POLARIS+: POLAR Investigation of the Sun using Solar Sailing

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This paper presents an overview of the POLARIS+ (POLAR Investigation of the Sun) proposal made to the European Space Agency's 2016 call for New Ideas for the Science Programme. The POLARIS+ mission concept uses solar sail propulsion, plus an optional Venus gravity assist, to place a spacecraft in a 0.48 au circular orbit around the Sun, with an inclination of 75° with respect to the solar equator. In this orbit, at least 59% of the time will be spent at latitudes higher than the maximum latitude reached by Solar Orbiter, and each pole is visible to a view-zenith angle of less than 60° for over 37 days. This first extended view of the high-latitude regions of the Sun will enable crucial observations not possible from the ecliptic viewpoint, or from Solar Orbiter. While Solar Orbiter will give the first glimpse of the high-latitude magnetic field and flows to probe the solar dynamo, it does not provide sufficient viewing of the polar regions to achieve the primary objective of POLARIS+, to determine the relationship between the magnetism and dynamics of the Sun's polar regions and the solar cycle. This paper presents the science objectives of the POLARIS+ mission concept, alongside the scientific payload needed to achieve these objectives and a system level analysis of this concept. It is clearly identified that the use of solar sail propulsion is the major challenge of the POLARIS+ concept, and as such the motivation and contribution of this paper.

Keywords: Solar, sail, Sun, remote sensing, poles, space weather

1. Introduction

In late-2018, a new era in solar physics will begin with the launch of Solar Orbiter. This mission will get close to the Sun, 0.28 au perihelion, and out of the ecliptic plane, 25° at the end of nominal mission and up to 34° in the extended phase. This will be the first ever view of the solar poles, and will open a new world in understanding the dynamo and how the activity cycle works.

Following the pioneering steps of Solar Orbiter, it is anticipated that for a detailed understanding of the activity cycle of our star, regular and long duration studies of the poles will be necessary. Solar Orbiter will not have sufficiently long observations of the polar regions, and indeed plans only occasional orbits to concentrate on helioseismology due to telemetry restrictions. In order to determine the relation between magnetism and dynamics of the Sun's polar region, and the solar cycle, requires a different, longer-term approach. This fundamental science question, drives not only the heliosphere in our own solar system, but also aids understanding of other stars with their associated exoplanets.

The POLARIS+ mission concept seeks to place a spacecraft in a 0.48 au, circular orbit around the Sun with an inclination of 75° with respect to the solar equator; the solar obliquity to ecliptic is assumed to be 7.25°. The mission concept to place a spacecraft into a high-inclination, or polar, orbit over the Sun using solar sail propulsion has been extensively studied since the nineteen seventies. [1–14] From the earliest studies, it has been clear that such a mission is technically challenging and, in most likelihood, requires the maturation of a form of low-thrust propulsion currently considered as advanced, such as solar sailing. [15,16] Prior studies have however consistently determined that the key technology challenge is the readiness and availability of such solar sail technology. As such, and in-light of recent advances in small spacecraft technology, this study further develops the system design with a mass reduction focus aiming to minimise the required solar sail size.

2. Science Aims & Objective

The primary objective of POLARIS+ is to determine the relationship between the magnetism and dynamics of the Sun's polar regions and the solar cycle.

Extended observations from high-latitudes will revolutionize our understanding of the internal structure and dynamics of the Sun and its atmosphere. The rapid, four-month polar orbit combined with a suite of remote-sensing instrumentation further enables unprecedented studies of the physical connection between the Sun and the corona. Moreover, POLARIS+ serves as a pathfinder for a permanent solar polar sentinel for space-weather prediction in support of NASA’s *Vision for Space Exploration*, of ESA's *Space Situational Awareness*, and a broad range of other programmes affected by space weather.

The following science aims can be achieved because of the observations enabled by the short-period, highly-inclined POLARIS+ polar orbit.

A1: What is the 3D structure of the solar magnetic field, and how does it vary over a solar cycle?

Huge advances have been made in helioseismology in recent decades, mapping out the internal structure of the Sun, with complex meridional flows and torsional oscillations occurring. However, the whole process of the Sun’s polar magnetic field reversal still remains a mystery due to the difficulty of measuring this region. The poles are in some sense the key to understanding all stellar activity and constraining dynamo and flux transport models. The difficulty with helioseismology is that several timescales are required; hours long, to investigate the structure and dynamics on supergranular scales, weeks long, to investigate the evolution of active regions, and months long, to resolve the tachocline, at 0.7 solar radii, structure and dynamics. This mission concept allows access to all these physical regimes, something that no other mission can achieve.

A2: What is the 3D structure of convection and circulation flows below the surface, and how does it affect solar activity?

The flows beneath the surface at the poles will be determined using helioseismology. These will be combined with observations from the Earth's perspective to give a full view of flows on the Sun. The process of magnetic flux emergence at all scales can then be understood in this context. This process is key to driving all solar activity. The POLARIS+ view of the Sun will allow, during solar minimum, a 3D view of the streamer belt. It is, as yet, unknown how uniform (or not) the streamer belt is and how this evolves with time. Coronal mass ejections (CMEs) will be understood in three-dimensions using the POLARIS+-view, providing a way to distinguish between truly ‘global’ CMEs and nearly simultaneous events. The final advantage of this viewpoint is to provide boundary conditions for models, both by providing the polar fields, and increasing the frequency with which whole-Sun views (“synoptic charts”) will be produced. These both provide boundary conditions to the global fields, which will help us predict whether eruptions can escape the Sun or not, or if they are held down by the over-lying magnetic field.

A3: How does the solar radiance vary with latitude?

The measurement of the total solar irradiance (TSI) is a key parameter for understanding the solar influence on the Earth’s climate, and has been studied from space since 1978. POLARIS+ will reveal the TSI change with latitude, which allows characterisation of various contributions to the Sun’s radiative output at all latitudes. As well as aiding understanding of the Earth’s environment, this will also yield input into understanding Sun-like stars whose polar orientations are challenging to establish and whose activity cycles are apparently quite different.

A4: What advantages does the polar perspective provide for space-weather prediction?

There will be a coronagraph on-board that will monitor Earth and Mars-directed CMEs from their point of origin to 15 solar radii from the high-latitude perspective. For events that are observed as ‘halos’ from the Earth, this will give better speed estimates and allow detection of events that would be invisible as halos, and yet would be geoeffective. The increased solar coverage will allow longer monitoring of active regions over their lifetime. The polar view will provide for the first time a global view of CMEs from a star, with obvious space weather advantages. The measurements of the polar fields will allow improved photospheric magnetic boundary conditions for global models. POLARIS+ will often be in the position to provide early space weather warnings, and a Beacon Mode such as that on STEREO would be implemented.

By providing a unique perspective on the global structure and evolution of the interior flows in the Sun and the response of the solar corona, POLARIS+ will significantly advance our knowledge of key solar phenomena, our understanding of the Sun as a star, and our ability to forecast the Sun’s effects on the space environment. The observations of the polar region are at the heart of understanding one of the fundamental questions in solar physics and astrophysics: how and why does the Sun vary?

3. Payload

The scientific payload needed to achieve the mission objectives consists of a set of remote sensing instruments. All instruments have a very high Technology Readiness Level (TRL), being derived from past and current missions such as Solar Orbiter. The selected remote sensing instruments are a dopplergraph and magnetograph imager (Doppler-Stokes Imager, DSI), a white-light coronagraph, classical and heliospheric, (COR), an Extreme ultraviolet imager (EUVI), an ultraviolet spectrograph (UVS), and a Total Solar Irradiance (TSI) monitor. All imaging instruments will have a typical spatial resolution of 2 to 4 arcseconds.

Table 1 summarises the scientific aims that are addressed by each instrument, while Table 2 summarises the resource requirements of each. The total instrument mass, including a 20% margin, is 45 kg, while the total power load, including a 20% margin, is 67 W, and the combined data rate is just over 165 kbps. The physical size of each instrument is less than one metre in length.

Table 1 Science aims and contributing instruments

	Remote Sensing				
Science Aim	**DSI**	**TSI**	**EUVI**	**COR**	**UVS**
A1	▨	▨			
A2	▨	▨	▨	▨	
A3	▨	▨	▨		▨
A4			▨	▨	▨

Table 2 Payload resource summary, including a 20% margin; note DSI and EUVI require internal pointing

	Remote Sensing				
	DSI	**TSI**	**EUVI**	**COR**	**UVS**
Mass (kg)	7	3	10	10	15
Power (W)	12	6	12	15	22
Absolute pointing (3σ)	30′	30′	30′	10″	0.5″
Pointing stability (3σ)	0.02″/s	6′/s	0.1″/s	7″/s	n/a
Data rate (kbps)	75	0.4	40	40	10
UFOV	1.5°	16°	1.5°	2.5°	10″×1.4°

4. Mission Design

In many previous solar polar mission concepts, the mission science goals required an Earth resonant orbit, placing the spacecraft near to the solar limb as seen from Earth to allow observation of the corona along the Sun-Earth line. An Earth resonant orbit limits the orbit radius to $N^{-2/3}$ au, where N is an integer representing the resonant value. Although such a science requirement is not present in POLARIS+ a resonant orbit is maintained to allow continuous spacecraft visibility from Earth for ease of spacecraft operations.

The transfer trajectory to a high-inclination, circular orbit is divided into three phases. Phase one follows Earth escape, on-board the launch vehicle, and is a reduction of orbit radius coupled with some plane change. The final orbit radius in this phase can be the final, or target orbit radius, or can be less than this. Phase two is a rapid increase in orbit inclination, at a near-constant orbit radius. Phase three is an optional phase, where the orbit radius can be increased back to the final, or target orbit radius, and can include some plane change. The inclusion of the optional third phase exploits the $(1/radius^2)$ variation in radiation pressure during the second phase to affect more rapid plane change than would result at a larger orbit radius. It has been shown previously that such a third phase reduces the transfer time, for a fixed sail performance, or reduces the required sail performance for a fixed transfer time, however it does lead to increased thermal loads on the spacecraft. [4]

From [11,13] the required sail lightness number, β, for a given transfer time, t, for a three-phase transfer is

$$\begin{aligned}\beta = \left(1/\left(6t\sqrt{\mu}\right)\right)\big(&\mathrm{Csc}[\alpha]\mathrm{Sec}[\alpha]^2(2\mathrm{Sec}[\gamma_1]a_0^{3/2} \\ &+ 2\mathrm{Sec}[\gamma_3]a_2^{3/2} + a_1^{3/2}(-3\pi i_0 \\ &+ 3\pi i_3 - 2(\mathrm{Sec}[\gamma_1] + \mathrm{Sec}[\gamma_3] \\ &- \mathrm{Log}[a_1^{3/2}/a_0^{3/2}]\mathrm{Tan}[\gamma_1] \\ &+ \mathrm{Log}[a_2^{3/2}/a_1^{3/2}]\mathrm{Tan}[\gamma_3]))))\big)\end{aligned} \quad (1)$$

where μ is the gravitational parameter of the Sun, α is the sail pitch angle, a is the semi-major axis, assumed equivalent to the orbit radius due to the circular orbit, i is the orbit inclination, and γ is the augmented sail clock angle, defined in [11] as being measured from the transverse axis in a Gaussian, spacecraft centred coordinate system, [17] such that $\gamma = (\pi/2 - \delta)$, where δ is the conventionally defined sail clock angle. [15] The semi-major axis and inclination subscripts 0, 1, and 2 refer to the initial conditions, the conditions at the end of phase 1, and the final, or target conditions, respectively. The augmented sail clock angle subscripts 1 and 3 refer to the augmented sail clock angle in phases one and three.

The initial and target conditions are known, and the semi-major axis for phase 2 can be defined for a given thermal load analysis. From [18–20] the optimal sail pitch angle is $\alpha = \tan^{-1}(1/\sqrt{2})$. As such, Eq. (1) contains only two unknowns, γ_1 and γ_3.

Solving Eq. (1), Figure 1 shows the required sail characteristic acceleration for a range of three-phase transfer times to the target orbit, define in Table 3; the target inclination corresponds to an inclination of 75° with respect to the solar equator. Where the minimum solar approach matches the target radius the transfer reduces to a two-phase transfer.

It should be noted that a Venus gravity assist (VGA) could reduce the required sail size, or transfer duration by 3 – 6 months. However, to maintain a conservative design, at this stage such an option is not baselined due to associated risks.

Table 3 Initial and target orbit conditions

Parameter	**Value**	
Initial semi-major axis / radius	1	au
Initial inclination	0	deg
Target semi-major axis / radius	0.48	au
Target inclination	67.75	deg

Taking a solar radius of 696000 km, an ellipticity of 0.00005, and a uniform solar rotation period of 609 hours the worst-case view-zenith angle (VZA) achieved over the ‘surface’ of the Sun through a single revolution at 0.48 au, 121.5 days, is shown in Figure 2. The VZA is defined as the angle between the local zenith and a vector towards the spacecraft. Hence, when directly overhead the VZA is zero. It is seen that all latitude points below 70° are viewed to a VZA of less than 5°. It is also seen that a VZA of 25.5° is achieved at the poles, and whist not shown near-uniform coverage at or below 1° VZA is achieved for latitudes below 65°. Considering further the time spent over different regions of the Sun, it is also noted in Figure 2 that each pole is visible to a VZA of less than 60° for 37.7 days, whist the equatorial region is similarly visible for only 26.1 days of each orbit,

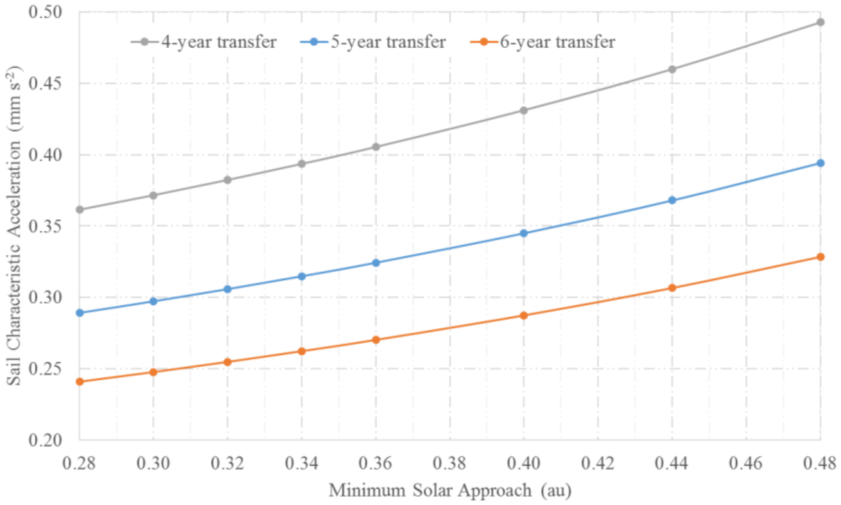

Figure 1 Required sail characteristic acceleration for 4, 5, & 6 year three-phase transfers to the target orbit

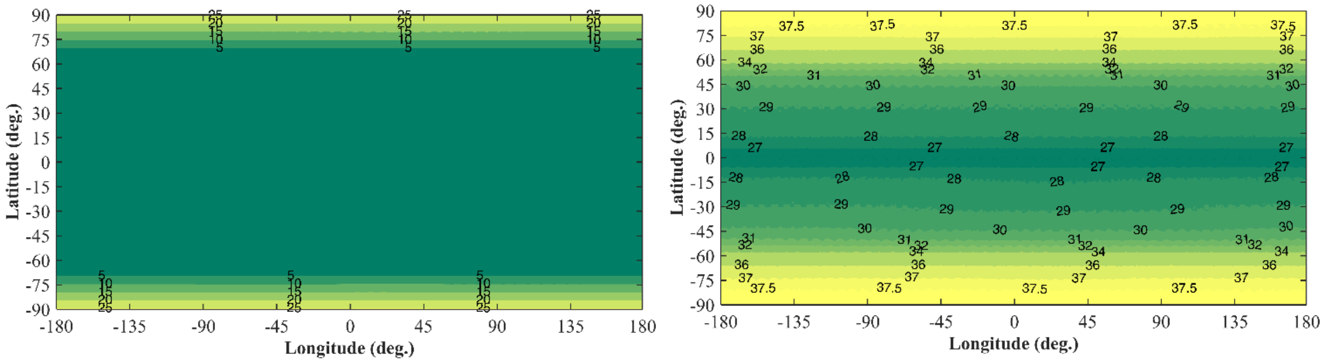

Figure 2 Contour plot of achieved maximum view zenith angle over one orbit, left, and of cumulative number of days visible to VZA < 60° over one orbit, right

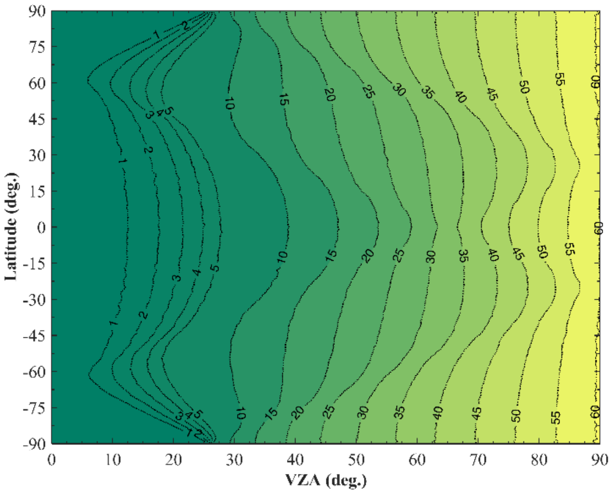

Figure 3 Contour plot of cumulative number of days visible at a given VZA and latitude

cumulatively. Figure 3 show the cumulative number of days that a given latitude is visible for to any given VZA, hence it is seen that increasing the maximum VZA to 65°, increases the time the poles are visible up to 41.6 days each orbit. It should be noted that the contour boundaries shown in Figure 2 and Figure 3 are not smooth due to numerical noise, from the trajectory integrator step-size, and hence should not be interpreted as exact.

5. System Design

Using the payload defined in Table 2, a parametric system design was conducted using an updated version of the same model used in [4]. As such, the solar sail is a sub-system of the spacecraft, and is jettisoned on arrival at the target orbit.

The spacecraft is three-axis stabilised, and uses a 1.5m Ka-band high-gain antenna for science telemetry downlink, achieving 600 kbps at maximum slant range, and X-band for uplink. The solar sail uses tip-vanes for attitude control, and inflatable booms to support the sail film. The film is assumed to be a 2μm CP1 polyimide substrate with a vapour deposited aluminium coating on the front, and chromium on the rear. The solar sail system includes structural and deployment elements that are jettisoned following sail deployment.

Figure 4 shows the spacecraft mass, minus the solar sail, for a range of minimum solar approaches, that is the radius during phase two of the transfer. It is noted that reducing the minimum solar approach from 0.48 au to 0.28 au results in a significant mass increase of almost 17%, due predominantly to an increase in thermal and power sub-system masses. Figure 4 also shows total launch mass, including all margins, for a range of mission durations. It is seen from Figure 4 that the launch mass initially decreases, despite the increased spacecraft mass. This is because that increase is more than compensated for by the $(1/radius^2)$ variation in radiation pressure, and hence the reduction in required solar sail size. However, as the minimum solar approach is further reduced the total launch mass begins to rise. As such, a small reduction in minimum solar approach below the target radius can minimise the launch mass, however all launch masses less than are 620 kg, the upper limit of a Soyuz vehicle to enable the VGA option.

Figure 5 shows the required sail side length for a range of minimum solar approaches, and mission durations. As in [4], a minimum turning point is again identified, however this turning point is at a much lower radius than for the total launch mass.

6. Discussion

The Solar-C Plan-A mission concept studied alternative scenarios to achieve a highly inclined orbit about the Sun at, or within 1 au distance without a solar sail. [21] These studies considered the use of both a Jupiter gravity assist, to change the orbit inclination, and Earth and Venus gravity assists as well as solar electric propulsion (SEP), to achieved a high-inclination orbit. However, the studies were broadly speaking unable to fulfil the POLARIS+ requirements. The same result was obtained when SEP was considered for Solar Orbiter. [22]

The Solar Polar ORbiter Telescope (SPORT) mission concept also studied highly inclined orbits using a gravity assist manoeuvre at Jupiter, [23,24] similar to what was used by ESA's Ulysses mission. This option required a large launch vehicle, an evolution of the Long March 5, CZ-5E, was considered, to show that an orbital inclination greater than 60°, with successive Venus gravity assists providing a decreasing orbital period from five years to two years, with an aphelion down from 5 au to 1.6 au, and a perihelion close to that of Venus. [23,24] This solution has two major drawbacks in terms of radiation and orbital distance. Firstly, the passage through Jupiter's radiation belts will have a severe impact on the payload. Secondly, the large variation of the spacecraft–Sun distance has a severe thermal impact upon instruments needing a highly stable thermal environment, and instruments such as the coronagraphs that need a stable field of view.

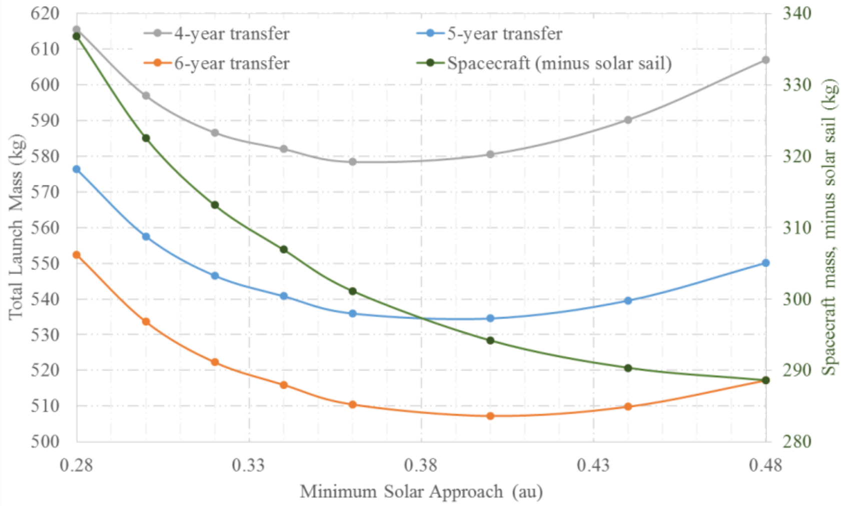

Figure 4 Spacecraft mass, minus the solar sail, and total launch mass for a range of minimum solar approaches

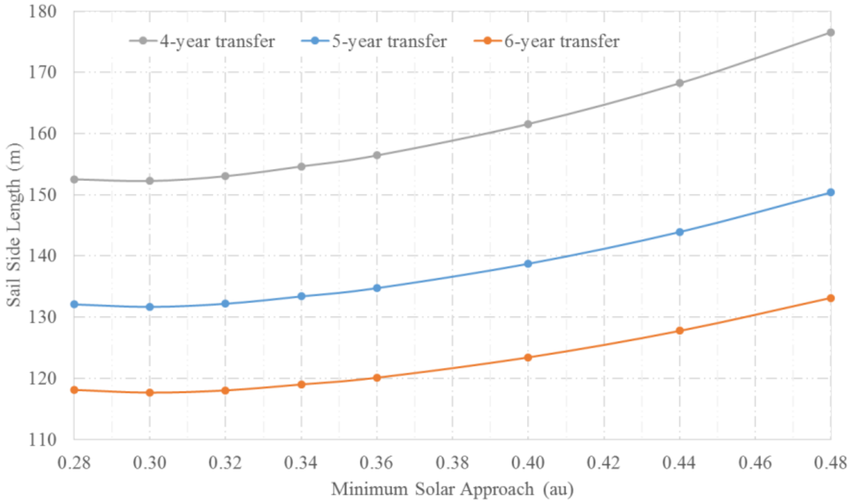

Figure 5 Required sail side length for a range of minimum solar approaches

7. Conclusions

To gain sufficiently long observations of the polar regions it has been found that solar sail propulsion is required. It was found that a circular orbit of radius 0.48 au, with inclination to the Ecliptic plane of 67.75° provides a worst-case view-zenith angle of 25.5° of the solar poles, and that all latitude points below 70° are viewed to a view-zenith angle of less than 5°. Furthermore, each pole is visible to a view-zenith angle of less than 60° for 37.7 days. As such, the pole will be visible throughout a complete revolution of the pole, approximately 35 days. By doing so it will be possible to determine the relationship between the magnetism and dynamics of the Sun's polar regions and the solar cycle. It was found that the total launch mass is compatible with a Soyuz launch, and is minimised for a closest solar approach less than 0.48 au. It was also found that the sail size can be minimised by further reducing the minimum solar approach, but that a square sail size of greater than 120 m per side is likely to be required.

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