Optical Solar Sail Degradation Modeling

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The Problem

- The optical properties of the thin metalized polymer films that are projected for solar sails are assumed to be affected by the erosive effects of the space environment
- Optical solar sail degradation (OSSD) in the real space environment is to a considerable degree indefinite (initial ground test results are controversial and relevant in-space tests have not been made so far)
- The standard optical solar sail models that are currently used for trajectory and attitude control design do not take optical degradation into account $\rightarrow$ its potential effects on trajectory and attitude control have not been investigated so far
- Optical degradation is important for high-fidelity solar sail mission analysis, because it decreases both the magnitude of the solar radiation pressure force acting on the sail and also the sail control authority
- Solar sail mission designers necessitate an OSSD model to estimate the potential effects of OSSD on their missions

Our Approach

- We established in November 2004 a "Solar Sail Degradation Model Working Group"[1] (SSDMWG) with the aim to make the next step towards a realistic high-fidelity optical solar sail model
- We propose a simple parametric OSSD model that describes the variation of the sail film's optical coefficients with time, depending on the sail film's environmental history, i.e., the radiation dose
- The primary intention of our model is not to describe the exact behavior of specific film-coating combinations in the real space environment, but to provide a more general parametric framework for describing the general optical degradation behavior of solar sails

[1] the authors and Volodymyr Baturkin, Victoria L. Coverstone, Benjamin Diedrich, Gregory P. Garbe, Marianne Görlich, Manfred Leipold, Franz Lura, Leonel Rios-Reyes, Daniel J. Scheeres, Wolfgang Seboldt, Bong Wie

Overview

Different levels of simplification for the optical characteristics of a solar sail result in different models for the magnitude and direction of the SRP force:

Model IR (Ideal Reflection)

Most simple model

Model SNPR (Simplified Non-Perfect Reflection)

Optical properties of the solar sail are described by a single coefficient

Model NPR (Non-Perfect Reflection)

Optical properties of the solar sail are described by 3 coefficients

Generalized Model by Rios-Reyes and Scheeres

Optical properties are described by three tensors. Takes the sail shape and local optical variations into account

Refined Model by Mengali, Quarta, Circi, and Dachwald

Optical properties depend also on light incidence angle, surface roughness, and temperature

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The Non-Perfectly Reflecting Solar Sail

The non-perfectly reflecting solar sail model parameterizes the optical behavior of the sail film by the optical coefficient set

$$\mathcal{P} = \{\rho, s, \varepsilon_{\mathrm{f}}, \varepsilon_{\mathrm{b}}, B_{\mathrm{f}}, B_{\mathrm{b}}\}$$

The optical coefficients for a solar sail with a highly reflective aluminum-coated front side and with a highly emissive chromium-coated back side are:

$$\mathcal{P}_{\mathrm{Al|Cr}} = \{\rho = 0.88, s = 0.94, \varepsilon_{\mathrm{f}} = 0.05, \\ \varepsilon_{\mathrm{b}} = 0.55, B_{\mathrm{f}} = 0.79, B_{\mathrm{b}} = 0.55\}$$

Nomenclature

ρ: reflection coefficient

s: specular reflection factor

ε_{f} and ε_{b}: emission coefficients of the front and back side, respectively

B_{f} and B_{b}: non-Lambertian coefficients of the front and back side, respectively

Overview (Reprise)

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Those models do not include **optical solar sail degradation** (OSSD)

Data Available From Ground Testing

- Much ground and space testing has been done to measure the optical degradation of metalized polymer films as second surface mirrors (metalized on the back side)
- No *systematic* testing to measure the optical degradation of candidate solar sail films (metalized on the front side) has been reported so far and preliminary test results are controversial
  - Lura et. al. measured considerable OSSD after combined irradiation with VUV, electrons, and protons
  - Edwards et. al. measured no change of the solar absorption and emission coefficients after irradiation with electrons alone
- Respective in-space tests have not been made so far
- The optical degradation behavior of solar sails in the real space environment is to a considerable degree indefinite

Simplifying Assumptions

For a *first* OSSD model, we have made the following simplifications:

1. The only source of degradation are the solar photons and particles
2. The solar photon and particle fluxes do not depend on time (average sun without solar events)
3. The optical coefficients do not depend on the sail temperature
4. The optical coefficients do not depend on the light incidence angle
5. No self-healing effects occur in the sail film

Solar radiation dose (SRD)

Let p be an arbitrary optical coefficient from the set $\mathcal{P}$. With OSSD, p becomes time-dependent, $p(t)$. With the simplifications stated before, $p(t)$ is a function of the solar radiation dose $\tilde{\Sigma}$ (dimension $\left[\mathrm{J/m^2}\right]$) accepted by the solar sail within the time interval $t - t_0$:

$$\tilde{\Sigma}(t) \triangleq \int_{t_0}^{t} S \cos\alpha \, dt' = S_0 r_0^2 \int_{t_0}^{t} \frac{\cos\alpha}{r^2} \, dt'$$

SRD per year on a surface perpendicular to the sun at 1 AU

$$\tilde{\Sigma}_0 = S_0 \cdot 1\,\mathrm{yr} = 1368\,\mathrm{W/m^2} \cdot 1\,\mathrm{yr} = 15.768\,\mathrm{TJ/m^2}$$

Dimensionless SRD

Using $\tilde{\Sigma}_0$ as a reference value, the SRD can be defined in dimensionless form:

$$\Sigma(t) = \frac{\tilde{\Sigma}(t)}{\tilde{\Sigma}_0} = \frac{r_0^2}{T} \int_{t_0}^{t} \frac{\cos\alpha}{r^2} \, dt' \quad \text{where} \quad T \triangleq 1\,\mathrm{yr}$$

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$\Sigma(t)$ depends on the solar distance history and the attitude history $\mathbf{z}[t] = (r, \alpha)[t]$ of the solar sail, $\Sigma(t) = \Sigma(\mathbf{z}[t])$

Differential form for the SRD

The equation for the SRD can also be written in differential form:

$$\dot{\Sigma} = \frac{r_0^2}{T} \frac{\cos\alpha}{r^2} \quad \text{with} \quad \Sigma(t_0) = 0$$

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Assumption that each p varies exponentially with $\Sigma(t)$

Assume that $p(t)$ varies exponentially between $p(t_0) = p_0$ and $\lim_{t\to\infty} p(t) = p_\infty$

$$p(t) = p_\infty + (p_0 - p_\infty) \cdot \mathrm{e}^{-\lambda\Sigma(t)}$$

The degradation constant λ is related to the "half life solar radiation dose" $\hat{\Sigma}$ ($\Sigma = \hat{\Sigma} \Rightarrow p = \frac{p_0+p_\infty}{2}$) via

$$\lambda = \frac{\ln 2}{\hat{\Sigma}}$$

Note that this model has 12 free parameters additional to the 6 p_0, 6 p_∞ and 6 half life SRDs $\hat{\Sigma}_p$ (too much for a simple parametric OSSD analysis)

Reduction of the number of model parameters

We use a degradation factor d and a single half life SRD for all p, $\hat{\Sigma}_p = \hat{\Sigma}\ \forall p \in \mathcal{P}$

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EOL optical coefficients

Because the reflectivity of the sail decreases with time, the sail becomes more matt with time, and the emissivity increases with time, we use:

$$\rho_\infty = \frac{\rho_0}{1+d} \qquad s_\infty = \frac{s_0}{1+d} \qquad \varepsilon_{\mathrm{f}\infty} = (1+d)\varepsilon_{\mathrm{f}0}$$

$$\varepsilon_{\mathrm{b}\infty} = \varepsilon_{\mathrm{b}0} \qquad B_{\mathrm{f}\infty} = B_{\mathrm{f}0} \qquad B_{\mathrm{b}\infty} = B_{\mathrm{b}0}$$

Degradation of the optical parameters in dimensionless form

$$\frac{p(t)}{p_0} = \begin{cases} \left(1 + d\mathrm{e}^{-\lambda\Sigma(t)}\right) / (1+d) & \text{for} \quad p \in \{\rho, s\} \\ 1 + d\left(1 - \mathrm{e}^{-\lambda\Sigma(t)}\right) & \text{for} \quad p = \varepsilon_{\mathrm{f}} \\ 1 & \text{for} \quad p \in \{\varepsilon_{\mathrm{b}}, B_{\mathrm{f}}, B_{\mathrm{b}}\} \end{cases}$$

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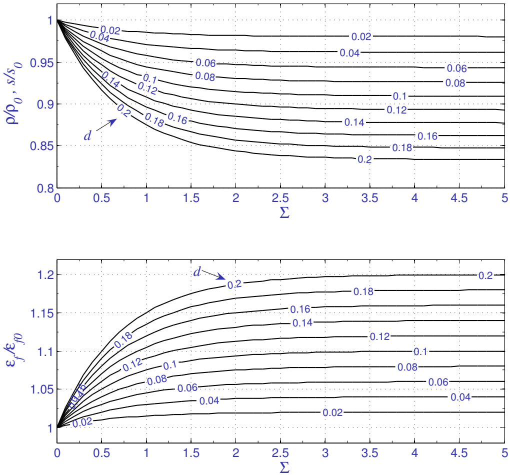
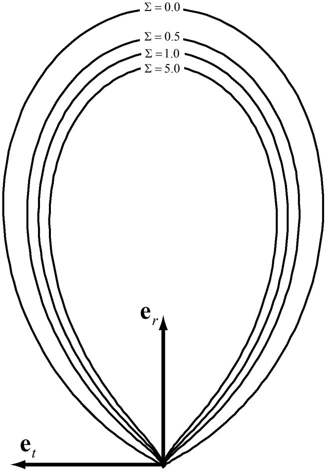
OSSD Effects

on the optical coefficients and the SRP force bubble



“degradation” of optical coefficients



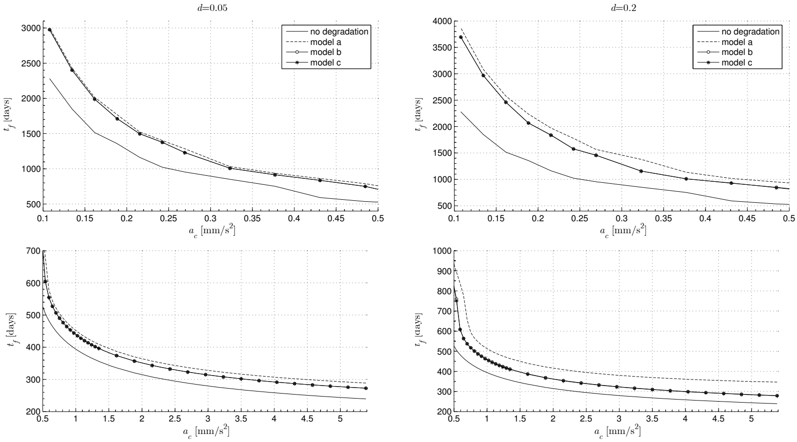
“degradation” of SRP force bubble

Mars Rendezvous

- Solar sail with $0.1\,\mathrm{mm/s^2} \leq a_c < 6\,\mathrm{mm/s^2}$
- $C_3 = 0\,\mathrm{km^2/s^2}$
- 2D-transfer from circular orbit to circular orbit
- Trajectories calculated by G. Mengali and A. Quarta using a classical indirect method with an hybrid technique (genetic + gradient-based algorithm) to solve the associated boundary value problem
- Degradation factor: $0 \leq d \leq 0.2$ (0–20% degradation limit)
- Half life SRD: $\hat{\Sigma} = 0.5\,(S_0 \cdot \mathrm{yr})$
- Three models:
  - ▷ Model (a): Instantaneous degradation
  - ▷ Model (b): Control neglects degradation ("ideal" control law)
  - ▷ Model (c): Control considers degradation

Mars Rendezvous

Trip times for 5% and 20% degradation limit



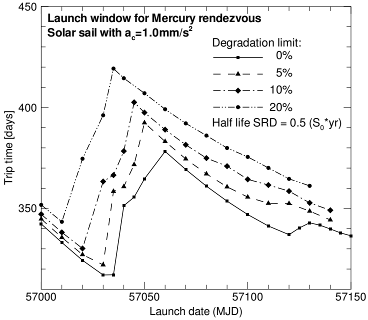
- OSSD has considerable effect on trip times
- The results for model (b) and (c) are indistinguishable close

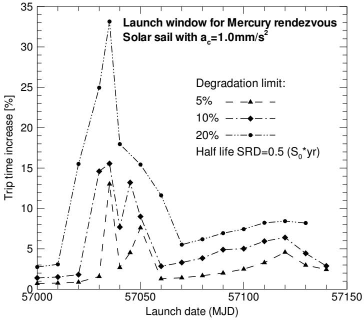
Mercury Rendezvous

- Solar sail with $a_c = 1.0\,\mathrm{mm/s^2}$
- $C_3 = 0\,\mathrm{km^2/s^2}$
- Trajectories calculated by B. Dachwald with the trajectory optimizer GESOP with SNOPT
- Arbitrarily selected launch window $\mathrm{MJD}\,57000 \leq t_0 \leq \mathrm{MJD}\,57130$ (09 Dec 2014 – 18 Apr 2015)
- Final accuracy limit was set to $\Delta r_{f,\max} = 80\,000\,\mathrm{km}$ (inside Mercury's sphere of influence at perihelion) and $\Delta v_{f,\max} = 50\,\mathrm{m/s}$
- Degradation factor: $0 \leq d \leq 0.2$ (0–20% degradation limit)
- Half life SRD: $\hat{\Sigma} = 0.5\,(S_0 \cdot \mathrm{yr})$

Mercury Rendezvous

Launch window for different *d*

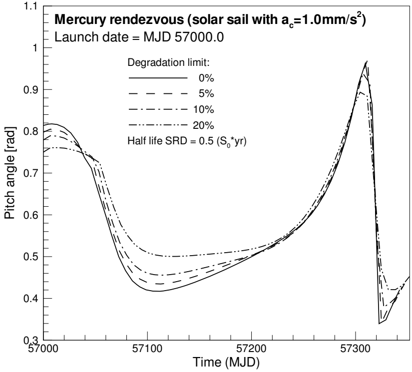




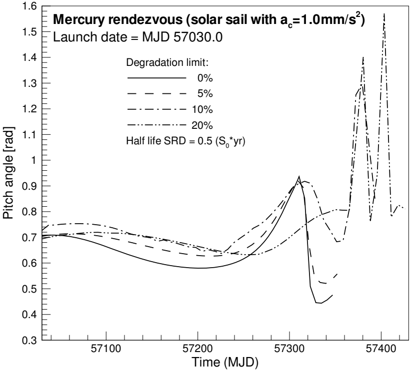
- Sensitivity of the trip time with respect to OSSD depends considerably on the launch date
- Some launch dates considered previously as optimal become very unsuitable when OSSD is taken into account
- For many launch dates OSSD does not seriously affect the mission

Mercury Rendezvous

Optimal α-variation for different d



Launch at MJD 57000.0



Launch at MJD 57030.0

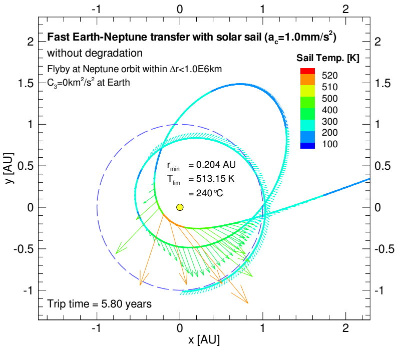
- OSSD can also have remarkable consequences on the optimal control angles
- Given an indefinite OSSD behavior at launch, MJD 57000.0 would be a very robust launch date

Fast Neptune Flyby

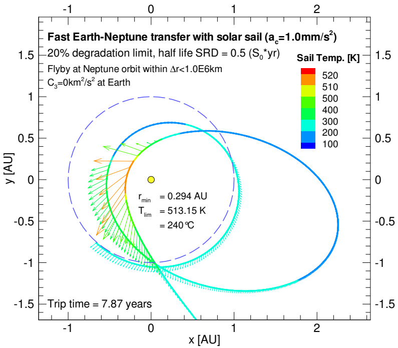
- Solar sail with $a_c = 1.0\,\mathrm{mm/s^2}$
- $C_3 = 0\,\mathrm{km^2/s^2}$
- Trajectories calculated by B. Dachwald with the trajectory optimizer InTrance
- To find the absolute trip time minima, independent of the actual constellation of Earth and Neptune, no flyby at Neptune itself, but only a crossing of its orbit within a distance $\Delta r_{f,\max} < 10^6\,\mathrm{km}$ was required, and the optimizer was allowed to vary the launch date within a one year interval
- Sail film temperature was limited to 240°C by limiting the sail pitch angle
- Degradation factor: $0 \leq d \leq 0.2$ (0–20% degradation limit)
- Half life SRD: $0 \leq \hat{\Sigma} \leq 2$ $(S_0 \cdot \mathrm{yr})$

Fast Neptune Flyby

Topology of optimal trajectories for different *d*



$d = 0$



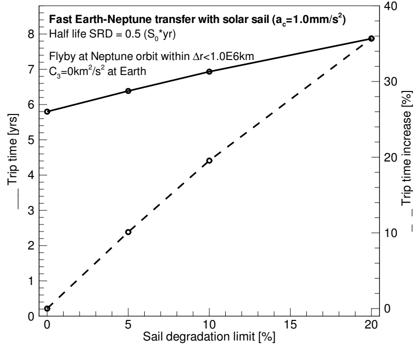
$d = 0.2$

With increasing degradation:

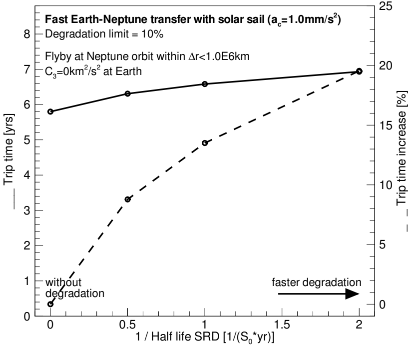
- Increasing solar distance during final close solar pass
- Increasing solar distance before final close solar pass
- Longer trip time

Fast Neptune Flyby

Trip time and trip time increase for different d and $\hat{\Sigma}$



Different degradation factors d ($\hat{\Sigma} = 0.5\,(S_0 \cdot \mathrm{yr})$)

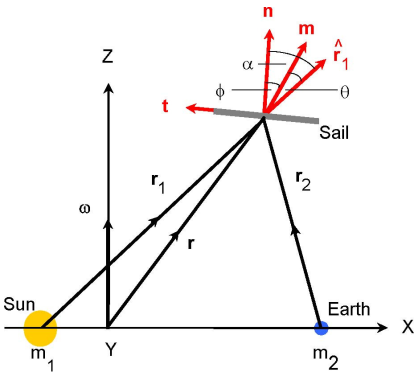


Different half life SRDs $\hat{\Sigma}$ ($d = 0.1$)

Comparable results have been found by M. Macdonald for a mission to the heliopause.

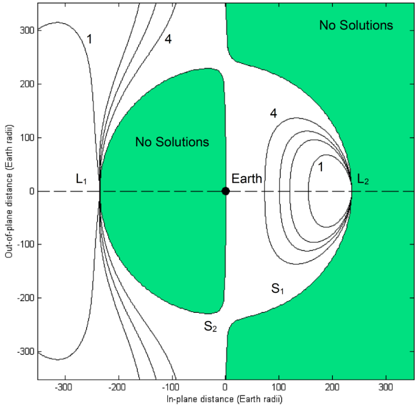
Artificial Lagrange-Point Missions

- Sun-Earth restricted circular three-body problem with non-perfectly solar sail
- SRP acceleration allows to hover along artificial equilibrium surfaces (manifold of artificial Lagrange-points)
- Solutions calculated by C. McInnes

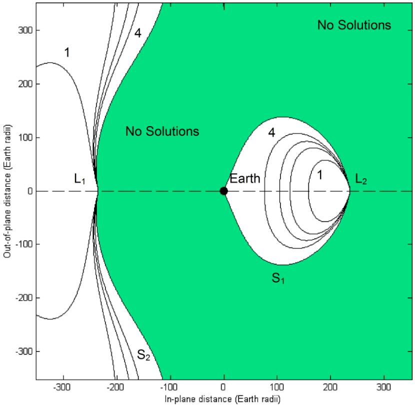


Artificial Lagrange-Point Missions

Contours of sail loading in the *x*-*z*-plane



$\rho = 1$



$\rho = 0.9$

[1] $30\,\mathrm{g/m^2}$ [2] $15\,\mathrm{g/m^2}$ [3] $10\,\mathrm{g/m^2}$ [4] $5\,\mathrm{g/m^2}$

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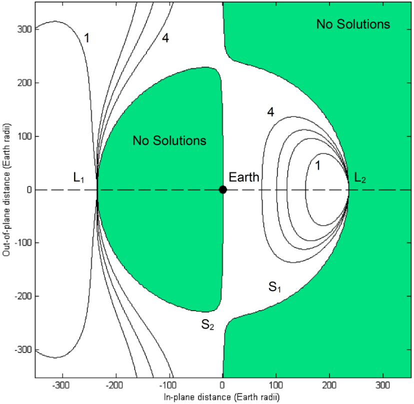
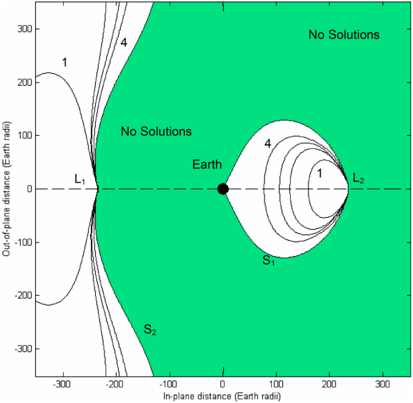


$\rho = 1$

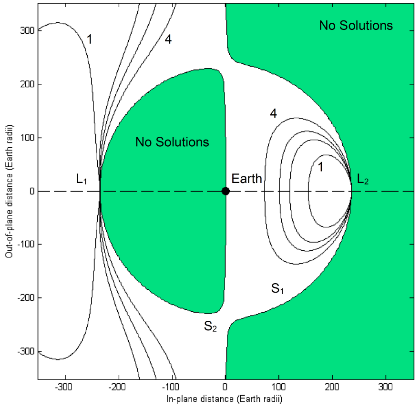


$\rho = 0.8$

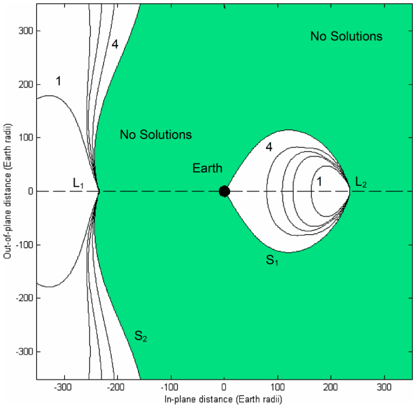
[1] $30\,\text{g/m}^2$ [2] $15\,\text{g/m}^2$ [3] $10\,\text{g/m}^2$ [4] $5\,\text{g/m}^2$

Artificial Lagrange-Point Missions

Contours of sail loading in the x-z-plane



$\rho = 1$



$\rho = 0.7$

[1] $30\,\mathrm{g/m^2}$ [2] $15\,\mathrm{g/m^2}$ [3] $10\,\mathrm{g/m^2}$ [4] $5\,\mathrm{g/m^2}$

Summary and Outlook

- All our results show that optical solar sail degradation has a considerable effect on trip times and on the optimal steering profile. For specific launch dates, especially those that are optimal without degradation, this effect can be tremendous
- Having demonstrated the *potential* effects of optical solar sail degradation on future missions, more research on the *real* degradation behavior has to be done
- To narrow down the ranges of the parameters of our model, further laboratory tests have to be performed
- Additionally, before a mission that relies on solar sail propulsion is flown, the candidate solar sail films have to be tested in the relevant space environment
- Some near-term missions currently studied in the US and Europe would be an ideal opportunity for testing and refining our degradation model

Optical Solar Sail Degradation Modeling

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