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Space sails for achieving major space exploration goals: Historical review and future outlook

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ABSTRACT

Space sails are a continuum of lightweight, thin, large-area, deployable technologies which are pushing forward new frontiers in space mobility and exploration. They encompass solar sails, laser-driven sails, drag sails, magnetic sails, electric sails, deployable membrane reflectors, deployable membrane antennas, and solar power sails. Some have been flight tested with operational heritage, while some are concepts planned to reach maturity in the coming decades. The number of flown and planned missions has increased rapidly in the past fifteen years. In this context, it is time to recognise the advantages of space sails for supporting the achievement of a wide range of major space exploration goals. This paper evaluates, for the first time, synergies between the broad spectrum of space sail technologies, and major space exploration ambitions around the world. The study begins by looking to the past, performing a global, historical review of space sails and related enabling technologies. The current state of the art is mapped against this technological heritage. Looking to the future, a review of major space exploration goals in the next decades is conducted, highlighting domains where space sails may offer transformational opportunities. It is hoped that this paper will further the ongoing transition of space sails from a promising flight-proven technology into a go-to component of space mission programme planning.

Contents

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1. Introduction

Solar sails are a mature technology for propellant-free propulsion. A lightweight reflective membrane provides a large area for receiving incident solar photons. The resulting light pressure pushes the spacecraft, allowing trajectory control [1]. Beyond solar sails, other paradigms have been proposed to harness reflective sails for driving forward new frontiers in space exploration. One is the laser-propelled sail, employing photons from a directed laser beam instead of the Sun's rays, for objectives including interplanetary and interstellar travel [2]. In a planetary atmosphere, gas particles are the medium of interest rather than photons. Lightweight deployable films provide a means of harnessing atmospheric drag in missions requiring de-orbit [3], or aerocapture, aerobraking, entry, descent, and landing [4]. When the membrane is replaced with a system of wires or tethers, used to generate a magnetic or electric field, the spacecraft functions as a magnetic sail [5] or electric sail [6]. In addition to propulsion, a deployable space membrane can be used as a reflector, to support photovoltaic power generation on Earth [7] or to support space-based astronomy as a sunshade [8] or starshade [9]. It can also be employed as an antenna, providing a lightweight unfoldable communication surface for satellites large and small [10]. Another use case is as a solar power sail, to supply lightweight power-generating areas for missions from near Earth [11] to deep space [12].

This continuum of lightweight, thin, large-area, deployable technologies which are pushing forward new frontiers in space mobility and exploration can be referred to as *space sails*. A more detailed discussion on the positioning of space sails with respect to similar terms such as gossamer space structures and lightsails is provided later in the paper. There are many apparent synergies between different types of space sail, with room to be cultivated further. The eight types of sails described above are illustrated in Fig. 1. Some have been flight tested with operational heritage, while some remain at the concept stage, planned to reach maturity in the coming decades. Against this backdrop, it is time to recognise the advantages of space sails for supporting the achievement of a wide range of space exploration goals.

As the previous examples highlight, space sailing spacecraft architectures cater to missions at Earth, in the inner and outer solar system, and even beyond. Such destinations are aligned with major space exploration goals. For instance, the NASA-commissioned report *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032* calls for a US mission to Uranus in the late 2030s [13]. The *Global Exploration Roadmap* by the International Space Exploration Coordination Group (ISECG), representing 27 space agencies and government organisations, calls for step-by-step exploration of the Moon by the 2030s and Mars by the 2040s [14]. Similarly, ESA's *Terrae Novae 2030+ Strategy Roadmap* sets out ambitions for boosting European capabilities in lunar and Mars exploration by the late 2030s [15]. JAXA's 2018–2025 *Plan for achieving Mid to Long-term Objectives of National R&D Agency Japan Aerospace Exploration Agency* identifies "Innovation in space engineering for spacecraft and space transportation systems" as one focal point of its Space Science and Technology Roadmaps for the 2020s and beyond [16]. These are only some examples of space exploration goals which could be realised by leveraging the capabilities of space sails.

On the one hand, several authoritative review studies have already been written on individual space sailing technologies, including the solar sail [1,26], laser-driven sail [27,28], drag sail [3,4], magnetic sail [5,29,30], electric sail [6,31], deployable membrane reflector [7, 9], deployable membrane antenna [10,32,33], and solar power sail [11, 34]. On the other hand, these focus mainly on principles of operation and enabling technologies. The important synergies between different types of space sail have not yet been considered in detail. In fact, understanding and availing of such synergies is essential to unlock the full benefits of space sails for future space exploration. This requires a

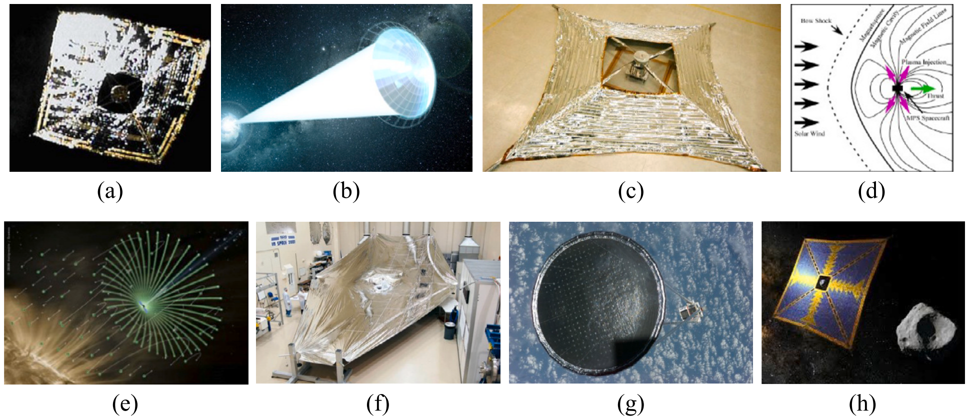


Fig. 1. Different types of space sail, with a flown or concept example of each. (a) Solar sail: IKAROS [17]. (b) Laser-driven sail: Breakthrough Starshot [18]. (c) Drag sail: De-Orbit Mechanism (DOM) [19]. (d) Magnetic sail: Magnetoplasma Sail (MPS) [20]. (e) Electric sail: E-sail [21]. (f) Deployable membrane reflector: JWST sunshade [8]. (g) Deployable membrane antenna: Inflatable Antenna Experiment (IAE) [22]. (h) Solar power sail: OKEANOS [12]. Image sources are in Appendix A.

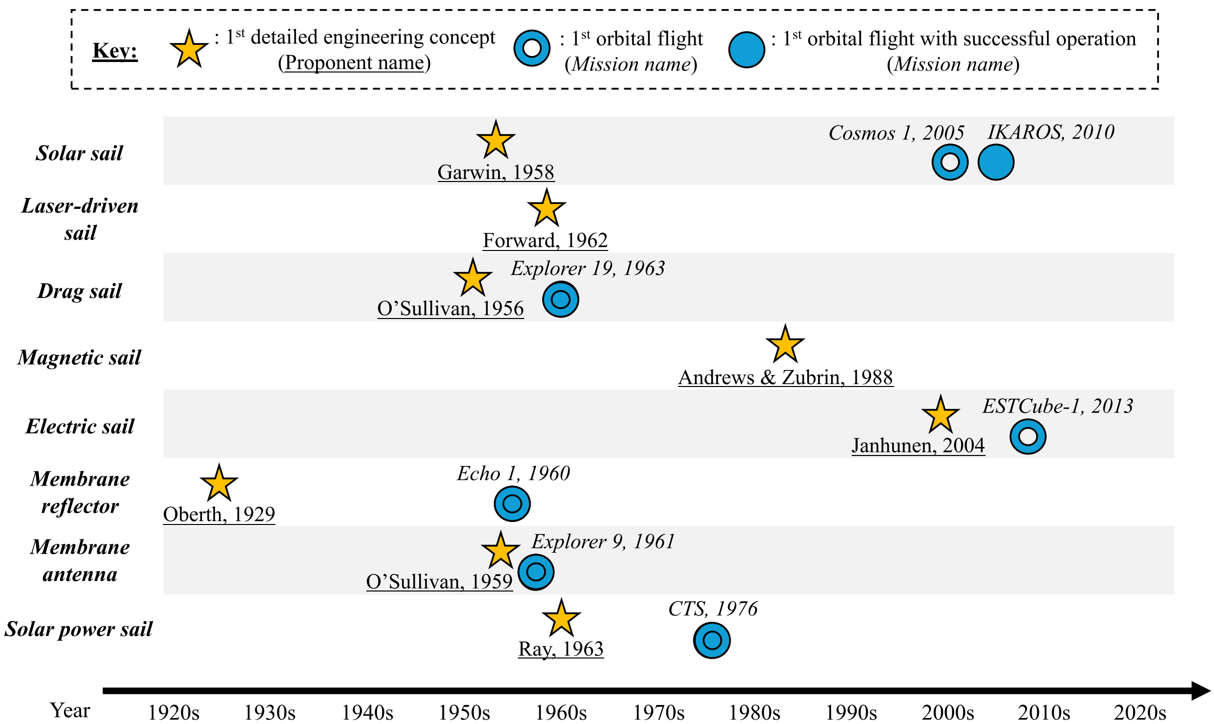


Fig. 2. Timeline of major firsts for each type of space sail. Details are provided in Section 2.1. Cosmos 1 was lost at launch vehicle failure before orbit [23]. Explorer 19 functioned as a drag sail, reflector, and antenna [24]; in this paper it is categorised as the former. The tether of ESTCube 1 was never deployed [25]. Explorer 9 functioned as a drag sail, reflector, and antenna [24]; in this paper it is categorised as the latter. To the authors' best knowledge, there have not yet been any orbital flight tests of laser-driven sails or magnetic sails.

grasp of the state-of-the-art spanning the full breadth of space sailing technologies. Moreover, to turn a promising technology into one that is used for practical space exploration, alignment with major space exploration goals should be assessed. In response, the two main novel contributions of this trans-disciplinary review paper are: (i) to bridge between different types of space sail, re-conceptualising their development as comprising synergistic exchanges among a continuum of related technologies; and (ii) to go beyond a simple technical review, towards an inter-disciplinary assessment of space sails' past, present, and future input to the achievement of global space exploration goals.

The paper begins in Section 2 by briefly explaining the working principle and major milestones to date for each type of space sail. Then, in Section 3 a review of the state of the art around the world is performed via a catalogue of 220 space sail missions. Synergies among different types of space sail are assessed. Section 4 then shifts the focus to the future, posing the question: given space sails' promising track record, what roles may they play in driving forward the next generation of space exploration goals around the world? Domains are highlighted where space sails may offer transformational opportunities in this regard. The paper culminates in Section 5 with a global outlook on planned next steps for space sail development and utilisation, near Earth and in deep space. It is hoped that this paper will further the ongoing transition of space sails from a promising flight-proven technology into a go-to component of space mission programme planning, as a stepping stone towards new destinations and international partnerships in space.

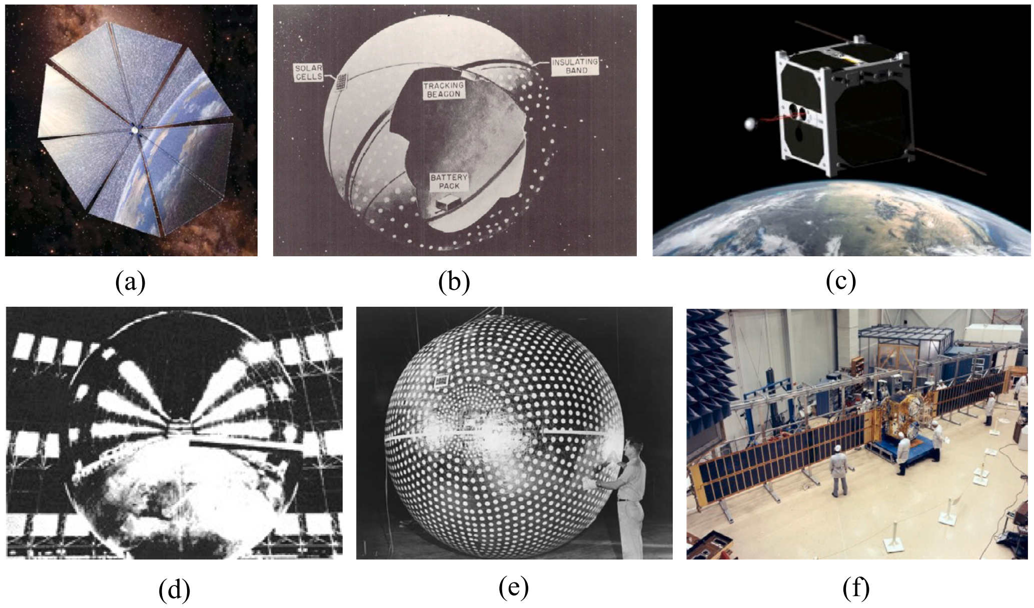


Fig. 3. First orbital flight of different types of space sail. (a) Solar sail: Cosmos 1. It was lost at launch [23]. (b) Drag sail: Explorer 19. It functioned as a drag sail, reflector, and antenna [24]; in this paper it is categorised as the former. (c) Electric sail: ESTCube 1. Its tether, shown stowed in the figure, was never deployed [25]. (d) Deployable membrane reflector: Echo 1 [24]. (e) Deployable membrane antenna: Explorer 9. It functioned as a drag sail, reflector, and antenna [24]; in this paper it is categorised as the latter. (f) Solar power sail: CTS [35]. To the authors' best knowledge, there have not yet been any orbital flight tests of laser-driven sails or magnetic sails. Image sources are in Appendix A.

2. Definitions and working principles

For each type of space sail, the working principle, important milestones, and available varieties are briefly explained. Their positioning vs. the concept of space sail is discussed, with the solar sail emerging as a convenient mid-point within the space sail spectrum.

2.1. Types of space sail

This subsection offers a high-level overview of key features of each type of space sail, as a foundation for the state-of-the-art review and synergy assessment in Section 3. The purpose is not to provide an exhaustive review of enabling principles and technologies, for which the reader is directed to the literature surveys referenced in Section 1. Fig. 2 shows a timeline of important milestones for each type of space sail. Fig. 3 depicts corresponding space sail missions.

2.1.1. Solar sail

Solar sails are thin, lightweight reflective membranes. Solar radiation pressure is exerted by the reflection of incident solar photons at their surface, producing a propulsive force [1,26]. Best performance is achieved in the inner solar system, where solar radiation pressure is highest, decaying with the square of the to-Sun distance. The idea of using solar sails for propellant-free propulsion precedes the start of space exploration [36]. The first rigorous engineering study was conducted in 1958 by Richard Garwin [37], and the first in-space demonstration was made in 2010 by IKAROS [17]. The latter is shown in Fig. 1(a). Enabling technologies have gained maturity via a series of missions including successful [38], unsuccessful [23], ongoing [39], and cancelled [40] ones. Their Technology Readiness Level (TRL) [41] for near-Earth and deep space propellant-free propulsion of small spacecraft is around 7–9. More advanced missions are being conceptualised including sundivers, intended for solar system escape after performing a near-Sun manoeuvre [42].

2.1.2. Laser-driven sail

Laser-driven sails have the same principle of operation as solar sails, except that solar photons are replaced by "synthetic" ones, e.g., from an Earth-based laser. A collimated light beam impinges on the sail, providing thrust. Significantly higher photon pressures can be achieved than for solar sails, determined by the laser source. The drawback is large mechanical and thermal stresses on the sail membrane, but the benefit is high achievable accelerations for trips to interplanetary targets, and even to interstellar distances within the duration of a human lifetime [2]. The idea of a laser-driven sail was first proposed in 1962 by Robert Forward [43], only two years after the invention of the laser [44]. Laser-driven sails are still at the concept and early experiment stage [18,45], with a TRL of 2–4 for propulsion of spacecraft in Earth orbit. No orbital flight tests have yet been made. Interestingly, as part of the first attempted orbital flight of a solar sail, by Cosmos 1, beamed microwave propulsion was considered as a potential extended mission objective, though using a non-coherent microwave beam rather than a maser [23,46].

2.1.3. Drag sail

Different from the solar sail and laser-driven sail, the working medium of the drag sail is gas in a planetary atmosphere. Gas particles collide with the deployable membrane, imparting a drag force and reducing the orbital energy. If unimpeded, this results in orbital decay and atmospheric entry. In this sense, drag sails can be viewed as propulsive devices since they provide a delta-V. Based on available information, William James O'Sullivan conceived of the earliest variant of the drag sail. In 1956, he made a proposal to measure atmospheric density at orbital altitudes in LEO using an inflatable balloon satellite, with a high area-to-mass ratio and thus high sensitivity to air drag [47]. This idea spurred the development and flight of balloon satellites for multiple applications in the 1960s. In fact, the earliest drag sails in orbit, developed as part of the Air Density Explorer series and earlier Explorer 9 mission, also functioned as reflectors and antennas [24]. Several decades later, in the early 2000s deployable conical "ballute"-type membranes for atmospheric entry were flight tested for the first time, with the aim of not simply de-orbiting satellites but of enabling their safe recovery [4].[1] Most recently, in the early 2010s planar,

[1] A contraction of balloon and parachute, the ballute refers to "any inflatable drag device for high speed deceleration", typically conical in shape [4].

lightweight drag sails for controlled de-orbit were flight tested for the first time, following on from LEO flight tests of the NanoSail-D2 solar sail [48]. They have now reached a high level of technological maturity for de-orbiting satellites of various sizes in LEO, with a TRL of 9.

2.1.4. Magnetic sail

The magnetic sail also achieves propellant-free propulsion using a medium different than solar sails and laser-driven sails: space plasma, instead of photons. A magnetic field is generated by the spacecraft using one or several current loops, and provides a propulsive force by deflecting incoming plasma [5]. The concept was proposed by Dana Andrews and Robert Zubrin in 1988 [49]. Later variations have included the Mini-Magnetospheric Plasma Propulsion (M2P2) sail and the Magnetoplasma Sail (MPS), in which the required size of current-conducting loops is reduced by using onboard plasma injection [29], though a finite amount of propellant is required. Fig. 1(d) shows an illustration of MPS. Another is the plasma magneto-shell (PMS), for deceleration and controlled atmospheric entry via interaction with a planetary atmosphere [50]. Ground-based experimental studies, such as in a plasma wind tunnel, have been conducted [29], and magnetic sails are presently at a TRL of 2 for use onboard a spacecraft in interplanetary space. Initial research into magnetic sails gained interest via promising results of magnetohydrodynamic (MHD) simulation studies, but follow-up investigations based on the particle-in-cell (PIC) and related methods showed significantly lower performance. These findings have impacted the size of the magnetic sail community and its research efforts.

2.1.5. Electric sail

The electric sail, like the magnetic sail, achieves propellant-free propulsion by deflecting incident space plasma, but using an electric field instead of a magnetic one [6,31]. The electric field is produced by charged wires or tethers. These are maintained in a taut configuration, for example by centrifugal force. The electric sail was proposed in 2004 by Pekka Janhunen for use in interplanetary space. He notes that “This work drew inspiration from (...) study of magnetic sails” [21]. In the initial concept, shown in Fig. 1(e) and called the solar wind electric sail, space plasma is provided by ions in the solar wind [21]. As a first step towards interplanetary flight, proof-of-concept experiments are being conducted in Earth orbit. In this case, plasma is provided by the ionosphere instead of the solar wind, and the resulting electrostatic force opposes the spacecraft’s motion, leading to de-orbit. This type of electric sail is referred to as a plasma brake or Coulomb brake [6,51]. The TRL of the solar wind electric sail for spacecraft propulsion in a heliocentric orbit is around 3–5, and that of the plasma brake for use onboard a spacecraft in LEO is around 5–7. Note that electrodynamic tethers (EDT) can also be used to de-orbit (and even raise the orbit of) satellites in a planetary ionosphere with a planetary magnetic field, using current-carrying tethers rather than electrostatically-charged ones [52]. In this paper, EDTs are not included within the scope of electric sails, nor of magnetic ones.

2.1.6. Deployable membrane reflector

The deployable membrane reflector, like the solar sail, is used to reflect incident photons. However, the purpose is not to provide thrust but rather to act as an electromagnetic wave relay. Deployable reflectors offer significantly larger surface areas than could otherwise be stowed inside the payload fairing of a launch vehicle. In 1929, Herman Oberth performed the first detailed engineering assessment of spaceborne deployable reflectors for illuminating the Earth’s surface [53]. Later, in 1951 Kenneth Gatland suggested using a deployable metallised paper balloon in Earth orbit to provide radar and optical reflection [54]. Shortly thereafter, in 1960 the Echo 1 inflatable metallised balloon became the first large-scale deployable space structure to orbit the Earth, performing radio wave relay [55]. It is shown in Fig. 3(d). The first flight test of a large planar membrane reflector was Znamya 2 in 1993, as a technology demonstration for beaming solar photons to Earth [56]. In the above examples, the reflector is used to redirect photons towards a target. However, it can also be used in the opposite way, to reflect photons away from a target. The sunshade and starshade (or external occulter) belong to this category. One recent example is the sunshade of the James Webb Space Telescope (JWST), shown in Fig. 1(f), which provides passive thermal control of the telescope payload by reflecting incoming sunlight [8]. Deployable membrane reflectors for multiple applications onboard spacecraft in LEO as well as in deep space are at a TRL of 9.

2.1.7. Deployable membrane antenna

The deployable membrane antenna, like the deployable reflector, can provide a larger aperture than a conventional non-deployable antenna, for a given launched payload volume. Electromagnetic waves are either passively reflected by the deployable membrane to or from an active part of the antenna, in which case it behaves as a simple reflector antenna, or actively absorbed or generated by devices on the membrane itself. The first detailed engineering design of a deployable membrane antenna was made by William James O’Sullivan. In 1959, he filed a patent for a “self supporting space vehicle” [57]. It includes a design for a parabolic reflector made of aluminised Mylar which can ostensibly be used as a reflector antenna. Indeed, although the word antenna is not used in the patent, it is categorised under “Balloon antennas” and has been cited by other patents for reflector antennas. The first orbital flight of a membrane antenna was Explorer 9 in 1961. The inflatable balloon satellite consisted of two aluminised hemispheres separated by a plastic strip, which served as antennas to transmit a radio beacon [24]. Parabolic inflatable membrane antennas have also flown in space, starting with the Inflatable Antenna Experiment, deployed from the Space Shuttle in 1996 [22]. It is shown in Fig. 1(g). Since then, diverse designs have been developed and launched, including mesh antennas [58] and reflectarray antennas [59]. Most recently, an ongoing NIAC-funded study is developing a km-scale deployable wire mesh radio antenna concept for a lunar crater telescope [60]. Moderately-scaled, deployable membrane antenna reflectors, microstrip antennas, and reflectarray antennas for use onboard spacecraft in LEO are at a TRL of 7–9.

2.1.8. Solar power sail

For the solar power sail, like the solar sail, solar photons are the medium of interest. However, rather than being used to provide a propulsive force, photons are absorbed by photovoltaic arrays on the membrane surface and provide solar-electric power. A large energy-collecting area is advantageous for applications requiring high power, or for regions of space where the available solar flux is low like the outer solar system. Kenneth Ray was one of the first to conduct research on deployable solar arrays with a flexible substrate, as part of a programme instituted in 1963 [61]. The first in-orbit deployment of a large flexible solar array was done onboard the Communications Technology Satellite (CTS) in 1976 [35], followed by the much larger Solar Array Flight Experiment (SAFE) in 1984 [62]. Building on these early developments, in the 1990s multiple Japanese institutions developed the concept of the solar power sail, going beyond a simple flexible solar array wing with rigid support structures, towards a lightweight self-supporting membrane [63]. The first in-space demonstration was made by IKAROS in 2010, which functioned both as a solar sail and solar power sail [17]. Fig. 1(h) shows the planned successor mission of IKAROS, OKEANOS [64], ultimately not selected for further development. For the purpose of this study, the term solar power sail encompasses both SAFE-type deployable solar arrays with a flexible substrate and rigid support structure, and OKEANOS-type self-supporting membranes. The TRL of the former is around 8–9 for use onboard spacecraft in Earth orbit and in deep space, while that of the latter is around 6–8 for the same use cases.

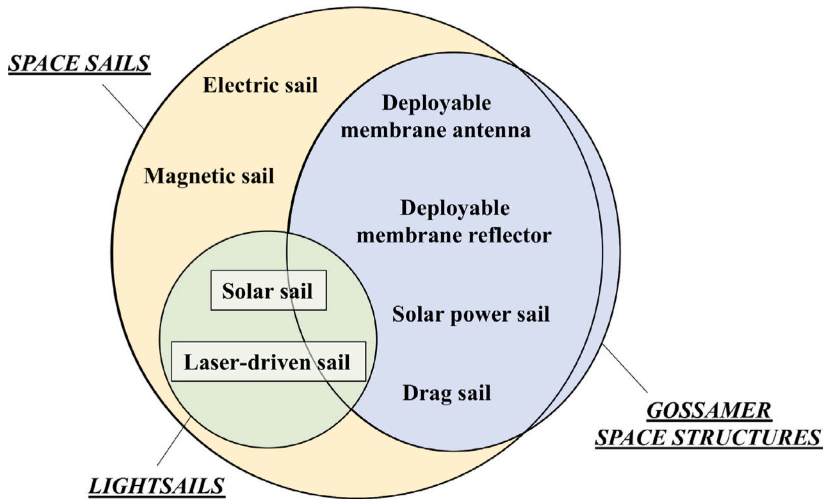


Fig. 4. Space sails, gossamer space structures, and lightsails.

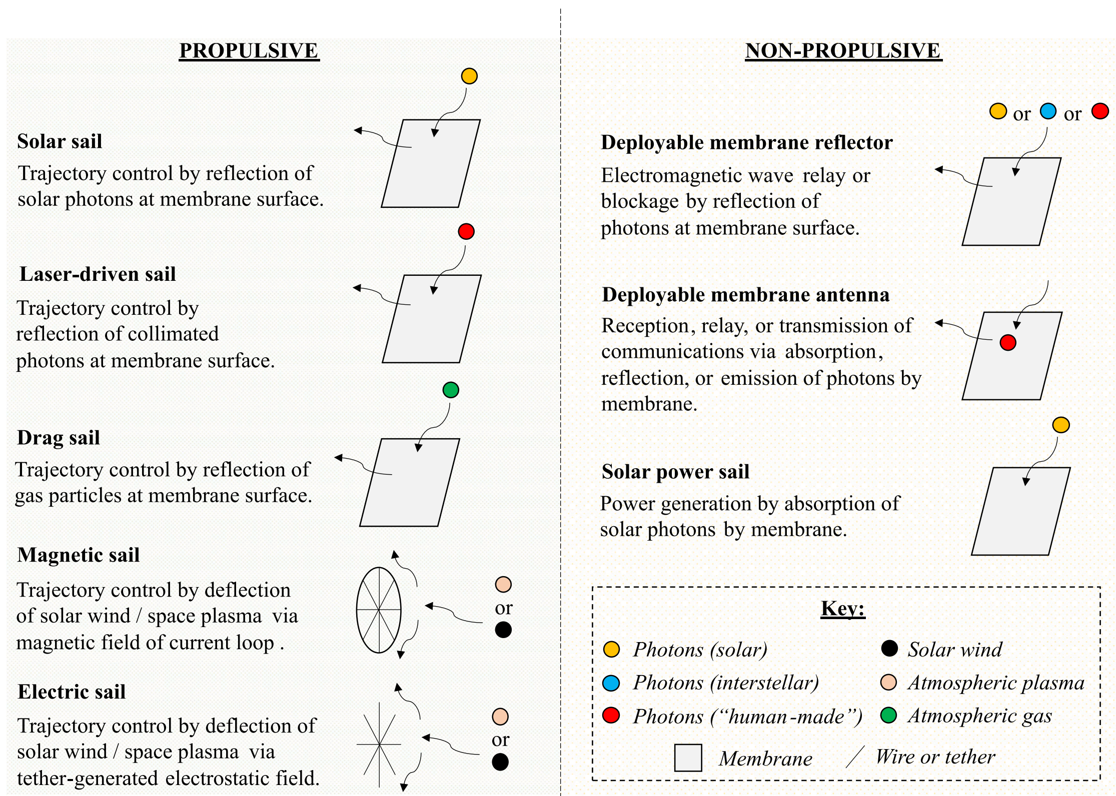


Fig. 5. Spectrum of space sail technologies, divided into propulsive and non-propulsive categories. The basic function of each is indicated. The type of medium needed for the sail to achieve its function is shown. The main structure consists either of one or several membrane(s), or wire(s) and tether(s). Drag sails are categorised as propulsive, in the sense that they provide a delta-V in a planetary atmosphere.

2.2. Concept of space sail

In the existing literature, different concepts have been used to categorise deployable lightweight membrane space technologies, from the viewpoint of structures and propulsion. These are illustrated in Fig. 4.

The first concept is the *gossamer space structure* [65,66]. It refers to "the general category of space ultra-low-mass structures, such as inflatables or many other forms of expandables", often with "the terms membrane, inflatable, and gossamer structures used interchangeably" [65]. Tether-type spacecraft without continuous membranes, like most electric sails and magnetic sails, are typically not included. Most solar sails and laser-driven sails are gossamer space structures, but some are not, like ChipSats and ChipSails, as will be discussed in Section 3. Hence, in Fig. 4 they straddle the boundary of gossamer space structures.

The second concept, related to propulsion, is the *lightsail* [45]. It refers to "a highly reflective surface that can be used to propel a spacecraft using the radiation pressure from the reflection of a strong light source" [18], including the Sun or a ground-based photon engine. Solar sails and laser-driven sails are the two main examples.

As explained in Section 1, this paper focuses on a concept broader than both gossamer space structures and lightsails: the space sail. Features and functions of this synergistic spectrum of technologies,

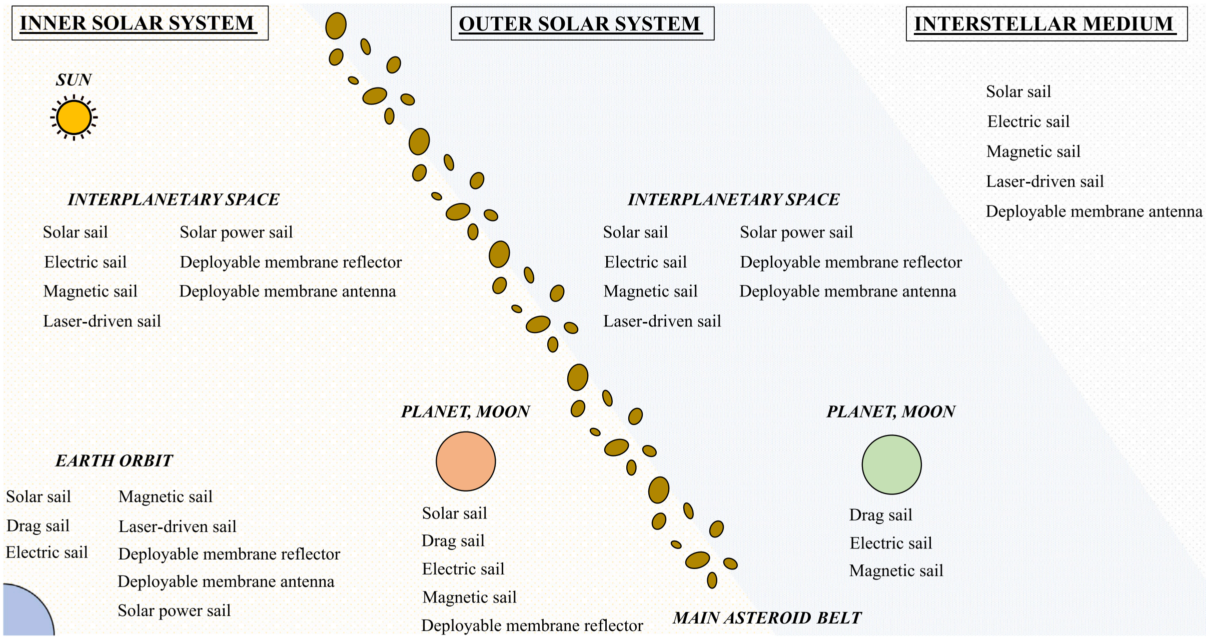


Fig. 6. Most promising space sail destinations, by sail type. Interplanetary space includes asteroids, comets, and dwarf planets.

(partially) encompassing both gossamer space structures and lightsails, as well as contiguous technologies like electric sails and magnetic sails, are summarised in Fig. 5. The distinction between propulsive and non-propulsive space sails is explored in more detail in Section 3. Note that gossamer space structures also include inflatable human habitats [67], expandable rovers [68], and so on: these are beyond the scope of space sails.

The term space sail draws attention to the role that thin, lightweight, deployable, large-area membrane technologies are playing to extend the boundaries of space mobility and exploration. This includes providing easier access to new mission types and destinations. Fig. 6 shows some of the most promising space sail destinations. In Earth orbit, the presence of an atmosphere and magnetic field offers favourable conditions for using the drag sail, electric sail, and magnetic sail. Such conditions are also found, to varying extents, at the planets Venus, Mars, the gas giants and ice giants, and at the moons Triton and Titan. In the inner solar system more generally, relatively high solar illumination provides favourable conditions for the solar sail, solar power sail, and deployable membrane reflector. Proximity to the Sun is also an advantage for electric and magnetic sail missions, taking advantage of the solar wind.

Starting from the inner solar system, sail craft equipped with a solar sail, electric sail, or magnetic sail can progressively build up a large delta-V enabling travel to the outer solar system or beyond. In this context, small bodies like asteroids in the asteroid belt, and trans-Neptunian objects (TNOs) in the outer solar system, are other candidate destinations. Mission times can be reduced by first performing a near-Sun manoeuvre, as in a sundiver solar sail mission, or via acceleration by an Earth-based photon engine, as in a laser-driven sail mission. In terms of non-propulsive sails, the large energy-collecting area of the solar power sail offers support for missions to the limit of the inner solar system and start of the outer solar system, where solar illumination remains appreciable. The deployable membrane antenna offers advantages for communication over interplanetary distances and/or within a small satellite form factor.

2.3. Solar sail: midpoint of the space sail spectrum

The shared features of space sails are illustrated in Fig. 7. Solar sails provide a convenient entry point for studying the broader spectrum of space sails, for four reasons.

The first reason is historical. The solar sail was among the first space sails to have been conceptualised. The detailed engineering concept was proposed in the 1950s, before the laser-driven sail, magnetic sail, electric sail, deployable membrane antenna, and solar power sail, as shown in Fig. 2. Although the drag sail and deployable membrane reflector were arguably conceived of earlier, planar designs only emerged later via cross-pollination with solar sails, as discussed in Section 3. In fact, even before the 1950s, in 1908 Svante Arrhenius had described the potential for solar radiation pressure to move objects across interstellar distances in the context of panspermia. Then in the 1920s, Konstantin Tsiolkovsky, Friedrich Zander, and John Desmond Bernal discussed the engineering potential of solar photon pressure as a means of propulsion for thin mirror-equipped spacecraft [69].

The second reason is that large, deployable reflective space structures often provide useful data to inform solar sail development, and conversely that knowledge of solar sailing is usually needed to predict the performance of contiguous technologies, even when photon-driven propulsion is not among the mission objectives. For instance, the earliest large-scale deployable space structures unintentionally performed solar sailing [24]. One example is the Echo-1 reflector, a large inflatable balloon satellite (see Fig. 3(d)) launched in 1960 for communications relay in space. Its orbit was markedly affected by solar radiation pressure [55]. More generally, all deployable reflective space membranes with a high area-to-mass ratio are susceptible to photon pressure-induced orbital changes, as will be seen in Section 3. Therefore, the development history of space sails has been intertwined with solar sailing from the beginning.

The third reason is that the solar sail provides a convenient "common denominator" among other space sail technologies. Of the eight space sails, the working principle of the solar sail arguably shares the most common features with the others. This is illustrated in Fig. 7. Solar sails (usually) comprise a lightweight membrane structure, like laser-driven sails, drag sails, solar power sails, and deployable membrane reflectors and antennas. They are optically reflective, like laser-driven sails and (some) reflectors. They provide propellant-free propulsion, like laser-driven sails, drag sails, (most) magnetic sails, and electric sails. Moreover, solar sails can be used in many of the same regions of space as other space sails, as shown in Fig. 6 and as discussed above.

The fourth and final reason, explained in more detail in Section 3, is that advancing the technological maturity of solar sails helps raise

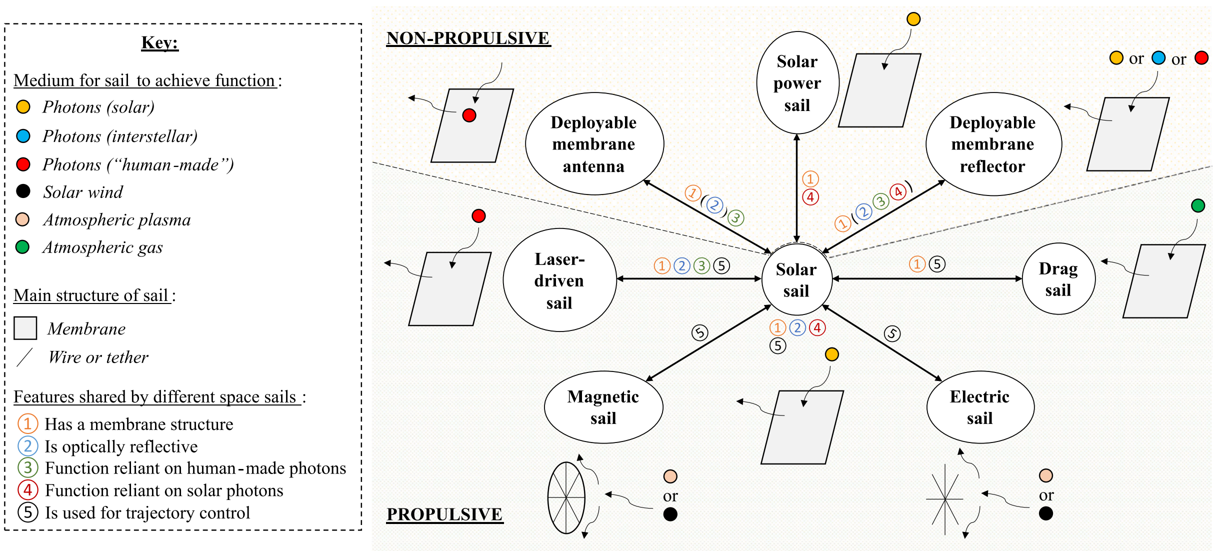


Fig. 7. Shared features of space sails, with the solar sail as a convenient midpoint.

the maturity of other space sails, and vice-versa. On the one hand, addressing technical barriers for high-performance solar sailing automatically brings benefits for contiguous non-propulsive space sails and drag sails. Indeed, these typically have less strict area-to-mass ratio requirements yet benefit from advancements in the state of the art, for instance to improve stowability and ease of deployment from small satellite form factors. Conversely, other propulsive space sails like laser-driven sails, electric sails, and magnetic sails tend to have even more demanding structural and operational requirements than solar sails: further development of these technologies may push forward the frontiers of traditional solar sailing.

In summary, solar sails have many features in common with other space sails. Advancements in solar sail technologies are expected to benefit other contiguous space sails, and vice-versa. As such, solar sails offer a convenient entry point for studying the history, state-of-the-art, and future prospects of space sails as a whole.

2.4. Space sail overlaps, combinations

Eight distinct types of space sail have been described, but in fact they present significant overlap. This is clear from simple visual inspection of Fig. 1: some space sails look similar to one another. There is a fundamental reason for their substitutability: maximising surface area while reducing areal mass. This leads to a flat (or curved) surface which is thin. The rest is determined by the deployment method and mission-specific requirements.

Indeed, by changing the mission environment, a given sail type can play the role of another. For instance, when operating in a planetary atmosphere, most space sails function as a drag sail [55,70,71]. Moreover, with minor design modifications, one type of space sail can be used as another. For instance, by installing photovoltaic cells on a solar sail membrane, it can be used as a solar power sail [17]. By installing a thin-film phased array on a reflective membrane, a lightweight transceiver is obtained [72].

These qualitative observations provide evidence of synergies between the eight space sails, with solar sails emerging as a convenient midpoint in the space sail spectrum. They also hint at the possibility of combining the functions of multiple space sails within a single structure. A more nuanced, quantitative assessment of these synergies is performed in Section 3.

3. Synergies among state-of-the-art space sails

This section reviews the state of the art of space sails. The aim is to identify synergies between space sails and assess how such synergies could be leveraged to support their further development. A catalogue of 220 missions was produced, spanning the full range of space sail types. It comprises both flown sails and mission concepts. By sail type, the number of sails is: 53 solar sails, 8 laser-driven sails, 52 drag sails, 14 magnetic sails, 21 electric sails, 34 deployable membrane reflectors, 18 deployable membrane antennas, and 20 solar power sails. A complete list is provided in Appendix B. Figs. 8 and 9 offer an overview. Efforts were made to include missions from around the world, drawing upon source materials in different languages. The authors acknowledge that some missions have inevitably been omitted, but to their best knowledge, the database provides a comprehensive cross section through the current state of the art of space sails.

Standard, general performance metrics are selected for simple comparison of the different types of space sail. The focus is on ease of understanding by mission designers and space exploration programme managers, not limited to space sail experts. For some missions and parameters, data was not available and is accordingly omitted, as explained below. For data used in the graphs in Section 3, the reader is referred to Appendix B.

Total sail loading is the total spacecraft mass per unit deployed sail area. It provides a "fairer" comparison between the different space sails than sail assembly loading. It includes all systems needed for effective sail operations (e.g., power supply and storage, attitude control, and so on), while sail assembly loading is based on sail mass only. Total sail loading is arguably the most important parameter for comparing the eight space sails, since a value can be computed for each of them (subject to the availability of data), as shown in Fig. 8. It indicates the extent to which they are lightweight with a large deployed area. In general, low values indicate better performance, meaning that a large-area structure can be deployed relative to the spacecraft's mass. For instance, for a solar sail, a larger characteristic acceleration is available. Therefore in this section, when discussing space sails as a whole, it is assumed that a low total sail loading is desirable. In some cases however, a large total sail loading is desirable. For instance, for a plasma injection-type magnetic sail, large total sail loading means that the magnetic propulsion system's mechanical structures are compact compared to the spacecraft (though the "virtual" sail area produced by the spacecraft's magnetosphere may be significantly larger, as discussed in Section 3.4).

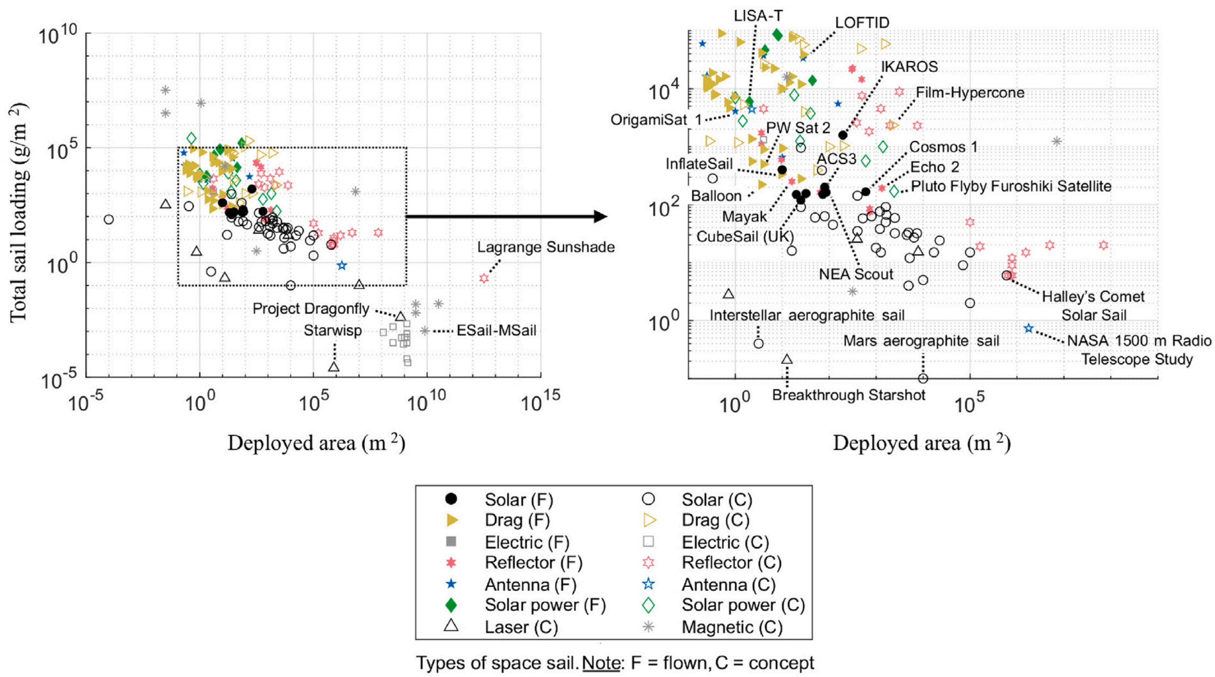


Fig. 8. Total sail loading vs. deployed area among space sails in the catalogue of 220 missions in Appendix B.

Table 1
State-of-the-art space sails: best achievable performance metrics for flown sails, among those in Appendix B.

Sail type	Total sail loading (g/m^2)	Characteristic acceleration (mm/s^2)	Characteristic thrust (mN)	Sail deployed area (m^2)	Sail packing efficiency (m^2/m^3)	Sail thickness (μm)
Solar	120	0.076	5.5	600	43 000	2.1
Drag	222	–	–	28.3	9600	6
Electric	–	0.0057	0.0258	–	–	25
Reflector	74	–	–	1330	8000	5
Antenna	660	–	–	154	1000	6.35
Solar power	6000	–	–	411	833	100

Notes:
– The reader is referred to the start of Section 3 for assumptions used for each sail type.
– The characteristic acceleration and thrust shown are the expected, ideal values. Among flown solar sails, only IKAROS has experienced measurable photon-induced acceleration and thrust in real flight: 0.004 mm/s^2 and 1.12 mN at 1 AU from the Sun [74]. The acceleration and thrust of ESTCube 2 [51], acceleration of CubeSail (UK) [75], and thrust of Cosmos 1 [23] are expected values since their sail payload was not deployed during orbital flight.

In some cases, special consideration is needed when computing values of total sail loading, and the following decisions are made in this paper. The authors acknowledge that other approaches could also be used. Regarding the sail area, for plasma brake electric sails which consist of a single tether, with negligible projected area, the total sail loading is taken as undefined. (In the case of multi-strand hoytethers, strictly speaking a projected area can be computed, but this is not done in the present study.) For spherical sails, like balloon satellites [24], the cross-sectional area is used. For solar wind electric sails, magnetic sails, and other sails with a sparse grid- or mesh-like structure, the area is that enclosed by or enclosing the sail's tether, wires, or mesh. For instance, for a solar wind electric sail with spin-tensioned radial tethers, the area is that formed by a circle enclosing the radial tethers. As for the mass, values of total sail loading are not computed for ground-based space sails (e.g., the LCRT [60]), or space sails deployed from the Space Shuttle (e.g., SAFE [62]) or from the ISS (e.g., SAW [73]), since a large proportion of the total mass is not dedicated to operation of the space sail itself. Conversely, the mass and total sail loading are also not computed for space sail prototypes which comprise only a sail subsystem, without other systems needed for complete operation in the mission environment.

Characteristic acceleration indicates a sail's propulsive capability. Its product with spacecraft mass is called *characteristic thrust*. Large values are desirable to achieve significant orbital changes within short mission times, such as for fast interplanetary transfers. The evaluation method differs depending on the type of space sail, making direct comparison between space sails challenging in some cases.

- For solar sails, it is the acceleration experienced due to solar radiation pressure assuming the sail is facing the Sun, at a distance of 1 astronomical unit (AU). A crease-free sail with perfect specular reflection and its surface perpendicular to the to-Sun direction experiences a solar radiation pressure of 9.1×10^{-6} Pa at 1 AU from the Sun. Deviation from this ideal case is measured by the sail efficiency (≤ 1), which accounts for imperfect optical properties of the sail and the details of its shape. For ease of comparison of the different solar sails, a perfect (i.e., unit) efficiency is assumed. The corresponding characteristic acceleration is referred to as the ideal characteristic acceleration.[2]
- For electric solar wind sails, the characteristic acceleration is obtained in the same way. The sail is assumed to be perpendicular to the Sun, at 1 AU, operating under nominal mission conditions.

[2] For reference, real values of sail efficiency are typically in the range of 0.7–0.9 (e.g., 0.69 for IKAROS in space [74], and 0.88 for Sunjammer during a ground test [76]).

Table 2
Missions in Table 1.

Sail type	Total sail loading	Characteristic acceleration	Characteristic thrust	Sail deployed area	Sail packing efficiency	Sail thickness
Solar	CubeSail, UK	CubeSail, UK	Cosmos 1	Cosmos 1	NEA Scout	ACS3
Drag	Balloon	–	–	LOFTID	InflateSail	PW Sat 2
Electric	–	ESTCube 2	ESTCube 2	–	–	ESTCube 1
Reflector	PAGEOS	–	–	Echo 2	Mayak	Znamya 2
Antenna	Explorer 9	–	–	IAE	OrigamiSat 1	IAE
Solar power	LISA-T	–	–	SAW	LISA-T	LISA-T

Table 3
State-of-the-art space sails: best achievable performance metrics for concept sails, among those in Appendix B.

Sail type	Total sail loading (g/m^2)	Characteristic acceleration (mm/s^2)	Characteristic thrust (mN)	Sail deployed area (m^2)	Sail packing efficiency (m^2/m^3)	Sail thickness (μm)
Solar	0.1	91.4	3684	600 000	62 025	0.21
Laser	2.55×10^{-5}	2×10^{8}	4.6×10^{5}	6.79×10^{8}	–	5×10^{-4}
Drag	394	–	–	2248	14 815	5
Magnetic	1.05×10^{-3}	10^{4}	10^{8}	3.14×10^{10}	–	70
Electric	4.33×10^{-5}	7.2	1800	1.39×10^{9}	3.57×10^{9}	10
Reflector	0.2	–	–	3.14×10^{12}	5.0×10^{5}	2.2
Antenna	0.73	–	–	1.8×10^{6}	750	12.7
Solar power	170	–	–	2410	3429	10

Note: The reader is referred to the start of Section 3 for assumptions used for each sail type.

Table 4
Missions in Table 3.

Sail type	Total sail loading	Characteristic acceleration	Characteristic thrust	Sail deployed area	Sail packing efficiency	Sail thickness
Solar	Mars aerographite sail	Mars aerographite sail	Halley's Comet Solar Sail	Halley's Comet Solar Sail	Team Encounter Solar Sail	Aurora Project heliopause probe
Laser	Starwisp to Alpha Centauri	Wafer scale spacecraft	Wafer scale spacecraft	Project Dragonfly	–	Project Dragonfly
Drag	Drag Sail Conceptual Design	–	–	Film-Hypercone	Practical Aerostable Sail	Aerodynamic Deorbit Experiment
Magnetic	ESail-MSail	Magbeam	Magbeam	Magsail for interstellar flight	–	Magnetic sail on deployable membrane
Electric	Radial E-sail	Square E-sail	Square E-sail	Radial E-sail	HERTS	Radial E-sail
Reflector	Lagrange Sunshade	–	–	Lagrange Sunshade	Lagrange Sunshade	NASA SOLARES
Antenna	NASA 1500 m Radio Telescope Study	–	–	NASA 1500 m Radio Telescope Study	LADeR	NASA 1500 m Radio Telescope Study
Solar power	Pluto Flyby Furoshiki Satellite	–	–	Pluto Flyby Furoshiki Satellite	PIERIS	Pluto Flyby Furoshiki Satellite

- For laser-driven sails, electric plasma brake sails, and magnetic sails, it is assumed to be the nominal value in the given mission environment.
- For drag sails, acceleration is not considered. On the one hand, drag sails do provide propulsion, in the sense that they create a delta-V in a planetary atmosphere, as mentioned in Section 2. However, it is highly dependent on local air density, varying significantly with multiple parameters including orbital altitude and space weather activity. (For the interested reader, acceleration due to air drag in a planetary atmosphere can easily be computed based on the total sail loading [77]).
- For solar power sails, membrane reflectors, and membrane antennas, acceleration and thrust are not considered, since these sails are (usually — see counter-examples in Section 3.9) not intended to provide propulsion. However, if assumed to be optically reflective, an acceleration and thrust can be computed in the same way as for a solar sail.

In addition to total sail loading, acceleration, and thrust, basic mechanical parameters are also considered: the *sail deployed area*, the *sail packing efficiency* (or area-to-volume ratio), and the *sail membrane thickness*. In the context of large, thin, lightweight deployable structures, large values are desirable for the former two, and a small one for the latter. The sail packing efficiency is the ratio of deployed sail area by stowed sail volume, including sail support structures and deployment mechanisms. These parameters provide helpful engineering insight into the classes of missions for which space sails have been applied and are expected to be applicable. Note that for sails consisting of a wire mesh or tether like most electric and magnetic sails, the wire or tether diameter is used as a substitute for thickness. For solar power sails, the thickness comprises both the solar cell and supporting membrane structures (e.g., substrate, protective coating, and so on).

Tables 1, 2, 3, and 4 show the current state-of-the-art for each type of space sail. They list extrema of currently achievable values of the above six parameters: minima of total sail loading and thickness; maxima of characteristic acceleration and thrust, and of deployed sail area and packing efficiency. Tables 1 and 2 show flown sails, while Tables 3 and 4 show mission concepts. Fig. 9 shows the time evolution of the deployed sail area, total spacecraft mass, membrane thickness, and sail packing efficiency for missions from the sail database (see Appendix B), highlighting those listed in Tables 1 to 4. These overview tables and figures will be returned to at the end of this section, when discussing synergies between the space sails, and implications for their future development and utilisation. Beforehand, in the next subsections, the state-of-the-art is described for each type of space sail.

3.1. Solar sail

Flown solar sails

Eleven solar sail missions have flown in the last 20 years. They are shown in Fig. 10(e). Of these, five ended before the sail could be deployed (Cosmos 1, launched in 2005 [78]; NanoSail-D, 2008 [79];

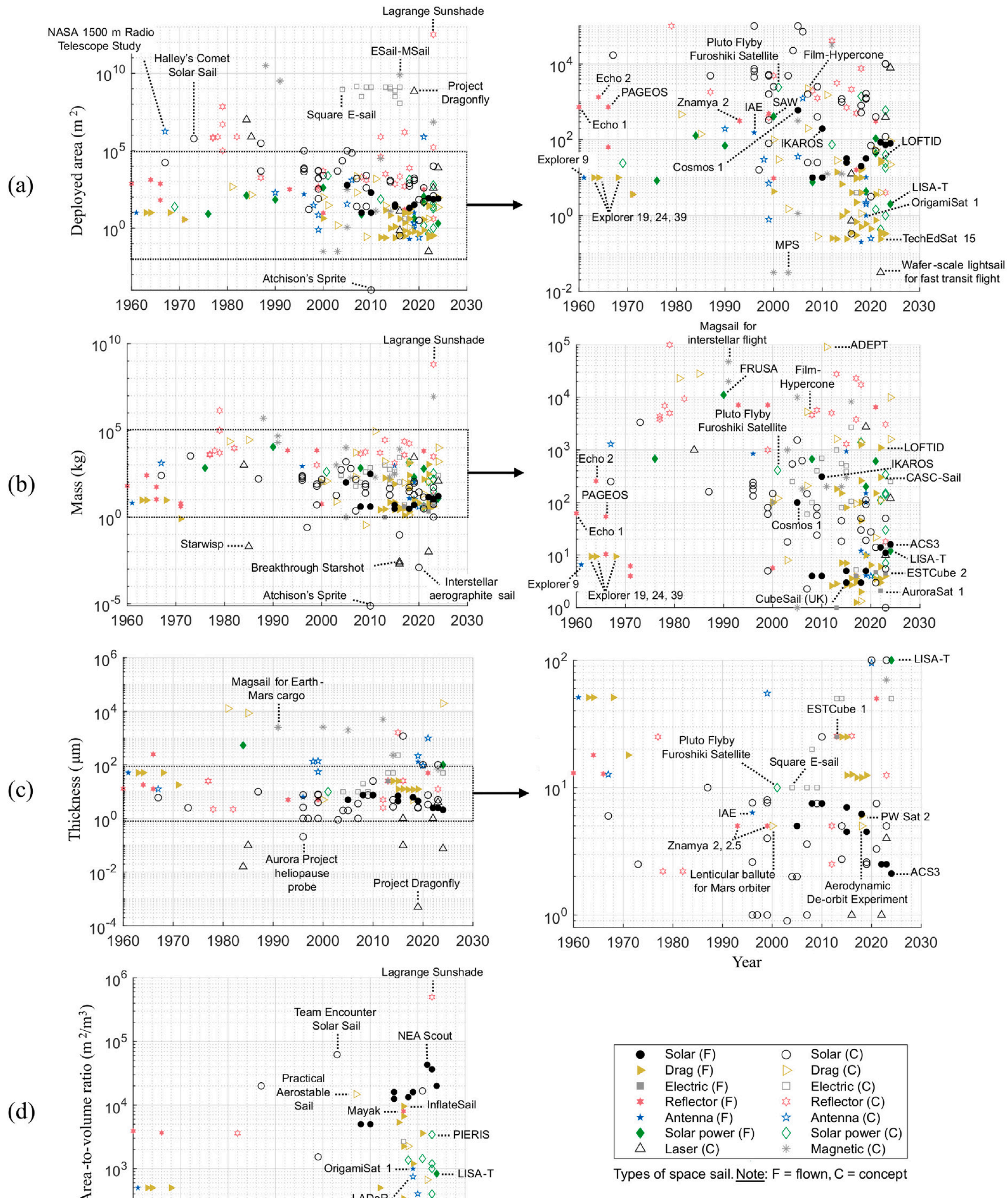


Fig. 9. Time history, among space sails in the catalogue of 220 missions in Appendix B, of: (a) deployed area, (b) total spacecraft mass, (c) membrane thickness, and (d) sail deployed area to stowed volume ratio for selected space sails. For flown missions, the year indicates the date of launch. For concepts, the year is the approximate date of first description.

CubeSail (UK), 2015 [75]; CubeSail (US), 2018 [80]; and NEA Scout, 2022 [81]), only three have experienced orbit changes due to solar radiation pressure (IKAROS, 2010 [74]; NanoSail-D2, 2010 [79]; and LightSail 2, 2019 [71]), and only IKAROS performed solar sailing continuously over an extended flight period of several months [74]. The Gama Alpha (2023 launch) [39] and ACS3 (2024) [82] missions are ongoing. Two sails were intended for operation in deep space (IKAROS [74] and NEA Scout [81]), but only IKAROS was successful. The remaining missions have been in LEO.

Through these mixed successes, flown solar sails have progressively advanced the maturity of key enabling technologies. Central among these is the reflective, metallised (or more precisely, for all missions launched to date, aluminised) plastic sail membrane, which provides the solar sailing effect. To maximise the available acceleration from

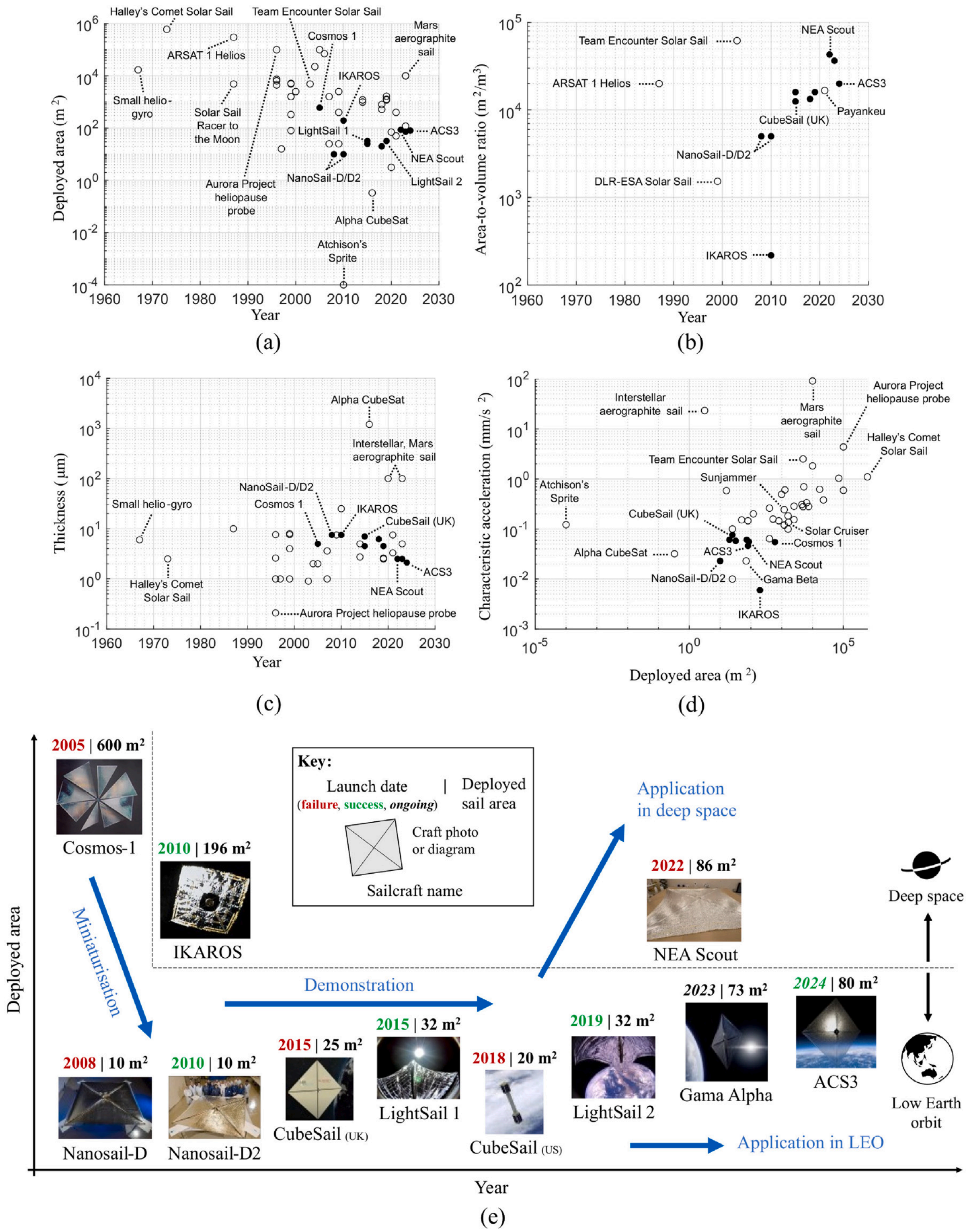


Fig. 10. Solar sail. Time history, among sails in the database in Appendix B, of: (a) deployed area, (b) deployed sail area to stowed volume ratio, (c) thickness, and (d) characteristic acceleration. For flown missions, the year indicates the date of launch. For concepts, the year is the approximate date of first description. The graphic in (e) is adapted from [83], and images sources are in Appendix A.

solar radiation pressure, the membrane should be as large and as lightweight as possible. For easy use onboard a spacecraft, it should be highly compact when stowed and simple to deploy. Flown solar sail missions have demonstrated to meet increasingly demanding performance requirements in each of these domains.

Missions flown before 2015 had a membrane thickness in the range of 5–7.5 μm, while those flown after 2020 have achieved as low as 2.1 μm, as shown in Fig. 10(c). Membrane substrate materials have diversified away from Mylar and Kapton [75,78] towards PEN and CP1 [81,82]. Single-sided aluminised membranes [79] have given way to double-sided aluminised [80] and aluminium–chromium [82] sided ones, with improved durability and thermal performance. This has proceeded in parallel with the development of sail support structures with increased specific strength. For those sails with a rigid support structure, there has been a shift from triangular rollable and collapsible (TRAC) booms [71] towards deployable composite booms (DCB) [82].

One consequence of these trends has been an order-of-magnitude increase in achievable sail deployed area to stowed volume ratios, from around 1000–10,000 m^2/m^3 [79] to close to 100,000 m^2/m^3 [81]. We are nearing the stage where a 100 m^2 class sail can be deployed from a 1U CubeSat volume.

The miniaturisation and easier stowability of solar sails has led to two main trends, depicted in Fig. 10(e). Firstly, smaller sails, typically tens of square metres in size, are finding applications in Earth orbit such as for post-mission disposal, aiding in the development of drag sails (see Section 3.3). Secondly, larger sail areas, reaching hundreds of square metres, are being used for deep space missions requiring larger solar sailing delta-Vs. These sails are creating challenges for attitude control and have promoted flight tests of a variety of control methods. There has been a transition from no control or passive control (NanoSail-D/D2 [79]), to active control with reflectivity control devices or RCD (IKAROS [17]), active mass translators (CubeSail (UK) [75]), reaction wheels and magnetic torquers (LightSail 2 [71], ACS3 [82]), and thrusters (NEA Scout [81]).

The above trends, combined, result in state-of-the-art total sail loading and ideal characteristic acceleration in the order of 100 g/m^2 and 0.1 mm/s^2 for flown solar sails, as shown in Table 1, Fig. 8, and Fig. 10(d). These advancements in membrane technology have not only reduced the weight and size of solar sails, but have also significantly improved their performance and versatility in space missions.

Flown solar sails represent the tip of a large iceberg of proposed missions, with varying levels of technological maturity. Two major types can be identified: (i) concepts using traditional solar sails, with structures and materials similar to those of flown solar sails; and (ii) concepts opening up previously unexplored frontiers in structural engineering and material science.

Concepts using traditional solar sails

The earliest mission concepts emphasised large deployed sail areas, for deep space missions needing large delta-Vs, as described by Mitsugi in 1987: "Since the solar radiation pressure is very weak, a solar sail spacecraft must be large in size, and light in weight in order to get high acceleration performance" [84]. This explains why most solar sail concepts prior to the 2000s had areas exceeding 1000 m^2, even reaching up to 1 km^2, as in Fig. 10(a). In this context, several ground-based tests of large membranes were performed by the World Space Foundation, the German Aerospace Center (DLR), and others, thus increasing the TRL of deployable membrane manufacturing and deployment for space sails, not limited to solar sails [85]. Indeed, this development effort directly contributed to that of other space sails, and notably of deployable membrane reflectors, antennas, drag sails, and solar power sails, as discussed in later subsections.

In the last two decades, most solar sail concepts are below the 10^4 m^2 limit, indicating a new paradigm for solar sail development. Friedman writes in 2024 that: "Based on experiences now building sailcraft and deploying and controlling things in space it seems that 10^4 m^2 may be as large as we should think about at present. That would be a 100 × 100 m^2 sail, which actually might require boom stiffening or guy-wires" [86].

Two major architectures have been adopted for traditional solar sail concepts with metallised plastic membranes. The first was developed by Richard MacNeal in the 1960s: the Heliogyro [87]. Multiple sail strips, or blades, are arranged in a propeller-like configuration. Spin motion and changes in blade pitch are used to maintain structural stability and for attitude control. The concept was developed further by Halley's Comet Solar Sail in the 1970s [40], and inspired many subsequent mission concepts including Cosmos 1 [78] and UltraSail [80].

The second architecture, dominant since the 1980s, is the flat, square solar sail. One reason for the popularity of the square, also among other types of space sail, is that it offers the maximum structural efficiency, i.e., sail area per unit length of rigid support structures, of any polygon, increasing stowability [88]. Indeed, all solar sail concepts currently at TRL > 5 have square sails: Solar Cruiser [89], Gama Beta [39], and Alpha CubeSat [90]. Sunjammer reached a TRL of around 6 before the project was discontinued in 2014.

In terms of planned destinations, there have been three movements, similar to those followed by the flown solar sails in Fig. 10(e) and forming a "U-shaped" trend with respect to their distance from Earth. The first mission concepts (e.g., Halley's Comet Solar Sail [40]) were intended for interplanetary trips. Later concepts recognised the convenience of testing smaller sails closer to Earth, in LEO. For instance, a new category of small solar sail concepts called solar kites was created in the 1990s–2000s with a side-length of a few metres [91,92]. Based on the successful LEO operation of multiple solar sails, deep space has again emerged as a destination. NEA Scout was the first attempt at interplanetary solar sailing using a CubeSat. Following mission failure due to communication malfunction, more recent concepts have been proposed. These include the Gamma spacecraft, part of the Gama series of solar sails developed as a commercial technology demonstrator [39], and Project Svarog, developed as a student initiative [93]. Notably, Project Svarog, a solar sail mission concept aiming at solar system escape, is steadily gaining in technological maturity through steps including a sub-orbital sail deployment test in October 2024 via the European BEXUS programme [94], and a planned orbital demonstration in LEO in 2025/2026, with potential to shift the TRL of solar sails for destinations further out in the solar system.

Concepts opening up previously unexplored frontiers in structures and materials

The cutting edge of solar sail research consists of disruptive mission proposals employing novel structures and materials to open up new regions of the design parameter space. These missions have lower TRLs than those described above, but are rapidly gaining maturity through hardware development and testing.

One research direction is into sparse membranes. Consisting mostly of empty space, they have significantly higher area-to-mass ratios than conventional solar sails, as shown in Fig. 8. Examples include the Mars and interstellar aerographite sail concepts [95,96], with total sail loadings as low as 0.1 g/m^2, an order of magnitude less than the most advanced mission concepts with metallised plastic sails. It is worth noting that aerographite has already been synthesised in the laboratory [97]. In other words, a significantly higher characteristic acceleration can be achieved with a drastically reduced sail area. All-metal sails, like the Aurora Project heliopause probe concept, offer another approach. The metal layer is launched together with a plastic substrate, which is either delaminated or ashed away after in-space deployment, leaving behind a metal sail with sub-micrometre thickness [98].

Another research direction is into highly miniaturised solar sails, in the form of ChipSats [99], ChipSails [100], SpaceChips, PCBSats [101], and Smart Dust [102]. Atchison's Sprite, indicated in Fig. 10(a), is one example. These present advantages for low-cost, swarm-type, distributed missions in Earth orbit and in deep space. Such spacecraft concepts are both leveraging and driving the miniaturisation of spacecraft subsystems, not limited to solar sails, alongside trends in micro-electromechanical systems (MEMS). Efforts towards launching large swarms of highly-miniaturised space sails into Earth orbit have ostensibly been dampened by space debris mitigation concerns, noting that it is challenging to track cm-scale and smaller objects with presently available technologies [103].

A final research direction is into membranes with high thermal resistance for close solar swingbys, also known as sundiver missions. For example, a sundiver demonstration concept called LightCraft is being developed as part of research into solar sailing interplanetary smallsats [104]. This work is proceeding alongside the development of materials with resistance to severe thermal, radiation, and plasma loading, like ceramics and carbon [105]. Novel ways of manipulating light at the sail surface are also being investigated. Examples include diffractive sails for more efficient out-of-plane heliocentric manoeuvres [106], and retroreflective sails for improved control over the direction of thrust [90].

In summary, state-of-the-art solar sail concepts are advancing solar sailing performance both by extrapolating total sail loadings and characteristic accelerations along trendlines already achieved by flown missions, but also by disrupting the parameter space through innovations in structures and materials. Several concepts in the former category presently have high TRLs and are expected to be launched within the next few years, and active research into the latter is underway. The development of solar sails has influenced and been influenced by that of other space sails. Such synergies are explored in more detail below.

3.2. Laser-driven sail

Laser-driven sails have been proposed as candidates for interplanetary and interstellar travel, since they can reach high, even sub-relativistic velocities by reflecting focused, high-powered lasers [2] (or collimated microwaves [107] or X-rays [108]), as explained in Section 2. Significantly higher acceleration can be achieved than by using a solar sail, as seen when comparing Figs. 10(d) and 11(d). Correspondingly, more severe technical challenges exist. Indeed, no laser-driven sails have yet flown in space, though pathways to orbital flight are being actively studied [28]. Proposed mission concepts cover an extremely broad range of deployed sail areas, spacecraft masses, and membrane thicknesses, as can be seen in Fig. 11(a)–(d).

The Laser-pushed flyby lightsail [109], Starwisp [107], and Project Dragonfly [110] are missions employing the thin, large-area, lightweight sail approach. They have respective thicknesses of 16 nm, 100 nm, and 0.5 nm, deployed sail areas of 10 km^2, 0.8 km^2, and 680 km^2, and total sail loadings of 0.1 g/m^2, 2.6×10^{-5} g/m^2, and 0.004 g/m^2. The Laser-pushed flyby lightsail and Starwisp were both proposed by Robert Forward in the mid 1980s, and rely on an aluminium membrane, ostensibly leveraging extensive testing and characterisation of thin aluminised membranes and grids during the development of early solar sails, deployable membrane reflectors and antennas, and drag sails, as discussed in Section 3.1. Specifically, the laser-pushed sail consists of a stand-alone aluminium membrane with nanometre-scale thickness [109]. Starwisp consists of a sparse membrane formed of an aluminium wire mesh with distributed sensors and circuitry and doubling as an antenna, propelled by microwaves [107]. Since the late 1980s, studies on thermal loading of laser-driven lightsails led to a shift away from solar sail-like metallised sail membranes towards alternatives like thin-film dielectric and other materials [18]. For instance, one recent mission concept, Project Dragonfly, consists of a graphene monolayer [110]. These missions all aim at interstellar travel with either flyby [107] or deceleration [110] at the target star system, or even round trips [109] back to Earth, noting that Robert Forward considered both flyby and round-trip options for the Laser-pushed lightsail [109]. In interstellar mission concepts, deceleration remains an open challenge. For instance, Parkin recently suggested that significant evolution of the laser driven lightsail may eventually enable large payload acceleration for interstellar settlement missions [111]. A significant challenge of these is deceleration in the target stellar system. This could possibly involve very efficient fusion propulsion [112]. It is interesting to note this combination of laser-driven lightsail high payload acceleration from Earth and high efficiency fusion deceleration was explored by James Cameron in the science fictional Avatar films [113].

Since the early 2000s, there has been a shift towards smaller-scale laser-driven sails, alongside the development of compact satellite form factors like CubeSats [2]. Philip Lubin's Starlight Program [114] was an early contributor. A wafer-type, cm-sized spacecraft bus with gram-level mass and miniaturised embedded subsystems is attached to a reflective membrane with a metre-order side length, providing extremely high acceleration when illuminated by a space-based or Earth-based laser. The membrane consists of dielectric material on plastic, with properties tailored to those of the illuminating laser beam. Scaled-up versions were also considered for human or cargo interplanetary missions [2]. Wafer-only laser-driven sails have also been proposed. A recent example is the wafer-scale lightsail [115]. The spacecraft consists of a disc with a cm-scale diameter and μm-scale thickness. These missions offer the prospect of laser-driven propulsive control of swarms of small reflective spacecraft, for both interplanetary and interstellar applications. An artist's impression of a wafer type spacecraft is shown in Fig. 11(e). Note that such spacecraft are similar to the ChipSat and ChipSail solar sails mentioned in Section 3.1, hinting at potential synergies between the two. Lasers have also been considered for formation control of even smaller objects, such as granular spacecraft in large-aperture telescopes with distributed space optics [116].

Breakthrough Starshot [18], which is a descendent of the Starlight Program, is in an intermediate size and thickness category, as can be seen in Fig. 11(a) and (c). An artistic rendition is shown in Fig. 11(e). From the viewpoint of total sail loading, it is quite close to the region already achieved in flight tests of solar sails, as can be seen in Fig. 8: it is only one to three orders of magnitude away in terms of total sail loading and deployed area. On the other hand, it is planned to experience accelerations of up to 10^5 m/s^2, as indicated in Fig. 11(d). A 100 GW-class ground-based laser provides propulsion, requiring advanced sail materials with exceptional thermal resistance. Based on ongoing research, silicon nitride is one candidate for meeting the requirements [45], and has been selected for other laser-driven sail concepts too [115,117]. Other materials have been considered to provide required optical properties and thermal resistance, such as artificial diamond film [118]. Another challenge is beam-riding stability, and one promising solution is to use metagratings at the sail surface for passive beam centring [119].

The realisation of interstellar missions like Starwisp, Breakthrough Starshot, and Project Dragonfly is being planned through an incremental approach. Interplanetary laser-driven sail missions within the solar system are being studied as an intermediate stepping stone. Such missions include fast manoeuvring of wafer satellites in Earth orbit [115]; the Earth-Mars Rapid Transport Mission for fast transportation of small interplanetary cargo [117]; and the Astrobiology Precursor mission to Enceladus and Europa [120]. The use of Earth-based lasers for space debris removal may offer another means to mature enabling technologies before application to deep space [121].

In summary, state-of-the-art laser-driven sails tend to operate in more challenging regions of the parameter space than solar sails. As such, a step-by-step development approach is being pursued, emphasising near-Earth missions before interplanetary and interstellar ones. This process is likely to bring benefits to other space sails with less stringent technical requirements, like solar sails. Indeed, many laser-driven sail concepts combine the functions of multiple different types of space sail, opening prospects for their synergistic development. For instance, the Earth-Mars Rapid Transport Mission for fast transportation of small interplanetary cargo suggests combining a laser-driven sail, magnetic sail, electric sail, and drag sail within a common spacecraft structure [117]. A more detailed discussion on multi-sail missions is offered at the end of this section.

3.3. Drag sail

Beyond reflecting light, deployable membranes also offer a means of increasing air drag in a planetary atmosphere. Sail deployment reduces a satellite's ballistic coefficient, i.e., the mass divided by the product of the deployed area and the drag coefficient, increasing its sensitivity to air resistance. State-of-the-art drag sails have been developed through

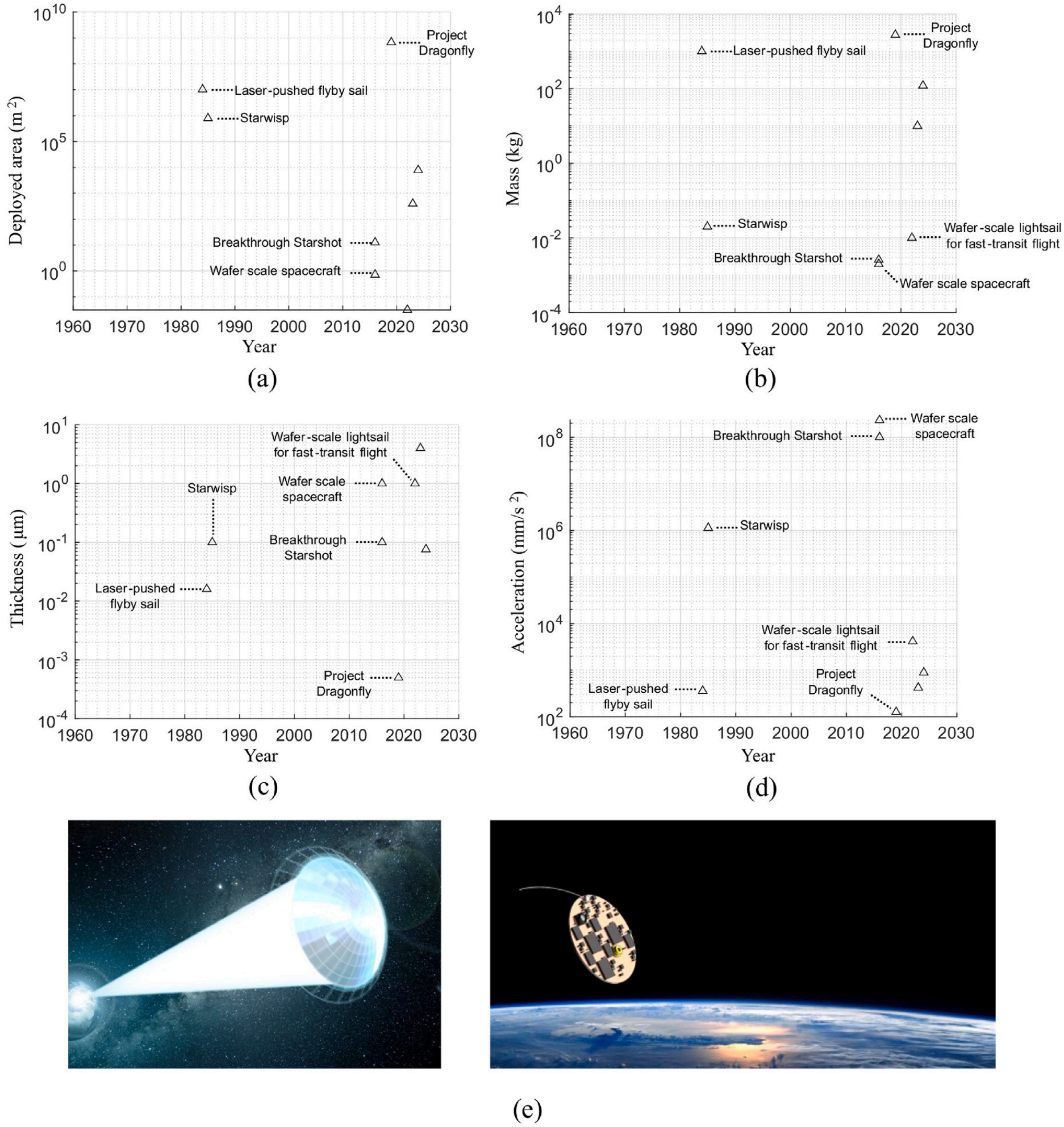


Fig. 11. Laser-driven sail. Time history, among sails in the database in Appendix B, of: (a) deployed area, (b) mass, (c) thickness, and (d) acceleration. The year is the approximate date the mission concept was first described. Images in (e) are of (left) Breakthrough Starshot and (right) a wafer type spacecraft, with sources in Appendix A.

a series of three movements now proceeding in parallel, discussed in more detail below. Representative examples of each are shown in Fig. 12(e). Reflectors and antennas were developed in synergy with drag sails from the beginning, and in the last two decades solar sails have made a significant input to their development too. Many missions have already flown, as can be seen in Fig. 12, and novel mission concepts are opening new frontiers in sail shapes, structures, and sizes.

Deployable membrane for aeronomy

The earliest drag sails were used for terrestrial aeronomy, i.e., science of the upper atmosphere. The Air Density Explorer series of inflatable balloon satellites – Explorer 19, 24, and 39 – launched by the NASA Langley Research Center in the 1960s, were the first deployable membrane structures used for intentionally changing a satellite's orbit via air drag [24]. The aim was to obtain information on the Earth's atmosphere, with satellite de-orbit occurring as a by-product. Interestingly, the Air Density Explorers also functioned as a reflector and antenna, due to their metallised reflective surface with a plastic band separating the two hemispheres at the equator. The Explorer 9 mission, which laid the groundwork for the Air Density Explorers by demonstrating the proof of concept and has a similar appearance, is shown in Fig. 12(e).[3] The Air Density Explorers leveraged inflatable technologies from the Echo 1 and 2 reflectors. All these missions relied on aluminised polyimide membranes with micrometre-scale thickness, and some employed strain rigidisation to avoid shape changes after inflation. As discussed in Sections 3.1 and 3.2, flown solar sails and early laser-driven sail concepts use almost the same material, highlighting their common heritage and cross-pollination. Though the use of drag

[3] In this paper, Explorer 9 is categorised as a membrane antenna, since it preceded the NASA Air Density Explorer program, even though it too was used for aeronomy.

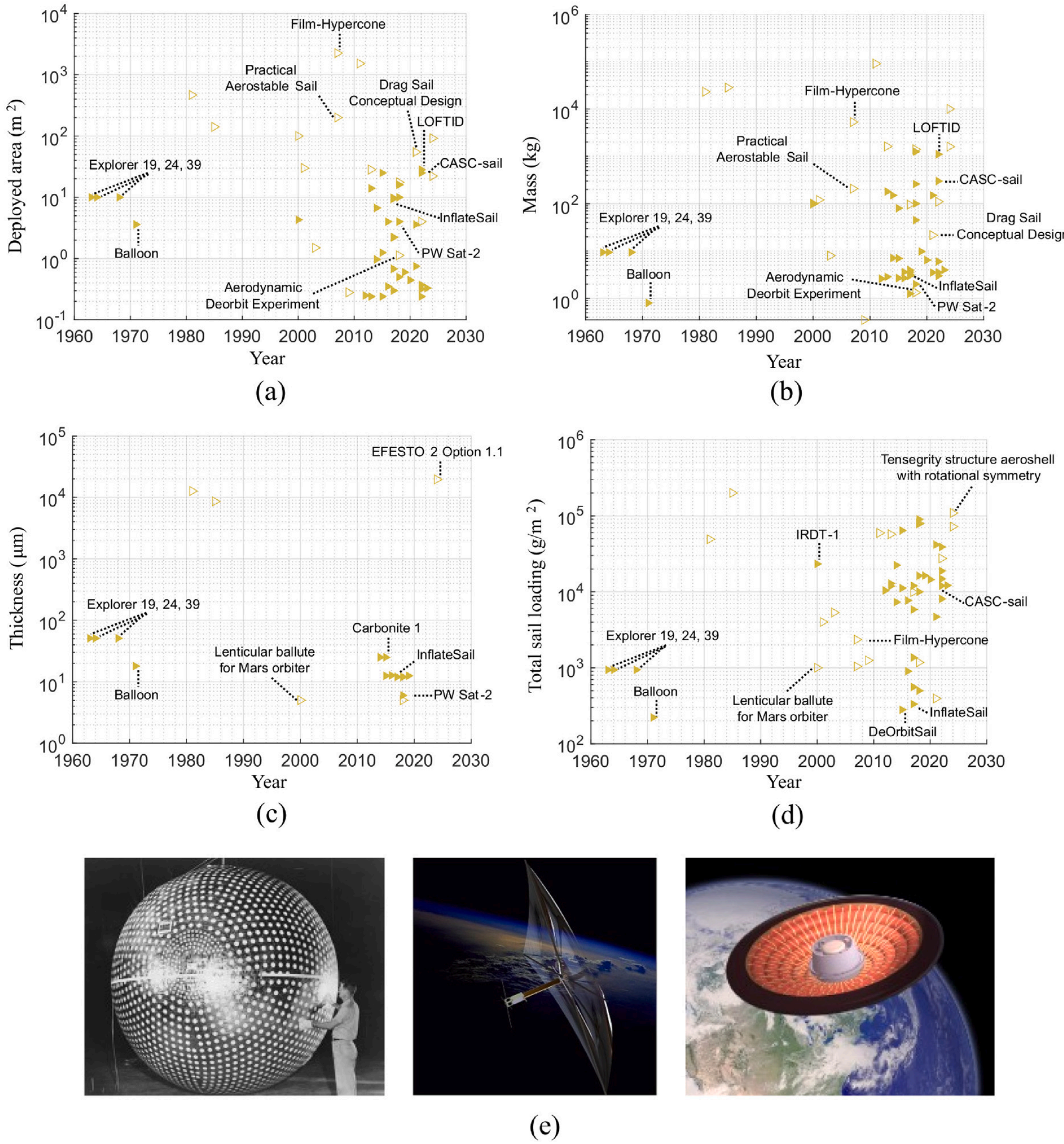


Fig. 12. Drag sail. Time history, among sails in the database in Appendix B, of: (a) deployed area, (b) mass, (c) thickness, and (d) total sail loading. For flown missions, the year indicates the date of launch. For concepts, the year is the approximate date of first description. Data sources for each sail are in Appendix B. Images in (e) are of (left) Explorer 9, (middle) InflateSail, and (right) LOFTID, with sources in Appendix A.

sails for aeronomy missions has become less popular, research in this area continues to the present day [122].

Deployable membrane for satellite de-orbit and disposal

Since the early 2010s, drag sail missions have gained popularity due to growing global demand for post-mission de-orbiting and space debris removal in LEO. This is clear from the large number of data-points in Fig. 12(a)–(d) in the 2010s onwards. Several dozen missions have flown, ranging from the small TechEdSat series Exo-Brake missions [123] with deployed areas as small as 0.24 m^2, to the large 25 m^2 DeOrbitSail and CASC-sail. Fig. 12(e) shows a rendering of InflateSail, a transparent drag sail launched into LEO in 2017 [124]. In a historical "full-circle", flown solar sails, which rely on membrane technologies initially developed for aeronomy experiments in the 1950s and 60s as discussed above, have contributed to the growing development of drag-sails for use in LEO. Notably, NanoSail-D2 realised the first deployment of a space sail from a CubeSat in LEO in 2010, as a stepping stone towards a solar sailing mission [48]. Two years later, in 2012 the RAIKO mission performed the first in-orbit demonstration of a planar drag sail, with an aluminised polyimide membrane [125]. The in-space testing of these structures has not only advanced potential solutions to space debris, but also provided test data for deployment mechanisms and attitude control systems of sail structures generally [48]. Drag sails for satellite de-orbit from LEO rely on almost the same technologies as flown solar sails, including sail materials (e.g., polyesters [124], polyimides [125]), thicknesses (in the order of 10 µm or less, as shown in Fig. 12(c)), and deployment mechanisms (e.g., coilable booms, self-deployed via stored strain energy [126] or deployed by motor [127]). Metallisation, used to increase reflectivity and provide photon-based propulsion for a solar sail, has a different function for LEO drag sails. It offers a means of protecting the membrane from the space environment, such as atomic oxygen and UV radiation, both of which can degrade thin plastic sheets [128].

As seen in Figs. 8, 9, and Fig. 12(a)–(d), drag sails extend the trendline of solar sail flown and conceptual missions into regions of lower deployed area and higher total sail loading, associated with thicker membranes. This is because air drag in LEO is relatively large, and sufficient deceleration can be produced over the month- to year-long timescales of de-orbit even with high total sail loadings. Despite this, Fig. 12(c) reveals that membrane thickness has reduced over time, suggesting efforts towards more compact, lightweight drag sail payloads for easier use onboard satellites of all types, as confirmed by the wide range of sail areas in 12(a) and satellite masses in Fig. 12(b). A wide variety of research [129] and commercial applications [19] employing drag sails in LEO continues to this day. One area of investigation is passive attitude stabilisation using a pyramidal sail shape [127].

Deployable membrane for aerocapture, entry, descent, and landing

The advancing maturity of drag sails for Earth orbit has opened new prospects for deep space applications. In fact, aeroassisted orbital transfers have been studied since the early 1960s [130], for applications including aerocapture, aerobraking, and orbital plane change. As opposed to the above-mentioned drag sails for de-orbit in LEO, where the satellite burns up in the atmosphere after mission completion, the challenge is instead to protect the satellite from thermal and mechanical loads until landing or insertion into the new orbit. The result is typically bulkier membranes which occupy a different region of the plots in Fig. 12(a)–(d), as discussed below.

An area that gathered especially strong interest in the 1970s–80s, and has experienced a recent resurgence, is deployable aerobrakes for orbital transfer vehicles (OTV), to increase payload capacity for transfers from GEO to LEO with interplanetary applications as well [131]. One research direction has been into relatively thick, flexible multilayer structures for applications requiring aerocapture, or for entry, descent, and landing (EDL) of spacecraft. In both cases, severe aerodynamic heating occurs, requiring adequate thermal protection. Common membrane materials for such applications include polyamide fibres like Kevlar [132] and ceramic fibres like Nicalon and Nextel [133], encasing an insulator layer like felt [134]. Though limited public information is available on the thickness of such membranes, a value in the range of a few millimetres or more is common, as indicated by the EFESTO 2 Option 1.1 sail in Fig. 12(c), which belongs to this category.

Since the late 1990s, concentric inflatable toroids covered with a flexible thermal protection membrane have emerged as a popular option for low-mass aero-assisted re-entry and descent, as an alternative to bulky rigid heat shields and deployable parachutes. One of the first flight demonstrations in LEO was made by IRDT 1 in 2000 [135]. The most recent was made by LOFTID, depicted in Fig. 12(e), in 2022 [136]. Flight tests have proceeded alongside concept studies, such as AIR [137].

Deployable membranes supported by a rigid umbrella-like structure are another alternative. Multiple mission proposals have been made in this category in the last two decades. These include ADEPT for payload transfers between Earth and Mars [138], and ADEPT-VITaL for a Venus entry probe [139]. Tensegrity structures have been suggested, to reduce the mass of support structures, such as in the TANDEM mission concept [140] and tensegrity aeroshell with rotational symmetry mission concept [141]. As can be seen in Fig. 12(d), these structures are relatively bulky, with a significantly larger total sail loading than drag sails for de-orbit in LEO.

Yet another alternative, usually more lightweight than the two above structures, is a tension shell. The deployable membrane is attached to the payload upstream, and supported by a single ring at its trailing edge. Anderson was among the first to focus on tension shell structures for application to atmospheric entry vehicles [142], with later research done in Japan from the 1980s [143]. Mission concepts in this category include Film-Hypercone [144], FEATHER [145], and Small THz Spacecraft with Aeroshell [146] (with membranes made of fibre-reinforced Kapton for the former, and Zylon for the two latter). The EGG [147] and BEAK [148] missions, part of a multi-decade deployable aeroshell development program at around a dozen Japanese universities [149], were two technology demonstration missions of the tension shell drag sail, flown in LEO in 2017 and 2023 respectively. As can be seen in Fig. 12(d), tension shell drag sails like Film-Hypercone occupy an intermediate region of the total sail loading parameter space, located between bulky flexible membrane heat shields like IRDT 1, and lightweight de-orbit drag sails like InflateSail. Due to their relatively high area-to-mass ratio, they offer aerodynamic deceleration at high altitudes, reducing peak aerodynamic heating and enabling the use of thinner membranes without significant thermal resistance. This is illustrated by a related mission concept, the Lenticular ballute for Mars orbiter [150]. It experiences low aerodynamic heating during planetary entry, enabling the use of a simple Kapton membrane with a thickness comparable to that of flown solar sails, as shown in Fig. 12(c).

In summary, drag sails encompass a broad range of technologies, with two primary applications at present. The first is satellite de-orbit and disposal, by accelerating orbital decay via air drag. Technologies inherited from flown solar sails, like thin metallised plastic membranes and deployable booms, have played a major role in enabling the development of these technologies. The second is aerocapture, aerobraking, entry, descent, and landing, where the deployable drag sail provides a lightweight alternative to a rigid heat shield or bulky parachute, or to a large propulsive manoeuvre. In this case, the deployable membranes are typically heavier, thicker, and made of different materials than solar sails, to accommodate more severe thermal loads. Even so, synergies between lightsails and drag sails may exist in this area too. For instance, a recent proposal for Interplanetary Rapid Transit Missions from Earth to Mars using a laser-driven sail [117] raises the possibility of using a common structure for the laser-driven sail and for atmospheric entry at Mars. Indeed, severe thermal loads are also experienced by some solar sails like sundivers, and by laser-driven sails. This suggests open potential for further leveraging synergies between drag sails, solar sails, and other types of space sail, as discussed at the end of this section.

3.4. Magnetic sail

Magnetic sails offer another option for propellant-free spacecraft trajectory control, as discussed in Section 2. Like the laser-driven sail, no missions have yet flown in space. Unlike lightsails and drag sails, which obtain propulsion via direct contact between the propulsion medium – photons or gas particles – and the sail structure, for magnetic sails propulsion is obtained via interaction between the propulsion medium – space plasma – and a magnetic field onboard the spacecraft. There is no direct contact between space plasma and the sail's mechanical structure. The magnetic field creates a "virtual" sail, which can be significantly larger than the actual spacecraft. The available propulsive thrust is proportional to the solar wind pressure, which is around three orders of magnitude less than the solar radiation pressure used by solar sails [69]. The challenge for providing appreciable thrust is therefore to produce extremely large virtual sail areas. Two main design approaches have been used for this purpose.

Magsail type

The first and earliest approach is based on the Magsail concept introduced by Andrews and Zubrin [49]. A superconductive current-carrying wire loop is attached to the spacecraft, and provides a spacecraft-centred magnetosphere. An example is shown in the left-hand side of Fig. 13(d). Initial designs called for loop diameters in the order of tens of kilometres, and research into large-sized magnetic sails has continued to this day. One example is a combined electric and magnetic sail [151]. Another is a magnetic sail printed on a modular deployable membrane with flexible printed circuits [152], highlighting potential synergies with deployable membrane technologies used by solar,

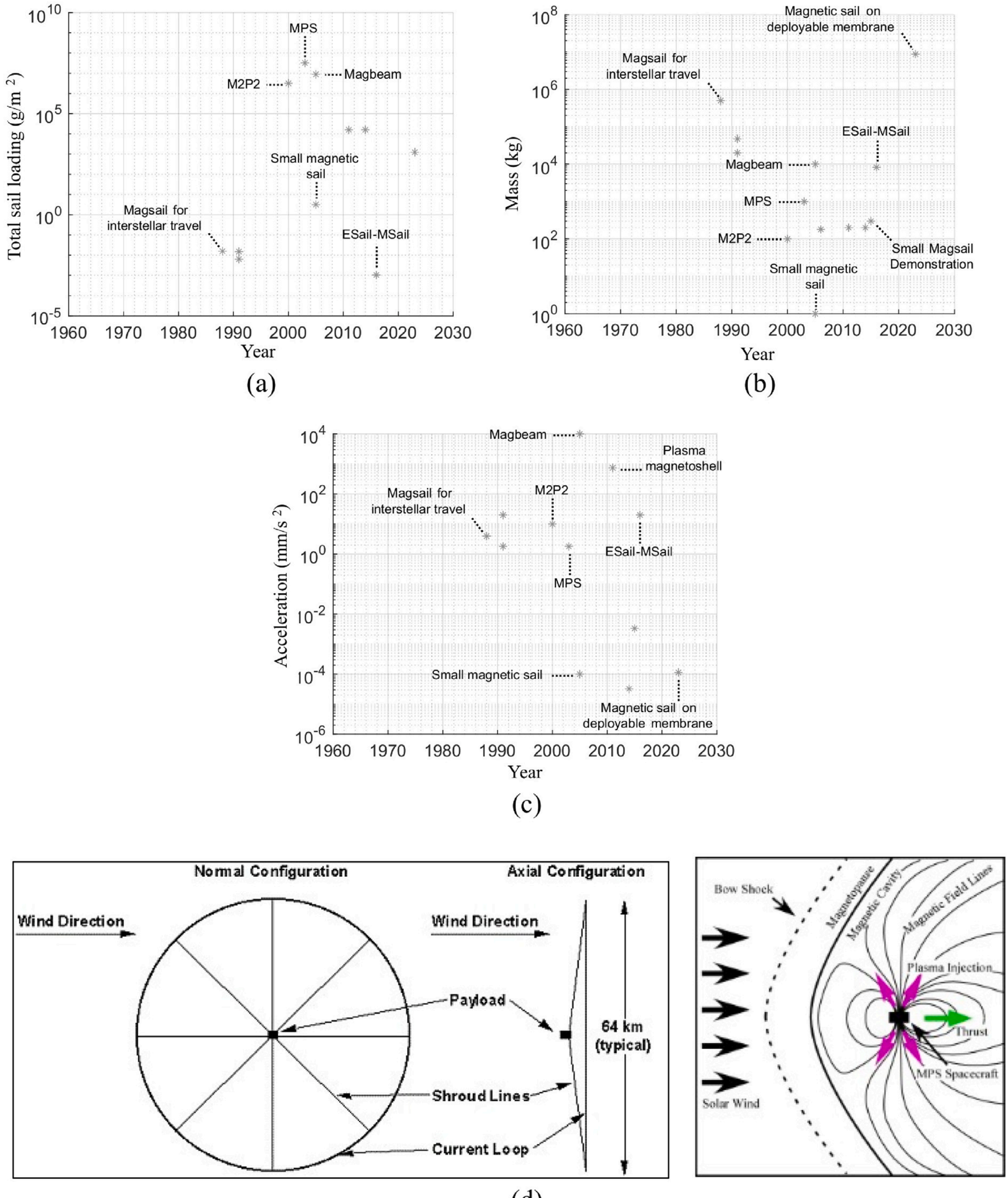


Fig. 13. Magnetic sail. Time history, among sails in the database in Appendix B, of: (a) total sail loading, (b) mass, and (c) acceleration. The year is the approximate date the mission concept was first described. Images in (d) are of (left) a variant of Magsail and (right) MPS, with sources in Appendix A.

laser, and drag sails. In fact, the seminal Magsail concept proposed by Andrews and Zubrin was envisioned to operate in tandem with a laser-driven sail, by providing deceleration on arrival at the target star system after interstellar cruise [49].

In parallel, other work has considered the possibility of miniaturising magnetic sails, but relatively poor thrust-to-weight performance has been obtained compared to alternative technologies like electric thrusters and solar sails [153]. Two example mission concepts are the Small magnetic sail [154] and Small Magsail Demonstration [69].

For many Magsail-type magnetic sails, high-temperature superconductors such as yttrium barium copper oxide (YBCO) and copper oxide [151] have been considered for the spacecraft's coils, and many concepts feature wires with a diameter in the order of a few millimetres [49,154]. Applications to interstellar [151] and interplanetary [69, 154] missions have both been considered.

Plasma injection type

Another research direction has been into means of increasing the size of the spacecraft's magnetosphere without using large mechanical structures, via plasma injection. The spacecraft is equipped with a plasma source. By exhausting the plasma near the centre of an onboard dipole magnetic field, the spacecraft's magnetosphere is expanded. The area available for interaction with the solar wind is thus increased, enabling more thrust to be generated. The size of the magnetosphere is determined via a balance between plasma-driven expansion and contraction due to incident solar wind, such that the size increases with distance from the Sun, potentially providing a near-constant force and acceleration [155]. Two pioneering concept studies in this area are Mini-Magnetospheric Plasma Propulsion (M2P2) [155] and Magneto-plasma Sail (MPS) [20]. A rendering of the latter is in Fig. 13(d). As shown in Fig. 13(a)–(c), these are relatively compact spacecraft with a mass in the order of 100–1000 kg, yet provide acceleration in the same order as Magsail, for applications like interplanetary and interstellar travel. Proposals to demonstrate the concept via flight experiments have been made, like the Magnetic sail engineering satellite, intended for launch into a highly eccentric Earth orbit [156], but no missions have yet flown.

Two variants of the plasma injection magnetic sail are Magbeam [157] and Plasma Magnetoshell [50]. The former is conceived for significant delta-V manoeuvres by beaming plasma from a large satellite acting as a power source to a small satellite equipped with magnetic coils, for applications like orbit raising around the Earth and Earth escape [157]. The latter is intended for braking in a planetary atmosphere, by charge exchange between injected plasma and the incoming neutral atmosphere, followed by deflection via the spacecraft's magnetosphere. The function is similar to a drag sail. Applications to Neptune aerocapture have been considered [50]. In both cases, significantly higher plasma densities than available in the solar wind enable large accelerations to be achieved despite a high total sail loading (i.e., compact spacecraft structure), as shown in Fig. 13(a) and (c). Designs free of superconducting materials have been proposed, for example using aluminium or copper wire coils [50,155].

The Plasma Magnet (PM) [158] represents a mid-point between the classic Magsail concept and plasma-injection concepts like M2P2 and MPS. PM comprises two km-scale wire hoops. After initial inflation of a spacecraft-centred magnetosphere using onboard plasma injection (like M2P2 and MPS), solar wind plasma is entrained into and sustains the magnetosphere, resulting in propellant-free propulsion (like Magsail).

In summary, two main design architectures for magnetic sails have been proposed, for applications near Earth and in deep space, encompassing interplanetary orbit transfers, aerobraking, and station-keeping in non-Keplerian orbits [30,159]. Though magnetic sails have yet to be flown in space, their TRL has slowly been raised through a series of ground tests [50,157]. Thin-film magnetic sails embedded onto flexible membranes have also been studied [152]. These examples highlight important and growing synergies with other types of space sail.

3.5. Electric sail

The electric sail and magnetic sail share common features. Like the magnetic sail, the electric sail produces a "virtual" sail area significantly larger than the spacecraft's mechanical structure. Yet different from the magnetic sail, an electrostatic field is used rather than a magnetic one. Though the concept was proposed only two decades ago [21], flight tests have already been conducted, owing to more favourable properties than the magnetic sail, as discussed below. There are two main types of electric sail.

Solar wind electric sail

The solar wind electric sail is intended to operate in interplanetary space, where a spacecraft is exposed to the solar wind. It consists of a network of wires, biased to a positive potential using an electron emitter onboard the spacecraft. (Some negatively-biased solar wind electric sails have also been studied [160].) The resulting electrostatic field repels incoming solar wind ions, providing momentum to the attached spacecraft. Though the seminal concept consisted of a square mesh of charged wires [21], a radial configuration has been adopted in most subsequent mission concepts [161,162], whereby the charged wires are maintained taut via spin motion. An example is shown in Fig. 14(d). Similar to the magnetic sail, since the available solar wind pressure is extremely small compared to solar radiation pressure, long, km-scale wires are commonly assumed, as highlighted by the extremely large deployed areas in the upper right-hand corner of Fig. 14(a). Despite this, due to the use of thin wires with micrometre-scale diameters [21,161] and low power requirements for the electron emitter, such sail concepts are compatible with small-sized spacecraft in the 100–1000 kg class, as shown in Fig. 14(b). Aluminium wires have emerged as a popular choice in mission concept studies [163]. Solar wind electric sails have been envisioned for different applications including solar system escape or interstellar missions [164], flyby and rendezvous with solar system targets [165], station-keeping at artificial Lagrange points [166], and inner-solar system missions [167].

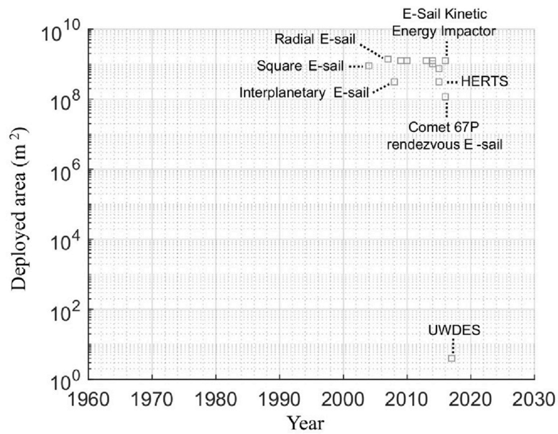
Plasma brake

As a stepping-stone towards deep space missions, flight demonstration of electric sails has been conducted in Earth orbit using CubeSats. Within the Earth's magnetosphere, the solar wind is negligible. Instead, charged particles in the Earth's ionosphere are utilised. Moreover, rather than using multiple radial tethers, a single tether is employed. The result is a so-called plasma brake [6]. Electrostatic force is used to reduce a satellite's orbital energy and induce orbital decay, similar to a drag sail, though de-orbit is possible from higher altitudes. By contrast with the solar wind electric sail, the plasma brake is biased to a negative potential, and provides Coulomb drag via interaction with low-speed but high-concentration ions (relative to the solar wind) in the ionosphere. Achievable acceleration is comparatively low, as can be seen in Fig. 14(c), but application over an extended time period of months or years enables effective orbital decay. In most cases, there is no need for an ion gun to maintain tether potential, as the spacecraft naturally acquires negative charge owing to the greater mobility of electrons. Compatibility with kg-class CubeSats, as shown in Fig. 14(b), enables relatively low-cost flight experiments.

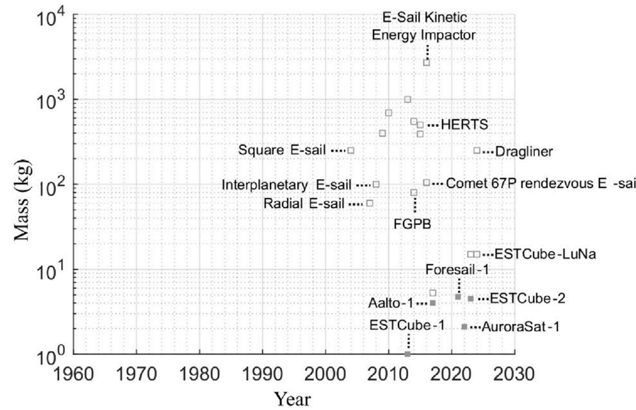
Multiple flight tests have been conducted since the mid-2010s, including ESTCube 1 [168], Aalto 1 [169], Foresail 1 [51], AuroraSat 1 [170], and ESTCube 2 [51]. An example is shown in Fig. 14(d). In all cases, the plasma brake payload was never deployed due to reasons including communications issues and failure to release the satellite from its launch vehicle. Even so, these attempts have raised the maturity of enabling technologies such as multi-strand tethers (presenting improved resistance to debris) with wire diameters ranging from 25-50 μm, called hoytether or heytether [171]. A rebooted single-tether CubeSat mission called ESTCube-LuNa is being planned for solar wind electric sail demonstration in lunar orbit [25].

Finally, several electric sail concepts have been proposed at the interface between multiple different types of space sail. Two particularly interesting ones are the E-sail with small photonic blades [172] and Freely guided photonic blade (FGPB) [173]. The former uses small solar sails, made of aluminised Kapton membranes, at the tips of a solar wind electric sail's tethers for spin control [172]. The latter is based on a similar design, and the size of its component parts can be adjusted so that the sail functions alternatively as a solar wind electric sail, a heliogyro solar sail, a plasma brake, a drag sail, or their combination [173].

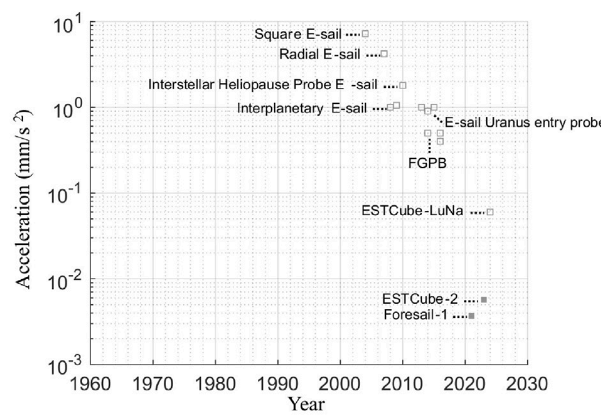
In summary, electric sails offer an alternative means of propellant-free propulsion than solar, laser-driven, drag, and magnetic sails. Flight tests have already been conducted, owing to more compact spacecraft architectures and better compatibility with currently available technologies than magnetic sails. It is worth noting that the deployment of large, lightweight structures from CubeSats, such as km-long plasma brakes, builds on earlier flight heritage of deployable flexible membranes onboard solar sail and drag sail missions in LEO, such as



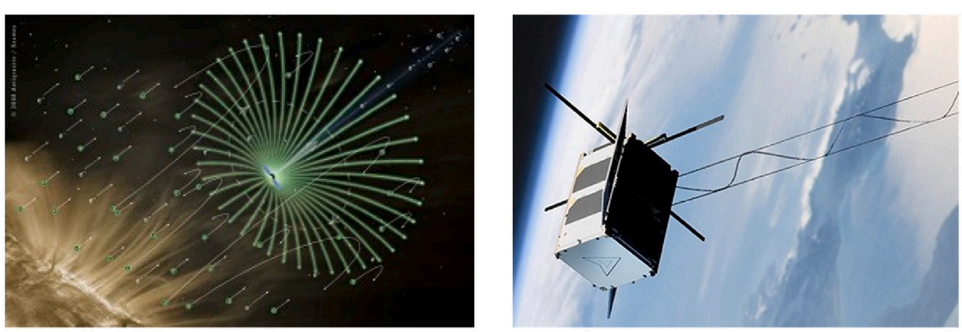
(a)



(b)



(c)



(d)

Fig. 14. Electric sail. Time history, among sails in the database in Appendix B, of: (a) deployed area, (b) mass, and (c) acceleration. For flown missions, the year indicates the date of launch. For concepts, the year is the approximate date of first description. Images in (d) are of (left) a variant of the radial E-sail and (right) AuroraSat 1, with sources in Appendix A.

NanoSail-D2 [38] and RAIKO [125]. Another important point is that one of the critical technologies for both electric and magnetic sails is the mechanism for deploying the sail tethers, which usually includes a spool. A similar technology is used by some space sails of other types too, as discussed in more detail in Section 3.9. It seems to be a single point of failure for single-tether missions and its reliability is quite critical. Moreover, although electric sails differ from membrane-type space sails like solar sails in certain aspects, they provide a complement and highlight the importance of developing large, lightweight space structures for other forms of propulsion. Such observations highlight important synergies between electric sails and other types of space sail.

3.6. Deployable membrane reflector

Alongside propulsive space sails, non-propulsive sails such as deployable membrane reflectors, antennas, and solar power sails are also being developed, sharing some common features and heritage, as discussed in this subsection and the next two. Three different types of reflectors can be identified: passive communication relays, Earth illuminators, and sunshades or external occulters.

Passive communication relay

The earliest flown reflectors were used as passive radio communication relays. The 1960s and early 1970s witnessed a growing demand for long-distance communications at the Earth's surface, before the

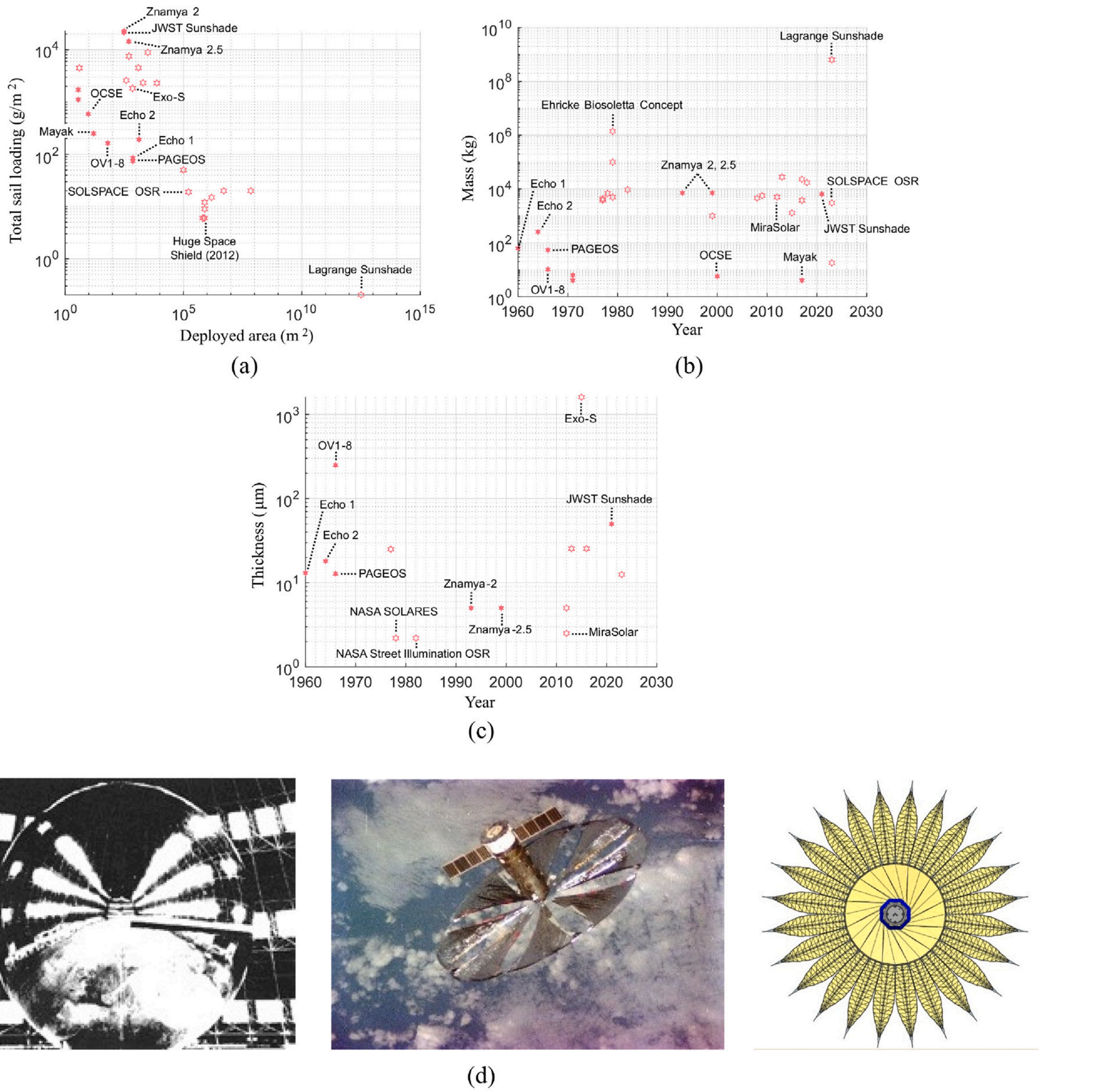


Fig. 15. Deployable membrane reflector. Plots, showing sails in the database in Appendix B, of: (a) total sail loading vs. deployed sail area, and time history of (b) mass and (c) thickness. For the JWST sunshade, the projected area is used, rather than the total multi-layer sail wetted area. For flown missions, the year indicates the date of launch. For concepts, the year is the approximate date of first description. Images in (d) are of (left) Echo 1, (middle) Znamya 2, and (right) a sharshade from NASA's Starshade Technology Development program, with sources in Appendix A.

advent of active communication satellites. In response, a series of flight tests was conducted on orbiting reflectors, including Echo 1, Echo 2, PAGEOS, OV1-8, Gridsphere 1, and Gridsphere 2 [24]. A picture of Echo 1 is shown in Fig. 15(d). These tests benefited from cross-pollination with the aforementioned Air Density Explorer series of balloon satellites for aeronomy experiments, which functioned as early drag sails (see Section 3.3). Moreover, they laid a foundation for the development of micrometre-thickness aluminised plastic membranes with Mylar and PET substrates [24]. Indeed, inspection of Figs. 8, 9, and 15 reveals that the total sail loading and thickness of these early reflectors are comparable to those of flown solar sails. As such, these missions paved the way for modern solar sail development, including by establishing the effect of solar radiation pressure (and air drag) on large reflective structures with high area-to-mass ratios, even though they were not intended to perform solar sailing [24]. These missions also involved important comparative studies on structural considerations such as materials and the application of inflatables for large space structures [24]. At around the same time, orbital flights were conducted on reflectors with sparse structures, consisting of wire meshes launched within a plastic membrane, exposed to the space environment after photolysation of the plastic substrate [24]. Though passive orbiting reflectors for ground-to-ground communications lost popularity in the early 1970s with the advent of active communication satellites, reflective balloon satellites have still continued to be used from time to time for other purposes, including geodesy [174] and satellite tracking [175].

Earth illuminator

In parallel, interest has grown in using deployable reflectors to illuminate the Earth's surface by redirecting sunlight from orbit. Building on Oberth's pioneering work in the late 1920s [53], multiple concept studies were conducted in the 1970s and 1980s, with extremely large areas and low total sail loading, as shown in Fig. 15(a) and (b). Again, these values are consistent with flown and concept solar sails, suggesting interoperability and synergistic development. Proposed concepts include NASA's orbiting solar reflector study to enhance terrestrial solar energy [176], followed by a near-identical but more consolidated NASA SOLARES concept [177]. A similar concept was also studied by NASA for illuminating several large cities across the US [178]. A series of designs by Ehricke [179] provide among the most expansive studies on the subject, aiming at industrial enhancement of terrestrial solar energy for electric power generation and illumination of the Earth for various purposes, including agriculture by enhancing photosynthesis, street illumination and climate management.

The first orbital flight of an Earth illuminating reflector was made in the 1990s. Znamya 2 demonstrated the proof of concept, utilising a design initially intended to function as a solar sail [56]. A picture is shown in Fig. 15(d). The mission's success marked the start of continuing studies on orbiting solar reflectors for Earth illumination. For instance a related technology study was conducted in the 2000s by Lior [7], followed by the MiraSolar concept proposed by Fraas [180]. One ongoing example is the SOLSPACE project [181]. The SOLSPACE project studied the orbiting solar reflector concept in detail, offering a near-term outlook on space-based solar power with orbiting solar reflectors, for applications beyond electricity generation [182,183]. The SOLSPACE project also proposed a technology demonstration roadmap that includes step-by-step integrated demonstrations [184]. In recent years, there has been a transition towards concepts using multiple small reflectors rather than a monolithic large one, emphasising scalability via constellations and formation flight [180,182,185], including in the private sector.[4]

Interestingly, artistic applications of orbiting deployable reflectors have also been considered, for various purposes including advertising and inspiration [186]. One example in the 1980s is ARSAT 0 Dialogue [186,187], which later evolved into a solar sail mission proposal called ARSAT 1 Helios [186,187]. A more recent one is Mayak [188], intended to double as a drag sail. It was launched in 2017 but its sail failed to deploy. These two examples highlight again the close synergies between deployable reflectors and other types of space sail.

Starshade and sunshade

Work on deployable reflectors has also contributed to the development of large sunshades and starshades for thermal and optical control of critical space infrastructure and more speculative space-based geoengineering applications. In this case, the objective is to reflect incident light away from a target, rather than towards it.

A starshade, or external occulter, is a light-blocking screen used in astronomy for exoplanet observation [9]. It is placed between a telescope's imaging system and a target star, to block out light from the star and make it easier to observe its surrounding planetary system. Large telescope — starshade separation distances (in the order of tens of thousands of kilometres) and large screen areas (tens of metres across) are needed to obtain a good quality shadow with minimum diffraction. Deployable membranes have received attention as promising screen candidates due to their favourable optical properties and ability to provide large areas with low mass.

Starshade mission concepts experienced a boom starting from the mid-1990s due to growing interest in exoplanet studies [189]. Initial concepts like UMBRAS [190] and BOSS [191] employed rectangular membranes in formation flight with the NGST (now known as the JWST). BOSS utilised a circularly symmetric transmission function imprinted on a transparent membrane to control diffraction via apodisation. Both used thin deployable membranes with a high area-to-mass ratio, and deployment from a rolled-up configuration like that used for the Hubble Space Telescope's solar array was considered [192], showing overlap with the design of deployable solar arrays.

In the mid-2000s, improved shadowing performance and easier manufacturing was obtained using an opaque screen, consisting of a central disc attached to shaped petals, as shown in Fig. 15(d). Several starshade concepts for space telescopes based on this design have been proposed, including for New Worlds Observer [193], THEIA [194], Exo-S [189], HabEx [195], and WFIRST [196]. Several parallel layers of membrane material with micrometre-scale thickness (e.g., Kapton) are commonly used, to maintain shadowing performance in the event of micro-meteoroid impact [193,194]. In some cases, like for Exo-S, low-density foam is added between the layers as a further means of impeding transmission of light after puncture [197], resulting in relatively large total membrane thickness as shown in Fig. 15(c). Due to stringent tolerances on petal shapes and positions for achieving required shadowing performance, extensive efforts have been invested into development of high-precision starshade deployment and support structures, which are usually stiff and bulky [189], resulting in relatively high total membrane loading as shown in Fig. 15(a). In addition to starshades for space telescopes, concepts for Earth telescopes have also been proposed, like the Remote Occulter [198].

Alongside starshades, sunshades are also being developed, with the aim of providing shielding from incident sunlight. One application has been to space telescopes. An example is the sunshield of the JWST (also called Sunshield Membrane Assembly, or SMA [199]), used for thermal management. It comprises five aluminised Kapton membranes each with an area of hundreds of square metres, with a thickness ranging from 25 to 50 μm, arranged on top of each other [200,201]. The LUVOIR A sunshade is another example, with a simpler design than that of the JWST, featuring only three thin-film layers deployed via coilable boom [202].

Applications of sunshades for geoengineering have been envisaged, too. Deployed areas are significantly larger than sunshades for space and Earth telescopes, given the aim of altering the Earth surface climate on regional or continental scales. Examples of recently proposed concepts are the Huge Space Shield [203,204], Lagrange Sunshade [205] and SOLSPACE combined climate service [183]. Extremely low total sail loading in the order of that of high-performance solar sails is being targeted as can be seen in Fig. 15(a), for practical launch and deployment of the large sun-blocking screens. Indeed, Matloff remarks than the Lagrange Sunshade is highly susceptible to solar radiation pressure, and that care is needed to avoid unintended solar sailing [205], though transparent occulters with near-zero radiation pressure are being studied as well [206].

In summary, deployable membrane reflectors have been developed for multiple applications, presenting synergies with other space sails. Large, lightweight reflector surfaces call for thin deployable membranes, and have prompted advancements in micrometre-level thickness thin film manufacturing and deployment technologies, which have also been applied to certain solar sails and drag sails. While passive communication relays and Earth illuminators have relatively relaxed shape accuracy requirements, there are more stringent tolerances for starshades, leading to research on high-precision support structures, applicable to other deployable space sails. Similar synergies can be identified for another type of non-propulsive space sail: the deployable membrane antenna.

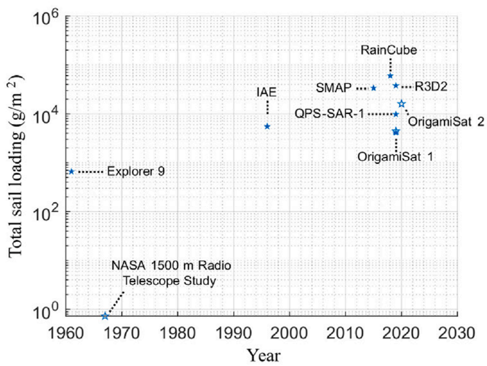
3.7. Deployable membrane antenna

The deployable membrane antenna traces its origins back to inflatable balloon satellites, in the form of simple passive reflecting curved membranes for communications applications. It has found continued usage in this domain to the present day, in increasingly small satellite form factors. More recently, flat, deployable reflectarray antennas have gained popularity, enabled by the miniaturisation of thin-film electronics. Both types of membrane antennas have flight heritage, and have common points with other varieties of space sail, as discussed below.

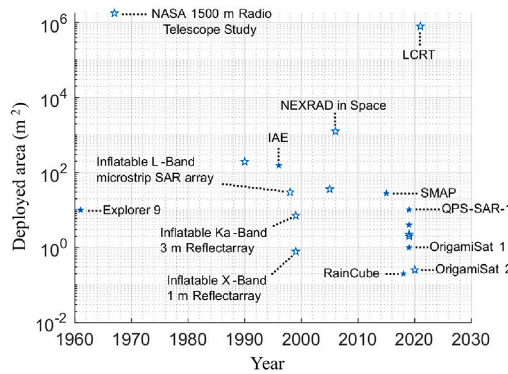
Spherical and parabolic antenna reflector

The first deployable membrane antennas were simple curved surfaces for reflecting incident radio waves. Flight experiments of spherical

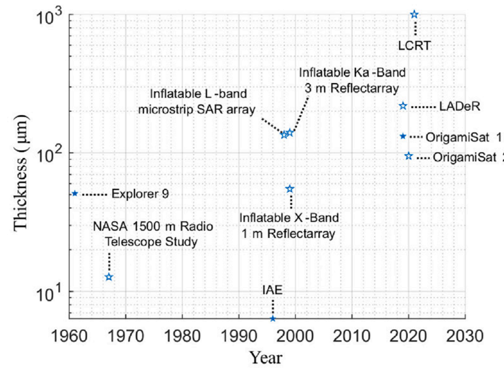
[4] A good example is Reflect Orbital: https://www.reflectorbital.com/.



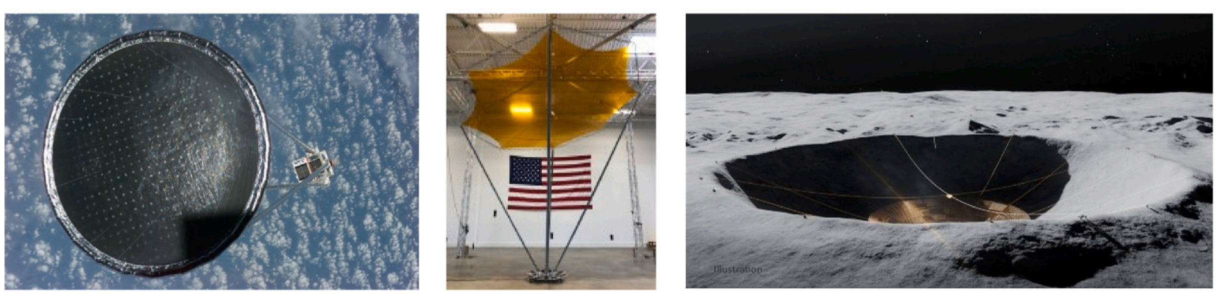
(a)



(b)



(c)



(d)

Fig. 16. Deployable membrane antenna. Time history, among sails in the database in Appendix B, of: (a) total sail loading, (b) deployed area, and (c) thickness. For flown missions, the year indicates the date of launch. For concepts, the year is the approximate date of first description. Images in (d) are of (left) the Inflatable Antenna Experiment (IAE), (middle) R3D2, and (right) the proposed Lunar Crater Radio Telescope (LCRT), with sources in Appendix A.

balloon antennas like Explorer 9 were conducted as early as the 1960s, as part of multi-space-sail development programs comprising deployable membrane reflectors and antennas for passive communications, aeronomy, and geodesy [24]. This early example shows that synergistic space sail development can bring about fast-paced, mutually-beneficial advancements, by pooling common technologies like thin metallised membranes, inflation mechanisms, and strain rigidisation.

Starting from the 1990s, mission concepts and flight experiments involving inflatable lenticular antenna reflectors were developed. One side is transparent to radio waves, and the other side acts as a parabolic dish reflector antenna. The Inflatable Antenna Experiment (IAE), shown in Fig. 16(d), is an early example. The 14 m diameter parabolic antenna consists of an aluminised Mylar sheet with a thickness of 6.35 μm, supported by an inflatable torus and three inflatable booms made of neoprene-coated Kevlar [22]. In other words, the IAE advanced the maturity of deployable membrane technologies commonly used in other types of space sail like solar sails and drag sails. It also provided data on the shape accuracy and dynamics of inflatable space structures. Other mission concepts include Quasat, a 6 m diameter radio antenna for a space telescope. A full-scale model was developed on the ground [207]. Another proposed concept is NEXRAD in Space, a 40 m diameter reflector antenna for weather monitoring on Earth [208]. The former employs an aluminised Kapton and Kevlar substrate, while the latter uses aluminised Mylar, both supported by an inflatable rigidisable torus.

Sparse membranes consisting of a deployable mesh have also been proposed and flight tested for reflecting antenna systems. These include both very large and very small designs. The NASA 1500-m Radio Telescope Study [209] and Lunar Crater Radio Telescope (LCRT) [60] are two examples of the former, with a km-scale diameter and featuring aluminium wires or ribbons with a mm-scale diameter or thickness. An artist's impression of the LCRT is shown in Fig. 16(d). There are clear structural commonalities with the magnetic and electric sail, presented in Sections 3.4 and 3.5, suggesting the potential for synergistic development.

At the other end of the size spectrum, recent years have seen the launch of deployable parabolic mesh antenna reflectors onboard increasingly more compact satellites in Earth orbit, starting from 100 to

1000 kg class ones like SMAP [210] and QPS-SAR-1 [211] and leading to 10 kg class nanosatellites like RainCube [212], notably for Earth remote sensing. CloudCube is planned as a follow-on mission to the latter [213]. As shown in Fig. 16(a) and (b), the deployed antennas have a relatively small size and high total sail loading, suggesting room for further mass savings via cross-pollination with other types of space sail.

Thin flat array antenna

Alongside curved membrane antennas, the development of miniaturised electronics opened prospects for flat membrane antennas in the 1990s [32], which have been actively developed to this day. Writing in 2005, Leipold highlights synergies with the development of solar sails: "many design aspects and technological solutions of the on-going solar sail development effort can be transferred to the completely different application of large microwave membrane antennas", noting common challenges such as "to manufacture sails using thin, ultra lightweight film membranes and to manufacture deployable ultra lightweight booms, to pack the sail membranes and the undeployed booms into a small volume which fits into the fairing of the launcher, and to deploy these ultra lightweight" structures [214]. Writing in 2002, Huang describes expected advantages of using a flat membrane antenna compared to a curved one: "It is believed that it will be significantly simpler to maintain in space the required surface tolerance of a flat 'natural' surface, such as a planar array, than a curved 'non-natural' surface, such as a parabolic reflector. In addition, a planar array offers the possibility of wide-angle beam scanning, which cannot be easily achieved by a parabolic reflector" [215]. Three main types of thin flat array antenna can be distinguished: the micro-strip array antenna, reflectarray antenna, and active phased array antenna. (Note that non-planar designs of these antennas have also been proposed and developed.)

The Inflatable L-band microstrip SAR array was the first inflatable array antenna ever developed, for ground tests by NASA's JPL in the late 1990s. It consisted of three parallel Kapton membranes, separated by a few millimetres, coated in copper etched into microstrip patches and power dividing lines [215,216]. The Kapton dielectric layer had a thickness of 130 μm, coated in 5 μm of copper. The membrane was supported by a rectangular inflated tube frame, rolled up into a cylinder when stowed. Around the same time, the JPL developed two circular inflatable reflectarray antennas, with diameters of 1 and 3 m, for operation in the X-band and Ka-band [215]. The X-band one featured two 50 μm thickness Kapton membranes each with a 5 μm copper coating, separated by a distance of 1.3 mm maintained by foam discs. The Ka-band one featured a single 130 μm thickness polyimide membrane coated on both sides with 5 μm of copper, etched into microstrip patch elements on one side and un-etched (i.e., acting as a ground plane) on the other [215]. The need for multiple membrane layers and coatings, tailored to specific communication frequency bands, leads to relatively thick membranes, as seen by comparison with the IAE in Fig. 16(c). (Note that in the plot, for multi-layer membranes only the thickness of individual membranes is considered, ignoring separation distances between them).

Later concepts have included DLR's SAR membrane antenna [214] and JPL's LADeR [217]. The latter, a reflectarray antenna, consists of a dual-membrane thin-film structure. Both membranes have a polyimide substrate and Quartz-epoxy facesheet, with a thickness in the order of hundreds of micrometres. One membrane features copper dipoles and the other a copper ground plane. The two membranes are separated by a few millimetres using collapsible S-shaped springs. As for the support structure, LADeR's designers refer to the TRAC booms used in the NanoSail-D2 solar sail mission [217], providing further evidence of cross-pollination between solar sails and deployable membrane antennas.

These developments paved the way for the first orbital flight of a deployable membrane reflectarray antenna, R3D2, in 2019 [218]. The deployed antenna payload is shown in Fig. 16(d). It features a Kapton membrane with copper etchings, supported by four CFRP booms and a pantograph [218]. Other flight demonstrations are planned in the near future. One is OrigamiSat 2 [219]. It has a pop-up two-layer reflectarray membrane antenna similar to that of LADeR, deployed by the elastic energy of coiled hybrid CFRP-metal convex tape booms. The mission builds on flight heritage of a deployable membrane shape memory alloy antenna onboard OrigamiSat 1 [220].

One final research direction is into membrane-type active phased array antennas [221]. For now, rigid circuit boards are required (i.e., the result is a plate rather than a membrane), but studies are being done on alternatives such as flexible printed circuits employing liquid crystal polymer. Electrical compensation enables good communication performance despite low membrane flatness [221].

In summary, deployable membrane antennas have shared features with other space sails from the beginning. Although they typically have smaller deployed areas and larger thicknesses than solar sails and de-orbiting drag sails, they leverage common technologies such as metallised thin plastic membranes and lightweight deployable booms. Moreover, extremely large wire mesh antenna concepts like the LCRT have similar structures to those of electric and magnetic sails, hinting at potential synergies for their future development.

3.8. Solar power sail

The final type of space sail examined in this review article is the solar power sail. The concept of a large, flexible self-supporting solar array membrane like OKEANOS [12] is comparatively recent, but builds on several decades of heritage in the development of flexible solar array wings. Both types of solar arrays are referred to as solar power sails in this study, as explained below.

Flexible solar array paddle

Flexible solar arrays have been developed since the late 1950s, with the aim of enabling lower mass electrical power systems for satellites, as explained in Section 2. Incremental advancements have been made to this day. The first large scale ground test was made in the late 1960s as part of a roll-up solar array concept study called RSA250 [222]. The 24 m^2 array consisted of silicon solar cells mounted on a flexible Kapton substrate, deployed by a coilable steel boom. Shortly thereafter followed the first orbital flight test of a deployable flexible solar array onboard the Communications Technology Satellite (CTS). It consisted of an accordion-folded solar array blanket with cells mounted on a flexible Kapton-fibreglass substrate, protected by coverglass [35]. In 1984, SAFE, a significantly larger flexible solar array, was deployed from the Space Shuttle. It consisted of two sheets of 25 μm thickness Kapton with a copper printed circuit laminate in between, partially covered in solar cells [62].

These technology demonstrations formed the foundation for the deployable solar arrays of the Hubble Space Telescope – FRUSA [223] – and of the ISS – SAW [73] and later iROSA [224]. FRUSA and iROSA were deployed from a rolled-up configuration, while SAW was accordion-folded. SAW remains the largest flexible solar array blanket ever flown in space. Since 2021, several iROSA units have been installed on the ISS to replace the ageing SAW. In addition to a two-fold increase in beginning-of-life solar cell efficiency vs. SAW, iROSA features advancements such as deployment via the strain energy of coiled carbon composite booms [224], similar to those used in recent solar sail missions like ACS3 [82].

Flexible solar array paddles have also started to be deployed from small spacecraft, including in deep space. Examples are the UltraFlex system onboard the Phoenix Mars lander in 2008 [225], and the ROSA system onboard the DART asteroid impactor in 2021 [226]. The former features solar cells installed on a lightweight open-weave mesh-type substrate, and an artist's impression is shown in Fig. 17(e). Most recently, in 2024 the LISA-T spacecraft, a 6U CubeSat, was

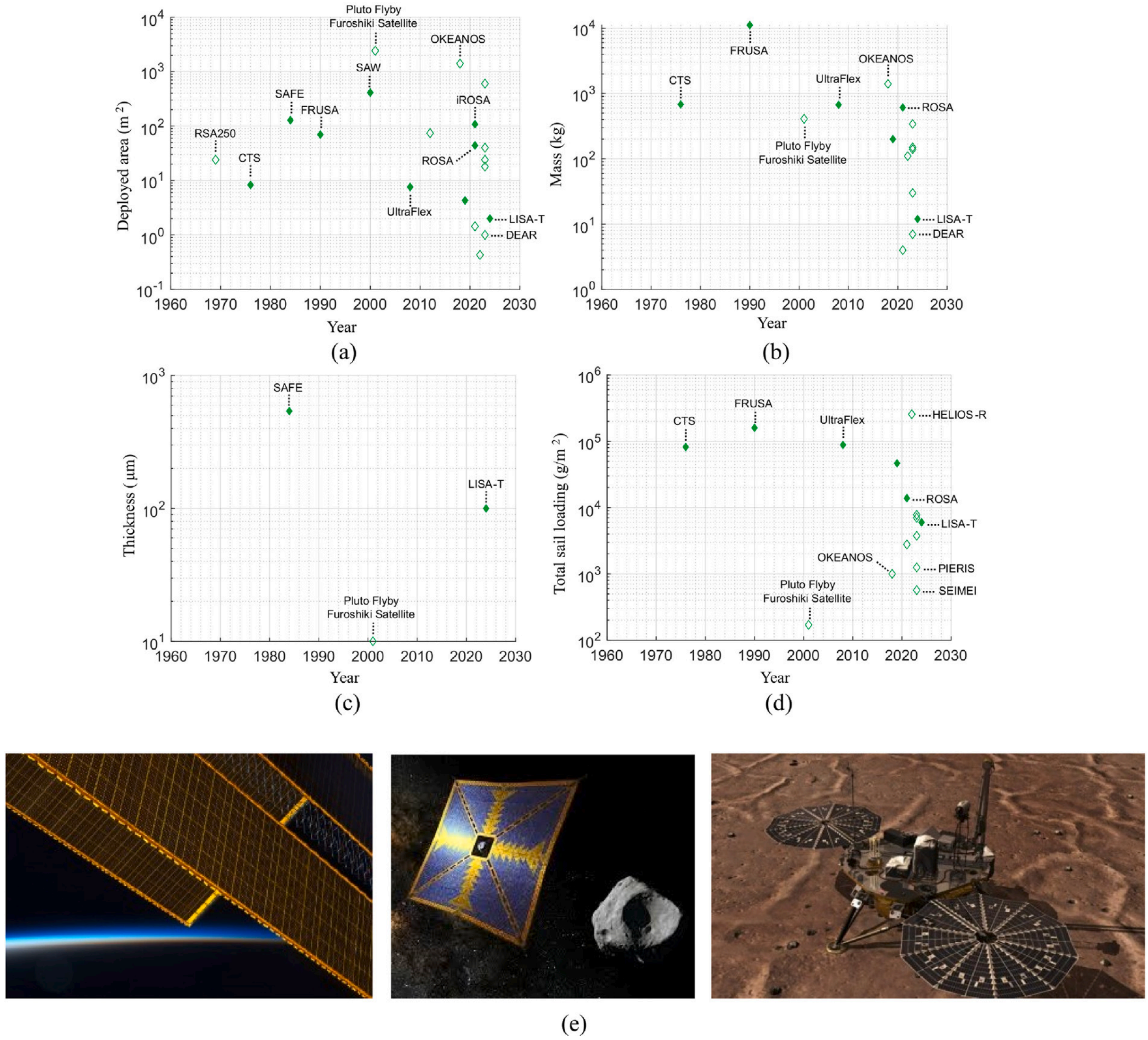


Fig. 17. Solar power sail. Time history, among sails in the database in Appendix B, of: (a) deployed area, (b) mass, (c) thickness, and (d) total sail loading. For flown missions, the year indicates the date of launch. For concepts, the year is the approximate date of first description. Images in (e) are of (left) the Solar Array Wings (SAW) of the ISS, (middle) OKEANOS, and (right) UltraFlex deployed from the Phoenix Mars Lander, with sources in Appendix A.

launched into Earth orbit with thin-film flexible solar cells embedded into a toughened CP1 membrane [227]. This type of structure has been referred to as Polyimide Embedded Photovoltaics (PE-PV) [228], a thin, low mass, flexible stack of polyimide substrate, thin-film solar cell, and protective polyimide coating, with a total thickness of around 100 micrometres or less. Other CubeSat-deployed flexible membrane solar array concepts have recently been proposed and are being developed, like PowerCube [229] and DEAR [230]. Through this sequence of flown and proposed missions, achievable solar array thicknesses have been reduced by around an order of magnitude over the past 40 years, as shown in Fig. 17(c), and are approaching those of other space sails like solar sails. (Note that for many deployable solar array membranes, limited data was found on the total thickness including solar cells, hence the small number of datapoints in Fig. 17(c).) Indeed, proposals have been made to incorporate DEAR into future solar sail missions [231]. Also, the developers of LISA-T emphasise that the spacecraft “utilises lessons learned from solar sail development in the design and fabrication of these petals” [227]. Both examples highlight growing synergies between solar power sails and other types of space sail.

OKEANOS-type solar power sail

Such synergies are particularly apparent in the IKAROS and OKEANOS missions, by ISAS/JAXA in Japan. Though known primarily as a solar sail, IKAROS featured flexible thin-film solar cells on 5% of its surface area [17], hence its comparatively large total sail loading in Fig. 8. This highlights the possibility of combining solar sailing with solar electric power generation and other propulsion types as per the mission needs. As for OKEANOS, the solar power sail was planned to drive the spacecraft’s ion thrusters for outer solar system exploration [12], without solar sailing. A rendering of OKEANOS is shown in Fig. 17(e). After OKEANOS was not selected for further development, alternative mission concepts featuring smaller OKEANOS-derived solar array paddles have been developed, such as OPENS0 [232] and OPENS2 [233]. A combined solar power sail and solar sail mission called PIERIS is also under consideration [232].

In summary, solar power sails have advanced from bulky solar cells embedded into a thick flexible blanket, towards thin-film membranes suitable for being embedded into solar sails. In parallel, extremely large, flexible and stowable, high-efficiency solar array wings have been developed for high-power applications like human spaceflight activities onboard the ISS. Advances in solar power sails have proceeded in parallel with the maturation of deployable solar concentrators [234] and space solar power satellites [235], which are opening up other frontiers in large-area space-based power generation.

3.9. Synergies: assessment and discussion

The above review of the state of the art reveals synergies between the different types of space sail. Some are already being utilised, while others show potential to be leveraged further. These synergies manifest especially strongly in three areas. The sails': design, applications, and development history.

Synergies of design

The eight types of space sail share common structures and materials in two notable design areas: the thin flexible membrane, and the sail deployment and support structure.

In terms of thin flexible membranes, regardless of sail type, reducing the thickness enables stowage and launch within a smaller volume, reducing the mass enables lower total sail loading, and increasing the area provides a larger surface for interacting with particles of gas, plasma, or electromagnetic waves. For sails relying on direct collisions between incoming particles or waves and the sail's structure, metallised (and specifically, aluminised) plastic membranes have emerged as a popular design choice. These include solar sails, laser-driven sails, drag sails, deployable membrane reflectors, deployable membrane antennas, and solar power sails. As early as the 1960s, large sheets of aluminised Mylar and PET with a thickness in the order of 10 μm were used in flight tests of deployable membrane drag sails, reflectors, and antennas, in the form of balloon satellites [24]. These experiments not only provided data on the in-space dynamics of thin deployable sails, but also advanced knowledge in methods for manufacturing, assembling, testing, and characterising micrometre-thickness metallised membranes. The technology was later transferred to flat membrane solar sails [17], drag sails [125], antennas [22], reflectors [236], and solar power sails [12], using a wider variety of plastic substrates like Kapton [237], CP1 [79], PEN [124,238], and APICAL NP [12]. Early laser-driven sails employed thin metallised membranes too [109], and thin plastic substrates have been incorporated into some recent designs as well [2]. As shown in Fig. 9(c), many different types of space sail have a similar thickness, around 10 μm or less, with values as low as a few micrometres for the most recent flown solar sails [238]. A general downward trend can be observed across all sail types.

In addition, membrane metallisation presents advantages even when solar sailing is not among the mission objectives: for drag sails, it increases resistance to degradation of the plastic substrate via atomic oxygen bombardment and/or exposure to UV radiation; for antennas, it raises the ability to reflect or radiate radio waves; for sunshade-type reflectors, it provides thermal control in the form of multi-layer insulation. Plastic-only membranes, too, have contributed to the advancement of multiple types of space sail. Thin Kapton [35,62,239] and more recently CP1 [227] membranes, with embedded photovoltaics and protective coatings, have found applications in large flexible deployable solar arrays.

In summary, the above examples reveal important synergies between space sail membranes. In most cases, advancements in sail thickness, materials, manufacturing, and testing methods are transferable between different types of sail. This will likely remain true in future as well, considering potential synergies between membranes with high thermal resistance for application to sundiver solar sails, laser-driven sails, and aerobraking drag sails for entry, descent, and landing, as well as membrane materials with extremely low sail loading like aerographite for multiple applications.

In terms of deployment and support structure, synergies between different types of space sail can be observed as well. For instance, inflatable structures have been used across a wide range of flown and concept space sail missions, comprising shapes like linear booms [124,186, 216], tori [135,147,240], lenses [22,150], and balloons [24]. Most recently, there has been growing interest in rigid deployable composite booms for a variety of applications. For instance, since the 1990s carbon fibre reinforced plastic (CFRP) booms have been used to support the deployed membranes of solar sails [241], drag sails [124], solar power sails [242], and deployable membrane antennas [214], scalable from a few metres to close to 20 m in length [238]. Indeed, writing in 2005, Leipold highlights synergies between the solar sail and deployable membrane antenna: "The functional requirements of the solar sail boom assembly are therefore generally comparable to a SAR membrane antenna application. Consequently the technologies being used for the solar sail offer potential spin-offs for a SAR antenna design" [214]. Various options for boom deployment are available, including passive extension via stored strain energy [224] and actuation via motors [127]. In this regard, another critical technology common to multiple different types of space sail is the mechanism for deploying the sail, which usually contains a spool. Such a structure is used by both tether and wire-type sails like electric sails and magnetic sails, but also by membrane-type sails like some solar sails and drag sails, including for boom deployment. It can act as a single point of failure, for instance in single-tether missions, and therefore high reliability is needed.

Prior to deployment, another consideration is stowage of the sail and its support structure within a compact volume. As shown in Fig. 9(d), solar sails, drag sails, and reflectors typically have larger deployed area to stowed volume ratios than deployable membrane array antennas and solar power sails, given the need to accommodate sail-mounted structures like flexible circuitry and solar cells onboard the latter two. Despite this, folding the sail into as small a volume as possible is a challenge shared by all space sails. For membrane-type sails, various folding patterns have been adopted like Miura-Ori [243], accordion folding [35,62,239], flasher folding [197], z-folding [12], and rolling [216,224,244]. As for laser-driven sails, most studies provide limited details on the sail stowage and deployment method, suggesting there is still room for cross-pollination with other types of space sail. Although wire and tether-type sparse membranes like electric sails and magnetic sails have a significantly different structure to those mentioned above, the need to stow the sail within a compact volume before deployment is the same. In this context, stowage and deployment methods developed for plasma brake electric sails [171] and mesh-type antennas [58,60] may be transferable to other types of space sail like solar wind electric sails and magnetic sails.

Finally, successful space sail operation relies on maintaining an appropriate sail shape and sail orientation after deployment, potentially for an extended time duration. On the one hand, shape accuracy requirements differ significantly between different space sails. As an example, starshades with diameters of tens of metres are required to achieve sub-millimetre shape accuracy to provide required shadowing performance via apodisation [189], needing rigid, high-precision support structures. On the other hand, some challenges are shared by all space sails, such as attitude control of a flexible structure, reliable operation even after impact by a resident space object (like space debris or a micrometeoroid), and sail integrity in the harsh space environment. For instance, in his seminal 2004 paper on the solar wind electric sail, Janhunen writes: "Questions related to the shape, including how to keep the mesh in its desired shape, are very similar in the electrical sail to what they are when designing solar sails" [21]. He goes so far as to say that: "Because solar sail designs have been studied by many authors, we do not dwell on the subject here" [21]. Indeed, from a structural and operational perspective, the square E-sail [21] resembles the square solar sail, while the spin-tensioned radial E-Sail [161,162] resembles the helio-gyro solar sail. Looking to the future, continued cross-pollination between space sails is expected to bring mutually-beneficial outcomes.

Synergies of application

Synergies are not only apparent in the way space sails are designed, but also in the way they are used. This manifests in two ways: a given

Table 5
Multi-functional space sails, intentionally designed to play several different roles as part of their primary mission objectives.

Mission	Solar sail	Laser-driven sail	Drag sail	Magnetic sail	Electric sail	Membrane reflector	Membrane antenna	Solar power sail	Description	Ref.
Flown										
Explorer 9, 19, 24, 39 (*1961*, *63*, *64*, *68*)			O			O	O		Balloon satellites for study of the upper atmosphere, with reflective metallised surfaces used in ground-based optical tracking and to transmit a radio beacon.	[24]
Gridsphere 1, 2 (*1971*)			O			O			Balloon satellites composed of a sparse wire mesh, used as passive communication relays and to investigate the impact of balloon design on aero-assisted orbital decay.	[24]
NanoSail-D (*2008*)	O		O						Solar sail precursor with a focus on aero-assisted orbital decay in LEO.	[38]
IKAROS (*2010*)	O							O	Solar sail with a flexible solar array on part of its surface.	[17]
NanoSail-D2 (*2010*)	O		O						Same as for NanoSail-D.	[38]
CubeSail, UK (*2015*)	O		O						Same as for NanoSail-D.	[237]
Mayak (*2017*)			O			O			Tetrahedral pyramid-shaped reflective sail to study the brightness of in-space objects, for aeronomy, and for fast de-orbit via air drag.	[122]
CubeSail, US (*2018*)	O		O						Same as for NanoSail-D.	[245]
OrigamiSat-1 (*2019*)							O	O	Multi-purpose deployable membrane with flexible solar arrays and antennas.	[220]
LISA-T (*2024*)							O	O	Deployable membrane with polyimide embedded photovoltaics and embedded antenna elements.	[227]
Concept										
NASA Solar Energy OSR (1400 km alt.) (*1977*)	O					O			Disc-shaped free-flying reflectors with orbital manoeuvring via solar sailing	[176]
NASA Solar Energy OSR (800 km alt.) (*1977*)	O					O			Square-shaped free-flying reflectors with orbital manoeuvring via solar sailing	[176]
NASA SOLARES (*1978*)	O					O			Disc-shaped free-flying reflectors with orbital manoeuvring via solar sailing	[246]
NASA Street Illumination OSR (*1982*)	O					O			Disc-shaped free-flying reflectors with orbital manoeuvring via solar sailing	[178]
Starwisp (*1985*)		O					O		Wire mesh sail for interstellar travel driven by Earth-based microwave beam, serving as an antenna by using microcircuits at the intersection of the wires.	[107]
Atchison's Sprite (*2010*)	O						O	O	Thin-film silicon chip-sat solar sail with embedded photovoltaics and transmit-only beacon.	[247]
E-sail with small photonic blades (*2013*)	O				O				Solar wind electric sail with small solar sails at the tips of its tethers, for propellant-free spin control.	[172]
FGPB (*2014*)	O		O		O				Scalable and adjustable electric sail with solar sails at the tips of its tethers, serving as a solar wind electric sail, or heliogyro solar sail, or plasma brake, or drag sail, or their combination.	[173]
Alpha CubeSat (*2016*)	O						O	O	Retro-reflective solar sail with four ChipSats embedded at its corners, each featuring a flexible solar cell and a helical antenna.	[90]
Breakthrough Starshot (*2016*)		O					O		Laser-driven sail craft for travel to Alpha Centauri, with thin-film metasurface for phased-array communication.	[72]
ESail-MSail (*2016*)		O		O	O				Laser-driven sail craft for travel to Alpha Centauri, with deceleration on arrival by an electric sail and a magnetic sail.	[151]
UWDES (*2017*)			O		O				Tuft of charged deployable thin wires used for de-orbiting microsatellites in Earth orbit via combined Coulomb drag and aerodynamic drag.	[248]
Project Dragonfly (*2019*)		O		O					Laser-driven sail craft for travel to Alpha Centauri, with deceleration on arrival via magnetic sail.	[110]

(*continued on next page*)

Table 5 (*continued*).

Kon-Tiki (*2019*)	O							O	Solar sail with polyimide embedded photovoltaics on part of its surface.	[228]
Gama Beta (*2020*)	O		O						Solar sail, to be used as a drag sail for de-orbiting the satellite at mission end.	[39]
OrigamiSat-2 (*2020*)							O	O	Deployable reflectarray antenna with a thin-film solar array on part of its surface.	[219]
HELIOS-R (*2022*)							O	O	Deployable membrane with a thin-film antenna and thin-film solar array on part of its surface.	[242]
LightCraft (*2023*)	O						O	O	Sundiver mission with multi-functional solar sail membrane, featuring embedded photovoltaics and thin-film antennas.	[104]
Interplanetary Rapid Transit Mission (*2023*)		O	(O)	(O)	(O)				Laser-driven sail craft for fast Earth–Mars transit, with deceleration on arrival by a Mars-based laser (or aero-assist, or an electric sail, or a magnetic sail).	[117]
Microsatellite aero sunlight reflectors (*2023*)			O			O			Formation flight control of microsatellites equipped with deployable reflectors using air drag in Earth orbit.	[249]
PIERIS (*2023*)	O							O	Solar sail with a flexible solar array on part of its surface.	[232]

Notes:
– The symbol “O” indicates that the sail is designed to achieve the corresponding function, as part of the primary mission objectives.
– For flown missions, the year indicates the date of launch. For concepts, the year is the approximate date of first description.

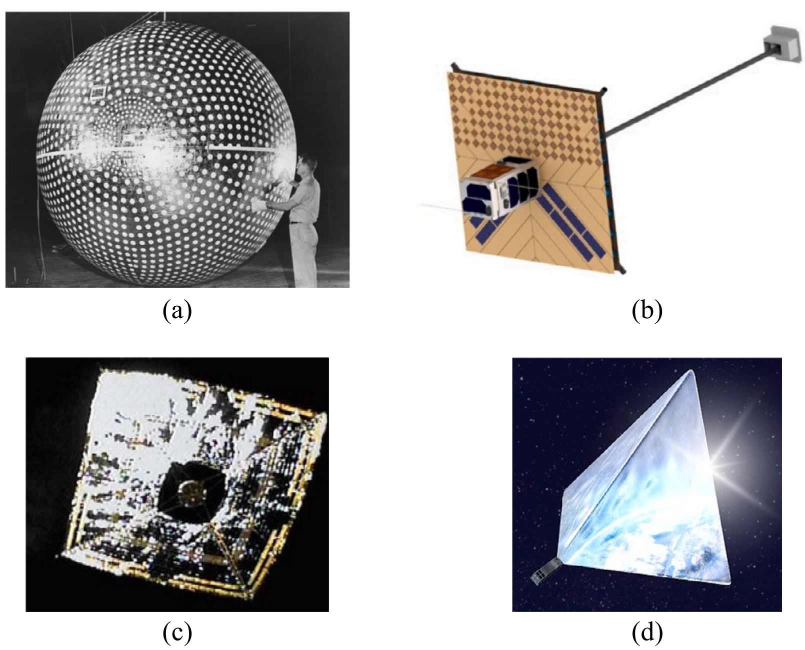


Fig. 18. Examples of multi-functional space sails. (a) Explorer 9, flown in 1961. The inflatable metallised balloon served as: a drag sail, due to its large deployed area and low mass; a reflector, due to its aluminised coating; an antenna, due to its two-hemisphere structure separated by a plastic strip at the equator. (b) OrigamiSat 2 concept, planned for launch in 2025. The deployable membrane serves as: a reflectarray antenna (top half); a solar power sail (bottom half). (c) IKAROS, flown in 2010. The large deployable membrane serves as: a solar sail; a solar power sail, owing to flexible solar cells on part of its surface area. (d) Mayak, launched in 2017. Based on available information, the sail was never deployed. Its pyramid-shaped metallised sail was intended as: a reflector, for studying the brightness of space objects; a drag sail, for accelerated de-orbit. Image sources are in Appendix A.

space sail functioning as multiple different types of space sail, and different sails providing complementary operations in the context of a space exploration or utilisation program.

As for multi-functional space sails, Table 5 provides close to 30 examples of a given space sail playing several different roles at the same time. Flown and concept missions are both included. Fig. 18 shows illustrative missions. Two important observations are as follows.

The first is that all eight of the different types of space sail appear. In other words, all space sails have potential to be combined with at least another, to extend the range of achievable mission outcomes. Various combinations have been considered. Particularly popular ones are the solar power sail and deployable membrane antenna (seven missions), solar sail and drag sail (six missions), and solar sail and solar power sail (six missions). For instance, for de-orbit applications, the solar sail — drag sail combination enables de-orbit from higher altitudes, using the solar sailing mode where air density is negligible, and switching over to the drag sail mode at lower altitudes where the atmosphere is thicker [39]. For solar sailing applications, installing thin-film solar electric generators and thin-film antennas on the sail membrane offers a means of reducing total spacecraft mass and increasing available solar photon acceleration [104,247]. Moreover, as can be seen in Appendix B, compared to other types of space sail, a large number of solar sail mission concepts have been proposed, spanning an extremely broad range of the design space as shown in Fig. 10 and as discussed in Section 3.1. Together, these points suggest that, while synergies are apparent between all types of space sail, solar sails offer an especially promising means of contributing to their mutually-beneficial development, lending support to the hypothesis made in Section 2.3.

The second important observation from Table 5 is that the number of multi-functional sails among both flown and concept missions has increased significantly in the last 15 years, even accounting for an overall increase in the number of missions during that time (see Appendix B). This reveals a growing awareness of and interest in leveraging synergies between types of space sail. One reason is the convergence of space sail topologies. On the one hand, many different configurations have been considered, as discussed in Sections 3.1 to 3.8. On the other hand, recent years have seen a growing popularity of flat, moderately-scaled sails with deployed surface areas in the order of metres to hundreds of metres squared, as shown in Fig. 9(a), among both flown and concept missions. In this context, the time appears right for further cultivating and availing of synergies between different types of space sail.

As for complementary operations, as already discussed in Section 2 (see Fig. 6) and as evidenced in Sections 3.1 to 3.8, different types of space sail cater to missions in different regions of space, from planetary surfaces, to their atmospheres, to interplanetary space and beyond. In this way, combining multiple missions using different types of space sail provides access to a wide range of near-Earth, interplanetary, and even interstellar destinations, in the context of comprehensive space exploration and utilisation programs.

Synergies of development

In fact, historically, many space sail development programs have grown by leveraging and promoting synergies between different space sails. NASA offers an interesting example. In the 1960s, the NASA Langley Research Center conducted flight tests of multi-functional space membranes emphasising synergies between inflatable balloon reflectors, antennas, and drag sails [24]. Building on this heritage, the NASA Jet Propulsion Laboratory led a concept study on the Halley's Comet Solar Sail in the 1970s [40], which prompted the formation of the Planetary Society and later launch of its Cosmos 1, LightSail 1, and LightSail 2 solar sail missions. In parallel, the NASA Marshall Space Flight Center funded development and ground testing of two large solar sails in the early 2000s through the "In-Space Propulsion Technology" (ISPT) project [250] on behalf of the NASA Science Mission Directorate [251], and later led its own solar sail activities culminating in the launch of NanoSail-D, NanoSail-D2, and NEA Scout. Collaboration with the NASA Ames Research Center during these missions contributed to the latter's expertise in miniaturised drag sails for CubeSats, which it is applying to the TechEdSat series of satellites [123]. In the 1970s, NASA Ames had led studies on orbiting thin-film solar reflectors for terrestrial power generation utilising solar sail technology [176,178]. The Marshall Space Flight Center is also developing membranes which combine the solar power sail and deployable antenna, inspired by technologies from its solar sail portfolio [227,228].

Another example can be found in Europe, where solar sail research and development took root in the 1990s. On an agency level, a leadership role was played by the European Space Agency (ESA) and the German Aerospace Center (DLR), with contributions also from the French space agency (CNES). Notably, in 1998 DLR and ESA established a joint funding programme for solar sail development [252]. The collaboration built upon DLR's earlier concept studies such as MESSAGE and ODISSEE (the latter co-led by NASA JPL). DLR developed niche expertise in deployable composite booms which it has applied to further solar sail missions [39,238] but also to deployable membrane antennas [214] and drag sails [253].

In Japan, the Institute of Space and Astronautical Science (ISAS, now part of the Japan Aerospace Exploration Agency, JAXA) began studies on deployable membranes for space exploration in the 1980s [143,243]. In 1985, the Solar Sail Union of Japan was formed as an ISAS study group, with the aim of developing a solar sail to enter the Earth–Moon solar sail race organised by U3P, a French NGO [243,254,255]. Japanese research on solar sails has continued to this day [83,256,257]. Since the 1990s, solar power sails have gained increasing attention [12,63,232,258]. In parallel, since the 2000s there has been active research on deployable aerodynamic decelerators [147,149]. Magnetic sails drew significant research efforts in the 2000s–2010s [20,69]. Some research groups have conducted work on multiple types of space sail simultaneously [83,145,154,259].

One final example is provided by Russia. In the 1980s, the US government initiated the Columbus 500 Space Sail Cup, with the aim of promoting solar sail development around the world [260]. Although the race did not materialise due to funding issues, many design proposals were generated, providing creative impetus for later flown missions. For instance, the former USSR's submission was used as the basis for the Znamya series of deployable membrane reflectors, launched in 1993 and 1999 [85]. The program lead, Space Regatta Consortium, emphasised a goal of developing "large thin film deployable structures as well as some applications", not limited to solar sails and reflectors [261]. According its website,"The Znamya Space Research Experimental Program, is to test in open space a new series of large thin-film structures formed by centrifugal forces, as well as to conduct other applied space experiments (e.g., flight trajectory generation, remote attitude control, illumination of the Earth surface, surface surveillance, and so on). In the future, we plan to use large thin-film structures for various purposes, such as: solar sails; power satellites; wake shields; anti-micrometeorite shields; solar reflectors; orbit-based antennas; on-orbit telescopes; other experiments" [261]. These examples reveal that a number of space sail missions have evolved through multi-sail programs spanning across a broad range of different types of space sail, providing further evidence of synergies between them.

In summary, space sails have been conceived, developed, and flown for a wide range of objectives. State of the art space sails span a broad range of the parameter space, for example in terms of deployed sail area and total sail loading. On the other hand, they present important synergies, not only in terms of design and application, but also of their development process. In particular, multi-sail missions, in which a given sail plays the role of several different types of sail, highlight intrinsic synergies between space sails for expanding the range of achievable mission outcomes and for maximising the utility of satellite structures. Such missions reveal a growing awareness of and interest in leveraging synergies between types of space sail. Flown solar sails have played an especially important role in this regard, contributing to the rising popularity of flat, moderately-scaled sails with a deployed surface area in the order of metres to hundreds of metres squared. Against this backdrop, the time appears right for further harnessing and promoting synergies between different types of space sail, towards the achievement of space exploration goals around the world.

4. Space sails for supporting the achievement of future space exploration goals

The idea of space sails has been of interest for fulfilling space exploration goals around the world for many years. They are an attractive solution for resource-constrained space missions. In this section, ongoing and future space exploration goals are outlined based on publicly available information, primarily in English, although attempts were made to identify activities from non-English resources, as well. These will be discussed as space sailing-*applied* and -*applicable* activities. The former will focus on technology development and space missions explicitly related to space sailing, whereas the latter will look at missions and programmes where space sailing may be of interest to reach the goals. The discussion focuses on space exploration goals of some of the major space agencies, which have historically shaped and continue to set the direction of global space exploration, as discussed in Section 1. Despite this, as will be explained, the variety of actors contributing to the formulation and realisation of these goals is becoming increasingly broad, with specific roles being taken up by private companies and other organisations, including via support (e.g., contracts) from major space agencies.

4.1. National Aeronautics and Space Administration (NASA)

The NASA Space Technology Mission Directorate (STMD) published the document "GO: Advanced Propulsion" in August 2023, outlining the agency's view on various propulsion systems in terms of function, potential, and level of development, spanning from the near (<10 years) to mid term (10–20 years) [262]. According to this document, the agency considers primarily solar sails but also magnetic sails as part of unique platforms for enabling novel capabilities, such as Sun or Earth pole sitting observatories. NASA activities on this front are currently at TRL 6 to 8 [262]. Strategically, these technologies (again, primarily solar sail) are described as "sustain", continuing the development of an existing portfolio of activities described in Section 3.9 and discussed later in this subsection. The document also compares propellant-less propulsion (PLP) systems against electric propulsion (EP) systems, in terms of historical developments and projected capabilities for various envisaged EP applications. Interestingly, magnetic sails are considered an option for high delta-V planetary missions of various sizes, as well as repositioning of crewed and uncrewed assets in cislunar space in the context of near-term EP applications. However, it is noted that significant development is required [262]. As for solar sailing, it is being considered for manoeuvrability and control of Earth orbiting satellites, with a focus on small spacecraft in the near term, with ACS3 being a good example [238]. Another comparison of PLP was made against mid-term applications of EP for precision control of constellations and space observatories. Solar sailing, particularly for small satellites and precision control, is noted as being under development in the context of projects NEA Scout, Advanced Composite Solar Sail System (ACS3), and Solar Cruiser [89,238,263].

NASA STMD published other noteworthy strategy documents in 2023. These include "LAND: Entry, Descent, and Landing to Enable Planetary Science Missions" [264]. It highlights drag sails within aerocapture/deorbit technology, particularly in the context of small satellites, as an enabler of missions to ice giants (e.g., Neptune and its moon Triton), with initial testing around the Earth [264]. Another document is "EXPLORE: Small Spacecraft Technologies", envisioning highly efficient propulsion, including solar sails, to enable more diverse small satellite missions [265]. Some other side documents, such as "EXPLORE: In-space Servicing, Assembly, and Manufacturing (ISAM) and Rendezvous, Proximity Operations and Capture (RPOC)", reference giant sail-like structures to be assembled in space for observatories, starshades, and related applications [266]. These examples all suggest an intent to reach various space exploration goals via space sailing.

As for existing projects, NASA is pushing forward with various solar sailing activities, despite the failure of NEA Scout (unrelated to its solar sail). NASA recently launched a 12U CubeSat in April 2024 within the ACS3 project, to deploy a 74 m^2 solar sail with a novel deployable composite boom technology [238], which was achieved successfully on 29 August 2024 [267]. ACS3 is a major solar sailing programme of NASA, developing the above-mentioned boom technology and validating sub-scale solar sails in Earth orbit with the aim of growing sail sizes progressively [238]. The project intends to reach a 500 m^2 solar sail area from 2025 onwards, for which the technology is presented as being mature [238]. In the near term of 3 to 5 years (interpreted here from the launch of ACS3, hence up to 2030), the project's goal is to reach a boom length that allows for deployment of a 2000 m^2 sail (45 m by 45 m square) [238]. Beyond the 2030s, larger sails are considered a possibility with further step-by-step validation of the ACS3 system, particularly targeting space weather applications with 5000 m^2 sails [238].

To that end, the Solar Cruiser mission is proposed to demonstrate capabilities of solar sail technology for space weather and heliophysics applications via a 40 m by 40 m sail [89]. The project could not receive a "go decision" for its planned 2025 launch. Similar to NEA Scout, the problem was not the sail. The decision was made to replace the craft's reaction wheels following failure on another NASA mission, leading to postponement of launch and budget overstretch to keep the project going. However, it appears that a 2028 launch may be possible with additional funding [89]. In either case, a number of ground tests are being performed for the Solar Cruiser deployment system, which would qualify its solar sail for launch [89] and may be used for other proposed missions based on Solar Cruiser technology. One example is the High Inclination Solar Mission, with four quadrants of Solar Cruiser sails (a total of 7000 m^2) [268]. Solar sailing opens up unique capabilities for large delta-V missions in principle. NASA's interest in sustaining solar sail technology may enable these missions to launch in the near to mid term. In parallel, it is worth noting that thin-film membrane technologies developed within NASA's solar sail portfolio are being adapted for other applications, like deployable membrane solar arrays and antennas [228].

To identify expected future space sailing-applied and -applicable activities, one indicator is the number of projects supported by the NASA Innovative Advanced Concepts (NIAC) programme. This provides insight into early-stage research and development areas which are well-positioned to grow further. NIAC projects are funded by STMD in line with envisioned future priorities in NASA Technology Strategy. Between 2015 and 2024, at least 12 projects have been supported by NIAC in which space sailing mission concepts, material studies, and related ideas were present (some have been supported multiple times or at multiple stages).[5] One example is an exoplanet imaging mission from the solar gravitation lens, with 16 small spacecraft equipped with a 1000 m^2 area solar sail [269]. Another is a diffractive solar sail project investigating more efficient use of the technology [106]. A project awarded funding in 2024 consists of a swarm of laser-driven picospacecraft for coordinated, autonomous exploration of the Alpha Centauri system [270].

Another indicator of expected future space sailing-applied and -applicable activities is provided by the "Decadal Survey" documents. These are used to shape NASA's future space exploration plans, and outline the community's scientific priorities. They are prepared and published by the National Academies of Sciences, Engineering and Medicine (NASEM) of the USA. The most recent document covers the decade starting in 2023, and is titled "Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032 (2023)" [13]. Below, only some of the highest priority missions are discussed, with a focus on space sailing. The highest priority Flagship mission recommendation is an Uranus Orbiter and Probe mission, for making atmospheric measurements among other objectives [13]. A mission such as this will require high delta-V to reach the planet, and deceleration upon arrival. As discussed above, the use of aerocapture/de-orbit technology is part of NASA's technology development strategy to enable such missions, and concept studies have already been conducted [271]. Aerocapture/de-orbit could be combined with solar sailing technology to satisfy demanding delta-V requirements, though it may be of less interest given the large distance from the Sun. Similar remarks can be made for the second priority mission, Enceladus Orbilander [13]. In

[5] Funded studies can be found at: https://www.nasa.gov/niac-funded-studies/ (accessed 21 May 2024).

this case, additional risks are associated with surface-emitted plumes from the geysers of Enceladus impinging on the sail structure, though its closer distance to the Sun could alleviate some of the delta-V requirements.

Among the four unranked recommended missions, Europa Lander and Neptune-Triton Odyssey [13] may benefit from space sailing technology in a similar way to the two highest priority missions, while facing similar issues. The Mercury Lander mission [13] could make significant use of solar sailing due to higher achievable thrust close to the Sun, potentially allowing for a smaller mission and lower launch cost. Similarly, the Venus Flagship mission, including an orbiter, lander, aerobot and small satellites [13], could make use of solar sails and drag sail technology for miniaturising satellite components. This is an area that NASA has already matured through the NEA Scout and ACS3 missions. Indeed, a white paper on deployable entry vehicles refers to several missions where this technology can directly be applied within the priorities outlined in the Decadal Survey, which includes Venus aerocapture for small satellite, alongside Mars, Titan, and ice giants as outlined earlier [272]. The paper further presents the significant benefit that maturing this technology could bring even as a secondary payload [272]. The authors note that aerocapture is still perceived by NASA as being a high-risk high-return technology [273]. However, NASA's ADEPT and HIAD programmes highlight significant progress already made in advancing the maturity of deployable membrane entry vehicles (see Section 3), suggesting further efforts and applications in this area.

NASA arguably has the most extensive publicly available goals for space sail development and utilisation, both applied and applicable. Another space agency with mature technology and a defined strategy for space sailing is JAXA, discussed in the next subsection.

4.2. Japan Aerospace Exploration Agency (JAXA)

JAXA demonstrated solar sailing with IKAROS [274], and has since developed the technology for future missions. One of these was the ambitious mission proposal OKEANOS, discussed in Section 3. Its cancellation due to cost considerations has opened up the discussion for JAXA (particularly researchers at its Institute of Space and Astronautical Science, ISAS) to re-evaluate ideas surrounding space sailing, both in terms of general technology development and mission ideas, around the Earth and in interplanetary space, as outlined in a recent document [232]. It is noteworthy that these ideas primarily centre around solar power sails rather than solar sails, continuing a trend that took root in Japan in the 1990s as discussed in Section 3.9. In parallel, research and development continues on the deployable aeroshell for aerocapture, entry, descent and landing, as part of an effort initiated in the early 2000s [147,149].

As for general technology development for solar sails and solar power sails, various kinds of deployable boom systems are currently under research at JAXA, an effort which is projected to continue into the future [232]. While the largest size to be developed is unclear, a sail smaller than 100 m^2 (10 m by 10 m square) appears to be the target due to limitations imposed by boom deployment, catering to small spacecraft [232]. Note that the focus on booms for sail deployment and support marks a departure from spin-type centrifugal deployment and membrane tensioning used in the IKAROS and OKEANOS missions. JAXA's focus on smaller sails appears in contrast with NASA's step-by-step incrementation of size, which may be indicative of future mission applications at JAXA, as discussed below.

Focusing on solar power sails and solar sails, JAXA's vision for the future of space sails includes various thin-film technologies which can be attached to a sail membrane: a versatile high-efficiency solar array paddle applicable to several classes of missions, high-capacity communication via an array antenna, high angular resolution interferometry for Earth and planetary applications, and a small deployable reflective sheet as a target marker for small body missions (departing from the spherical target markers used in Hayabusa missions) [232]. These are in contrast to NASA's focus on heliophysics and space weather applications [262]. The above vision suggests a dynamic era of space sail research at JAXA over the next decade with several potential space mission applications, discussed below. Another area of interest to JAXA is efficient utilisation of solar radiation pressure for spacecraft attitude and orbit control, notably by modifying the sail shape or configuration, as explained in more detail below [232].

JAXA has several existing space mission projects to mature its solar sailing and solar power sailing technology and apply it to potential future planetary exploration. Deployment of a 1 m square sail with fixed-boom technology was planned by the HELIOS payload in the RAISE-3 mission in 2022. It would have included sub-scale tests of thin-film solar power generation, interferometry, and high-capacity communication [232]. The failure of the Epsilon-6 rocket delayed this test mission, and now a rebooted HELIOS-R payload is planned onboard the RAISE-4 mission in 2024 [232]. For this mission JAXA added a new experiment within the payload, for sail shape control by shape memory alloy wires, in view of eventual application to orbit-attitude control of sail-equipped spacecraft including solar power sails [232].

JAXA is also developing a thin-film solar array paddle and associated components for world-leading solar power generation efficiency (200 W/kg), in the form of a 9 m^2 triangular solar power sail [232,275]. This technology is used in ongoing proposals for Saturn flyby and Trojan asteroid/Centaur missions, called OPENS0 and OPENS2 respectively, where OPENS stands for Outer Planet Exploration by Novel micro-Spacecraft. Both spacecraft are planned to be equipped with two solar array paddles each, with an increase in paddle area from 9 m^2 to 20 m^2 for the latter [232]. OPENS0 is equipped with chemical propulsion and OPENS2 with electric propulsion, both relatively small spacecraft with a wet mass of approximately 100–200 kg [232,233,275].

Another area to which JAXA plans to apply its solar power sail technology is exploration missions deployed from its planned deep-space orbit transfer vehicle (DSOTV). DSOTV is part of JAXA's mid- to long-term space strategy for allowing frequent access to the Moon and other deep space targets by smaller (and potentially cheaper) spacecraft, via an intermediate vehicle [276]. Such a vehicle offers potential to reduce the stringent delta-V requirements for escape from the Earth's gravitational well and transfer to interplanetary targets, by using a space depot and later a deep space depot [276]. To that end, a variant of the OKEANOS sail-craft and lander combination is planned to be used as a DSOTV and lander combination. DSOTV employs thin-film solar arrays, and the lander, with take-off capability, uses the deployable membrane target marker mentioned previously [232].

An alternative concept to DSOTV plus lander is DSOTV plus piggy-back satellite, to perform challenging missions. One envisaged payload is a small solar power sail spacecraft named PIERIS. It is a microsatellite with a 4.9 m by 4.9 m sail in pyramid configuration (canted by 5 deg, for attitude stabilisation under solar radiation pressure) [232]. The deployable membrane combines the functions of a solar power sail and solar sail, to demonstrate hybrid solar photon propulsion and electric propulsion (with a water ion thruster). A variant of this mission is also proposed to be injected to the Sun–Earth Lagrange point L2 [232]. While the exact objectives of this latter mission are unclear, it is understood that orbit-attitude control by low-thrust propulsion is aimed at. Moreover, JAXA's lunar exploration programme is to be supported by a 6U solar power sail CubeSat, using PIERIS technology stowed in a 2U volume [232]. In summary, JAXA's new solar power sail programme may enable multiple sample return and exploration missions extending to the outer solar system by combining several space sailing technologies (solar power sail, solar sail, deployable membrane antenna, deployable membrane reflector), in tandem with a lander and a DSOTV.

Focusing on drag sails, JAXA and the government of Japan have identified the deployable membrane aeroshell as a strategic technology for supporting the country's future space exploration and utilisation efforts. This is reflected in the "Medium-to long-term strategies in the field of space transportation systems" formulated by the Space Transportation System Committee of ISAS/JAXA [276]. The soft aeroshell for re-entry, under in-house development at ISAS/JAXA, is envisioned as a core technology for two of the three identified priority areas: "reusable orbit transportation system", for more frequent payload transfers between the ground and Earth orbit; and "deep space interorbital transportation system", for more frequent and flexible science and exploration missions [276]. The deployable membrane aeroshell also features in the March 2024 "Space Technology Strategy" by the Committee on National Space Policy of the Cabinet Office of Japan, as a means of supporting solar system science and exploration. It is described as a "a unique technology that is competitive worldwide, as it has been independently developed and demonstrated in Japan" [277]. The same report charts out a two-stage roadmap for solar system science and exploration using atmospheric entry, aerodynamic deceleration, and landing technology: development of deployable aeroshell technology and its demonstration in low-Earth orbit is planned for 2023–2027, followed by development for Mars landing missions and others in 2028-2032 [277].

Finally, "Low-cost elemental technologies for atmospheric entry and aerodynamic deceleration" (translated from Japanese) has been established as one of the technology development themes of the Space Strategy Fund, a 10-year multi-billion US dollar funding programme for space technology development and commercialisation spanning government, academia, and industry, with JAXA acting as the central hub [278]. It is noted that "Japan's low-cost, compact technology is a distinctive feature of the country, giving it an international advantage. In addition, the flexible and fiber material technology required to develop deployable aeroshells and the technology to weave special materials with high precision are Japan's strengths", opening prospects for "the recovery of materials from low Earth orbit and the Moon", with the observation that "an aeroshell has the advantage of being easier to recover and operate at sea in Japan, which is surrounded by oceans" (translated from Japanese) [278]. In this context, aeroshell-type drag sails, with simpler design and lower cost than those under development at NASA, are projected to continue playing an important role in future space utilisation and exploration efforts in Japan.

JAXA and NASA have dedicated programmes for space sail development, with specific applications already in place and to be grown further in the near- to long-term. This is consistent with their longstanding involvement and leadership in space sail research and utilisation, evidenced in Section 3. By contrast, some of the other major space agencies have no dedicated space sail research and development plans in the public domain. Available information is collated in the next two subsections for Europe, China, and India.

4.3. European Space Agency (ESA) and its member states

ESA activities in space sailing are primarily focused on drag sail development for space debris mitigation. The agency's recently released Zero Debris approach outlines eight recommendations, applicable not only to ESA but also to companies and institutions working with ESA [279]. Specifically, one is that satellites need to be disposed of within five years after a mission ends with a 90% success rate, whereas the previous recommendation was 25 years. This requires de-orbit technologies including drag sails. The above approach builds on ESA's Clean Space initiative to minimise the environmental impact of space missions, started in 2009 and given its current name in 2013 [280], which has included research and development of drag sails under the CleanSat programme [281]. While ESA does not appear to be directly involved in technology development in this regard, it funds several R&D activities across Europe, including in private industry.

One such activity is development of ADEO drag sail products by HPS GmbH via ESA contract, in collaboration with DLR [253]. ADEO drag sails have been developed in four different sizes, for different satellite classes ranging from 1 to 1500 kg [253]. The largest version, ADEO-L (25 m^2, targeting 200–1500 kg satellites), and an intermediate version, ADEO-N (5 m^2, for 1–250 kg satellites), are already in production [253]. The other two versions, ADEO-Cube which is the smallest (2 m^2, for 1–50 kg nano- and microsatellites), and ADEO-M (15 m^2, for 100–700 kg satellites), are currently under development [253]. ADEO-N products have already been launched on various LEO satellites, with more planned in the coming years [128]. In line with ESA's Zero Debris approach, these drag sail products are non-reflective to minimise light pollution [253,279]. Within the spectrum of drag sail type technologies, the EFESTO project carried out by a European consortium aims to develop inflatable heat shield technologies that may benefit future re-entry/aerocapture missions [272]. It is noted that technology maturation activities are ongoing as of 2022 [272].

To the best of the authors' knowledge, solar sailing technology is currently not considered for any of the ongoing space exploration activities of ESA. A derivative of ADEO-L, by the company HPS GmbH, is intended to operate as a solar sail, proposed for multiple asteroid rendezvous and Lagrange point missions [253]. This variant is based on DLR's Gossamer 1 solar sail mission proposal [253,282], with roots in the early 2000s as discussed in Section 3. Developments in this area at European companies (e.g., Gama and HPS GmbH), universities, and research institutes may renew interest for future missions. It is worth noting that HPS GmbH is applying its drag and solar sail technology to other types of space sail. Its portfolio includes deployable membrane antennas and deployable sunshade reflectors as well [253].

Nonetheless, an area in which ESA does have a recent interest is space-based solar power, through the SOLARIS programme.[6] SOLARIS aims at evaluating options for wireless power transmission from space as a form of clean energy. This includes the concept of orbiting solar reflectors [181]. Within the SOLARIS programme, ESA has commissioned two parallel studies in late 2023, one for microwave power beaming and the other for orbiting solar reflectors. The study on orbiting solar reflectors performed by Arthur D. Little has provided circular reflector designs with a space segment configuration similar to earlier results of the SOLSPACE project [182], for application to terrestrial hydrogen energy [283]. ESA's interest in this area appears to continue at least in the near term, with a focus on microwave power beaming. This focus may shift towards orbiting reflectors and other types of space sail as the associated technologies develop. To that end, ESA also funds general R&D studies in the areas of inflatable structures, deployment mechanisms, and space-based solar power through The Open Space Innovation Platform, in the form of specific and generic calls. This may enable further development of space sailing, benefiting future ESA programmes.

As for some of its member states, a report prepared by the European Patent Office, the European Space Policy Institute (ESPI), and ESA states that Germany leads total patent activities in solar sailing globally by a wide margin, followed in Europe by the UK and France, which have higher relative values compared to countries such as the US, China, and Japan [284]. These numbers, nevertheless, should be evaluated with caution due to the relatively low number of patents in the area of solar sailing [284], and therefore may be misleading when compared with the US, China, and Japan. Additionally, ESA supports DLR's DEAR solar power sail project [231]. It aims at developing scalable thin film solar arrays [231]. Present capacity is 100 W stowable in a 1U CubeSat volume (<2 kg). This system has been tested under ambient and vacuum conditions, and in-orbit demonstration is aimed at in the second half of 2024 [231]. This tangible example shows DLR's

[6] SOLARIS website: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/SOLARIS2 (accessed 21 May 2024).

continuous interest in space sail technology hardware development in addition to conceptual studies, reviving expertise cultivated in the 1990s and 2000s, as discussed in Section 3.

In France, CNES supports the private company Gama, which deployed its first solar sail in Earth orbit in 2023 [39] and plans to deploy more in the near future. In Italy, the Italian Space Agency (ASI) has funded a research project in 2022 on solar photon propulsion, in collaboration with the University of Rome "La Sapienza" and the University of Pisa. Studies have focused on sail structure, boom development, and mission analysis for a space weather mission (named Helianthus) at the Sun-Earth Lagrange point L1 [285,286], suggesting ongoing interest in solar sails within ASI's R&D activities. ASI is also leading the development of a small re-entry vehicle with deployable fabric membrane aero-brake called Italian Re-Entry NacellE for Microgravity Experiments (IRENE), as part of a joint effort with ESA. Deployment from a sounding rocket has already been conducted [287].

Finally, while there is no strategy laid out by the UK Space Agency on space sailing specifically, a programme thesis published by the country's recently formed Advanced Research and Innovation Agency (ARIA) (separate from the UK Space Agency) explicitly mentions solar reflectors as a means for responsible climate engineering [288]. Moreover, the agency's interest in broader areas such as space-based solar power, in-orbit servicing, and active debris removal may provide a fertile ground for companies and research institutes already active in space sailing R&D to avail of funding opportunities and respond to relevant applications in the near future. In this context, it is worth noting that multiple UK institutions have already developed space sails. For example, Cranfield University developed a family of drag augmentation systems within the ESA CleanSat programme in the mid-2010s [281]. At around the same time, the University of Surrey developed a deployable drag sail with an inflatable mast in the DEPLOYTECH (Large Deployable Technologies for Space) project, as part of the European Commission's FP7 funding programme. The multi-part project also comprised research by DLR on deployable booms for solar sails [289], and emphasised the multi-functional nature of space sails: "Large deployable structures are needed as the backbone and as an integral part of large reflectors, Earth observation antennas, radiators, sun shields and solar arrays" [289]. Interestingly, the E-sail, an invention from Finland, was also developed towards the prototype phase with FP7 funding [290], and ESA is currently funding follow-on research on satellite de-orbit using a plasma brake electric sail deployed from an autonomous module at the end of life of a LEO satellite [291,292].

4.4. China National Space Administration (CNSA)

Publicly available information in English on CNSA's space exploration plans is scarce, even more so for space sailing. The CNSA has an extensive planetary exploration programme comprising a series of Chang'e missions to the Moon, alongside the planned International Lunar Research Station, led jointly with Russia's Roscosmos [293], as well as a series of Tianwen (also called Planetary Exploration of China, PEC) missions to Mars, asteroids, comets, and the outer solar system, with landing and sample return plans for some of them [294, 295]. In addition, the Chinese space programme features an Earth orbiting crewed space station, named Tiangong and managed by the China Manned Space Agency (CMSA), and many satellites in Earth orbit [295]. To return space cargo to Earth more frequently and with lower cost, the state-owned defense company China Aerospace Science and Industry Corporation (CASIC) proposed the development of an inflatable deployable aerodynamic heat shield in 2014 [296]. The first flight of the so-called Flexible Inflatable Cargo Re-entry Vehicle was conducted by the CMSA in 2020, and though it is reported to have been unsuccessful [297], it indicates active efforts in this domain.

More broadly, published works affiliated with government institutions in solar sailing (e.g., [298]) and drag sailing (e.g., [3]) in recent years suggest ongoing activities in the area of space sailing. Indeed, China has already performed relevant in-orbit tests such as unfurling a 25 m^2 drag sail in LEO in 2022 [299], as stated in Section 3. Zhang et al. noted that current activities in the area of drag sails are focused on three-dimensional sail shapes, aiming at passive stabilisation of attitude motion, suggesting expected developments in the coming years [3], likely together with in-orbit use of existing technologies.

Such activities are expected to continue, potentially with larger sail sizes. One interesting and recent example is the so-called "Huge Space Shield", a concept proposed for sizes up to 1400 m in diameter. The deployment of two versions (1000 m and 1400 m) has been tested at small scale in laboratory experiments, and proposed for applications such as climate engineering from near-Earth orbits [203,204,300]. Such large sails may also be used for other applications such as the so-called "China moon" project [301]. Published widely in English-language media, it aims at illuminating the streets of Chinese city Chengdu at night to reduce electricity costs, with continuous availability also in case of disasters, similar to NASA concepts studied from the 1960s through early 1980s, as mentioned in Section 3.6. The project was tipped for launches in 2020 and 2022, but the current status is unknown [301]. Nevertheless, it is made public that China is interested in developing a solar power satellite by launching and assembling in space an ultra-large spacecraft by 2050 [302,303]. This may provide additional motivation to test large structures in space, with potential for other applications.

Finally, deployable membrane antenna technology is noted as "developing" in China, at a more theoretical and laboratory level, but work in this area has been described as "in rapid progress", with 20 to 30 m diameter antennas under development [304]. Therefore advancements in this area may be expected by utilising space sailing technology.

4.5. Indian Space Research Organisation (ISRO)

As for ISRO, available information is again limited. India plans to continue expanding its space exploration activities through ISRO's Space Vision 2047, including through the development and operation of the Bharatiya Antariksha Station (BAS) – a national space station in Earth orbit – as well as missions to the Moon, Mars, and Venus, with a focus on increasing the country's self-reliance in the space sector [305,306]. Space sailing technology could be part of these endeavours similar to other space agencies.

Indeed, the agency has several completed projects in areas such as inflatable structures [307]. One ISRO-supported university satellite project is the STUDSAT CubeSat, equipped with a drag sail demonstration payload [308]. A document outlining "Research Areas in Space", published by ISRO in 2023, includes an explicit mention of solar sailing as one application of inflatable structures [309]. To that end, a list of ongoing projects supported by ISRO includes at least one small satellite solar sail mission, carried out by Savitribai Phule Pune University to obtain radiation measurements in the Earth's outer atmosphere [310]. These activities suggest a level of interest in India for future space sail development. More broadly, multiple space sailing applicable areas are apparent among ISRO's activities, as discussed below.

4.6. Other space sailing applicable areas

Thus far, this section has focused on individual space agencies and mainly considered their applied space sailing activities, i.e., explicitly incorporating space sails. This complementary subsection examines ongoing activities where space sailing may be applicable, i.e., may offer advantages over alternative approaches. The focus is on cross-cutting, global space exploration goals where mission architectures are flexible and still not finalised, with potential to incorporate space sails. Indeed, space sailing unlocks "multiplicity" as a mission driver, as discussed in Sections 2 and 3 and as explained in more detail below. Multiplicity may be seen from three perspectives: the first is mission frequency to a single destination, the second is multiple destinations in the same mission, and the third is multiple types of deployable structures or functions within a single sail membrane.

Active debris removal (ADR)

In-orbit debris removal services are an area where space sailing may find valuable applications. Passive debris removal is already being successfully carried out by drag sails, and this may be extended by other space sails, such as solar sails and plasma brake electric sails, to higher altitudes where air drag is insufficient for de-orbit, and to active debris removal (ADR) as well. Financial viability and the business case for ADR are still being debated, though regulatory pressure is increasing notably due to the previously mentioned Zero Debris approach of ESA [279], in line with that of other agencies. Some point to the negligible impact of removing singular space debris with respect to overall population [303]. Solar sailing may offer advantage through multi-debris removal missions, spanning a wider range of altitudes than drag sails. How the idea translates in terms of a business case remains unclear, and challenges for capturing non-cooperative space debris exist. Nevertheless, solar sails still appear as an attractive option for multiple-target ADR applications, complementing passive options via drag sail and single-target ADR applications via plasma brake electric sail.

Mission life extension (MLE)

Despite doubts over the business case of ADR, mission life extension (MLE) applications are considered financially more viable [311]. This is because most space missions end not due to satellite failure, but because of propellant depletion and loss of control over satellite orbital altitude and attitude [303]. Two types of missions can be envisaged to address this. The first may be an in-orbit refuelling depot, that is manoeuvrable over a range of altitudes with solar sailing. For example, such an architecture may offer one possible approach for implementing the space depot envisaged by JAXA within its previously mentioned mid- to long-term strategy [276]. The second type may be orbit correction missions, where a tug spacecraft propelled by a solar sail corrects the orbit of the serviced satellite. Near-Earth applications of solar sailing are already being considered by NASA for orbit correction (see Section 4.1), and MLE may offer another application.

In fact, solar sailing has already been used for MLE in past missions, in some cases via makeshift approaches. One notable example is the Hayabusa asteroid sample return mission by ISAS/JAXA, which experienced numerous difficulties. These included losing two of its three reaction wheels, as well as the chemical reaction control system. Ingeniously, the mission team improvised an alternative method for attitude control during the return trip to Earth, using the spacecraft's solar panels: "It used solar radiation torque to maintain the spacecraft spin direction, keeping it automatically pointed towards the Sun like an arrow in the wind" [312]. Another is the Kepler space telescope mission by NASA, during which two reaction wheels were lost and solar radiation pressure was used as a back-up method for spin control of the remaining two wheels [313]. These examples highlight the feasibility of using solar sailing for MLE via both orbit and attitude control, with further gains in performance expected when using dedicated deployable sails rather than makeshift approaches.

In-space manufacturing and assembly

While some R&D in space sailing aims at growing the size of sails themselves (see, in particular, Section 4.1), solar sailing could also provide a method for building megastructures in space. Space stations, solar power satellites, orbiting solar reflectors, and related projects – incorporating multiple types of space sail including solar power sails and deployable reflectors – all aim at ultra-large structures in orbit. These may only be realisable by in-orbit manufacturing and assembly. In-orbit transport of structures may be carried out by solar sail-propelled spacecraft. Indeed, a recent report commissioned by NASA highlights that one enabler of financial viability of solar power satellites is a low-thrust satellite-delivery structure for assembly [314]. While the report does not specifically mention solar sailing, it is an effective low-thrust propulsion system that may meet the requirements.

Cargo missions

Space sails offer advantages for supporting cargo missions between Earth and various non-terrestrial stations. In Earth orbit, examples are the International Space Station, Tiangong space station, and the planned Bharatiya Antariksha Station, noting that commercial stations are also under development. The former in particular receives a constant stream of cargo of scientific payloads and other supplies, as well as crew. Deployable membrane re-entry drag sails offer a means of returning cargo to Earth, such as the products of in-space experiments and manufacturing, as discussed in Sections 4.1 to 4.5. The low altitude of these stations could limit applications of cargo transport by solar sailing due to atmospheric drag (typically dominant over solar radiation pressure at their altitude, around 400 km), and another consideration in the case of crew transport is a long transfer duration. The issue of long travel times with propulsive space sails will be returned to in more detail in Section 5. Despite this, one area where solar sailing may offer advantage is the Lunar Gateway [315]. This space station initiative around the Moon, spearheaded by NASA and several other space agencies as one of the next non-terrestrial human destinations, will be serviced by cargo payloads in much the same way as the ISS. Again, there may be specific constraints for crew transport, but low-risk cargo could be shuttled between Earth and Moon orbits by propulsive space sailing, not limited to solar sails, as mentioned in the case of magnetic sails in NASA documents (see Section 4.1). Such cargo may include landers and other surface assets for supporting future activities on the lunar surface.

Similar approaches could be applied to future Mars missions as well, in the context of fulfilling the Global Exploration Roadmap [14], and even to interplanetary cargo transport to more distant destinations in the longer term, potentially complemented by laser-driven propulsion. In addition, solar power sails are an attractive option for meeting the electrical power requirements of future cargo missions between Earth, Mars, and the outer solar system, as evidenced in Section 4.2 on JAXA.

Lunar and Mars exploration

There are a number of challenges to be addressed for sustained presence on the Moon and Mars for crewed and uncrewed systems, as outlined in the Global Exploration Roadmap [14]. Focusing on the Moon, surviving the long lunar night presents itself as the greatest challenge. This is apparent from the Civil Space Shortfall Ranking survey conducted by NASA STMD, which aims at identifying priority "technology areas requiring further development to meet future exploration, science, and other mission needs" from among a shortlist of 187 areas [316]. In responses received from large and small industries, the two most important challenges for future lunar exploration are identified as power generation (#1) and thermal management to survive the lunar night (#2) [316]. In responses from academia, in-situ resource utilisation (ISRU) occupies the top three positions, in the areas of water and oxygen extraction from extraterrestrial materials and in-situ propellant production [316]. The report also lists solar sailing as one of the 187 shortfall areas [316].

Considering potential solutions, orbiting reflectors can harness solar energy from a variety of orbits to these destinations [317], potentially reducing operational and financial cost as well as the risk associated with other sources of power (e.g., nuclear). To that end, orbiting solar reflectors could provide light in its "raw form" which can be converted into electricity, utilised as heat for thermal management and ISRU activities, or used as illumination for crewed and uncrewed operations on the surface, including in permanently shadowed regions [318,319]. It was identified that a modest number of reflectors could provide the energy needed for a crewed presence on the Moon [319].

Such proposals are in accordance with critical technologies necessary for lunar exploration, such as large, flexible and deployable solar panels for power generation [14], but can be developed independently. Related to this point, heritage obtained through solar power sails or large membranes could create synergies with critical technologies employing other types of large deployable structures, such as in the case of the Lunar Crater Radio Telescope project [60], as discussed in Section 3. Moreover, future lunar navigation and communication services will greatly benefit from deployable gossamer antennas, some of which could be used for multiple purposes, as in the case of NASA's 1960s inflatable balloon satellites [24]. Solar sails and other propulsive space sails are already named for possible cargo missions, and scenarios like manoeuvring the Lunar Gateway station or small attitude corrections are among those that would benefit from space sailing technology [320].

Finally, end-of-life considerations for lunar exploration spacecraft and broader lunar sustainability discussions are underway with proposals including dedicated craters for spacecraft graveyards. Such proposals would also benefit from propellant-less propulsion systems, as part of potential lunar ADR and MLE missions in the future. In a much similar way, future Mars exploration will need to overcome power generation, communication, and navigation challenges at its surface for crewed and uncrewed systems, including ISRU capability. It was shown that power generation may be possible with solar reflectors [181], and space sailing technology has been demonstrated to be successful for applications such as aerobraking via deployable decelerators [147,321] and communication relay via reflectarray antennas [322].

Outer solar system and small body exploration

Space sailing is already being applied in interplanetary space. However, propellant-less propulsion enables multiple-target missions which would otherwise be limited in terms of number of targets or duration (for example, Lucy [323] and DESTINY$^+$ [324]). Solar sailing could offer multiple-target mission opportunities without constraints on mission duration in principle, even though sail degradation would reduce performance over time. This may be particularly useful for near-Earth object exploration missions, where the necessary delta-V is often lower than for reaching the Moon [325]. Such missions would aid in understanding asteroid properties, assessing deflection capabilities for potentially hazardous asteroids, and prospecting resources for asteroid mining. Solar (power) sails in orbit around the Earth may even be repurposed for such missions [326]. These targeted applications are in addition to ones already identified by space agencies such as NASA and JAXA, as discussed in Sections 4.1 and 4.2.

Finally, when considering applications of space sails for outer solar system exploration, there are opportunities to combine the functions of different types of space sail within a single sail, as discussed in Section 3.9. This is another aspect of the concept of multiplicity. A good example is ISAS/JAXA's "New Solar Power Sail Program in the Post-OKEANOS Era" (see Section 4.2). It explores prospects for combining the functions of a solar power sail, solar sail, deployable membrane reflector, and deployable membrane antenna in a single structure by attaching necessary thin-film devices on the sail membrane, offering advantages in terms of mass (and potentially launch cost) savings. Taken to the extreme, missions can be envisaged in the mid- to long-term where an entire spacecraft is embedded into a thin-film multi-functional membrane, making efficient use of a single structure to fulfil the role of multiple subsystems. Laser-driven sails may provide a stepping stone in this regard, in the context of potential fast-transit exploration missions in the inner and outer solar systems.

Based on the above review, space sails have been identified as a means for achieving near- to long-term space exploration goals around the world. This builds on a historical legacy of space sail development and utilisation by various organisations including major space agencies, as discussed in Section 3, marked by the leveraging of synergies between different types of space sail. Among the major space agencies, NASA and JAXA have the most clearly defined and expansive space sail utilisation programmes. ESA and its member states are also actively involved in space sail development and utilisation, with a focus on drag sails at the European level. CNSA and ISRO are visibly ramping up their activities in the area of space sails, despite limited publicly available information. Space agencies are not working in isolation: private companies and other organisations are also actively involved. For instance, they are being provided with contracts to contribute to the realisation of space sail development and utilisation programmes, and are in turn growing their own space sail R&D activities. On a global level, space sails appear applicable for fulfilling several cross-cutting space exploration goals shared by agencies and industry, and the concept of multiplicity is a key characteristic of space sails for enhancing space mobility.

Building on this foundation, the next, final section offers an outlook by sail type on expected challenges and opportunities associated with space sails for achieving global space exploration goals.

5. Outlook: Opportunities and challenges in the near to long term

This short final section summarises future planned space sailing activities in support of space exploration goals around the world, with a focus on those of major space agencies. The outlook, shown in Table 6, is based on the review of mission proposals and space agency goals in Section 4, drawing upon analyses from earlier parts of the manuscript. It is divided into space sailing applied and applicable activities, i.e., explicitly incorporating space sailing, or well-positioned to benefit from its utilisation. Cross-cutting trends are discussed below, encompassing opportunities and challenges. Although the focus is on space agency goals and activities, as mentioned previously these are expected to be realised by a combination of organisations including private companies, via the provision of contracts and other forms of support by space agencies, like regulations.

5.1. Opportunities

A demonstrated technology with more frequent use in the Earth-Moon system

Many types of space sail are shifting from the subject of technology demonstration towards becoming an enabling technology for operational mission objectives. Solar sails are being applied for small satellite manoeuvrability and control, in Earth orbit and beyond. Drag sails are seeing commercial use to support fast post-mission disposal for space sustainability in LEO. Deployable membrane atmospheric entry vehicles are being considered for more flexible and lower-cost orbit-to-Earth cargo transportation. Solar power sails are opening new possibilities for high power generation in small satellite form factors. Deployable membrane reflectors are planned to support enhanced Earth surface power generation. Deployable membrane antennas are being incorporated into small satellites for high-capacity communications. These are just some examples of public plans by major space agencies, and supporting partners such as private companies and universities, to use space sails as an enabler of more demanding mission objectives, especially in volume and mass constrained small satellites. On the other hand, laser-driven sails, electric sails, and magnetic sails remain at the technology demonstration stage. As shown in Table 6, multiple missions have been scheduled by major space agencies to advance their maturity in the near- to mid-term.

A multi-use technology with scope for cross-pollination and combination between different space sails

To maximise the impact of space sails, results are being transferred between development programmes of contiguous sail technologies. Lessons learned from research on one type of space sail are being used to enhance the performance of related technologies. Membrane structures initially developed for solar sailing are being repurposed as drag sails (e.g., see [237,331]), and vice-versa (e.g., see [253]). Solar power sails and solar sails are being developed within adjacent research programmes (e.g., see [232]). Solar sailing technology is being applied to membranes which combine the deployable solar power sail and deployable antenna [227,228]. Unified sails doubling as a solar

Table 6
Near-term (NT), and medium/long-term (MT/LT), applied and applicable planned space sail activities, with a focus on those of major space agencies reviewed in Section 4. Activities are categorised by sail type. Near-term missions are expected to be done within 10 years, and medium/long-term ones within more than 10 years. Listed activities are only illustrative, not exhaustive.

Sail type	
Destination	Applied and *applicable* activities
Solar sail	
Low-Earth orbit	– Applied: Small satellite manoeuvrability and control [262,265] **(NT)**
	– *Applicable*: Multiple-target active debris removal (ADR), mission life extension (MLE) **(MT/LT)**
Earth-Moon system	– Applied: Multiple-target interplanetary exploration beginning in Earth orbit [39] **(MT/LT)**
	– Applied: Small satellite mobility for lunar exploration and operations at Earth-Sun Lagrange points [89,232,253,286] **(MT/LT)**
	– *Applicable*: Cargo transportation to/from the Lunar Gateway **(MT/LT)**
	– *Applicable*: Transportation for in-space manufacturing of large space structures **(MT/LT)**
Deep space	– Applied: Heliophysics and space weather monitoring using large sail areas extended from past missions [238,262] **(MT/LT)**
	– *Applicable*: Mobility for orbiter and lander missions in the inner and outer solar system [13] **(MT/LT)**
	– *Applicable*: Mobility for direct exoplanet observation at the solar gravitational lens [104] **(MT/LT)**
Laser-driven sail	
Deep space	– Applied: Propulsion of small probes for interstellar exploration [270] **(MT/LT)**
	– *Applicable*: Propulsion of cargo for fast interplanetary transits **(MT/LT)**
	– *Applicable*: Propulsion of deep space probes for exploration in the inner and outer solar system **(MT/LT)**
Drag sail	
Low-Earth orbit	– Applied: Passive disposal of defunct spacecraft by commercial and other actors [19,129,253] **(NT)**
	– Applied: Educational satellite development with controlled de-orbit [327,328] **(NT)**
	– Applied: Transportation of small cargo from space stations to Earth's surface by membrane aero-brake [276,296,327] **(MT/LT)**
Deep space	– Applied: Small satellite aerocapture/aerobraking at Mars [276] **(NT)**
	– Applied: Small satellite aerocapture/aerobraking at ice giants [264] **(MT/LT)**
	– Applied: Transportation of small cargo to surface of celestial bodies with atmospheres by membrane aero-brake [276,296] **(MT/LT)**
	– *Applicable*: Passive disposal of defunct spacecraft from the orbit of celestial bodies with atmospheres **(MT/LT)**
Magnetic sail	
Earth-Moon system	– *Applicable*: Repositioning of crewed and uncrewed assets in cislunar space [262] **(MT/LT)**
Deep space	– *Applicable*: Mobility for high delta-V planetary missions [262] **(MT/LT)**
Electric sail	
Low-Earth orbit	– Applied: Disposal of defunct spacecraft by commercial and other actors [329] **(NT)**
Earth-Moon system	– Applied: Technology demonstration of the electric sail in the solar wind [25,329] **(MT/LT)**
Deep space	– *Applicable*: Disposal of defunct spacecraft from the orbit of celestial bodies with atmospheres **(MT/LT)**
	– *Applicable*: Mobility for high delta-V planetary missions **(MT/LT)**
Deployable membrane reflector	
Low-Earth orbit	– Applied: Earth surface illumination for reduced terrestrial power consumption [301] **(NT)**
	– Applied: Wireless power transfer from space to Earth's surface [181,182,185,288] **(MT/LT)**
Earth-Moon system	– Applied: Giant sails assembled in space for observatories and sunshades [266] **(MT/LT)**
	– *Applicable*: Wireless power transfer from space to the lunar surface **(MT/LT)**
Deep space	– Applied: Small body exploration via sheet target marker [232] **(MT/LT)**
	– Applied: Exoplanet observation via starshade [196] **(MT/LT)**
	– *Applicable*: Wireless power transfer from space to planetary surfaces in the inner solar system **(MT/LT)**
Deployable membrane antenna	
Low-Earth orbit	– Applied: Technology demonstration of the membrane reflectarray antenna [59,330] **(NT)**
	– Applied: Technology demonstration of the membrane active phased array antenna [221] **(NT)**
	– Applied: Commercial small satellite remote sensing using a deployable parabolic mesh reflector antenna [58] **(NT)**
Earth-Moon system	– Applied: Radio astronomy on the far side of the Moon [60] **(MT/LT)**
Deep space	– Applied: High-capacity communication with a membrane-type array antenna [232] **(NT)**
Solar power sail	
Low-Earth orbit	– Applied: Enhanced power supply for small satellites [227,231] **(MT/LT)**
Deep space	– Applied: Power supply for small body, outer solar system exploration [232,233] **(MT/LT)**
	– Applied: Power supply to support multi-sample return, and a re-usable deep space orbital transfer vehicle [232,276] **(MT/LT)**

wind electric sail, solar sail, drag sail, and plasma brake electric sail have been proposed [173]. These are only some of the many examples of multi-functional space sails presented in Section 3.9, noting that the number of flown and proposed missions has significantly increased over the past decade. Based on the above examples, cross-pollination is expected to remain a fundamental characteristic of future space sail development.

In terms of applicable activities, active debris removal from LEO could be realised by combined solar sail and drag sail, with the solar sail mode giving way to the drag mode at lower altitudes. Planned missions to outer solar system bodies such as Saturn and Uranus could be realised by combining a solar sail for low-thrust high-delta-V propulsion, with a solar power sail for large surface area power generation far from the Sun, with a membrane antenna for long-distance communications, and a deployable membrane aeroshell for aerocapture and aerobraking. These are just some examples of new possibilities for combining the functions of multiple types of space sail, in alignment with global space exploration goals.

A growing business case

To progress beyond research and development, a movement towards commercialisation of space sails for near-Earth applications is being promoted, including by space agencies. For instance, the French private company Gama, founded in 2020, has been supported by CNES and DLR to develop its series of solar sails. One was launched into LEO in 2023, and multiple successor missions are planned for 2025–2030 [39]. Japanese private company Cosmobloom, founded in 2023, is offering consulting services for gossamer space structure development and utilisation, including for applications like space solar power in Earth orbit and starshades for astronomical observation. These build on the founders' heritage in solar sail, solar power sail, and deployable antenna development, with support from advisors at JAXA [332]. German private company HPS GmbH, in collaboration with ESA and DLR, is developing a commercial European passive de-orbit sail system for LEO satellites, as part of a portfolio of thin-film membrane space structures including deployable membrane reflector antennas and thin-film sunshades [128]. Finnish company Aurora Propulsion Technologies is commercialising the plasma brake electric sail, with applications both for de-orbit from LEO and for exploration in deep space, and has been supported by an ESA Business Incubator Centre programme [329]. This trend towards the commercialisation of space sails is expected to continue. Space agencies are playing an important role in this regard, by providing funding (e.g., awarding contracts), a favourable regulatory environment (e.g., stricter de-orbit requirements, thereby prompting investments into drag sail technologies), and other incentives for space sail research and development. Looking to the future, more and more space sail systems are expected to become commercial off-the-shelf components, leading to significantly wider adoption in the space industry.

A means of supporting deep-space exploration and utilisation

Towards the end of the 2020s, traditional space sails are likely to have established themselves for various applications in the Earth-Moon system, as discussed above. This foundation would provide the basis for use cases at more distant locations, in more demanding environments, and incorporating more advanced enabling technologies, in line with the shift in focus of major space agencies from the Moon towards Mars. Immediate destinations where space sails will find their employment are orbits around the Sun and inner solar system planets, as well as small bodies (asteroids and comets). High delta-V mission concepts such as Sun polar observers will find this in solar sails, and Mercury and Venus missions concepts will also greatly benefit from solar sailing technology owing to their proximity to the Sun. Ongoing interest in Mars exploration will propel developments in aerocapture, aerobraking, and solar sailing. Similarly, continuous interest in asteroids and comets to unravel the formation of the solar system, to counteract existential threat of asteroid impact, and to develop an in-space mining economy will make solar sails attractive solutions for multiple observations missions. This will extend towards the outer solar system with missions to the asteroid belt enabled by solar power sails and low-thrust engines, possibly powered by additional deep-space transfer vehicles. Development of mission concepts towards Saturn and beyond will benefit from this technology as well. This will pave the way for the applications of other technologies such as electric sails, which may shift from technology demonstration of the plasma brake electric sail in Earth orbit towards demonstration of the solar wind electric sail in interplanetary space, and magnetic sails, which may be tested in an orbit around the Earth by this time. In the long-term, space sail development in the Earth-Moon region, inner solar system, and outer solar system will lay the foundations for more distant missions, building on the interstellar capabilities of the sundiver and laser-driven sails, as discussed in Section 3 and as is being studied in ongoing work [333].

A vector for space sustainability

A variety of space sails are expected to be part of the possible solutions for both terrestrial and space sustainability. Drag sails for passive de-orbit from LEO are only one example. Growing interest in on-orbit servicing, including ADR and MLE, could partly be met by solar sails. Both can benefit from the infinite propellant aspect of solar sails, particularly for multiple-target missions, to reduce the required number of spacecraft launches, extend the range of outcomes achievable in a single mission, and improve profitability. Similarly, it can be expected that new space companies could emerge for in-space cargo transportation around the Earth, and between Earth orbits and the Lunar Gateway station, for enhanced spacecraft mobility after launch without needing additional launches. An important caveat, discussed below, is that solar sails typically require a relatively long mission duration due to their low thrust: time saving is an important requirement for space missions from the viewpoint of cost saving and more frequent exploration, which may preclude the use of solar sails in some cases. Finally, rapid progression of climate change may create stronger demand for small scale deployments of solar reflectors as sunshades, along with deployable solar power sails, orbiting reflectors and antennas for space-based solar power.

5.2. Challenges

The above opportunities are subject to several important sources of risk, uncertainty, and limitations.

Longer flight duration with propulsive space sails

In terms of space mobility, one typical, intrinsic disadvantage of propulsive space sails is the mission duration. Laser-driven sails are a notable exception, as discussed at the end of this paragraph. Indeed, time saving is an important requirement for most space missions, from a viewpoint of cost reduction and more frequent exploration. In that regard, solar sails offer low thrust, leading to long flight times to achieve a given delta-V. The same also applies to solar wind electric sails and magnetic sails. Similarly, drag sails for accelerated orbital decay and planetary aerocapture or aerobraking usually realise their mission over a timescale of months or years. While it is possible to obtain step-changes in performance by disrupting the design parameter space through the use of new enabling technologies, e.g., extreme heat-resistant materials for sundiver solar sail missions and active metasurfaces for laser-driven sails (see Section 3), these remain mid- to long-term ambitions. This important caveat must be carefully considered when employing sail craft for enhancing mobility in space exploration. As a result, for some applications space sails will not be satisfactory. One likely example is missions involving transportation of crew, where time savings are especially critical, notably when traversing high-risk regions like planetary radiation belts. On the other hand, robotic platforms, automated refuelling depots, and spacecraft for transporting materials and supplies are likely to benefit from space sails for enhanced mobility. It is worth noting that laser-driven sails are an exception in this case, since they can go to interplanetary and even interstellar distances significantly faster than other space sails. Although no laser-driven sails have yet flown in space, international research programmes [18] and step-by-step development roadmaps [2] are ongoing, which may open other pathways for fast space sail missions to deep space in the mid- to long-term.

Other challenges

Space sails also face challenges common to all advanced space technologies. The first is disruptions due to funding. A notable example is the termination of the Halley's Comet Solar Sail programme by NASA in the early 1980s, in favour of investment into electric propulsion technology. More recently, mission proposals such as the OKEANOS solar power sail and Solar Cruiser solar sail have also seen their funding stopped. Looking to the future, certain proposed space sail mission concepts will require large capital investment, such as for building a hundreds of GW-class Earth-based photon engine needed to propel a laser-driven sail to sub-relativistic speeds (noting that studies are already being done on cost estimation and reduction [18,111]), or for building large structures to be installed on planetary surfaces like the Lunar Crater Radio Telescope with a km-scale diameter [60]. However, considering space sail technologies as a whole, the current shift in funding of space sails away from space agencies and government institutions towards private actors, combined with diversified commercial applications, suggests that future funding for space sails will be more resilient to unexpected contingencies. Indeed, Section 5.1 provided specific examples of commercialisation activities spanning electric sails, drag sails, solar sails, deployable membrane reflectors, deployable membrane antennas, and solar power sails.

A second cross-cutting challenge is bottlenecks contingent on enabling technologies. For example, laser-driven sails, sundiver solar sails, and aerobraking drag sails must withstand severe mechanical constraints like high surface forces and thermal loads. In some cases their realisation is contingent on fundamental advancements in material science, which may act as choke-points for the achievement of advanced space sail missions. However, research and development into advanced space sails is expected to help expand new frontiers in space technology and material science in general, even if planned missions require a longer development time than expected.

In summary, space sails have a long history of development and utilisation, not only by major space agencies but also by private companies, universities, and other organisations. This legacy is expected to extend into the future: space sails feature within the space exploration programmes of multiple countries, both explicitly in the form of planned missions, and implicitly as an applicable enabling technology for realising programme goals. Indeed, space sails have emerged as a demonstrated technology with multiple applications in the Earth-Moon system, including commercial ones and for promoting space sustainability, and in deep space for easier mobility. At the same time, realising the full potential of space sails is contingent on securing stable funding, exploiting overlaps and unique points with respect to competitor technologies for the same applications, and overcoming bottlenecks in terms of enabling technologies. Cross-sectoral, inter-agency, international collaboration will be an important tool for addressing these challenges, including by leveraging synergies within the spectrum of space sail technologies.

6. Conclusion

Space sails represent a continuum of lightweight, thin, large-area, deployable technologies which are pushing forward new frontiers in space mobility and exploration. The two main novel contributions of this trans-disciplinary review paper were: (i) to bridge between different types of space sail, re-conceptualising their development as comprising synergistic exchanges among a continuum of related technologies; and (ii) to go beyond a simple technical review, towards an inter-disciplinary assessment of space sails' past, present, and future input to the achievement of global space exploration goals. It was shown that the state of the art has advanced rapidly in recent years, one major contributor being synergistic exchanges and combinations between different space sail technologies. Looking to the future, space sails seem well positioned to contribute to the achievement of major space exploration goals around the globe. This alignment could be exploited to maximise the benefits attainable from space sails and their enabling technologies. The authors hope this paper will contribute to the ongoing transition of space sails from a promising technology into a standard component of the space mission designer's toolkit.

CRediT authorship contribution statement

Maximilien Berthet: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. **James Schalkwyk:** Writing – review & editing, Project administration, Methodology, Conceptualization, Data curation. **Onur Çelik:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. **Debdut Sengupta:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. **Ken Fujino:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. **Andreas M. Hein:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. **Luciana Tenorio:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. **Josué Cardoso dos Santos:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization, Data curation. **S. Peter Worden:** Writing – review & editing, Conceptualization. **Philip D. Mauskopf:** Writing – review & editing, Conceptualization. **Yasuyuki Miyazaki:** Writing – review & editing, Conceptualization. **Ikkoh Funaki:** Conceptualization, Writing – review & editing. **Shinjiro Tsuji:** Writing – review & editing, Conceptualization. **Piotr Fil:** Writing – review & editing, Conceptualization. **Kojiro Suzuki:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Sources of images used in this article

Sources of images used in this article are listed below. All were successfully accessed on 22 September 2024.

Fig. 1:

- IKAROS: https://global.jaxa.jp/projects/sas/ikaros/topics.html
- Breakthrough Starshot: https://blog.seas.upenn.edu/how-to-design-a-sail-that-wont-tear-or-melt-on-an-interstellar-voyage/
- De-Orbit Mechanism (DOM): https://www.nakashimada.co.jp/space/freedom/
- Magnetoplasma Sail (MPS): https://stage.tksc.jaxa.jp/asplab/en/simgs/r1_1_1.jpg
- E-sail: https://electric-sailing.fi/
- JWST sunshield: https://www.esa.int/Science_Exploration/Space_Science/Super-tough_sunshield_to_fly_on_James_Webb_Space_Telescope?ref=curiocial.com
- Inflatable Antenna Experiment (IAE): https://www.nasa.gov/image-detail/amf-s77e5027/
- OKEANOS: https://stage.tksc.jaxa.jp/wp-eplab/mission/

Fig. 3:

- Cosmos 1: https://www.planetary.org/space-images/cosmos1_art_sail_and_earth_sternbach

Table 7
Space sail database: flown sails.

Year	Sail/mission name	Objectives and/or description	Ref(s)
Solar sail			
2005	Cosmos 1	Increase the orbital altitude via solar sailing, using eight triangular sail blades	[23,78]
2008	NanoSail-D	Deploy a square solar sail from a CubeSat and use it for de-orbit via air drag	[38,79,334]
2010	***IKAROS***	Spin-deploy a large square solar (power) sail in space, conduct interplanetary solar sailing	[17,74,274]
2010	NanoSail-D2	Deploy a square solar sail from a CubeSat and use it for de-orbit via air drag	[38,70]
2015	CubeSail (UK)	Deploy a square solar sail from a CubeSat, change orbit by solar sailing, de-orbit via air drag	[75,237,335]
2015	LightSail 1	Deploy a square solar sail and downlink images of it	[336,337]
2018	CubeSail (US)	Deploy a long sail ribbon, and assess its stability and orbital manoeuvring performance	[80,245]
2019	LightSail 2	Control a CubeSat's orbit via solar sailing using a square sail	[71,336,337]
2022	***NEA Scout***	Deploy a square solar sail and demonstrate stable spacecraft pointing (and solar sailing)	[81,263]
2023	Gama Alpha	Spin-deploy a square sail, and validate the sail behaviour and control algorithms	[39,338]
2024	ACS3	Deploy a composite solar sail, demonstrate solar sailing, characterise the deployed dynamics	[82,339,340]
Drag sail			
1963	Explorer 19	Study atmosphere via effect of air drag on orbit of inflated strain-rigidised balloon satellite	[24]
1964	Explorer 24	Study atmosphere via effect of air drag on orbit of inflated strain-rigidised balloon satellite	[24]
1968	Explorer 39	Study atmosphere via effect of air drag on orbit of inflated strain-rigidised balloon satellite	[24]
1971	Balloon	Study effect of air drag on satellite orbit, by comparison between different balloon satellites	[24]
2000	IRDT 1	Demonstrate re-entry and descent from LEO of a two-stage conical inflatable aero-brake	[135]
2012	RAIKO	Deploy a planar drag sail and use it to de-orbit a 2U CubeSat	[125]
2013	STPSat 3	Deploy self-contained dragNET payload at end of mission to remove satellite from orbit	[48,341,342]
2013	TechEdSat 3	Deploy Exo-Brake parachute to advance small payload quick return technology	[343]
2014	Sprout	Test the deployment, attitude dynamics of a large membrane deployed from a nanosatellite	[344,345]
2014	TechDemoSat 1	Deploy Icarus-1 sail using stored strain energy to remove satellite from orbit at end of life	[281,346,347]
2015	Carbonite 1	Deploy Icarus-3 sail using stored strain energy to remove satellite from orbit at end of life	[281,346,348]
2015	DeOrbitSail	Demonstrate low-cost, fast satellite de-orbit via deployment of a lightweight square sail	[349,350]
2015	TechEdSat 4	Deploy Exo-Brake parachute to advance small payload quick return technology	[343,351]
2016	Can X7	Deploy a modular sail after long-term stowage in space for satellite de-orbit at end of mission	[352,353]
2016	TechEdSat 5	Deploy Exo-Brake drag sail with adjustable drag area to demonstrate active drag modulation	[354,355]
2017	FREEDOM	Deploy the thin film drag sail DOM and evaluate its performance for satellite de-orbiting	[19]
2017	EGG	Deploy inflatable aeroshell in LEO and observe effect on orbital decay	[147,321]
2017	InflateSail	Demonstrate effectiveness of drag sail to dramatically accelerate satellite atmospheric re-entry	[124]
2017	TechEdSat 6	Deploy Exo-Brake drag sail with adjustable drag area to demonstrate active drag modulation	[356]
2017	URSA MAIOR	Demonstrate small drag sail for CubeSat de-orbit, in view of commercial applications	[357]
2018	RemoveDebris	Deploy DragSail payload at end of mission to accelerate de-orbit within ADR demonstration	[358]
2018	PW Sat 2	Test and visualise deployment of drag sail in space and compare effectiveness vs. analysis	[359,360]
2018	SSO-A Upper	De-orbit a 1250 kg host spacecraft using a commercial, self-contained drag sail payload	[331]
2018	SSO-A Lower	De-orbit a 260 kg host spacecraft using a commercial, self-contained drag sail payload	[331]
2018	ESEO	Demonstrate deployment of self-contained drag sail DOM and de-orbit of host spacecraft	[346,361]
2019	SIASAIL I	Test and visualise deployment of drag sail in space as solar sail precursor mission	[299]
2020	TechEdSat 10	Deploy Exo-Brake drag sail with adjustable drag area to demonstrate active drag modulation	[327]
2021	TechEdSat 7	Deploy Exo-Brake drag sail with fixed inflatable struts to demonstrate accelerated de-orbit	[327]
2021	ADEO N2	Test and visualise deployment of a drag sail in space, evaluate its de-orbiting performance	[128]
2022	CASC-sail	De-orbit a 300 kg compartment of a Long March 2D launch vehicle using a drag sail	[298]
2022	TechEdSat 13	Deploy Exo-Brake drag sail with rigid collapsible struts to demonstrate accelerated de-orbit	[327]
2022	TechEdSat 15	Deploy Exo-Brake drag sail with adjustable drag area to demonstrate active drag modulation	[327]
2022	SBUDNIC	Demonstrate accelerated post-mission de-orbit by deploying drag sail with open-source design	[328]
2022	LOFTID	Demonstrate re-entry and landing of payload from LEO using large conical inflatable aeroshell	[136,240]
2023	BEAK	Demonstrate drag-modulated orbital control via two-stage aeroshell deployment and jettison	[148]
Electric sail			
2013	ESTCube 1	Observe interaction between a 10 m charged tether and plasma in the ionosphere	[168]
2017	Aalto 1	Deploy a 100 m tether, charge it, estimate the Coulomb drag force, demonstrate de-orbiting	[169]
2021	Foresail 1	Deploy a 300 m tether, charge it, estimate the Coulomb drag force, demonstrate de-orbiting	[51]
2022	AuroraSat 1	Deploy a 45 m tether, charge it, demonstrate de-orbiting	[170]
2023	ESTCube 2	Deploy a 300 m tether, estimate Coulomb drag force in positive and negative modes, de-orbit	[51]
Deployable membrane reflector			
1960	Echo 1	Inflate 30 m diameter balloon, demonstrate passive reflection of microwaves	[24,362,363]
1964	Echo 2	Inflate 41 m diameter rigidisable balloon, demonstrate passive reflection of microwaves	[362–364]
1966	OV1–8	Deploy 9 m diameter grid sphere, test reflection of microwaves, compare to ground tests	[24]
1966	PAGEOS	Perform global geodetic survey by taking pictures of 30 m inflatable balloon satellite in orbit	[174]
1971	Gridsphere 1	Deploy 2 m diameter grid sphere in space, calibrate radars, inform future spacecraft design	[24]
1971	Gridsphere 2	Deploy 2 m diameter grid sphere in space, calibrate radars, inform future spacecraft design	[24]
1993	Znamya 2	Deploy, test, control large thin film structure in space, perform Earth illumination experiment	[56,85,261]
1999	Znamya 2.5	Verify improvements of film structure, perform Earth illumination experiment, test attitude control	[85,236,261]
2000	OCSE	Calibrate Earth-based lasers for satellite tracking using 3.5 m diameter rigidisable balloon	[175,365]
2017	Mayak	Deploy pyramid-shaped membrane to study brightness of space objects, and for de-orbit	[122,188]
2021	***JWST sunshade***	Shield the JWST telescope platform from light and heat using five large sheets of aluminised Kapton	[201]
Deployable membrane antenna			
1961	Explorer 9	Study atmosphere via balloon satellite, with two aluminised hemispheres as antennas for radio beacon	[24]
1996	IAE	Validate deployment of 14 m inflatable parabola, measure surface accuracy, test damping	[22,363]

(*continued on next page*)

Table 7 (*continued*).

2015	SMAP	Capture global data on soil moisture with 6 m diameter rotating deployable mesh antenna reflector	[210,366,367]
2018	RainCUBE	Demonstrate precipitation profiling using parabolic deployable membrane antenna with 0.5 m diameter	[212,368]
2019	QPS-SAR-1	Demonstrate X-band SAR using parabolic mesh antenna with 3.6 m diameter	[211]
2019	R3D2	Demonstrate next-generation small satellite communication using 1 m reflectarray membrane antenna	[59,218]
2019	OrigamiSat 1	Deploy and visualise multifunctional membrane structure, with commercially available components	[220]
Solar power sail			
1976	CTS	Deploy and test flexible solar array blanket with cells mounted on Kapton-fibreglass substrate	[35]
1984	SAFE	Deploy and retract large flexible solar array, test structural dynamics and power generation	[62]
1990	FRUSA	Power the Hubble Space Telescope within small mass and volume via flexible unrollable solar array	[223,244]
2000	SAW	Power the ISS via accordion-folded solar array blankets with cells mounted on a flexible circuit	[73,239]
2008	***UltraFlex***	Power the Mars Phoenix lander via circular fan-folded deployable solar array with open-weave mesh	[225,369,370]
2019	TMSAP	Demonstrate record power-to-weight ratio space solar array, with cells on lightweight CFRP sheet	[371–373]
2021	***ROSA***	Power the DART spacecraft using compact flexible unrollable solar array blankets	[226,374]
2021	iROSA	Power the ISS as a supplement to SAW, with high-efficiency flexible unrollable solar array blankets	[224]
2024	LISA-T	Demonstrate deployment, operation, in-space survivability of Polyimide Embedded Photovoltaics	[227,375,376]

- Explorer 19: https://en.wikipedia.org/wiki/Explorer_19#/media/File:Explorer_19_-_01.jpg
- ESTCube 1: https://en.wikipedia.org/wiki/ESTCube-1#/media/File:ESTCube-1_illustration.jpg
- Echo 1: https://space.jpl.nasa.gov/msl/QuickLooks/pictures/echo.gif
- Explorer 9: https://commons.wikimedia.org/wiki/File:Explorer_9.jpg
- CTS: https://www.asc-csa.gc.ca/eng/multimedia/search/image/738

Fig. 10:

- Cosmos 1: http://www.russianspaceweb.com/cosmos_solar_sail.html
- NanoSail-D: https://www.nasa.gov/mission_pages/smallsats/nsd_bluesail.html
- IKAROS: https://global.jaxa.jp/projects/sas/ikaros/topics.html
- NanoSail-D2: https://science.nasa.gov/science-news/science-at-nasa/2011/24jan_solarsail
- CubeSail (UK): https://amsat-uk.org/2014/07/11/ssc-cubesail-satellite/
- LightSail 1: https://www.planetary.org/space-images/lightsail-in-space
- CubeSail (US): https://www.cubesail.us/
- LightSail 2: https://www.planetary.org/articles/ls2-deploys-sail
- NEA Scout: https://www.planetary.org/space-images/nea-scout-1
- Gama Alpha: https://gamaproject.notion.site/Gama-launches-its-Gama-Alpha-solar-sail-mission-6421331fade145de8393ad0b0c7769a5
- ACS3: https://space.skyrocket.de/img_sat/acs3_1.jpg

Fig. 11:

- Breakthrough Starshot: https://blog.seas.upenn.edu/how-to-design-a-sail-that-wont-tear-or-melt-on-an-interstellar-voyage/
- Wafer type spacecraft: https://www.deepspace.ucsb.edu/projects/wafer-scale-spacecraft-development

Fig. 12:

- Explorer 9: https://commons.wikimedia.org/wiki/File:Explorer_9.jpg
- InflateSail: https://www.eoportal.org/satellite-missions/inflatesail
- LOFTID: https://www.nasa.gov/general/low-earth-orbit-flight-test-of-an-inflatable-decelerator-loftid-overview/

Fig. 13:

- Magsail: https://centauri-dreams.org/wp-content/uploads/2014/08/Magnetic_Sail_1.gif
- MPS: https://stage.tksc.jaxa.jp/asplab/en/simgs/r1_1_1.jpg

Fig. 14:

- E-sail: https://electric-sailing.fi/
- AuroraSat 1: https://space.skyrocket.de/doc_sdat/aurorasa-1.htm

Fig. 15:

- Echo 1: https://space.jpl.nasa.gov/msl/QuickLooks/pictures/echo.gif
- Znamya 2: https://en.wikipedia.org/wiki/Znamya_(satellite)#/media/File:Znamya-2.jpg
- NASA starshade: https://exoplanets.nasa.gov/internal_resources/969/

Fig. 16:

- IAE: https://www.nasa.gov/image-detail/amf-s77e5027/
- R3D2: https://www.darpa.mil/ddm_gallery/Wallaby%20P-DaHGR%20deployed.jpg
- LCRT: https://www.jpl.nasa.gov/news/lunar-crater-radio-telescope-illuminating-the-cosmic-dark-ages

Fig. 17:

- SAW: https://www.nasa.gov/wp-content/uploads/2023/03/iss040e087239.jpg
- OKEANOS: https://stage.tksc.jaxa.jp/wp-eplab/mission/
- UltraFlex: https://www.jpl.nasa.gov/images/pia10760-how-phoenix-looks-under-itself

Fig. 18:

- Explorer 9: https://commons.wikimedia.org/wiki/File:Explorer_9.jpg
- OrigamiSat 2: https://www.titech.ac.jp/news/img/news-32071-p1.jpg
- IKAROS: https://global.jaxa.jp/projects/sas/ikaros/topics.html
- Mayak: https://space.skyrocket.de/doc_sdat/mayak.htm

Appendix B. Catalogue of space sails

The catalogue of 220 space sails compiled for this article is shown. For flown sails, in Table 7, the date is that of launch. For concepts, in Table 8, it is the approximate date of first description. Sails used in deep space are in bold italics. Others are used in Earth orbit. A database containing values of important parameters for each of the 220 sails is provided in [377].

Table 8
Space sail database: mission concepts.

Year	Sail/mission name	Objectives and/or description	Ref(s)
Solar sail			
1967	***Small helio-gyro***	Demonstrate Earth orbit escape with small experimental two-bladed helio-gyro	[87]
1973	***Halley's Comet Solar Sail***	Rendezvous with Halley's Comet using 12-bladed helio-gyro via near-Sun manoeuvre	[40,378]
1987	***Solar Sail Racer to the Moon***	Travel from near GEO to the Moon using square sail with guide vanes for attitude control	[243,254]
1987	***ARSAT 1 Helios***	Perform solar polar observation using large square sail with inflatable rigidisable booms	[186,187]
1996	***MESSAGE***	Perform interplanetary transfer to Mercury, provide capture into Sun-synchronous orbit	[379,380]
1996	***Vigiwind***	Monitor solar geomagnetic storms via station keeping sunward of Earth-Sun L1 point	[381]
1996	***Geostorm***	Monitor solar geomagnetic storms via station keeping sunward of Earth-Sun L1 point	[85,379]
1996	***AURORA Project heliopause probe***	Escape from solar system by all-metal sail with small science probe via near-Sun manoeuvre	[98,382]
1997	MOUSE	Control orbit around Earth and in interplanetary space via small-scale solar kite	[91]
1999	***ODISSEE***	Validate sail fabrication, storage, deployment, and operation from GTO to lunar polar flyby	[241]
1999	***Solar Blade Heliogyro Nanosatellite***	Perform station keeping in Earth orbit and outward spiral to Moon, using 4-bladed helio-gyro	[85,383]
1999	Minimum Sail Project Concept	Validate square sail deployment, orbit-raising performance from MEO, and jettison	[85]
1999	***Sub-L1 Sail Project Concept***	Validate square sail deployment, and transit to/station-keeping at Earth-Sun sub-L1 point	[85]
1999	DLR-ESA Solar Sail	Demonstrate in-orbit deployment of square sail, full extension of supporting CFRP booms	[214,384]
1999	***Pluto Flyby Solar Sail***	Perform Pluto flyby via micro-spacecraft with square solar sail using near-Sun manoeuvre	[385]
2000	***ENEAS***	Rendezvous with a NEA using a square sail, to perform remote sensing	[386]
2003	***Team Encounter Solar Sail***	Escape from solar system using large square solar sail with commercial payload	[387]
2004	***Solar Polar Orbiter***	Provide transfer to low-altitude solar polar orbit for close observation, then be jettisoned	[36,388,389]
2005	***UltraSail***	Perform outer planet rendezvous via 4-bladed helio-gyro with tip-satellites in formation flight	[390]
2006	***Interstellar Heliopause probe***	Provide transfer to interstellar medium using square solar sail via two near-Sun manoeuvres	[36,391,392]
2007	GeoSail	Demonstrate solar sailing technology and use it for station keeping in Earth's magnetotail	[393,394]
2007	Microsolar Sail SK	Perform station keeping in Earth's magnetotail using a constellation of small-scale solar sails	[92]
2009	Gossamer 1	Demonstrate and visualise deployment of a small, low-cost solar sail at low altitude in LEO	[395,396]
2009	Gossamer 2	Visualise deployment of improved sail design, demonstrate limited orbit and attitude control	[395,396]
2009	***Gossamer 3***	Visualise sail deployment, demonstrate full orbit and attitude control in lunar swing-by	[395,396]
2010	Atchison's Sprite	Perform passive solar sailing in geo-, helio-centric, or other space regions by mm-size chip-sails	[247]
2014	***Sunjammer***	Demonstrate sail deployment, attitude control, and station keeping at sub-L1 or other position	[76,397]
2014	HELIOS Heliogyro	Validate 6-bladed helio-gyro deployment, controlled sailing, structural dynamics, orbit change	[398]
2016	Alpha CubeSat	Verify the performance of a highly retroreflective material for light-sail propulsion	[90]
2018	***HIPERSail***	Provide a versatile, low-thrust propulsion capability for small spacecraft deep space missions	[82,339]
2018	TugSat	Move defunct GEO satellites to higher graveyard orbit using sail-equipped CubeSat	[399]
2019	***Solar Cruiser***	Validate sail deployment, station-keeping at Sun-Earth sub-L1, pointing, inclination change	[89,400]
2019	***Kon-Tiki***	Similar to Solar Cruiser, plus pointing control with RCDs	[228]
2019	***Helianthus***	Develop solar sail technology, monitor solar geomagnetic storms at Earth-Sun sub-L1 point	[285]
2020	Gama Beta	Demonstrate sail deployment, control law, orbit raising, and qualify sail as drag sail	[39,338]
2020	***Interstellar aerographite sail***	Study interplanetary medium using small payload propelled by hollow aerographite sphere	[95]
2021	***Payankeu***	Travel from high Earth orbit to Moon, capture picture of far side, operate dust counter on sail	[401]
2021	***Solar polar orbit diffractive sail***	Perform out-of-plane heliocentric manoeuvre by thrust vectoring using sail surface grating	[106]
2022	***Project Svarog***	Reach heliopause within 100 years from launch, using CubeSat via near-Sun manoeuvre	[93]
2023	***SunVane*** (SGL telescope)	Provide transfer to Sun gravitational lens via near-Sun manoeuvre, for exoplanet imaging	[402]
2023	***Mars aerographite sail***	Perform Mars flyby by rapid transfer from Earth orbit using hollow aerographite sphere	[96]
2023	***LightCraft***	Prove feasibility of solar sailing interplanetary smallsats to fly through and out of solar system	[104]
Laser-driven sail			
1984	***Laser-pushed flyby sail***	Perform one-way flyby of α Centauri using 65 GW laser-driven sail with 40 year flight	[109]
1985	***Starwisp to Alpha Centauri***	Perform one-way flyby of α Centauri using 10 GW maser-driven mesh sail with 21 year flight	[107]
2016	***Wafer scale spacecraft***	Perform sub-relativistic flight using 70 GW laser-driven wafer-scale craft equipped with sail	[114,403]
2016	***Breakthrough Starshot***	Perform one-way flyby of α Centauri using 200 GW laser-driven sail with 20 year flight	[18,72,111]
2019	***Project Dragonfly***	Perform 106 year flight to α Centauri using 100 GW laser-driven sail, decelerated on arrival	[110]
2022	Wafer-scale lightsail for fast-transit flight	Perform fast Earth orbital manoeuvring of wafer-scale craft using MW-class laser	[115]
2023	***Interplanetary Rapid Transit Mission***	Provide rapid transfer of small payloads to Mars using GW-class laser-driven sail	[117]
2024	***Astrobiology Precursor Mission***	Perform flyby of Enceladus or Europa plumes using GW-class laser with ~5 year flight	[120]
Drag sail			
1981	Aerobraked Orbital Transfer Vehicle	Perform single-pass aerobraking from GEO to LEO using inflatable, jettisonable ballute	[132]
1985	OTV-44ft	Increase payload capacity of orbital transfer vehicle for operation with ISS, via aerobraking	[133]
2000	***Lenticular ballute for Mars orbiter***	Provide aerocapture of microsatellite payload using inflatable lens supported by torus and net	[150]
2001	SPORT	Transfer small satellite from GTO to LEO via multi-pass aerobraking over several weeks	[126,404]
2003	AIR	Provide easier sample return from the ISS via tether-deployed inflatable re-entry capsule	[137,405]
2007	***Film-Hypercone***	Perform Mars aerocapture of large payload via thin-film conical tensile membrane	[144]
2007	Practical Aerostable Sail	Provide end-of-life disposal of LEO satellites via deployable membrane with shuttlecock shape	[406]
2009	FEATHER	Recover payload from small satellite via aeroshell deployment by aerodynamic heating	[145]
2011	***ADEPT***	Provide large payload transfer between Earth and Mars by umbrella-type deployable aeroshell	[138]
2013	***ADEPT-VITaL***	Decelerate lander released from interplanetary Venus entry probe to subsonic conditions	[139]
2017	***Small THz Spacecraft with Aeroshell***	Perform Mars aerocapture, entry, descent, landing of 100 kg craft using membrane aeroshell	[146]
2018	***TANDEM***	Provide Venus entry, descent, landing, locomotion via common structure with membrane shell	[140]
2018	Aerodynamic Deorbit Experiment	Validate Passively Stable Pyramid Sail for satellite de-orbit in LEO, using CubeSat prototype	[127]
2021	Drag Sail Conceptual Design	De-orbit a 20 kg satellite from an initial altitude of 800 km in LEO using a square sail	[407]
2022	D-Sail	Demonstrate deployable drag sail for de-orbiting microsatellites after their nominal mission	[129,408]
2024	***Tensegrity structure symmetric aeroshell***	Support multi-purpose planetary exploration via membrane aeroshell with tensegrity structure	[141]
2024	EFESTO 2 Option 1.1	Enhance maturity of European inflatable heatshields via Earth re-entry test flight	[134]

(*continued on next page*)

Table 8 (*continued*).

Magnetic sail			
1988	***Magsail for interstellar flight***	Provide propulsion for interstellar flight using current loop in large superconducting cable	[49]
1991	***Magsail for Earth-Mars cargo***	Transport cargo back and forth between Earth and Mars via return trips of Magsail	[409]
1991	***Magsail for escape from LEO***	Transport payload from LEO to interplanetary space using Magsail in geomagnetic field	[410]
2000	***M2P2***	Escape solar system via mini-magnetosphere made by injecting plasma into solenoid coils	[155]
2003	***MPS***	Explore outer planets via magnetic sail with magnetoplasmadynamically expanded plasma	[20]
2005	***Magbeam***	Beam plasma from a power source to a small satellite for large manoeuvres in Earth orbit	[157]
2005	***Small magnetic sail***	Test performance of small, lightweight magnetic sail in solar wind at 1 AU from Sun	[154]
2006	Magnetic sail engineering satellite	Test MPS concept via small satellite mission in highly-eccentric geocentric orbit	[156]
2011	***Plasma magnetoshell (PMS)***	Decelerate atm. entry probe by charge exchange between injected plasma and atmosphere	[50]
2012	***Plasma magnet (PM)***	Inflate mini-magnetosphere using plasma injection, sustain it by entraining solar wind	[158]
2014	***Small-Scale Magnetic Sail Spacecraft***	Test thrust performance of small magnetic sail in solar wind	[153]
2015	***Small Magsail Demonstration***	Demonstrate Magsail concept in Earth escape orbit using small superconducting wire loop	[69]
2016	***ESail-MSail***	Perform efficient interstellar transfer, decelerate via combined electric and magnetic sail	[151]
2023	***Magnetic sail on deployable membrane***	Increase thrust by combining multiple magnetic coils printed on a deployable membrane	[152]
Electric sail			
2004	***Square E-sail***	Provide thrust using square grid of positively charged copper wires in solar wind	[21]
2007	***Radial E-sail***	Provide thrust using spin-tensioned positively charged radial wires in solar wind	[161]
2008	***Interplanetary E-sail***	Transfer payload to Mars or Venus via radial spin-tensioned charged hoytethers	[162]
2009	***Negative polarity E-sail***	Provide thrust using solar wind electric sail with negative polarity and ion gun	[160]
2010	***Interstellar Heliopause Probe E-sail***	Escape solar system within 25 years from launch via near-Sun manoeuvre and sail jettison	[164]
2013	***E-sail with small photonic blades***	Control spin motion of charged tethers in solar wind using small solar sails at their tips	[172]
2014	***FGPB***	Enable multiple applications like E-sail, photonic sail, de-orbiting, via adjustable design	[173]
2014	***E-sail Uranus entry probe***	Deliver atmospheric entry probe to Uranus in 6 years using E-sail jettisoned at Saturn distance	[411]
2015	***Interplanetary E-sail (revisited)***	Provide thrust for payload transfer to Mars or Venus via radial spin-tensioned hoytethers	[167]
2015	***HERTS***	Provide escape from solar system of scientific probe within 10-15 years from launch	[412]
2016	***E-Sail Kinetic Energy Impactor***	Deflect asteroid using projectile equipped with E-Sail, using adjustable tether potential	[413]
2016	***Comet 67P rendezvous E-sail***	Provide rendezvous of small science probe with Comet 67P	[165]
2017	UWDES	De-orbit LEO/MEO satellites at mission end using charged wire tuft deployed into 3D shape	[248]
2023	Foresail 2	Deploy a 300 m tether, demonstrate operation as plasma brake and E-sail in eccentric orbit	[414]
2024	***ESTCube-LuNa***	Deploy a 2 km tether, visualise it, test operation as solar wind E-sail in lunar orbit	[25]
2024	Dragliner	Deploy a 5 km tether using autonomous module, demonstrate LEO satellite de-orbit	[291,292]
Deployable membrane reflector			
1977	NASA Solar Energy OSR (1400 km alt.)	Provide solar illumination of Earth for energy generation via constellation of disc mirrors	[176]
1977	NASA Solar Energy OSR (800 km alt.)	Provide solar illumination of Earth for energy generation via constellation of square mirrors	[176]
1978	NASA SOLARES	Enhance terrestrial solar energy, agriculture, via constellation of disc mirrors	[177,178]
1979	Ehricke Lunetta Concept	Provide night illumination of rural and urban areas via constellation of mirrors	[179]
1979	Ehricke Powersoletta Concept	Enhance output of terrestrial solar-electric power stations via constellation of mirrors	[179]
1979	Ehricke Biosoletta Concept	Support seafood production in Antarctic and Artic waters via constellation of mirrors	[179]
1982	NASA Street Illumination OSR	Provide illumination of major US cities, with applications for emergency response as well	[178]
1987	ARSAT 0 Dialogue	Provide artistic function by reflecting light using mirror, visible to people on Earth	[186]
1999	***UMBRAS***	Enhance JWST astronomy via formation flight with deployable rectangular occulter	[190,415]
2000	***BOSS***	Enhance JWST astronomy via formation flight with square transmissive occulter	[191]
2008	***New Worlds Observer***	Enable direct exoplanet imaging via formation flight of telescope with apodised occulter	[193,416]
2009	***THEIA***	Enable direct exoplanet imaging via formation flight of telescope with apodised occulter	[194,417]
2012	MiraSolar	Enhance output of terrestrial solar-electric power stations via constellation of mirrors	[180]
2012	Huge Space Shield (2012)	Weaken global warming by blocking sunlight using deployable disc-shaped mirrors	[300]
2013	***LUVOIR A sunshade***	Provide thermal control of LUVOIR space telescope via three-layer thin-film sunshade	[202]
2015	***Exo-S***	Enable direct exoplanet imaging via formation flight of telescope with apodised occulter	[189,197]
2016	***HabEx***	Enable direct exoplanet imaging via formation flight of telescope with apodised occulter	[9,195]
2017	***Starshade Rendezvous Probe***	Enhance WFIRST-AFTA astronomy via formation flight with deployable apodised occulter	[9,196]
2017	Huge Space Shield (2017)	Weaken global warming by blocking sunlight using deployable disc-shaped mirrors	[203,204]
2018	Remote Occulter	Enable direct exoplanet imaging by ground-based telescope via occulter in eccentric orbit	[198,418,419]
2023	***Lagrange Sunshade***	Provide Earth climate control via transmissive sunshade membrane with diffractive pattern	[205]
2023	Microsatellite aero sunlight reflectors	Make reconfigurable pixel image in sky via reflector-equipped formation of CubeSats	[249]
2023	SOLSPACE OSR	Enhance output of terrestrial solar power plants via train of orbiting hexagonal reflectors	[182,249]
Deployable membrane antenna			
1967	NASA 1500 m Radio Telescope Study	Perform radio astronomy via sparse paraboloid reflector made of aluminium ribbons	[209]
1990	Quasat	Perform radio astronomy via inflatable rigidisable lenticular antenna, one side RF transparent	[207]
1998	Inflatable L-band microstrip SAR array	Test inflatable SAR rectangular antenna on ground, made of three parallel membranes	[215,216]
1999	Inflatable X-Band 1 m reflectarray	Test inflatable X-band disc-shaped antenna on ground, made of two parallel membranes	[215]
1999	Inflatable Ka-Band 3 m reflectarray	Test inflatable Ka-band disc-shaped antenna on ground, made of single membrane	[215]
2005	SAR membrane antenna	Advance maturity of microstrip membrane antenna supported by CFRP booms	[214]
2006	NEXRAD in Space	Perform weather monitoring via inflatable lenticular antenna, one side RF transparent	[208,420]
2019	CloudCube	Study precipitation structures and dynamics via deployable Ka-band mesh antenna	[213]
2019	LADeR	Advance maturity of reflectarray antenna for small satellites, made of two parallel membranes	[217]
2020	OrigamiSat 2	Demonstrate pop-up deployable reflectarray membrane antenna onboard LEO CubeSat	[219,421]
2021	***LCRT***	Perform radio astronomy via deployable parabolic mesh suspended from walls of lunar crater	[60]
Solar power sail			
1969	***RSA250***	Advance the maturity of roll-up solar array for interplanetary spacecraft design concept	[222]
2001	***Pluto Flyby Furoshiki Satellite***	Provide power to Pluto flyby probe via deployable spin-tensioned solar power sail	[63,422]
2012	***MegaFlex***	Scale UltraFlex (circular fan-folded array) technology to larger power and improved stowability	[225,369,423]
2018	***OKEANOS***	Validate solar power sail for low cost deep space exploration, in rendezvous with a Jupiter Trojan	[12,232]

(*continued on next page*)

Table 8 (*continued*).

2021	PowerCube	Develop, demonstrate a 100 W deployable membrane solar array with 1U stowed volume	[229]
2022	HELIOS-R	Monitor in-orbit deployment and power generation performance of flexible thin-film solar array	[242]
2023	DEAR	Develop, demonstrate a 100 W deployable membrane solar array with 1U stowed volume	[230,231]
2023	***SEIMEI***	Provide power to low-cost Enceladus plume sampling probe with solar electric propulsion	[259]
2023	***OPENS0***	Provide power for Saturn flyby engineering demonstration via membrane solar array paddle	[232,275,424]
2023	***OPENS2***	Provide power for solar electric propulsion in Trojan asteroid rendezvous via two membrane paddles	[233]
2023	***PIERIS***	Visualise sail deployment, perform Earth & Venus swingbys with combined solar & solar power sail	[232]

Data availability

A link to the database containing values of important parameters for each of the 220 sails described in Appendix B is provided here [377].

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