A New Model for the Planetary Radiation Pressure Acceleration for Optical Solar Sails

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Delft University of Technology

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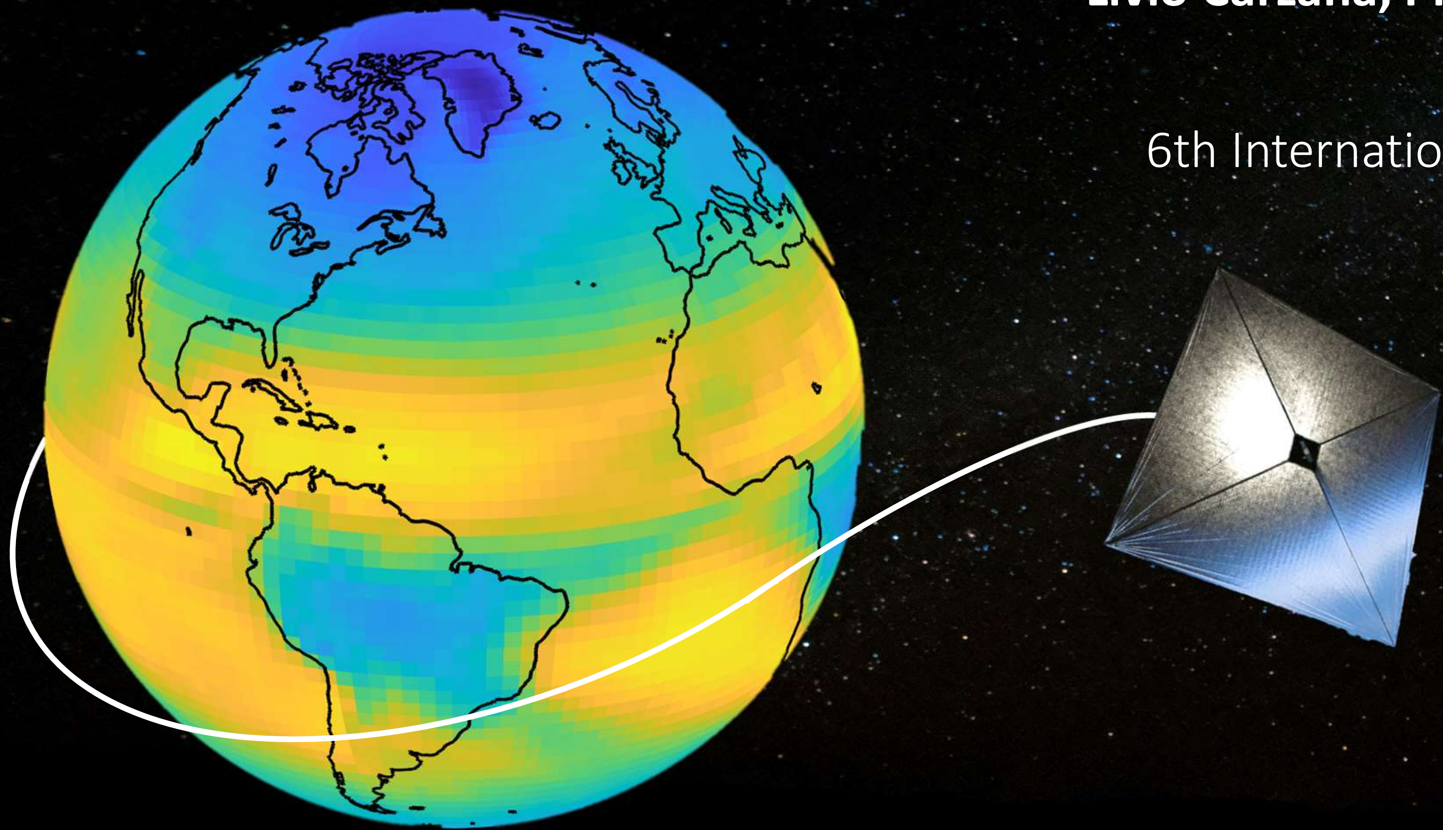

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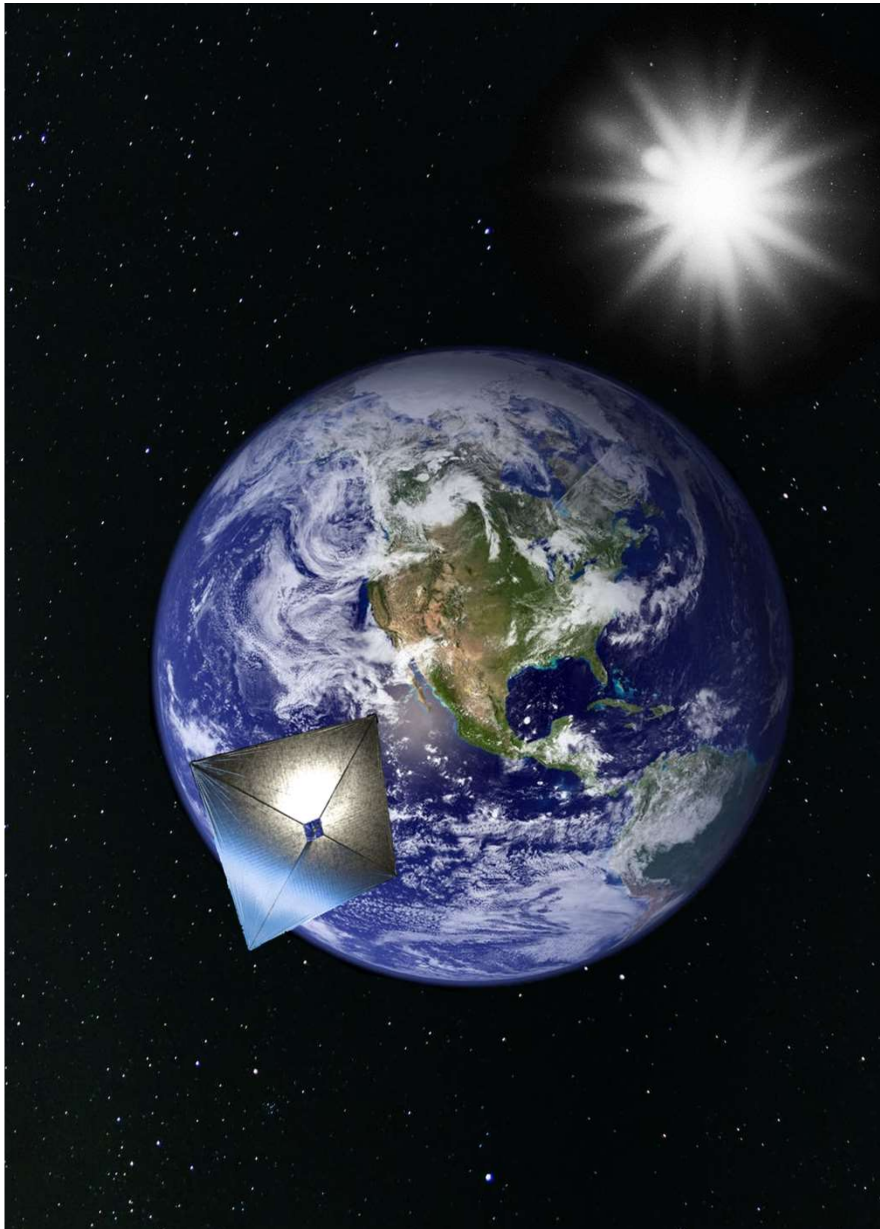
Research Interest

Several missions have been/will be launched in proximity of the Earth

Near-Earth dynamical environment:

- Gravitational forces
- Solar radiation pressure
- Eclipses
- Atmospheric drag



ACS3 solar-sail rendered image - Courtesy of NASA Langley Research Center

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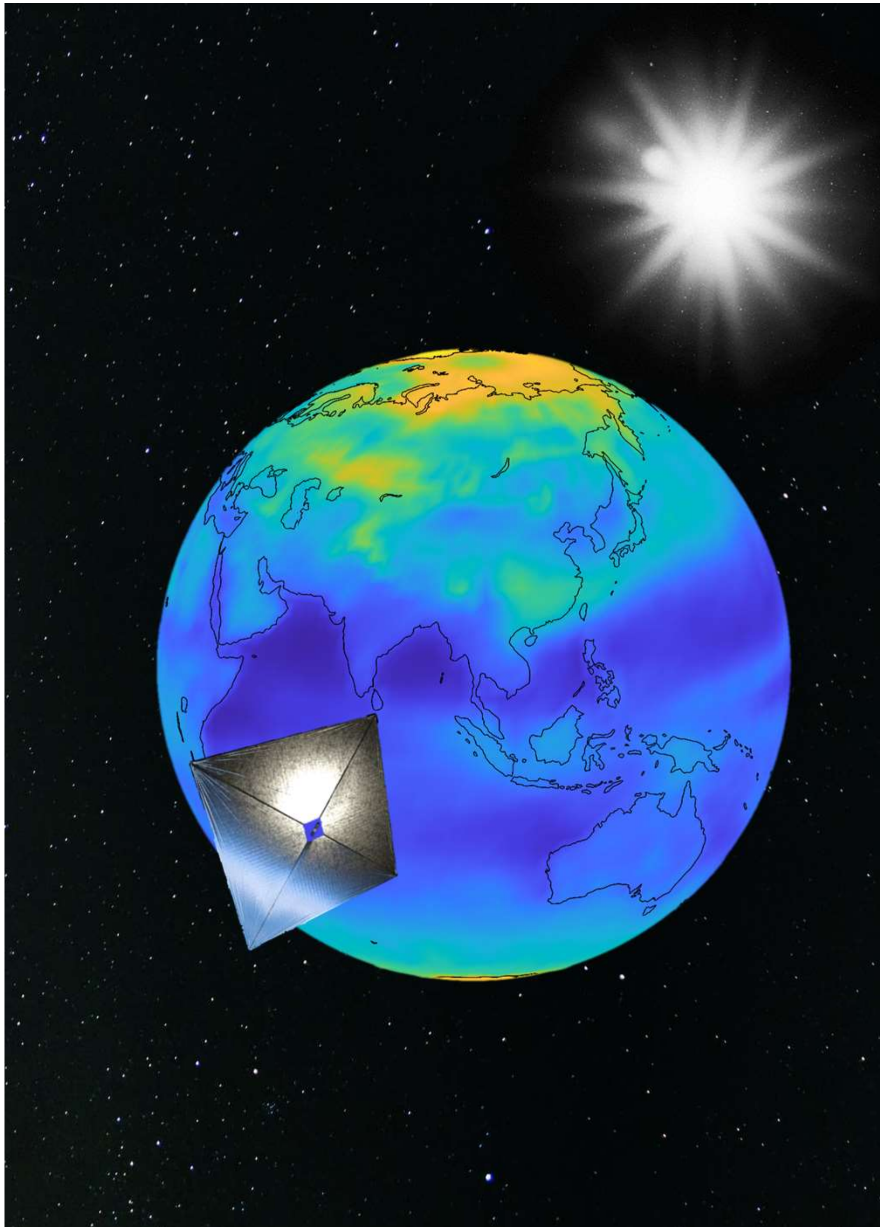
- **Planetary radiation pressure**



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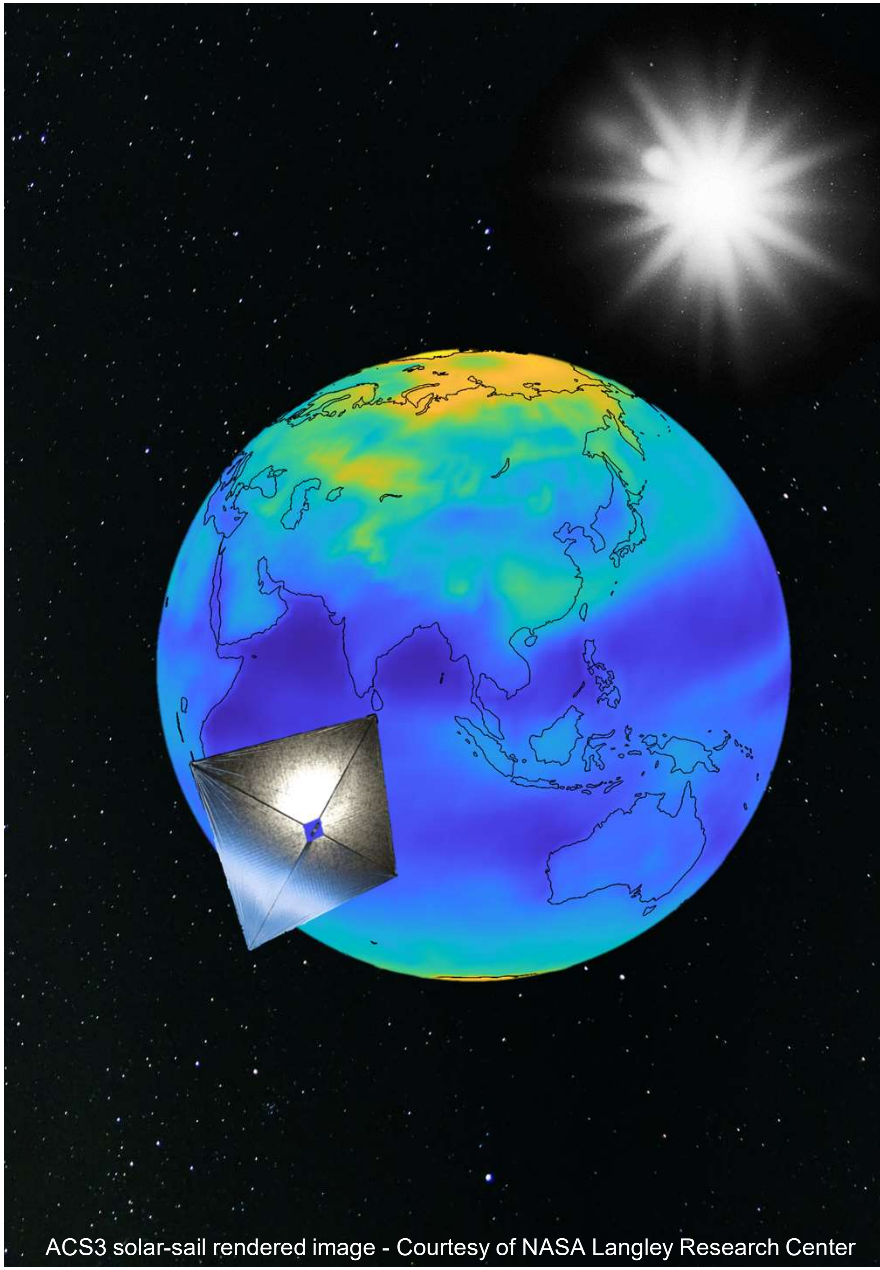
Research Interest

Several missions have been/will be launched in proximity of the Earth

Near-Earth dynamical environment:

- Gravitational forces
- Solar radiation pressure
- Eclipses
- Atmospheric drag
- **Planetary radiation pressure**
  - Significant magnitude (up to ~20% of the SRP)
  - Research interest in accurately modelling the PRP-perturbed solar-sail dynamics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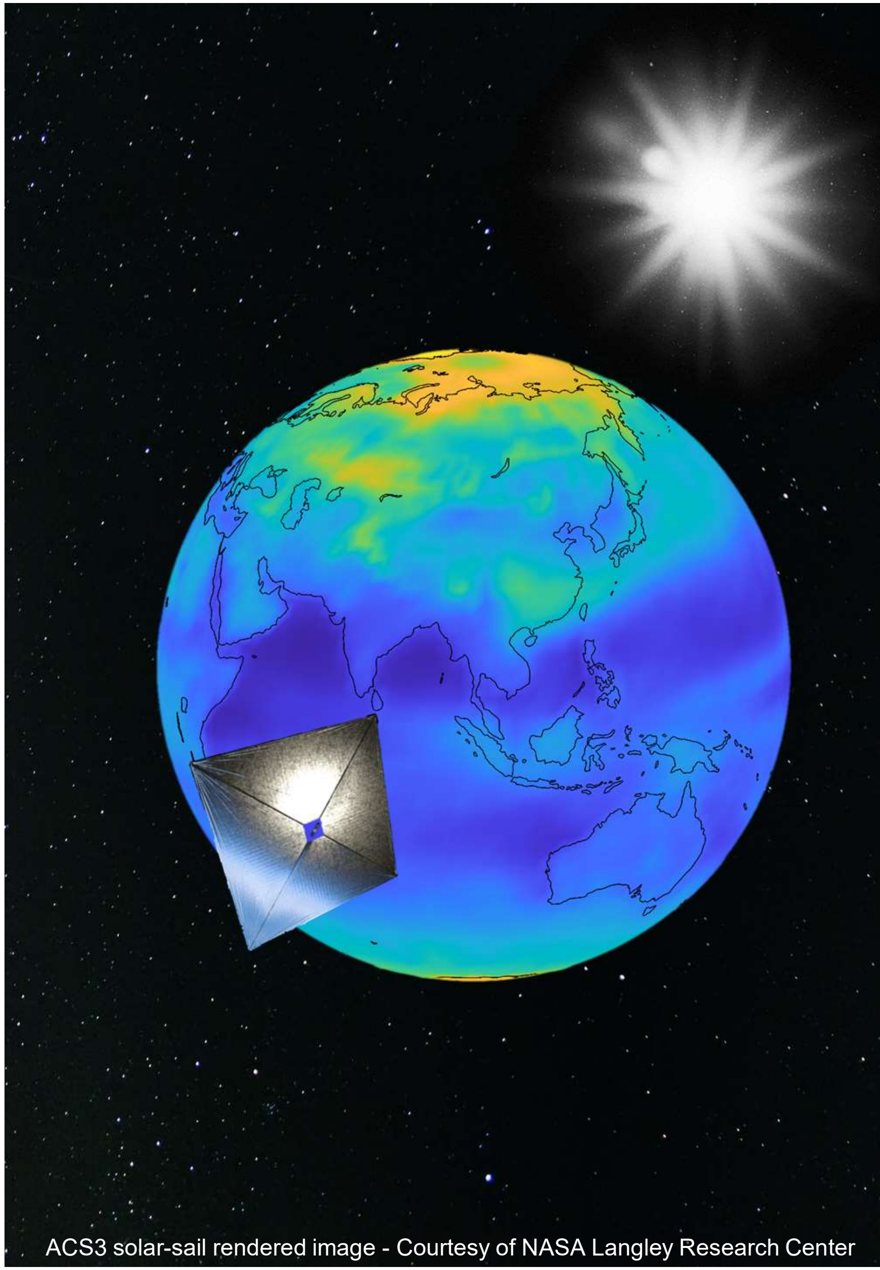
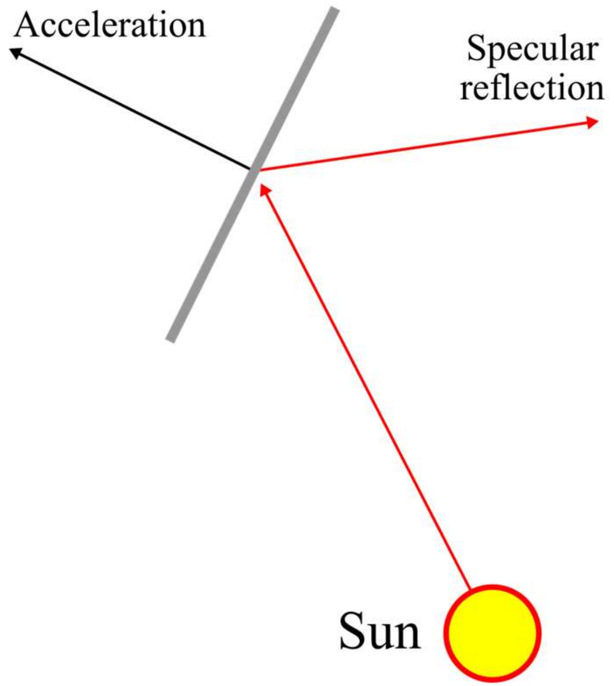


Pre-existing Models & Gap of Knowledge

PRP Acceleration is determined based on:

- Solar-sail Model
  - Ideal (perfectly reflecting) model



Pre-existing Models & Gap of Knowledge

PRP Acceleration is determined based on:

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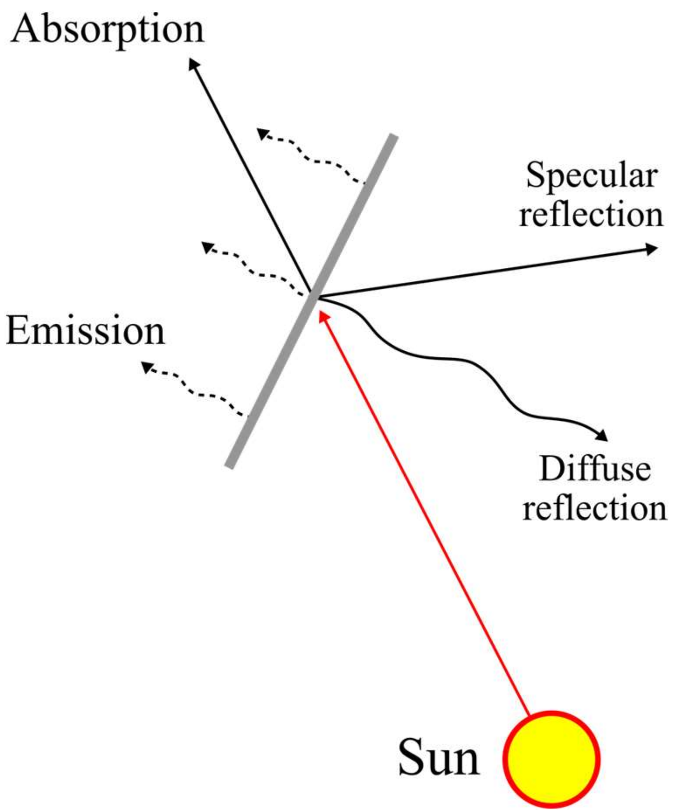

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PRP Acceleration is determined based on:

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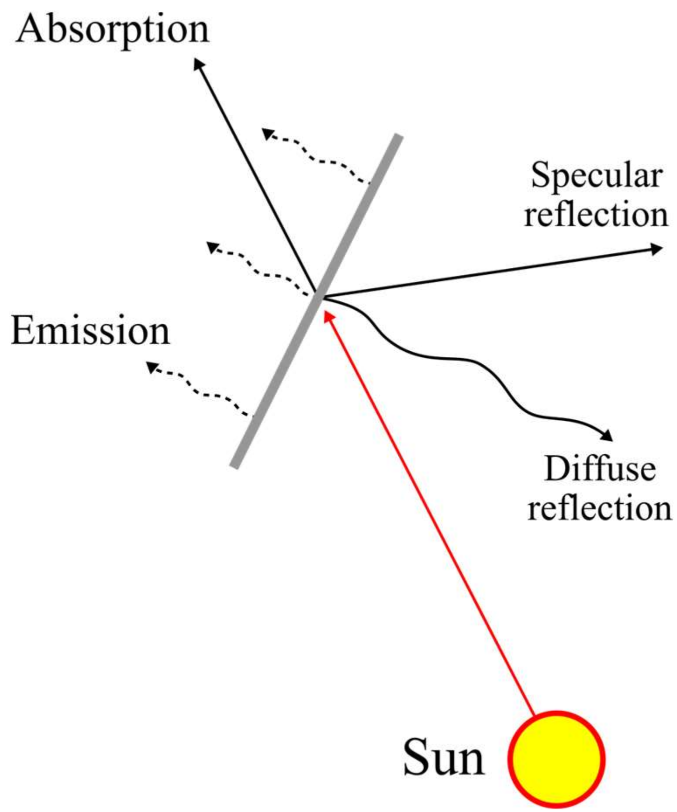

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PRP Acceleration is determined based on:

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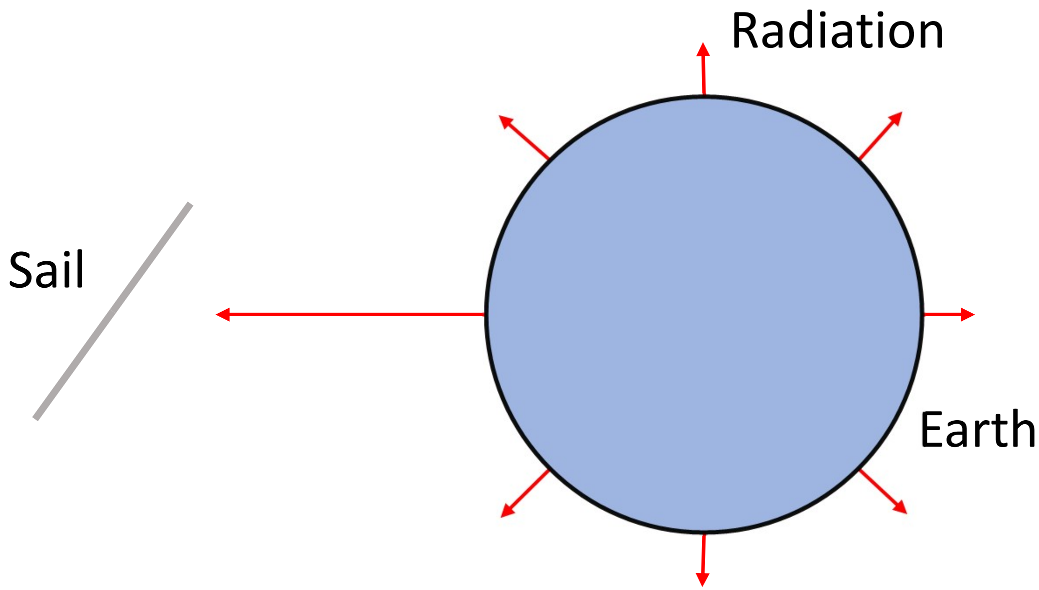
- Planetary Radiation Model
  - Point-like source model



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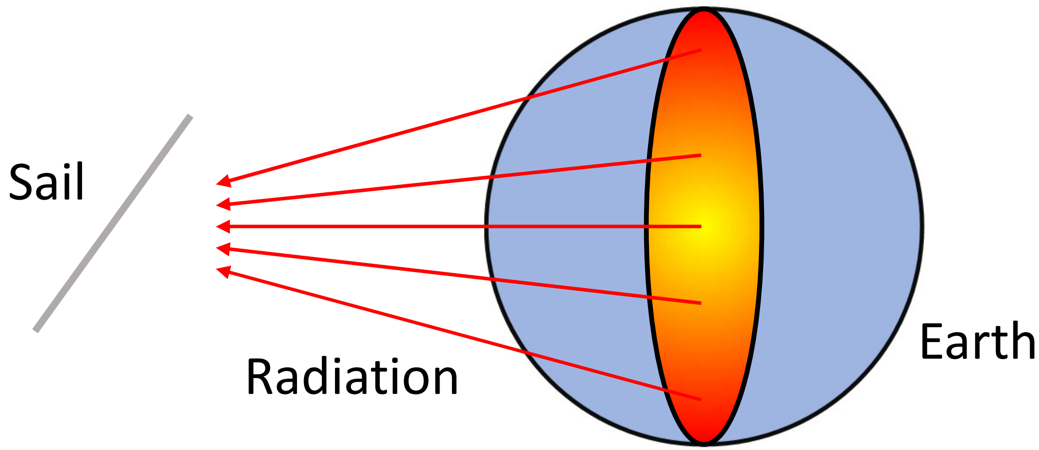
  - Point-like source model
  - Finite-disk source model



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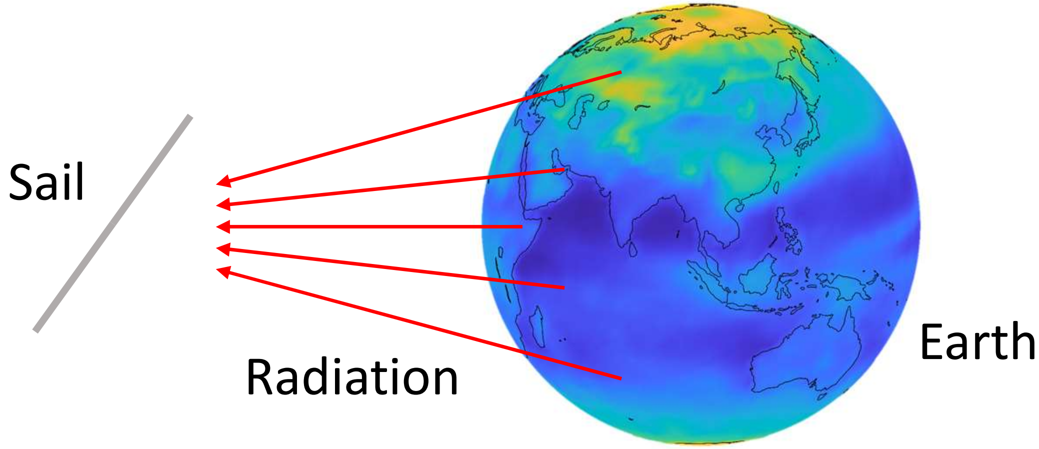
  - Numerical (based on radiation maps)



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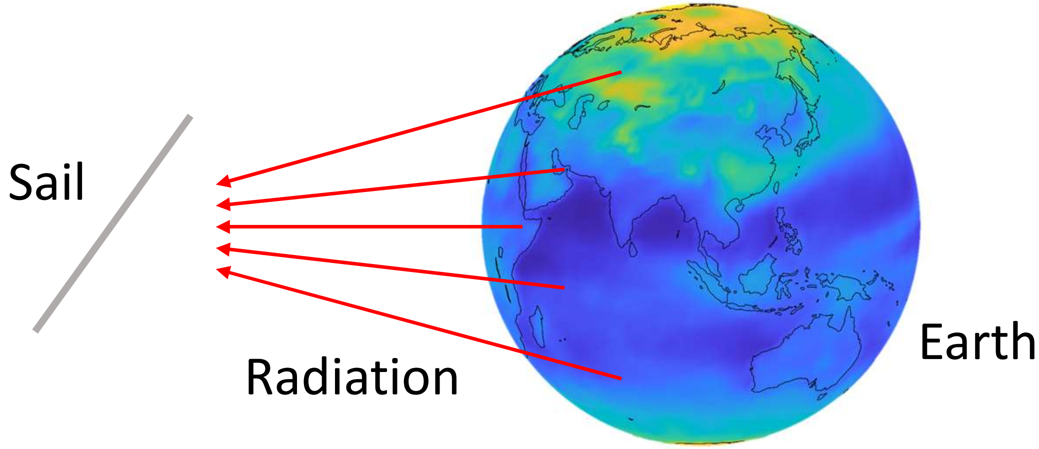
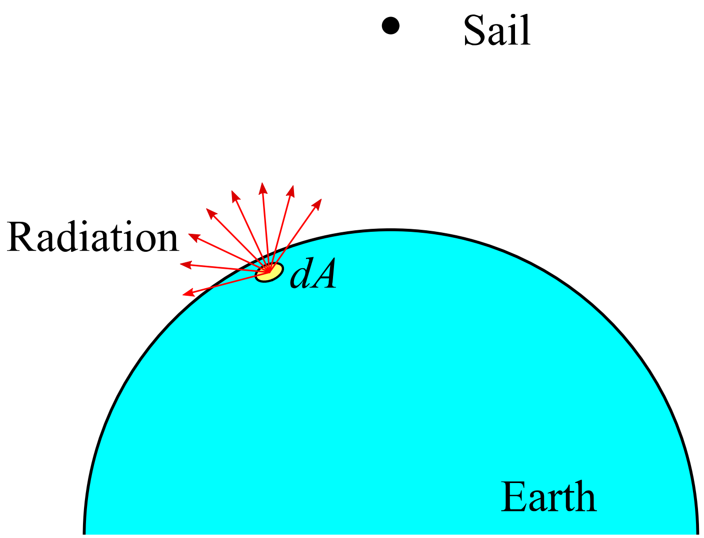
  - **Spherical source model**
  - Numerical (based on radiation maps)



Optical PRP Acceleration Model

Spherical Radiation Source Model

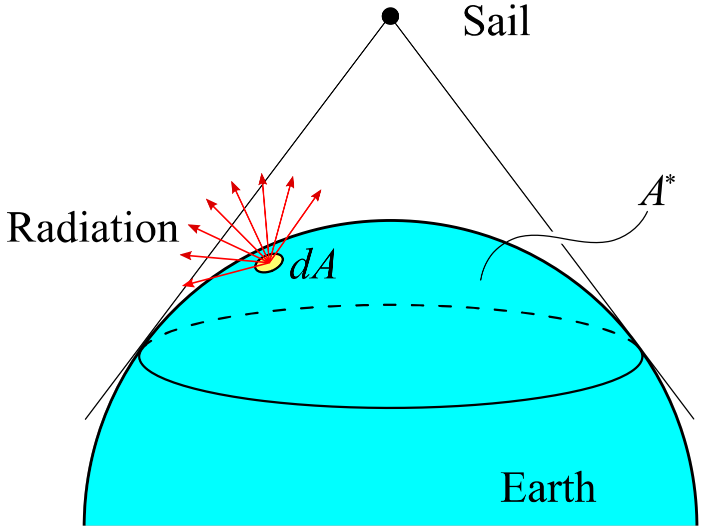
- Spherical Earth model



Optical PRP Acceleration Model

Spherical Radiation Source Model

- Spherical Earth model
- Limited visibility of the Earth from the sailcraft



Optical PRP Acceleration Model

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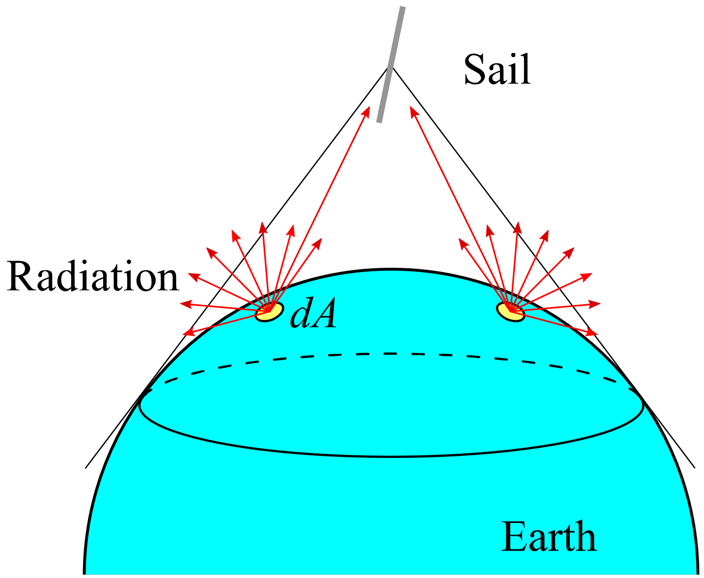
- Limited visibility of the Earth from the sailcraft
- Simultaneous illumination of both sides of the sail



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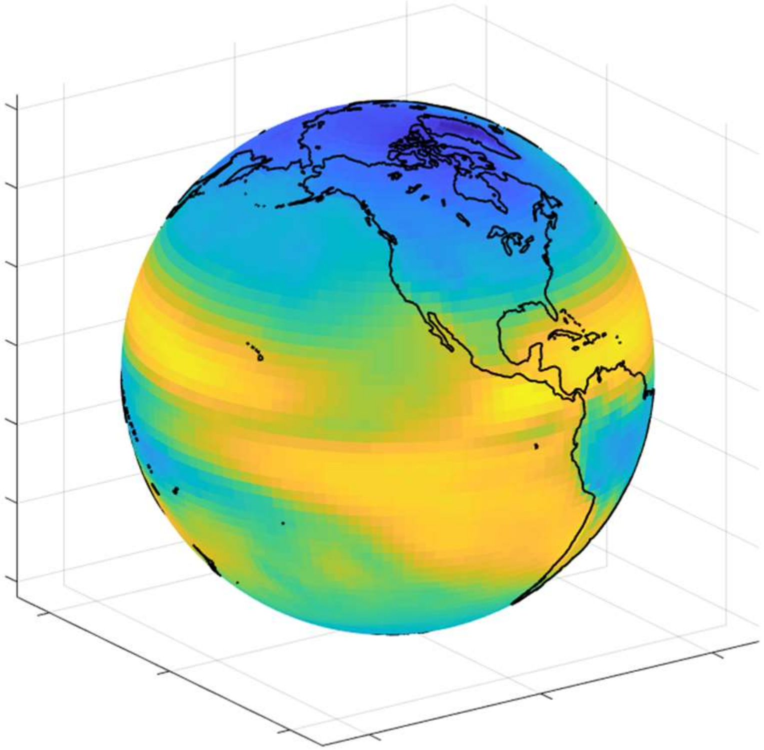

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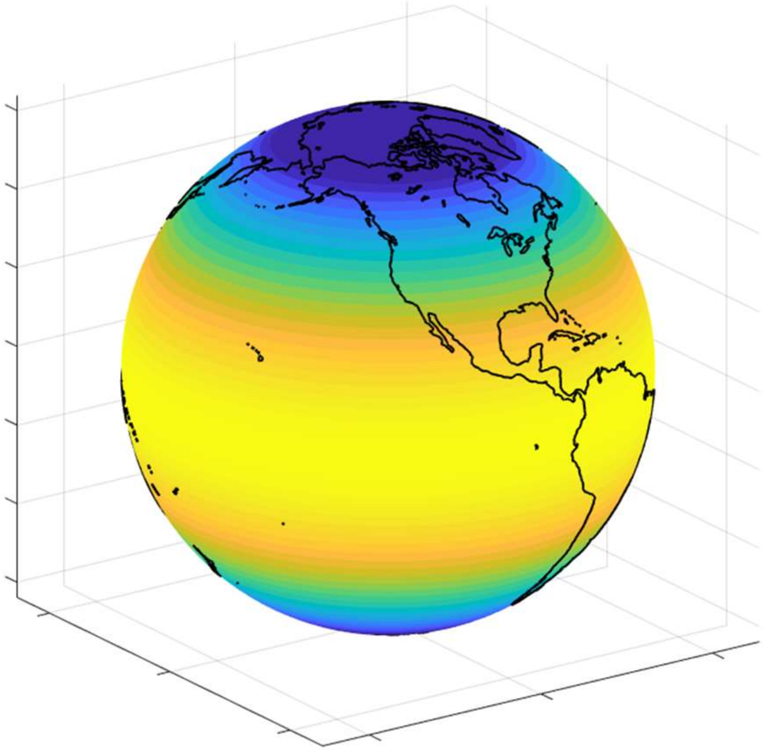
- Limited visibility of the Earth from the sailcraft
- Simultaneous illumination of both sides of the sail
- Isotropic radiation from the visible part of the Earth
  - Modeled assuming a sinusoidal variation of intensity



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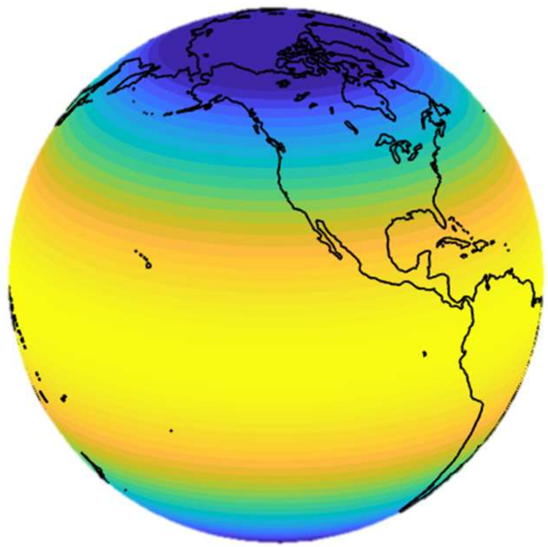

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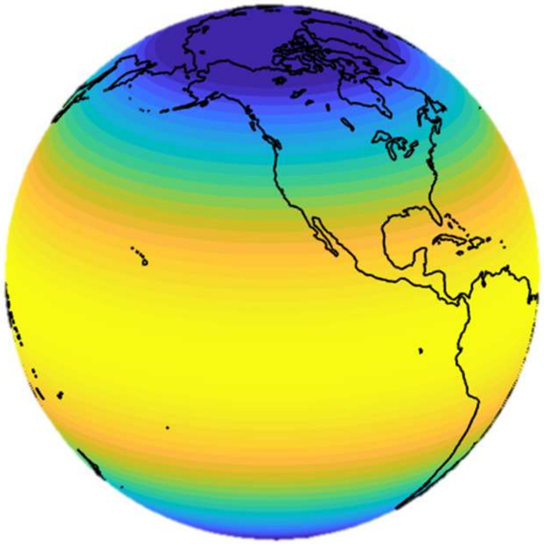

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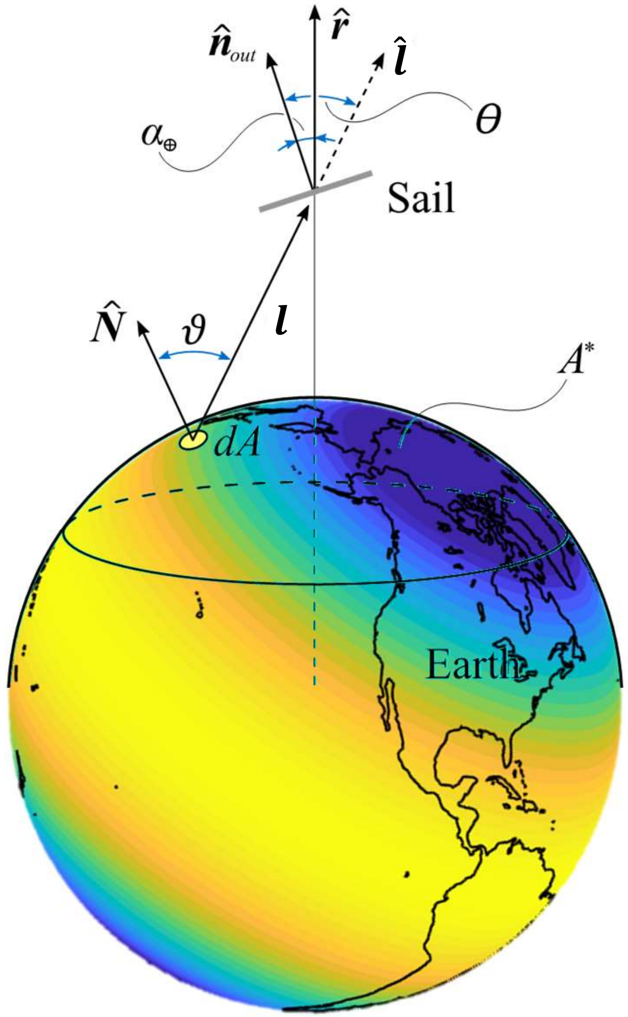
Under these assumptions, the flux defined by each piece of Earth surface irradiating the sail is found **analytically**

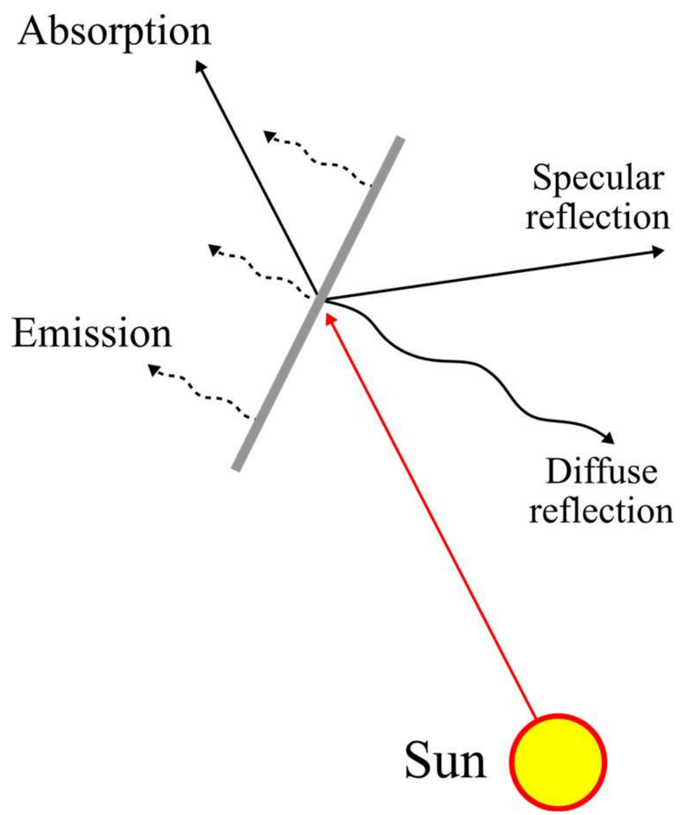


Optical PRP Acceleration Model

Optical Sail Model for PRP

- Equivalent of the optical sail model for SRP
- Accounts for:
  - Specular reflection of both sail sides
  - Diffuse reflection of both sail sides
  - Absorption of both sail sides
  - Emission, based on sail temperature

This model allows to define the acceleration contribution given by the radiation emitted by each piece of Earth surface



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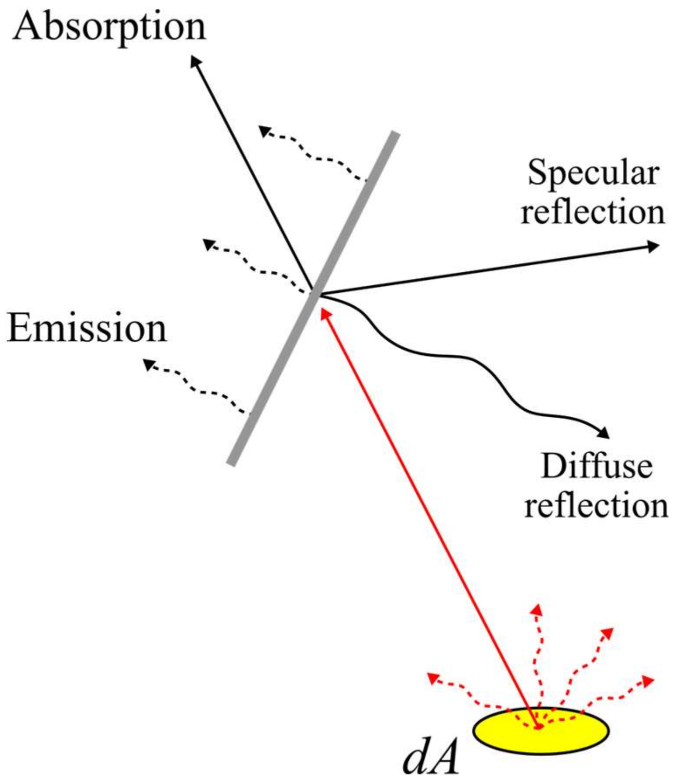

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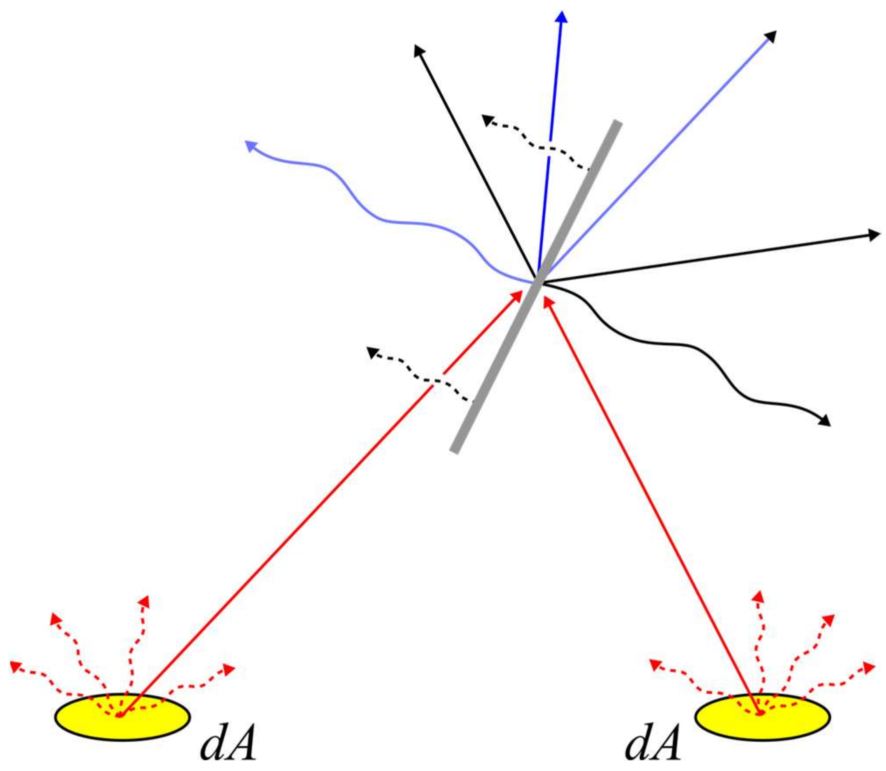

Optical PRP Acceleration Model

PRP Acceleration Integral

Spherical Radiation Source Model + Optical Sail Model → PRP acceleration

$$\boldsymbol{a}_{PRP} = \frac{S}{c\sigma\pi}\left\{ \int_{A^*} (1+\tilde{r}s)\frac{\cos(\vartheta)\cos^2(\theta)}{l^2}\hat{\boldsymbol{n}}\,dA \right.$$

→ Specular reflection & Normal absorption

$$+ \int_{A^*} \tilde{r}(1-s)B\frac{\cos(\vartheta)\cos(\theta)}{l^2}\hat{\boldsymbol{n}}\,dA$$

→ Diffuse reflection

$$+ \frac{\varepsilon_f B_f - \varepsilon_b B_b}{\varepsilon_f + \varepsilon_b}\int_{A^*} (1-r)\frac{\cos(\vartheta)\cos(\theta)}{l^2}\hat{\boldsymbol{n}}\,dA$$

→ Emission

$$\left. + \int_{A^*} (1-\tilde{r}s)\frac{\cos(\vartheta)\sin(\theta)\cos(\theta)}{l^2}\hat{\boldsymbol{t}}\,dA \right\}$$

→ Transversal absorption

Analytical Solution

Accuracy Analysis

Parametric Analysis on ACS3 Mission

Simulation settings:

- Circular, 715 km, Sun-sync. orbits
- Orbit-raising steering law
- Entire range of LTANs
- All Months
- Optical SRP model (a_c: 0.045 mm/s^2)
- Different PRP models

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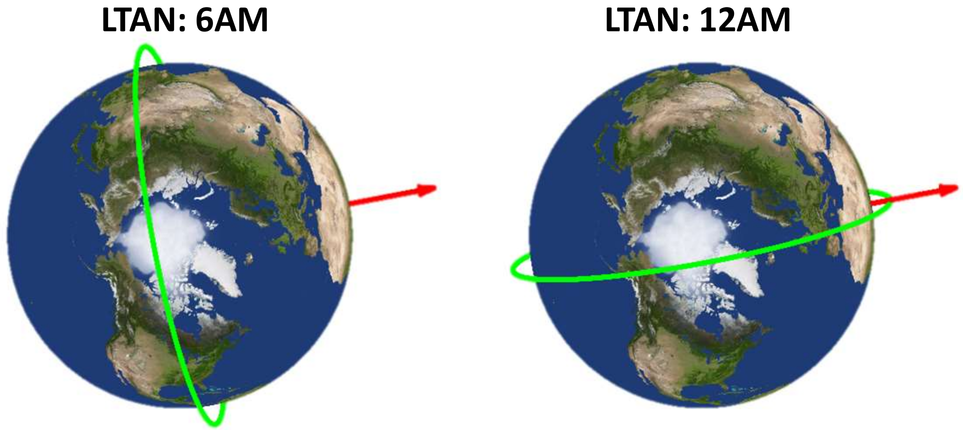

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- Entire range of LTANs
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- **Different PRP models**
  - No PRP
  - PRP with ideal sail model
  - PRP with optical sail model
  - Numerical PRP (monthly Earth radiation maps) with optical sail model

Accuracy Analysis

Parametric Analysis on ACS3 Mission

Simulation settings:

- Circular, 715 km, Sun-sync. orbits
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- Entire range of LTANs
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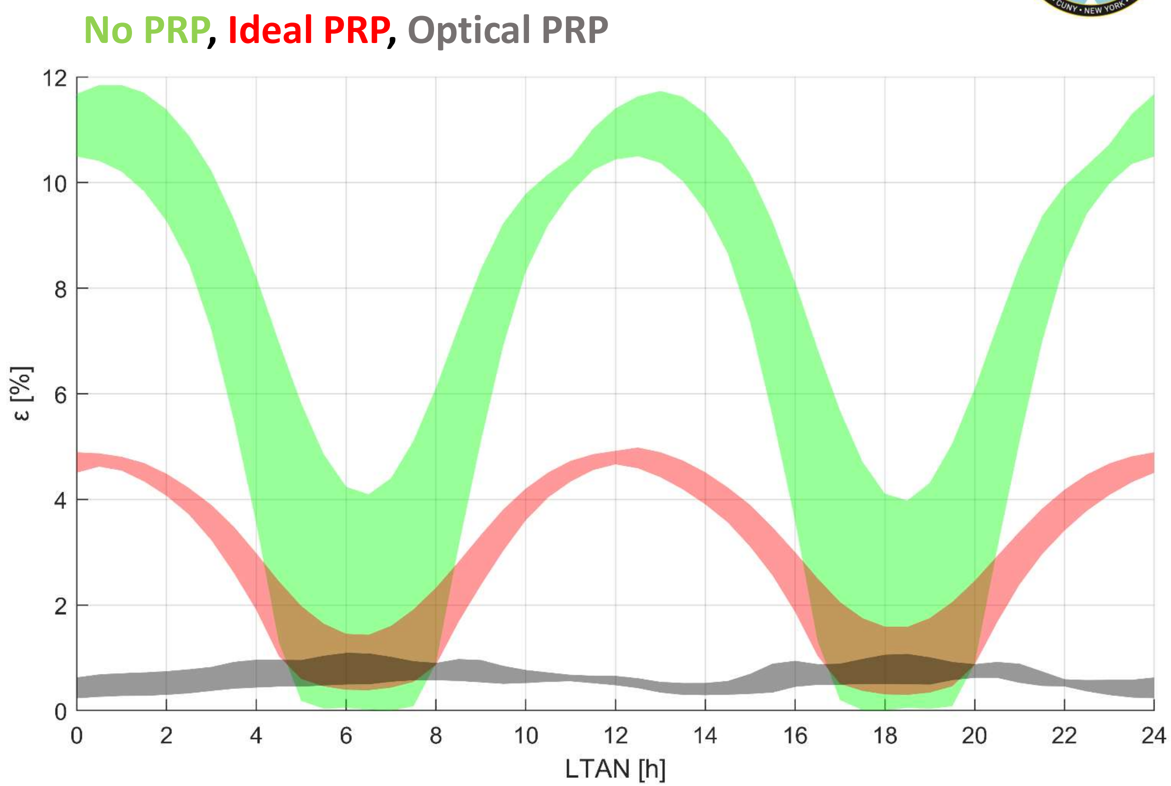
- Optical SRP model (a_c: 0.045 mm/s^2)
- Different PRP models

Comparison against numerical model:

- Max. error of No PRP model: 12%
- Max. error of Ideal PRP model: 5%
- Max. error of Optical PRP model: 1.1%



Accuracy Analysis

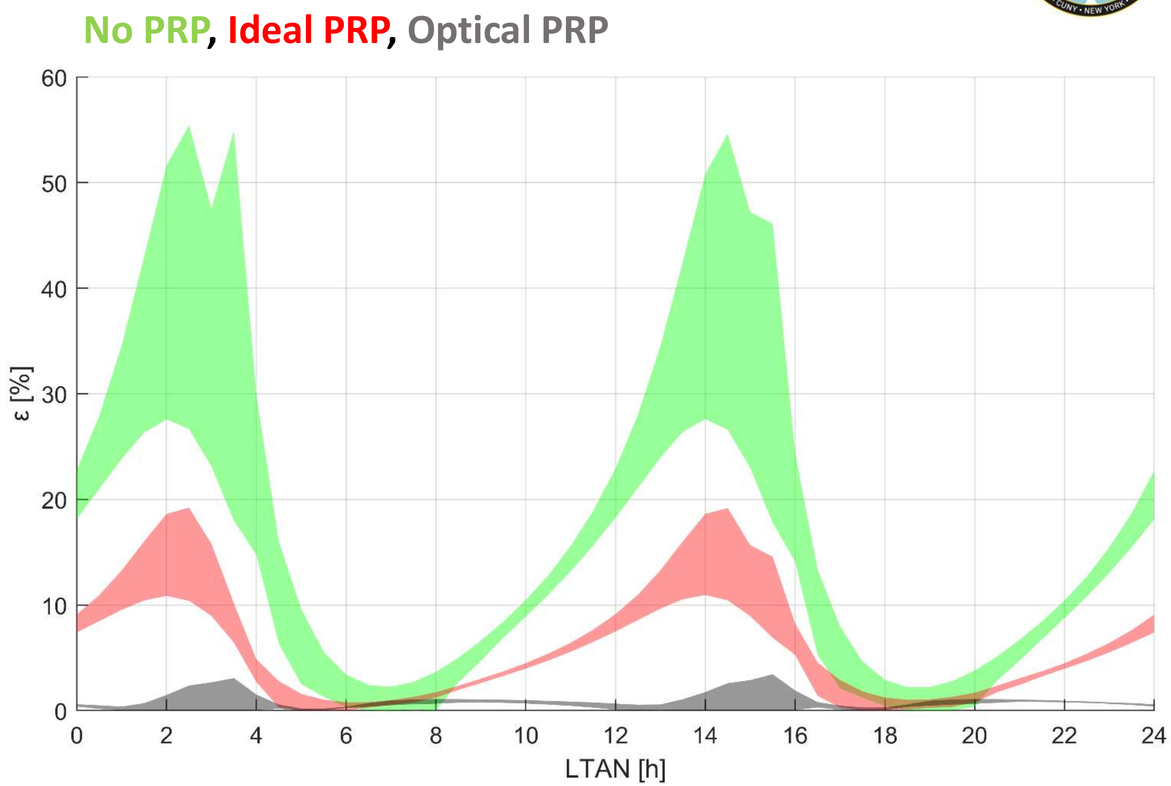
Parametric Analysis on ACS3 Mission

Simulation settings:

- Circular, 715 km, Sun-sync. orbits
- Inclination-changing steering law
- Entire range of LTANs
- All Months
- Optical SRP model (a_c: 0.045 mm/s^2)
- Different PRP models

Comparison against numerical model:

- Max. error of No PRP model: 55%
- Max. error of Ideal PRP model: 19.2%
- Max. error of Optical PRP model: 3.4%



Conclusions

- Research interest

- Pre-existing models & gap of knowledge:
  - Analytical models → Low fidelity
  - Numerical models → Accurate, but need for Earth radiation maps and computational effort

- Description of the Optical PRP Acceleration Model
  - Definition of the Spherical Radiation Source Model
  - Definition of the Optical Sail Model for PRP

- Accuracy analysis:
  - Orbit raising: Max. error of No-PRP/Optical PRP equal to 12% / 1.1%
  - Inclination changing: Max. error of No-PRP/Optical PRP equal to 55% / 3.4%
  - PRP perturbation especially for eclipsing orbits (LTAN at 12:00-14:00)

- Runtime gain: 100~150 times faster than numerical model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Andrew Heaton, Marshall Space Flight Center
Thank you for your attention
TU Delft