Advanced Composite Solar Sail System (ACS3) Mission Update

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NASA Langley Research Center

With special thanks to:

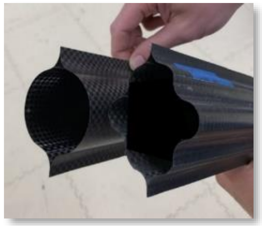
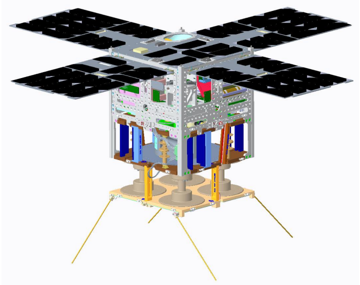
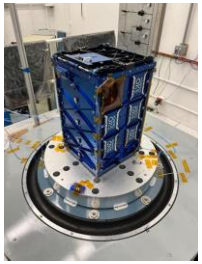
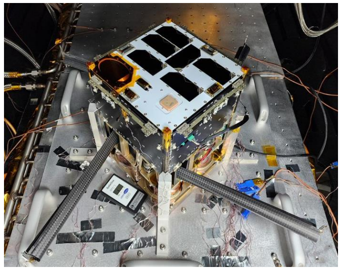
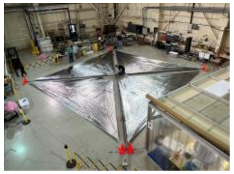
Jeannette Heiligers and Livio Carzana
TU-Delft

June 2023

Overview

- Introduction to NASA Deployable Composite Boom (DCB) technology
- ACS3 Objectives and Mission Concept
- ACS3 Flight Systems Overview
  - *ACS3 spacecraft integration and testing highlights*
- Extensibility of ACS3/DCB technology to future (larger) solar sail missions.
- **ACS3 Mission Orbit and Launch Update**



(ELaNa19 Liftoff, Photo credit: Trevor Mahlmann)

NASA Deployable Composite Booms Project (DCB)

High performance deployable composites for small spacecraft applications

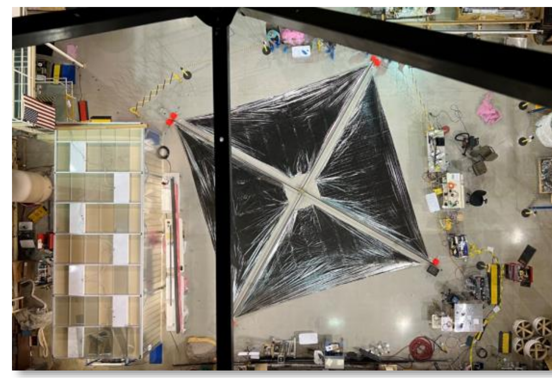
(Fernandez; 2017 2021)

- **Objectives (DCB): advance manufacturing and space 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).
- **Advantages over metallic deployables and open cross-section booms:**
  - Closed cross-section design for high bending and torsional stiffness; high load carrying capability
  - High packaging efficiency for small volume spacecraft.
  - Low thermal expansion to limit thermally-induced deflections and shape distortions.
  - 25% of the mass of comparable metallic booms.
- ***The Advanced Composite Solar Sail System (ACS3) will demonstrate DCB composite booms in space.***
  - The ACS3 80-m^2 solar sail is derived from a full-scale DCB 400-500 m^2 solar sail design.
  - Current DCB ACS3 7-m boom technology and manufacturing processes are scalable to 16.5-m deployable boom lengths.

DCB 16.5-m boom cross section

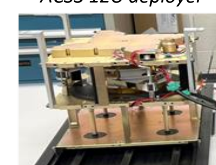
ACS3 7-m boom

ACS3 80-m^2 flight solar sail



DCB 400-500-m^2 class solar sail

ACS3 12U deployer

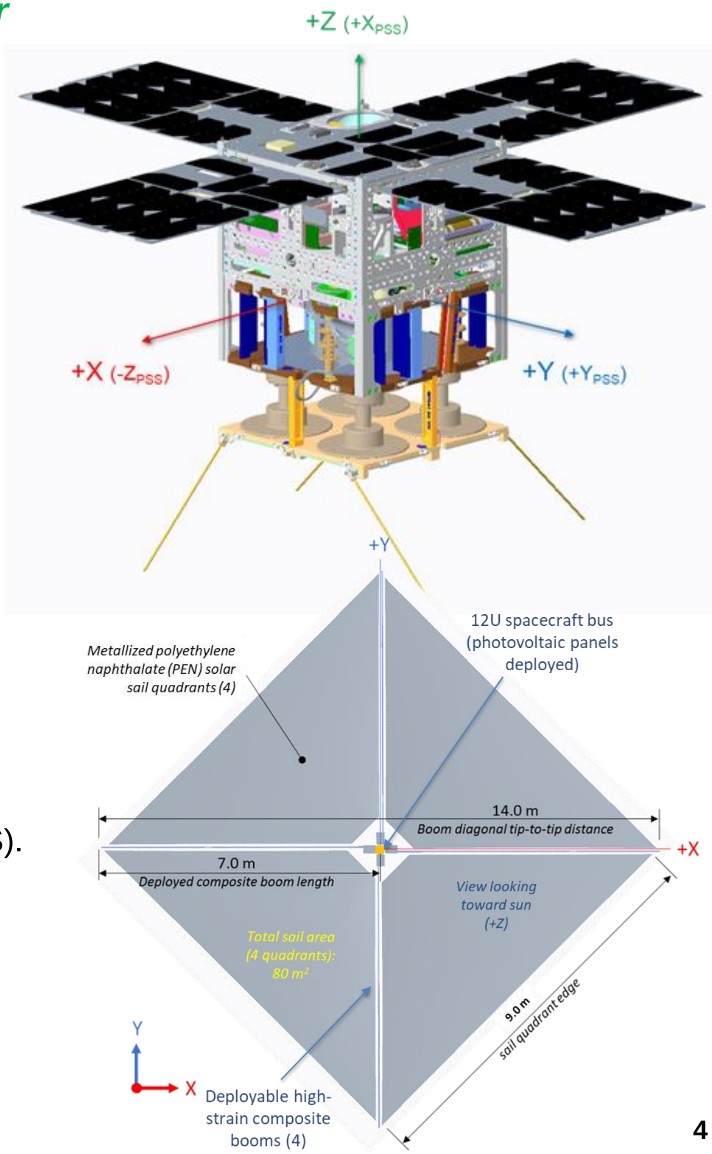


DCB (I) 27U deployer

Advanced Composite Solar Sail System (ACS3) Solar Sail Technology Demonstrator (2018)

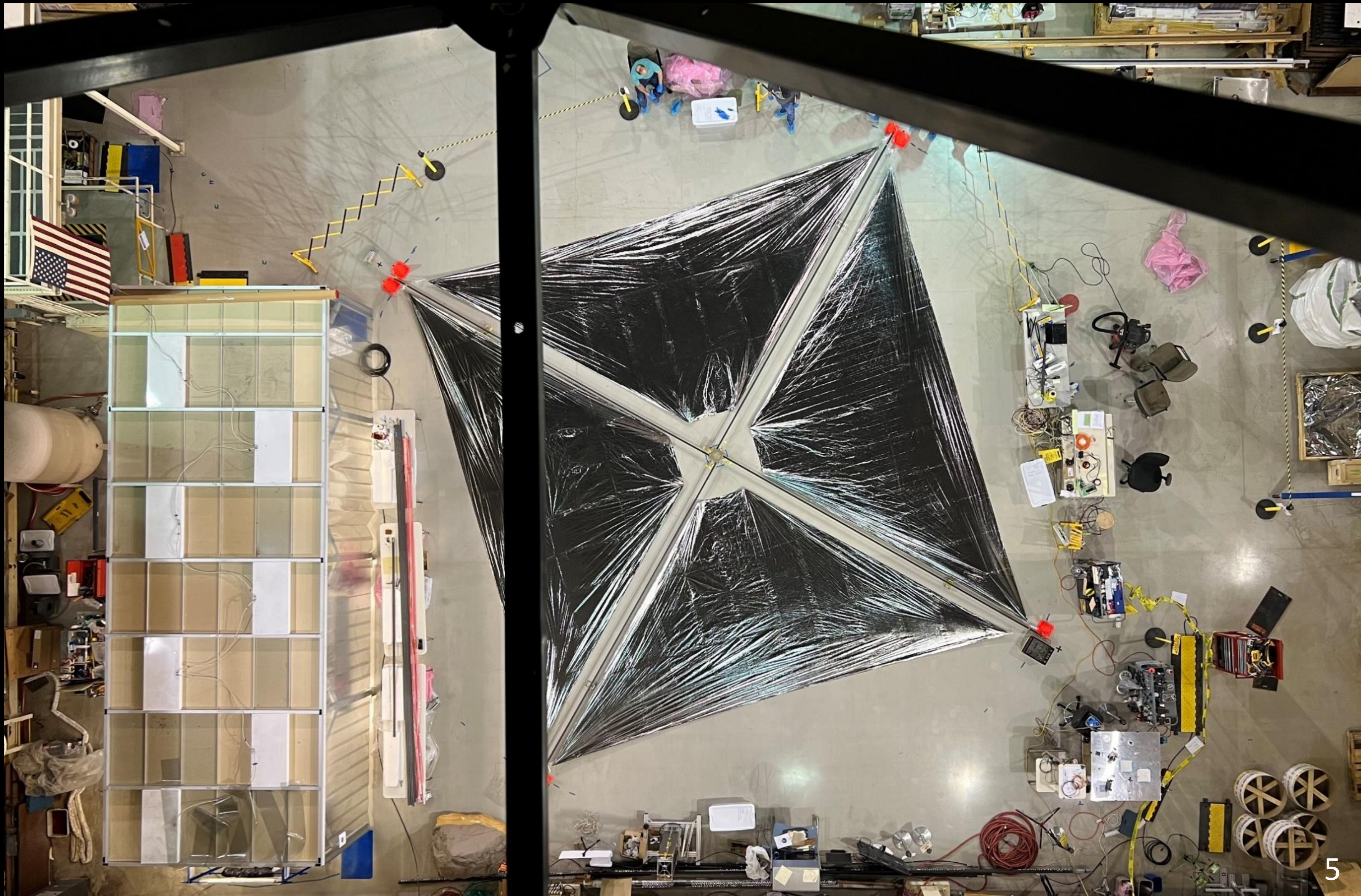
- ***ACS3 is a sub-scale low-Earth orbit (LEO) solar sail technology flight demonstration for future composites-based small-sat solar sail propulsion systems.***
  - **Sponsor: NASA Small Spacecraft Technology Program (SSTP)**
  - **Composite Technology: NASA Game Changing Development Program (GCDP), Deployable Composite Booms Project (DCB)**
  - **Designated as a NASA *research & technology demonstration project***
- **Launch: Late 2023 – early 2024 (TBD)**
  - **Orbit: 715 km - 1000 km (TBD) LEO** – Midnight-Noon Sun Synchronous preferred; highest altitude possible for drag mitigation.
- **Objectives:**
  - **Primary**: ***On-orbit deployment and characterization of a smallsat-class composite solar sail propulsion system.***
  - **Secondary**: ***Demonstrate controlled solar sailing flight via semi-major axis (SMA) raising/lowering; Characterize deployed structural dynamics.***
- **Partner roles and responsibilities:**
  - **NASA Ames Research Center (ARC)** – Lead for ACS3- provides payload control avionics (AS) for SBS and camera system, camera system for sail deploy capture, and AS Flight Software (FSW).
  - **NASA Langley Research Center (LaRC) -** ACS3 Sail/Boom Subsystem (SBS).
  - **AST Space Mobile USA / NanoAvionics US** - Spacecraft bus.
  - **NanoAvionics US / ExoLaunch –** Dispenser.
  - **Santa Clara University Robotic Systems Lab** – ACS3 operations support.
  - **Rocket Lab -** Launch provider.
- ***ACS3 solar sail will validate sail technologies for future larger-scale solar sails.***

ACS3 12U Spacecraft and Deployed Solar Sail



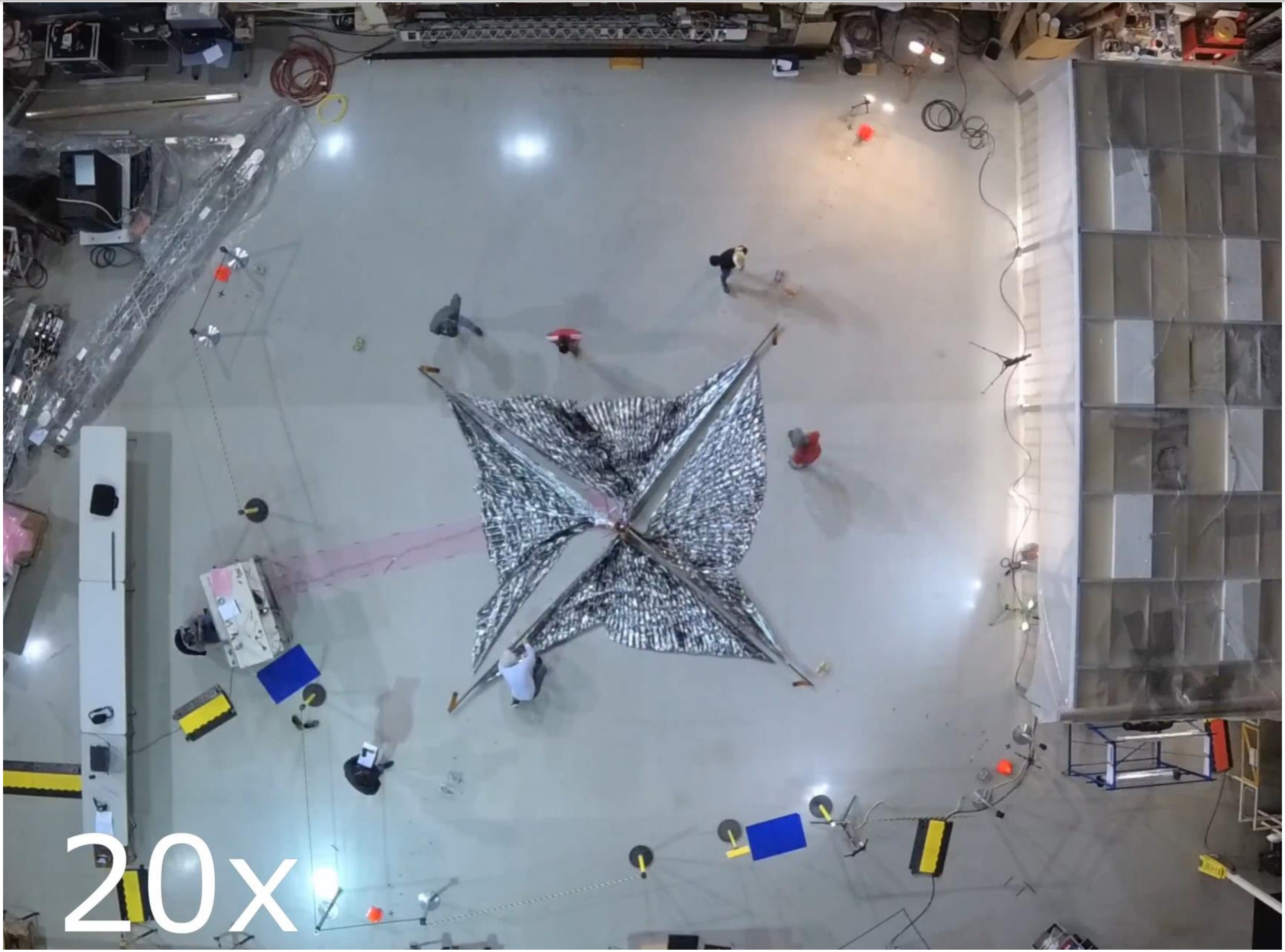
Advanced Composite Solar Sail System (ACS3)

DCB 7-meter composite booms; 80-m² solar sail area (NASA LaRC, 5/21/2022)



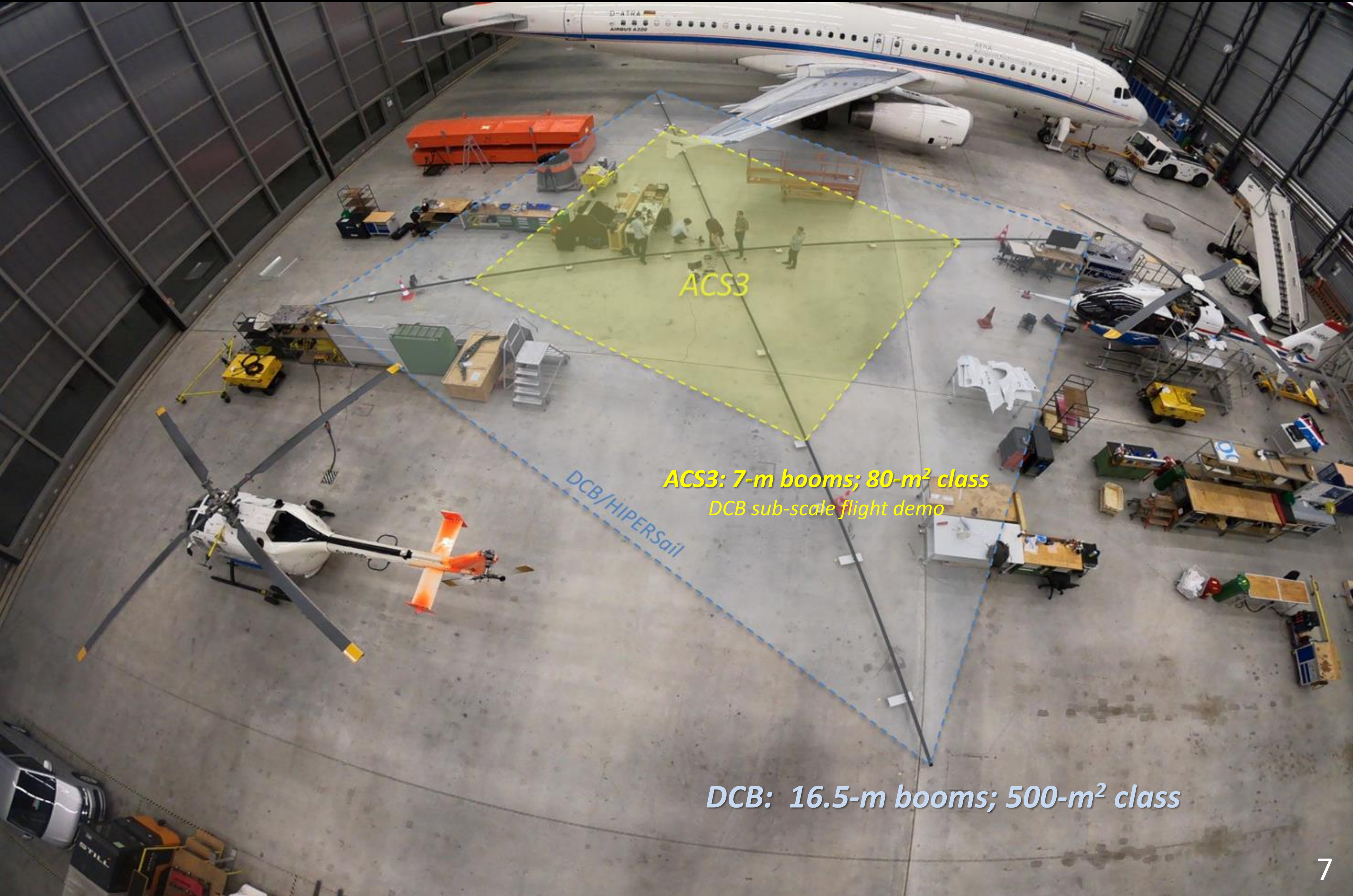
SBS Prototype Deployment Testing w/ Development Sails

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

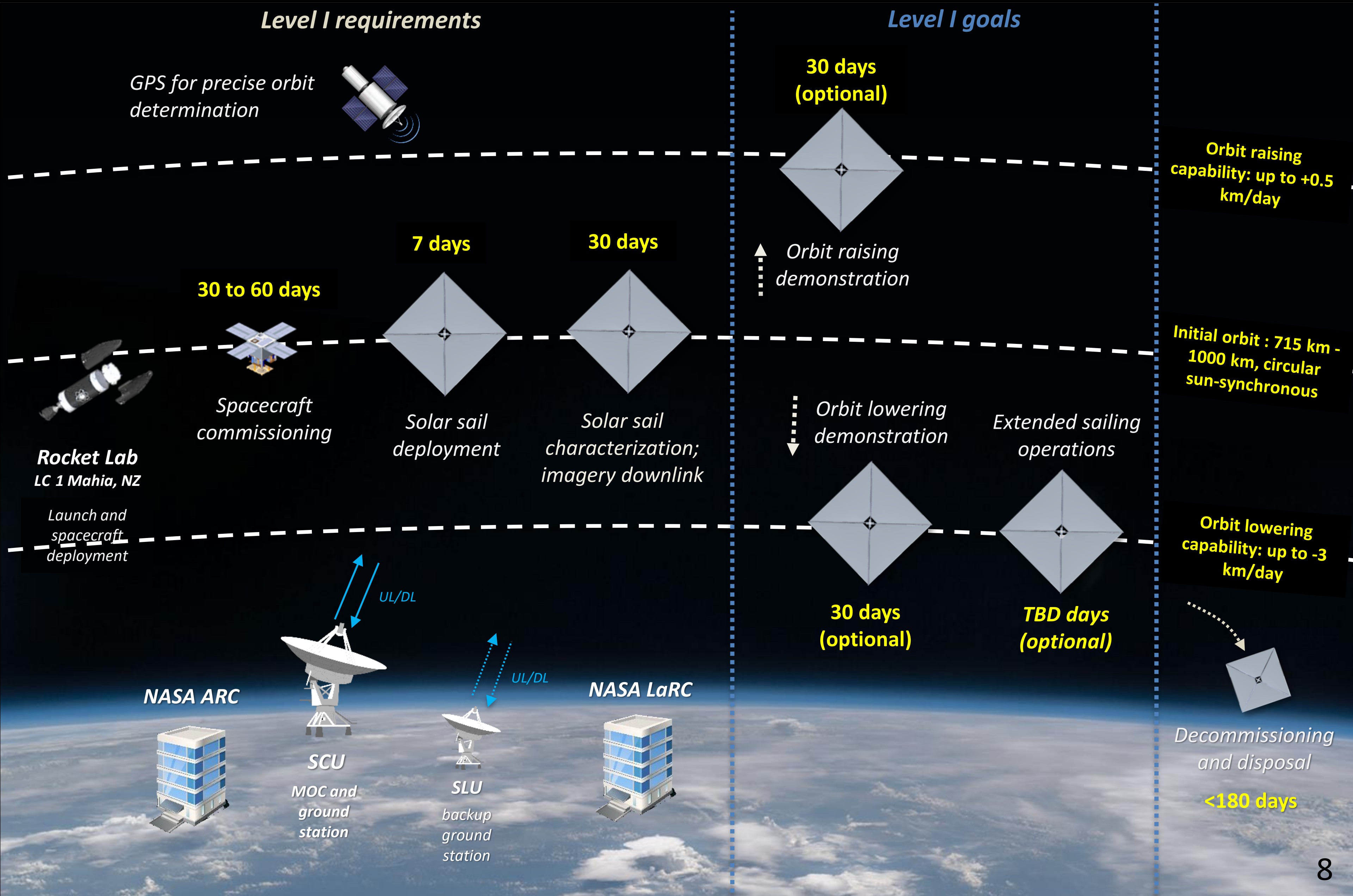


Extensibility to Future Solar Sail Applications

DCB 16.5 meter composite boom solar sail (DLR 11/12/2019); ACS3 7 m boom sail shown to scale.

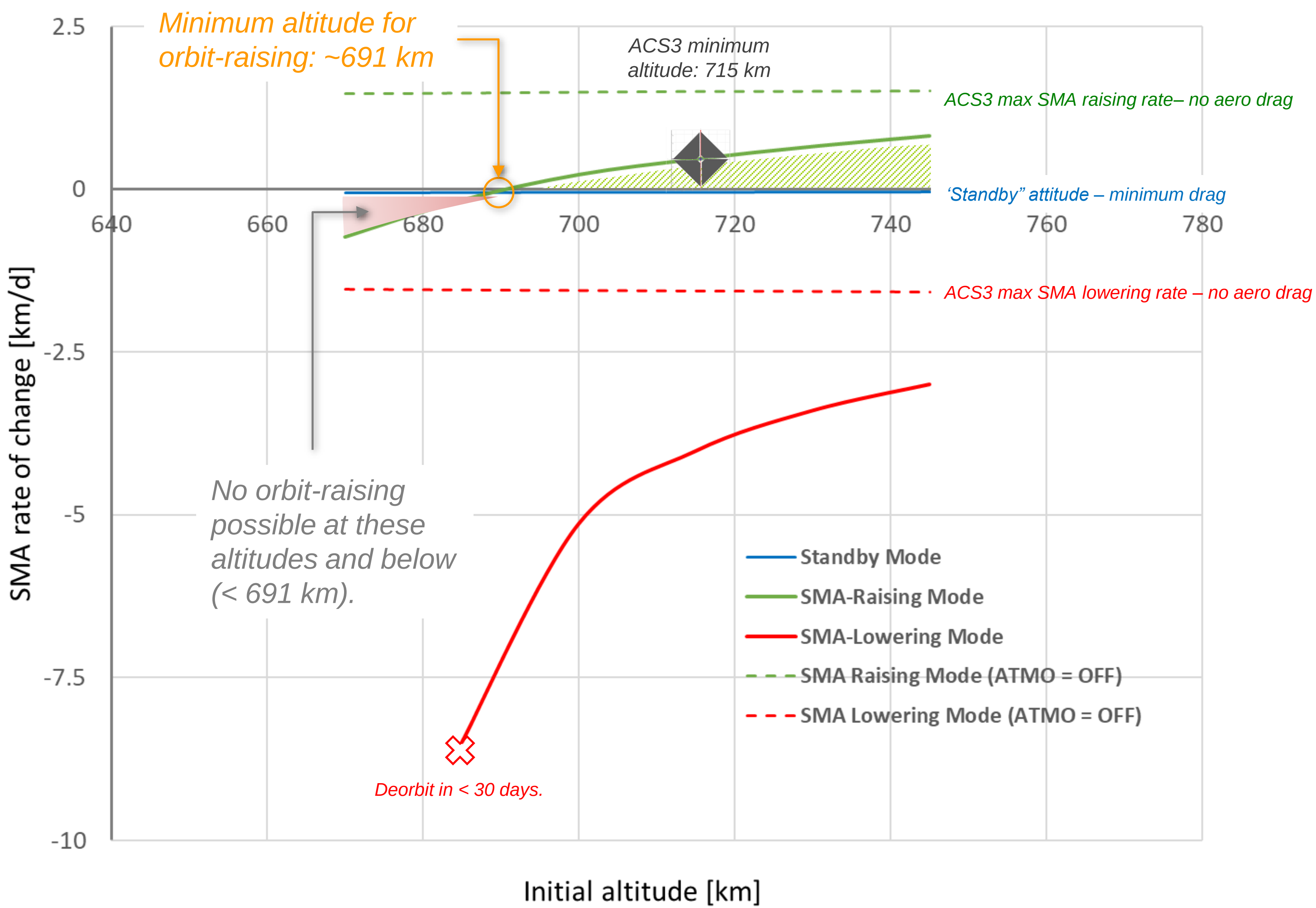


ACS3 Concept of Operations [2023]



ACS3: Theoretical Semi-Major Axis (SMA) Raising/Lowering Capability

[Noon Midnight SSO, 1 August 2022 deployment, locally optimal steering]



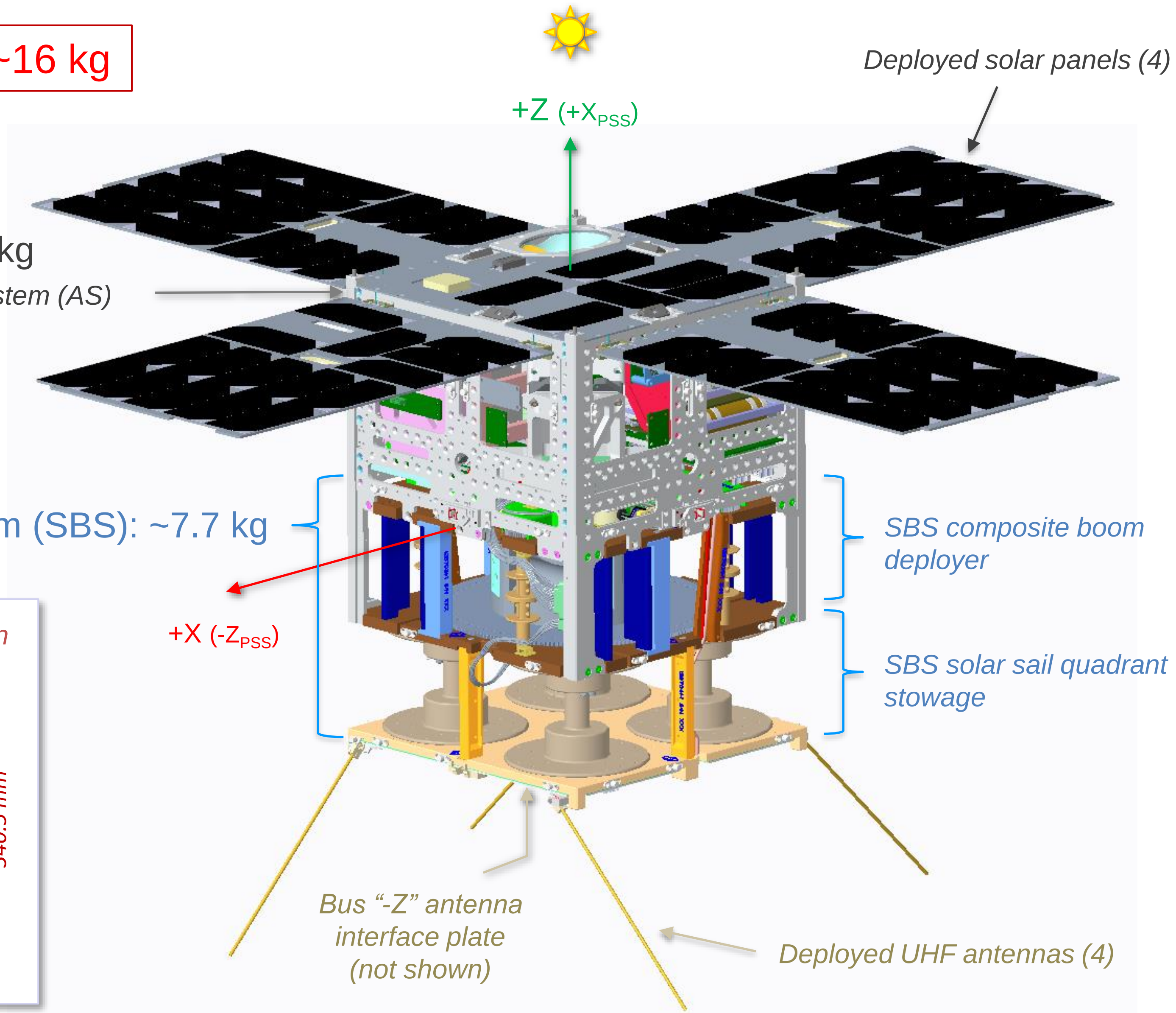
ACS3: Spacecraft Elements
[solar panels and UHF antennas deployed; sail and booms omitted]

Total ACS3 Mass: ~16 kg

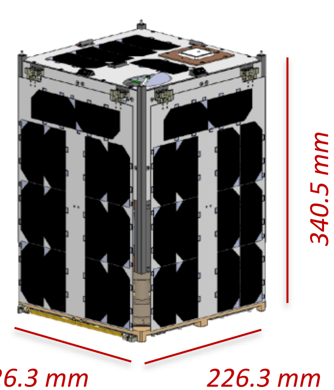
Spacecraft Bus: ~ 8.3 kg

Includes Payload Avionics System (AS)
- *Sail Diagnostic Cameras (4);*
- *SBS control electronics.*

Sail-Boom Subsystem (SBS): ~7.7 kg



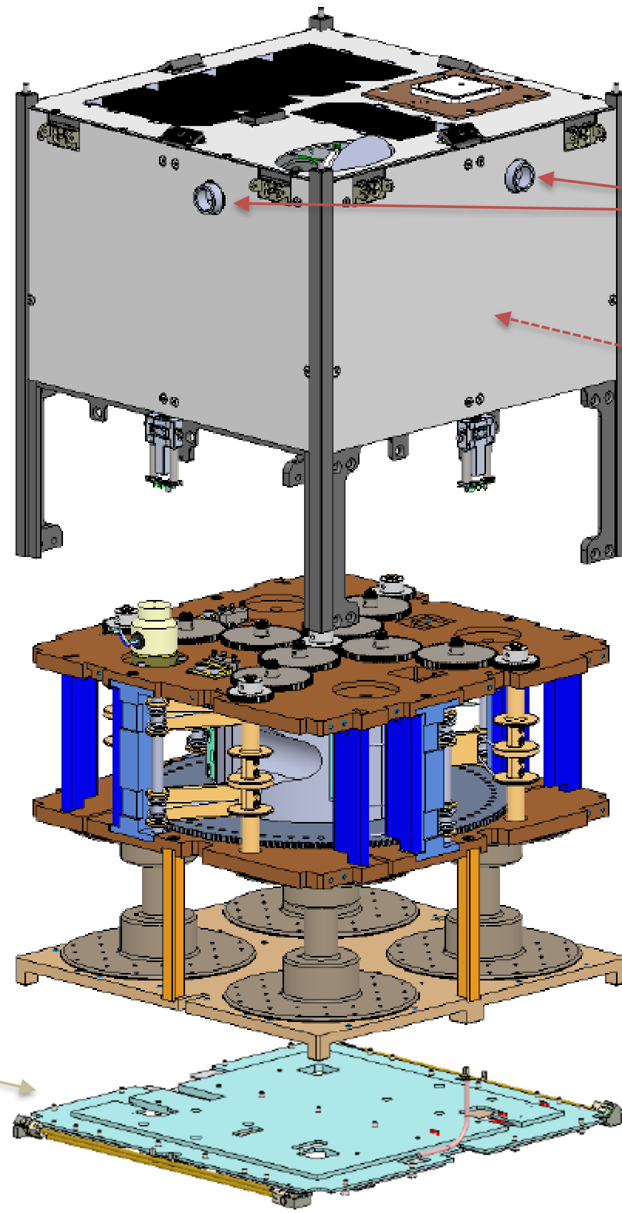
12U Stowed configuration



ACS3: 12U Spacecraft Subsystems

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

- NASA ARC
- NASA LaRC
- AST-NanoAvionics



Spacecraft Bus:

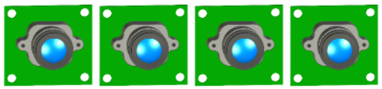
- S-band transceiver
- UHF radio
- Flight computer
- ADCS
  - Reaction wheels (4)
  - Magnetorquers (3 x 3-axis)
  - Sun sensors (5)
  - GPS receiver
  - Star tracker
  - IMU
- EPS

Sail-Boom Subsystem: (SBS)

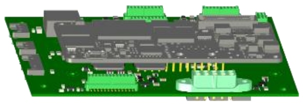
Spacecraft bus "-Z" plate:

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

Payload Avionics System: (AS)



AS sail diagnostic cameras (4)



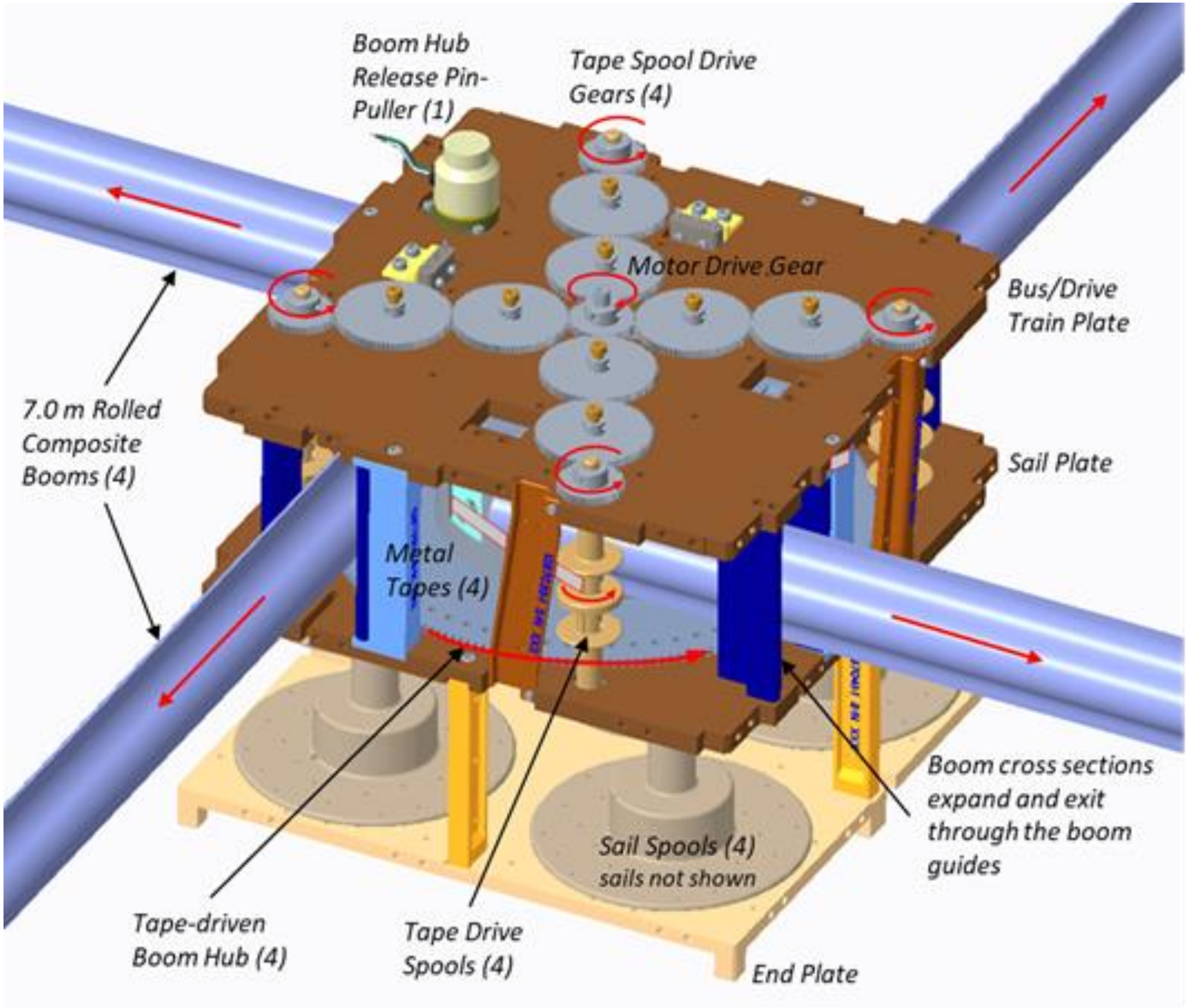
AS payload control electronics

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

SBS composite boom deployer

SBS solar sail quadrant stowage

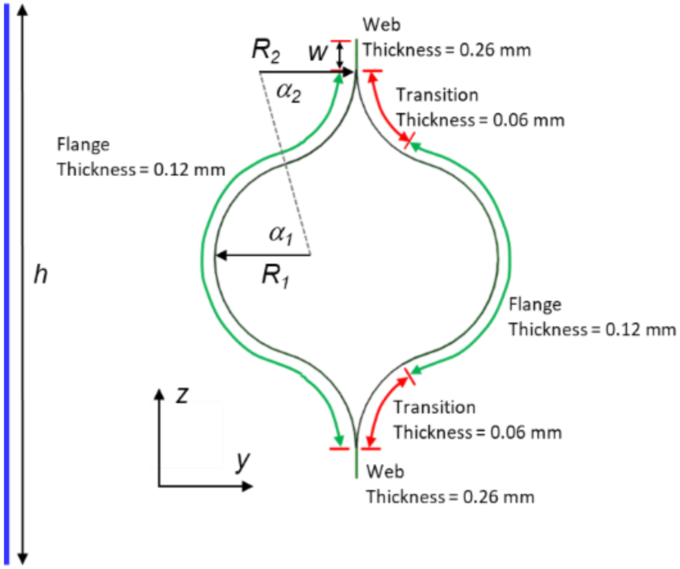
ACS3: Sail-Boom Subsystem Deployer Design



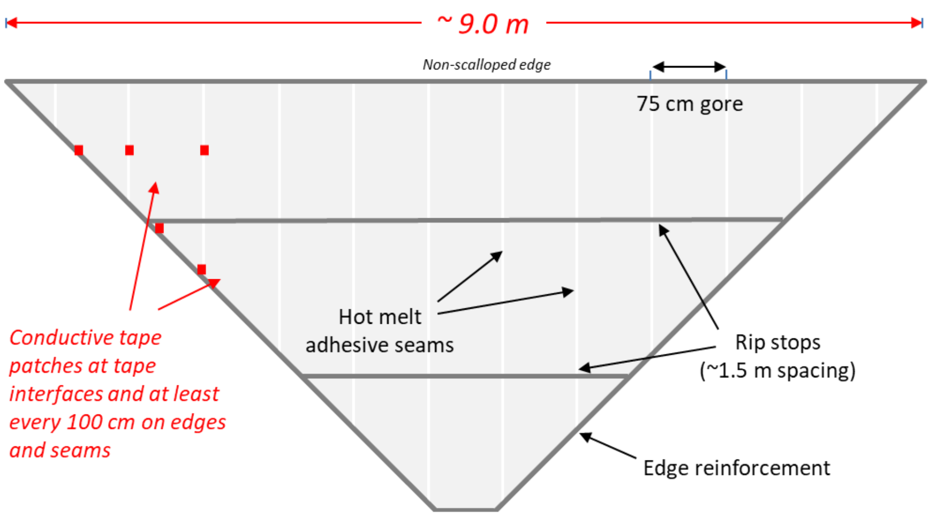
ACS3: Deployable Composite Boom Design

- ACS3 uses ***collapsible tubular mast*** (CTM) composite booms developed by the NASA 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 Research Center.

Individual Boom Mass: 164 g

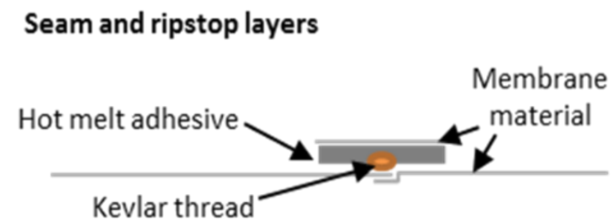


ACS3: Solar Sail Quadrant Design and Fabrication

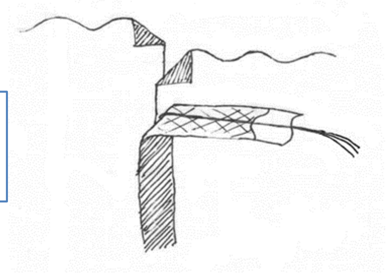


Quadrant Design

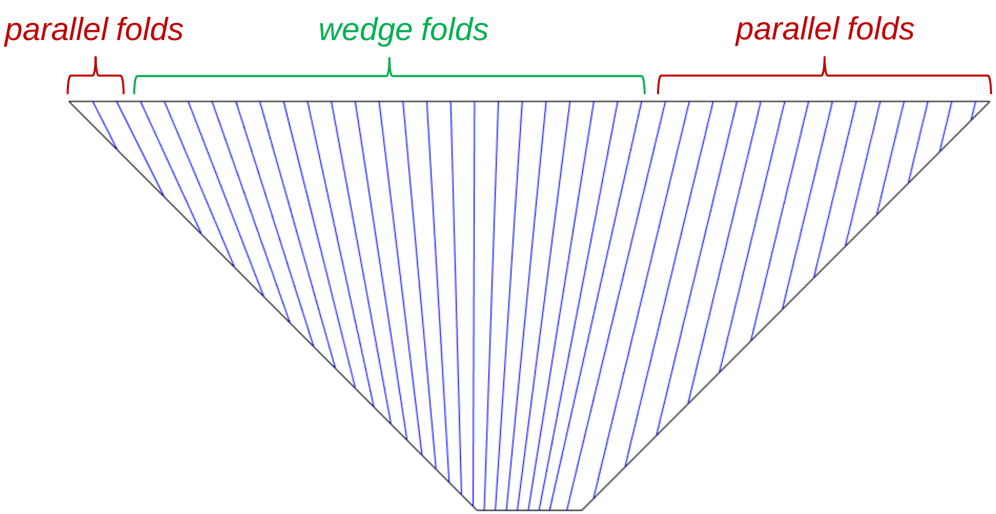
Individual Quadrant Mass (w/ hardware): 85 g



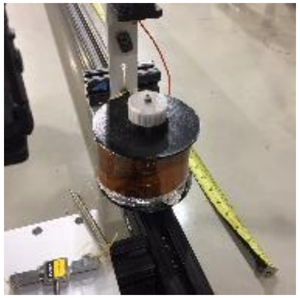
Flight membrane material: 2.115-μm Al/PEN/Cr



Seam detail



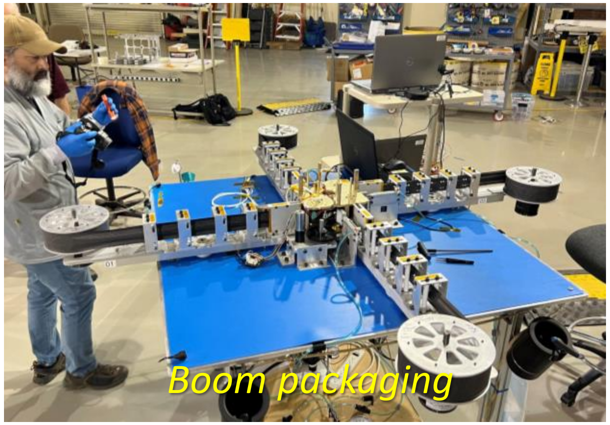
Quadrant folding scheme

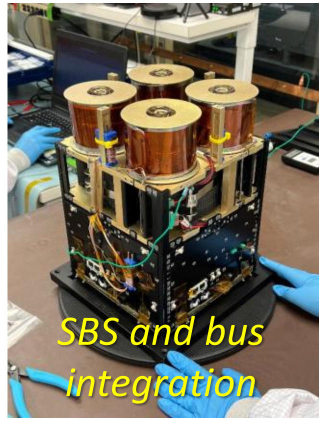


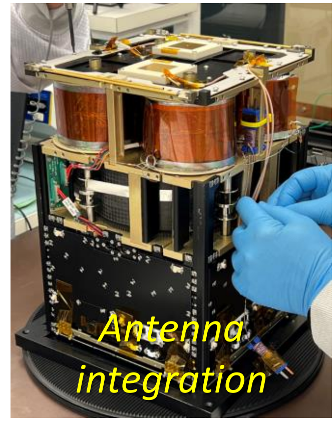
Quadrant spooled for stowing

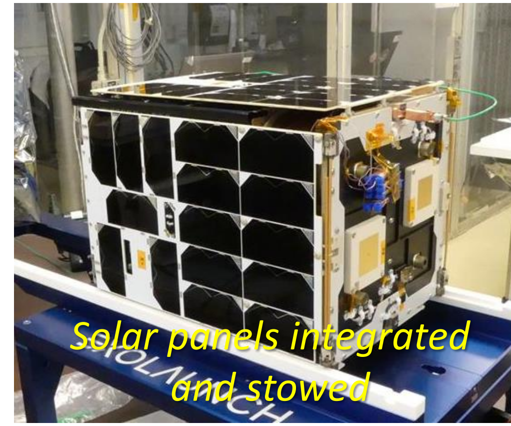
ACS3: Integration and Environmental Testing (highlights)

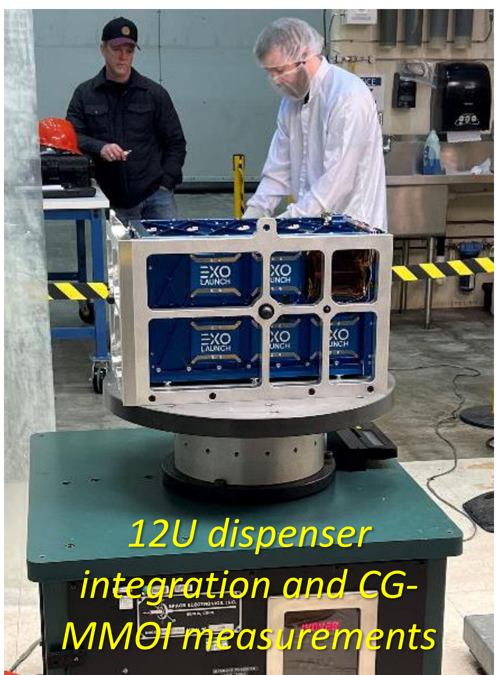
NASA Langley Research Center, February April, 2023

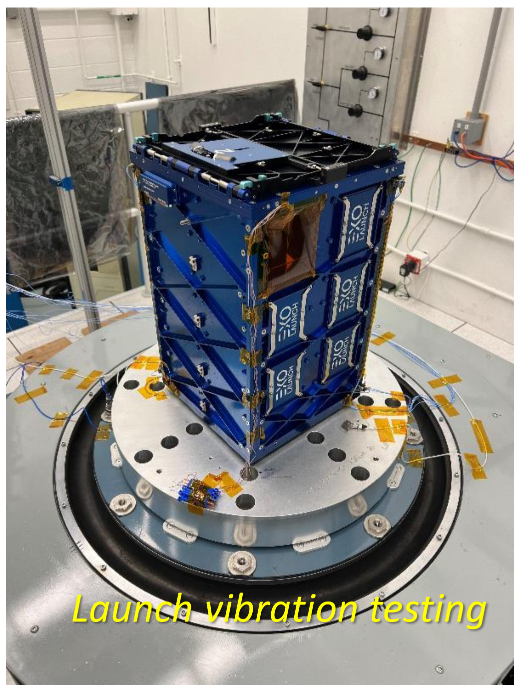

Boom packaging

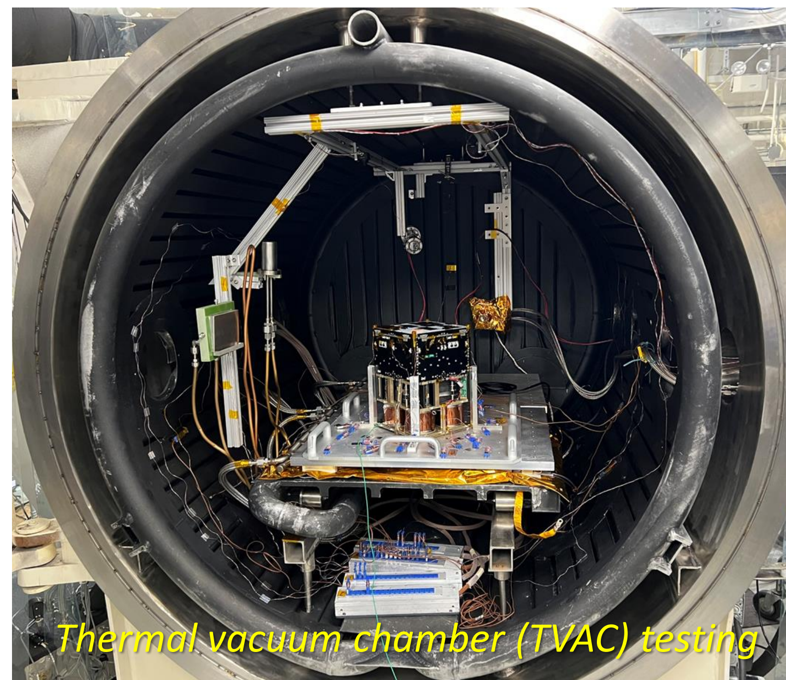

SBS and bus integration


Antenna integration

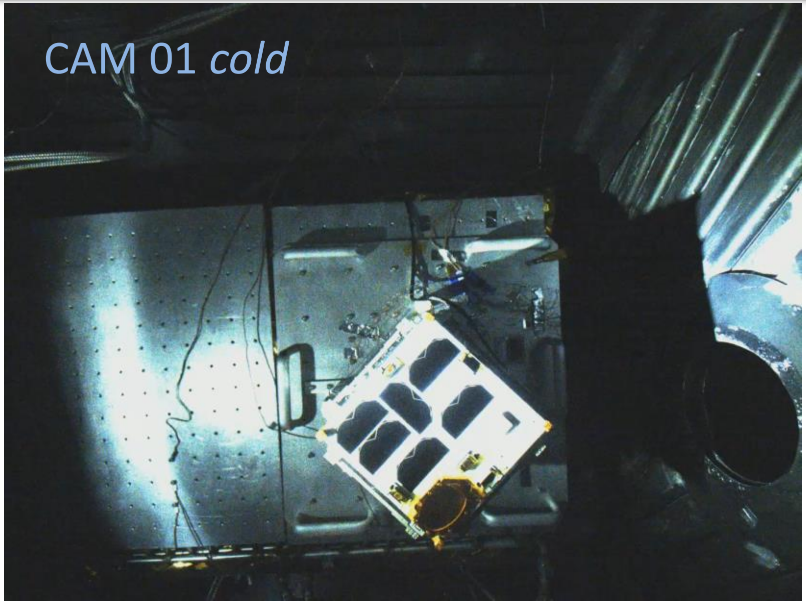

Solar panels integrated and stowed

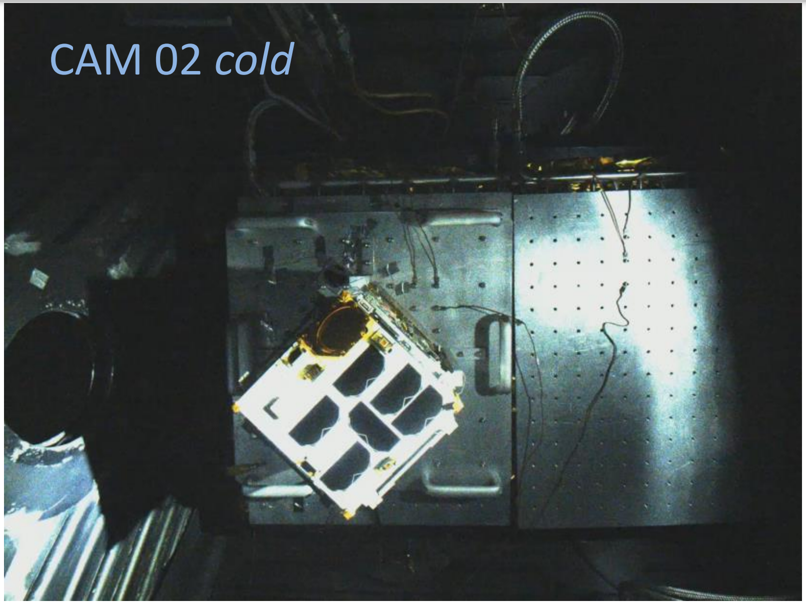

12U dispenser integration and CG-MMOI measurements

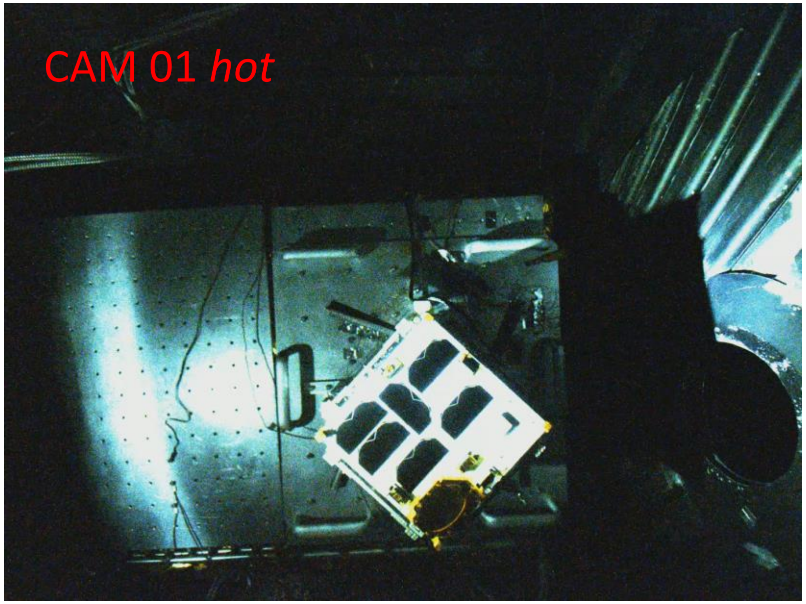

Launch vibration testing

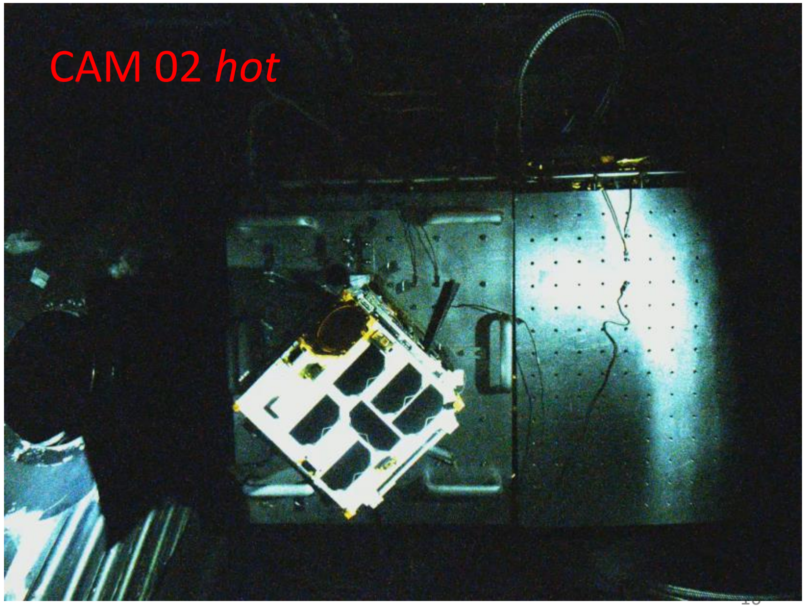

Thermal vacuum chamber (TVAC) testing

ACS3: TVAC cold (-8° C) and hot (+38° C) boom partial deployments

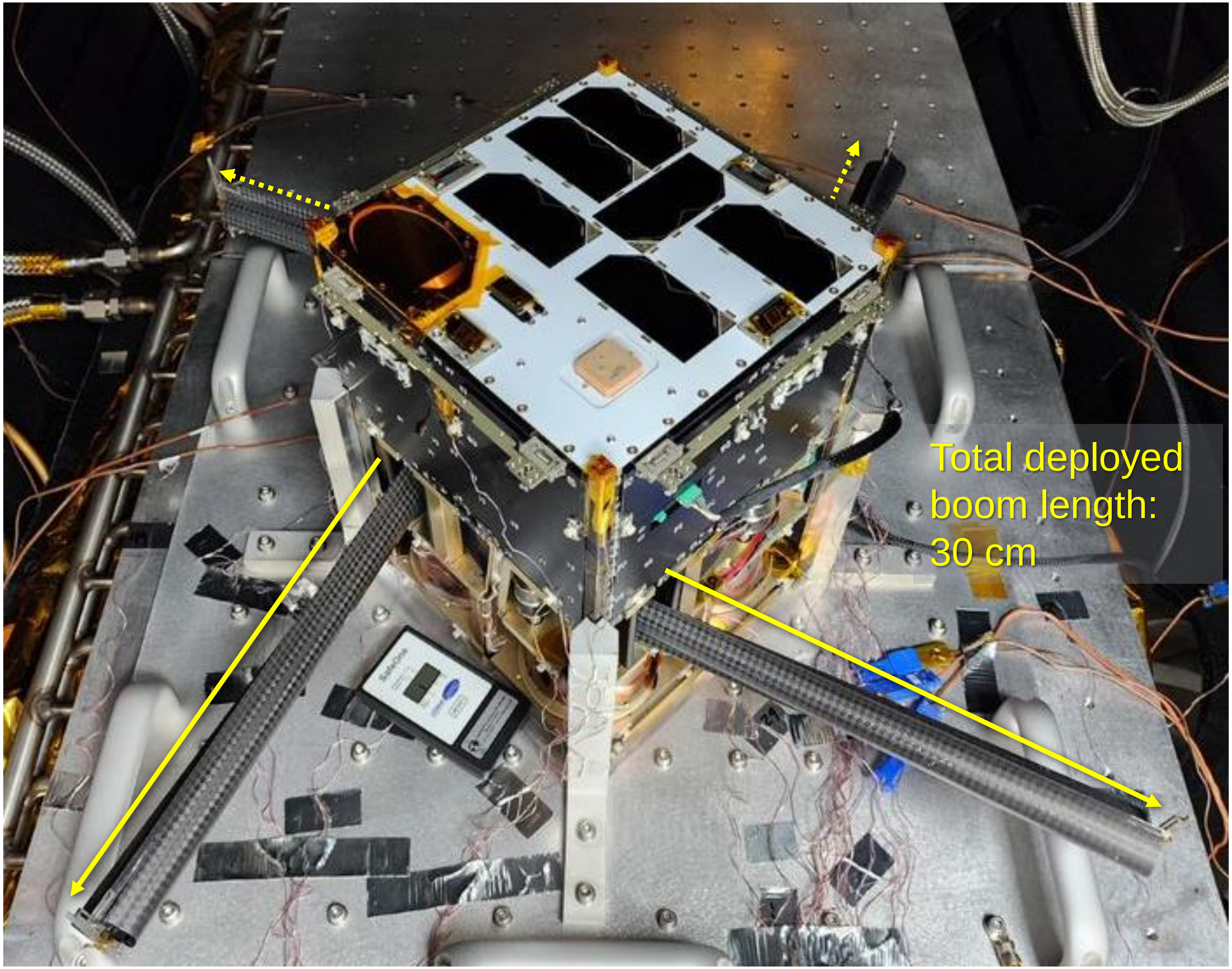








ACS3: Completed TVAC partial boom deployments



ACS3: Post-environmental full boom deployment
(continued from TVAC partial deployments)

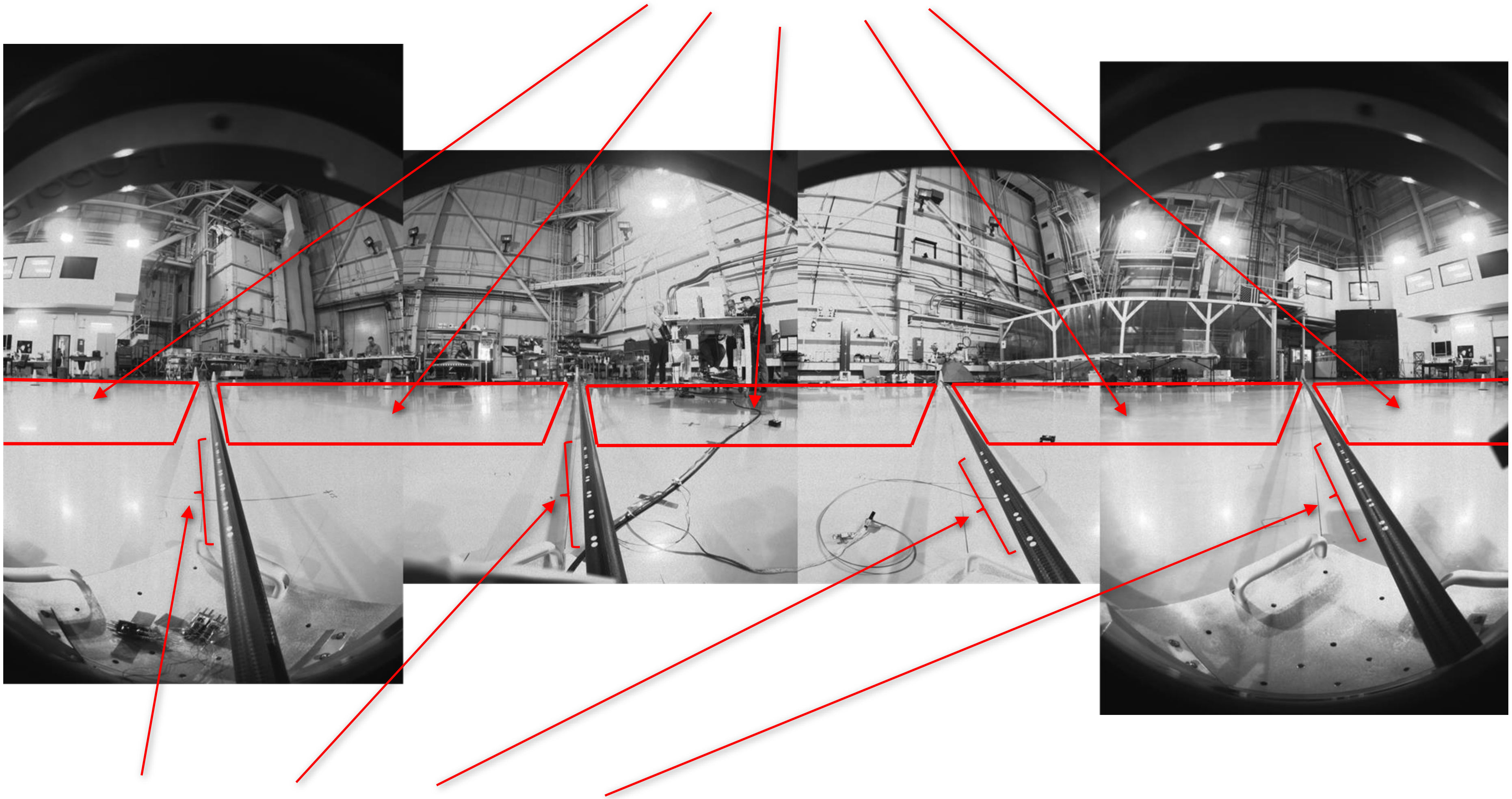
ACS3: AS Camera System 360 degree composite video

(XT 018 02 R04C, post-TVAC full boom deployment)

ACS3: AS Camera System 360 degree composite image

(XT 018 02 R04C, post-TVAC full boom deployment)

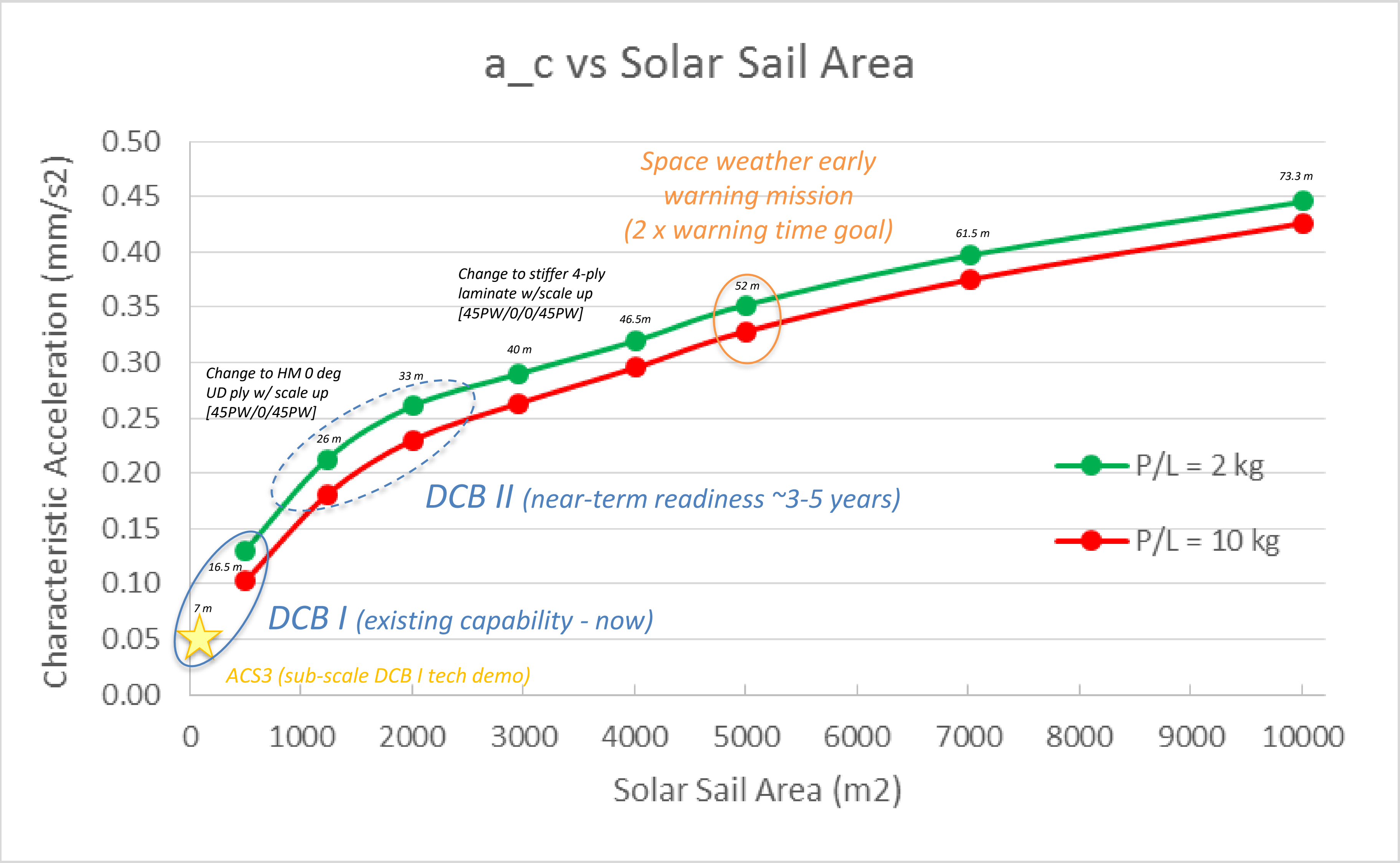
Approximate locations of sail quadrants at full deployment.



Boom fiducial targets at full deployment.

*Example** Solar Sail Performance vs. Sail Area Trends *(a_c @ 1 AU)*

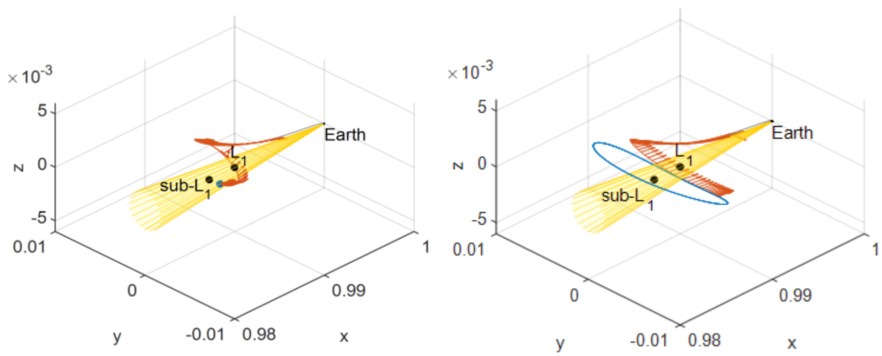
DCB/ACS3 Boom Technology



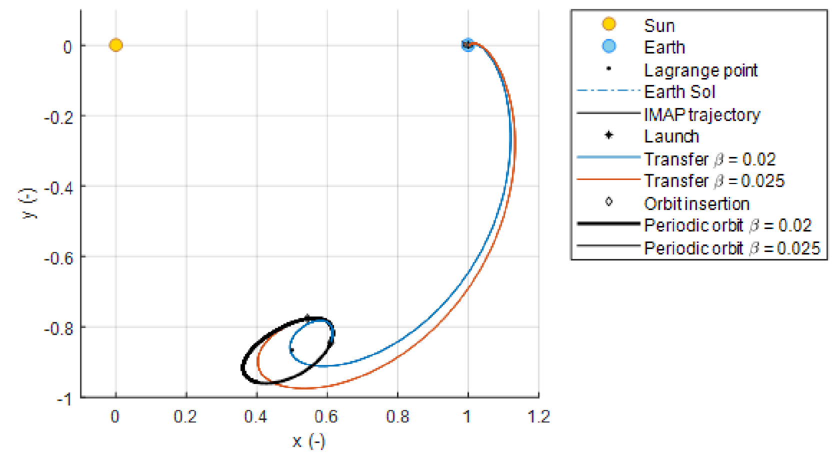
** Based on representative deployer and mission systems. (Others possible.)*

Example Near-Term DCB I Technology Solar Sail Missions (Heiligers, 2018-2022) a_c = 0.12-0.15 mm/s^2 class (β=0.02-0.025)

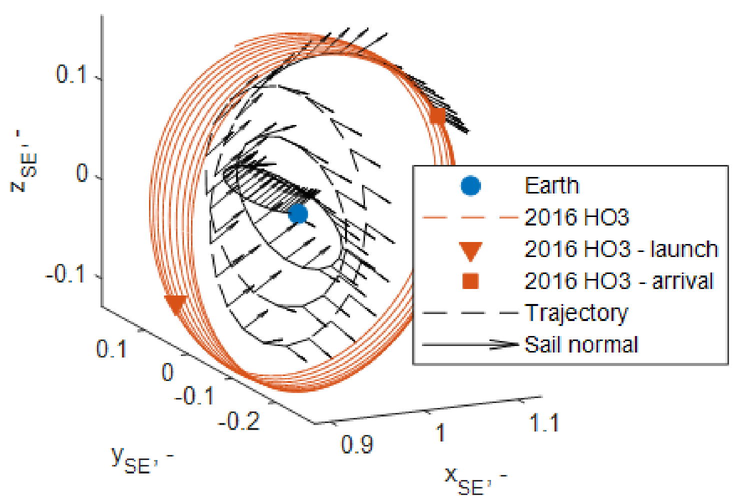
Sun-Earth Sub-L1 Space Weather EW



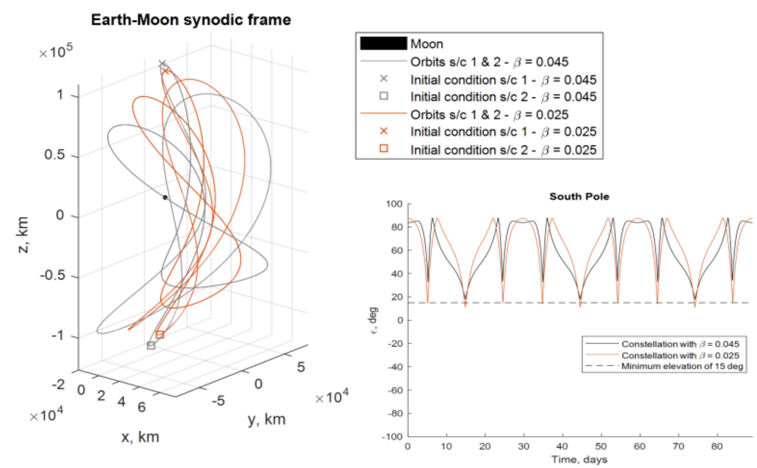
Sun-Earth L1-L5 Transfers



NEA Planetary Science



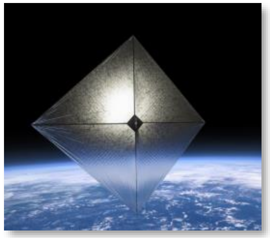
Lunar South Pole Comm Relays



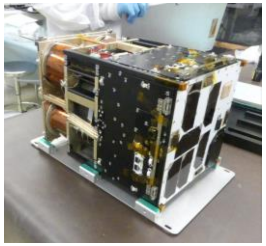
ACS3 Project Summary and Launch Status

(June 2023)

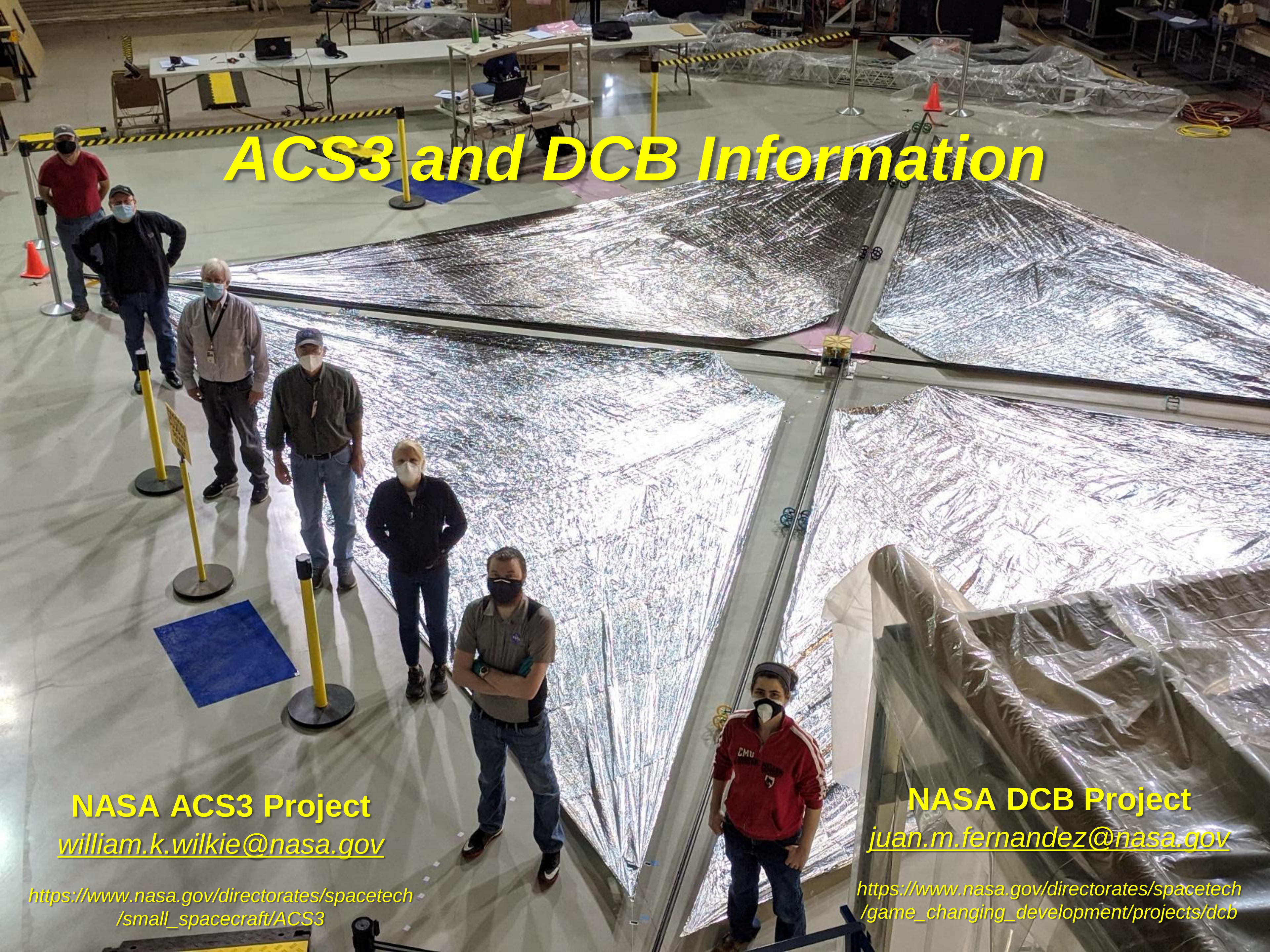
- **ACS3 Project Summary:**
  - *80-m² sub-scale deployable composite boom solar sail technology flight demonstration in LEO.*
    - *ACS3 boom length: 7 m*
  - *ACS3 solar sail design is scaled <u>down</u> from a 500-m² class solar sail design.*
    - *16.5-m booms. (Limit of current NASA DCB tooling.)*
  - *ACS3/DCB composite boom technology extensible to 2000-m² class solar sails in near-term.*
    - *Boom lengths up to 33 m.*
  - *ACS3 will demonstrate sail deployment and attempt orbit raising/lowering via controlled solar sailing, final orbit permitting (see below).*
- **Mission Orbit Update:**
  - Circular, sun-synchronous orbit. (expected)
  - MLTAN: TBD.
    - Midnight-noon/noon-midnight ± 2 hours preferred for ACS3.
  - Altitude: 715 km – 1000 km (TBD)
    - Higher altitudes preferred to preserve SMA raising demonstration capability
- **ACS3 Launch Update:**
  - **ACS3 to be remanifested from July 2023 launch to later launch due to heavier than anticipated primary payload.**
    - **ACS3 is a secondary rideshare payload.**
  - **ACS3 now expected to launch in late calendar year 2023 or early calendar year 2024 (TBD).**
  - **Launch from Rocket Lab Launch Complex 1 (LC-1), Mahia , NZ (still expected).**
- **ACS3 Spacecraft Readiness:**
  - ACS3 solar sail payload and 12U spacecraft assembly, integration and testing complete.
    - Spacecraft undergoing end-to-end radio communications testing at NASA Ames Research Center and Santa Clara University.
    - Solar panel stowing and 12U dispenser integration to occur NET Launch-minus 10 weeks.



(ELaNa19 Liftoff, Photo credit: Trevor Mahlmann)



ACS3 and DCB Information



NASA ACS3 Project

william.k.wilkie@nasa.gov

https://www.nasa.gov/directorates/spacetech/small_spacecraft/ACS3

NASA DCB Project

juan.m.fernandez@nasa.gov

https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/dcb

Advanced Composite Solar Sail System (ACS3) Mission Update

APPENDIX

Representative Properties for the ACS3 Solar Sail Spacecraft
(updated from [1], 10/26/2021)

Property	Value	Units
Total spacecraft mass, including sail	16	kg
Spacecraft mass moments of inertia, sail deployed (I_{xx}, I_{yy}, I_{zz})	10.5, 10.5, 21	$kg\text{-}m^2$
Center of mass offset forward of nominal sail plane	0.05	m
Sail-Boom Subsystem (SBS) mass	7.7	kg
Bus mass	8.3	kg
Boom deployed length	7.0	m
Boom mass, each	0.164	kg
Sail quadrant area, each	20	m^2
Sail membrane thickness, including metallization	2.115×10^{-6}	m
Sail quadrant mass, each	0.085	kg
Sail specular reflectance fraction, aluminum face	0.74	-
Solar absorption fraction, aluminum face	0.10	-
Infrared emissivity, aluminum face	0.03	-
Sail specular reflectance fraction, chromium face	0.23	-
Solar absorption fraction, chromium face	0.57	-
Infrared emissivity, chromium face	0.6	-
Effective characteristic acceleration at 1.0 AU, a_c	0.045	$mm\text{-}s^{-2}$
Effective lightness number, b	0.0077	-
Maximum angular turning rate	0.5	$deg\text{-}s^{-1}$

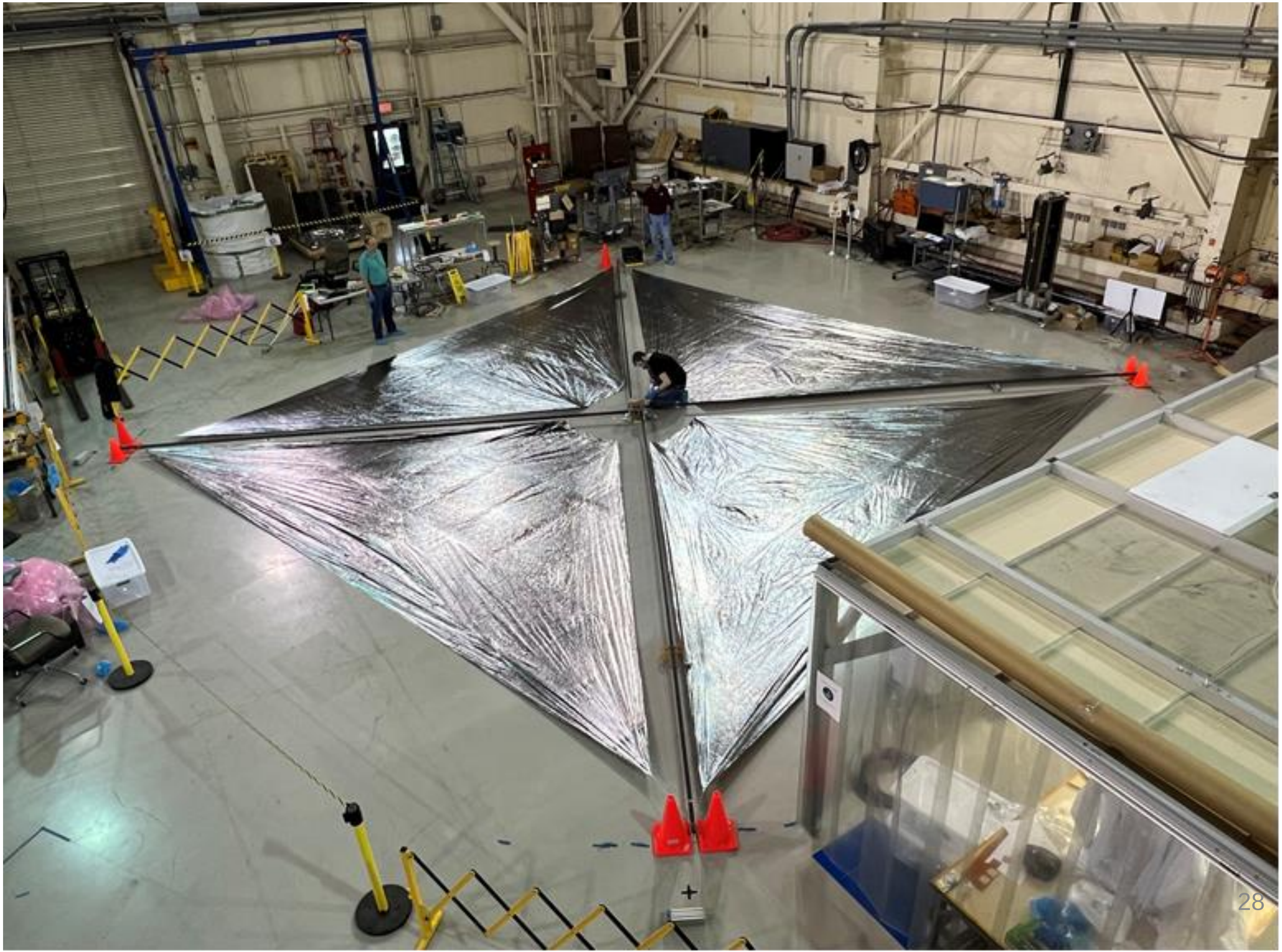
[1] Wilkie, K. "The NASA Advanced Composite Solar Sail System (ACS3) Flight Demonstration: A Technology Pathfinder for Practical Smallsat Solar Sailing," *Proceedings of the AIAA/USU Conference on Small Satellites, Next on the Pad*, SSC21-II-10. https://digitalcommons.usu.edu/smallsat/2021/all2021/146

ACS3: Level 1 Requirements

Ref: A9SP 2002 XR003, Project Level 1, 2, & 3 Requirements", Rev A Draft, ACS3 Project, NASA Ames Research Center

Requirement Number	Requirement Title	Requirement Text	Rationale
Project Requirements			
1.1	Sail Deployment	ACS3 **shall** deploy a composites-based small satellite solar sail on-orbit.	The ACS3 mission goal is to raise the Test Readiness Level (TRL) of NASA high strain deployable composite boom technology, lowering the risk of its use on future flight missions by successful on-orbit deployment of the ACS3 composite solar sail system. Note: Method of Verification that this L1 requirement is met will be one or more of: (1) Images of the fully deployed sail (with 80% coverage) from on-board cameras, or (2) boom hub encoders/limit switches confirming full deployment of all four booms, or (3) Ground images confirming full deployment, or (4) data confirming expected flight characteristics of the spacecraft with a fully deployed solar sail.
1.2	Boom Length & Sail Area	ACS3 **shall** deploy a solar sail with a minimum boom support structure length of 6.5 meters, and a corresponding minimum sail area of 70 square meters.	Based on recent mission studies, a solar sail area of 360 square meters, with a corresponding boom length of 14 meters, should be sufficient to perform a range of small spacecraft deep space missions, including Sun/Earth sub-L1 space weather monitoring and small body reconnaissance missions. To retire technical risk for these future mission-scale solar sails, the ACS3 technology demonstration solar sail should be of an appropriate scale relative to future full-scale solar sails to produce representative loads on the sail membranes and composite boom structures. For +/- 20% structural similitude with a future 360-m2 full-scale solar sail concept, boom lengths between 6.5 and 7.0 meters, which corresponds to total deployed sail areas between 70 and 82 square meters (with a minimum nominal sail membrane stress of 21 kPa), will be adopted for the ACS3 solar sail. (Ref: ACS3 Solar Sail Structural Scaling Requirements, rev. b, 20190308.)
1.3	Boom Technology Scalability	ACS3 **shall** demonstrate in the space environment the deployment of thin-ply high-strain composite boom technology developed by the GCD program's DCB project.	A goal of the ACS3 flight demonstration is to validate deployable composite boom technology for use on future sub-ESPA-class solar sail missions. ACS3 will use boom technology currently under development by the STMD Game Changing Development Program (GCDP) Deployable Composite Booms (DCB) project. This will ensure composite boom material plies, laminates, thicknesses, stowage strains, viscoelastic creep behavior, and manufacturing techniques are similar and relevant to those of larger composite boom systems being developed for future small-spacecraft mission applications.
Project Goals			
1.4	Sail Characteristic Acceleration	ACS3 **should** estimate the effective characteristic acceleration of the ACS3 solar sail spacecraft.	The characteristic acceleration of a solar sail spacecraft is the most fundamental measure of thrust capability of a solar sail. This can be estimated by orienting the sail to its optimal orbit raising rotation angle and measuring the orbit altitude change per unit time. The effective characteristic acceleration can be derived from this, which is analogous to a delta V change per unit time. The characteristic acceleration estimate can then be compared to the design characteristic acceleration to gauge how well the sail performed. Note: Method of Verification will be as measured from onboard GPS or ground radar.
1.5	Sail System Structural Dynamics	ACS3 **should** characterize on-orbit boom system dynamics.	Characterizing the boom system dynamics, including observed displacement of the boom tips, and detectable fundamental frequencies of the sail/boom system assists in validating the sail/boom subsystem flexible mode model. This information would be valuable for scaling the sail/boom system to a larger size.

ACS3: Sail-Boom Subsystem (SBS)
(flight system, pre-integration fit check)



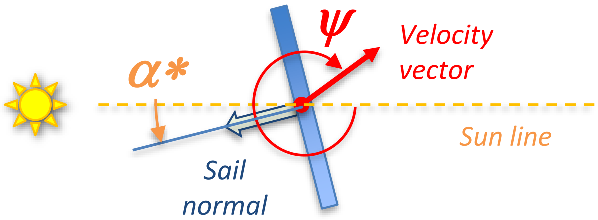
SMA Raising/Lowering Steering Profile [ref: McInnes, 1999]

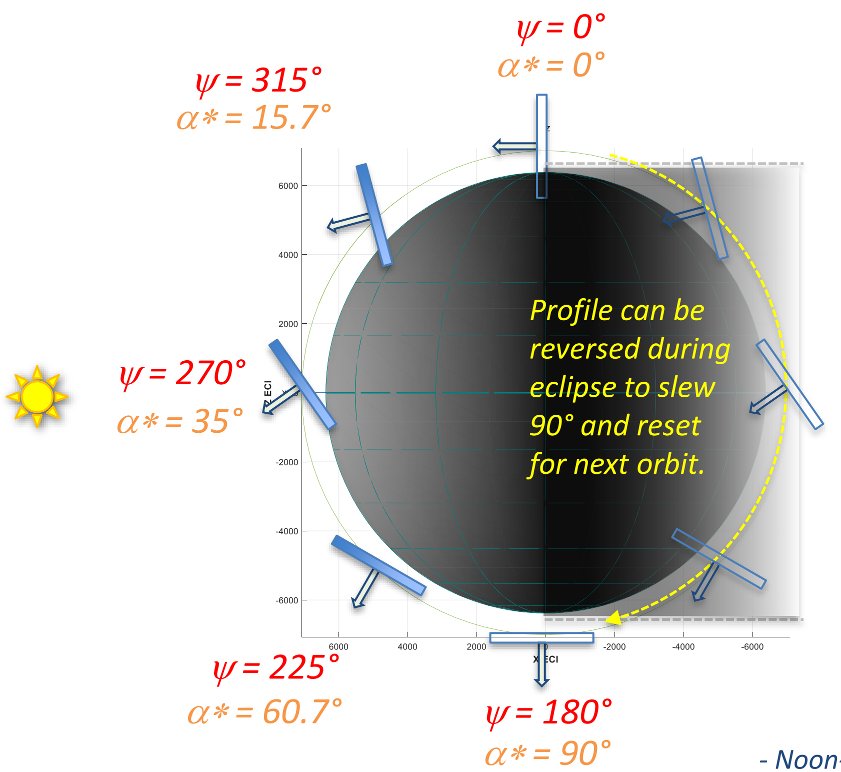
- **Locally optimal steering law for maximum energy gain/loss each orbit.**
  - Sail oriented at all times to maximize solar radiation thrust component in direction of flight.
  - For lowering, thrust component opposite direction of flight is maximized.

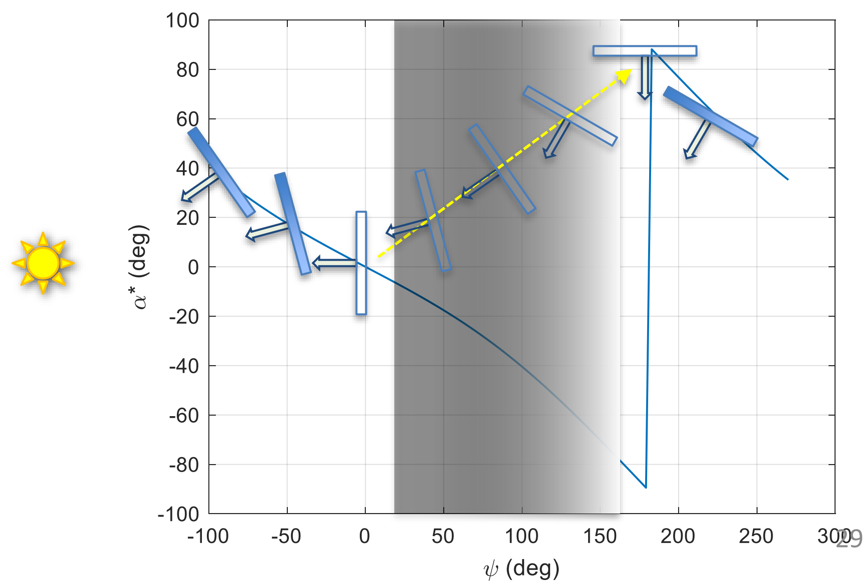
Locally optimal sail pitch angle.

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. -

Relationship between Solar-Sail Altitude and Solar Activity [Mengali, Quarta, 2005]

- Sun pointing simulation with fully deployed sail, no J2 perturbations (only drag and solar radiation pressure):
  - T_0 = March 1, 2022; T_{END} = May 1, 2022
  - 700 km initial altitude, 0 deg RAAN, 45 deg inclination
  - NRL atmospheric density model; F10.7 = 150 sfu; Ap Index = 4
- Nondimensional variable ***f*** : *Defined as twice the ratio of local dynamic pressure to solar radiation pressure for an ideal solar sail:*

$$f = \frac{\rho v^2}{P}$$

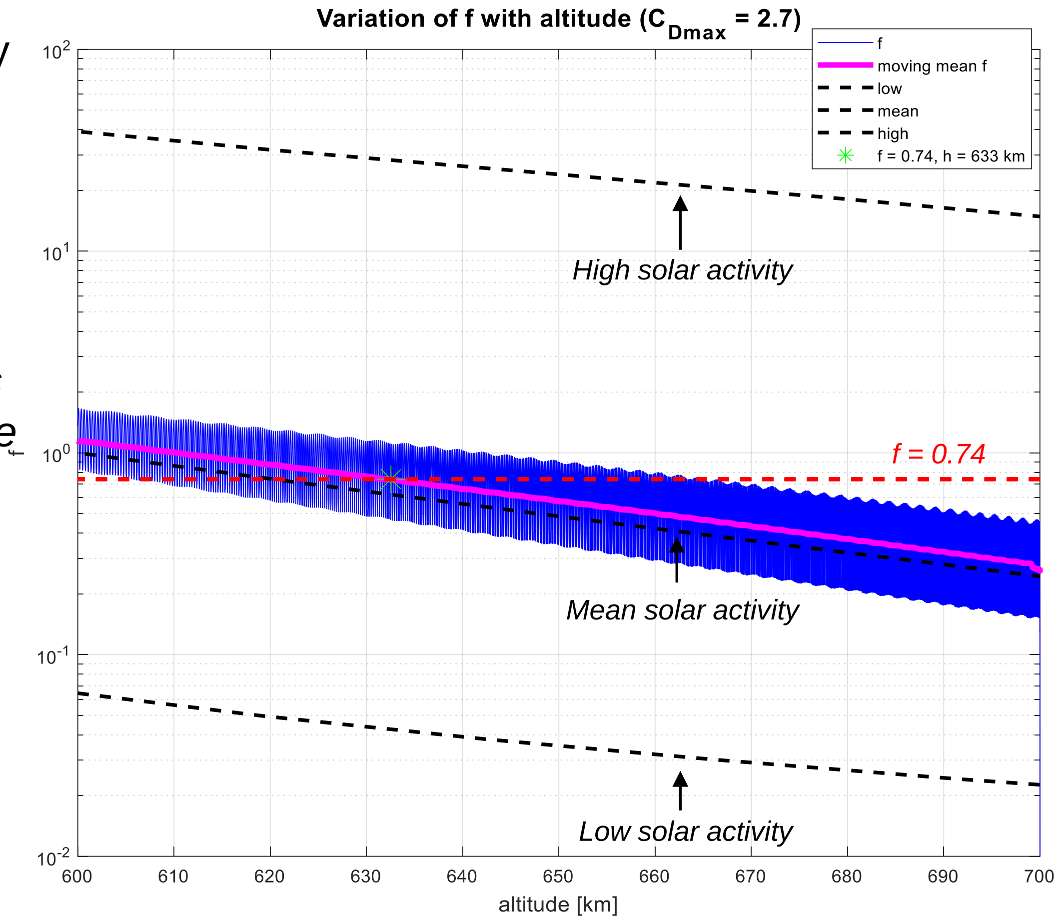
- For near-circular orbits:

$$f \cong \frac{\mu \rho}{P r}$$

- *At the minimum sailing altitude, maximum sail thrust equals maximum aerodynamic drag*:

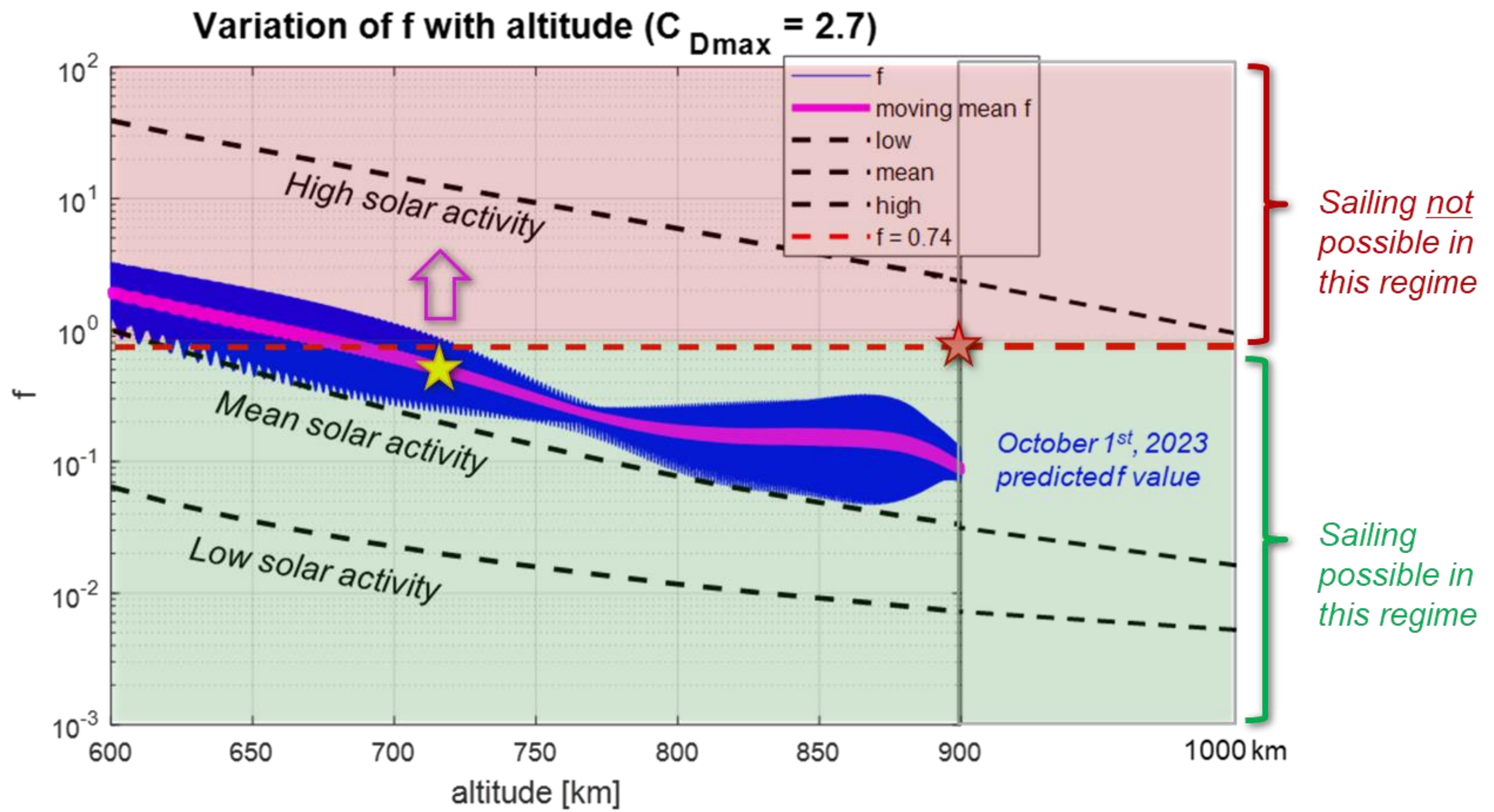
$$PA = \frac{\rho A v^2 C_D}{2} \qquad f C_D/2 = 1$$

where $C_D = 2.7$, f $= 0.74$.



Ref: Mengali, G., and Quarta, A. A., "Near-Optimal Solar-Sail Orbit-Raising from Low Earth Orbit," Journal of Spacecraft and Rockets, Vol. 42, No. 5, Sept.-Oct. 2005, pp. 954-958.

ACS3: Predicted solar cycle effect on near-term sailing capability *(f ≤ 0.74)*



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DCB Technology Scaling Roadmap for Future Solar Sailing Applications