvious limitation of this approach is that once the centrifugal force is reduced or removed, the sail may deform due to spacecraft maneuvers or thermal effects, since it lacks a rigid supporting structure. If the spacecraft continues spinning continuously, it effectively behaves as a gyroscope, which significantly influences its attitude dynamics.

The second method involves deployment and tensioning of the sail using «booms» [7]. This approach is more technically complex. A central unit contains the «booms» in a stowed configuration (typically coiled, folded, or rolled hollow tubes made of lightweight materials). The sail segments are attached to the ends of these booms, while the folded membrane is stored around the central unit. During deployment, the booms extend outward, stretching the sail segments. Boom extension can be achieved in various ways: via mechanical actuators, by inflating the booms, or passively through the release of stored elastic energy. Once fully deployed, the sail is held in place in three-dimensional space, allowing the spacecraft–sail system to be approximated as a rigid body to a certain extent. A photographic example of such a deployment process can be found in [102], while a more detailed overview of deployment methods is given in [69].

Attitude and trajectory control mechanisms

Controlling a solar sail spacecraft involves controlling both the thrust force generated by the sail, which governs the motion of the center of mass, and the torque acting on the spacecraft, which governs its rotational motion. Since the thrust depends on the sail's orientation relative to the Sun, controlling the thrust is effectively equivalent to controlling the spacecraft's attitude.

Various methods can be used to generate control torques and achieve the desired attitude dynamics. These include: attitude control thrusters, gyroscopes and reaction wheels, sail segments with adjustable reflectivity, mechanisms for shifting the center of pressure relative to the center of mass (e.g., by moving ballast masses), articulated sails capable of rotation, sails with variable geometry, and auxiliary tip sails (analogous to mizzen sails on maritime vessels), etc.

For example, the IKAROS mission employed gas thrusters and variable-reflectivity elements embedded in the sail for attitude control [93, 64]. The NEA Scout mission planned to demonstrate torque control via internal mass shifting and also included four reaction wheels [56]. The ACS3 spacecraft is equipped with four reaction wheels and several magnetic torque rods for attitude control [102].

The choice of a particular control method depends on numerous factors, including mass and volume constraints, mission environment, and engineering considerations.

Integration with other spacecraft subsystems

The overall efficiency of a solar sail system can be significantly improved by integrating components of other spacecraft subsystems directly into the sail membrane. For instance, the IKAROS sail (Fig. 5) incorporated elements with controllable optical properties (for attitude control), thin-film solar cells (for power generation), and dust detectors (as scientific instruments). Such integration allows effective use of the large sail surface without

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[7] On a sailing vessel, a boom is a horizontal beam that carries the sail and is attached at one end to a mast.

significantly reducing its functional area. Potentially integrated components include solar panels, antennas, optical sensors, and elements of scientific payloads. However, this approach requires careful consideration of several factors: the placement of embedded components (taking into account the compact stowage configuration prior to launch), the routing of power and data connections across the sail, and the impact of embedded systems on the mechanical and optical performance of the sail.

Ground testing

Before launch, comprehensive ground testing of solar sail systems is essential. This includes verifying proper deployment, assessing structural loads, validating subsystem performance, evaluating the resulting sail shape after deployment (including wrinkling effects), and measuring the actual optical properties of the sail material. Such testing requires specialized infrastructure. Deployment tests typically require large, enclosed spaces (e.g., hangars), and may involve support systems to compensate for gravity. Measuring optical properties requires dedicated instrumentation such as radiometers. Examples of ground testing campaigns for solar sails can be found in [65, 55, 76, 82, 102, 101, 66], while [41] provides a detailed report on the measurement of optical properties, including reference values for key optical coefficients of solar sail materials.

Mathematical aspects

Modeling sail's optical properties

Accurate calculation of the solar radiation pressure force acting on a sail requires a realistic model of the interaction between the sail and photons of solar electromagnetic radiation. The simplest (zeroth-order) approximation is the model of an ideal specularly reflecting surface. In this model, all photons incident on a small flat sail element are perfectly reflected, resulting in a relatively simple expression for the generated acceleration. This model can be refined by introducing an efficiency coefficient with values between 1 and 2 [9], yielding a non-ideal specular reflection model. In this case, reflection is still purely specular, but photon losses due to absorption by the sail are taken into account.

A more advanced approach is the optical model of the sail, which includes not only specular reflection but also diffuse reflection and thermal emission from both the front and back sides of the sail. In such a model, the expression for the force acting on a sail element becomes significantly more complex (see [61]). Unlike the simpler models—where the force is always directed along the surface normal—the optical model introduces a tangential force component. The parameters of the optical model depend on the sail material and must be determined experimentally. However, relatively few experiments on sail optical properties have been conducted [41, 97], and the validation of available data remains an open issue.

It is important to note that all these models rely on simplifying assumptions that may limit their accuracy. For example, the optical model typically assumes a continuous membrane (i.e., no perforations or discontinuities) and constant optical coefficients. In reality, optical properties may depend on the angle of incidence (anisotropy), and they may change over time due to material degradation caused by solar radiation and the solar wind. If the sail membrane is not continuous—for example, if it is perforated—then conventional optical models become insufficient, and diffraction and interference effects must be taken into account.

Modeling of forces and torques

The forces and torques generated by a solar sail depend on its optical properties, the direction of incident light, the distance from the Sun, and the sail's geometry. The simplest geometric model assumes an ideally flat sail. In this case, the force is described by a relatively simple expression, and the center of pressure coincides with the geometric center. The exact shape of the sail is not critical in this approximation, though simple geometries such as triangles, squares, rectangles, or circles are typically considered.

When the sail cannot be assumed perfectly flat, a more general approach is required—commonly referred to as the generalized or tensor model of the solar sail [77]. In practice, it is also important to account for wrinkles and deformations, which are the subject of dedicated studies [72, 10, 5].

Standard models typically neglect multiple reflections of sunlight and shadowing effects between different parts of the sail or spacecraft. When such effects become significant, the only viable approach is numerical integration over the sail surface, discretized into small elements.

In addition to sail geometry, the resulting forces depend on the intensity of solar radiation, which can also be modeled at different levels of fidelity. The simplest approach treats the Sun as a point source. While often sufficient, this approximation can be refined by accounting for the finite size of the Sun and limb darkening effects. A more detailed discussion can be found in [61, 52].

Another important aspect is the interaction between the sail and the solar wind[8]. Although the sail is initially electrically neutral, exposure to solar radiation and charged particles can lead to the accumulation of static charge. As a result, electromagnetic forces from the solar wind may act on the sail, and internal tension may arise due to charge repulsion [50]. This effect is particularly important for missions involving close solar approaches, where both radiation intensity and particle flux increase as distance from the Sun decreases.

Modeling of sail structural dynamics

As discussed earlier, solar sails are often modeled as flat surfaces or, more generally, using tensor-based representations to capture the effects of shape and optical properties on generated forces and torques. In reality, the sail is not only non-flat but can also change its shape over time.

Such deformations may arise due to various factors: spacecraft attitude dynamics, actively controlled shape (controlled elements), radiation pressure, electrostatic effects, thermal deformations, gravity-gradient forces, and local changes in material properties due to degradation. If these changes occur slowly (over months or years), they can be incorporated by periodically updating sail parameters within existing models. However, in some cases—especially with active control—the sail shape may evolve much more rapidly

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[8] The term «solar wind» refers to a stream of charged particles emanating from the Sun. It consists primarily of electrons, protons, and alpha particles.

(with characteristic frequencies on the order of 0.1–1 Hz [19]). This leads to the need for dynamic modeling of the sail membrane over time. Examples of studies on sail structural dynamics can be found in [96, 23, 19, 6].

Modeling of sail degradation

During flight, a solar sail is exposed to space radiation and the solar wind, leading to changes in the material properties of the membrane and, consequently, affecting the spacecraft dynamics [79]. This process is commonly referred to as *sail degradation*, because in most cases these changes are detrimental to mission performance.

A significant number of theoretical and experimental studies have been devoted to this topic. For example, [30] presents a parametric degradation model that is widely used in simulations due to its relative simplicity. The physical processes governing the interaction between the sail material, space radiation, and the solar wind are discussed in detail in [50]. A separate line of research focuses on the formation of hydrogen bubbles (hydrogen blistering) within the sail material [89, 90, 51], which can further alter its structural and optical properties.

Despite the extensive body of laboratory experiments and theoretical work, it is important to emphasize that, to the best of the author's knowledge, no in-space experiments have yet been conducted to directly study solar sail degradation. As a result, the real in-flight evolution of sail properties and its impact on mission performance remain uncertain.

In-flight calibration

As discussed above, real solar sails are characterized by uncertainties in both optical and geometric parameters. Consequently, it is not possible to accurately predict sail behavior in space based solely on ground testing results. This gives rise to the problem of in-flight calibration of sail parameters. To date, only a limited number of studies have addressed this issue [78, 21, 16], with some of them [21, 16] conducted specifically in support of the ACS3 mission mentioned earlier. It is expected that this area will see increased research activity in the coming years.

Trajectory design and optimization

A substantial body of research is devoted to the trajectory design of solar sailing spacecraft. This is arguably one of the most extensive areas in the field, primarily because it allows exploration of ambitious mission concepts—such as travel to distant planets or even interstellar space—without being constrained by engineering limitations. Indeed, the number of studies on solar sail trajectory design has been steadily growing since 1951. Today, one can find works addressing missions near Earth, the Moon, and the Sun, as well as missions to other planets and beyond the Solar System. Given the sheer volume of literature, it is impractical to enumerate all contributions. Instead, the reader is referred to classical monographs [9, 61] and recent review papers [18, 69, 83, 39], which provide comprehensive overviews and extensive references.

However, it is worth noting, that the abundance of studies does not imply that all problems have been solved. Trajectory optimization for solar sails remains a highly complex task due to factors such as the wide range of possible mission scenarios, multi-revolution trajectories, nonlinear dynamics, coupling between attitude and orbital motion, limited control authority, and various engineering and operational constraints. As a result, each mission still requires detailed, case-specific analysis.

Attitude dynamics and control

Similarly, plenty of studies address the (un)controlled attitude dynamics of solar sail spacecraft. Unlike orbital motion, which can often be described using relatively simple models, attitude dynamics is influenced by a number of challenging factors: sail wrinkles and deformations (not known a priori), uncertainty in the location of the center of pressure, large moments of inertia, limited control authority, execution errors in control inputs, inaccuracies in dynamic models, constraints imposed by payload and subsystem requirements. These factors make the analysis, control law design, and stability assessment of solar sail attitude motion a highly complex and resource-intensive task. Therefore, despite the extensive literature, many problems remain open, and each specific mission typically requires dedicated analysis.

As with trajectory design, it is impractical to survey all existing works. Instead, reference is made to two classical studies [99, 100], as well as the previously mentioned review papers [39, 69], which provide further information and bibliographic resources on solar sail attitude dynamics.

VI. Current state and future outlook

Solar sails have the potential to unlock many new opportunities for space exploration (see Section IV). However, achieving this requires further technological development, as the field is still in its formative stage. To date, all successful solar sail missions have been technology demonstrators, aimed primarily at validating system functionality and demonstrating the fundamental feasibility of solar sailing. The only mission in which the sail was considered not as the purpose in itself but as a propulsion system—NEA Scout—was unsuccessful, as the spacecraft failed to establish communication after launch. Nevertheless, NEA Scout featured the highest characteristic acceleration achieved so far, approximately 0.06 mm/s^2. For solar sails to become practically effective, accelerations on the order of at least 0.1 mm/s^2 are required. For this reason, solar sails cannot yet be considered a mature, fully developed technology, and it is unlikely that the number of solar sailing missions will increase in the near-term future.

At the same time, the technology is clearly progressing. Whereas early solar sail missions were largely driven by enthusiasm, today both governmental and private organizations are actively studying and planning applications of solar (and related) sail technologies. The technology readiness level (TRL) currently ranges from about 2 (in Russia) to 8 (in the United States). For example, the American and Japanese space agencies—NASA and JAXA—have publicly available programs dedicated to the development of various types of sails, including solar sails [18, sec. 7]. In particular, the previously discussed ACS3 mission is part of NASA's program to advance sail deployment technologies, especially composite boom systems, and to test solar sails in Earth orbit, with plans to scale sail sizes up to 500 m^2. The European Space Agency (ESA) does not currently have official solar sail programs but is interested in the related technology of drag sails. Meanwhile, national agencies such as the German Aerospace Center (DLR), the French National Centre for Space Studies (CNES), and the Italian Space Agency (ASI) are investing in research related to solar sails and adjacent technologies. For instance, CNES supports the Paris-based private company Gama, which specializes in atmospheric sails and also plans to develop solar sails. More detailed information on the plans of various space agencies (NASA, JAXA, ESA, CNSA, ISRO) can be found in [18, sec. 7]. The Russian space agency, in turn, has not published any official plans related to solar or atmospheric sails. However, given the ongoing transformation and active development of the national space sector, the emergence of Russian sail-based projects in the near future cannot be ruled out. Prior experience in solar sailing projects («Znamya-2», «Cosmos-1», «Sail-BMSTU») can also contribute to the appearance of new solar sailing missions, as well as the rise of private space companies.

Summarizing the above, the following outlook for solar sails can be proposed. Under favorable conditions—most importantly, the availability of funding—solar and drag sails may occupy a distinct niche within the next 10–30 years and then be used relatively frequently for a wide range of applications. The primary focus of development will likely be on increasing sail size (and thus the characteristic acceleration) and on creating reliable, standardized technological solutions. A key milestone will be the first successful mission in which a solar sail will serve as a mean to achieve mission objectives rather than the objective in itself. Such a mission would establish an important precedent, providing a strong argument in favor of using solar sails in future missions. Without such a precedent, solar sails will continue to be perceived primarily as high-risk experimental systems driven by scientific curiosity.

Another crucial step will be the commercialization of sail-related technologies. Initially, this will likely take the form of ready-to-use drag sail modules for satellites—including CubeSats—to enable post-mission deorbiting. Bringing such technology to market will help attract funding and attention, thereby supporting further development, including non-commercial directions. To the best of the author’s knowledge, the only private company currently specializing in sail technologies is Gama [98]. Among the near-term planned missions, only three have a real chance of implementation: a successor to ACS3 (no name) [101], GamaBeta [66], and Space Weather Investigation Frontier (SWIFT) [46]—with the first two still being technology demonstrators.

In conclusion, solar sails today offer significant promise and a fertile ground for further development. However, the ultimate trajectory of the technology remains uncertain and will be determined only with time.

Conclusion

This work presents a comprehensive overview of solar sailing concept, covering in detail its historical development from early speculative ideas in science fiction to the most recent implemented missions: «Znamya-2», «Cosmos-1», «IKAROS», «LightSail» 1 and 2, «NEA Scout», and «ACS3». The fundamental operating principles of solar sails were also described, along with key scientific and engineering challenges that arise in the design of solar sailing missions. These, among others, include sail deployment mechanisms, attitude and trajectory control methods, modeling of material degradation, in-flight calibration, trajectory design, and the development of attitude control laws. The work also outlined all potential application areas of solar sails known to the author, including near-Earth missions, transportation and maintenance of non-Keplerian orbits in the Earth–Moon system, missions to other planets and near-Earth asteroids, as well as exploration of the outer Solar System and interstellar space. Finally, the author provided an assessment of the current state of solar sailing concept and outlined his vision of its future prospects. Although the technology is not fully mature, it may—though not necessarily—become common within next few decades. In that case, solar sails could provide humanity significant amount of new knowledge about universe and contribute to humanity's space expansion.

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