Solar-sail Steering Laws to Calibrate the Accelerations from Solar Radiation Pressure, Planetary Radiation Pressure, and Aerodynamic Drag

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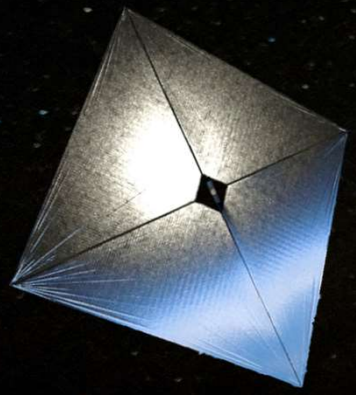

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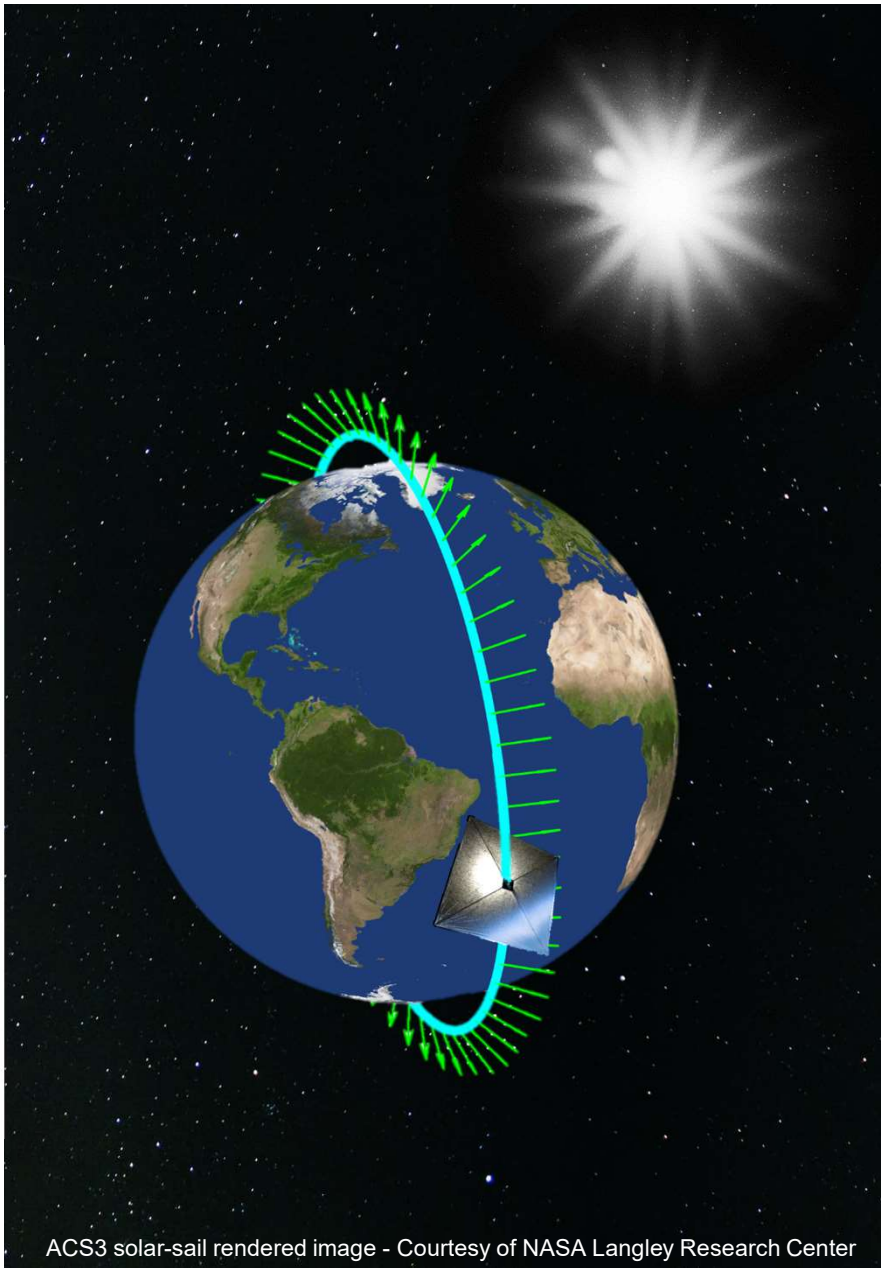
Research Interest

Available acceleration models are:

- Idealistic, based on simplifying assumptions, e.g.:
  - Sail shape
  - Optical characteristics
  - Near-Earth dynamical environment
- Deterministic, without uncertainties
- Need for calibration:
  - Determine real-life sailcraft performance
  - Allow updates of models and mission design



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

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  - Aerodynamic drag
- Design of Calibration Steering Laws
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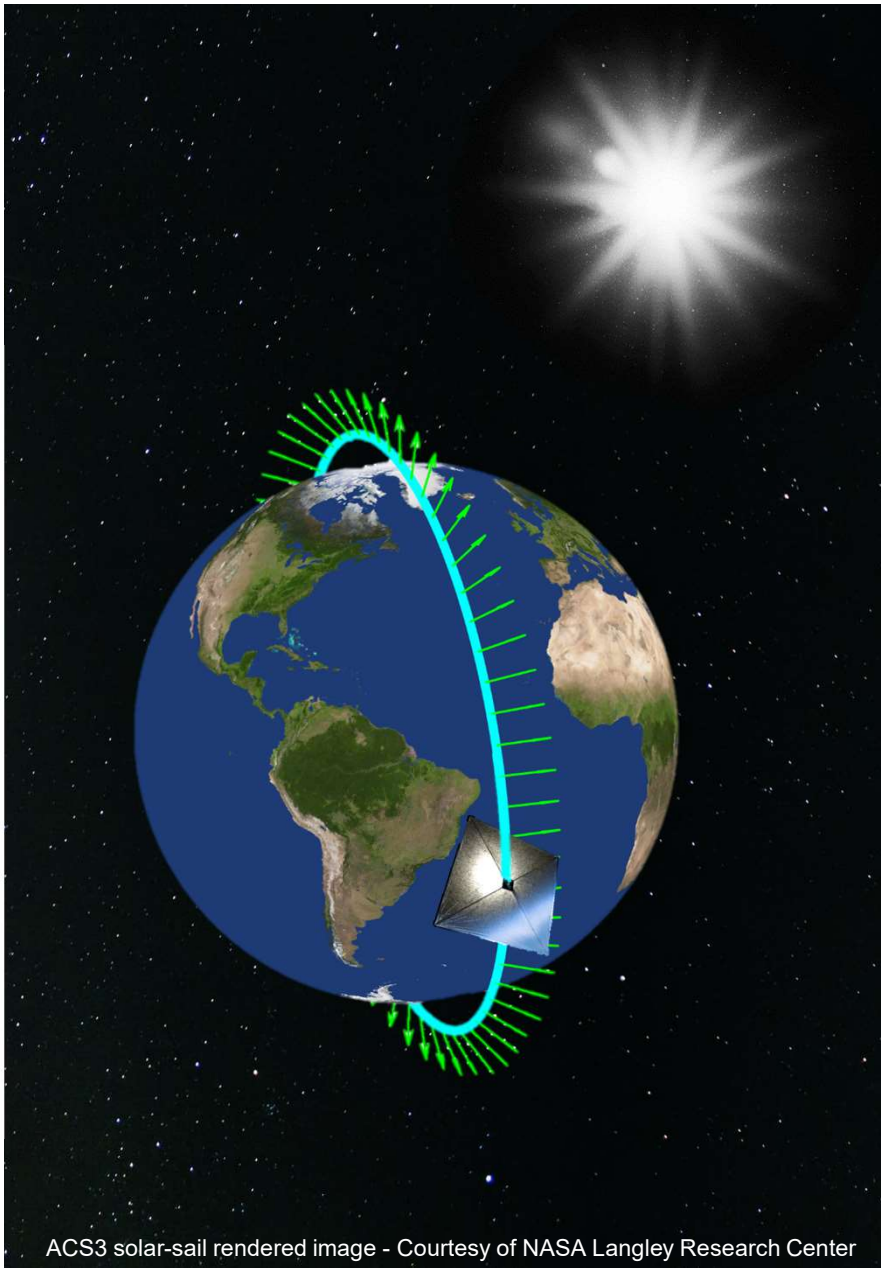
  - Characterization of acceleration envelopes
  - Characterization of residual accelerations
- Analyses
  - Operational constraints and challenges
  - Results
- Conclusions



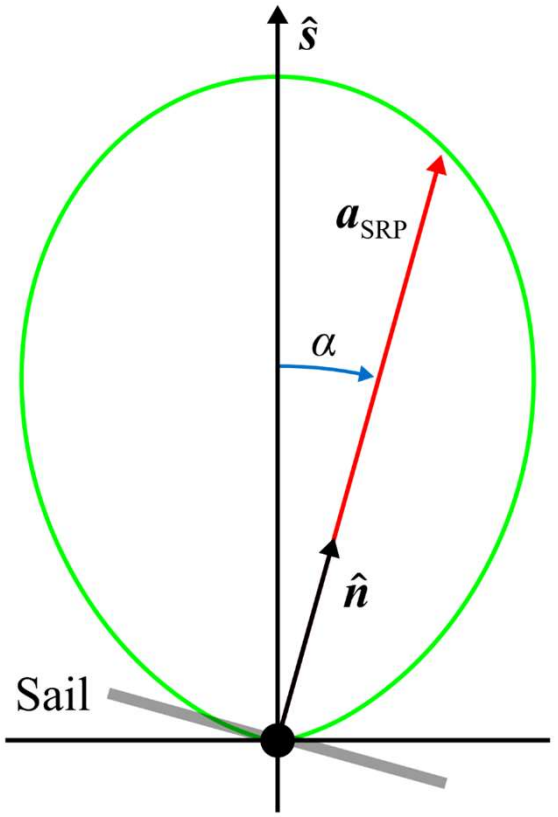
ACS3 solar-sail rendered image - Courtesy of NASA Langley Research Center

Solar-Sail Acceleration Envelope Curves

AE curve: Set of all accelerations achievable by a sail by changing its attitude

For each acceleration there exist:

- Specific AE shape
- Specific reference direction (attitude of max. acceleration)
  - SRP: sunlight direction

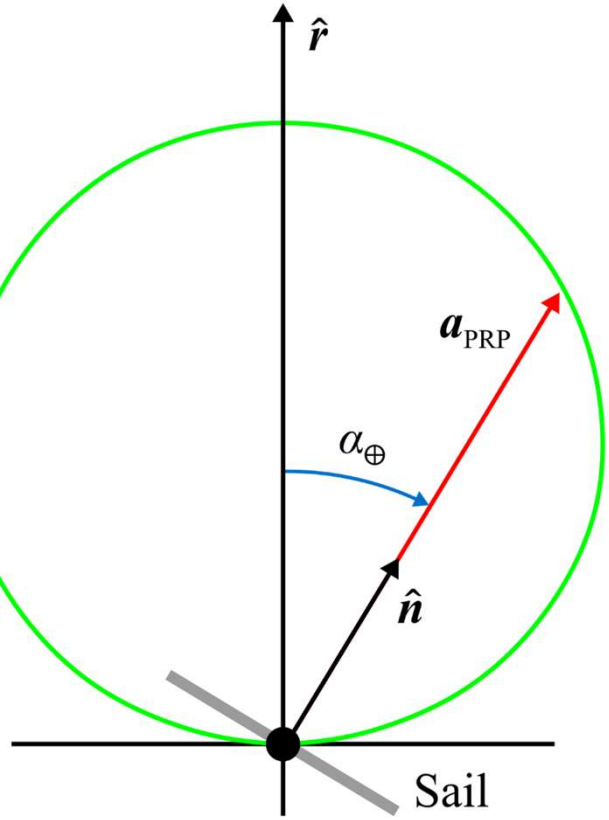


Solar-Sail Acceleration Envelope Curves

AE curve: Set of all accelerations achievable by a sail by changing its attitude

For each acceleration there exist:

- Specific AE shape
- Specific reference direction (attitude of max. acceleration)
  - SRP: sunlight direction
  - PRP: radial direction

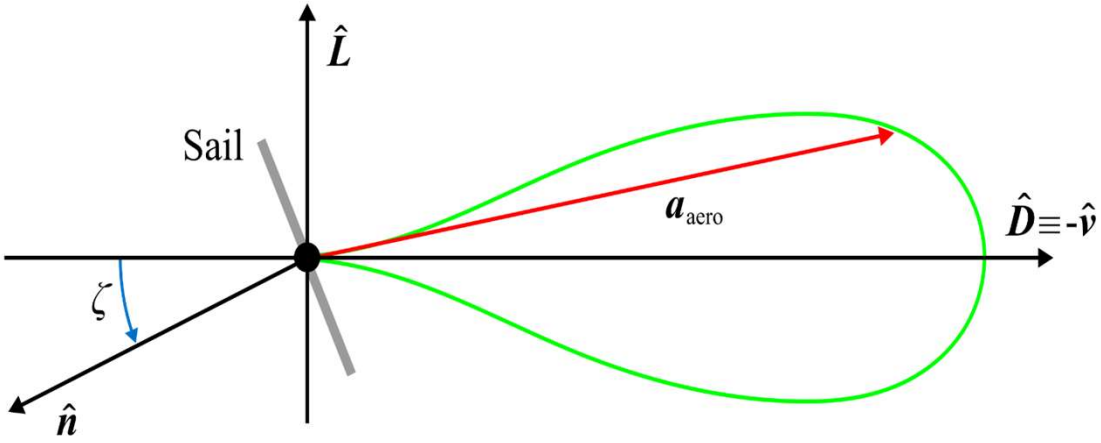


Solar-Sail Acceleration Envelope Curves

AE curve: Set of all accelerations achievable by a sail by changing its attitude

For each acceleration there exist:

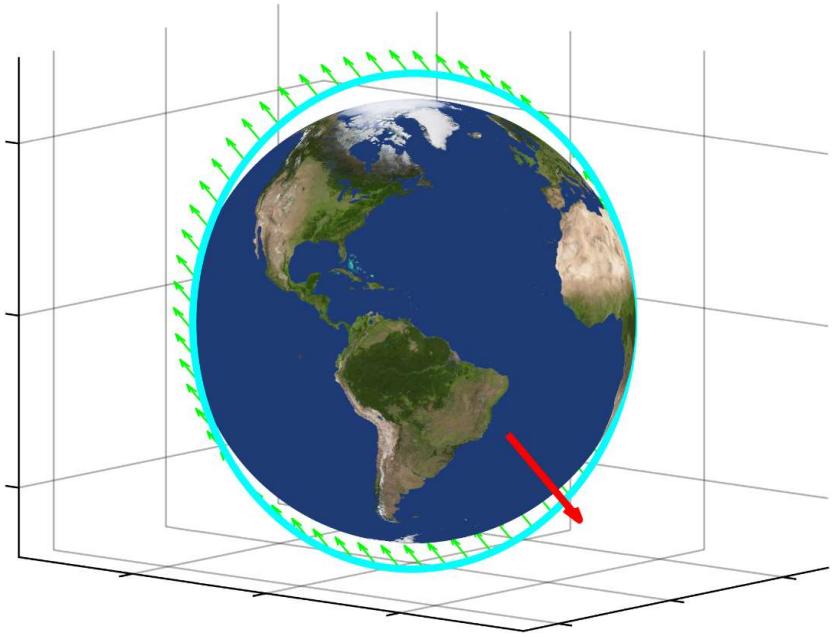
- Specific AE shape
- Specific reference direction (attitude of max. acceleration)
  - SRP: sunlight direction
  - PRP: radial direction
  - Drag: velocity direction



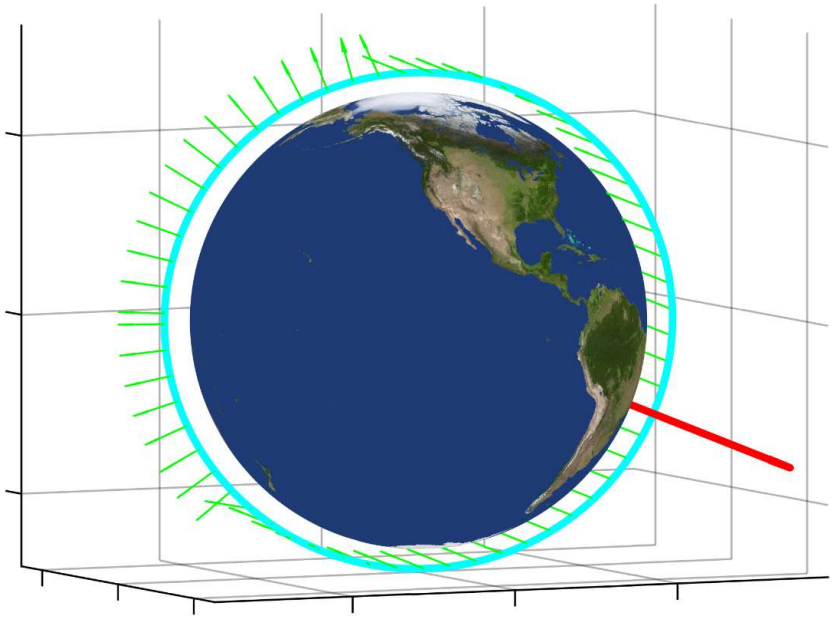
Design of Calibration Steering Laws

Characterization of Maximum SRP Acceleration

LTAN: 6AM



LTAN: 12AM



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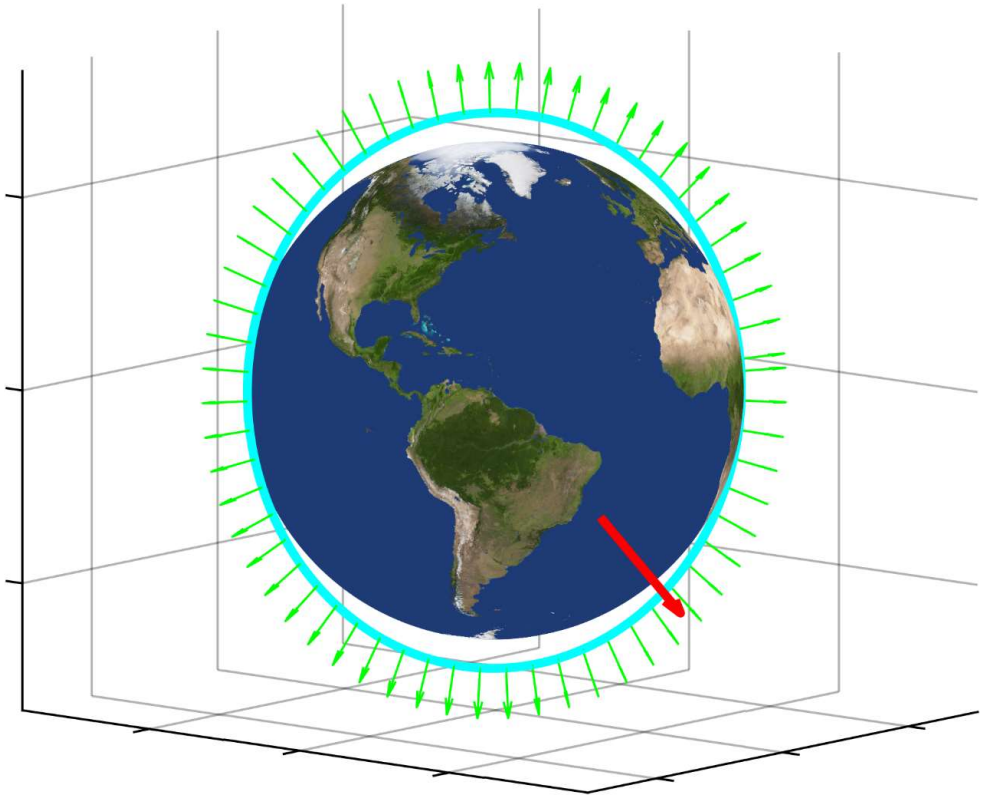
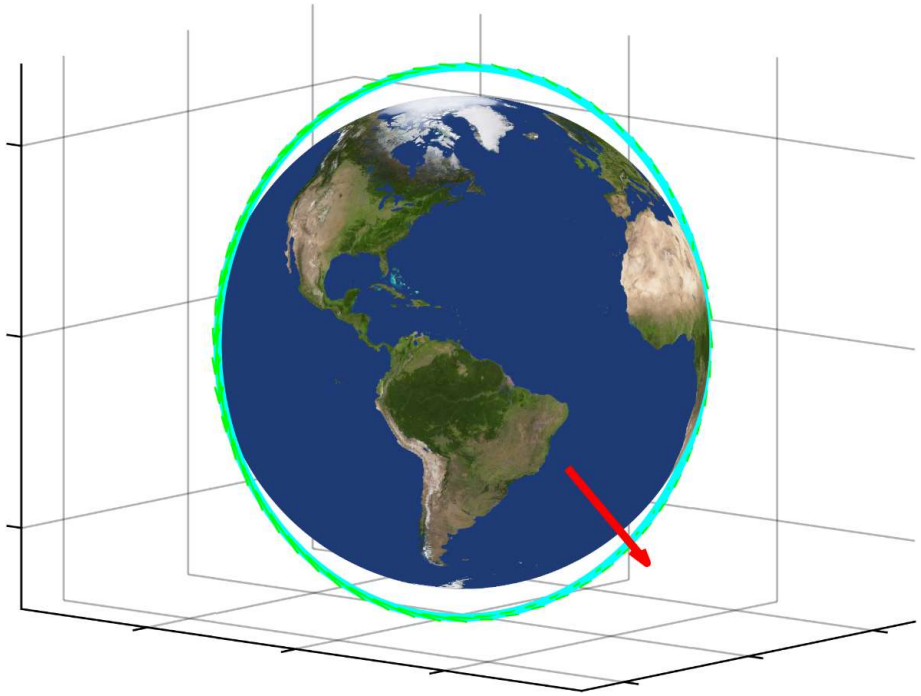
Design of Calibration Steering Laws

Characterization of Maximum PRP Acceleration



Design of Calibration Steering Laws

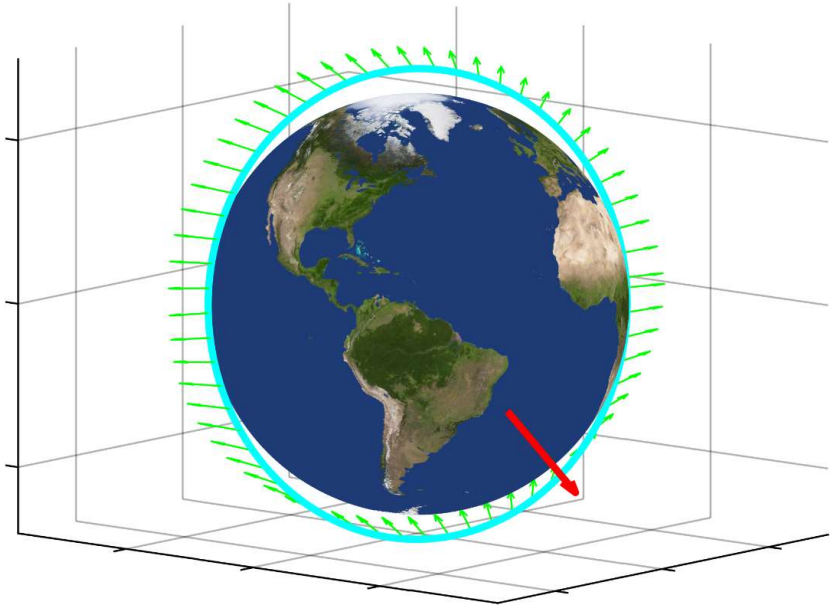
Characterization of Maximum Aerodynamic Acceleration



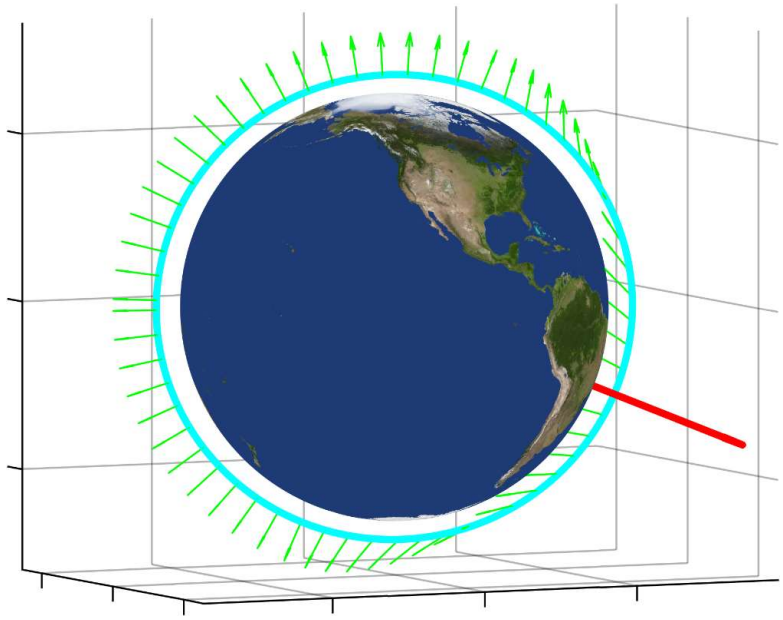
Design of Calibration Steering Laws

Characterization of SRP Acceleration Envelope Curve

LTAN: 6AM

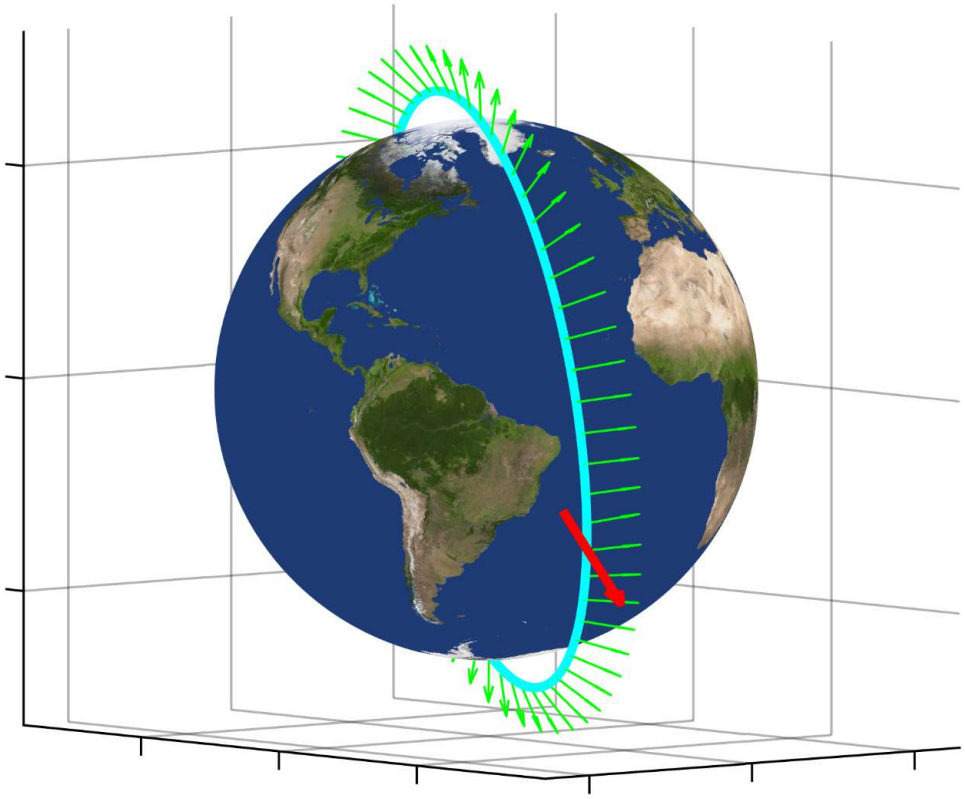


LTAN: 12AM



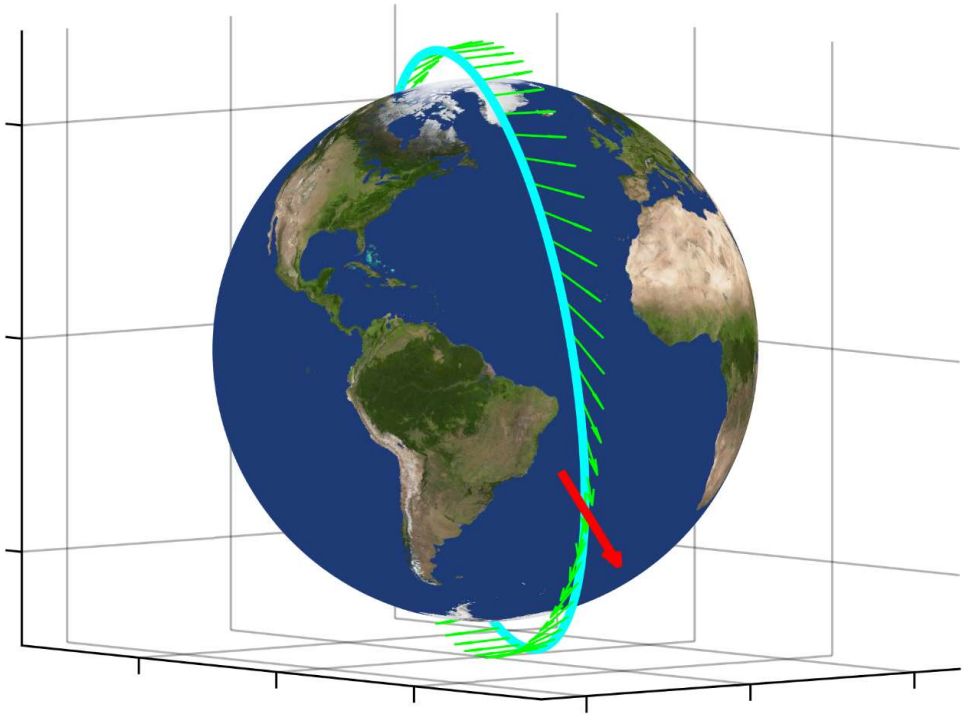
Design of Calibration Steering Laws

Characterization of PRP Acceleration Envelope Curve



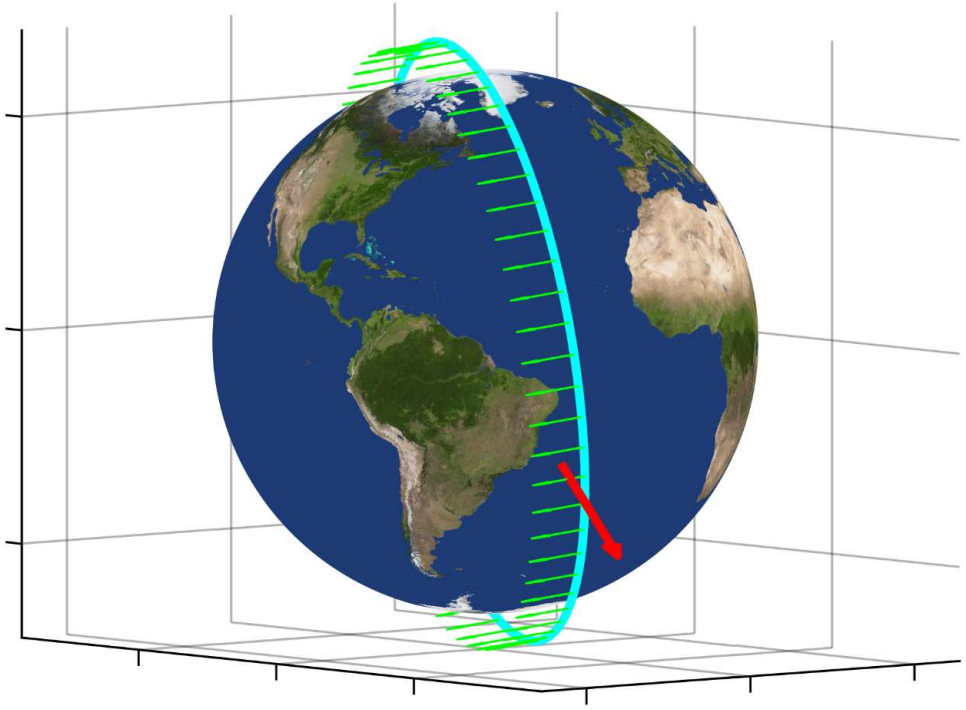
Design of Calibration Steering Laws

Characterization of Aerodynamic Acceleration Envelope Curve



Design of Calibration Steering Laws

Characterization of Residual Accelerations



Analyses

Operational Constraints & Challenges

- Altitude loss
- Sailcraft max. attitude rate of change → Attitude control system capabilities
- Exposure of sail's back side to:
  - Sunlight
  - Ram direction (atomic oxygen)

  → Sail material degradation
- Lack of illumination of solar cells → Power generation issues
- Interference due to other accelerations → Challenging calibration

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Analyses

Simulation Settings: ACS3 Mission

- Circular, 715 km, Sun-synchronous orbits
- LTANs: 6AM, 9AM, 12AM
- Start date: Dec 1st, 2023 (expected deployment date)
- Duration: 10 days

- Entire set of calibration steering laws
- Max. attitude RoC: 0.5 deg/s

- Characteristic acceleration: 0.045 mm/s^2
- Dynamics: Central gravity + J2
  Ideal SRP acceleration
  Ideal PRP acceleration (spherical Earth radiation model)
  Aerodynamic acceleration (NRLMSISE-00)

Results

CSL	Initial LTAN	Calibration Target (Perturbation)			Δh [km]	Max. Attitude RoC [deg/s]	Sail's Back Side Exposure [% orbital period]		Solar Cells' Exposure to Sunlight ($\alpha \leq 80$ deg) [% orbital period]
		SRP Acc.	PRP Acc.	Aerodyn. Acc.			Sunlight	Ram direction	
Max. SRP Acc.	6 AM	**Max**	(Minor)	(Minor)	7.656	0	0	50	83.18
	9 AM	**Max**	(Intermediate)	(Intermediate)	9.736	0.5	0	36.08	68.21
	12 AM	**Max**	(Full)	(Full)	12.106	0.5	0	34.23	64.34
Max. PRP Acc.	6 AM	(Minor)	**Max**	(Zero)	0.013	0.061	50	0	21.87
	9 AM	(Intermediate)	**Max**	(Zero)	0.016	0.061	50	0	11.27
	12 AM	(Full)	**Max**	(Zero)	0.012	0.061	50	0	08.75
Max. Aerodyn Acc.	6 AM	(Minor)	(Zero)	**Max**	36.985	0.061	41.63	0	36.00
	9 AM	(Intermediate)	(Zero)	**Max**	36.705	0.061	34.06	0	30.61
	12 AM	(Full)	(Zero)	**Max**	36.440	0.061	32.21	0	29.27
SRP AE Curve	6 AM	**Full**	(Full)	(Intermediate)	8.379	0.061	0	50	71.99
	9 AM	**Full**	(Full)	(Intermediate)	8.308	0.061	0	25	55.60
	12 AM	**Full**	(Full)	(Full)	9.282	0.061	0	25	53.24
PRP AE Curve	6 AM	(Full)	**Full**	(Zero)	0.006	0.086	50	0	28.93
	9 AM	(Intermediate)	**Full**	(Zero)	0.013	0.086	50	0	14.13
	12 AM	(Intermediate)	**Full**	(Zero)	0.007	0.086	48.36	0	08.41
Aerodyn. AE Curve	6 AM	(Full)	(Zero)	**Full**	17.961	0.096	41.63	0	39.53
	9 AM	(Intermediate)	(Zero)	**Full**	19.193	0.086	34.07	0	32.13
	12 AM	(Intermediate)	(Zero)	**Full**	19.594	0.086	32.05	0	21.70
Residual Acc.	12 AM	**Zero**	**Zero**	**Zero**	0.002	0	0	0	0

Results

Calibration of SRP Acceleration

- Moderate loss in altitude
- Less severe disturbance from PRP and drag for LTAN at 6AM
- Sail back side in ram direction
- Large attitude RoC (mitigation)

CSL	Initial LTAN	Calibration Target (Perturbation)			Δh [km]	Max. Attitude RoC [deg/s]	Sail's Back Side Exposure [% orbital period]		Solar Cells' Exposure to Sunlight ($\alpha \leq 80$ deg) [% orbital period]
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Residual Acc.	12 AM	**Zero**	**Zero**	**Zero**	0.002	0	0	0	0

Results

Calibration of PRP Acceleration

- No loss in altitude (drag is decoupled)
- Severe disturbance from SRP for increasing LTANs
- Sail back side exposure to sunlight
- Power generation issues (solar cells facing the Earth)

CSL	Initial LTAN	Calibration Target (Perturbation)			Δh [km]	Max. Attitude RoC [deg/s]	Sail's Back Side Exposure [% orbital period]		Solar Cells' Exposure to Sunlight ($\alpha \leq 80$ deg) [% orbital period]
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Residual Acc.	12 AM	Zero	Zero	Zero	0.002	0	0	0	0

Results

Calibration of Aerodynamic Acceleration

- Severe loss in altitude
- Severe disturbance from SRP for increasing LTANs
- No disturbance from PRP (PRP is decoupled)
- Sail back side exposure to sunlight
- Possible power generation issues

CSL	Initial LTAN	Calibration Target (Perturbation)			Δh [km]	Max. Attitude RoC [deg/s]	Sail's Back Side Exposure [% orbital period]		Solar Cells' Exposure to Sunlight ($\alpha \leq 80$ deg) [% orbital period]
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Residual Acc.	12 AM	Zero	Zero	Zero	0.002	0	0	0	0

Results

Calibration of Residual Accelerations

- No major issues except for power generation

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Residual Acc.	12 AM	Zero	Zero	Zero	0.002	0	0	0	0

Conclusions

- Research interest
- Definition of the acceleration envelope curves and reference directions
- Design of calibration steering laws:
  - Characterization of maximum accelerations
  - Characterization of acceleration envelope curves
- Operational Constraints & Challenges
  - Altitude decrease
  - Attitude control system capabilities
  - Sail degradation
  - Power generation issues
- Analyses:
  - SRP calibration: feasible, better for LTAN at 6AM, sail back side exposed to ram direction
  - PRP calibration: feasible for a short period, power generation issues
  - Drag calibration: feasible for a short period, large altitude loss
  - Residual accelerations' calibration: major power generation issues

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