The NASA Advanced Composite Solar Sail System (ACS3) Flight Demonstration: A Technology Pathfinder for Practical Smallsat Solar Sailing

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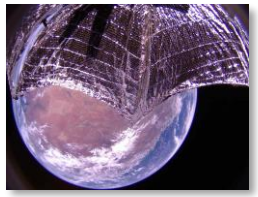
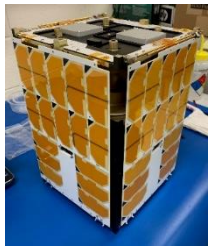
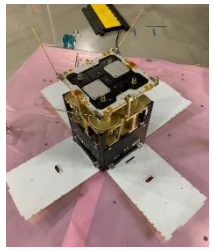
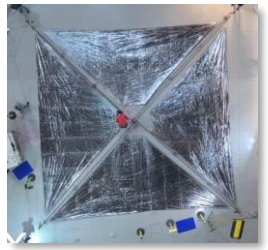
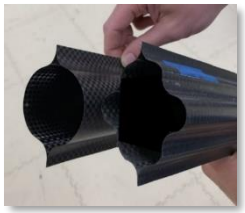
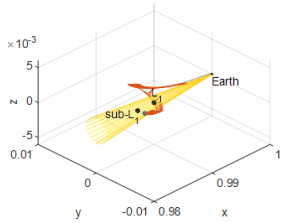
Overview

- Motivation and Background
  - *Metallic deployable booms and solar sails*
- NASA Deployable Composite Boom (DCB) technology
- The Advanced Composite Solar Sail System (ACS3) technology demonstrator
  - *ACS3 Flight Systems*
  - *ACS3 Mission*
  - *Extensibility to Future Small Sat Solar Sail Missions*
- Summary/Status

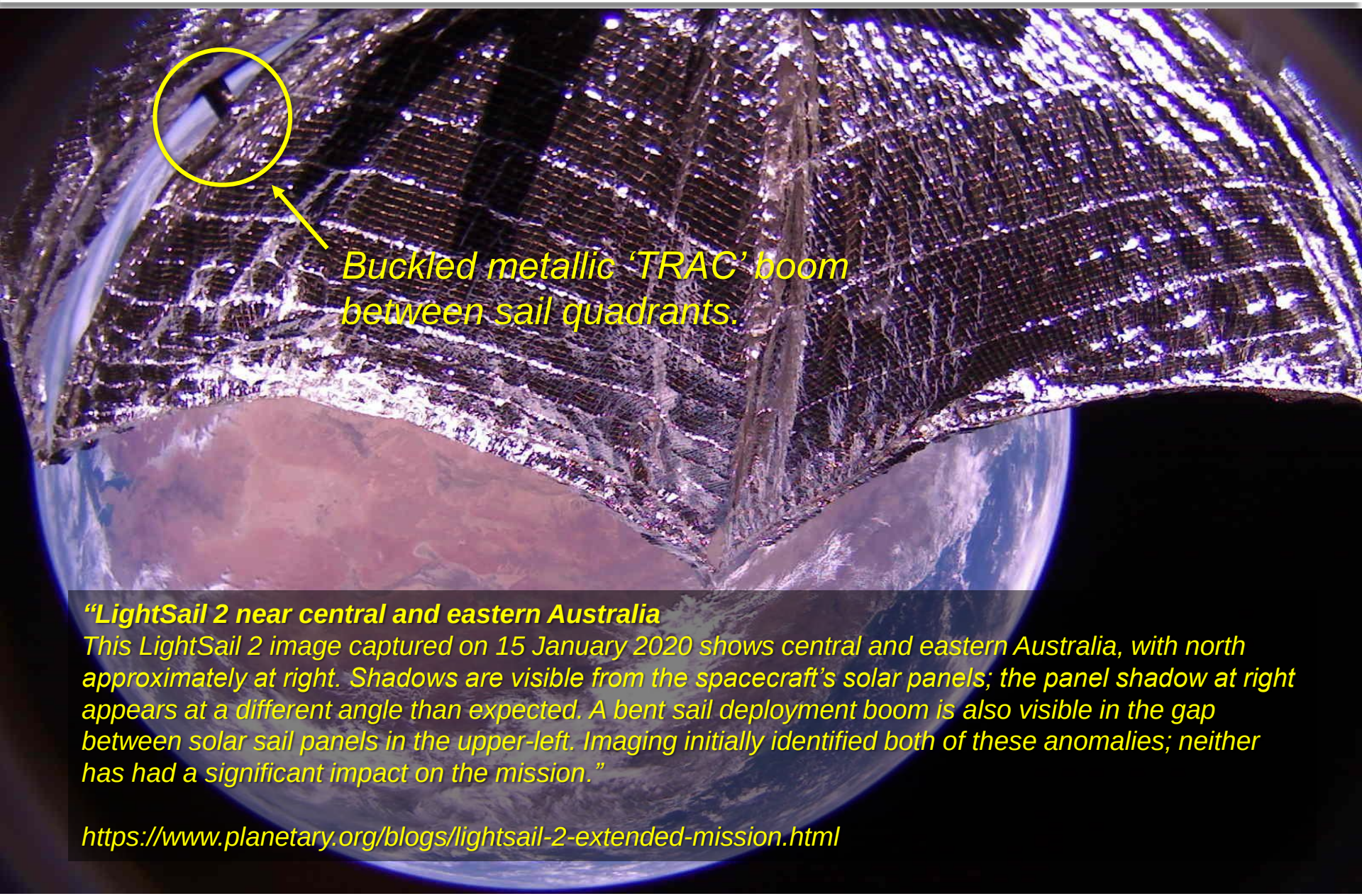



LightSail 2 Update: Boom Buckling Anomaly

ref: The Planetary Society, 17 June 2020



"LightSail 2 near central and eastern Australia

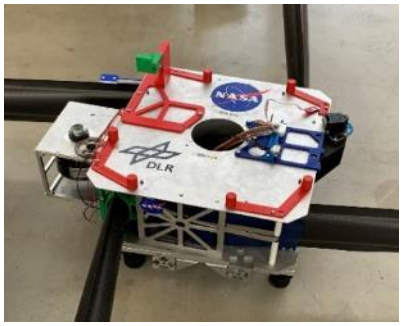
This LightSail 2 image captured on 15 January 2020 shows central and eastern Australia, with north approximately at right. Shadows are visible from the spacecraft's solar panels; the panel shadow at right appears at a different angle than expected. A bent sail deployment boom is also visible in the gap between solar sail panels in the upper-left. Imaging initially identified both of these anomalies; neither has had a significant impact on the mission."

https://www.planetary.org/blogs/lightsail-2-extended-mission.html

NASA Deployable Composite Boom Project (DCB)

Developing high performance deployable composites for small sat applications

- **The Deployable Composite Booms project (DCB) was begun in 2017 to advance manufacturing and flight readiness of compact deployable composite booms:**
  - Sponsor: NASA Space Technology Mission Directorate (STMD) Game Changing Development Program
  - Collaboration between NASA and German Aerospace Research Agency (DLR).
- **Benefits:**
  - High bending and torsional stiffness.
    - *Closed cross-section can carry high compression loads, minimizing risk of collapse.*
  - High packaging efficiency.
    - *Ideal for small volume spacecraft.*
  - High thermal stability.
    - *Insensitive to thermal distortions.*
  - Low weight.
    - *< 25% mass of comparable metallic booms.*
  - Scalable.
    - *DCB/ACS3 7-m boom technology is extensible to 14-m to 16.5-m deployable boom lengths.*
- ***The Advanced Composite Solar Sail project (ACS3) will demonstrate DCB composite boom technology for solar sailing applications.***



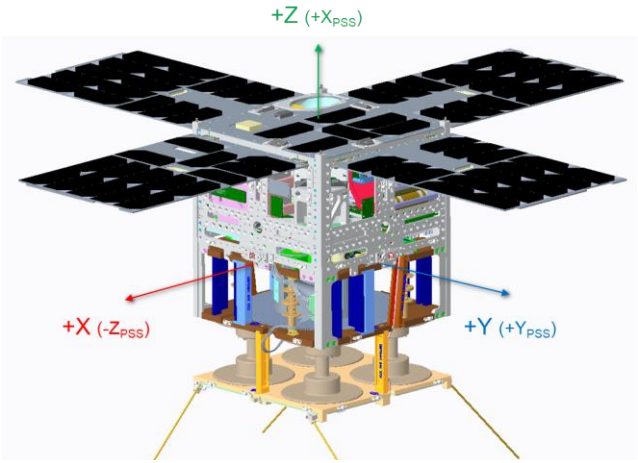
https://gameon.nasa.gov/projects/deployable-composite-booms-dcb/

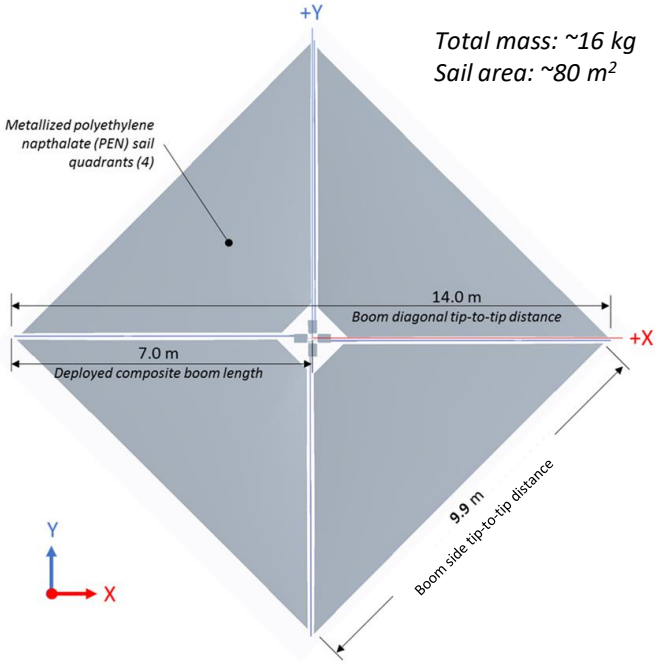
Advanced Composite Solar Sail System Project (ACS3)

LEO Solar Sail Structures Technology Demonstration [20210620]

- ***ACS3 is a low-Earth orbit (LEO) flight demonstration of a composites-based small-sat solar sail propulsion system.***
  - **Sponsor: STMD Small Spacecraft Technology Program (SSTP)**
  - **Composite Technology: STMD Game Changing Development Program (GCDP), Deployable Composite Booms Project (DCB)**
  - **NPR 7120.8 Research & Tech. Demonstration Project**
- **Launch: 1 July – 31 December 2022**
  - **Orbit: 715 km x 715 km altitude to minimize aerodynamic drag; sun-synchronous orbit preferred; mid-inclination orbit acceptable.**
- **Objectives:**
  - **Primary**: ***On-orbit deployment and characterization of a smallsat-class composite solar sail propulsion system.***
  - **Secondary**: ***Demonstrate controlled solar sailing flight (e.g., SMA-raising/lowering) in LEO; Characterize deployed structural dynamics.***
- **Partner roles and responsibilities:**
  - **NASA Ames Research Center** – ACS3 payload control avionics, sail diagnostic camera system, and payload FSW.
  - **NASA Langley Research Center** –ACS3 solar sail system payload.
  - **NanoAvionics US**- 12U Spacecraft bus.
  - **Santa Clara University Robotic Systems Lab** – CubeSat operations support.
- ***ACS3 architecture is scalable to future larger solar sails.***

ACS3 12U Spacecraft and Deployed Solar Sail





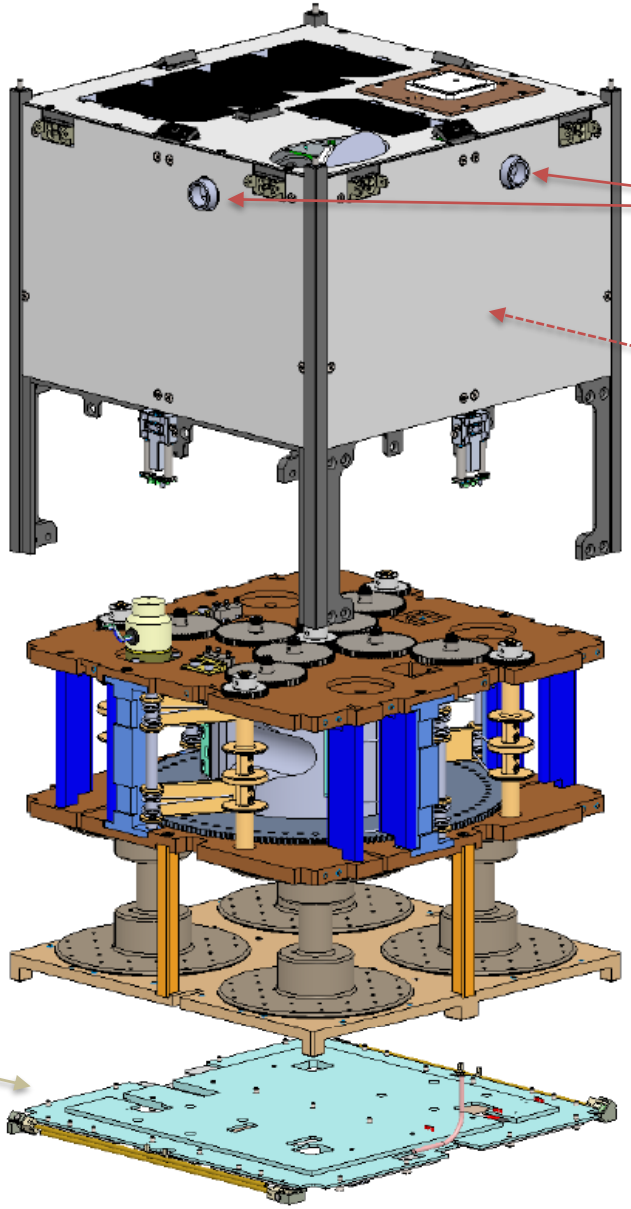
ACS3: 12U Spacecraft Subsystems

[solar panels, UHF antennas, sail quadrants, and booms omitted]

NASA ARC

NASA LaRC

AST-NanoAvionics



Spacecraft Bus:

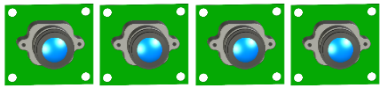
- S-band transceiver
- UHF radio
- Flight computer
- ADCS
  - Reaction wheels (4)
  - Magnetorquers (3 x 3-axis)
  - Sun sensors (5)
  - GPS receiver
  - Star tracker
  - IMU
- EPS

Sail-Boom Subsystem: (SBS)

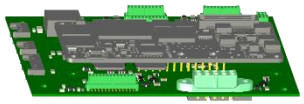
Spacecraft bus "-Z" plate:

- Pop-up UHF antennas (4)
- S-band antenna patches (2)
- Sun sensor (1)

Payload Avionics System: (AS)



AS sail diagnostic cameras (4)



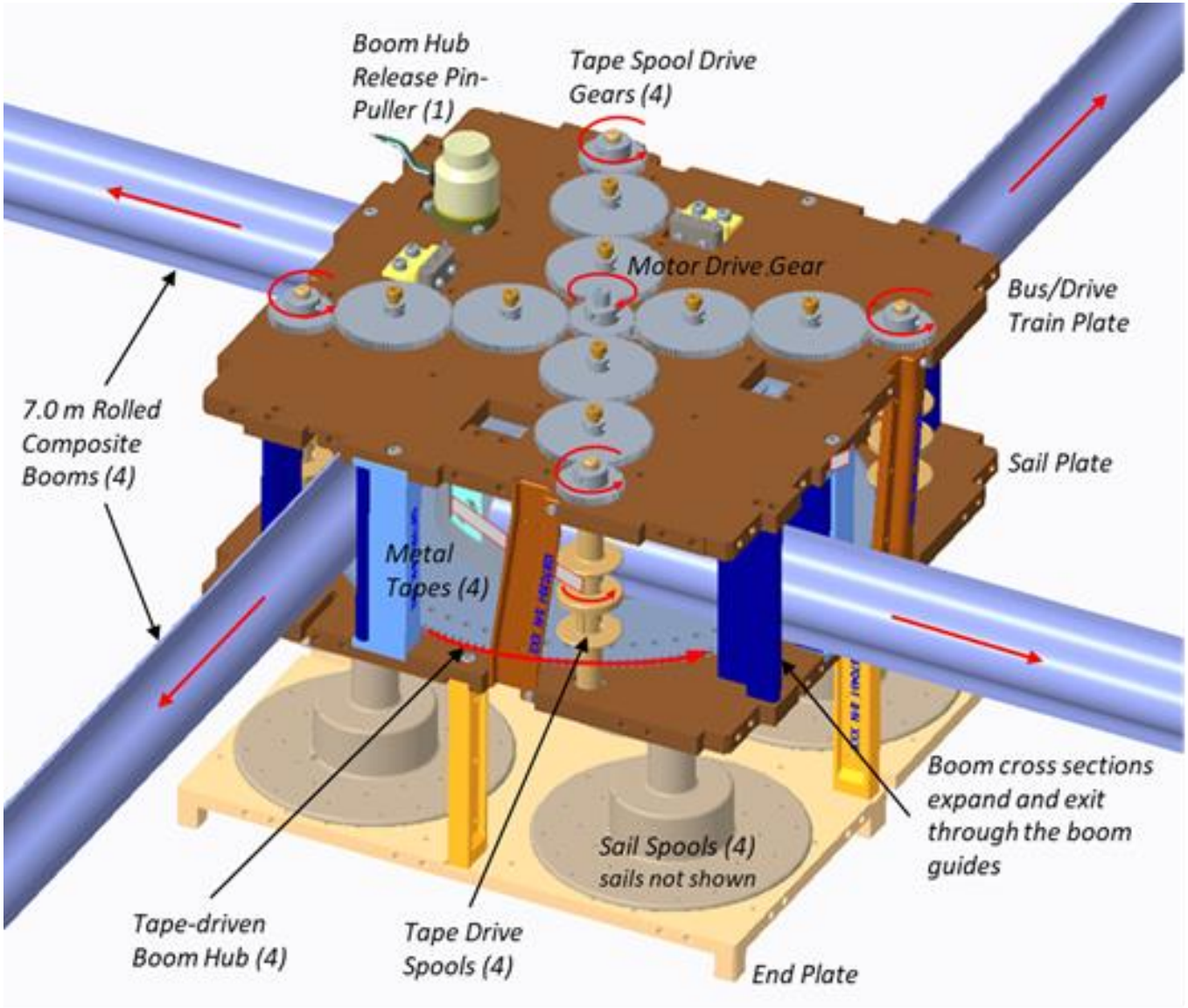
AS payload control electronics

- Board included with spacecraft bus avionics stack.
- Controls sail diagnostic cameras and SBS.

SBS composite boom deployer

SBS solar sail quadrant stowage

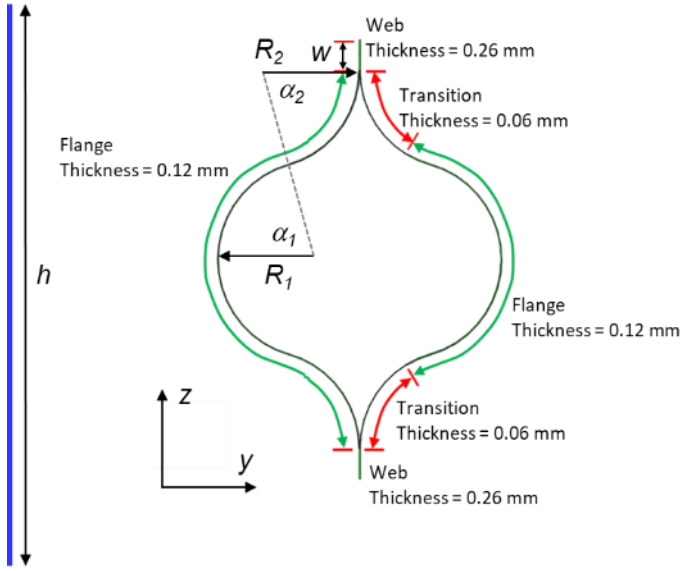
ACS3: Sail-Boom Subsystem Deployer Design



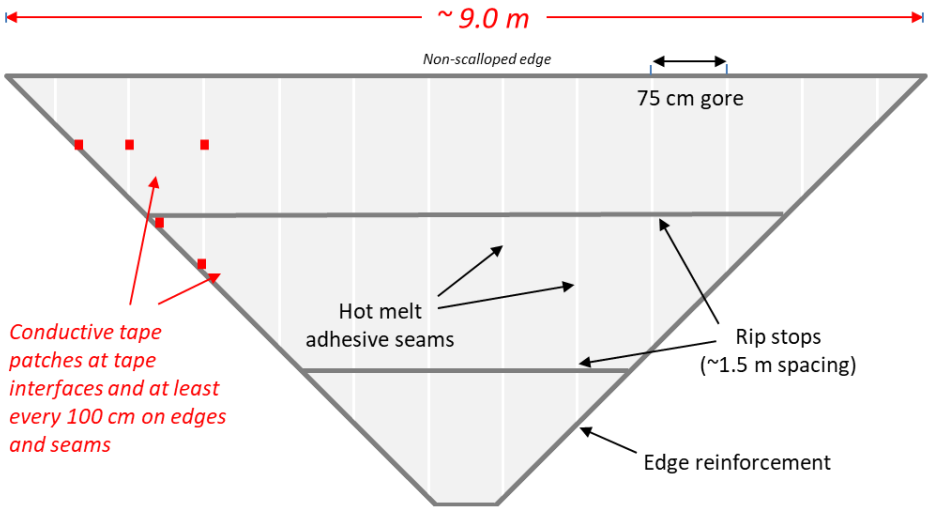
ACS3: Deployable Composite Boom Design

- ACS3 uses ***collapsible tubular mast*** (CTM) composite booms developed by the NASA STMD/GCDP Deployable Composite Booms (DCB) project.
- ACS3 booms are 7.0 m long.
  - Cross-section geometry:
    - Flattened height, *h*: 65 ± 0.5 mm
    - Expanded CS geometry:
      - CS width: 33.0 mm, height: 49.9 mm
      - Web height, *w*: 3.5 - 4 mm
  - Laminate Properties:
    - Web [45PW/0-90PW/45PW]
      - $E_{11} = E_{22} = 5.23e+07\ mN/mm^2$
    - Flange [45PW/0-90PW]
      - $E_{11} = E_{22} = 3.76e+07\ mN/mm^2$
    - Transition [45PW]
      - $E_{11} = E_{22} = 1.46e+07\ mN/mm^2$
- Optimized for minimum coiling diameter and high deployed stiffness.
  - Minimum safe coiling diameter: 115 mm.
  - ACS3 boom hub diameter: 120 mm.
- Fabricated by NASA Langley.

Individual Boom Mass: 164 g

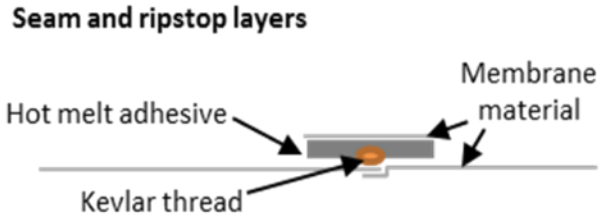


ACS3: Solar Sail Quadrant Design and Fabrication

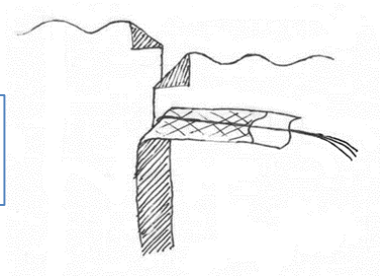


Quadrant Design

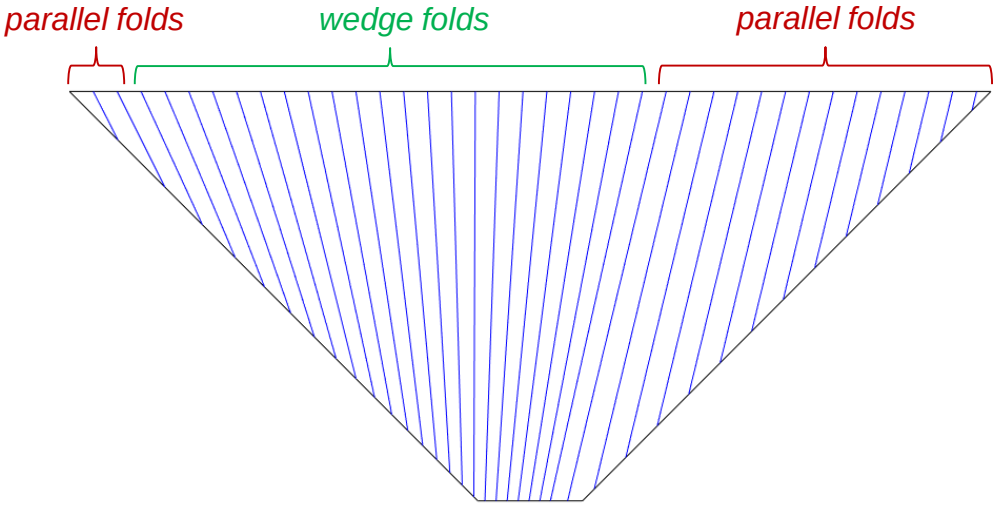
Individual Quadrant Mass (w/ hardware): 85 g



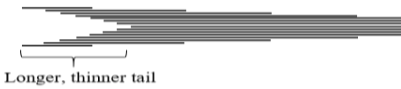
Flight membrane material: 2.115 μm Al/PEN/Cr



Seam detail



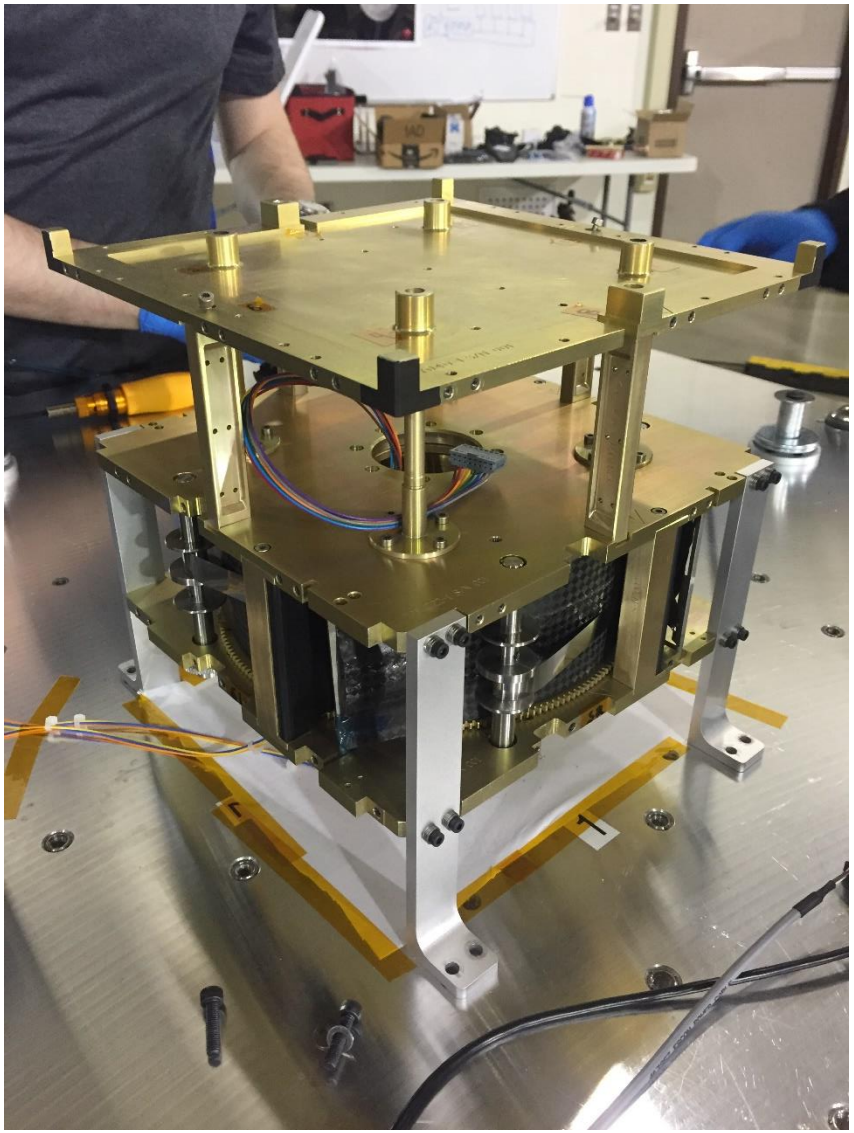
Quadrant folding scheme



Quadrant spooled for stowing

ACS3: Boom Packaging

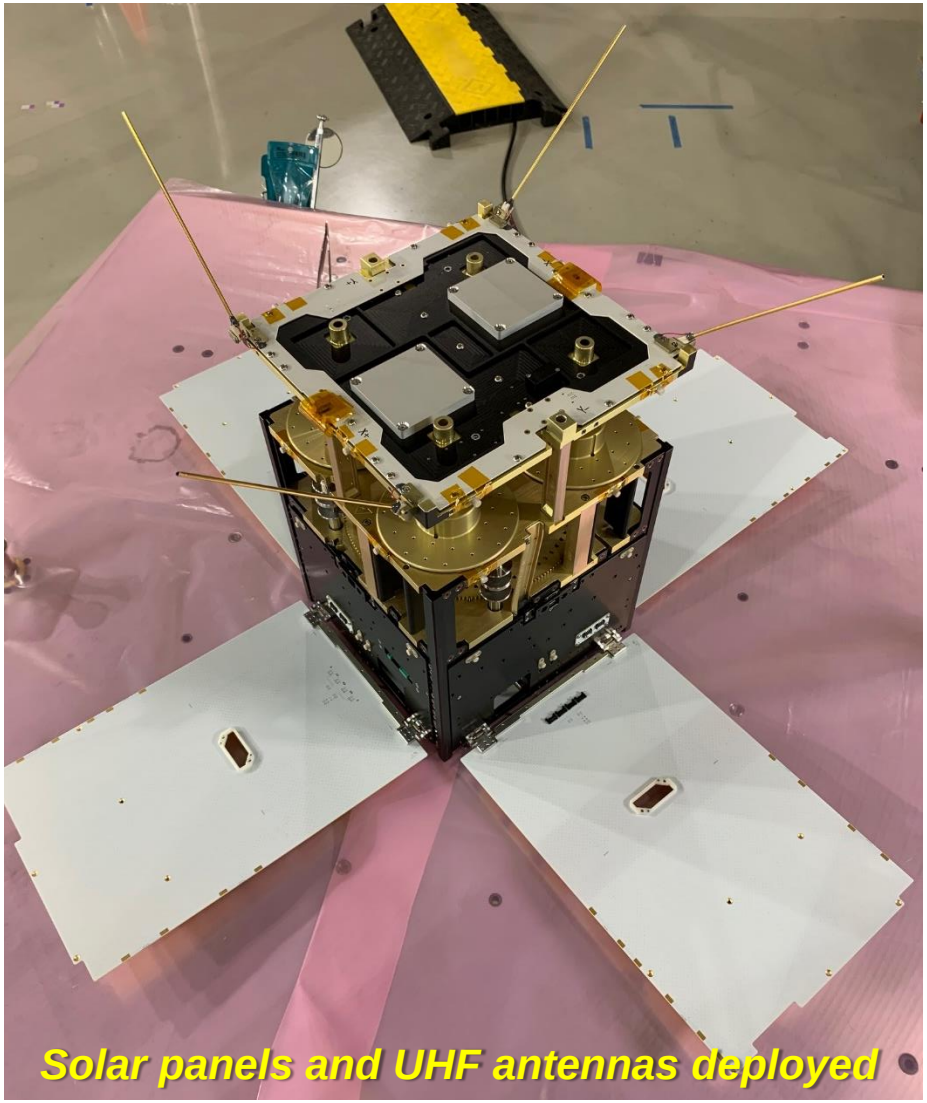
Boom reeling and packaging MGSE



SBS Flight Unit with Development Booms

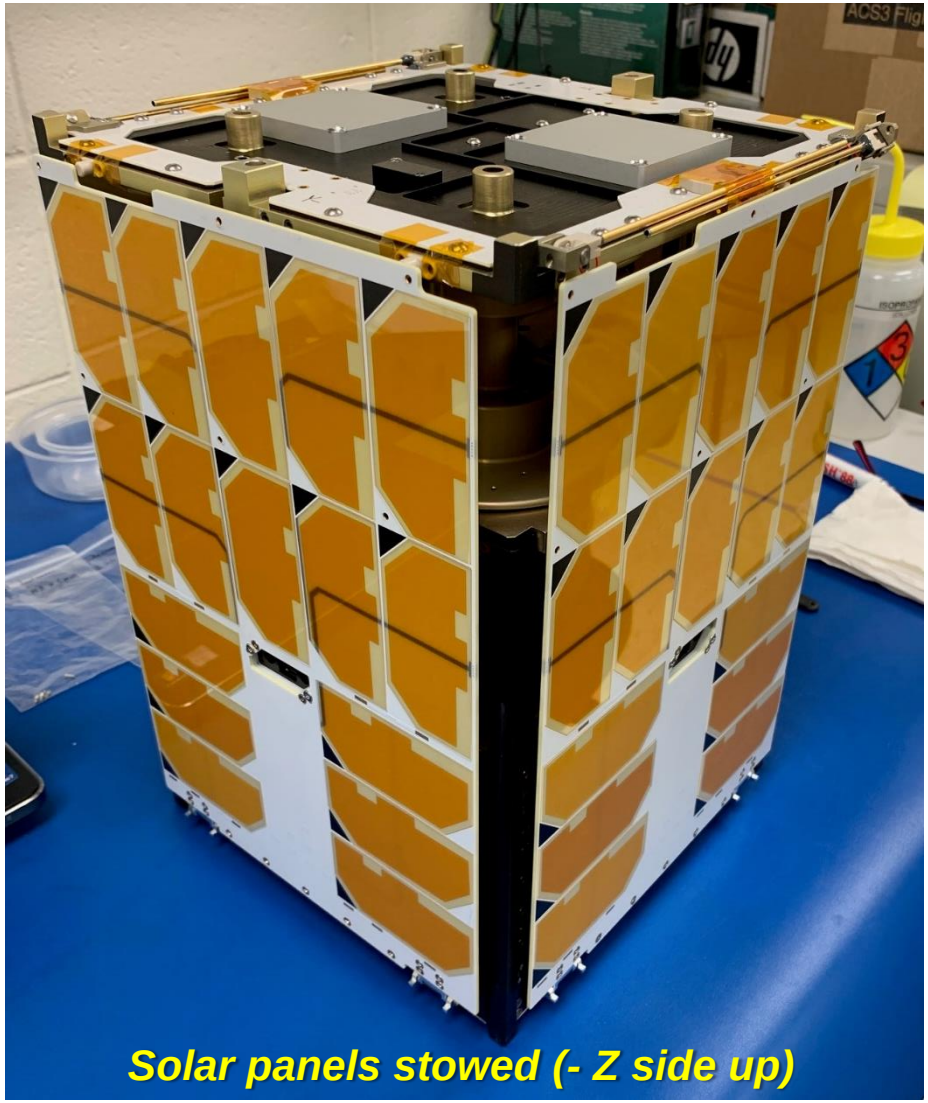
ACS3: SBS Flight Unit w/ Bus Structural Model – Solar Panels Stowed/Deployed *–Z side up*

Pre-Sail Deployment Configuration



Solar panels and UHF antennas deployed

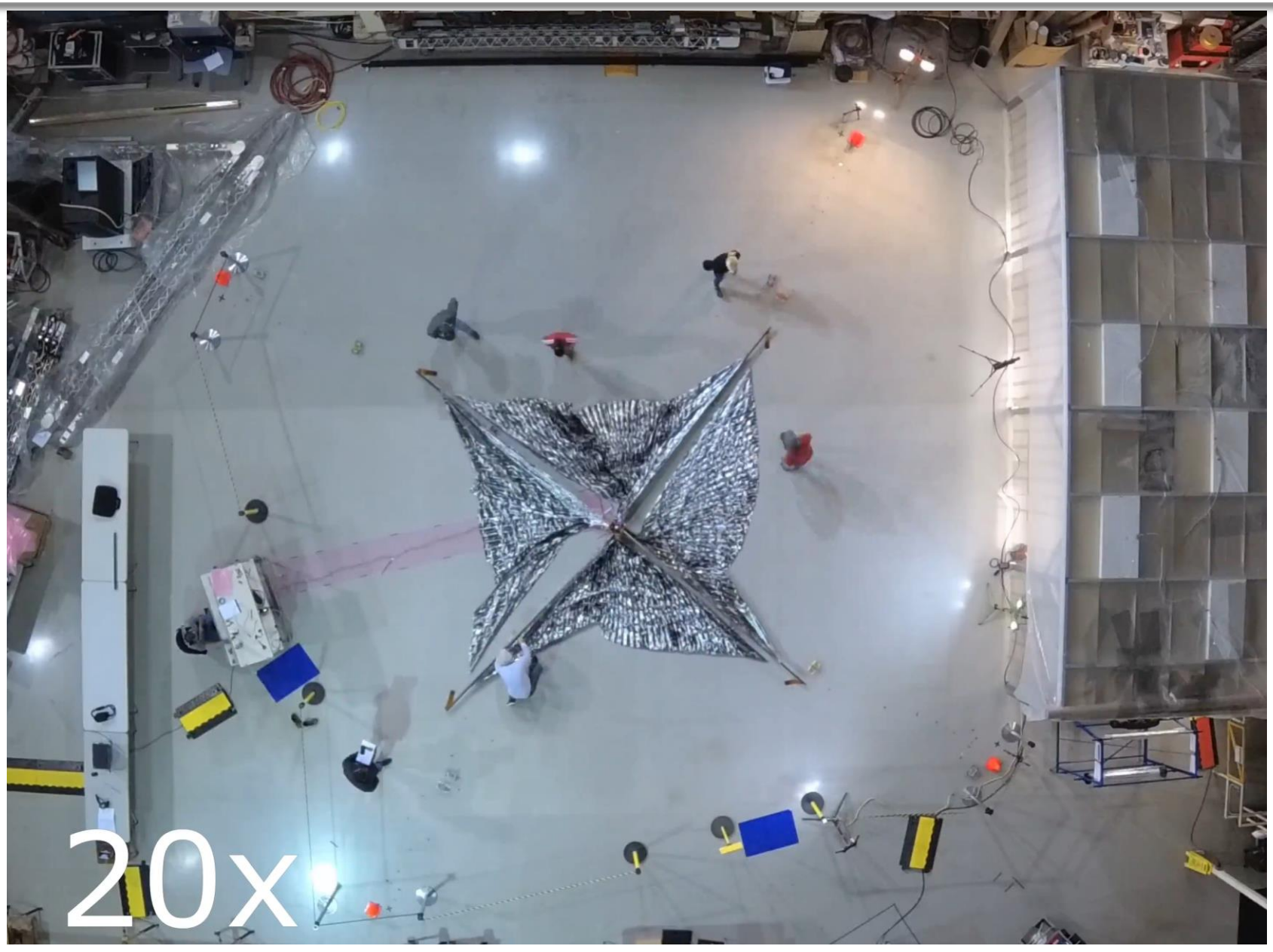
Launch Configuration



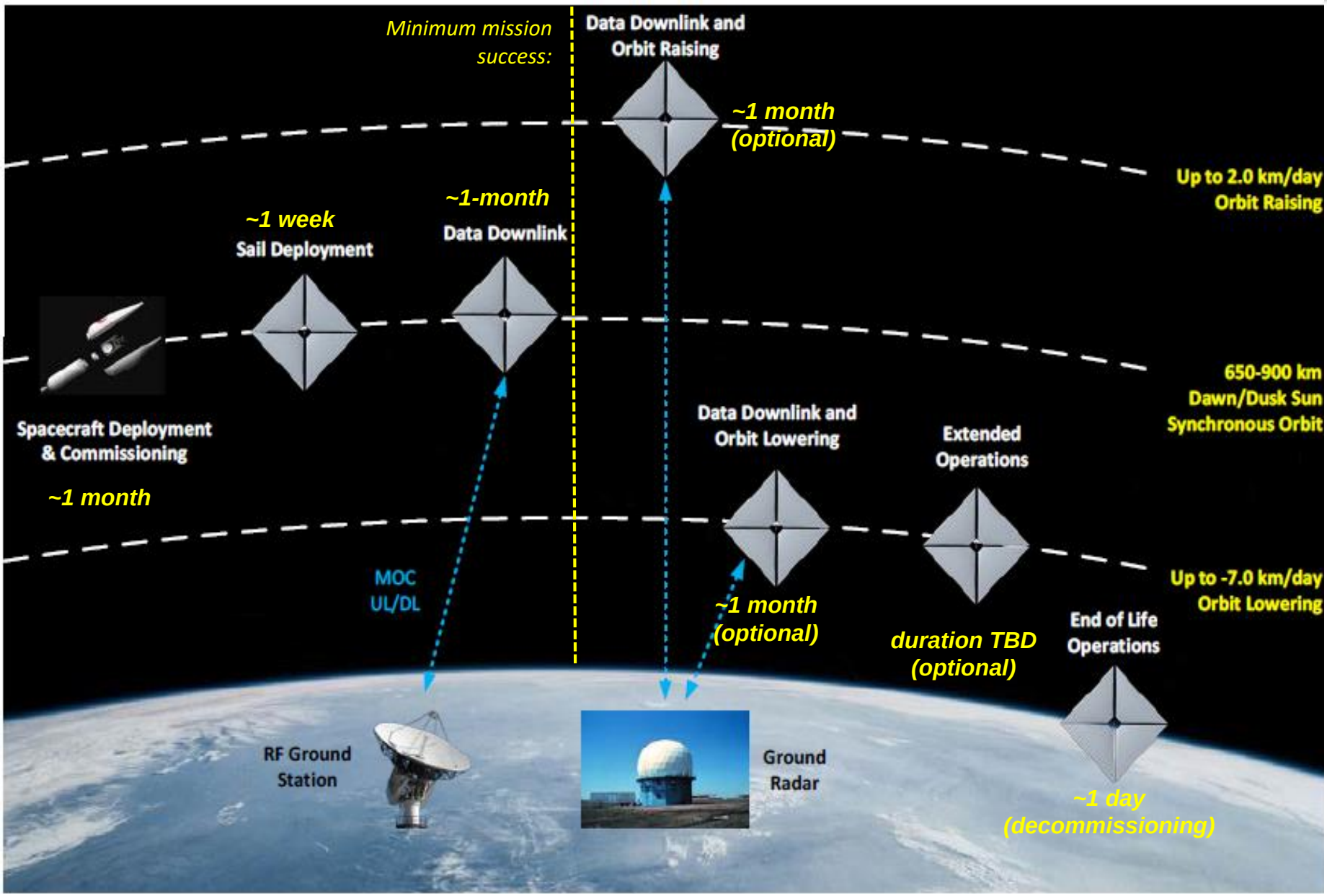
Solar panels stowed (- Z side up)

SBS Prototype Deployment Testing w/ Development Sails

Deployment Test #6, 1x tensioning springs **** Deployment time: 26 minutes ****



ACS3: Technology Demonstration Concept of Operations



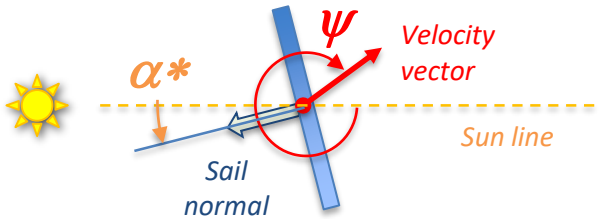
SMA Raising/Lowering Sail Steering Profile [ref: McInnes, 1999]

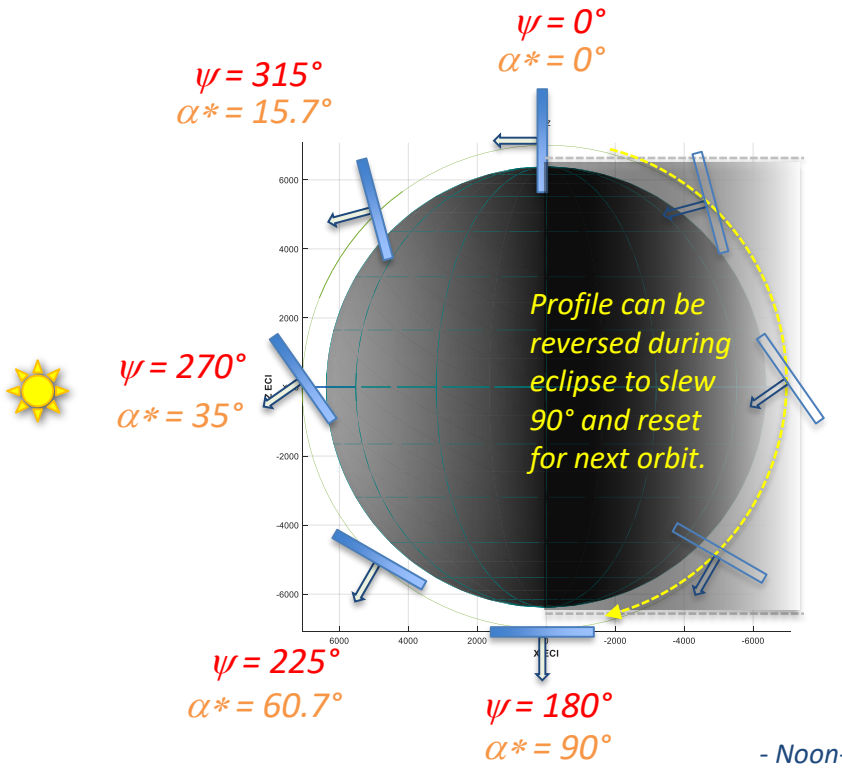
- **Locally optimal steering law for maximum energy gain/loss each orbit.**
  - Sail oriented at all times to maximize solar radiation thrust component in direction of flight.
  - For lowering, thrust component opposite direction of flight is maximized.

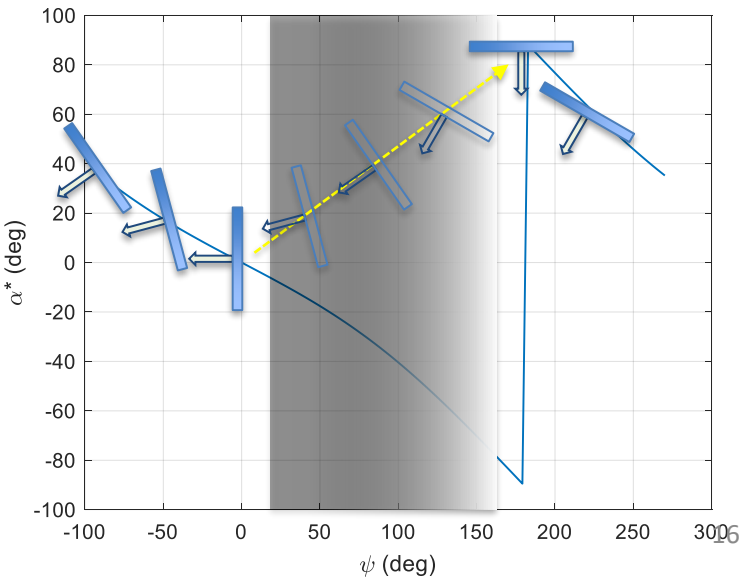
Locally optimal sail pitch angle.

Angle of velocity vector with respect to sun line.

$$\alpha^* = \frac{1}{2}\left[\psi - \sin^{-1}\left(\frac{\sin\psi}{3}\right)\right]$$



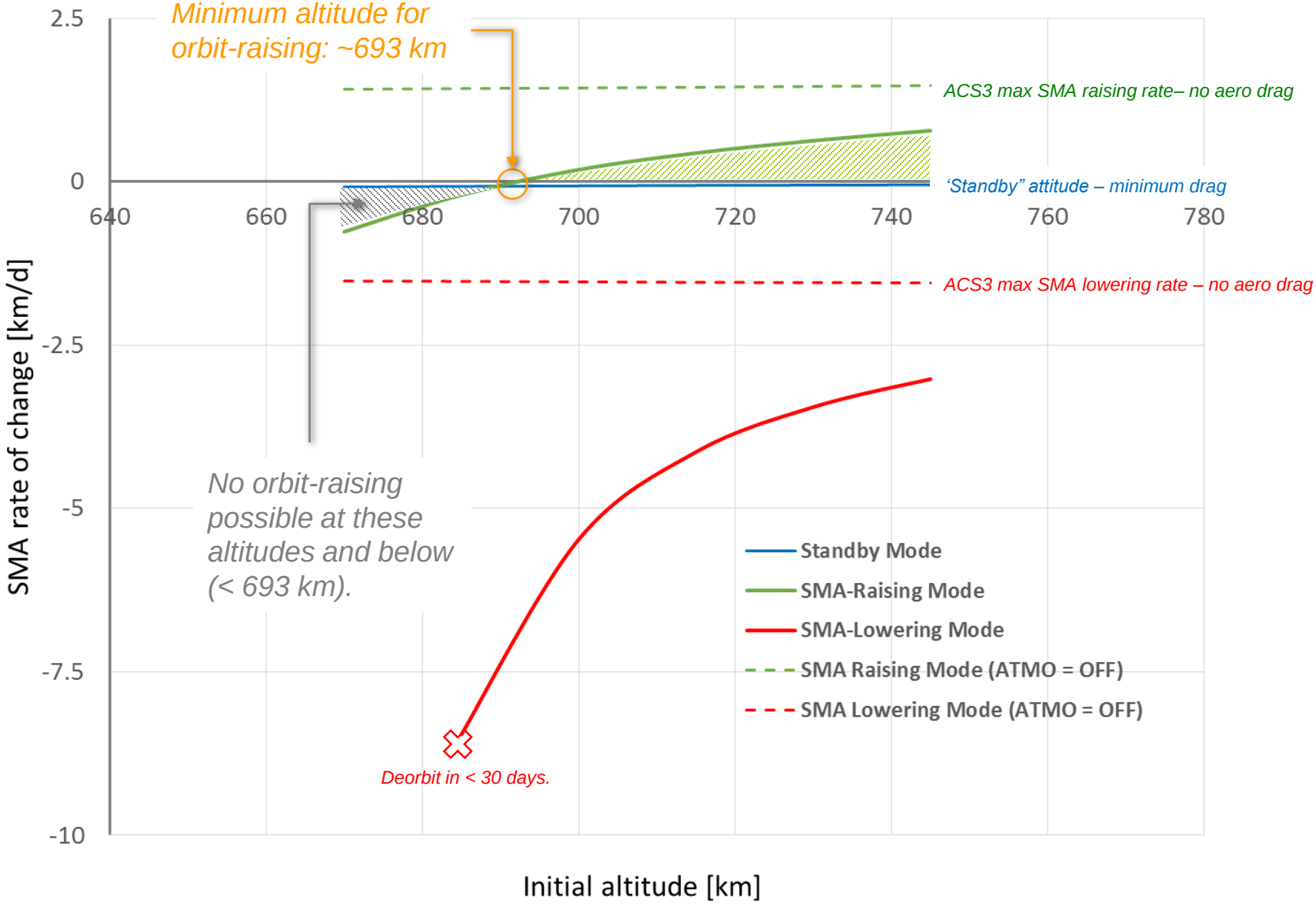




- Noon-midnight SSO example shown. -

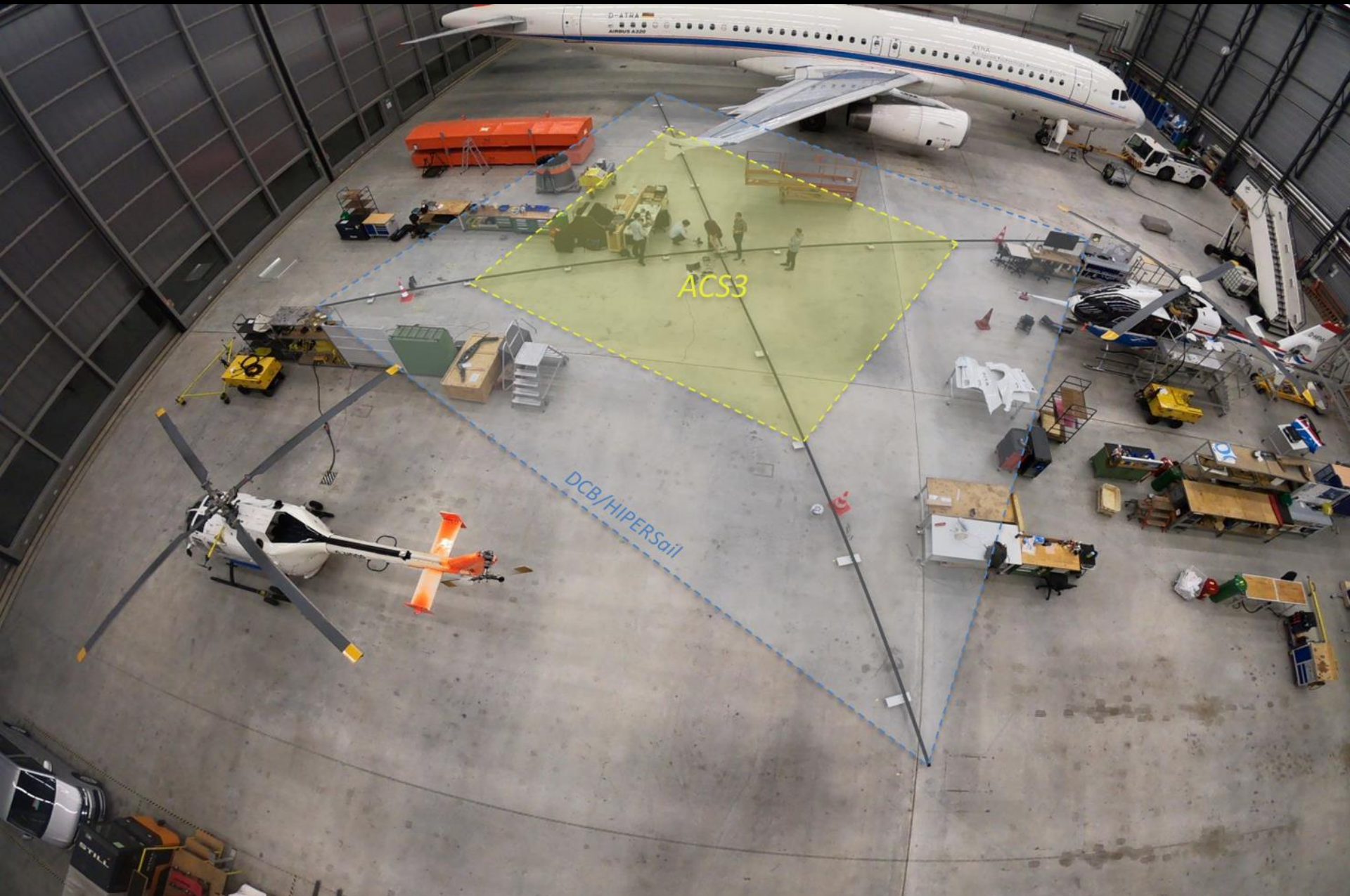
ACS3: 670-745 km, i = 45 deg: Altitude Effect on SMA Raising/Lowering

[1 August 2022 deployment, $RAAN_0$ = 130 deg; 'SMA Raising'; ACS3 v.18]



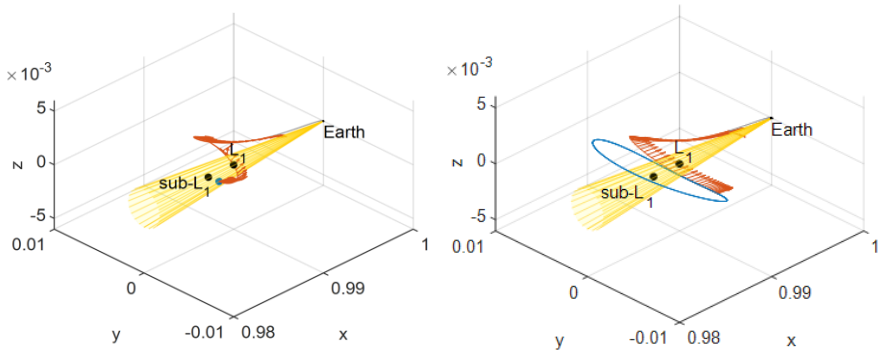
Extensibility to Future Solar Sail Applications

DCB 16.5-meter boom deployment testing at DLR ca. 11/12/2019

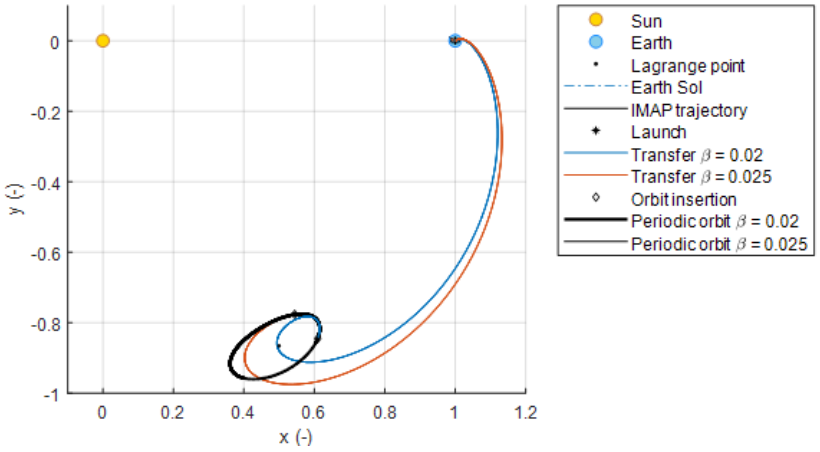


DCB/ACS3 Solar Sail Mission Applications β=0.02-0.025

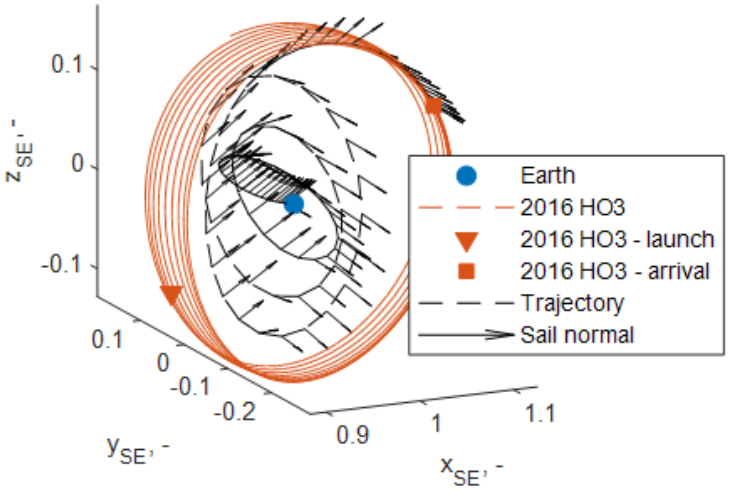
Sun-Earth Sub-L1 Space Weather EW



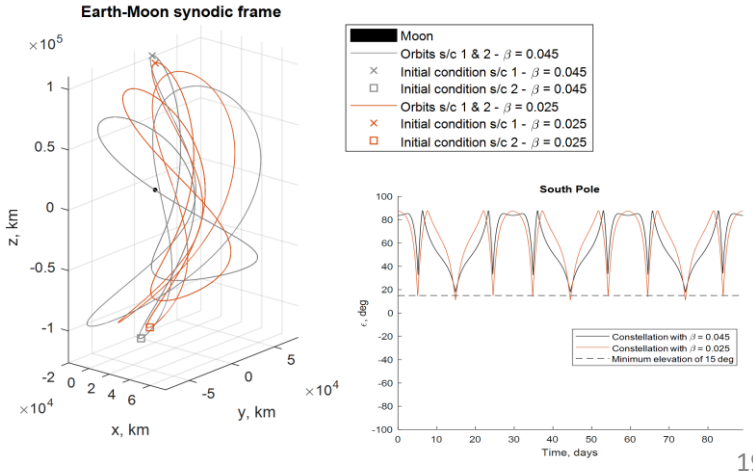
Sun-Earth L1-L5 Transfers



NEA Planetary Science

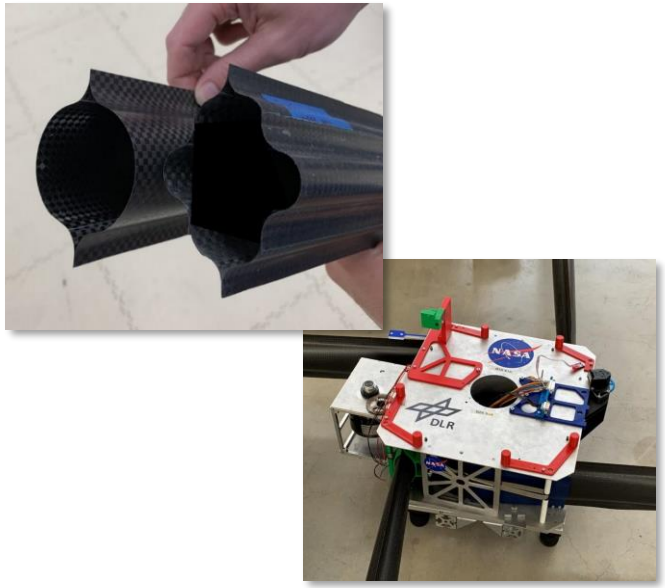


Lunar South Pole Comm Relays

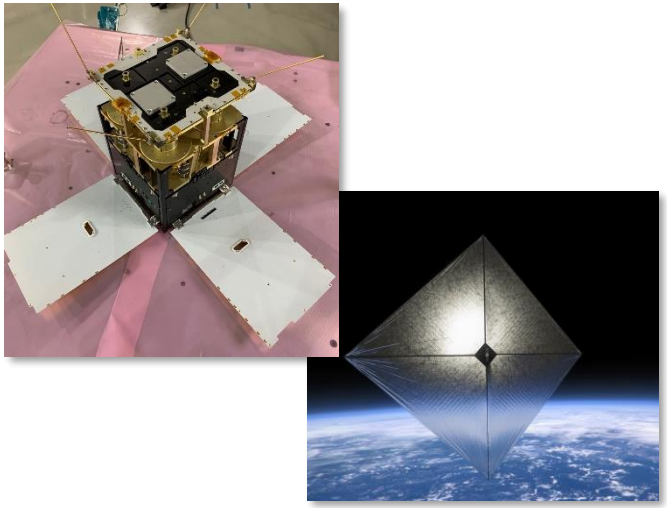


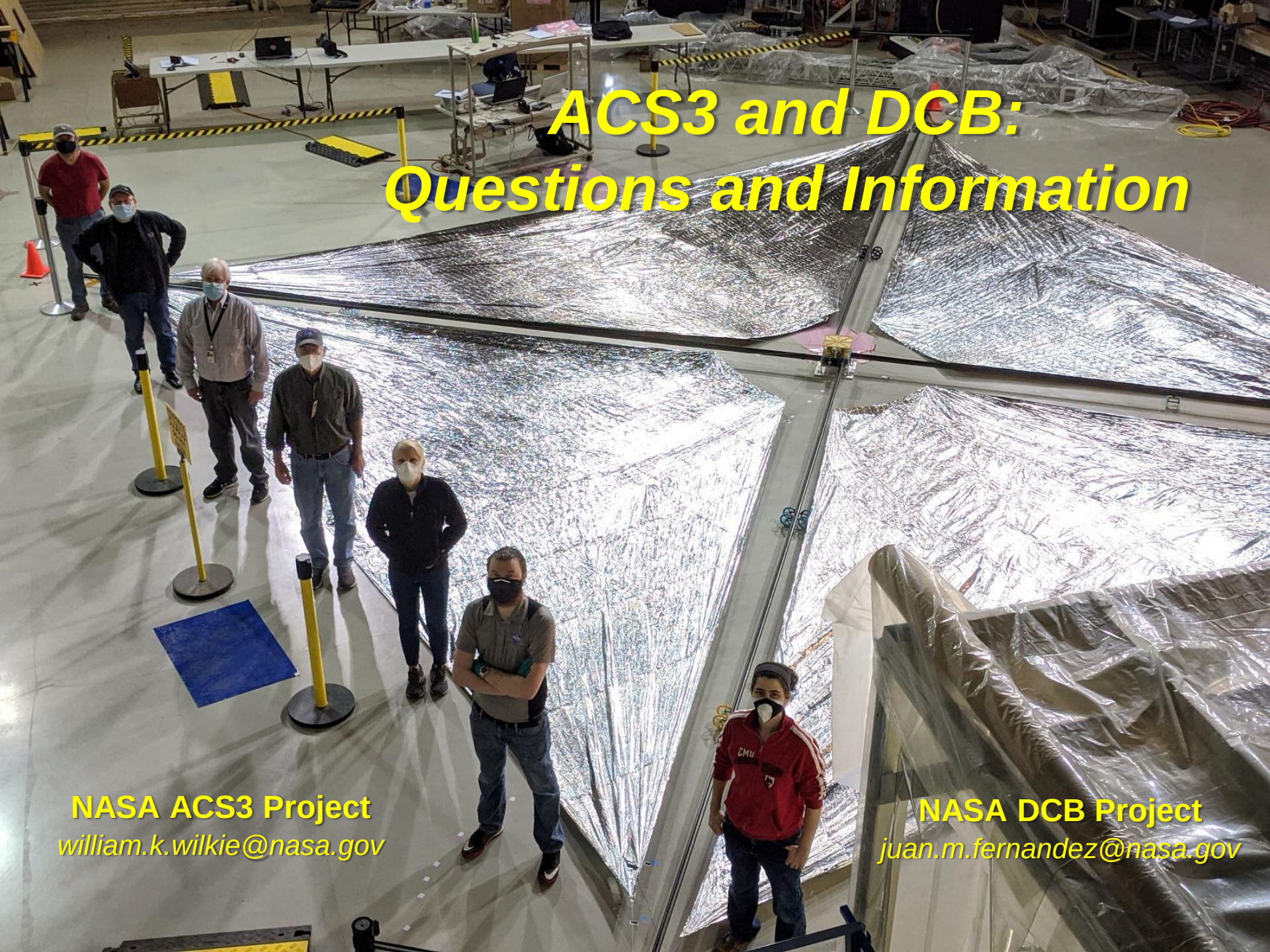
ACS3 and DCB Projects: Summary and Status
(ca. June 2021)

- **Deployable Composite Booms Project (DCB):**
  - *DCB-1: successfully developed DCB design and manufacturing capabilities to 16.5-m scales.*
  - *DCB-2: follow-on project approved for FY22 start.*
  - ***DCB-2 will develop larger-scale deployable composite booms and manufacturing capabilities.***



- **Advanced Composite Solar Sail Project (ACS3):**
  - *80 m^2 sub-scale solar sail flight demonstration of DCB-1 technology in LEO.*
  - Solar sail payload and 12U spacecraft Assembly, Integration and Testing underway.
  - ***ACS3 launch window: July-December 2022.***





ACS3 and DCB: Questions and Information

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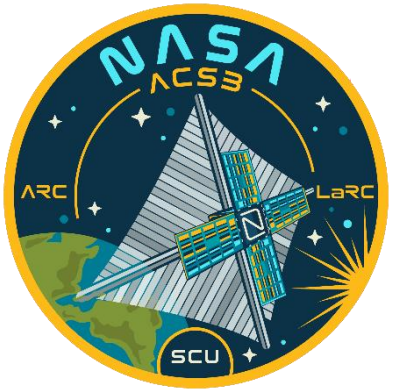
NASA
ACS3
ARC
LaRC
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