



Effects of radiation induced optical degradation on Earth bound solar sail manoeuvring capabilities[☆]

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Abstract

Metallised thin films represent the state of the art for current solar-sail missions operating around Earth. Previous testing has demonstrated that when exposed to high fluences (2.2×10^{17} particles/cm²) of low energy (<12 keV) protons, hydrogen blistering can occur in the metallised films. This blistering leads to degradation of the optical performance of the metallised surface as the reflectivity becomes less specular and more diffuse. In this paper, experimental degradation data from ground-based radiation testing is used to evaluate the effect of degradation on the solar-sail manoeuvring capabilities. The testing was previously conducted using The German Aerospace Centre (DLR) Institute of Space Systems Complex Irradiation Facility (CIF) and links proton fluence to reductions in specular reflectivity for metallised thin films. The impact on the manoeuvring capabilities of a solar sail due to the effects of proton induced degradation is demonstrated through numerical modelling of the degraded sail in Earth orbit. There was found to be a strong temperature dependence on the time to the onset of radiation degradation and the rate of degradation after onset. Warmer sail temperatures were found to cause a faster onset of degradation but a lower overall degradation across the mission. This warm degradation progression compares to the colder sail temperatures that were found to have a more significant level of degradation but a later onset of damage. The worst case trapped radiation environment for sail degradation was found to be around 21,000 km altitude but remains at levels sufficient to cause degradation in a feasible mission lifetime at geostationary orbit.

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1. Introduction

Solar sailing has potential to fulfil a mission profiles such as long duration or multiple target visitation missions as propellantless continuous thrust propulsion is able to

access mission profiles beyond the delta-V limitations of conventional propulsion systems.

Reflective thin film membrane technology represents the current state of the art solar sailing materials (Johnson et al., 2011). IKAROS was the first functional interplanetary mission, developed by the Japanese Aerospace Exploration agency (JAXA). The mission used 7.5 µm thick polyimide film with a vapor deposited 80 nm thick aluminium reflector (ONO et al., 2013). Notably, DLR worked on the development of Gossamer-I which utilised a 7.5 µm polyimide Uplex-S[®] foil with both faces coated in 100 nm thick vacuum deposited aluminium reflectors

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Nomenclature

a_{ARP}	Acceleration due to albedo radiation pressure	P_{1AU}	Solar radiation pressure at 1 AU
a_{BBRP}	Acceleration due to black body radiation pressure	a_{PRP}	Acceleration due to planetary radiation pressure
a_{J2}	Acceleration due to J2 perturbation	S	Planetary radiation flux at the sail location
a_{SRP}	Acceleration due to solar radiation pressure	l	Distance between surface element dA and the sail
A	Sail area	dA	Differential surface element of Earth
B_f	Non-Lambertian coefficient front	A^*	Visible planetary surface area irradiating the sail
B_b	Non-Lambertian coefficient back	G_{FNS}	Normal specular geometrical factor for planetary radiation pressure
C_θ	Change of capture at angle θ	G_{FND}	Normal diffuse geometrical factor for planetary radiation pressure
$C(\theta, e)$	Change of capture at angle θ and energy e	G_{FT}	Transverse geometrical factor for planetary radiation pressure
F_0	Offset fluence	c	Speed of light
F_c	Characteristic force	J_2	Second zonal harmonic coefficient of Earth's gravity field ($1.082626925639 \times 10^{-3}$)
f_n	Force in sail normal direction	E_r	Earth's equatorial radius (6378.1363 km)
f_t	Force in sail transverse direction	f_e	Incident directional proton flux at energy e (protons/sr/s)
P	Solar irradiance	f_{Ce}	Captured proton flux at energy e
ρ	Reflectivity	f_C	Effective capture flux (ECF); total protons captured per unit area per second across all energy bins
s	Specular reflectivity	e	Proton energy (keV)
α	Pitch angle	e_{min}, e_{max}	Minimum and maximum proton energy of interest for capture (0–12 keV)
θ	Angle of incidence	N_θ	Number of discrete angles of incidence used in capture probability averaging
ϵ_f	Emissivity of the sail front		
ϵ_b	Emissivity sail back		
μ	Earth gravitational parameter ($398600.4415 \text{ km}^3/\text{s}^2$)		
ν	Shadow factor		
σ	Sail mass-to-area ratio (areal density)		
ϑ	Angle between surface element normal and sail-to-element direction		
r	Sailcraft position vector in Earth-centred inertial frame		

(Seefeldt et al., 2017). In 2024, NASA's ACS3 mission was launched into Earth orbit. Its sail membranes consist of 2 μm thick polyethylene naphthalate (PEN) with a 100 nm thick aluminium reflector and a 15 nm chromium emissive face (Kang et al., 2021).

The question of the degradation of these thin film membranes when exposed to the space environment and the consequential impacts of this on the solar-sail performance characteristics have so far been addressed through two key approaches, namely experimental testing and mathematical modelling, respectively.

Early experimental work on the radiation degradation of materials involved the bombardment of reflective membranes by high electron fluxes with a “Dose Until Failure” approach to testing (Edwards et al., 2004). These tests were focused on the mechanical properties of the films and concluded that the “thermo-optical properties of candidate solar sail materials are not significantly degraded by space exposure.” Later work contradicted this conclusion and focused instead on the effects of proton radiation damage on the sail, switching from a traditional ionising dose based

metric for radiation damage to a focus on proton implantation and hydrogen recombination in the material (Sznajder et al., 2018; Sznajder & Geppert, 2014). The mechanism driving the degradation observed in these test campaigns is hydrogen blistering. This degradation type is caused by proton implantation inside the metallic reflective material followed by recombination into H_2 filled blisters that deform the material reducing its effective thermo-optical properties through morphological changes to the surface (Sznajder et al., 2018). These changes in the thermo-optical properties have been linked to temperature and proton fluence. In space testing of solar sail candidate materials has been undertaken in the MISSE 1 and MISSE 2 test campaigns (Dever et al., 2008) on the International Space Station. In these campaigns sail materials were exposed to the space environment in low Earth orbit and brought back to Earth for examination of the changed mechanical properties.

When it comes to the impacts of degradation on the solar-sail performance characteristics, there has been effort in the modelling of the potential effects of radiation

degradation on the sail's manoeuvring capabilities. Notable work on the mathematical models developed the link between the environmental history of the sail, its optical properties and radiation dose. This modelling work produced the Optical Solar Sail Degradation model (OSSD) (Dachwald et al., 2007). A model was developed linking effects of different levels of surface roughness on a reflective sail to reduction in sail performance across interplanetary trajectories produced the Refined Solar Sail Force Model (Mengali et al., 2007; Sznajder et al., 2021). Kezerashvili & Matloff examined the effects of near-sun space-environment effects on thin film solar sails (Kezerashvili & Matloff, 2009). This work calculated minimum reflector thicknesses effects on sail performance and temperature. This work also focused on modelling the effects of ionising radiation on sails and the mechanisms of ionising damage to the sail materials. These two bodies of work contribute to the understanding of the evolution of sail materials in the space environment and focus on complementary aspects of radiation effects to the proton induced blistering considered in this paper.

The aim of this paper is to link the experimentally derived radiation induced degradation (Klein, et al., 2025), an improved proton dose calculation method, and the sail optical model to sail performance. To this aim, an improved sail dose calculation method is developed and radiation modelling tools are used to derive an “effective captured fluence” representing the total fluence of protons that are embedded inside the sail's aluminium layer. By linking this effective captured fluence with DLR's semi-empirical model (Klein, et al., 2025), the time-dependent optical coefficients of the sail can be obtained. Using these time-dependent optical coefficients in the optical sail model (McInnes Colin, 1999) yields realistic sail accelerations, which are then used in the NESTOR sail trajectory optimisation toolkit (Carzana et al., 2022, 2024) to determine the effect of the radiation damage on the capability of the solar sail to optimally change its orbital parameters.

Finally, case studies of sails operating in the worst case low-energy proton environment around Earth are modelled over a 15-year mission. The performance of the radiation-degraded sail over time is studied and compared to a pristine sail; in particular, the evolution of the performance and the significance of the degradation levels and temperatures effects are discussed.

2. Model and simulation

In this section, the mathematical model describing the motion of the sail is explained alongside the control laws and computational modelling tools.

2.1. Numerical solar sail orbit propagation

For the simulations performed in this study, the solar-sail trajectory optimising toolkit Near-Earth Solar-sail

Trajectory Optimiser (NESTOR) is used. NESTOR was developed at the Delft University of Technology specifically for Earth-bound solar sailing (Carzana et al., 2022, 2024). For NESTOR's deployment in this study, the optical sail model was used with both Solar Radiation Pressure (SRP) and Planetary Radiation Pressure (PRP) exploited for locally optimal control of the sail.

The equations of motion of the sail are defined as:

$$\ddot{\mathbf{r}} + \frac{\mu}{r^3} \mathbf{r} = \mathbf{a}_{\text{SRP}} + \mathbf{a}_{J2} + \mathbf{a}_{\text{BBRP}} + \mathbf{a}_{\text{ARP}} \quad (1)$$

where $\mathbf{r} = [x, y, z]^T$ is the sailcraft position vector in an inertial earth centred reference frame, $\mu = 398600.4415 \text{ km}^3/\text{s}^2$ is the Earth gravitational parameter, $\mathbf{a}_{\text{SRP}}$ is the acceleration due to photon pressure from direct solar photon radiation, a_{J2} is the acceleration arising from Earth's non-uniform gravitational field, a_{BBRP} is the sail acceleration due to photon pressure from the thermal emission of Earth onto the sail (black-body radiation pressure), and a_{ARP} is the sail acceleration due to photon pressure from light reflected from Earth onto the sail (albedo radiation pressure) (Carzana et al., 2024).

2.2. The optical sail model

The optical sail model (McInnes Colin, 1999) is used in this study to calculate the force due to photon pressure on a solar sail. Unlike the ideal sail model, which assumes the sail to be a perfect (specular) reflector, the optical model accounts for the role of finite specular and diffuse reflection, and the effects of non-Lambertian reflection. Radiation damage to the sail can then be modelled as a reduction in specular reflectivity with increasing radiation dose, as opposed to the ideal model which has no terms to account for a reduction in the specular reflection. According to the optical model, the force on a solar sail can be decomposed into a component normal to the sail surface, f_n and a transverse component, f_t , which are defined as:

$$f_n = PA \left\{ (1 + \rho s) \cos^2 \alpha + B_f (1 - s) \rho \cos \alpha + (1 - \rho) \frac{\epsilon_f B_f - \epsilon_b B_b}{\epsilon_f + \epsilon_b} \cos \alpha \right\} \quad (2)$$

$$f_t = PA (1 - \rho s) \cos \alpha \sin \alpha \quad (3)$$

where P is the solar radiation pressure, A is the sail area, ρ is sail reflectivity, s is the specular reflection coefficient, α is the sail cone angle defined between the sail's normal vector and the direction of incoming illumination, ϵ_f and ϵ_b are the front and back emissivities, respectively, and B_f and B_b are the front and back non-Lambertian coefficients, respectively.

2.3. Acceleration due to solar radiation pressure

Further expanding on the optical force model in the numerical model the SRP induced acceleration $\mathbf{a}_{\text{SRP}}$ is a

product of the sum of the normal $\mathbf{a}_{\text{SRP},n}$ and tangential $\mathbf{a}_{\text{SRP},t}$ components:

$$\mathbf{a}_{\text{SRP}} = \mathbf{a}_{\text{SRP},n} + \mathbf{a}_{\text{SRP},t} \quad (4)$$

$$\mathbf{a}_{\text{SRP},n} = v \frac{P_{1\text{AU}}}{\sigma} \left[(1 + \rho s_f) \cos^2 \alpha + (1 - s_f) \rho B_f \cos \alpha + (1 - \rho) \frac{\varepsilon_f B_f - \varepsilon_b B_b}{\varepsilon_f + \varepsilon_b} \cos \alpha \right] \hat{\mathbf{n}} \quad (5)$$

$$\mathbf{a}_{\text{SRP},t} = v \frac{P_{1\text{AU}}}{\sigma} (1 + \rho s_f) \cos \alpha \sin \alpha \hat{\mathbf{t}} \quad (6)$$

where $\hat{\mathbf{n}}$ represents the sails normal direction with the positive component of the vector in the sunlight direction, $\hat{\mathbf{s}}$ and $\hat{\mathbf{t}}$ is the transversal direction defined by:

$$\hat{\mathbf{t}} = \hat{\mathbf{n}} \times \frac{(\hat{\mathbf{s}} \times \hat{\mathbf{n}})}{\|\hat{\mathbf{s}} \times \hat{\mathbf{n}}\|} \quad (7)$$

In Eqs. (4) and (5) σ is the sail mass to area ratio, and the term $v \in [0, 1]$ represents the shadow factor. This shadow factor accounts for the impact of eclipse on the suns illumination of the sail, where $v = 0$ in both umbra and penumbra.

And $P_{1\text{AU}}$ represents the SRP at 1 AU distance from the sun (Carzana et al., 2025).

2.4. J_2 gravitational acceleration

The a_{J_2} component in Eq. (1) is the acceleration due to the uneven gravitational field of the Earth, specifically its equatorial bulge, which is modelled through the J_2 zonal harmonic expansion term of the gravity field:

$$\mathbf{a}_{J_2} = -\frac{3}{2} \frac{E_r^2}{\mathbf{r}^5} \mu J_2 \left[(x\hat{\mathbf{x}} + y\hat{\mathbf{y}}) \left(1 - 5 \frac{z^2}{r^2} \right) + z \left(3 - 5 \frac{z^2}{r^2} \right) \hat{\mathbf{z}} \right] \quad (8)$$

where $\hat{\mathbf{x}}, \hat{\mathbf{y}},$ and $\hat{\mathbf{z}}$ are unit vectors pointing in the $[x, y, z]^T$ frame's x-, y-, and z-axis directions, respectively, Earth's radius is $E_r = 6378.1363$ km and $J_2 = 1.082626925639 \cdot 10^{-3}$ (Carzana et al., 2024; Nerem, 1994).

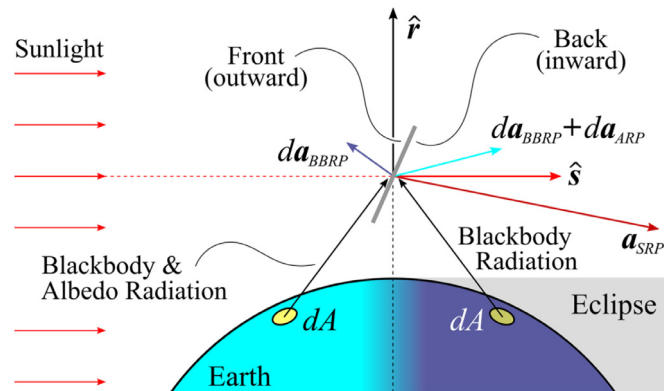


Fig. 1. Planetary radiation model (Carzana et al., 2025).

2.5. Acceleration due to planetary radiation pressure

The $\mathbf{a}_{\text{BBRP}}$ and $\mathbf{a}_{\text{ARP}}$ components of the sail acceleration are calculated according to the optical sinusoidal Planetary radiation pressure acceleration model (Carzana et al., 2025) as shown in Fig. 1. In this model the visible planetary surface A^* is assumed to irradiate isotopically with a constant radiation flux S for derivation of the planetary flux distribution see (Carzana et al., 2024). The radiation pressure, P , a sail is exposed to photon radiation emitted from a differential element of Earth's surface, dA is

$$dP = \frac{S}{\pi c} \frac{\cos \vartheta}{l^2} dA \quad (9)$$

where S is planetary radiation flux at the sail location and l is the distance between a surface element dA and the sail and $\vartheta \in [0, \pi/2]$ is the angle between the normal direction to dA .

$$\mathbf{a}_{\text{PRP}} = \frac{S}{c\sigma} \left\{ \frac{2}{3} [(1 + \rho_{\text{in}} s_{\text{in}}) G_{\text{FNS},\text{in}} - (1 + \rho_{\text{out}} s_{\text{out}}) G_{\text{FNS},\text{out}}] \hat{\mathbf{n}}_{\text{out}} + [(1 - s_{\text{in}}) \rho_{\text{in}} B_{\text{in}} G_{\text{FND},\text{in}} - (1 - s_{\text{out}}) \rho_{\text{out}} B_{\text{out}} G_{\text{FND},\text{out}}] \hat{\mathbf{n}}_{\text{out}} + \frac{\varepsilon_f B_f - \varepsilon_b B_b}{\varepsilon_f + \varepsilon_b} \left[(1 - \rho_{\text{in}}) G_{\text{FND},\text{in}} + (1 - \rho_{\text{out}}) G_{\text{FND},\text{out}} \right] \hat{\mathbf{n}} + \frac{2}{3\pi} [(1 - \rho_{\text{in}} s_{\text{in}}) G_{\text{FT},\text{in}} + (1 - \rho_{\text{out}}) G_{\text{FT},\text{out}}] \hat{\mathbf{t}}_{\text{out}} \right\} \quad (10)$$

The terms G_{FNS} , G_{FND} and G_{FT} indicate the normal specular, normal diffuse and transverse geometrical factors. These terms express the dependency of the PRP induced acceleration on the Earth to sail geometry. These terms are specified for both the inward and outward facing faces of the sail where A_{in}^* and A_{out}^* are regions of a surface A^* visible from the inward and outward faces of the sail respectively.

$$G_{\text{FNS}} = \frac{3}{2\pi} \int_{A^*} \frac{\cos \vartheta \cos^2 \theta}{l^2} dA \quad (11)$$

$$G_{\text{FND}} = \frac{1}{\pi} \int_{A^*} \frac{\cos \vartheta \cos^2 \theta}{l^2} dA \quad (12)$$

$$G_{\text{FT},\diamond} = \frac{3}{2\pi} \int_{A^*} \frac{\cos \vartheta \cos^2 \theta \sin \theta}{l^2} dA \quad (13)$$

where the $\diamond$ notation is a placeholder for *in* or *out* facing sides of the sail. When combined with the planetary radiation flux components, Eqs. (9)–(13) work to calculate the sail acceleration due to black body radiation pressure and albedo radiation pressure as a product of sail position around Earth and sail orientation relative to the surface.

2.6. Sail control laws

For the analyses in this paper, a locally optimal steering law to maximise the instantaneous rate of change of the semi-major axis (SMA) of the orbit is selected. At each moment in time, this steering law prescribes the sail attitude corresponding to the optimal SRP acceleration vector that maximizes the instantaneous rate of change of orbital energy (McInnes Colin, 1999). To account for real-life operational constraints, the control law is constrained to

prevent sail-attitude changes larger than an angular rate of 0.5 deg per second.

3. Space environment

Radiation in the space environment is diverse and consists of many different types of particles. However, with the focus of this work on proton blistering, the radiation of interest is protons that will be captured inside the 100 nm aluminium reflector. These protons will recombine with an electron to first form atomic hydrogen (H), and then molecular hydrogen (H₂) (Sznajder et al., 2021).

An ion incident on the surface of the sail material will either transmit through, be captured within or otherwise backscatter out of the sail. The type of behaviour is dependent on the energy of the ion and the angle of incidence. The material properties of the sail such as nuclear cross section and density also factor heavily. To calculate the probability that an incident ion at a given energy is captured inside the material, the ion-stopping software SRIM (Ziegler et al., 2010) is used. Some representative simulations are shown in Fig. 2 to highlight the relationship between proton energy and particle penetration depth. In these simulations, protons with energies of 1 keV, 6.5 keV, 10 keV and 20 keV interact with 100 nm (1000 Å) aluminium. The white marks indicate sites of proton interaction with the aluminium.

3.1. Hazardous region identification

To calculate the incident proton flux on the sail a radiation model is needed, of the available models the Space Plasma Model (SPM) provides a detailed output for low energy protons. SPM offers the most detailed description of the low-energy proton environment of the published

radiation models. In SPM an incidence flux of low energy protons can be broken down into directional fluxes across energy bins (Johnston et al., 2014). SPM's directional fluxes enable the user to calculate the effect of the anisotropic proton field with directional flux for a range of magnetic pitch angles relative to local magnetic field lines.

As seen in Fig. 3a, the probability of proton capture decreases rapidly with increasing energy as the probability of transmission rises. The probability of capture for an ion normal to the surface reduces from 8.1% at 10 keV to 0.85% at 20 keV as calculated using SRIM (Ziegler et al., 2010). Fig. 3b shows the angular capture dependence of a 6.5 keV proton with maximum capture occurring at 50 degrees incidence for this specific energy. The capture probability is used to select the energy range of interest from the available energy bins output by the radiation model. The energy range is determined as all particles up to 12 keV since energy bins higher than this do not have a significant chance of capture. Drawing from the capture probability and the energy bins output by SPM emin is set as 0 keV and emax is 12 keV. As can be seen in Figs. 2 and 3 it is clear that, as energy increases, the average depth of interaction increases too, as does the probability of transmission. Fig. 3b shows the effect of the protons angle of incidence on the capture probability for a 6.5 keV proton. It can be seen that transmission decreases with angle of incidence while backscattering increases with peak capture at 50 degrees incidence. These principles are used in Section 4 to identify the energy region of the proton radiation spectrum that is relevant to the development of proton blisters.

3.2. Derivation of the effective captured flux

In the previous section an energy range of interest was identified SPM can be then used to produce directional

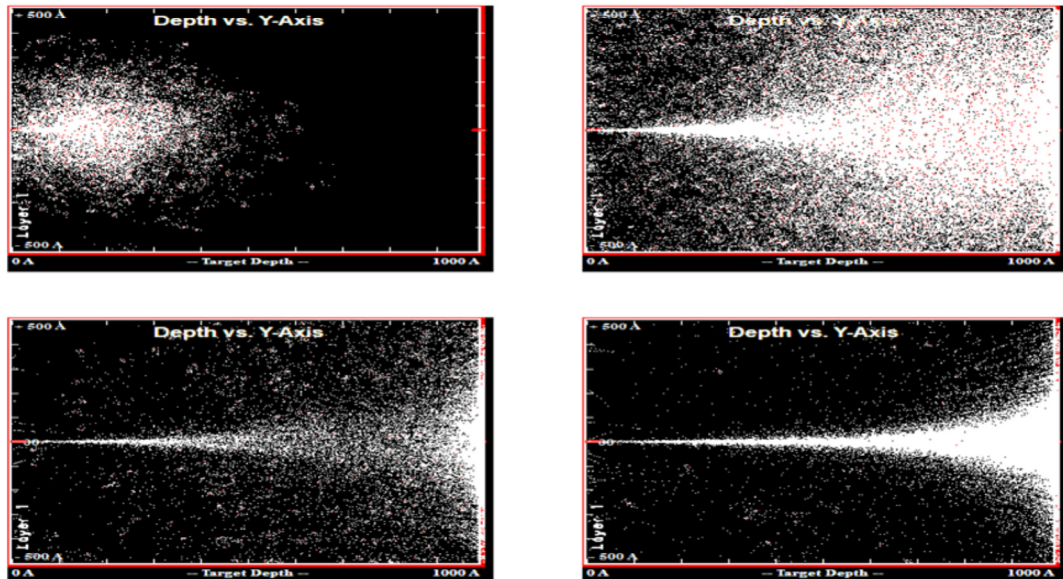


Fig. 2. a-d interaction of protons with 100 nm layer of Al with a range of energies highlighting penetration effects at differing energy levels generated with SRIM (Stopping and Range of Ions In Matter) (Ziegler et al., 2010). Left to right: (a) 1 keV (b) 6.5 keV (c) 10 keV (d) 20 keV.

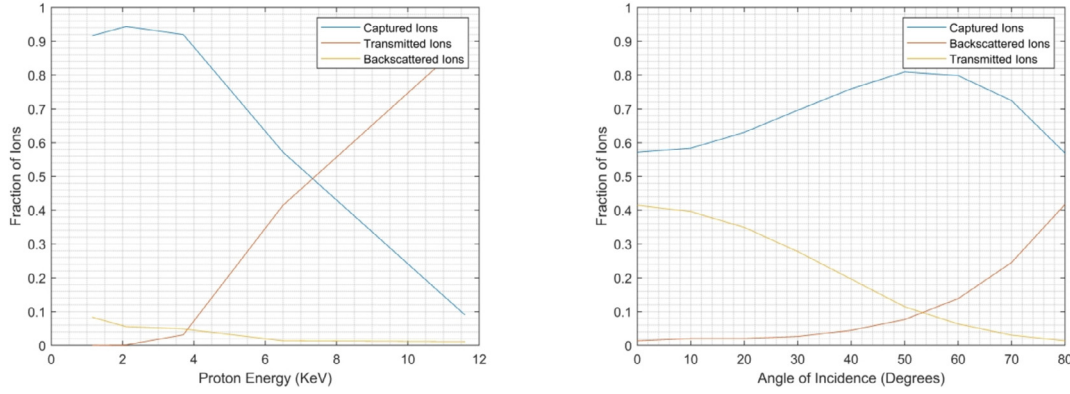


Fig. 3. (a) SRIM transmission plots for proton interaction with 100 nm aluminium across all angles of incidence and energies. (b) Transmission plot showing the interaction of 6.5 keV protons across angle of incidence.

proton fluxes and SRIM used to evaluate capture probabilities across angles of incidence and energy ranges e_{min} to e_{max} .

In a realistic scenario, protons will be incident on the surface of a sail from a range of directions. Therefore, it is necessary to derive an “effective capture flux” (ECF) for a given spectrum of proton energies and angular distributions. Given the specific energy of an incident proton flux, e , the captured portion of this proton flux can then be defined as:

$$f_{ce} = 2\pi f_e C(\theta, e) \quad (14)$$

where f_e is the incident directional flux in protons/sr/s at a given energy e , $C(\theta, e)$ is the probability of capture at a given energy and angle of incidence, θ , and 2π adjusts for the solid angle exposure of the plane of the sail. The average probability of capture of a proton at a given energy e and angle θ , $C(\theta, e)$, can be defined as:

$$C(\theta, e) = \frac{\sum_{\theta=0}^{\theta=\pi} C_{\theta} \cos \theta}{N_{\theta}} \quad (15)$$

where C_{θ} is the capture probability at angle of incidence θ , $\cos \theta$ represents Lambert’s cosine law distribution for incident flux, and N_{θ} is the number of angles of incidence binned. Therefore, substituting Eq. (15) into Eq. (14) and summing across all energy bins yields

$$f_c = \sum_{e_{min}}^{e_{max}} f_e \left(\frac{\sum_{\theta=0}^{\theta=\pi} C_{\theta} \cos \theta}{N_{\theta}} \right) 2\pi \quad (16)$$

In Eq. (16), f_c is the effective capture flux (ECF) expressing the number of protons captured per unit area of the sail surface per second across the entire energy range of interest (e_{min} , e_{max}). This energy range of interest was previously defined where probability of capture is significant, i.e., 1–12 keV. This method allows for the calculation of proton capture rates in a planar surface exposed to an anisotropic radiation flux. For a sail with different materials on the front and back surfaces the effective capture fluxes will differ for each surface since the capture probability $C(\theta, e)$ is dependent on both layer thickness and mate-

Table 1

Energy levels and respective proton capture fractions.

Energy keV	$C(\theta, e)$
1.15	0.561
2.10	0.587
3.70	0.592
6.50	0.459
11.6	0.186

rial. This method can then be used to calculate the ECF for both sides independently and if the degradation progression for the rear facing material is known this progression can be applied separately for the respective sail side.

Table 1 shows the captured fraction for each energy bin across the energy range of interest. The coefficient $C(\theta, e)$ is applied to the corresponding flux at a given energy level of the spectrum and the product of this summed across all energy bins to generate the effective capture flux.

Fig. 4 shows the 10-year average ECF calculated by SPM and then modified using Eq. (16), in the altitude range 8000–50,000 km, considering increments of 1000 km. This data was used to identify the region of greatest effective capture flux for equatorial orbits for the worst-case simulations in Section 5. A 95% confidence interval and 90 deg magnetic pitch angle were selected for generation of these 10-year average fluxes. The pitch angle of a sail relative to the magnetic pitch angle will vary both

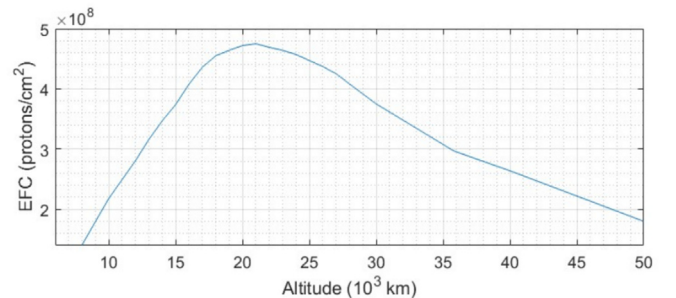


Fig. 4. 10-year average fluxes adjusted for effective captured flux across relevant orbital altitudes.

throughout each orbital revolution and over yearly cycles as the declination of the Sun changes. This variance in the angle is not modelled in the dose calculation. However, any discrepancies are expected to be enveloped within the 95% confidence interval on the flux calculation.

Fig. 4 shows the effective capture flux of these low-energy protons, this ECF reaches a maximum ECF of 4.75×10^8 protons/s/cm² at an altitude of 21,000 km. A fluence of 1×10^{17} p/cm² is sufficient to produce notable optical degradation as seen in experimental data (Sznajder et al., 2021). The maximum effective capture flux is sufficient to reach a fluence of 1×10^{17} protons/cm² in 2437 days (or 6.7 years) of operation at 21,000 km altitude.

4. Derivation of dependence of optical properties on radiation fluence

A series of radiation test campaigns (Klein et al., 2025; Sznajder et al., 2021; Sznajder & Geppert, 2014) have been conducted at DLR's Institute of Space Systems. In these campaigns, aluminised thin films were exposed to 2.5 keV protons with a total fluence of 2.2×10^{17} protons/cm². These proton irradiations were performed across a range of fixed sample temperatures with continuous measurement of the time- and fluence-dependent specular reflection of the samples. This data formed the basis of a semi-empirical model (Klein et al., 2025) that links the temperature and proton fluence to reductions in specular reflection. The semi-empirical model is a linear regression model derived from the observed changes in the specular reflection of the irradiated samples during irradiation and post irradiation measurements are used. The temperatures measured and end state values are shown in Table 2. Notably, this degradation progression data is captured only for mono-temperature irradiations where the sample does not experience significant temperature changes during irradiation. This constant temperature environment does not reflect the temperature of a sail undergoing locally optimal control based steering around Earth. A sail undergoing these manoeuvres will experience a rapidly changing thermal environment as the sail enter eclipse or alters its sun angle resulting in significant and rapid temperature swings. The constant temperature model represents a limitation of the available data as no experimental data for the effects of thermal cycling on degradation progression is available, future work seeks to address this limitation.

As can be seen in Fig. 5 there is a non-linear interaction between the sample temperatures during irradiation and the change in specular reflection. It can be seen that for temperatures between -50°C and -100°C the specular reflectance at the end of the testing is lowest showing that, for missions in this temperature range, a rapid degradation after a fluence of 1×10^{17} protons/cm² can be expected. One of the most important features of this degradation model is a factor called the offset fluence, F0. This factor represents the amount of protons that can be absorbed into 1 cm² of aluminium sail reflector before there is a measurable onset of degradation. F0 is shown to be heavily dependent on sail temperature (Klein et al., 2025) with this relationship visible as the transition from yellow to green in Fig. 5.

Fig. 6a shows the degradation progression against fluence for the specular reflectivity of a sail with a temperature of -36°C with the F0 marking the beginning of the degradation of the specular reflection. Fig. 6b applies this against a mission ECF of 4.63×10^8 protons/cm²/s showing the progression of the parameters in the context of a worst case mission flux, this specific mission scenario is explored further in section 5.2.

Fig. 7 shows the force bubbles for the end state of each sample post irradiation. The force bubble is the envelope of all possible force vectors as defined in the optical model. The most degraded sample, S1, has experienced a 23% reduction in the ratio of the normal and transverse force components, see Eqs. (2) and (3), compared to the pristine sample. With increasing temperature, increasing end-state performance of the sail is observed. This improved performance is mainly driven by the smaller reduction in specular reflection, s , at higher temperatures. From these data it is clear that the temperature of the samples is a major factor in the progression and end state of irradiated samples.

5. Case study low-energy high-flux region

To examine the impact of degradation on a solar-sails manoeuvrability to, a worst-case Earth-bound mission is selected where the sail will be exposed to the maximum effective capture fluxes. A sail undergoing SMA raising and lowering manoeuvres is used as the baseline comparison. The sail performance is evaluated at two different fixed temperatures -36°C and 100°C .

Table 2

Pristine and end state values for samples that were irradiated to 2.2×10^{17} protons/cm² (Sznajder et al., 2021).

Sample	Irradiation Temp °C	Total reflectance ρ	Specular reflectance s
Pristine	—	0.923	0.919
S1	−176	0.693	0.599
S2	−100	0.875	0.479
S3	31.6	0.895	0.781
S4	75	0.916	0.909
S5	113	0.917	0.904

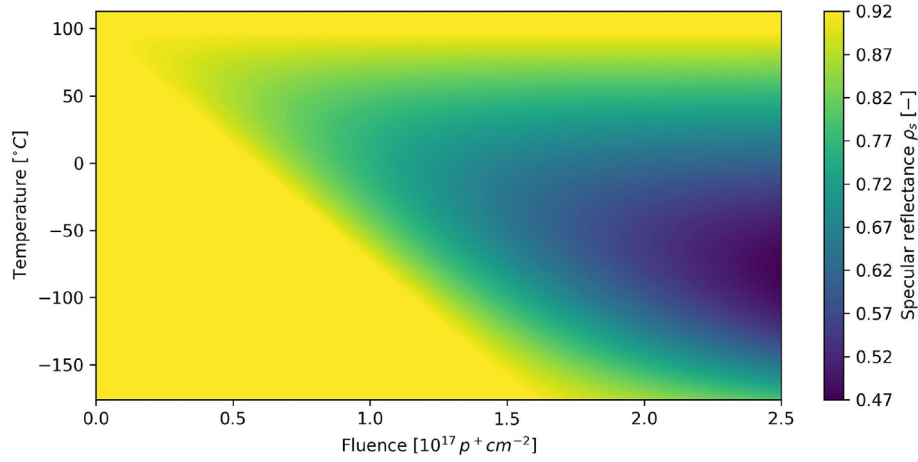


Fig. 5. DLR derived radiation fluence-temperature relationship with specular reflection (Klein, et al., 2025).

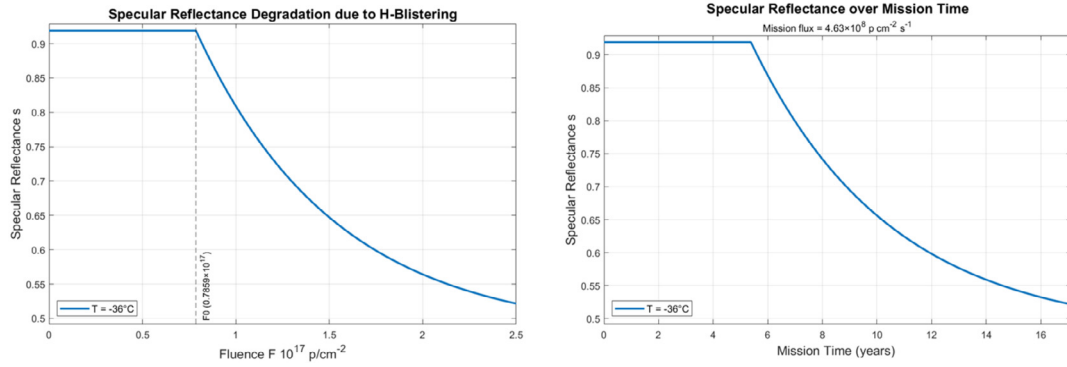


Fig. 6. a-b change in specular reflection of an irradiated sail against fluence (Klein et al., 2025).

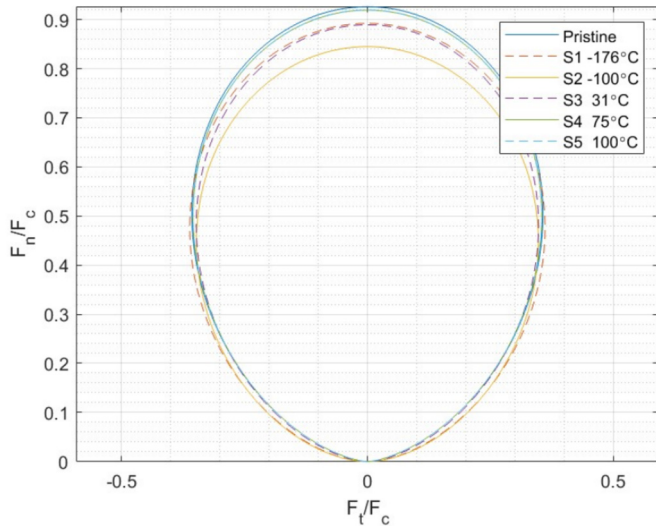


Fig. 7. Force bubbles at test sample end states (2.2×10^{17} protons/cm²).

5.1. Simulation initial conditions and parameters

Table 3 provides the pristine values of the optical parameters of the polyethylene naphthalate aluminium

Table 3

Pristine values of the optical parameters of the sail.

Front side	ρ	s	ε_f	B_f
	0.923	0.919	0.014	0.79
Back side	ρ_b	s_b	ε_b	B_b
	0.43	0.52	0.6	0.67

fronted chromium backed sail simulated. This Al-Cr sail is based on the design of the ACS-3 sailcraft. The front side values are taken from laboratory measurements (Sznajder & Geppert, 2014) and the back side coefficients from (Carzana et al., 2023). These values are used for the calculation of the sail accelerations due to SRP, BBRP and ARP. Of the coefficients in Table 3 only s is changed in the progression of the degradation model and the others are held as constant values. The backside sail optical coefficients ε_b and B_b are required for the calculation of the sail emissivity based acceleration, ρ_b and s_b are required for the optical PRP models as the back side of the sail is exposed to the BRP and ARP during manoeuvres.

Table 4 and Table 5 contain the initial conditions and spacecraft which are needed for repetition of the analysis. The spacecraft mass and sail area match ACS-3, the ratio-

nale for this choice is that these values are representative of an existing sail operating in Earth orbit.

Fig. 8 shows the operation of a pristine sail over a 15 year mission performing SMA raising and lowering on alternating years. This pristine sail operation is the baseline unirradiated simulation that serves for the comparison of the irradiated sail case studies and is used to calculate the expected radiation fluxes through the sails duration in each altitude band of 1000 km, see Fig. 4. In Section 3.2, the regions in Earth's equatorial plane that have the highest effective capture flux were identified. The actual flux will depend on the orbit altitude. To account for this dependency on altitude, the radiation spectra was weighted against the proportion of time the trajectory of the sail is in each 1000-km altitude band was used to create a weighted average ECF.

Table 6 contains the flux values for each altitude band with the final weighted average ECF of 4.63×10^8 Protons/cm²/s calculated for the sail operating across this

Table 4
Spacecraft physical parameters.

Spacecraft Mass	16 kg
Sail Area	80 m ²

Table 5
Spacecraft orbit initial parameters.

Altitude	18000 km	E_r	6378.1363
Eccentricity	0°	True Anomaly	321°
Inclination	0°	Start Date MJD2000	9131.5

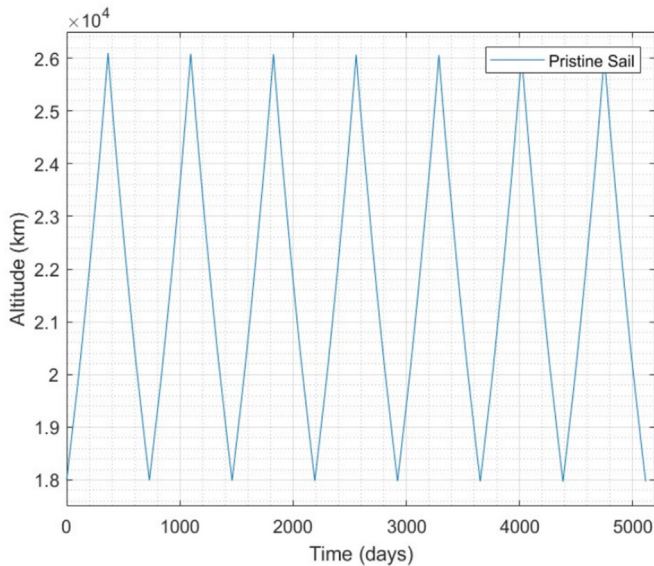


Fig. 8. Pristine solar sail undergoing 15 years of SMA changing manoeuvres, alternating between SMA raising and SMA lowering annually.

region of high fluxes of low energy protons. This flux is used to calculate the accumulated fluence and consequent degradation progression. A simulation was performed in which the sailcraft dynamics were propagated for a total of 15 years, both without proton damage degradation implemented and with proton degradation for sails with temperatures of -36°C and 100°C . The thermal equilibrium temperature for a sun pointing Al-Al two-side coated sail at 1 AU is 175°C and for an Al-Cr sail the temperature is -24°C . A sailcraft manoeuvring about the Earth will most likely *not* be continuously oriented perpendicular to the direction of sunlight, therefore resulting in colder sail temperatures. These factors, combined with the temperatures of the irradiated samples, led to the selection of -36°C and 100°C for this study (see Table 7).

5.2. Case: -36°C sail temperature

Fig. 9 shows the progression of the sail with a temperature of -36°C performing the SMA raising and lowering whilst undergoing degradation. The same figure also gives the performance of the pristine sail as shown previously in Fig. 8. In Fig. 10, it becomes clear that, as the offset fluence is exceeded, the ability of the sail to change altitude is reduced. The offset fluence of a sail at -36°C is 0.786×10^{17} protons/cm², and with a 95% confidence level of captured proton flux, the offset fluence is reached after 1965 days. Once the offset fluence has been reached, the trajectories diverge as the reduced specular reflection of the degraded sail results in a smaller sail acceleration as well as optimal cone angles that produce smaller accelerations.

In order to demonstrate the level of impact of radiation induced degradation on the loss of acceleration this loss can be compared to the acceleration effects of planetary radiation. In Fig. 9, the black dashed line highlights the point at which the loss of acceleration due to degradation is greater than the maximum value of the acceleration from ARP. At day 2127, a reduction in acceleration of $4.2 \times 10^{-7} \text{ m/s}^2$ has occurred due to degradation of the specular properties, which is greater than the largest calculated instantaneous acceleration due to ARP ($a_{ARP} = 4. \times 10^{-7} \text{ m/s}^2$). A similar result occurs for the BBRP acceleration, ($a_{BBRP} = 8.16 \times 10^{-7} \text{ m/s}^2$) with a reduction in acceleration of the same magnitude occurring at day 2154. It is notable that the magnitudes of the accelerations induced by ARP and BBRP are intrinsically linked to the altitude and orbit of the sailcraft (with proximity to Earth increasing the magnitude) as well as the sailcraft orientation. The average values of acceleration due to ARP and BBR across the simulation are $a_{ARP} = 1.01 \times 10^{-10} \text{ m/s}^2$ and $a_{BBRP} = 1.63 \times 10^{-10} \text{ m/s}^2$. These average values are exceeded by the loss of acceleration due to degradation within days of exceeding the offset fluence F0. In absolute terms, the reduction in the specular reflectivity for the -36°C case will see the sail's specular reflectivity reduce from a pristine value of 0.919 to an end-of-mission value of 0.57. The loss of sail acceleration due to degradation can be examined by

Table 6

Weighted average effective capture flux derived from pristine sail trajectory.

Altitude band (km)	Time in band (%)	ECF 95% confidence interval (Protons/cm ² /s)	Weighted ECF (Protons/cm ² /s)
18,000	15%	4.55×10^8	6.85×10^7
19,000	15%	4.64×10^8	6.74×10^7
20,000	13%	4.72×10^8	6.07×10^7
21,000	12%	4.75×10^8	5.85×10^7
22,000	12%	4.69×10^8	5.66×10^7
23,000	12%	4.64×10^8	5.46×10^7
24,000	10%	4.57×10^8	4.76×10^7
25,000	11%	4.47×10^8	4.89×10^7
Weighted Average Flux			4.63×10^8

Table 7

Mission cases and times to F0.

Case and altitude	Sail Temperature	Time to F0 (days)
Worst case ECF (18,000–26,000 km)	100°C	125
Worst case ECF (18,000–26,000 km)	–36°C	1965
GEO (35,786 km)	100°C	194
GEO (35,786 km)	–36°C	2923
ACS3 (1000 km)	100°C	17,500
ACS3 (1000 km)	–36°C	262,504

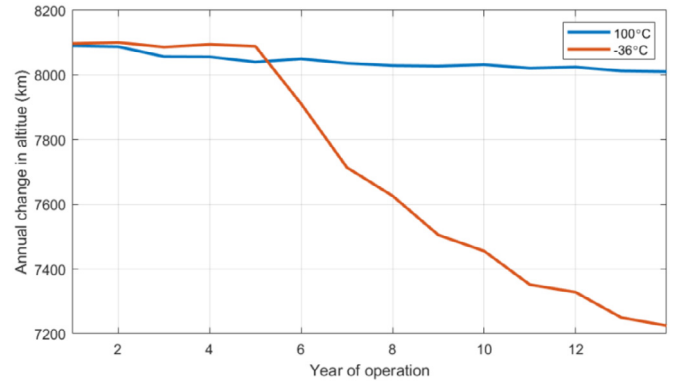


Fig. 10. Annual change in altitude of sailcraft.

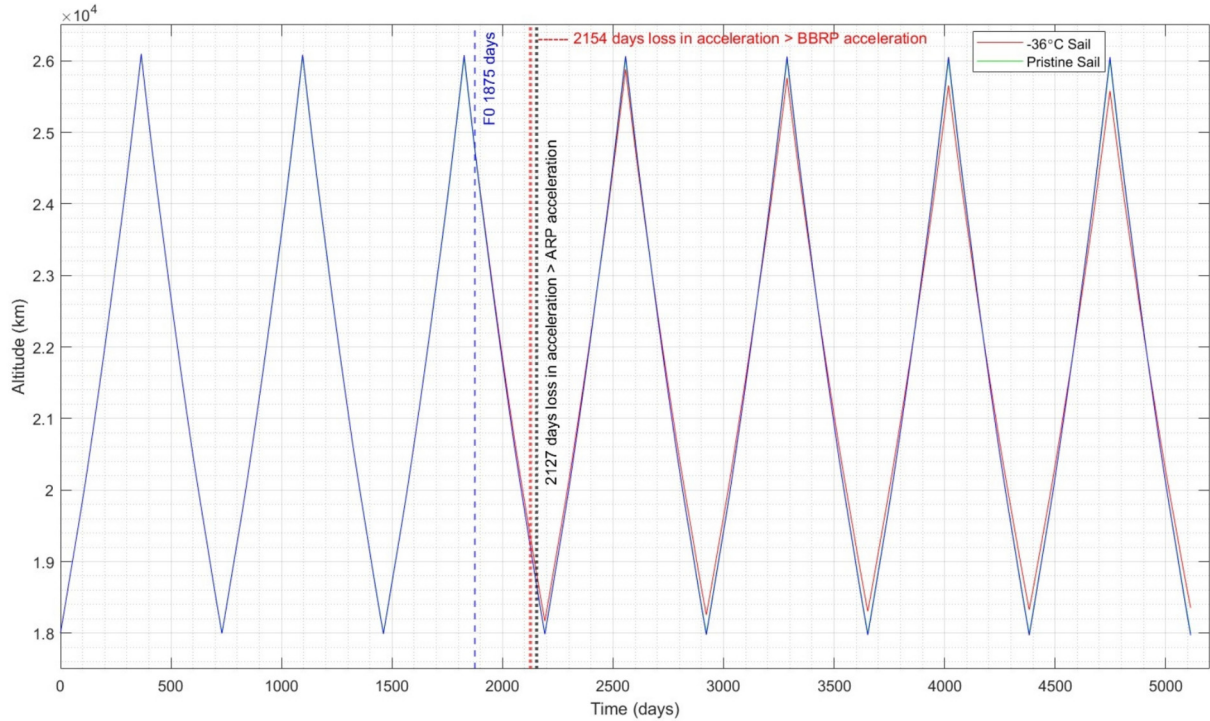


Fig. 9. 15-year SMA raising and lowering. Pristine sail and degraded sail at –36°C.

comparing the reduced ability to change the spacecraft's SMA to the pristine sail's performance. In the final year of operation, the degraded sail exhibits a SMA change capacity of 7224 km compared to 8082 km for a pristine sail, a 10.7% difference.

5.3. Case: 100°C sail temperature

Based on the observed experimental data (Klein et al., 2025), it was found that for higher sail temperatures, $\sim 100^\circ\text{C}$, the offset fluence is much smaller. The offset fluence of a sail at 100°C is 0.05×10^{17} protons/cm² corresponding to 125 days in the region of interest at 95% confidence level. Fig. 10 shows the evolution in altitude change for a -36°C and 100°C sail. The figure shows that the degradation has slightly reduced the performance of the sail. In the first year, the pristine sail was able to increase its SMA by 8097 km, whereas the degraded sail achieved an SMA increase of 8090 km; a difference of only 7 km. In the final year of the mission, this difference only increased to 92 km. The reduction in performance starts somewhat rapidly after F0 has been exceeded (at day 125): the specular reflection after 1870 days is 0.914, down from a pristine value of 0.919. After this point, the specular reflection continues to decrease but at a much-reduced rate of change reaching an end-of-mission value of 0.910.

According to the DLR semi-empirical model, the loss of acceleration due to degradation will not exceed the a_{ARP} and a_{BBRP} values within the simulation timeframe (Klein et al., 2025). The dataset comprising this model was measured to a final test fluence of 2.2×10^{17} protons/cm² which would correspond to a mission elapsed time of 5500 days in the simulated radiation environment.

5.4. Comparative mission profiles

Table 3 shows the time in days required for a sail operating at this level of proton irradiation to reach the offset fluence required for degradation to start. These results highlight the variability of the low-energy proton environment that constitutes the ECF. This range is clear when compared the worst-case orbits to the environment at 1000 km where ACS3 operates. The low-energy fluxes at low orbits are orders of magnitude smaller than peak fluxes. This discrepancy provides an offset fluence for ACS3 of over seven centuries. Geostationary orbits receive a smaller flux than the worst case at 2.97×10^8 protons/cm²/s which is 64% of the weighted peak ECF of 4.63×10^8 protons/cm²/s, resulting in a time to F0 of 194 days.

6. Conclusions

A new method for calculating mission-specific solar-sail proton capture for low-energy proton-induced hydrogen blistering has been introduced. This method allows the computation of the capture probability while accounting for the energy range of the low-energy environment and

the effects of angular distribution of flux. This method, along with proton flux spectra calculated using the Space Plasma Model (SPM), was used to identify and generate fluxes for the portion of the radiation environment that directly contributes to the development of hydrogen blisters. The range of equatorial altitudes that contain high levels of low-energy flux were identified with peak fluxes at 21,000 km. The NESTOR toolkit was used along with the semi-empirical model to simulate a 15-year-long mission of a sail across the worst-case low-energy proton environment. The worst-case flux simulations were performed for two sails at temperatures of -36°C and 100°C , these two cases exhibited different progression of radiation-induced degradation. The -36°C sail was shown to operate without apparent degradation for 5.4 years before an offset fluence threshold was reached and degradation began. For the 100 deg sail, the offset fluence was reached already after 125 days (0.34 years). Notably, while for the colder sail (-36°C) it takes longer for the degradation to set in, the magnitude and rate of degradation is larger than for the hotter sail (100°C). This temperature-induced discrepancy in degradation progression is seen in the capacity of the spacecraft to change its Semi-Major Axis (SMA) in a given year of operation. In the last year of the mission, the cold sail's degradation resulted in a 10.7% lower SMA-changing capability than a pristine sail. Conversely the hotter sail only underwent a 0.89% reduction in performance.

While this work focussed on the worst-case equatorial regions, other orbital regions were also briefly considered. The key takeaway from that analysis is that the low-Earth orbit environment does not possess significant fluxes of the protons energies required to induce optical degradation of an aluminium-coated solar sail. For example, the ACS3 mission is not expected to exceed the offset fluence (F0) for another seven centuries as its 1000 km sun synchronous orbit has limited fluxes of low energy protons. Geosynchronous orbits at 35,786 km altitude sit inside the low energy region but experience a flux of 64% compared to the worst-case regions. Therefore, in GEO, the amount of time before a -36°C sail shows signs of degradation will be longer than 8 years, compared to 5.1 years for the worst-case orbits.

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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