2

Solar Sailing: Applications and Technology Advancement

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1. Introduction

Harnessing the power of the Sun to propel a spacecraft may appear somewhat ambitious and the observation that light exerts a force contradicts everyday experiences. However, it is an accepted phenomenon that the quantum packets of energy which compose Sunlight, that is to say photons, perturb the orbit attitude of spacecraft through conservation of momentum; this perturbation is known as solar radiation pressure (SRP). To be exact, the momentum of the electromagnetic energy from the Sun pushes the spacecraft and from Newton's second law momentum is transferred when the energy strikes and when it is reflected. The concept of solar sailing is thus the use of these quantum packets of energy, i.e. SRP, to propel a spacecraft, potentially providing a continuous acceleration limited only by the lifetime of the sail materials in the space environment. The momentum carried by individual photons is extremely small; at best a solar sail will experience 9 N of force per square kilometre of sail located in Earth orbit (McInnes, 1999), thus to provide a suitably large momentum transfer the sail is required to have a large surface area while maintaining as low a mass as possible. Adding the impulse due to incident and reflected photons it is found that the idealised thrust vector is directed normal to the surface of the sail, hence by controlling the orientation of the sail relative to the Sun orbital angular momentum can be gained or reduced. Using momentum change through reflecting such quantum packets of energy the sail slowly but continuously accelerates to accomplish a wide-range of potential missions.

1.1 An historical perspective

In 1873 James Clerk Maxwell predicted the existence of radiation pressure as a consequence of his unified theory of electromagnetic radiation (Maxwell, 1873). Apparently independent of Maxwell, in 1876 Bartoli demonstrated the existence of radiation pressure as a consequence of the second law of thermodynamics.
The first experimental verification of the existence of radiation pressure and the verification of Maxwell's results came in 1900. At the University of Moscow, Peter Lebedew succeeded in isolating radiation pressure using a series of torsion balance experiments (Lebedew, 1902). Nichols and Hull at Dartmouth College, New Hampshire, obtained independent verification in 1901 (Nichols & Hull, 1901, 1903). Around this period a number of science fiction authors wrote of spaceships propelled by mirrors, notably the French authors Faure and Graffigny in 1889. However, it was not until the early 20th century that the idea of a

solar sail was accurately articulated. Solar sailing as an engineering principle can be traced back to the Father of Astronautics, Ciołkowski (translated as Tsiolkovsky) and Canders (translated as Zander or Tsander) (Ciołkowski, 1936; Tsander, 1924). There is some uncertainty regarding the dates of Ciołkowski's writings on the potential use of photonic pressure for space propulsion. However, it is known that he received a government pension in 1920 and continued to work and write about space. It is within the early part of this period of his life, in 1921 perhaps, which he first conceived of space propulsion using light. Upon the publication of the works of Herman Oberth in 1923, Ciołkowski's works were revised and published more widely, enabling him to gain his due international recognition.
Inspired by Ciołkowski, Canders in 1924 wrote "*For flight in interplanetary space I am working on the idea of flying, using tremendous mirrors of very thin sheets, capable of achieving favourable results*." (Tsander, 1924). Today this statement is widely, though not universally, bestowed the credit as the beginning of solar sailing as an engineering principle.
In 1923 the German rocket pioneer Herman Julius Oberth proposed the concept of reflectors in Earth orbit (Spiegelrakete, or Mirror rocket) to illuminate northern regions of Earth and for influencing weather patterns (Oberth, 1923). It was this work which caused the works of Ciołkowski to be revised and published more widely. In 1929 Oberth extended his earlier concept for several applications of orbit transfer, manoeuvring and attitude control (Spiegelführung, or Mirror guidance) using mirrors in Earth orbit (Oberth, 1929). This work has a clear parallel with that of Canders' from 1924. However, it is also of interest that in this work Oberth noted solar radiation pressure would displace the reflector in a polar orbit in the anti-Sun direction. Thus, with the central mass, i.e. Earth, displaced from the orbit plane Oberth had, in-effect, noted the application of solar sailing to what we now call Highly Non-Keplerian Orbits and which will be discussed later in Section 3.1.2.
Following the initial work by Ciołkowski, Canders and Oberth the concept of solar sailing appears to have remained largely dormant for over thirty years. In the 1950s the concept was re-invigorated and published once again in popular literature, this time in North America. The first American author to propose solar sailing appears to have been the aeronautical engineer Carl Wiley, writing under the pseudonym Russell Sanders to protect his professional credibility (Wiley, 1951). Wiley discussed the design of a feasible solar sail and strategies for orbit raising in some technical detail. In particular he noted that solar sails could be "*tacked*" allowing a spiral inwards towards the Sun. In 1958 Richard Garwin, then at the IBM Watson laboratory of Columbia University, authored a solar sail paper in the journal Jet Propulsion where he coined the term "*solar sailing*" (Garwin, 1958).
Subsequent to the discussion of solar sailing by Garwin, more detailed studies of the orbits of solar sails were undertaken during the late 1950s and early 1960s (Birnbaum, 1968; Cotter, 1959; Fimple; 1962; Gordon, 1961; London; 1960; Norem, 1969; Sands, 1961; Tsu, 1959). For a fixed sail orientation several authors have shown that solar sail heliocentric orbits are of the form of logarithmic spirals (Bacon, 1959; London, 1960).
Early comparisons of solar sailing with chemical and ion propulsion systems showed that solar sails could match or out perform these systems for a range of mission applications, though of course the level of assumed technology status is crucial in such comparisons (MacNeal, 1972). These early studies explored the fundamental problems and benefits of solar sailing, but lacked a specific mission to drive detailed analyses and to act as a focus for future utilisation. In the early 1970's the development of the Space Shuttle and the technological advances associated with deployable structures and thin films suggested that perhaps solar sailing was ready to move beyond paper studies (Cotter, 1973; Grinevitskaia;

1973; Lippman, 1972; MIT Student Project, 1972). In 1974 NASA funded a low-level study of solar sailing at the Battelle laboratories in Ohio which gave positive recommendations for further investigation (Wright, 1974). The Battelle laboratories recommendations were acted upon at NASA-JPL in an Advanced Mission Concepts Study for Office of Aeronautics and Space Technology (OAST) in FY1976 (Uphoff, 1975). During the continuation of the Battelle laboratories study Jerome Wright discovered a trajectory that would allow a relatively high-performance solar sail to rendezvous with comet Halley at its perihelion in the mid-1980's by spiralling towards the Sun and then changing the orbit inclination by almost 180 deg (Wright & Warmke, 1976). The flight time of four years would allow for a late 1981 or early 1982 launch, however the required level of solar sail[1] performance suggests the study was always over optimistic. Furthermore, as it turns out the first operational space shuttle flight did not occur until the November of 1982 (STS-5); as such, the shuttle could not have acted as the Comet Halley solar sail launch vehicle as had been originally envisaged. A seven to eight year mission had been envisaged using solar-electric ion propulsion, requiring a launch as early as 1977. These positive results prompted NASA-JPL to initiate an engineering assessment study of the potential readiness of solar sailing, following which a formal proposal was put to NASA management on 30 September 1976. At the same time a companion study and technology development program for Advanced Solar Electric Prolusion was initiated in order to allow it to be evaluated as a competitor for the Halley mission. During the initial design study an 800-m per side, three-axis stabilised, square solar sail configuration was envisaged, but then dropped in May 1977 due to the high risks associated with deployment of such a massive structure. The design work progressed to focus on a spin stabilised heliogyro configuration. The heliogyro concept, which was to use twelve 7.5 km long blades of film rather than a single sheet of sail film, had been developed by Richard MacNeal and John Hedgepath (Hedgepath & Benton, 1968; MacNeal, 1967). The heliogyro could be more easily deployed than the square solar sail by simply unrolling the individual blades of the spinning structure. As a result of this design study the structural dynamics and control of the heliogyro were characterised and potential sail films manufactured and evaluated (Friedman et al, 1978; MacNeal, 1971). As a result of the Advanced Solar Electric Prolusion companion study NASA selected the Solar Electric Propulsion (SEP) system in September 1977 upon its merits of being a less, but still considerable risk for a comet Halley rendezvous (Sauer, 1977). A short time later the SEP rendezvous mission was also dropped due to escalating cost estimates (Logsdon, 1989).

1.2 Recent technology developments and activities

Following the Comet Halley studies solar sailing entered a hiatus until the early 1990's when further advances in spacecraft technology led to renewed interest in the concept. The first ever ground deployment of a solar sail was performed in Köln in December 1999 by the German space agency, DLR, in association with ESA and INVENT GmbH when they deployed a square 20-m solar sail, shown in Fig. 1 (Leipold et al, 2000; Sebolt et al, 2000). This ground deployment and the associated technology developed by DLR and ESA has struggled to progress to flight, initially an in-orbit deployment was planned for 2006 however this project floundered, with a similar, but smaller, demonstration now planned for 2013 as part of a three-step solar sail technology development program (Lura et al, 2010).

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[1] The comet Halley solar sail had a required characteristic acceleration of 1.05 mm s^{-2}; see Wright, 1992 (pp. 42).

In 2005 NASA completed dual solar sail development programs, funding a solar sail design by ATK and another by L'Garde Inc. who used the inflatable boom technology developed under the IAE program. Both solar sail systems were deployed to 20-m (side length) in the large vacuum chamber at NASA Glenn Research Center's Space Power Facility at Plum Brook Station in Sandusky, Ohio, U.S.A, the world's largest vacuum chamber (Lichodziejewski et al, 2003; Murphy et al, 2003 & 2004). Following the deployment demonstrations the L'Garde design was down-selected due to its perceived scalability to much larger sail sizes for the subsequent NASA New Millennium Space Technology 9 (ST-9) proposal, prior to the ST-9 program being cancelled. However, it should be noted that the ATK sail was considered a lower risk option. The intention of the NASA funding was to develop solar sail technology to Technology Readiness Level (TRL) six, however a subsequent assessment found that actually both the L'Garde and ATK sail failed to fully achieve either TRL 5 or 6, with the ATK sail achieving 89% and 86%, respectively and the L'Garde sail reaching 84 % and 78 %, respectively (Young et al, 2007).

In May 2010 the first spacecraft to use solar radiation pressure as its primary form of propulsion was launched by the Japanese space agency, JAXA, onboard an H-IIA launch vehicle from the Tanegashima Space Center as an auxiliary payload alongside the Japanese Venus orbiter Akatsuki, formerly known as the Venus Climate Orbiter (VCO) and Planet-C, and four micro-spacecraft. The solar sail spacecraft is called IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) and like the Akatsuki spacecraft was launched onto a near-Venus transfer trajectory. The IKAROS is a square solar sail, deployed using spinning motion and 0.5 kg tip masses, the polyimide film used for solar sailing also has thin-film solar arrays embedded in the film for power generation and liquid crystal devises which can, using electrical power, be switched from diffusely to specularly reflective for attitude control (Mori et al, 2010). IKAROS has demonstrated a propulsive force of 1.12mN (Mori et al, 2010) and is shown in Fig. 3. The IKAROS mission is envisaged as a technology demonstrated towards a power sail spacecraft, using the large deployable structure to host thin-film solar cells to generate large volumes of power to drive a SEP system (Kawaguchi, 2010).

In addition to the traditional view of solar sailing as a very large structure several organisations, including NASA and the Planetary Society, are developing CubeSat based solar sails. Indeed, NASA flew the first CubeSat solar sails on board the third SpaceX Falcon 1 launch on 2 August 2008 which failed approximately 2 minutes after launch. It is however unclear how such CubeSail programs will complement traditional solar sailing and whether they will provide sufficient confidence in the technology to enable larger, more advanced solar sail demonstrator missions. It is clear that the technology of solar sailing is beginning to emerge from the drawing board. Additionally, since the NASA Comet Halley mission studies a large number of solar sail mission concepts have been devised and promoted by solar sail proponents. As such, this range of mission applications and concepts enables technology requirements derivation and a technology application pull roadmap to be developed based on the key features of missions which are enabled, or significantly enhance, through solar sail propulsion. This book chapter will thus attempt to link the technology application pull to the current technology developments and to establish a new vision for the future of solar sailing.

2. Performance metrics

To compare solar sail mission applications and concepts standard performance metrics will be used. The most common metric is the characteristic acceleration which is the idealised SRP acceleration experienced by the solar sail facing the Sun at a distance of 1 au. An ideal or perfect sail facing the Sun at a distance of 1 au will experience a pressure of 9.126 μN m^{-2}; however, in practise an efficiency factor must be added to this to account for non-ideal performance (Wright, 1992). The sail characteristic acceleration offers an excellent performance metric unsullied by difficulties in hardware development and implementation of the theory.

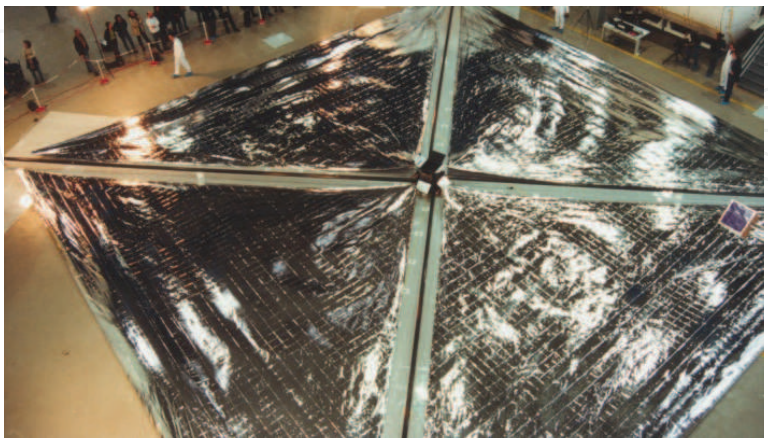

Fig. 1. DLR solar sail ground deployment test. Image credit DLR

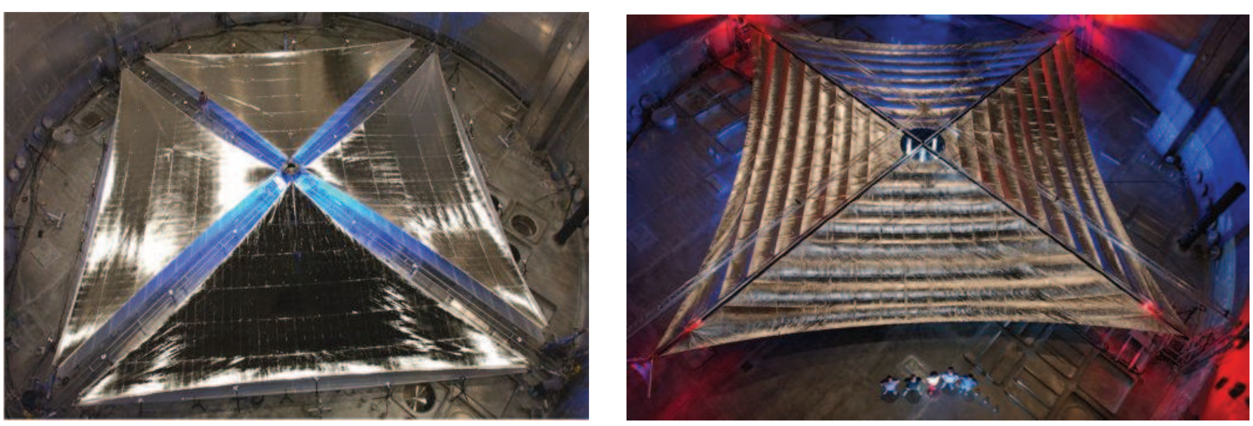

Fig. 2. 20-m solar sail deployment tests by ATK (left) and L'Garde (right) at NASA Glenn Research Center's Space Power Facility at Plum Brook Station. Image credit NASA

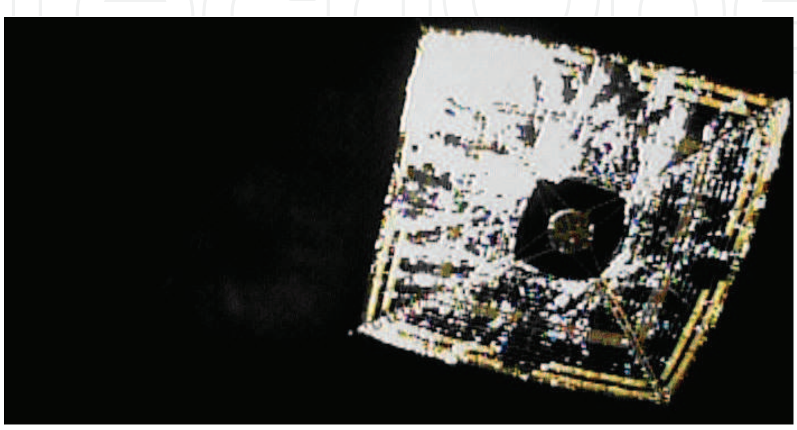

Fig. 3. IKAROS solar sail, imaged by free flying camera. Image credit JAXA

The sail assembly loading is the primary hardware performance metric for a solar sail, allowing a measure of the performance of the sail film and the efficiency of the solar sail architectural and structural design. The sail characteristic acceleration and assembly loading are defined as,

$$a_{S_c} = \frac{2P}{\sigma_S + (m_a / A)}, \ \sigma_S = \frac{m_S}{A} \tag{1}$$

where, P is SRP acting on the solar sail, m_a is mass attached to the solar sail, m_s is mass of the solar sail and A is the reflective surface area of the solar sail, typically assumed simply as the sail film area.

3. Solar sail mission catalogue

In the final quarter of the 20th century and opening decade of the 21st century solar sail propulsion has been proposed for a diverse range of mission applications ranging throughout the solar system. However, in-order to develop an application-pull technology development roadmap the concepts which are truly enabled or significantly enhance by solar sail propulsion must be identified. As such the mission catalogue will initially consider a wide range of mission concepts to allow definition of key characteristics of missions which are truly enabled or significantly enhance by solar sail propulsion. Subsequently critical missions which can act as facilitators to later, more technologically complex missions will be discussed in further detail. Through these considerations a solar sail application-pull technology development roadmap is established, using each mission as a technology stepping-stone to the next.

3.1 Identification of key characteristics

To aid the identification of key characteristics solar sail applications are divided into the seven categories below.

3.1.1 Planet-centred and other short orbit period applications

This category is essentially planet, minor-planet and small body centred trajectories. Planet-centred trajectory design has been largely restricted to escape manoeuvres or relatively simplistic orbit manoeuvring, such as lunar fly-by's or orbit inclination change (Eguchi et al, 1993; Fekete et al, 1992; Fimple, 1962; Green, 1977; Irving 1959; Lawden, 1958; Leipold, 1999; Macdonald, 2005a, 2005b; Morgan, 1979; Pagel, 2002; Sackett, 1977; Sackett & Edelbaum, 1978; Sands, 1961). Such trajectories place significant technology demands on the solar sail architecture, for example a locally optimal energy gain control profile for an Earth-centred orbit requires the sail to be rotated through 180 degrees once per orbit and then rapidly reset to maximise energy gain; as the sail size grows clearly this becomes an increasingly demanding technology requirement. It is noted that other simplistic orbit manoeuvres require similarly agile sail technology, for example an orbit plane-change require the sail to be rotated approximately 70.5 deg. twice per orbit (Macdonald, 2005a). This technology requirement for an agile sail is a significant disadvantage to the majority of short orbit period solar sail applications; however it should not be considered a blockage on the roadmap.
Two highly significant planet-centred solar sail applications have been identified which do not require, but may in-practise desire, active sail control and hence do not require an agile

sail; these are the GeoSail concept (Leipold et al, 2010; Macdonald & McInnes, 2000; Macdonald et al, 2007a) and the Mercury Sun-Synchronous Orbiter (Leipold et al, 1996a, 1996b). These two solar sail mission concepts are very similar, both using a solar sail with fixed attitude to independently vary a single orbit parameter due to the orbits shape and alignment with the primary body, and the alignment to the Sun, creating a non-inertial orbit. GeoSail rotates the argument of perigee of an eccentric orbit within the ecliptic plane at approximately 1 deg per day such that orbit apogee remains within the Earth's magnetotail. The Mercury Sun-Synchronous Orbiter meanwhile rotates the ascending node of an eccentric orbit whose orbit plane is at right-angles to the ecliptic plane such that the orbit plane remains perpendicular to the Sun-planet line, therefore enabling a sun-synchronous orbit at Mercury which is not possible naturally due to the high reciprocal of flattening of the planet.

3.1.2 Highly non-keplerian orbit applications

This category is, in some regards, an extension of the concept embodied by non-inertial orbits, with the sail providing a small but continuous acceleration to enable an otherwise unattainable or unsustainable observation outpost to be maintained.

Interestingly, as early as 1929 Oberth, in a study of Earth orbiting reflectors for surface illumination (Oberth, 1929), noted that solar radiation pressure will displace a reflector in a polar orbit in the anti-Sun direction. Since then a significant volume of work has been performed in this area; a comprehensive review of Highly Non-Keplerian Orbits (NKO) has recently been completed by McKay et al (2010) in which a range of orbits and applications are presented. Highly NKOs are typically characterised as requiring a small but continuous acceleration in a fixed direction, in this case provided by a solar sail with fixed attitude to provide the thrust required to compensate for the differences in gravitation and rotational force (gravity gradient) to displace the spacecraft to an artificial equilibrium point at a location some distance from a natural libration point.

Two primary solar sail applications of Highly NKOs are found in the literature; Geostorm and Polesitter (also called Polar Observer) (Biggs & McInnes, 2009; Chen-wan, 2004; Driver, 1980; Forward, 1991; Matloff, 2004; McInnes et al, 1994; Sauer, Jr., 2004; Waters & McInnes, 2007; West, 1996, 2000, 2004). The Geostorm mission concept provides real-time monitoring of solar activity; the spacecraft would operate sunward of the Earth's L_1 point, thus increasing the warning time for geomagnetic storms. By imparting a radial outward force from the Sun the solar radiation pressure *in-effect* reduces solar gravity and allows the L_1 point to be moved sunward. As sail performance is increased solar gravity is further '*reduced*', thus providing enhanced solar storm warning.

The Polesitter concept extends the Geostorm concept from a singular equilibrium point to derive equilibrium surfaces which extend out of the ecliptic plane and are again parameterised by the sail performance (McInnes et al, 1994). By extending the artificial equilibrium points out of the ecliptic plane, the small but continuous acceleration allows a spacecraft to be stationed above, or below, the second body within the 3-body problem. A further example of a highly non-keplerian orbit application is the Statite proposed by Forward (1991), which would use a high-performance solar sail to directly balance the solar gravity to hover stationary over the poles of the Sun.

The conceptually simple nature of the Geostorm and Polesitter missions is complicated by mission requirements, risk and budget factors and by the unstable nature of artificial equilibrium points. Although station-keeping should be possible (Biggs & McInnes, 2009;

Chen-wan, 2004; Sauer, Jr., 2004; Waters & McInnes, 2007) the requirement to station-keep increases the minimum level of technology requirement of the mission beyond, for example, the GeoSail mission discussed previously.

3.1.3 Inner solar system rendezvous missions

This category covers missions which use the solar sail to rendezvous, and perhaps bound the orbit to, a body in the inner solar system; defined as all bodies from the asteroid belt inwards, specifically excluding bodies which are, in-effect, part of the Jupiter system, for example the Hilda and Jupiter Trojan asteroids.

The use of solar sails for high-energy sample return missions to the inner planets has been discussed extensively within the literature (Garner et al, 2001; Hughes, 2006; Leipold, 1999; McInnes et al, 2002; Sauer, Jr., 1976; Tsu, 1959; Vulpetti et al 2008; Wright, 1992; Wright & Warmke, 1976) often without presenting the trajectory as part of a larger system-level trade on the propulsion selection criteria. Solar sailing, like other forms of low-thrust propulsion, requires that if a bound orbit about the target body is desired then at arrival the spacecraft must have, in-effect, zero hyperbolic excess velocity. Therefore, any wholly low-thrust interplanetary mission is required, unlike high-thrust missions, to *slow-down* prior to arrival at the target body and subsequently the transfer duration is typically significantly increased; this is especially true for bodies which can be relatively easily reached by high-thrust, chemical propulsion systems such as Mars and Venus. Furthermore, once the solar sail has been captured into a bound-orbit about the target body it then has the typical disadvantages discussed previously for planet-centred solar sail applications.

A sequence of assessment studies was previously conducted by the Authors and Hughes looking at solar sail sample return missions to Mars (McInnes et al, 2003a), Venus (McInnes et al, 2003b), Mercury (Hughes, 2006; McInnes et al, 2003c), and a small-body (McInnes et al, 2003d), with the specific objective of enabling a system-level trade on the propulsion selection criteria within each mission. Within each of these a complete system level analysis was performed, considering a range of mission architectures, attempting to define the most preferential solar sail architecture. The identified preferential solar sail architecture was then compared against alternative propulsion systems conducting a similar mission.

In all Mars Sample Return mission architectures it was found to be very difficult to justify the use of a solar sail due to the significantly increased mission duration (McInnes et al, 2003a). The "*grab-and-go*" architecture, identified as the most preferential for solar sailing required a mission duration of 5 – 6 years depending on the launch vehicle, while a similar all chemical propulsion mission could be completed in only 2 years, although requiring a slightly larger launch vehicle (McInnes et al, 2003a). A very similar scenario was found in the analysis of the Venus Sample Return mission (McInnes et al, 2003b). However, it was found that due to the increased launch mass sensitivity to returned mass the use of a solar sail for the Earth return stage offered potential real benefits; note the solar sail attached mass for this scenario was 323 kg requiring a sail of less than 100-m side length at an assembly loading of 6 gm^{-2}, with 20 % design margin. It was found that using a solar sail for the Earth return stage of a Venus Sample Return mission reduced the launch mass by approximately 700 kg, enabling a smaller, hence lower cost, launch vehicle to be used without notably impacting mission duration. Such a scenario does however have the typical disadvantages discussed previously for planet-centred solar sail applications when using the sail to escape the Venus gravity-well.

Considering both the Mercury and Small Body Sample Return missions it was found that due to the high-energy nature of the transfer trajectories only low-thrust propulsion systems offered viable mission concepts, with solar sailing offering potential benefits (Hughes, 2006; McInnes et al, 2003c, 2003d). Note the small-body target was asteroid 2001 QP153, with an orbit inclination of 50 deg. The Mercury Sample Return mission would have the typical disadvantages discussed previously for Short Orbit Period solar sail applications, however it was found that a large, high-performance solar sail would offer some potential benefits to such a mission (Hughes, 2006). It is of note that missions to small bodies, such as asteroid 2001 QP153, could negate the disadvantages discussed previously for short orbit period solar sail applications as the sail may not be required to enter a bound orbit about the small-body, if indeed a stable orbit could even be found.

3.1.4 Outer solar system rendezvous missions

The use of solar sails for outer solar system rendezvous missions has been long discussed within the literature (Garner et al, 2001; Leipold, 1999; Wright, 1992; Wright & Warmke, 1976). Furthermore, an assessment study was previously conducted by the Authors and Hughes looking at a range of solar sail Jupiter missions (McInnes et al, 2003e, 2004a), including concepts for exploration of the Galilean moons. As with low-thrust inner solar system rendezvous missions the hyperbolic excess velocity at the target outer solar system body must be lower than high-thrust missions. The inverse squared variation in SRP with solar distance however means that the sail performance is significantly reduced over the same sail at Earth. As such the requirement to reduce the hyperbolic excess velocity prior to arrival at the outer solar system body leads to prolonged transfer durations. Note however that due to the large moons within both the Jupiter and Saturn planetary systems capture can be performed using gravity assist manoeuvres to enable the hyperbolic excess velocity to be significantly greater than zero (Macdonald, 2005c). Furthermore, the duration required to reduce the orbit altitude following capture is also significantly prolonged due to the inverse squared variation in SRP with solar distance. Clearly, this class of mission becomes increasingly unattractive as the target body moves further from the Sun.

Outer solar system rendezvous missions are concluded to be unsuitable for solar sail propulsion due to the inverse squared variation in SRP with solar distance.

3.1.5 Outer solar system flyby missions

Outer solar system fly-by missions remove the requirement to reduce the hyperbolic excess velocity prior to arrival at the target body and as such negate much of the negative elements of solar sail outer solar system rendezvous missions. A Jupiter atmospheric probe mission was considered by the Authors and Hughes (McInnes et al, 2003e) as a potential Jupiter flyby mission. It was concluded that due to the mass of the atmospheric probes, of which three were required, and the relative ease of such a mission with chemical propulsion that solar sail propulsion offered little to such a mission. It is of note that as the target flyby body moves further from the Sun, and hence the difficulty of such a mission with chemical or SEP increases, solar sail propulsion becomes increasingly beneficial; ultimately leading to a peak in solar sail benefits for such missions in the Beyond Neptune category which will be discussed later.

3.1.6 Solar missions

Most previous missions to study the Sun have been restricted to observations from within the ecliptic. The Ulysses spacecraft used a Jupiter gravity assist to pass over the solar poles, obtaining field and particle measurements but no images of the poles. Furthermore, the Ulysses orbit is highly elliptical, with a pole revisit time of approximately 6 years. It is desired that future solar analysis be performed much closer to the sun, as well as from an out-of-ecliptic perspective. The Cosmic Visions mission concept Solar Orbiter intends to deliver a science suite of order 180 kg to a maximum inclination of order 35 deg with respect to the solar equator and to a minimum solar approach radius of 0.22 au using SEP. The inability of the Solar Orbiter mission to attain a solar polar orbit highlights the difficulty of such a goal with conventional propulsion. It has however been shown that a mid-term solar sail can be used to deliver a spacecraft to a true solar polar orbit in approximately five-years (Goldstein et al, 1998; Macdonald et al, 2006). The Solar Polar Orbiter (SPO) mission concept is a good example of the type of high-energy inner-solar system mission which is enabled by solar sail propulsion.

3.1.7 Beyond Neptune

A significant quantity of work in the past decade has been performed to assess the problem of trajectory and system design of a solar sail mission beyond Neptune (Colasurdo & Casalino, 2001; Dachwald, 2004a, 2004b, 2005; Garner et al, 2000, 2001; Leipold & Wagner, 1998; Leipold, 1999; Leipold et al, 2006, 2010b; Lyngvi et al, 2003, 2005a, 2005b; Macdonald et al, 2007b, 2010; McInnes, 2004b; Sauer, Jr., 2000; Sharma & Scheeres, 2004; Sweetser & Sauer, Jr., 2001; Vulpetti, 1997, 2002; Wallace, 1999; Wallace et al, 2000; West, 1998; Yen, 2001). It has been shown that solar sail propulsion offers significant benefits to missions concepts which aim to deliver a spacecraft beyond Neptune, for either a Kuiper Belt or Interstellar Heliopause (at approximately 200 au) mission. Such outer solar system missions initially exploit the inverse squared variation in SRP with solar distance by approaching the Sun to gain a rapid energy boast which generates a hyperbolic trajectory and allows the spacecraft to rapidly escape the solar system.

Solar sails mission concepts significantly beyond the Interstellar Heliopause were considered by Macdonald et al (2010). In-order to determine the limit of the solar sail concept an Oort cloud mission was examined using solely SRP to propel the spacecraft. It was found that although no fundamental reason existed why such a mission may not be possible the practicalities were such that the Interstellar Heliopause Probe (IHP) mission concept could be considered representative of the upper limiting bound of the solar sail concept.

3.1.8 Key characteristics

Solar sailing has traditionally been perceived as an enabling technology for high-energy missions; however, as has been shown in the preceding sections the key characteristics of a mission which is enabled, or significantly enhanced by solar sailing are more complex than simply this.

Solar sailing is, due to the lack of propellant mass, often noted as reducing the launch mass of an equivalent chemical or SEP concept, which is in-turn noted as reducing launch and mission cost. However, while it is accurate that the launch mass is typically reduced this does not directly result in a reduced launch vehicle cost as the reduction may not be sufficient to allow the use of a less capable, and hence lower cost, launch vehicle. As such the launch cost is only reduced if the reduced launch mass allows a smaller launch vehicle to be used, meaning that launch cost varies as a step function while launch mass linearly increases. Finally, it should be noted that if the total mission cost is high, say, 500+ M€ then

reducing the launch mass cost by 10 – 20 M€ is a cost saving of order 2 – 4 %, which may not be considered a good cost/risk ratio for the project and indeed, the cost saving may be insufficient to pay for the additional development of the technology. Thus for the reduction in launch mass to be an enabling, or significantly enhancing aspect of a solar sail mission concept the cost saving must also be a significant percentage of the total mission cost.
All solar sail mission concepts can be sub-divided into two classes, these are:

- Class One
  - Where the solar sail is used to reach a high-energy target and after which the sail can be jettisoned by the spacecraft, for example the Solar Polar Orbiter mission.
- Class Two
  - Where the solar sail is required to maintain a novel or otherwise unsustainable observation outpost, for example, highly non-keplerian or non-inertial orbit applications, such as Geostorm and GeoSail.

This distinction is important as the later compares very favourably against most other propulsion systems, especially as the mission duration and hence reaction mass is increased. However, a solar sail is a very large structure and could adversely impact the mission objectives either through a characteristically low pointing accuracy due to low frequency structural flexing, or due to the solar sail interfering with the local environment in, for example, particle and field measurements. Thus, a critical requirement on early solar sail demonstration missions must be to validate the simulated pointing accuracy of the platform and the effect of the sail on the local space environment.
From the mission catalogue it is seen that solar sail propulsion has been considered for a large range of mission applications, some of which it is more suitable for than others. Each of the solar sail applications within the mission catalogue are sub-divided by the level of enhancement offered by solar sail propulsion in Table 1. From Table 1 the key positive and negative characteristics of solar sail missions are defined in Table 2.

Enabled or Significantly Enhance	**Marginal benefit**	**No benefit**
Non-Inertial Orbits, such as GeoSail or a Mercury Sun-Synchronous Orbiter	Venus escape at end of sample return mission	Planetary escape at start of mission
Highly Non-Keplerian Orbits such as Geostorm and Polesitter	Mercury and high-energy small body Sample Return missions	Mars missions
Kuiper-Belt fly-through	Outer solar system planet fly-by	Outer solar system rendezvous and centred trajectories
Solar Polar Orbiter	Transit of Gravitational Lens region	Loiter at the Gravitational Lens
Interstellar Heliopause Probe	Oort Cloud	

Table 1. Solar sail missions by benefit

Positive Characteristic	Negative Characteristic
Very High Energy transfer trajectory	Mars and Venus rendezvous
Inner Solar System	Outer Solar System rendezvous
Highly Non-Keplerian and Non-Inertial orbits	Short orbit period with rapid slew manoeuvres
Final stage in a multi-stage system	High radiation environment
Fly-by beyond the orbit of Neptune	High pointing stability required
	Required to rendezvous with a passive body
	Fly-by beyond solar gravitational lens

Table 2. Solar sail mission key characteristics

3.2 Key missions
Three key mission will be briefly discussed, one from each of near, mid and far term.

3.2.1 Near-term: GeoSail
The GeoSail mission concept is motivated by the desire to achieve long residence times in the Earth's magnetotail, enabling high resolution statistical characterisation of the plasma in a region subject to a variety of external solar wind conditions (Alexander et al, 2002; Leipold et al, 2010a; Macdonald et al, 2000, 2003, 2007a; McInnes et al, 2001). This is accomplished by the novel application of a solar sail propulsion system to precess an elliptical Earth-centred orbit, interior to the lunar orbit, at a rate designed to match the rotation of the geomagnetic tail, the orientation of which is governed by the Sun-Earth line. The GeoSail mission concept is one of the earliest possible solar sail missions which can satisfy a clearly defined science requirement while also acting as a pathfinder to later, more technically demanding missions. The first true solar sail mission must not be an experiment but a demonstration which, through its heritage, enables more technically demanding missions. Considering GeoSail as a potential technology demonstration mission it is required to resolve known issues and validate simulations and prior experiments. In particular, measurement and analysis must be performed as to the effect of the sail on the local space environment. This is a key mission goal. The final engineering goal of GeoSail, or any sail demonstration mission, must be the successful demonstration of a sail jettison and separation manoeuvre; a key requirement of several solar sail missions such as the Solar Polar Orbiter and the Interstellar Heliopause Probe.
The GeoSail orbit has a perigee located above the planetary dayside at approximately 11 Earth radii (R_E), corresponding to alignment with the magnetopause. Apogee is aligned with the geomagnetic tail reconnection region on the night-side of the Earth, at 23 R_E. The orbit plane is within the ecliptic plane. With the spacecraft located in the ecliptic plane the sail normal is fixed at zero pitch, i.e. the sail is face-on to the Sun at all times, to induce the desired independent secular variation in the argument of pericentre (McInnes et al, 2001). Thus, by varying the sail thrust magnitude the rate of change of argument of pericentre can

be varied. The required sail characteristic acceleration is found to be 0.09985 mm s^{-2}; note the defined sail characteristic acceleration is adjusted to account for the prolonged shadow event each orbit. It is found that a square solar sail of order forty metres per side is required to conduct the GeoSail mission at an assembly loading of 34 g m^{-2}, using 3.5 µm Teonex® film and a boom specific mass of 40 gm^{-1} (Macdonald et al, 2007a). However, it was also found that for the GeoSail mission to provide sufficient heritage to later, more technically demanding missions, the design point was required to be more demanding than should the GeoSail mission be conducted in isolation. It is noted finally that the GeoSail orbit is well suited to a technology demonstration mission due to its proximity to Earth, allowing extended observation of the system from Earth.
In direct comparison of solar sail, SEP and chemical variants of the GeoSail concept it is found that a high-thrust mission has an annual Δv requirement of over 2 km s^{-1}, resulting in significant difficulties when attempting to perform mission durations of longer than approximately one-year. Conversely it is found that a SEP variant is rather attractive as the required thrust level is easily attainable with current technology. It is of note that the exhaust gases would need to be neutralised, especially for a geomagnetic tail mission, as the ionised particles would interfere with science measurements and spacecraft subsystems, this adversely impacts the propellant mass required. It is found that a SEP variant of GeoSail could have a nominal duration of at least two-years (Macdonald et al, 2007a). Therefore, the solar sail mission is increasingly attractive for increased mission durations. It is also of note that the solar sail mission was found to fit with a Vega launch vehicle, while the SEP variant just tipped into a Soyuz vehicle, hence incurring a notable launch cost increase.

3.2.2 Medium-term: solar [olar orbiter

The Solar Polar Orbiter (SPO) mission concept is motivated by the desire to achieve high latitude, close proximity observations of the Sun. Terrestrial observations of the Sun are restricted to the ecliptic plane and within the solar limb, thus restricting observations to within ± 7.25 deg of the solar equator. As discussed earlier the Ulysses spacecraft used a Jupiter gravity assist to pass over the solar poles, obtaining field and particle measurements but no images of the poles, however the orbit is highly elliptical, with a pole revisit time of approximately 6 years. It is desired that future solar analysis be performed much closer to the sun, as well as from an out-of-ecliptic perspective, this is the goal of the Cosmic Visions mission concept Solar Orbiter. However, the inability of the Solar Orbiter mission to attain a solar polar orbit highlights the difficulty of such a goal with conventional propulsion. The SPO mission uses a solar sail to place a spacecraft into an orbit at 90 deg inclination with respect to the solar equator (82.75 deg with respect to the ecliptic plane) and interior to the Earth's orbit. Additionally, the spacecraft orbit is phased such that it will remain near to the solar limb from a terrestrial perspective which eliminates solar conjunctions and hence loss of telemetry. Once the solar sail has delivered the spacecraft to the solar polar orbit it is jettisoned to allow the science phase of the mission to begin (Goldstein et al, 1998; Macdonald et al, 2006).
The third resonant orbit is defined as the target orbit as this places the spacecraft close to the Sun, while also being in a relatively benign thermal environment compared to higher order resonant orbits.
Macdonald et al (2006) conducted an analysis to determine the minimum required slew rate of the solar sail within the SPO mission. It was considered that during the orbit inclination increase phase of the trajectory, or the cranking phase, the sail pitch is fixed at $\arctan(1/\sqrt{2})$,

while the sail clock angle flips from 0 deg to 180 deg, however it is clear that the sail thrust vector cannot be rotated through approximately 70.5 deg instantaneously. Thus, the effect of variations in the sail slew rate on the cranking phase were quantified, concluding that a sail slew rate of 10 deg per day (10^{-4} deg s^{-1}) resulted in a performance degradation from the instantaneous slew of less than 0.5 %. A required sail slew rate of 10 deg per day was thus defined for the mission.

It is found that a square solar sail of order one-hundred and fifty metres per side is required to conduct the SPO mission at an assembly loading of 8 g m^{-2} and characteristic acceleration 0.5 mm s^{-2} (Macdonald et al, 2006).

Macdonald et al (2006) concluded that both conventional SEP and chemical propulsion could not be considered viable alternatives to solar sailing for an SPO mission. As such a comparison against new and novel propulsion systems was conducted, such as nuclear electric propulsion (NEP), radioisotope electric propulsion (REP) and Mini-Magnetospheric Plasma Propulsion (M2P2). It was expected that any NEP system will require a large launch vehicle due to the inherent nature of the system. Meanwhile, the use of a REP system would require extremely advanced radioisotope power sources to compete with solar power. M2P2 could potentially provide the required change in velocity needed to attain a true solar polar orbit. This concept is akin to solar sails, but has the advantage of not requiring large structures to be deployed. The drawback to this propulsion method is that the magnetic field generating system mass may be quite high. The lack of viable competing propulsion systems serves to highlight the potential of solar sailing for a solar polar mission concept. It is thus conclude that solar sailing offers great potential for this mission concept and indeed may represent the first useful deep space application of solar sail propulsion.

3.2.3 Far-term: interstellar heliopause probe

As previously discussed a significant quantity of work in the past decade has been performed to assess the problem of trajectory and system design of a solar sail mission beyond Neptune. A specific example of this class of mission is the Interstellar Heliopause Probe (IHP) concept which exploits the inverse squared variation in SRP with solar distance by approaching the Sun to gain a rapid energy boast which generates a hyperbolic trajectory and allows the spacecraft to rapidly transit the inner solar system prior to sail jettison at 5 au.

The IHP mission concept typically envisages the spacecraft arriving at a solar distance of 200 au in 15 – 25 years. The issue of an upper feasible limit on mission duration is difficult to quantify. For example, the Voyager spacecraft remain operational over three-decades since launch, yet the primary mission of these spacecraft was, approximately, three and twelve years for Voyager 1 and 2 respectively. However, both spacecraft have continued to provide scientifically interesting data and as such operations have continued. Typically any IHP mission would provide continuous science data from 5 au onwards, i.e. post-sail jettison, thus it is anticipated that the spacecraft will provide scientifically interesting data from an early stage. However, the primary goal of the mission is measurement of the interstellar medium, which therefore necessitates a funding commitment over a much longer period than originally envisaged for the Voyager spacecraft. Clearly the perceived upper feasible limit on mission duration has a significant impact on the required technology of the mission concept. It is of interest that previous NASA led activities have targeted a solar distance of 200 au in 15 years (Garner et al, 2000; Wallace, 1999; Wallace et al, 2000), while recent ESA and European activities have typically targeted a solar distance of 200 au in 25 years (Leipold et al, 2010b; Lyngvi et al, 2003, 2005a, 2005b; Macdonald et al, 2007b, 2010). The

NASA led activities clearly determine that a conventional square solar sail will not suffice for the short mission duration and that a spinning disc sail, or some other equally low sail assembly loading sail architecture, is required. However, the European studies exhibit some ambiguity on the required sail technology level which was recently considered by Macdonald et al who concluded that the ambiguity was perhaps due to a slight relaxation in the mission duration requirement (2010).
It is found that a disc solar sail of order one-hundred and fifty to two-hundred metres radius is required to conduct the IHP mission at an assembly loading of 1.5 – 2 g m^{-2}, delivering a characteristic acceleration of 1.5 – 3 mm s^{-2} (Macdonald et al, 2010; Wallace et al, 2000). It can be shown that a chemical IHP mission is feasible, however to provide a similar trip time it requires a heavy-lift launch vehicle and an Earth-Jupiter gravity assist trajectory which significantly limits the launch window opportunities. Note, the solar sail launch window repeats annually. Conventional chemical propulsion for the IHP mission appears unattractive from this concept, however should a specific impulse of over 450 seconds be achieved then such a variant, with a large burn at 4 solar radius may be possible from a Soyuz-like launch vehicle (McInnes et al, 2004b). The use of SEP is possible, again using a gravity assist trajectory; however, it is unlikely that a solar power system would be sufficient for an IHP mission. NEP is however an attractive option for the IHP mission and could be used to reduce trip time and launch mass over most other options, there will however be a limit to this launch mass reduction as the smallest fission reactor and engine size is likely to be of order 1200 kg (McInnes et al, 2004b). A major advantage of using NEP is that the reactor can be used to provide a power-rich spacecraft at 200 au and so provide high data rates through a modest high-gain antenna. The primary disadvantage of the NEP concept, beyond the attendant political issues, is that the spacecraft may be required to continue thrusting beyond the orbit of Jupiter to reach 200 au in the required timeframe. Continued thrusting may adversely impact the science objectives of the mission with a direct consequence for funding. Finally, M2P2 and electric sail technology may both offer interesting alternatives to solar sailing (Janhunen, 2008; Winglee et al, 2000).

4. Application pull technology development route

Considering the IHP mission as typical of the culmination of any solar sail application roadmap it is important that the technology requirements of this mission application be enabled by previous milestones on the roadmap, that is to say, previous missions. Hence, as the IHP mission requires a low sail assembly loading sail architecture it is critical that previous applications of solar sailing provide suitable heritage to this mission. The top-level technology requirements of each of the missions from within the catalogue, which satisfy the positive criteria detailed in Table 2, are shown in Fig. 4. It should be noted that Fig. 4., is independent of sail architecture as it simply relates the required sail surface area to the required sail assembly loading.
Each of the key missions discussed in Section 3.2 can be seen within Fig. 4. It is noted that despite, as discussed in Section 3.2.1, the GeoSail system analysis being over-engineered if the mission were conducted in isolation, rather than as part of a technology development roadmap, the GeoSail technology requirements still do not clearly fit within the application technology requirement bounds of the more demanding mission concepts. Indeed, for GeoSail to provide a simple log-linear technology trend towards the two other key missions discussed in Section 3.2 the sail assembly loading must be further reduced to approximately

20 – 25 g m^{-2}, while to reach the Mean Application Trend the sail assembly loading must be reduced to approximately 15 – 20 g m^{-2}.

5. Future advancement roadmap

The currently identified applications of solar sailing which will, due to the enabling or significantly enhancing aspects of solar sail propulsion, pull the technology development are, as seen in Fig. 4, significantly clustered about the mid to far-term technology; while the near-term remains sparsely populated. There can be little argument about the scientific value of missions such as SPO. However, the risk involved in directly attempting such a mission with solar sail propulsion would be so large as to be prohibitive.

Solar sailing is an elegant concept, however it must be pulled forward by mission applications at the same time as it is pushed by technology development. This also holds true for initial flight tests of solar sailing. As discussed in Section 3.2.1, unless such flight tests provide confidence in the technology and a clear path towards some enabling capability, they will not perform a useful function. A good example of this was the use of low cost sounding rockets by JAXA to test multiple sail deployment mechanisms during the short period of free-fall which allowed for several tests of scaled prototypes at the same cost as a single launch to orbit. By spreading the risk over several tests the inevitable unforeseen single point failures of deployment could be identified prior to launch of IKAROS in May 2010 as a full-scale demonstration mission (Mori et al, 2010; Normile, 2010; Sawada et al, 2010).

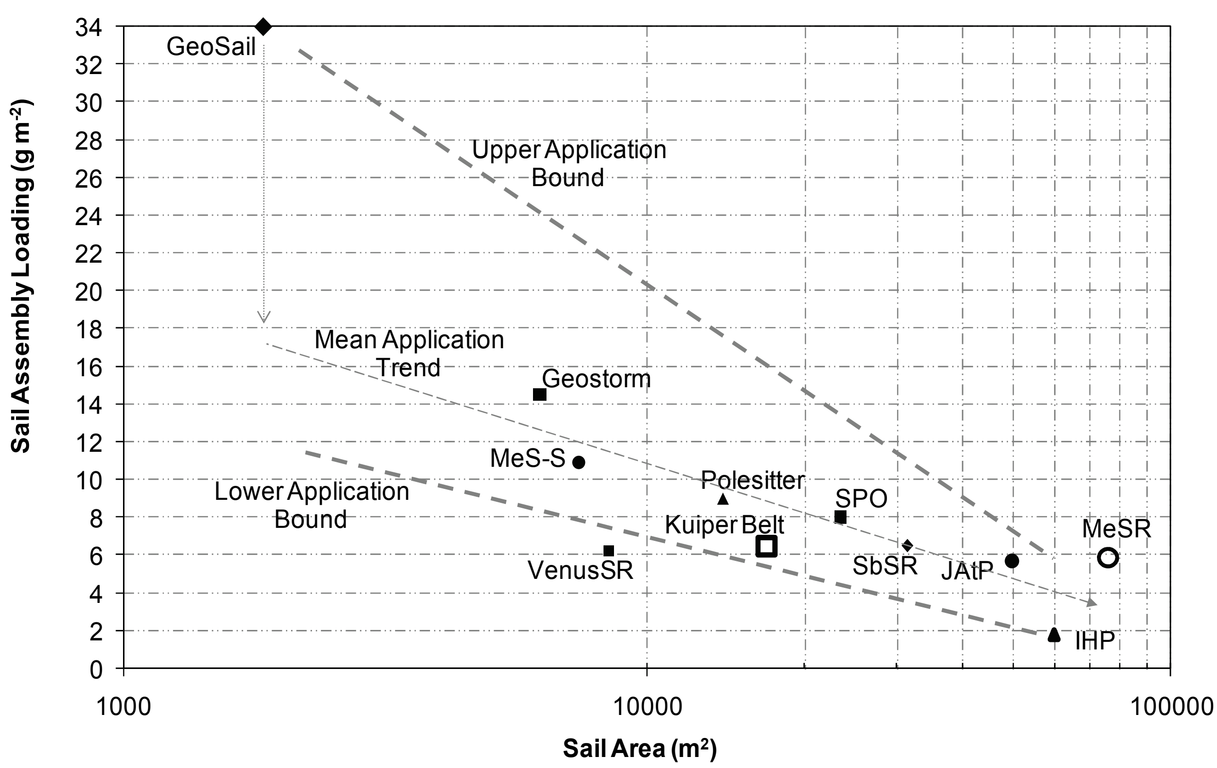

Fig. 4. Solar sail mission catalogue application technology requirements. IHP ≡ Interstellar Heliopause Probe; JAtP ≡ Jupiter Fly-by with Atmospheric Probe release; MeSR ≡ Mercury Sample Return; MeS-S ≡ Mercury Sun-Synchronous; SbSR ≡ High-Energy Small-Body Sample Return; SPO ≡ Solar Polar Orbiter; VenusSR ≡ Venus Sample Return.

With the clearly established clustering of identified enabling or significantly enhancing applications of solar sailing towards the mid to far-term a requirement exists to backfill these requirements. This can be achieved in two ways, the first of which is to develop mission concepts which are enabling or significantly enhancing by near-term solar sail propulsion in a similar way to the GeoSail concept. The alternative to this is to re-engineer the mission concepts and the vision of the future of solar sailing, such that the gap between near and mid-term applications is removed. This can be achieved by recognising and adapting the Advancement Degree of Difficulty (AD2) scale. TRLs define the maturity, or readiness, at discrete points in a schedule. However, this is only half of the engineer's problem. TRLs provide no information on how well, or easily, the technology will move from one TRL to the next, i.e. what is the risk of the technology development program. The AD2 scale was developed to address issues of programmatic risk and to aid the incorporation of low-TRL components into larger systems, however the founding principles can be adapted to larger scale, novel or advanced concepts such as solar sailing. The AD2 scale categorises risk from the lowest AD2, Level 1 (0% risk) defined as "*Exists with no or only minor modifications being required. A single development approach is adequate.*" Through to the highest AD2, level 9 (90 – 100 % risk), defined as "*Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.*" Performing a simple, top-level AD2, TRL project status analysis of solar sailing for an advanced technology demonstrator it is found that the project risk is, at best, acceptable, and that dual development approaches should be pursued to increase confidence.

To reduce the risk on the solar sail development roadmap the AD2 level must be reduced. This can be done in two ways, firstly by considering solar sailing as a primary propulsion source an extension of the use of solar sailing as an attitude control device and secondly by incorporating other low-thrust, high TRL propulsion technologies into the early solar sail technology development roadmap to bridge the gap between the near and mid-term applications, i.e. hybrid sail/SEP propulsion. The use of SRP for attitude control on large spacecraft in geostationary orbit and interplanetary space is common practise. Most notably, Mariner 10 used a small "*kite*" (31 cm × 76 cm) for manoeuvring by using the pressure of sunlight for attitude control. By using the ballast solar sail for attitude control manoeuvring the Mariner 10 project was able to extend the planned life of the mission and increase mission science returns (NASA/JPL, 1975, 1976; Shirley, 2002). A similar technique was employed by the MESSENGER mission to Mercury. Thus, the principles of solar sailing are already at a high TRL. The inherent programmatic risk in solar sailing is a direct result of the high AD2 in progressing immediately to a spacecraft using SRP as the sole primary propulsion system. The programmatic risk in solar sailing can be significantly reduced by hybridising the propulsion with a high TRL SEP system, which also offers critical advantages when considering trajectory generation due to the ability of an SEP system to thrust directly towards the Sun. The Mariner 10 and MESSENGER spacecraft both used a rather small kite, or solar sail, and there is no reason why other inner solar system missions would not similarly benefit from doing so. In this regard such missions would be primarily a SEP spacecraft which also has a small solar sail. The AD2 is then significantly reduced when incrementally reducing the size of the SEP system and increasing the size of the solar sail as its TRL is increased. Furthermore, through such a hybridisation it can be expected that the mid to far-term cluster of solar sail applications seen in Fig. 4 will shift down the sail area axis towards the near-term, therefore reducing the AD2 of concepts such as SPO.

Finally, it is of note that much of the recent solar sail technology development has focused on the CubeSat platform, including NanoSail-D (Johnson et at, 2010), the DLR led Gossamer program (Lura et al, 2010), the Planetary Societies Lightsail-1 (Biddy, 2010; Cantrell & Friedman, 2010, Nehrenz, 2010) and several others (Carroll et al, 2010; Lappas et al, 2010; Pukniel et al 2010). The low-cost nature of CubeSats allows the early risk to be spread over several low-cost missions where a failure can be tolerated much as it was with NanoSail-D. The gap between a CubeSat solar sail and, say, GeoSail is rather large and does not significantly mitigate the high AD2 of solar sailing. However, if a CubeSat based solar sail system can be successfully developed then it potentially would enable an increased solar sail kite to be incorporated onto a future SEP mission, allowing solar sailing to progress along its development roadmap.

6. Conclusions

A solar sail mission catalogue has been developed and presented. The mission catalogue was sub-divided into applications which were enabled, or significantly enhanced by solar sailing, of which solar sailing is of marginal benefit and of which solar sailing could be considered unconstructive. From this the key characteristics of solar sail enabled, or significantly enhanced, missions were detailed prior to a detailed discussion of three key applications of solar sailing and the presentation of a solar sail application pull technology development roadmap.

Considering the solar sail application pull technology development roadmap it was noted that the near-term was sparsely populated, with the significant majority of applications clustered in the mid to far term. The concept of a system level Advancement Degree of Difficulty was introduced and it was illustrated that how through, for example, hybridisation with solar electric propulsion the project risk of solar sailing could be reduced while simultaneously moving the cluster of mid to far term solar sail applications towards the near-term.

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The development and launch of the first artificial satellite Sputnik more than five decades ago propelled both the scientific and engineering communities to new heights as they worked together to develop novel solutions to the challenges of spacecraft system design. This symbiotic relationship has brought significant technological advances that have enabled the design of systems that can withstand the rigors of space while providing valuable space-based services. With its 26 chapters divided into three sections, this book brings together critical contributions from renowned international researchers to provide an outstanding survey of recent advances in spacecraft technologies. The first section includes nine chapters that focus on innovative hardware technologies while the next section is comprised of seven chapters that center on cutting-edge state estimation techniques. The final section contains eleven chapters that present a series of novel control methods for spacecraft orbit and attitude control.

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