An Overview of the NASA Advanced Composite Solar Sail (ACS3) Technology Demonstration Project

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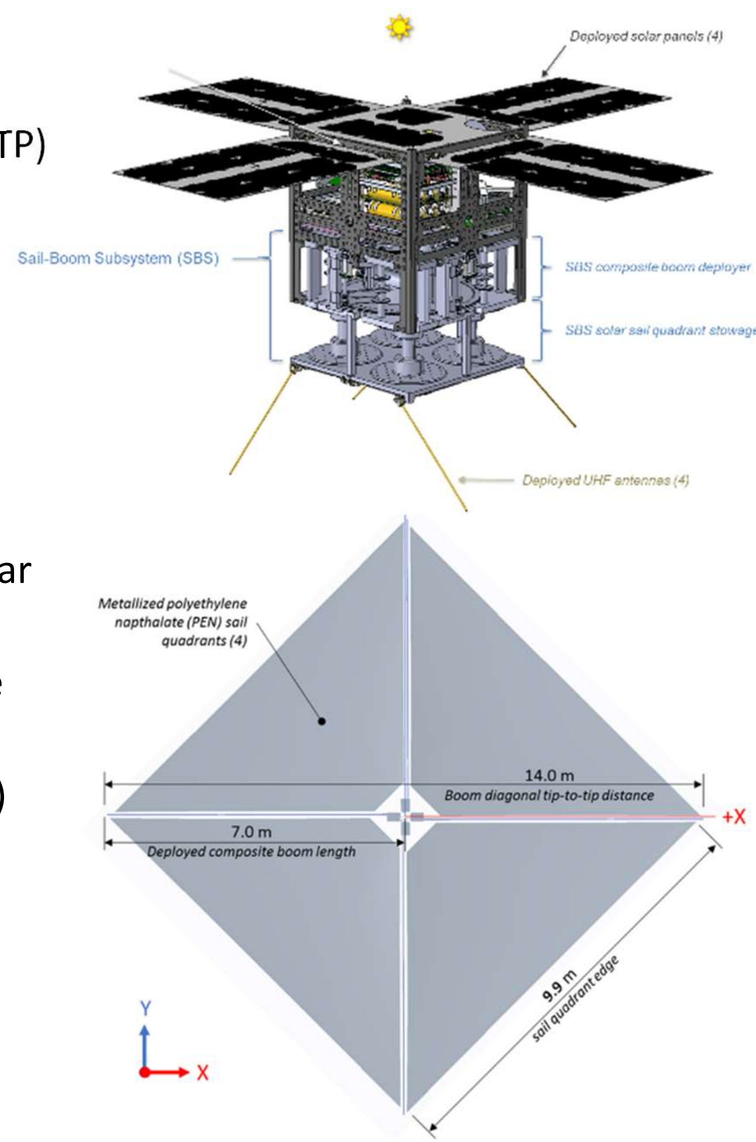
National Aeronautics and Space Administration
www.nasa.gov

Advanced Composite Solar Sail System Project (ACS3)

LEO Solar Sail Structures Technology Demonstration

- **Concept: Sub-scale (40%) high performance composites-based structure solar sail system deployment and characterization experiment in LEO.**
  - Sponsor: STMD Small Spacecraft Technology Program (SSTP)
  - Partnership between LaRC, ARC, Santa Clara University.
- **NPR 7120.8 Research & Tech. Demonstration Project**
- **Partner roles and responsibilities:**
  - **NASA Ames Research Center** –12U bus procurement and payload integration, ACS3 payload avionics including diagnostic camera system and FSW.
  - **NASA Langley Research Center** – responsible for ACS3 solar sail system payload and solar sail technology.
  - **Santa Clara University Robotic Systems Lab** – responsible for CubeSat operations support.
  - **STMD GCDP** - Deployable Composite Booms project (DCB) technology for booms. ← ***Key new structures technology***
    - ***7.0 m compact, high stiffness, low weight composite booms***
- ***Launch: ca. late-2021.***
  - 700 km LEO minimum altitude to minimize aero drag.
  - Sun-synchronous orbits preferred.

ACS3 12U Spacecraft and Deployed Solar Sail



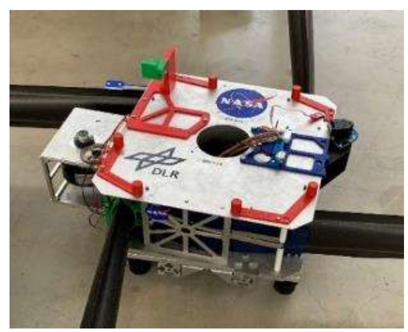
NASA Deployable Composite Boom Project (DCB)

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
  - 4-year ($4M) joint effort between NASA and German Aerospace Research Agency (DLR).
- **DCB composite booms are Ideal for small spacecraft requiring large dimension deployable structures, e.g., solar arrays, antennas, reflectors, sunshields.**
- **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 booms lengths.*
- **The Advanced Composite Solar Sail project (ACS3) will demonstrate DCB *composite boom technology* for solar sailing applications.**

Space Technology
Game Changing Development
Deployable Composite Booms

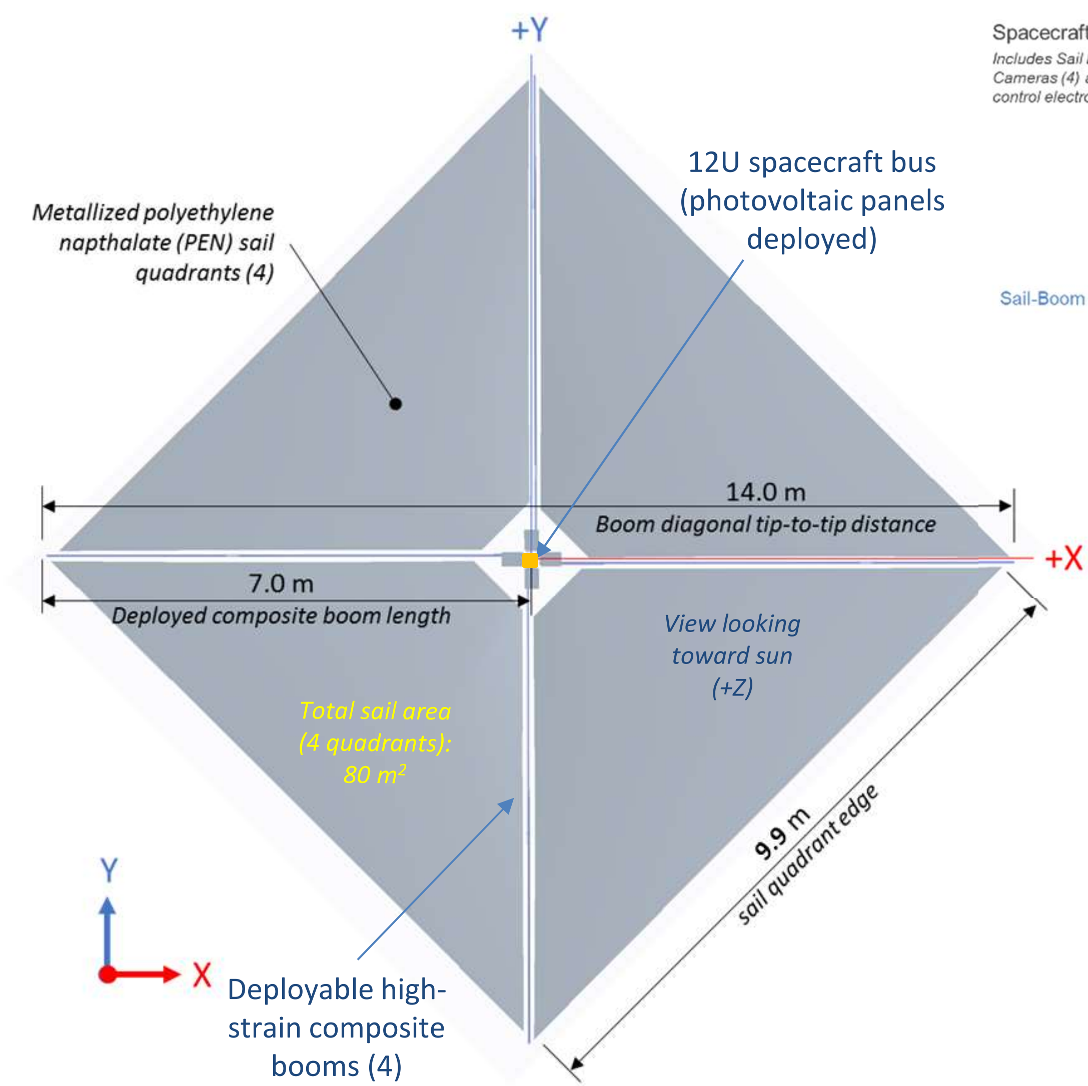
NASAfacts



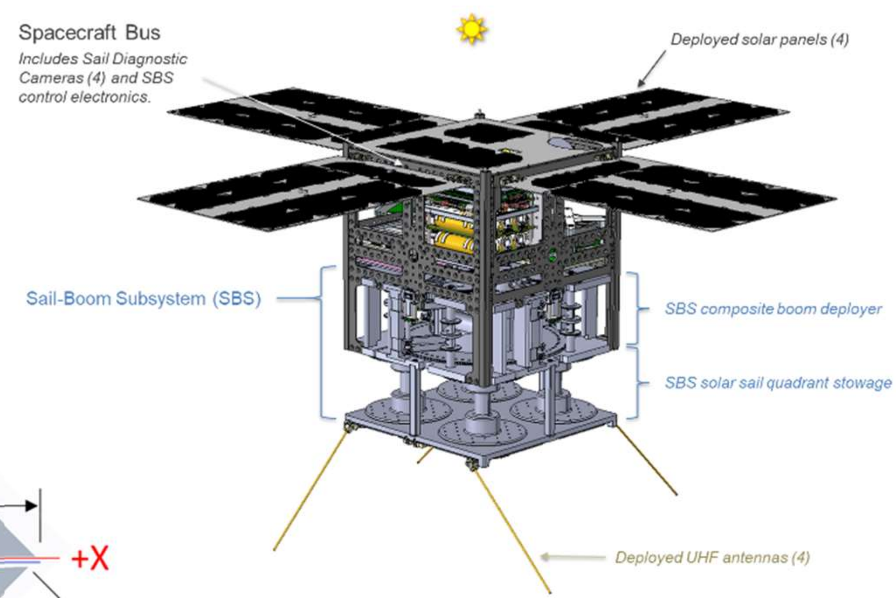
https://gameon.nasa.gov/projects/deployable-composite-booms-dcb/

ACS3: 12U Configuration – Sail Deployed

ACS3 12U Deployed Configuration

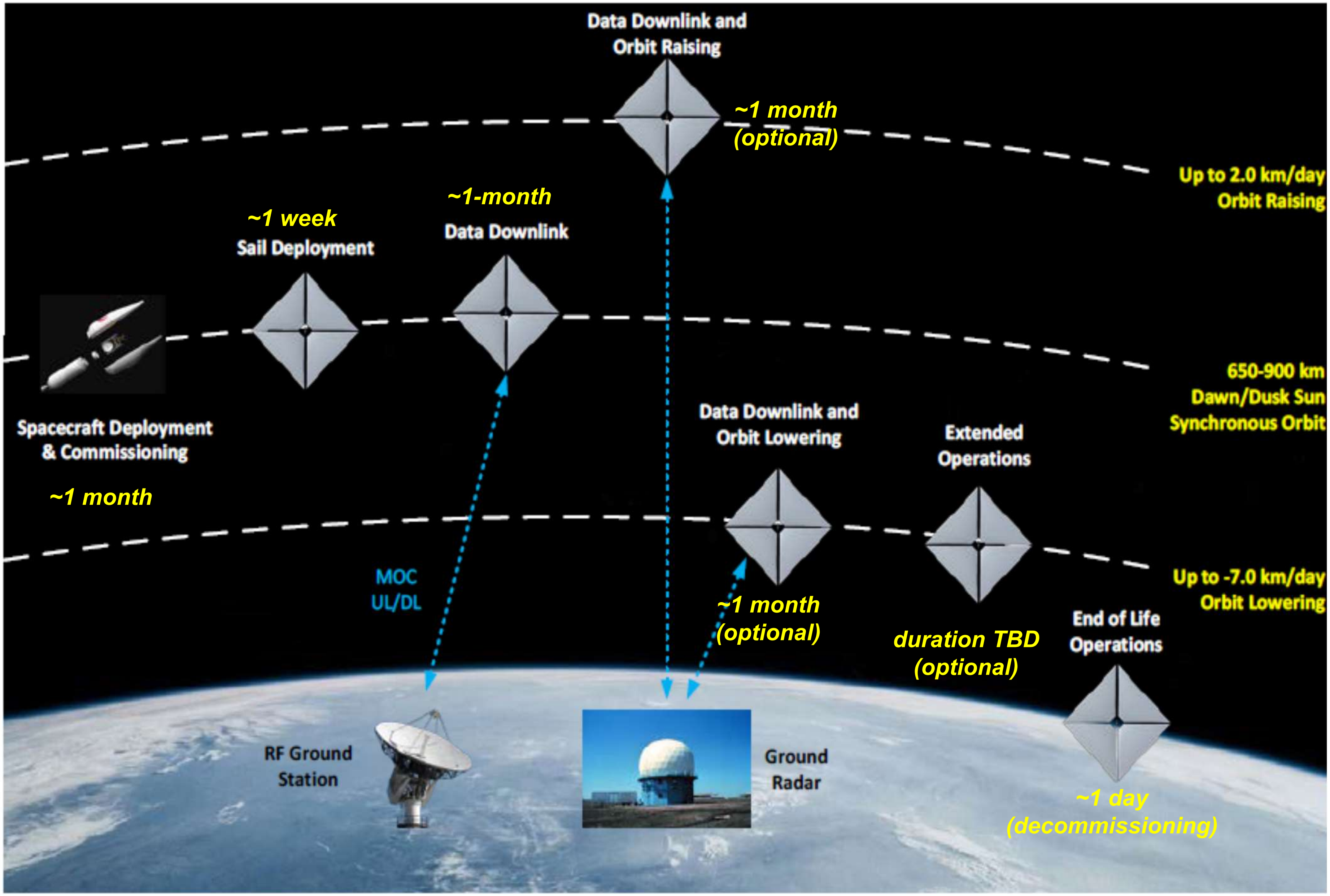


ACS3 12U Bus and Payload Arrangement



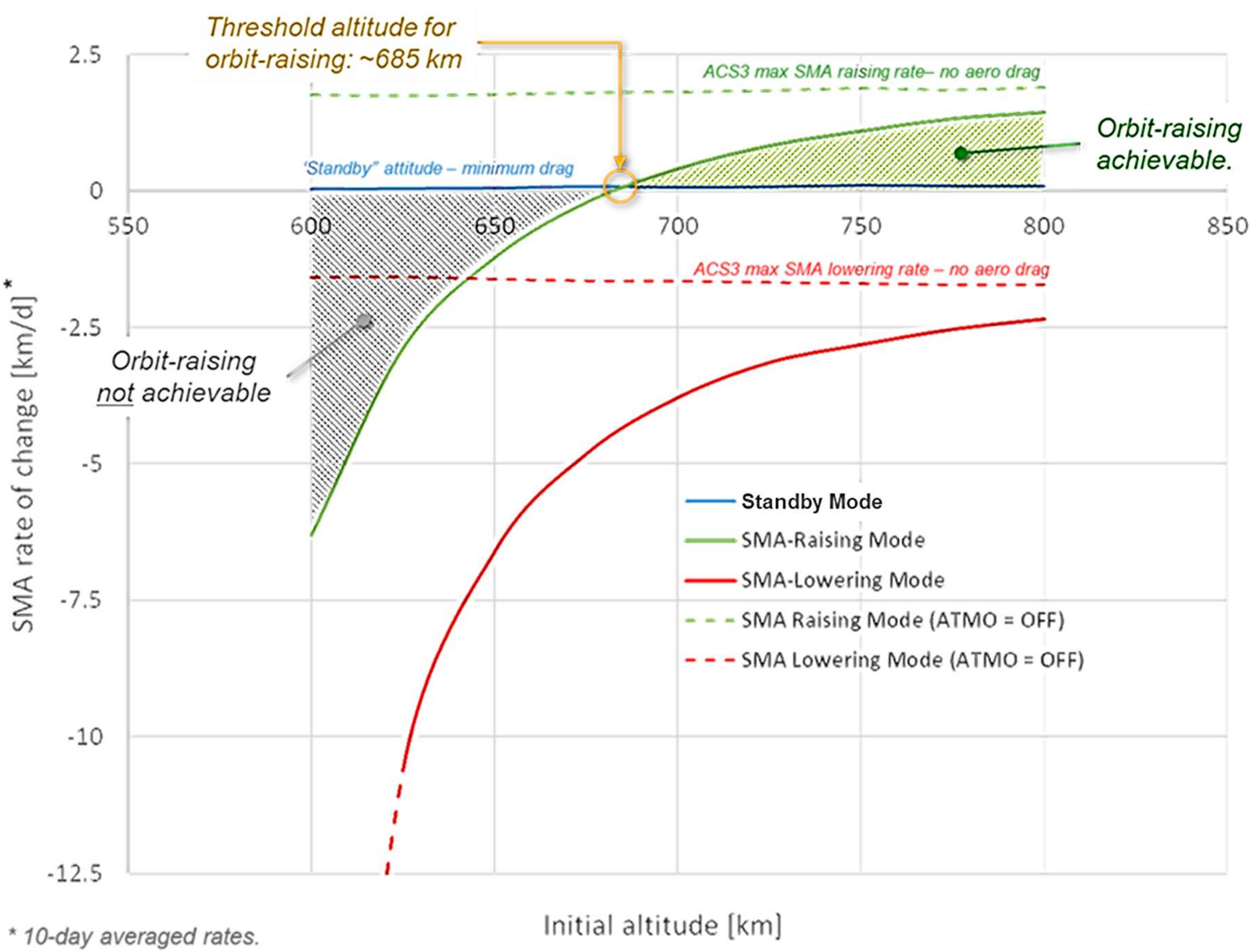
12U 'ACS3' Characteristics	
Sail system mass [kg]	< 9
Total space vehicle mass [kg]	< 18 (Targeting 15)
Total sail area [m^2]	80
Lightness number, β [-]	~0.008
Characteristic acceleration, a_c, 1 AU [mm/s^2]	~0.05

ACS3: Concept of Operations



ACS3: Orbit Raising-Lowering Capability

NM-SSO initial orbits; Locally Optimal Steering Law [ref: McInnes]

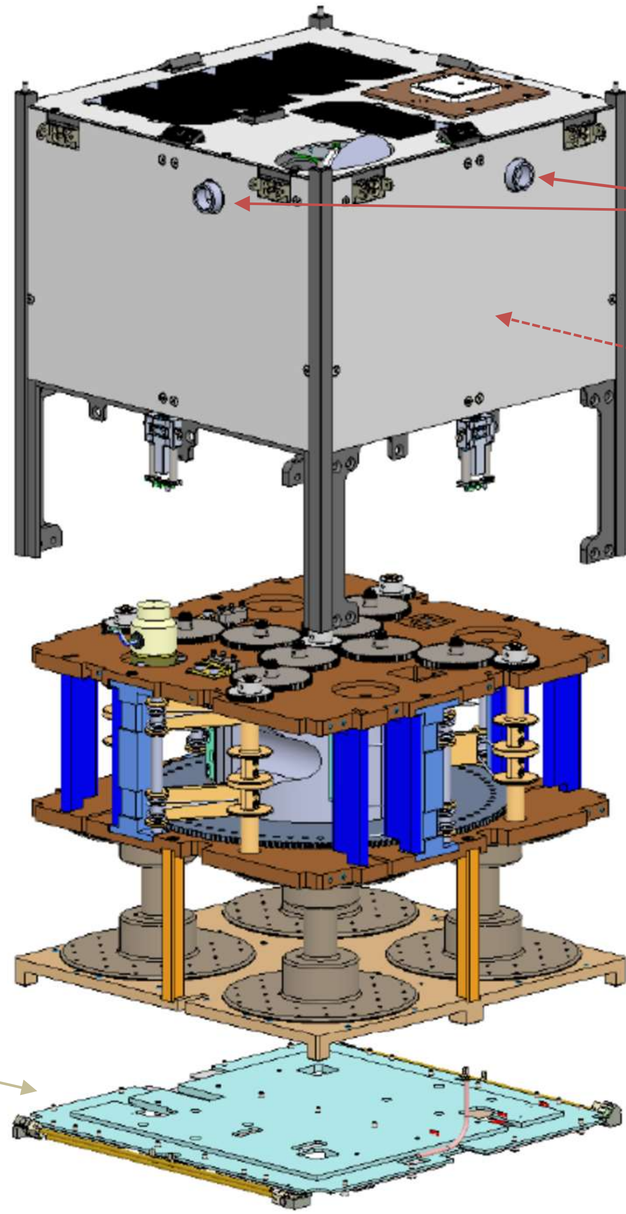


* 10-day averaged rates.

ACS3: Spacecraft Configuration Detail

20200115 configuration; solar panels, sails and booms omitted.

- NASA ARC
- NASA LaRC
- AST-NanoAvionics



Spacecraft Bus:

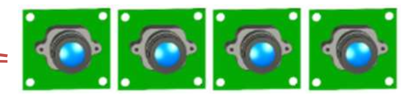
- S-band transceiver
- UHF radio
- Flight computer
- ADCS
  - Reaction wheels (4)
  - Magnetorquers (3 x 3-axis)
  - Sun sensors (5)
  - GPS receiver
  - Star tracker
  - IMU
- EPS

Sail-Boom Subsystem: (SBS)

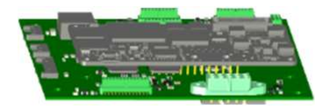
Spacecraft bus "-Z" plate:

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

Payload Avionics System: (AS)



AS sail diagnostic cameras (4)



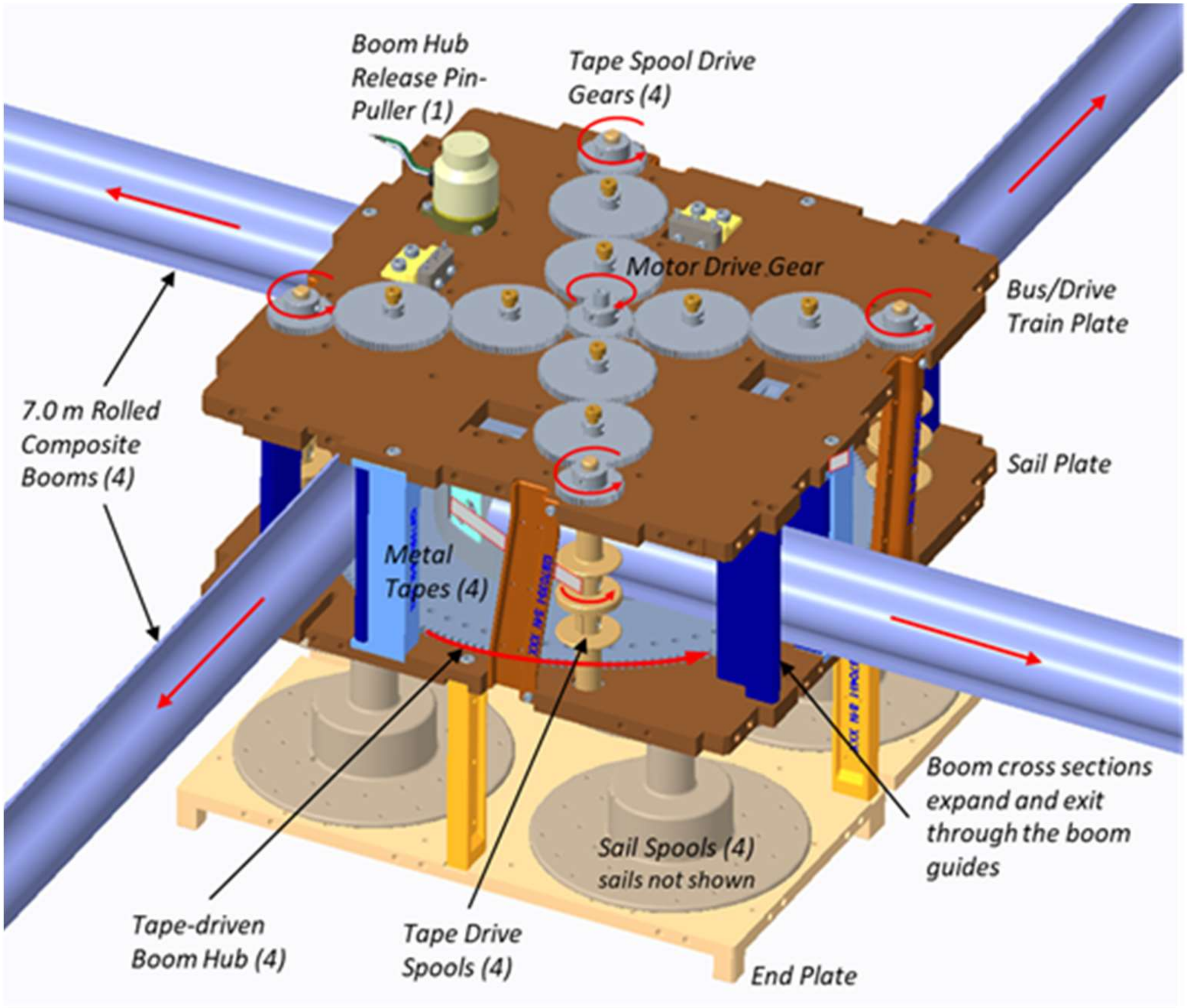
AS payload control electronics

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

SBS composite boom deployer

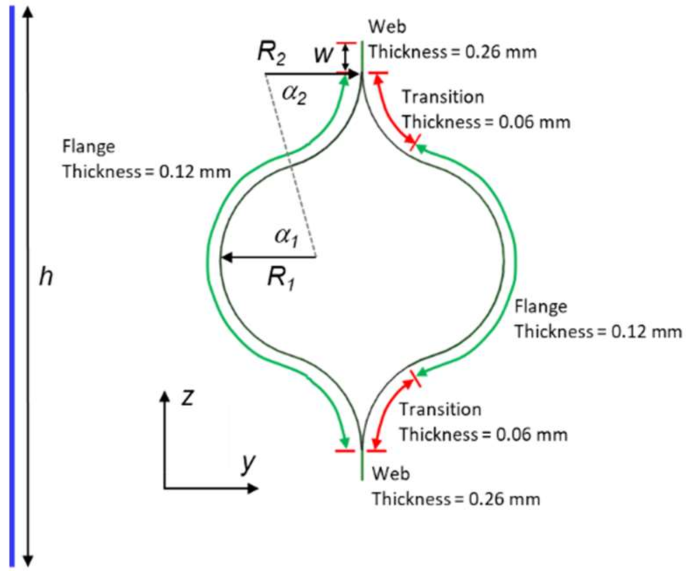
SBS solar sail quadrant stowage

ACS3: Sail-Boom Subsystem Deployer Design

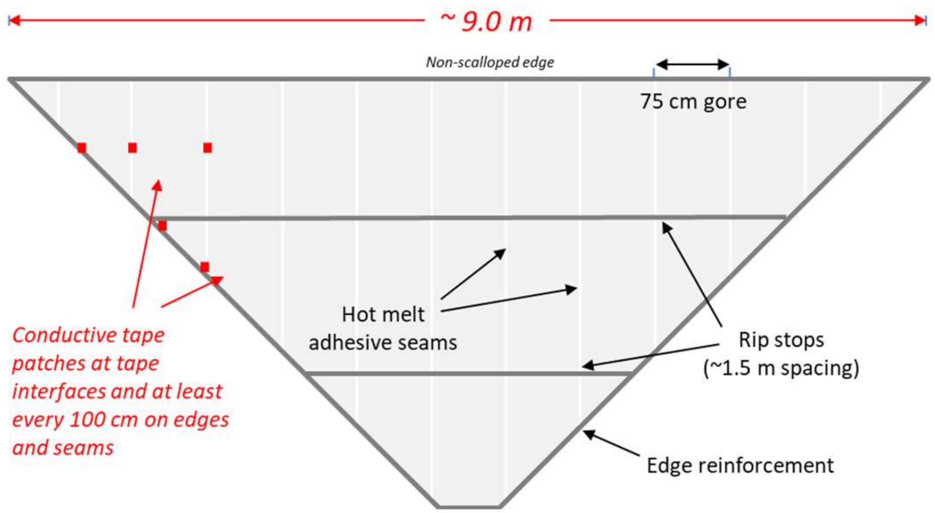


ACS3: Deployable Composite Boom Design

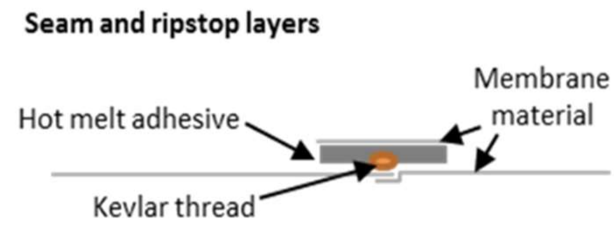
- ACS3 uses ***collapsible tubular mast*** (CTM) composite booms developed by the NASA STMD/GCDP Deployable Composite Booms (DCB) project.
- ACS3 booms are 7.0 m long.
  - Cross-section geometry:
    - Flattened height, *h*: 65 ± 0.5 mm
    - Expanded CS geometry:
      - CS width: 33.0 mm, height: 49.9 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.



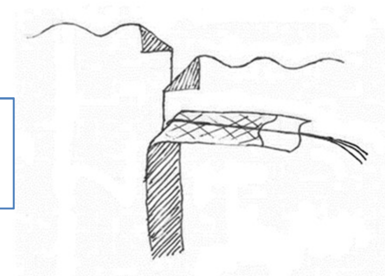
ACS3: Solar Sail Quadrant Design and Fabrication



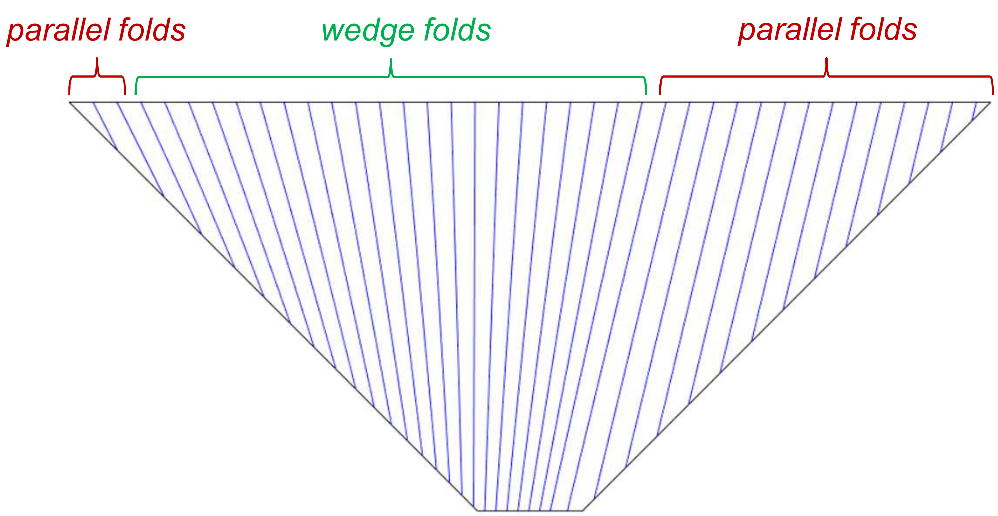
Quadrant Design



Flight membrane material: 2.115 μm Al/PEN/Cr



Seam detail

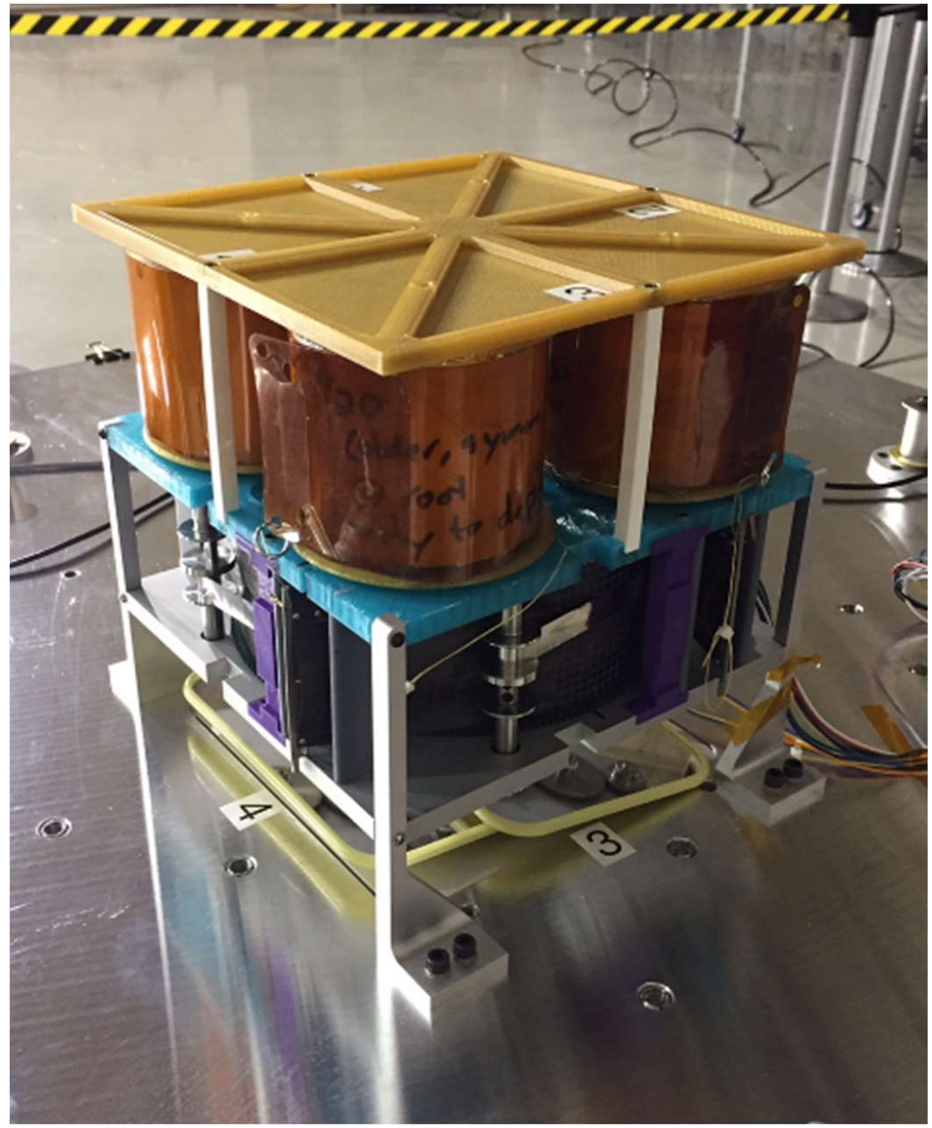


Quadrant folding scheme

Quadrant spooled for stowing

ACS3: Boom and Sail Packaging

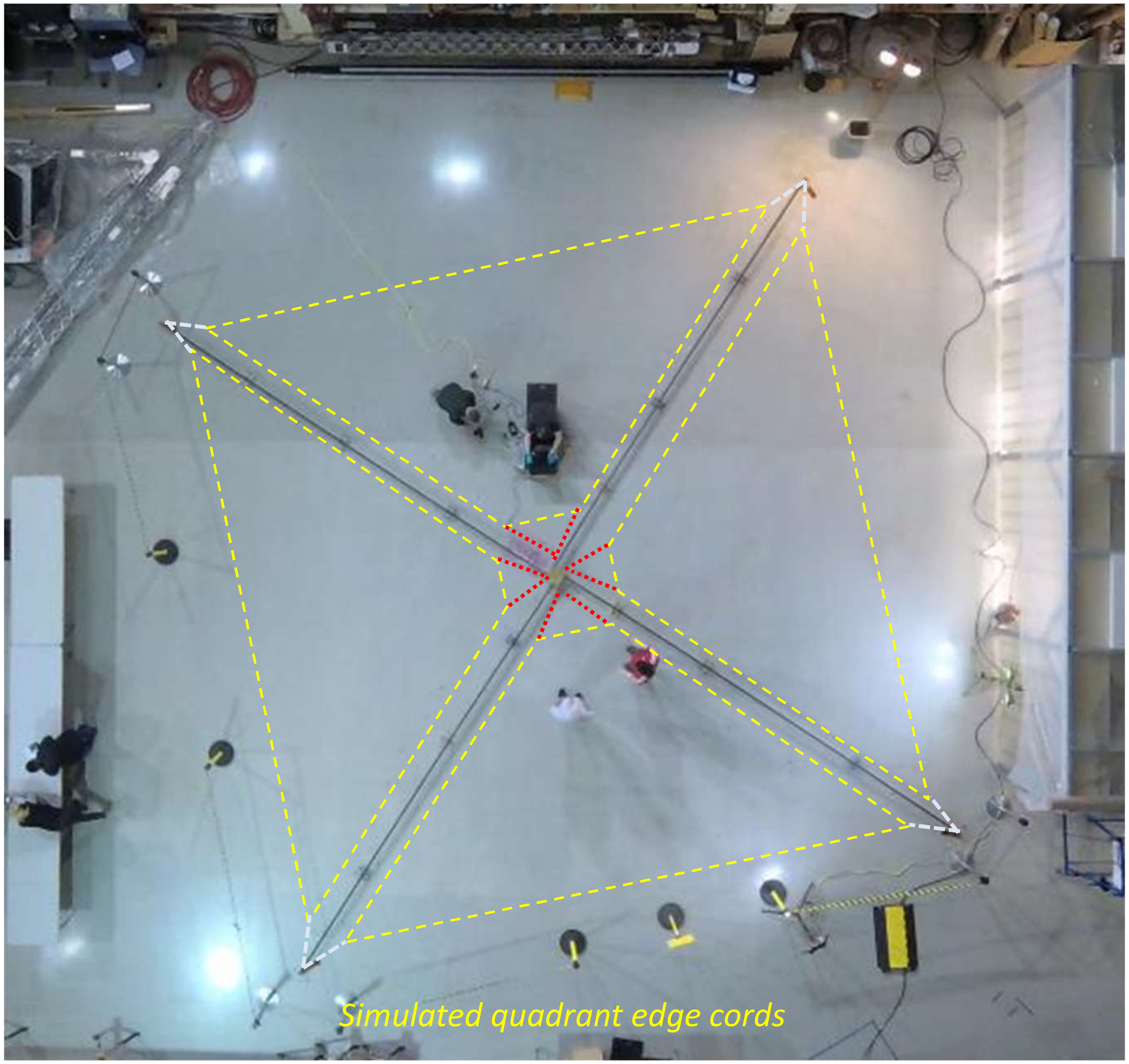
Boom reeling and packaging

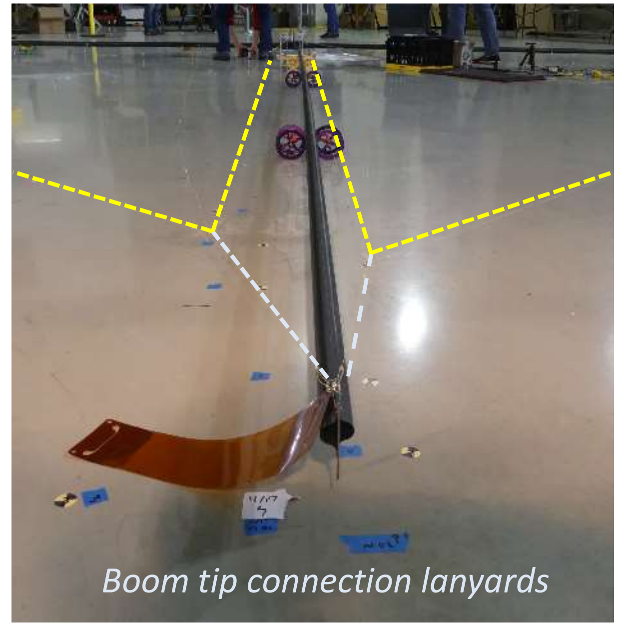


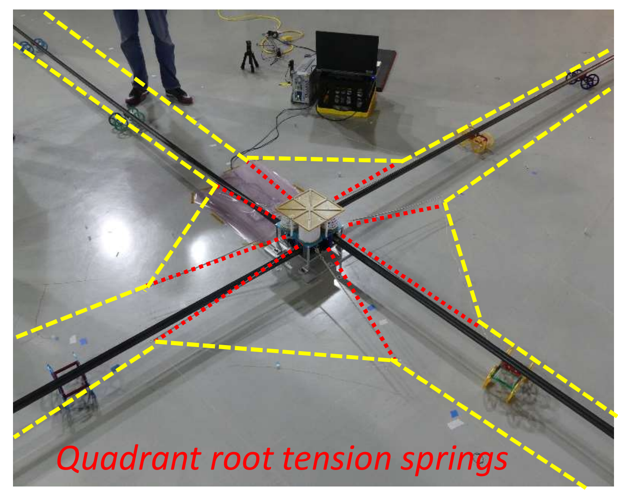
Sail and Booms Stowed in SBS Prototype

SBS Prototype Deployment Testing w/ Simulated Sail Quadrants

Deployment Test #5, 2x tensioning springs

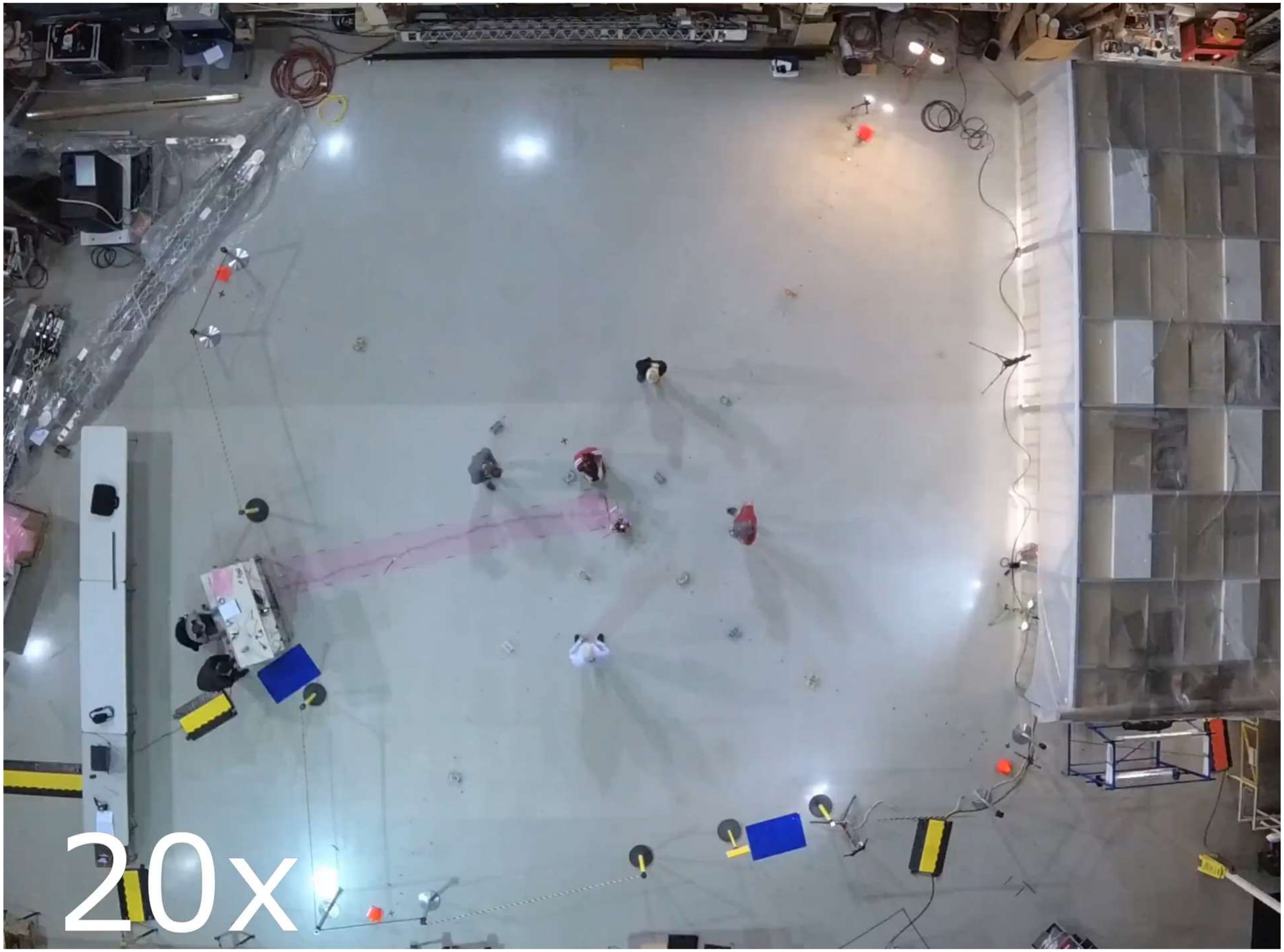






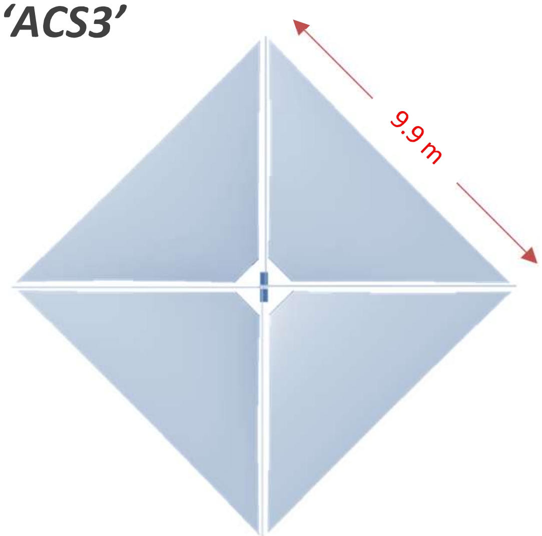
SBS Prototype Deployment Testing w/ Development Sails

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



ACS3: Extensibility to future solar sail applications

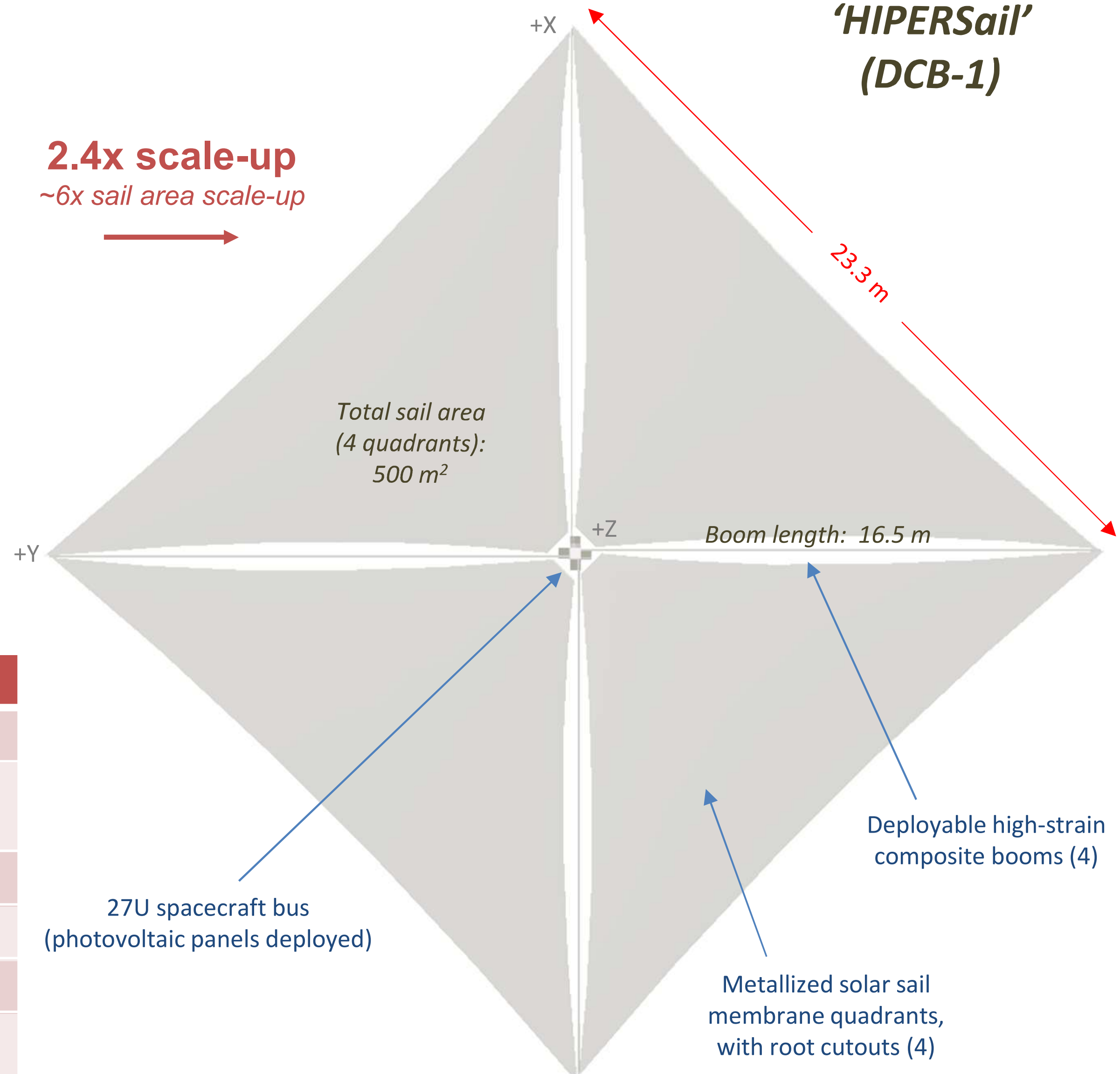
'ACS3'



2.4x scale-up

~6x sail area scale-up

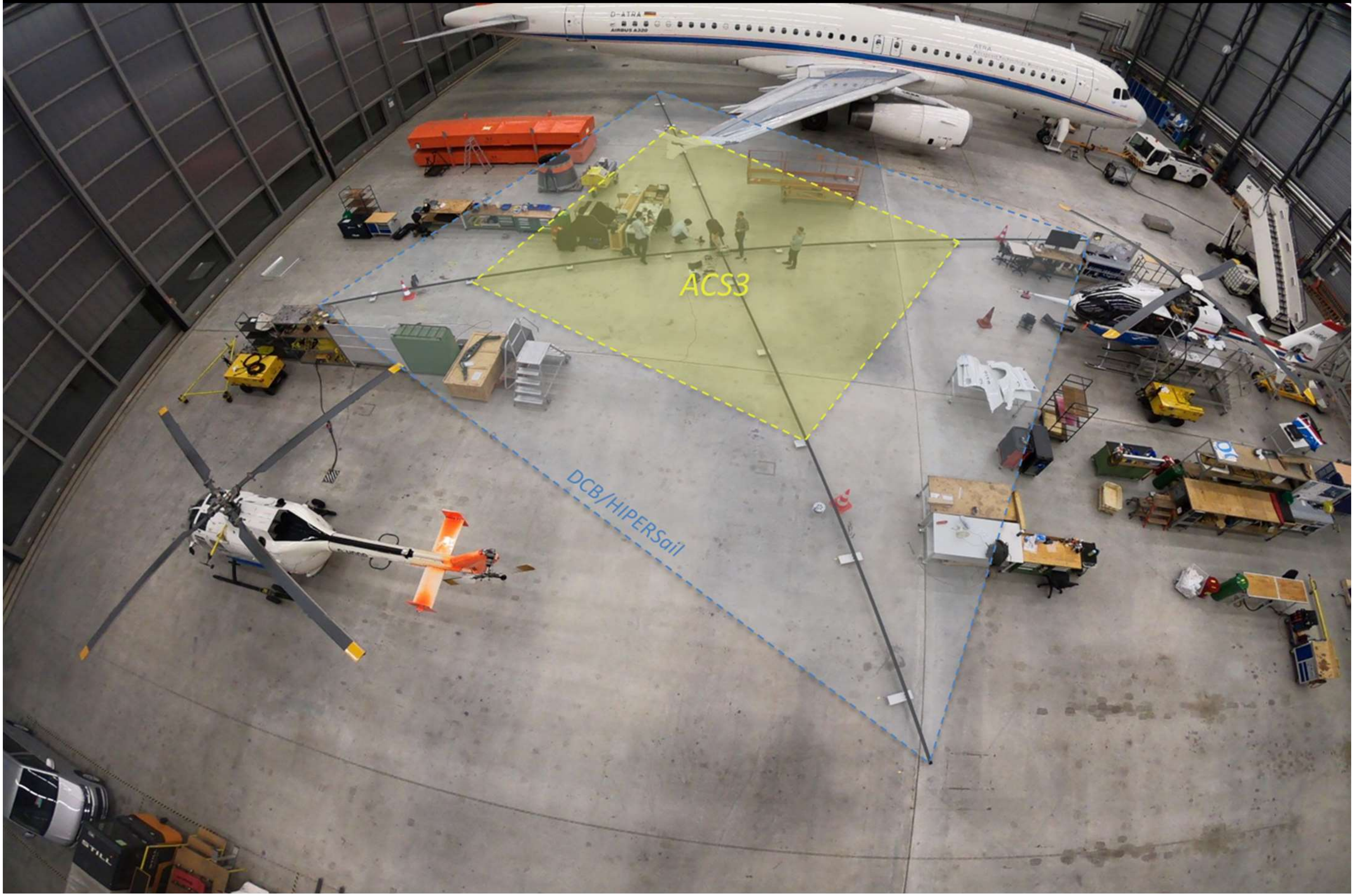
'HIPERSail'
(DCB-1)



27U 'HIPERSail' Characteristics	
Sail system mass [kg]	15-18
Total space vehicle mass, including contingency [kg]	25-30
EOL power, 1 AU [W]	50+
Total sail area [m^2]	360-520
Lightness number, β [-]	0.022 – 0.027
Characteristic acceleration, a_c, 1 AU [mm/s^2]	0.13 - 0.16

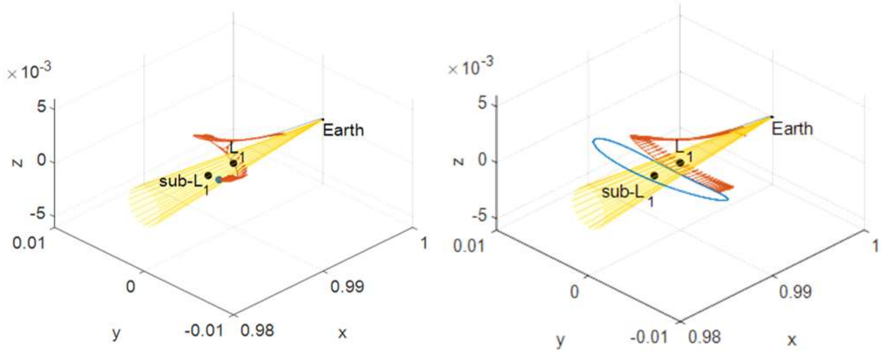
Extensibility to Future Solar Sail Applications

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

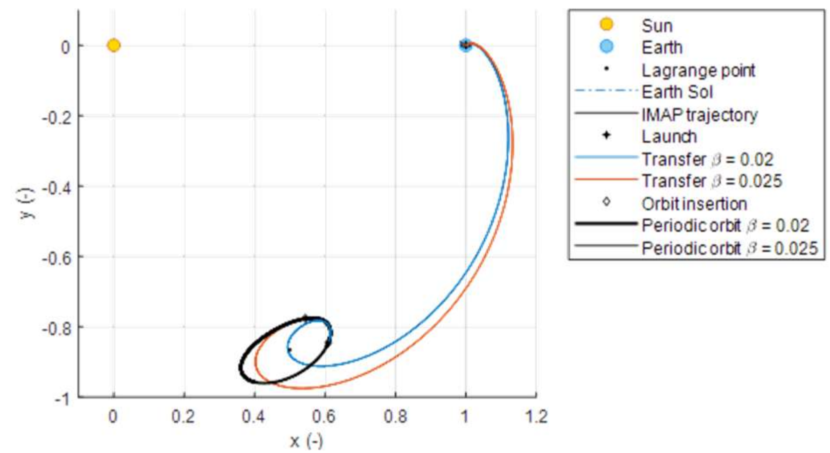


DCB/ACS3 Solar Sail Mission Applications β=0.02-0.025

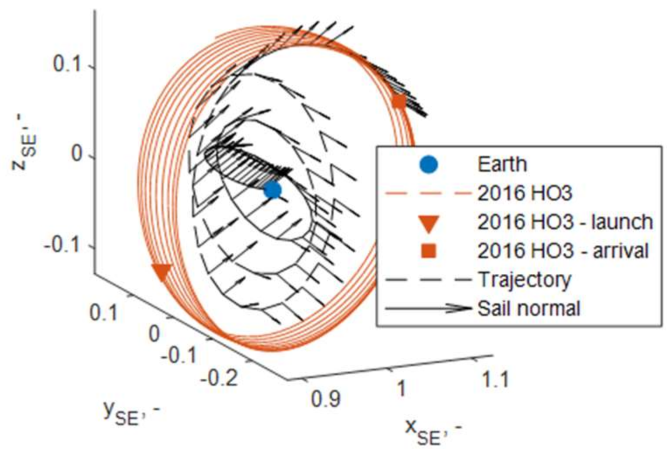
Sun-Earth Sub-L1 Space Weather EW



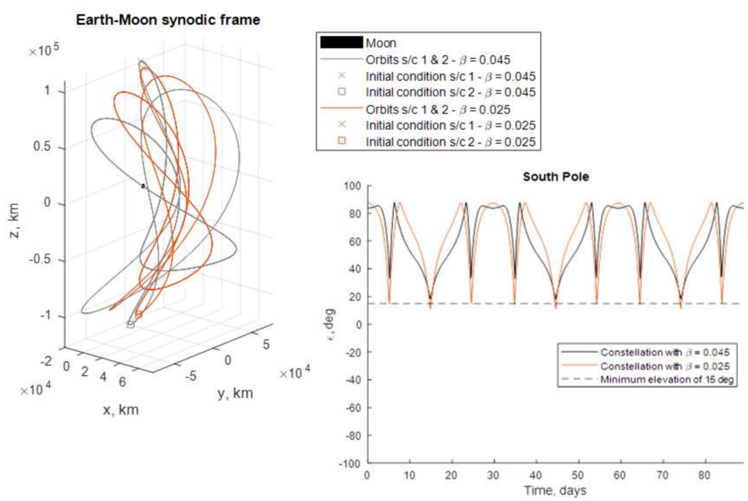
Sun-Earth L1-L5 Transfers



NEA Planetary Science

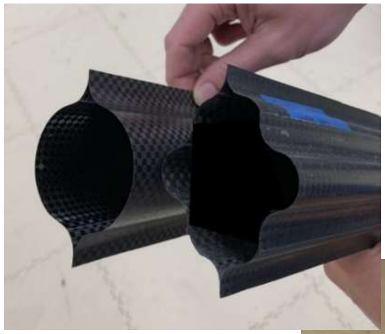


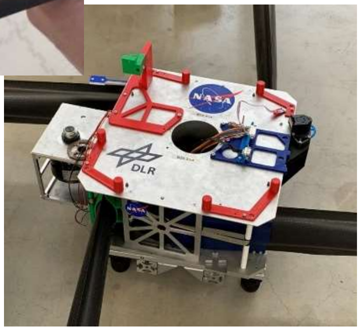
Lunar South Pole Comm Relays



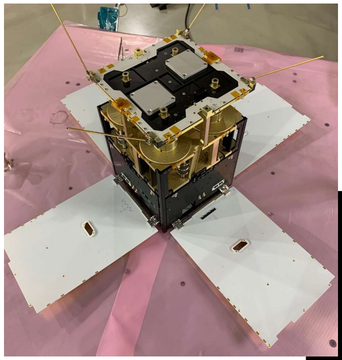
ACS3 and DCB Projects: Summary and Status
(ca. December 2021)

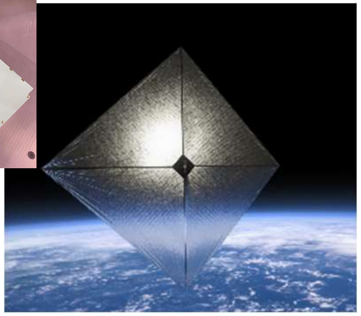
- **Deployable Composite Booms Project (DCB):**
  - *DCB-1: successfully developed DCB design and manufacturing capabilities to 16.5-m scales.*
  - *DCB-2: follow-on project approved for FY21 start.*
  - ***DCB-2 will develop larger-scale deployable composite booms and manufacturing capabilities.***

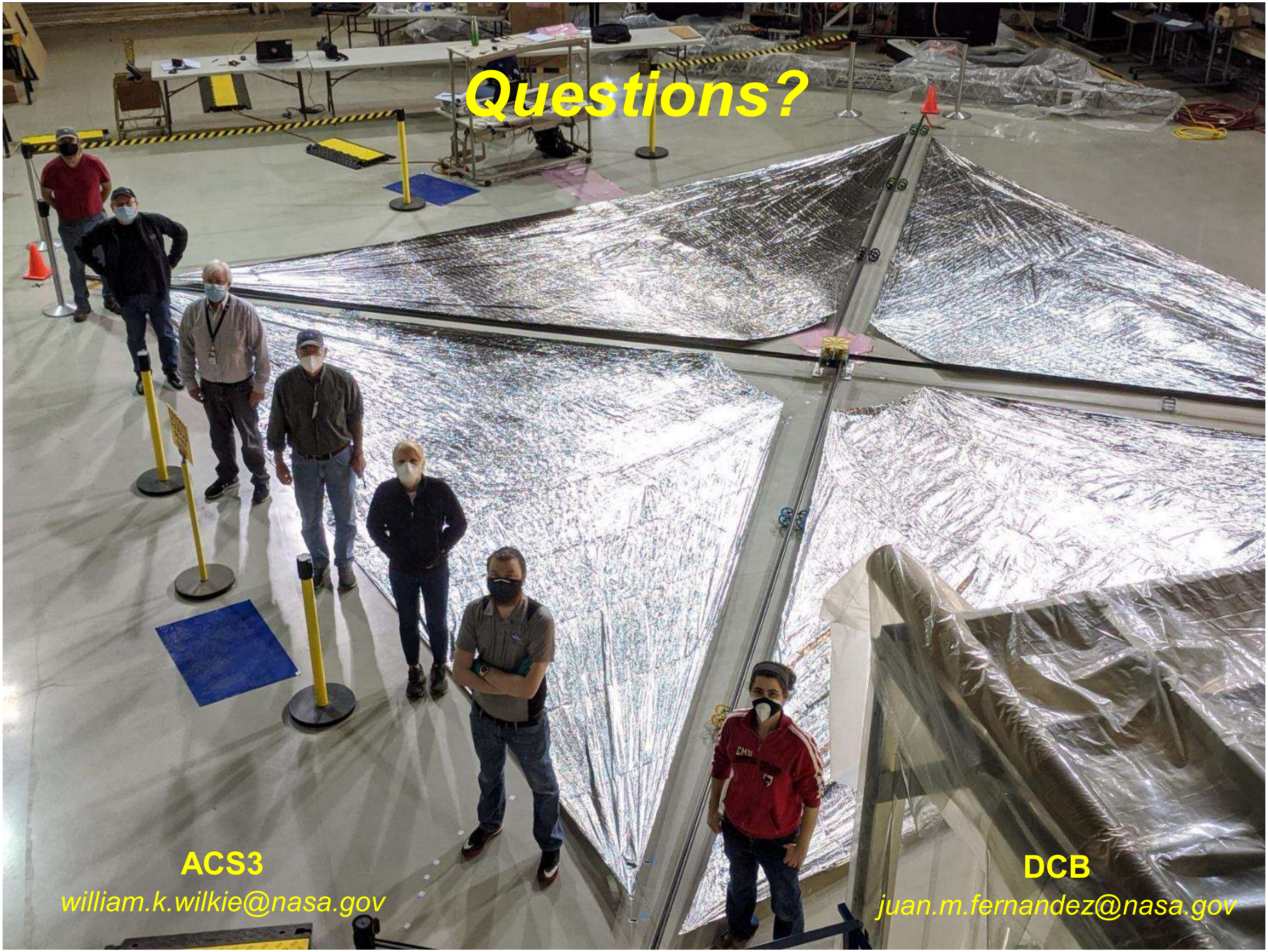




- **Advanced Composite Solar Sail Project (ACS3):**
  - *80 m^2 sub-scale solar sail flight demonstration of DCB-1 technology in LEO.*
  - Solar sail payload and 12U spacecraft Assembly, Integration and Testing underway.
  - ***ACS3 launch: ca. Q4 CY 2021.***






Questions?
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DCB
juan.m.fernandez@nasa.gov


NASA
ACS3
ARC
LaRC
SCU

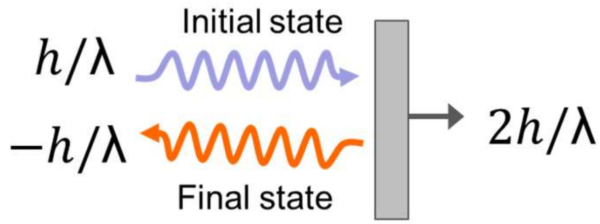
What is Solar Sailing?

- Solar sails are large area, lightweight membrane structures that produce *propellantless thrust* using momentum transfer of reflecting solar photons.

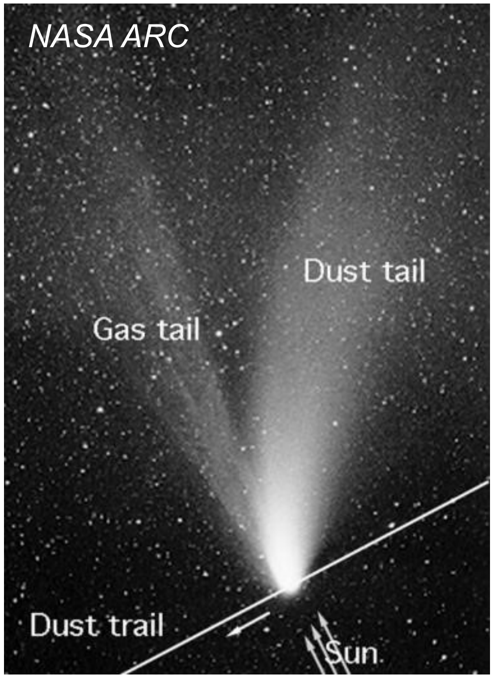
Momentum of a photon:

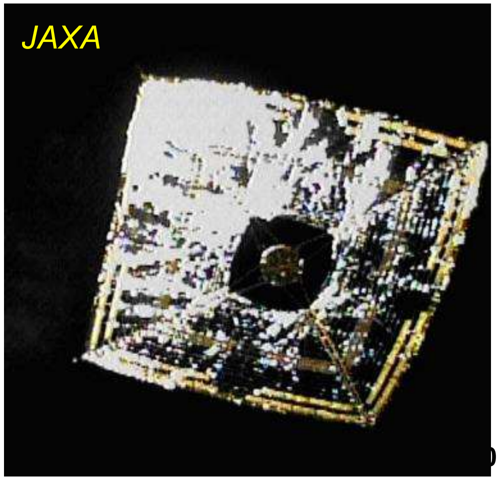
$$p_{photon} = \frac{h}{\lambda}$$

Momentum transfer to a perfect reflector:



- The momentum of sunlight is called *solar radiation pressure (SRP)*.
  - Comet tails are partly directed by SRP.
- Solar radiation pressure is **not** solar wind.
  - Solar wind forces, i.e., forces due to the charged particle flux of the sun, are ~10^{-3} smaller than SRP.
- The state of the art in solar sailing is the 14-m IKAROS solar sail, launched and successfully flown by JAXA in 2010.





Solar Sailing: A Brief History of Flight Projects
(launched 2005 through 2019)

2005

Cosmos 1
- Operator: Planetary Society
- Sail: 600 m2; inflatable booms.
- Bus: custom; 100 kg
- Launch date: 6/21/2005
- Status: Launcher failure.

NanoSail-D
- Operator: NASA ARC
- Sail: 10 m2; TRAC booms
- Bus: 3U; 4 kg
- Launch date: 8/3/2008
- Status: launcher failure.

2010

IKAROS
- Operator: JAXA
- Sail: 200 m2; centrifugal
- Bus: Custom; 315 kg
- Launch date: 5/20/2010
- Status: Mission success. Last contact in 2015.

2010

NanoSail-D2
- Operator: NASA MSFC
- Sail: 10 m2; TRAC booms
- Bus: 3U CubeSat; 4 kg.
- Launch date: 11/20/2010; deployed 1/17/2011
- Status: Mission success; deorbited 9/17/2011.

2015

Lightsail 1
- Operator: Planetary Society
- Sail: 32 m2; TRAC booms.
- Bus: 3U CubeSat; 4.5 kg.
- Launch date: 5/20/2015; deployed 6/7/2015.
- Status: partial success; one image of sail downlinked; deorbited 6/14/2015.

DeOrbitSail
- Operator: Surrey Space Centre
- Sail: 16 m2; composite booms.
- Bus: 3U CubeSat; 3 kg
- Launch date: 10/7/2015.
- Status: Sail failed to deploy.

2017

InflateSail
- Operator: University of Surrey
- Sail: 10 m2; composite tape booms; inflatable mast.
- Bus: 3U CubeSat; 3.2 kg.
- Launch date: 6/23/2017.
- Status: Success. Deorbited on 9/3/2017.

CNUSail
- Operator: Chungnam National University, South Korea.
- Sail: 4 m2; steel carpenter tape booms.
- Bus: 3U CubeSat; 4 kg.
- Launch date: 1/12/2018.
- Status: satellite failure.

CubeSail
?
- CU Aerospace.
- Sail: 20 m2; centrifugal.
- Bus: split 3U; kg total.
- Launch date: 12/16/2018
- Status: Beacon contact on initial orbit. Sail deployment delayed until orbit decays from 500 km to 350 km. Current status unknown.

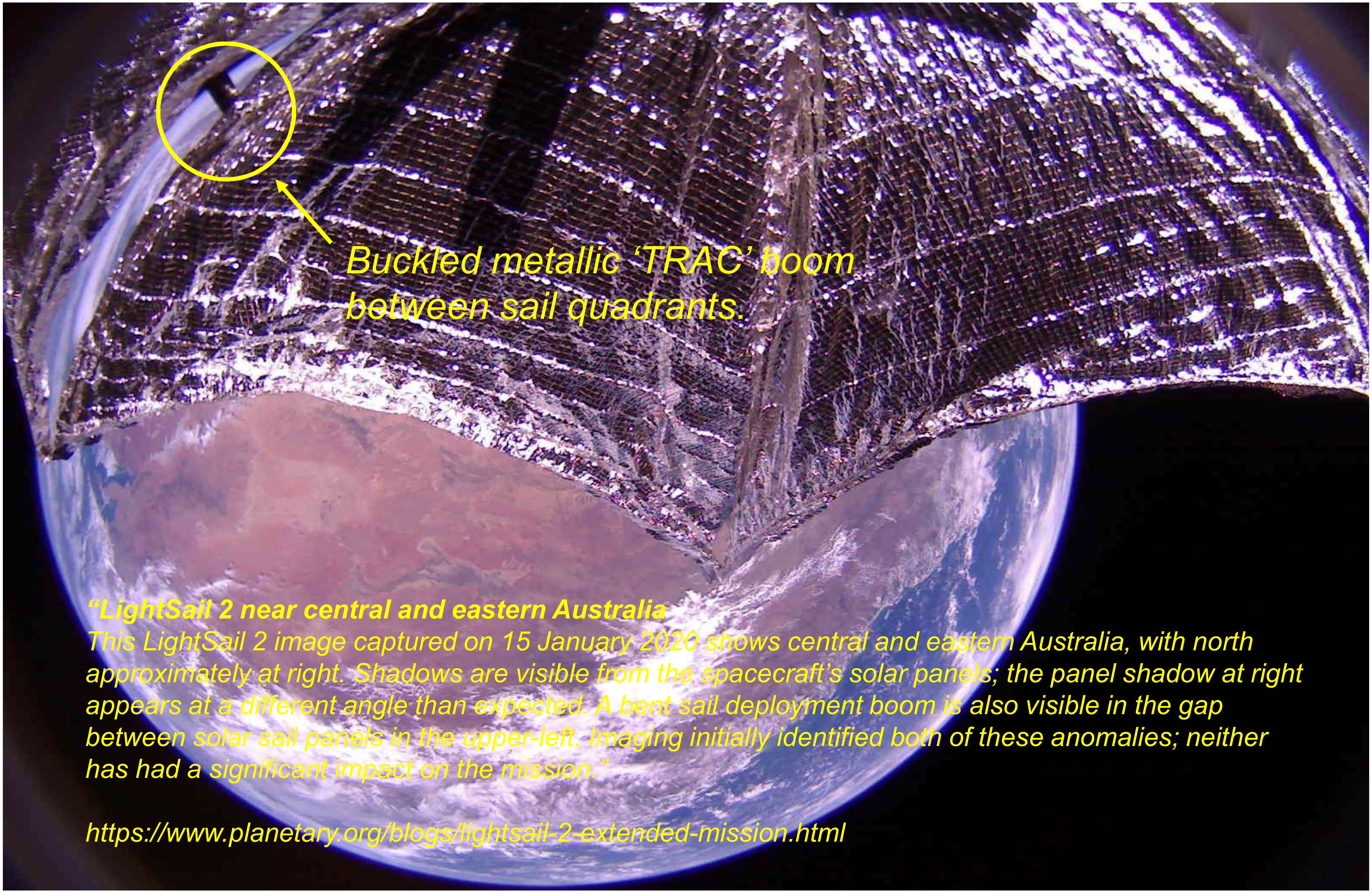
2019

Lightsail 2
- Operator: Planetary Society
- Sail: 32 m2; TRAC booms.
- Bus: 3U CubeSat; 5 kg.
- Launch date: 6/25/2019
- Status: Success; multiple sail images; orbit eccentricity modified.
- ***Boom collapse observed ca. June 2020.***

Launch failure *On-orbit failure* *Partial success* *Mission success*

LightSail 2 Update: Boom Buckling Anomaly

ref: The Planetary Society, 17 June 2020

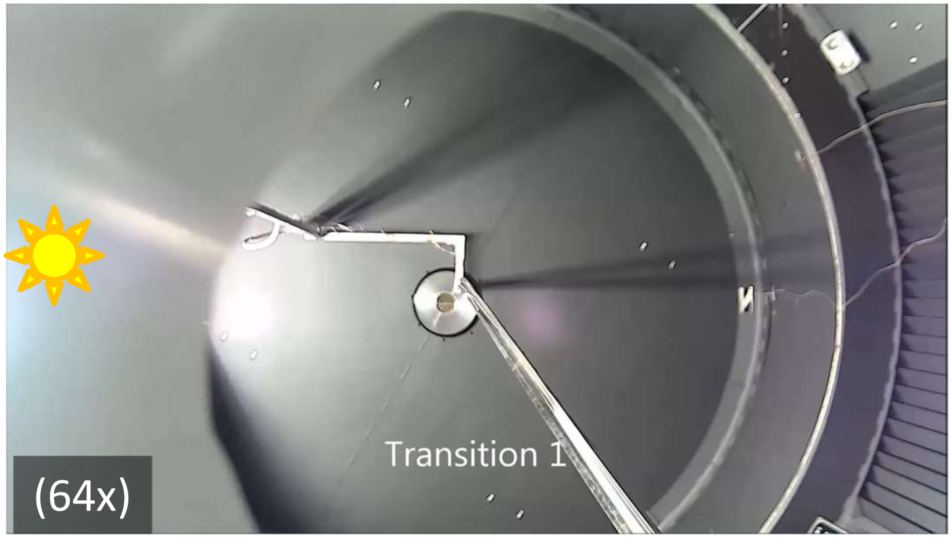


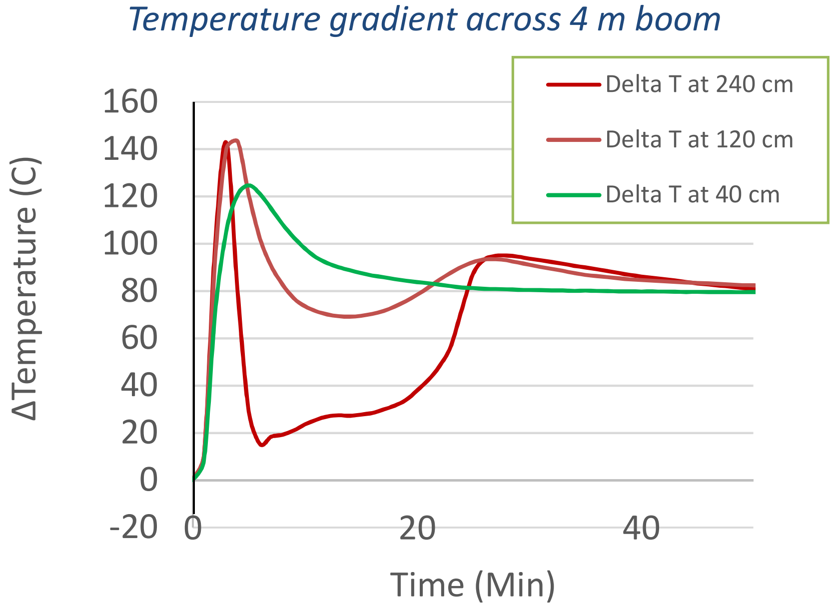
"LightSail 2 near central and eastern Australia

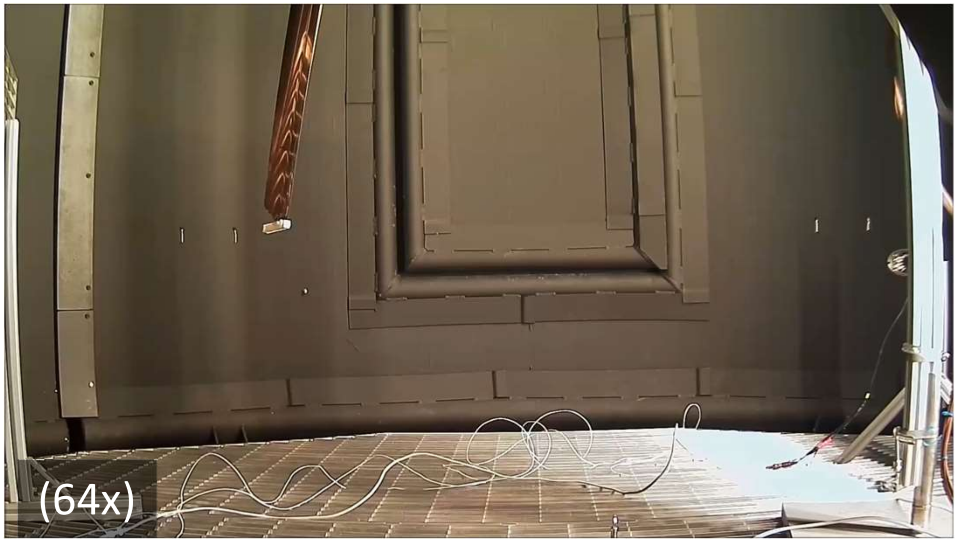
This LightSail 2 image captured on 15 January 2020 shows central and eastern Australia, with north approximately at right. Shadows are visible from the spacecraft's solar panels; the panel shadow at right appears at a different angle than expected. A bent sail deployment boom is also visible in the gap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

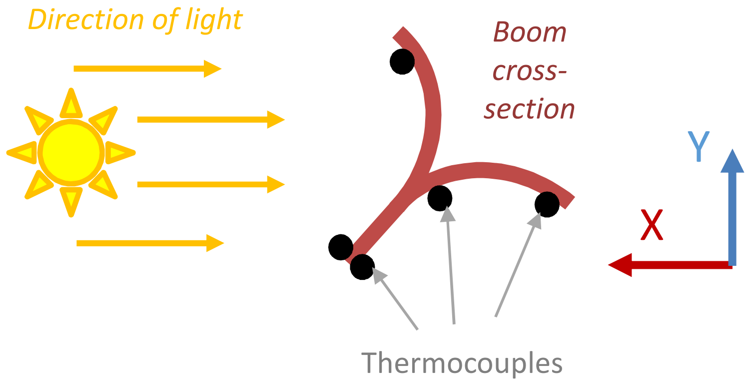
https://www.planetary.org/blogs/lightsail-2-extended-mission.html

NEA Scout Metallic TRAC Boom Thermal Vacuum Chamber Testing *[ca. 2017, MSFC, LaRC]*







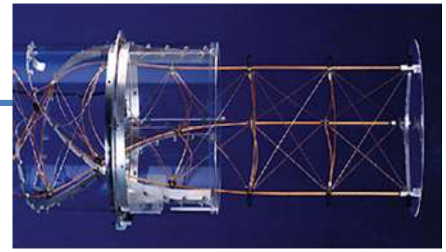


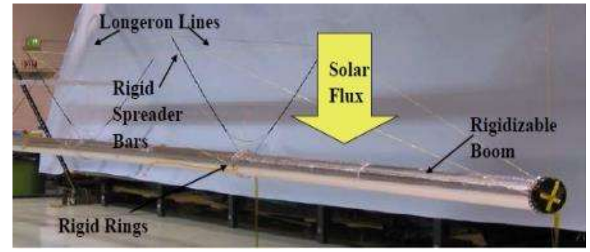
Motivation: Current Boom/Mast Technology Limitations on Deployed Length, Stowed Volume & Affordable Cost

Length (m)	Volume (U*)	Cost ($K)
< 100	> 150	> 500
< 40	> 30	> 100
< 25	> 3	> 20
< 5	> 0.5	> 10
< 2	> 0.1	> 1

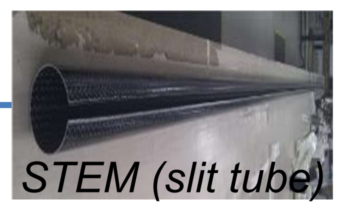
*** 1U = 10 cm x 10 cm x 10 cm = 1 liter**

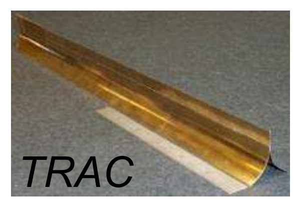
Coilable/Articulated Trusses & Inflatables





Deployable technology gap in this range:
5-25 m long, 3-30 L (U) volume, $20-100K





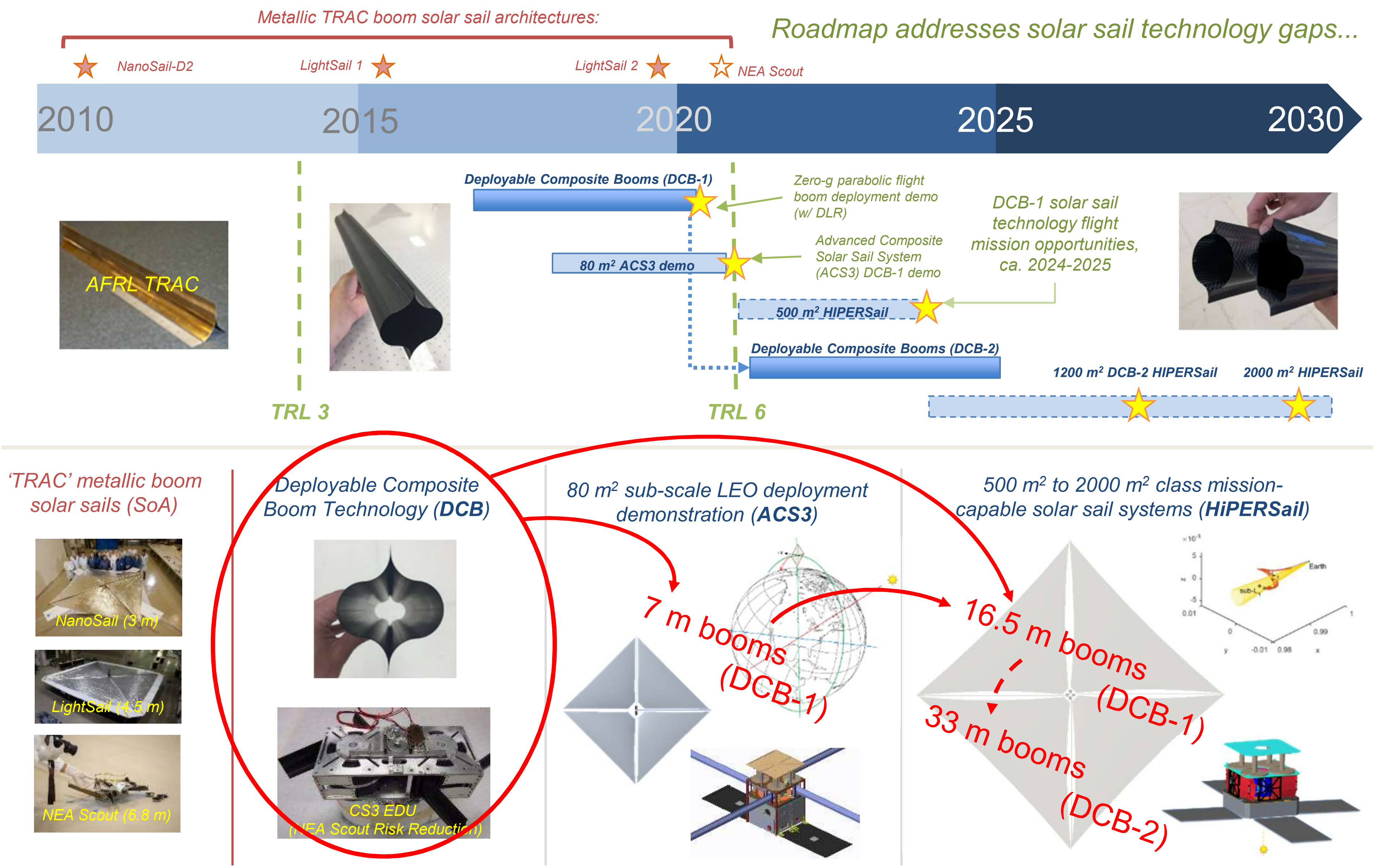
Case Study: NEA Scout Baseline Metallic TRAC booms versus Deployable Composite Booms

	Current NEA Scout Metal TRAC boom 	**Alternative Composite boom Down-selected: Mini-CTM** 
Material	Elgiloy (Co-Cr-Ni alloy)	Carbon Fiber/ Epoxy
Packaged height	35 mm	45 mm
Wall thickness	0.1 mm	0.14 mm
Can four (4) 7 m booms fit in 2U footprint area?	Yes	Yes
Boom linear density	59.8 g/m	**16.5 g/m**
Mass saving for four (4) 7 m booms	--	**1.22 kg**
Linear CTE	15.21 ppm/°C	**-0.11 ppm/°C**
Buckling Load at 7m	3.9 N	4.1 N
Torsional Stiffness	3.6E-3 N-m^2	**1.1 N-m^2**
Cost per boom	$ 15K	**$ 5K**

Significant performance benefits realized

Conclusions: Composite shell-based boom technology can provide significant mass savings and improved thermal and structural performance.

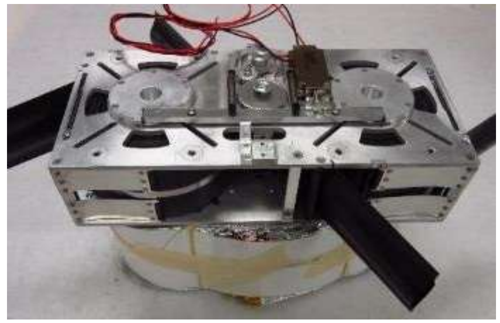
Small Spacecraft Deployable Composite Booms Solar Sail Technology Development Roadmap



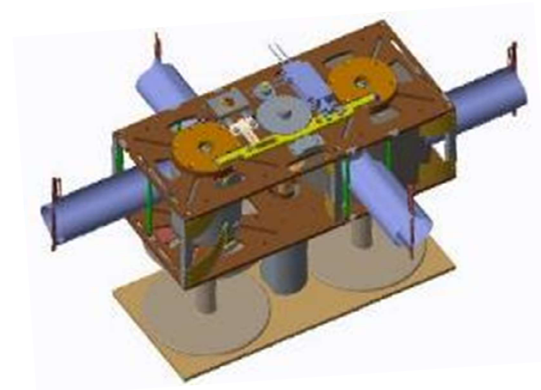
Composite Boom Deployer Evolution *(Tape-Puller Type)*

3U DLR-Surrey 'DeorbitSail' Deployer

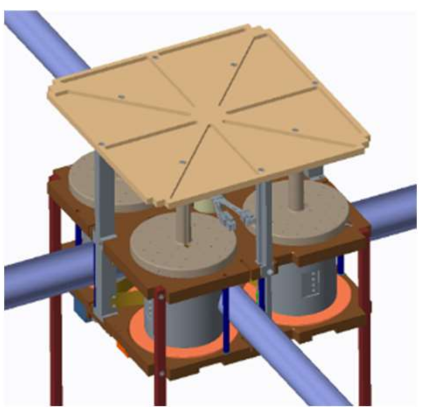
6U NASA 'CS3' deployer EDU
(NEAS risk-reduction)



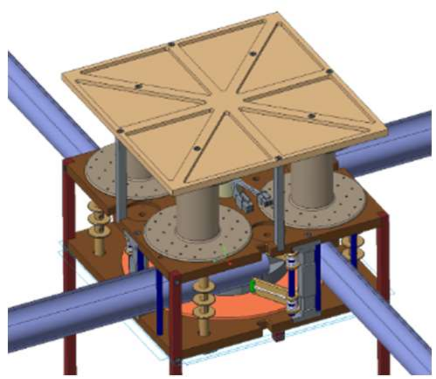
6U 'NASA ACS3' deployer concept



12U NASA 'ACS3' deployer concepts

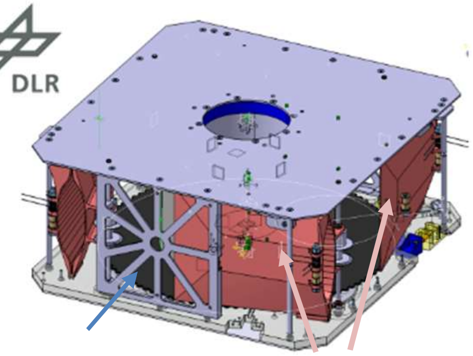


4-hub



1-hub

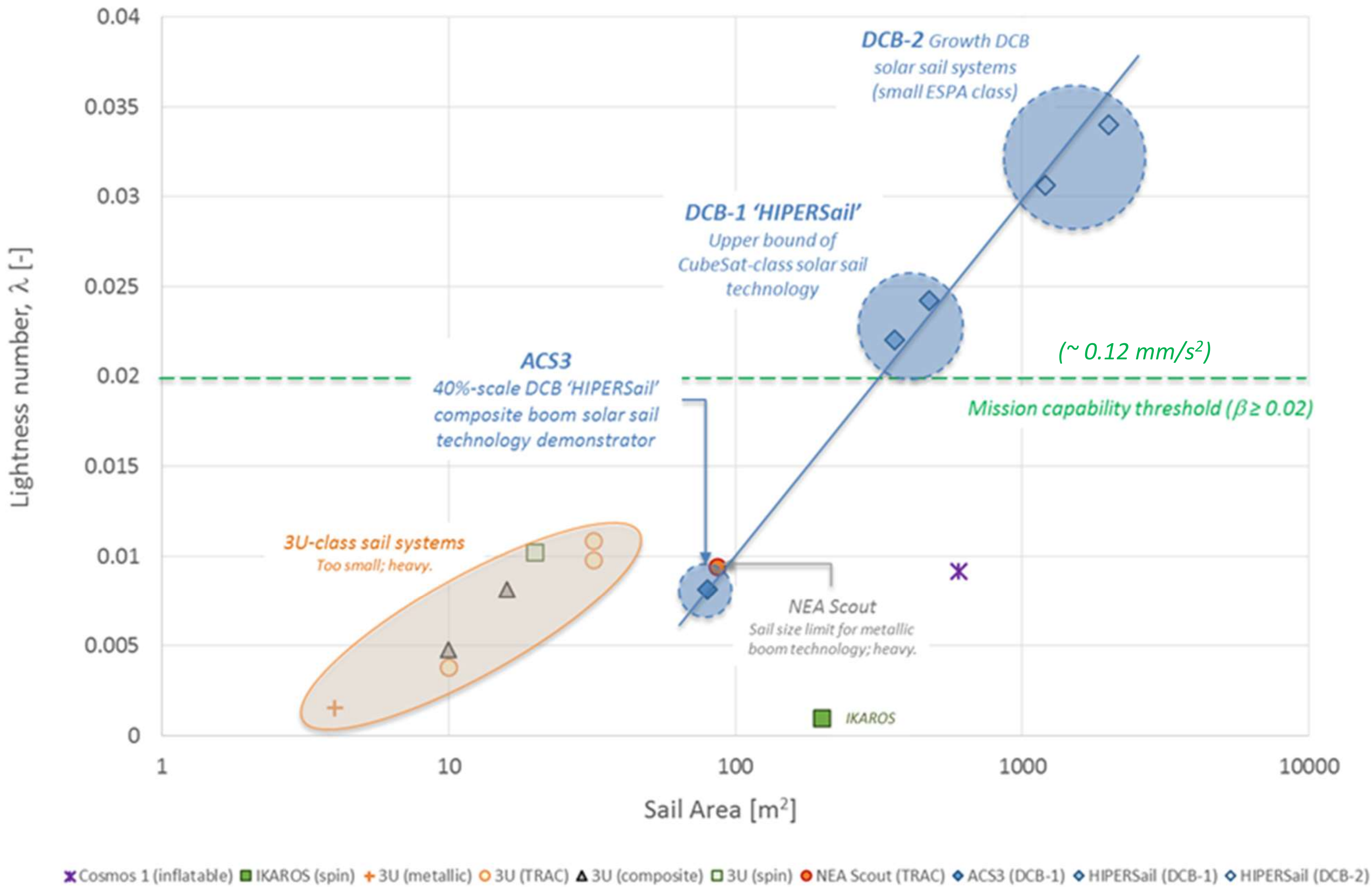
27U DLR deployer concept



Four 14-16.5-m co-coiled booms on single hub.

'Guide shell" feature stabilizes transition of boom cross section during deployment.

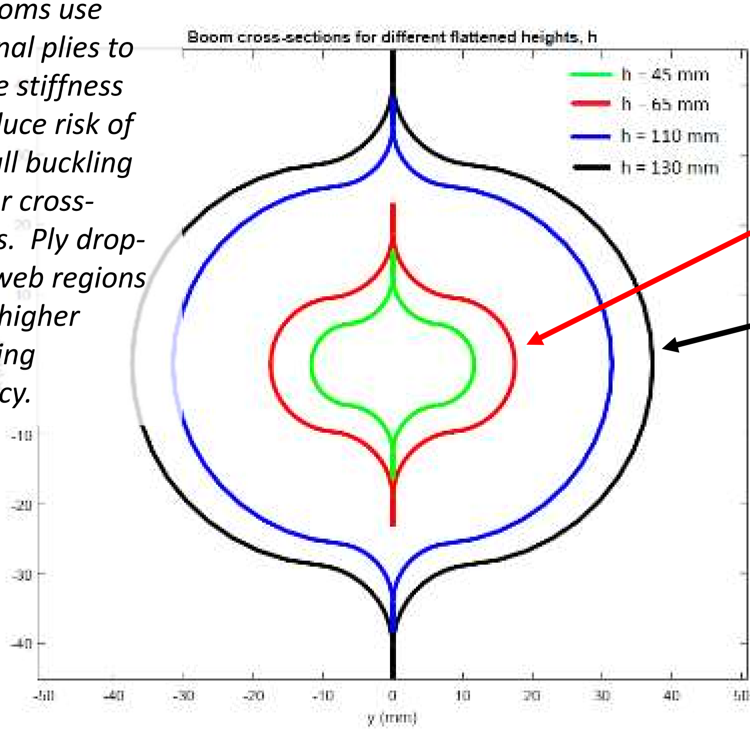
Solar Sailing: Smallsat Solar Sail Technology Performance Capabilities *vehicle lightness number vs. sail area*



Deployable Composite Boom (DCB) Technology Extensibility

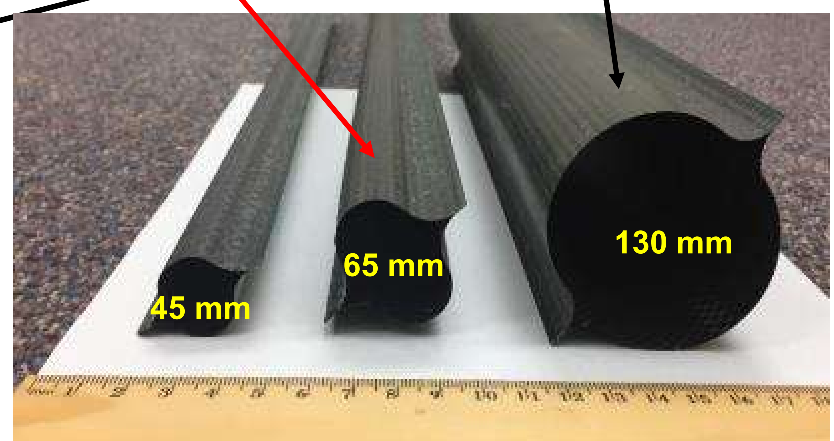
- *Original* 7-m deployable composite booms built for a NEA Scout compatible composite sail system.
  - h = 45 mm; 2-ply [±45 PW/0] ***high packaging efficiency*** laminate.
- *Next generation* 7-m booms for 12U Advance Composite Solar Sail System (ACS3) sub-scale solar sail flight demonstration (~80 m^2 sail)
  - h = 65 mm; 2-ply [±45 PW/0-90 PW] ***high stiffness*** laminate
- *Mission-scale* 16.5-m booms for future 27U ACS3-based solar sail systems - HIPERSAIL (~500 m^2 sail).
  - h = 110-130 mm; 3-ply [±45 PW/0/±45 PW] ***high stiffness*** laminate
  - Being developed under the Game Changing Development Program (GCDP) *Deployable Composite Booms (DCB) Project*.

DCB booms use additional plies to improve stiffness and reduce risk of thin-wall buckling in larger cross-sections. Ply drop-offs in web regions permit higher packaging efficiency.



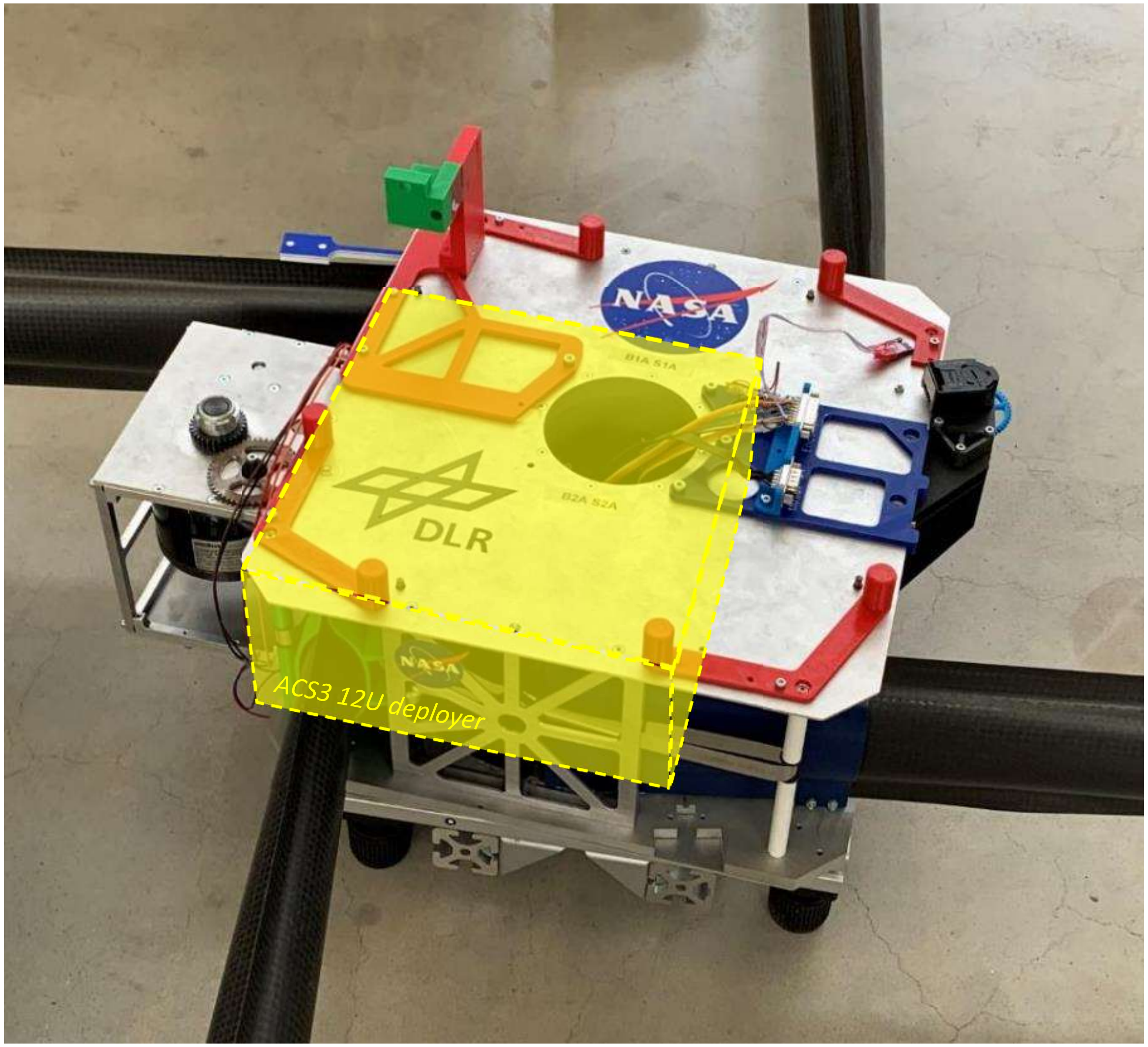
Will use new 65 mm tall composite booms for ACS3 Low Earth Orbit flight experiment.

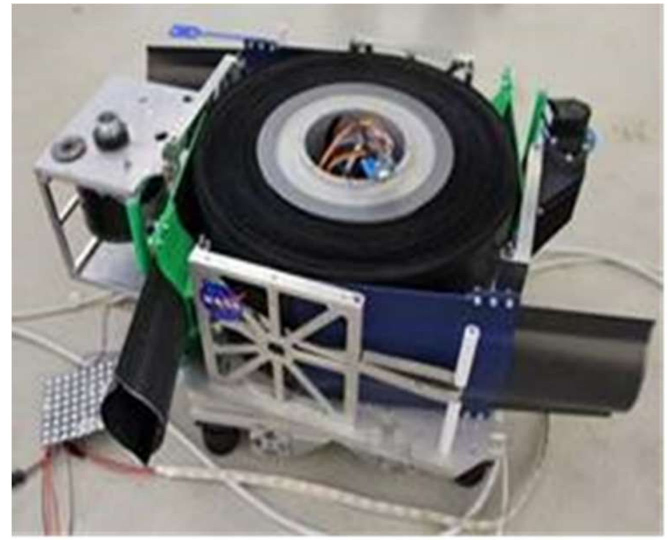
Will use new 130 mm tall composite booms for potential future solar sail Technology Demonstration Mission (HIPERSAIL)

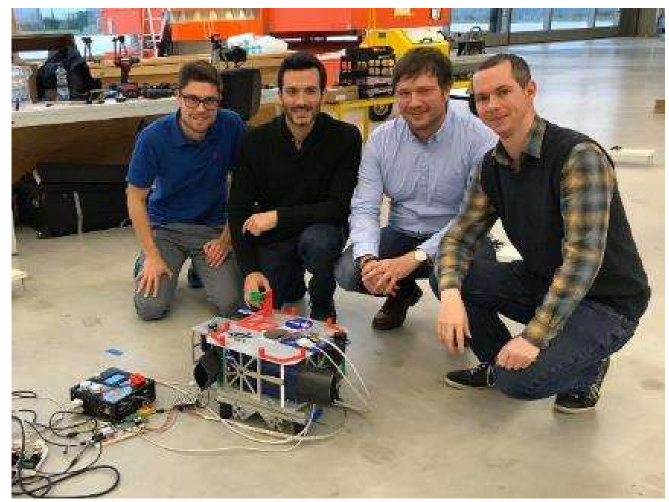


DCB: 4 x 16.5 m Boom Packaging Test at DLR

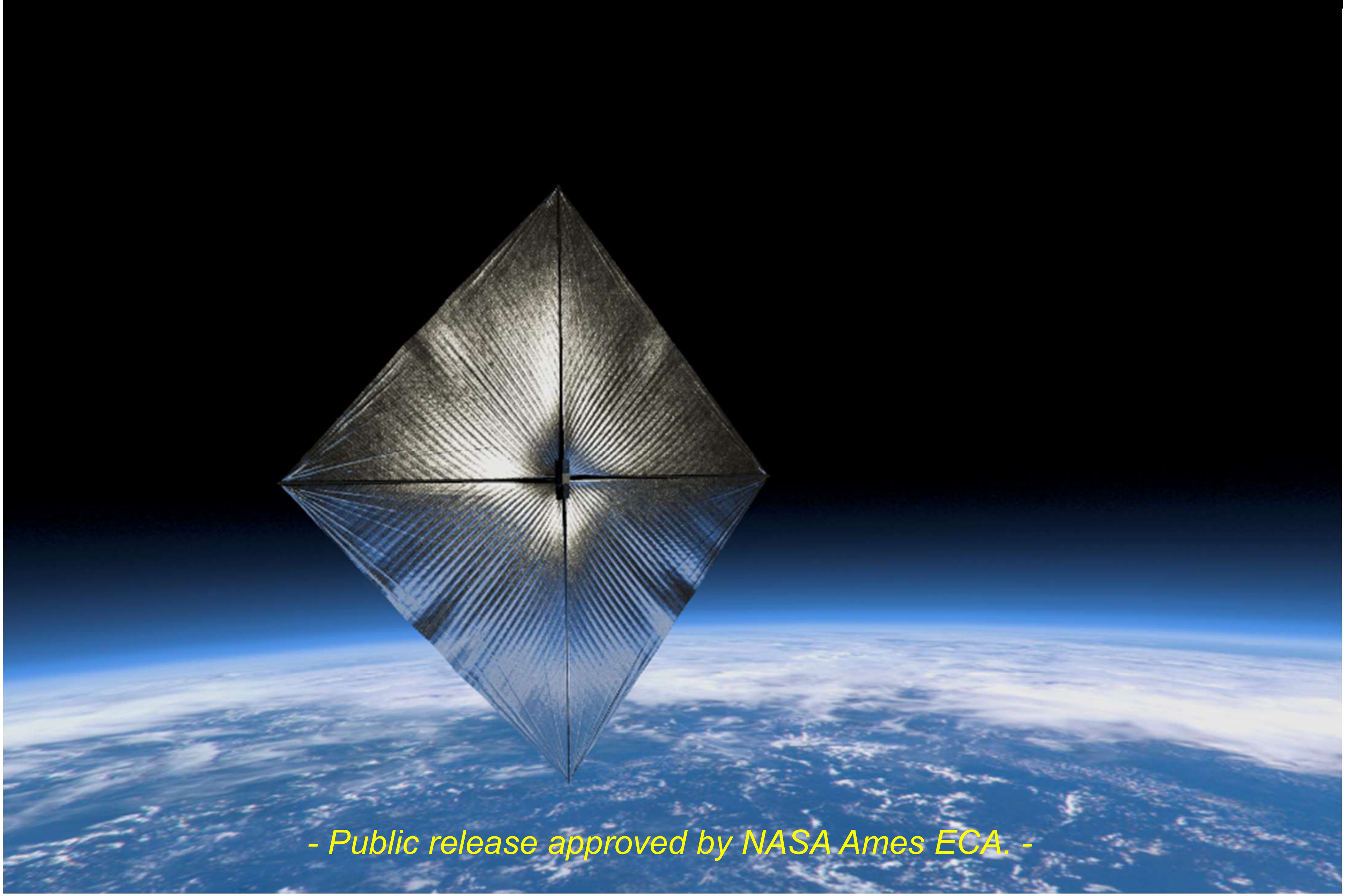
11/13/2019







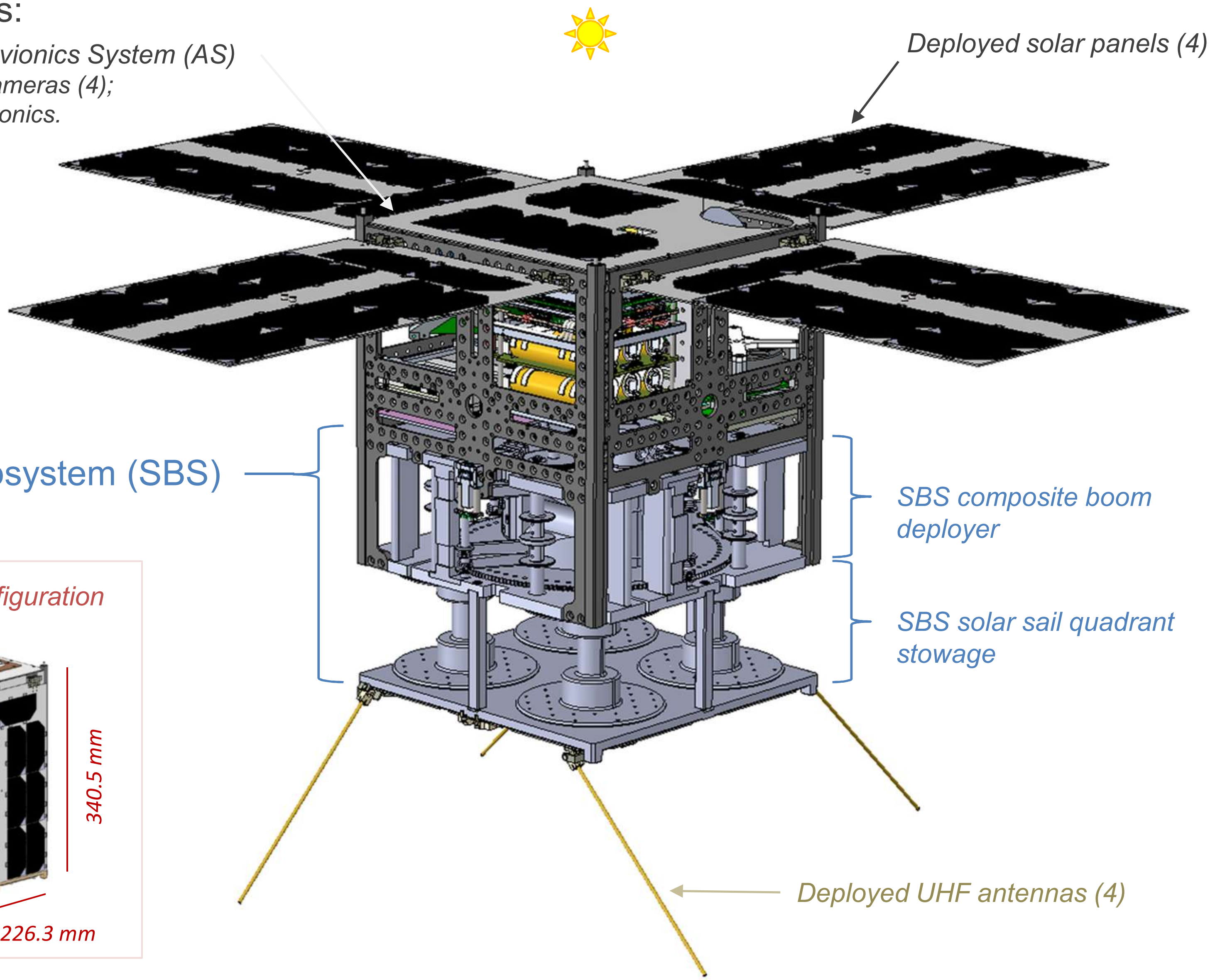
ACS3: flight animation

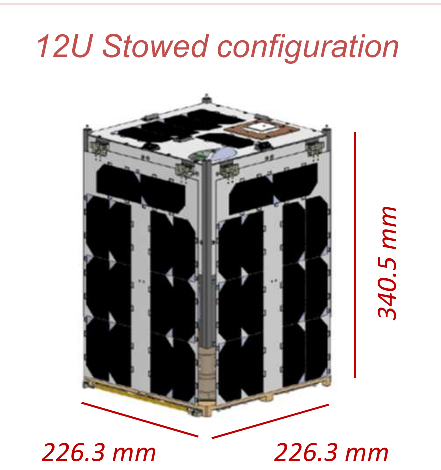


- Public release approved by NASA Ames ECA. -

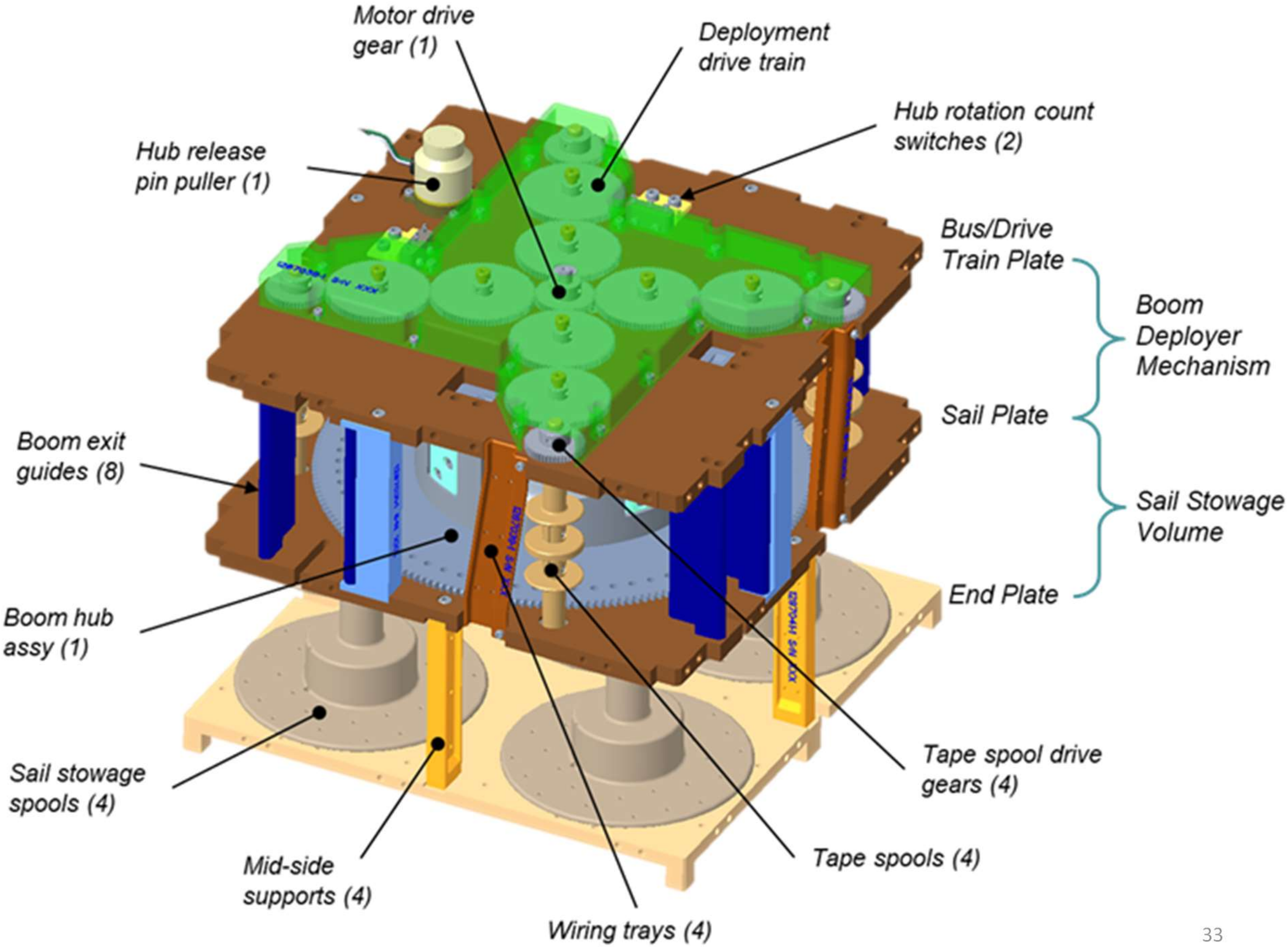
ACS3: 12U Spacecraft Configuration

20191219 configuration; sails and booms not shown.





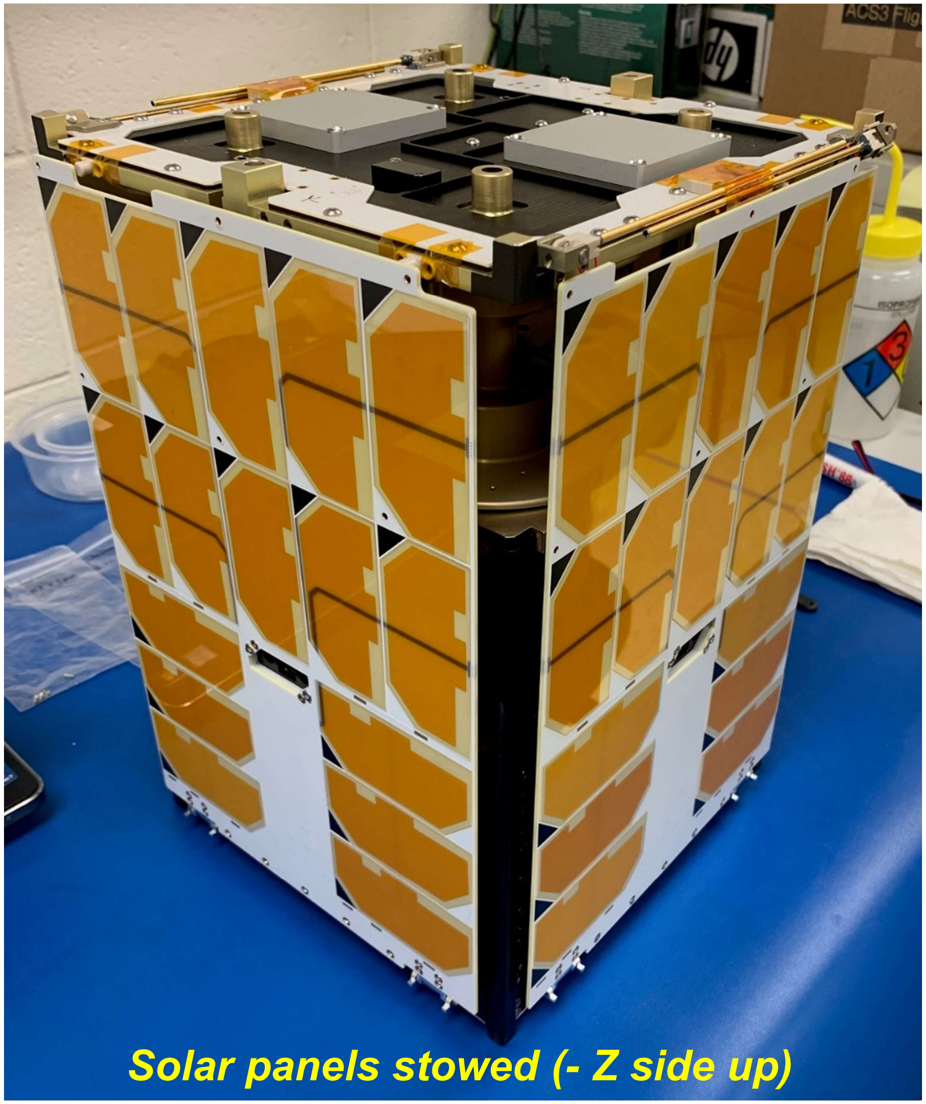
ACS3: SBS Final Design Detail [20200716]



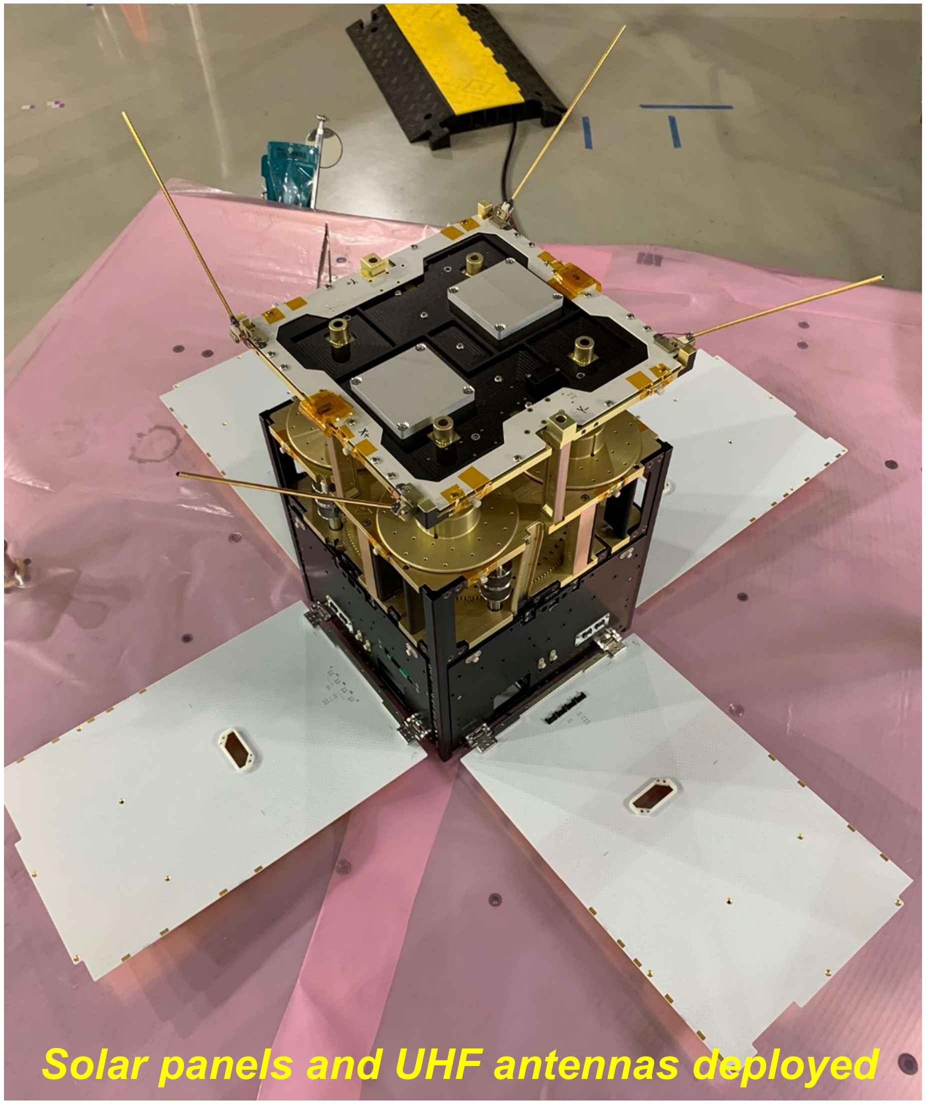
SBS Prototype Deployment Testing w/ Simulated Sail Quadrants

Deployment Test #5, 2x tensioning springs ****Deployment time: 25 minutes****

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

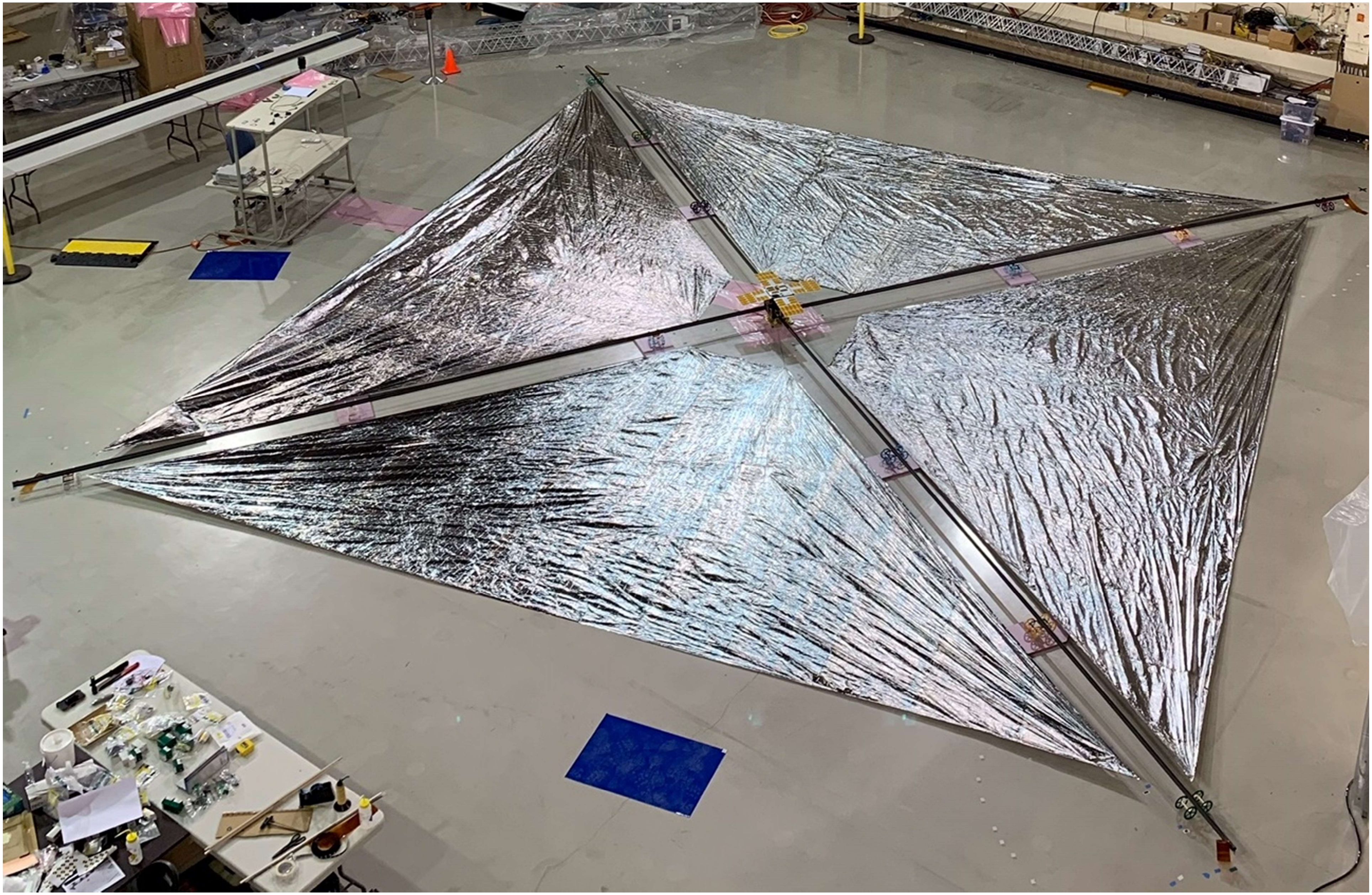


Solar panels stowed (- Z side up)



Solar panels and UHF antennas deployed

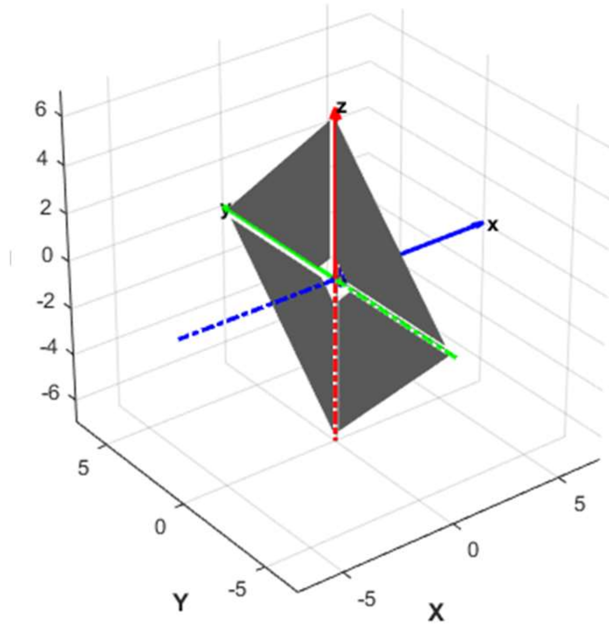
ACS3: Bus Structural Model and SBS Flight Unit and Development Booms/Sails *NASA LaRC 20201208*



ACS3: Solar Sail Rigid Body Models

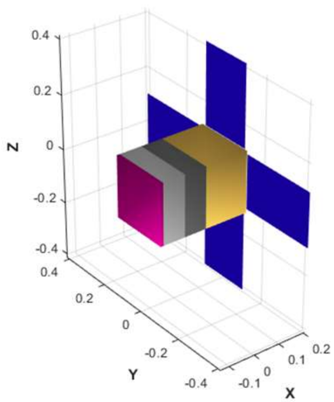
rev. 20200526; model ver. 16.a

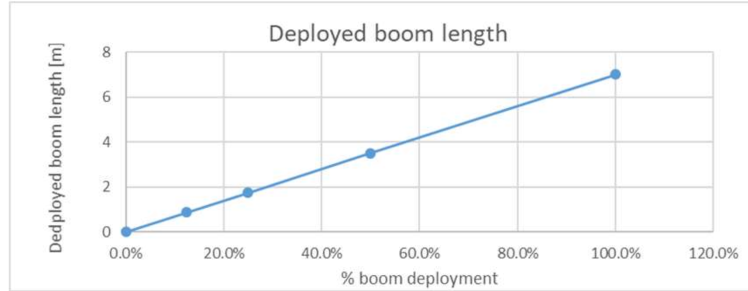
Sail fully deployed

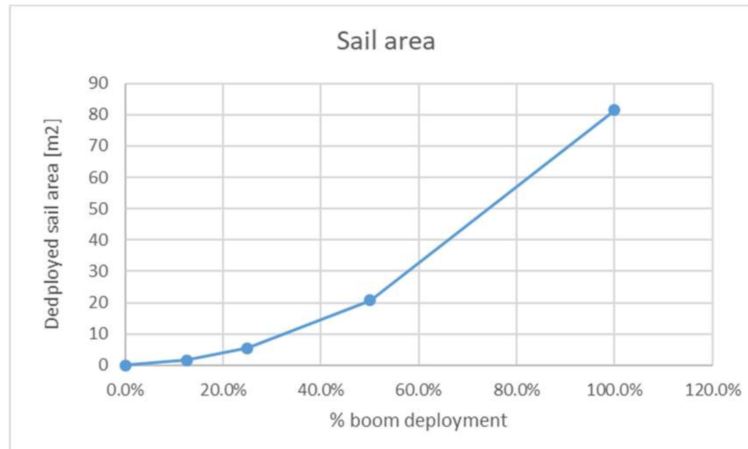


Sail stowed

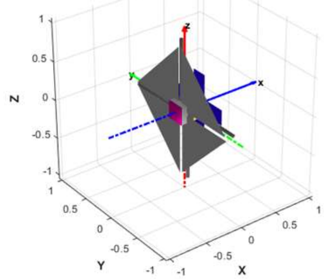
(solar panels deployed)



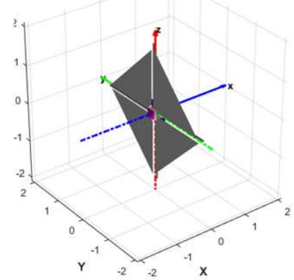




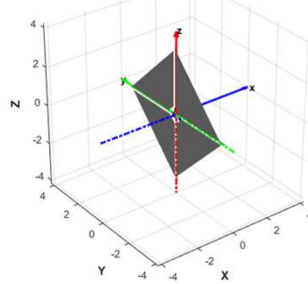
12.5%



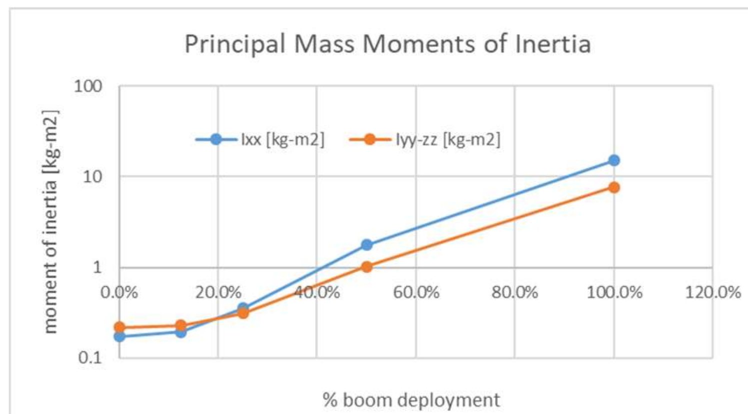
25%



50%



Intermediate deployed states

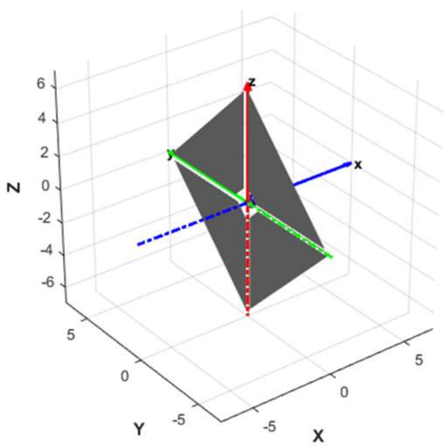


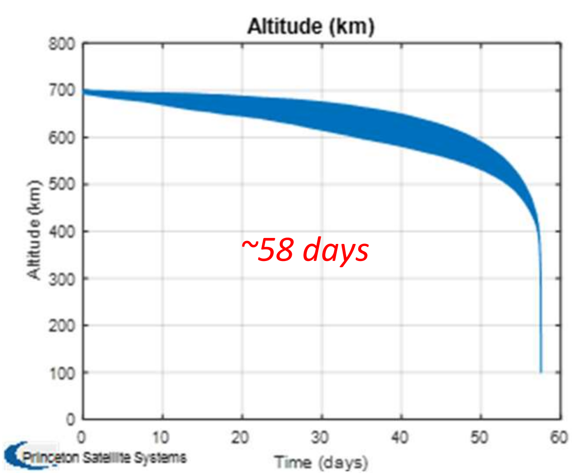
ACS3: Deorbiting Simulations *[Noon-Midnight Sun-Synchronous Orbits]*

rev. 20200526; model ver. 16.a; 9/22/2021 launch date

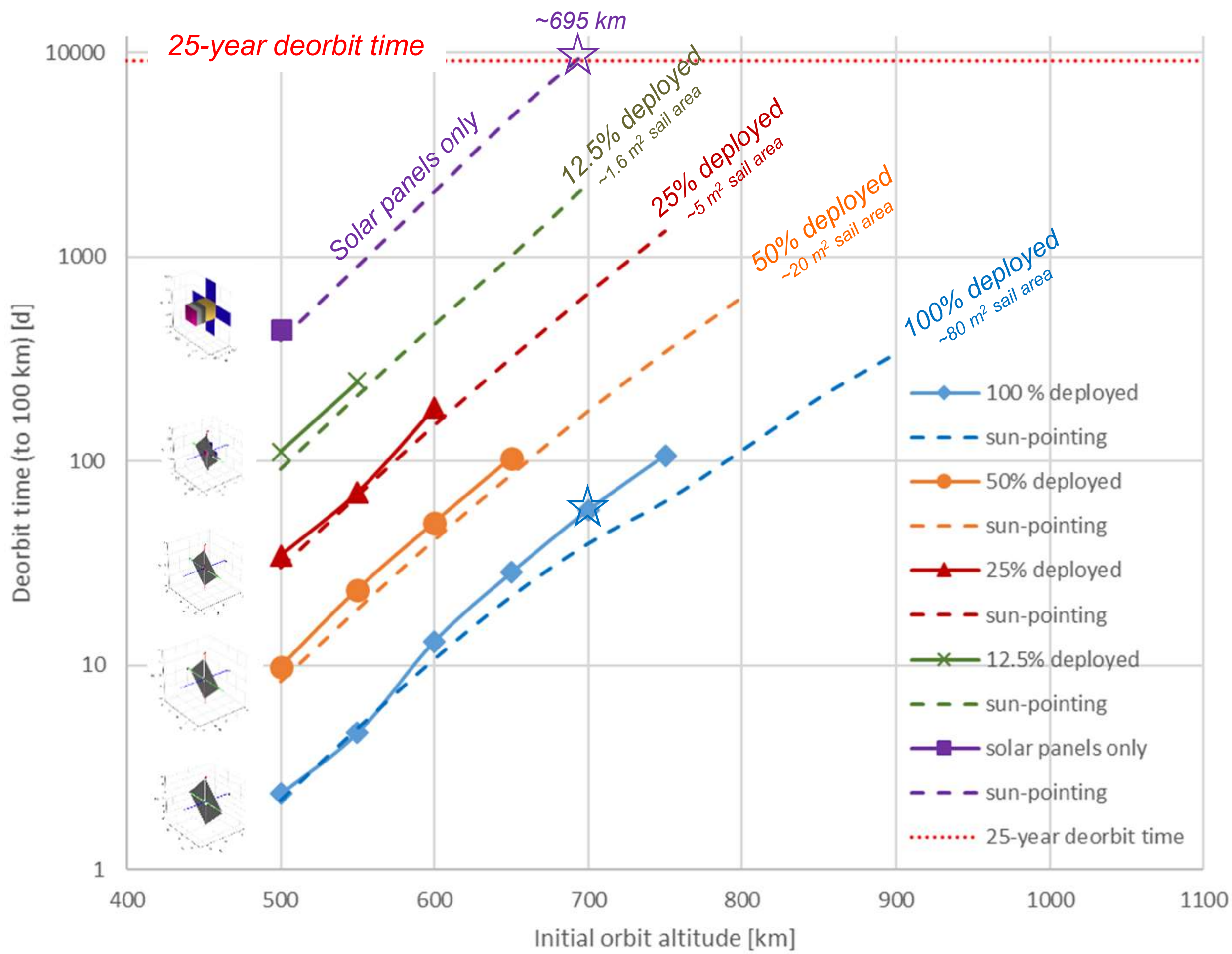
Time domain deorbiting simulation for fully deployed ACS3 solar sail: uncontrolled

700 km initial altitude (NM-SSO)





Deorbit time versus altitude and percentage of full boom deployment: uncontrolled and sun-pointing



Atmospheric Density Model for Preliminary Analyses

ref: Wertz, J.R., Spacecraft Attitude Determination and Control, Kluwer, 1976, p. 820.

- Matlab/PSS 'AtmDens2' function.
  - Based on Wertz, 1976.
- Outputs density for specified altitude.
- Valid from 0 to 1000 km.
- <u>Does not account for solar cycle effects.</u>

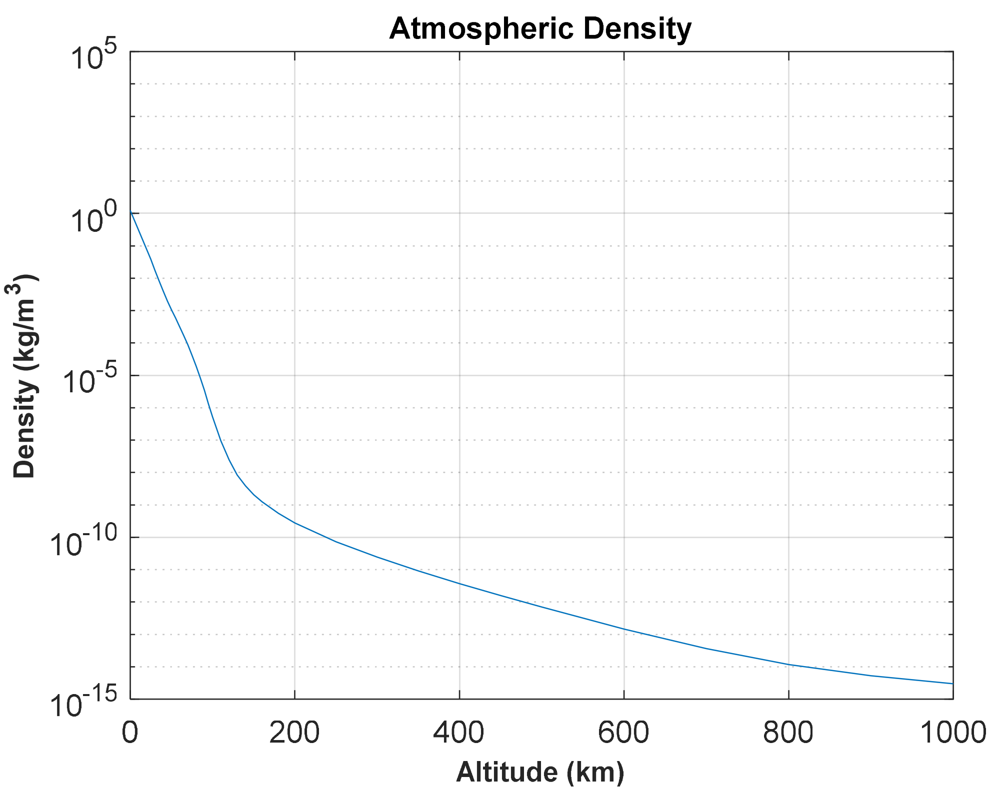


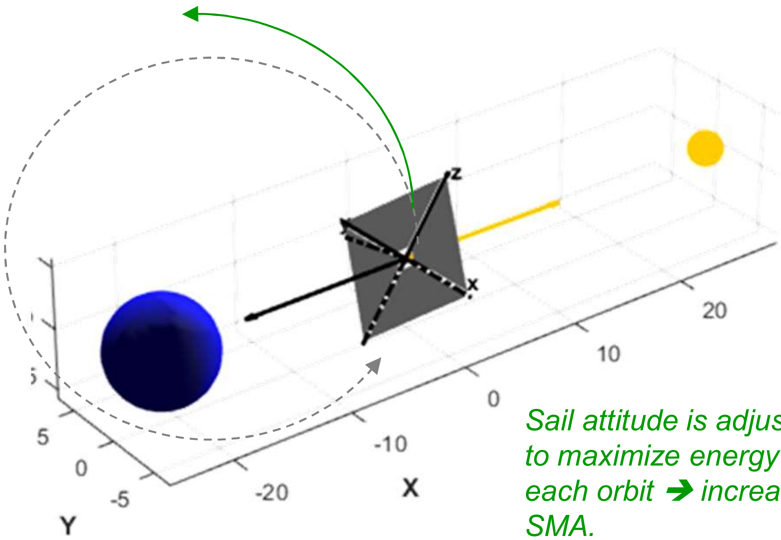
Table L-6 summarizes the properties of the upper atmosphere of the Earth. The mean profiles between 25 and 500 km are from the COSPAR International Reference Atmosphere, CIRA 72 [1972]. Between 500 and 1000 km, the CIRA 72 profile for $T_\infty = 1000\text{K}$ was used to indicate the densities to be expected. The maximum and minimum values of the density between 100 and 500 km were extracted from the explanatory material in CIRA 72 and indicate the variation in densities which can be obtained with the models. Sea level temperature and density are from the *U.S. Standard Atmosphere* [1976].

Table L-6. The Upper Atmosphere of the Earth

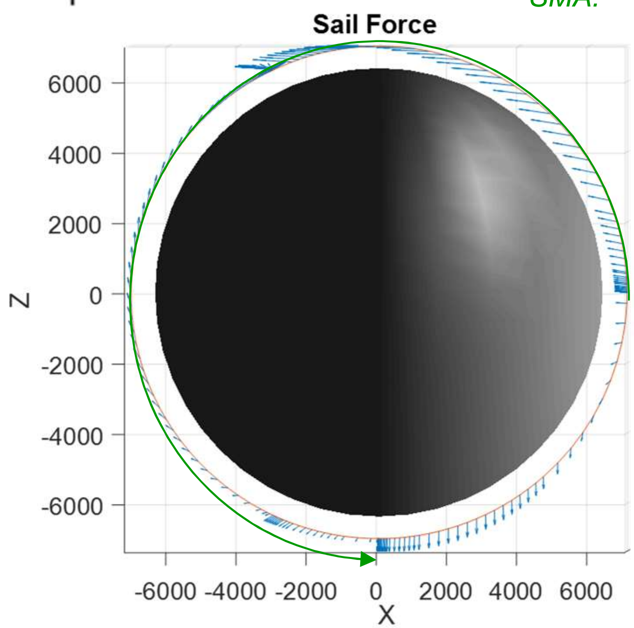
ALTITUDE (KM)	MEAN KINETIC TEMPERATURE (°K)	DENSITY (kg/m³)			SCALE HEIGHT (KM)
		MINIMUM	MEAN	MAXIMUM	
0	288.2		$1.225 \times 10^{+0}$		8.44
25	221.7		3.899×10^{-2}		6.49
30	230.7		1.774×10^{-2}		6.75
35	241.5		8.279×10^{-3}		7.07
40	255.3		3.972×10^{-3}		7.47
45	267.7		1.995×10^{-3}		7.83
50	271.6		1.057×10^{-3}		7.95
55	263.9		5.821×10^{-4}		7.73
60	249.3		3.206×10^{-4}		7.29
65	232.7		1.718×10^{-4}		6.81
70	216.2		8.770×10^{-5}		6.33
75	205.0		4.178×10^{-5}		6.00
80	195.0		1.905×10^{-5}		5.70
85	185.1		8.337×10^{-6}		5.41
90	183.8		3.396×10^{-6}		5.38
95	190.3		1.343×10^{-6}		5.74
100	203.5	3.0×10^{-7}	5.297×10^{-7}	7.4×10^{-7}	6.15
110	265.5	6.0×10^{-8}	9.661×10^{-8}	3.0×10^{-7}	8.06
120	334.5	1.0×10^{-8}	2.438×10^{-8}	6.0×10^{-8}	11.6
130	445.4	4.5×10^{-9}	8.484×10^{-9}	1.6×10^{-8}	16.1
140	549.0	2.0×10^{-9}	3.845×10^{-9}	6.0×10^{-9}	20.6
150	635.2	1.2×10^{-9}	2.070×10^{-9}	3.5×10^{-9}	24.6
160	703.1	6.5×10^{-10}	1.244×10^{-9}	2.0×10^{-9}	26.3
180	781.2	2.4×10^{-10}	5.464×10^{-10}	9.0×10^{-10}	33.2
200	859.3	1.0×10^{-10}	2.789×10^{-10}	3.2×10^{-10}	38.5
250	940.2	4.0×10^{-11}	7.248×10^{-11}	1.6×10^{-10}	46.9
300	972.8	1.6×10^{-11}	2.418×10^{-11}	8.8×10^{-11}	52.5
350	986.5	2.0×10^{-12}	9.158×10^{-12}	6.0×10^{-11}	56.4
400	992.6	3.7×10^{-13}	3.725×10^{-12}	5.0×10^{-11}	59.4
450	995.7	9.0×10^{-14}	1.585×10^{-12}	3.8×10^{-11}	62.2
500	997.3	1.3×10^{-14}	6.967×10^{-13}	3.0×10^{-11}	65.8
600	1000.0		1.454×10^{-13}		79
700	1000.0		3.614×10^{-14}		109
800	1000.0		1.170×10^{-14}		164
900	1000.0		5.245×10^{-15}		225
1000	1000.0		3.019×10^{-15}		268

ACS3: Orbit Semi-Major Axis (SMA) Raising and Lowering using Solar Radiation Pressure

Orbit Raising Mode

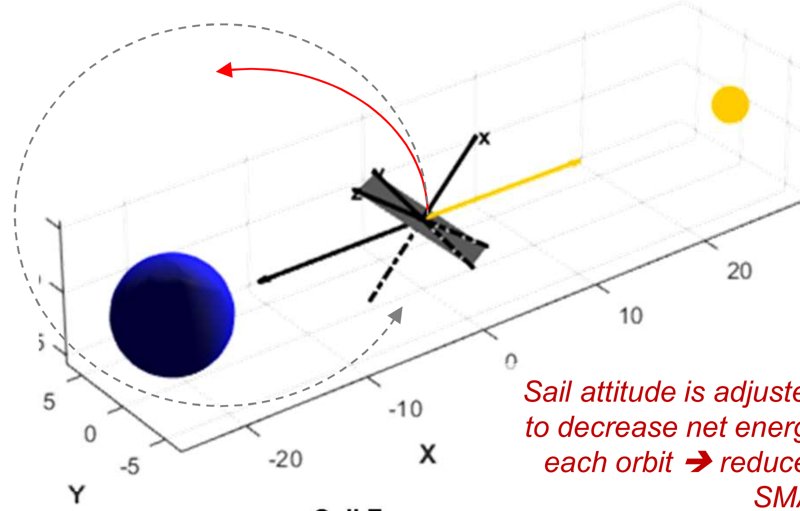


Sail attitude is adjusted to maximize energy gain each orbit ➔ increases SMA.

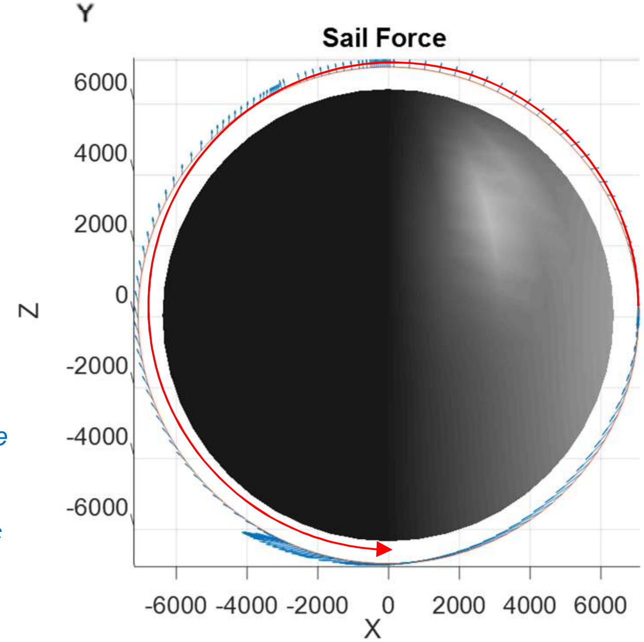


Net disturbance force from solar radiation pressure (Earth IR, albedo, aerodynamic drag) acting on sail.

Orbit Lowering Mode



Sail attitude is adjusted to decrease net energy each orbit ➔ reduces SMA.



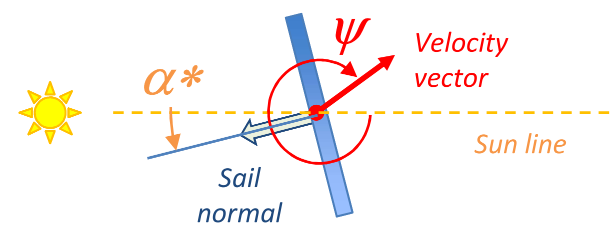
SMA Raising/Lowering Steering Profile [ref: McInnes, 1999]

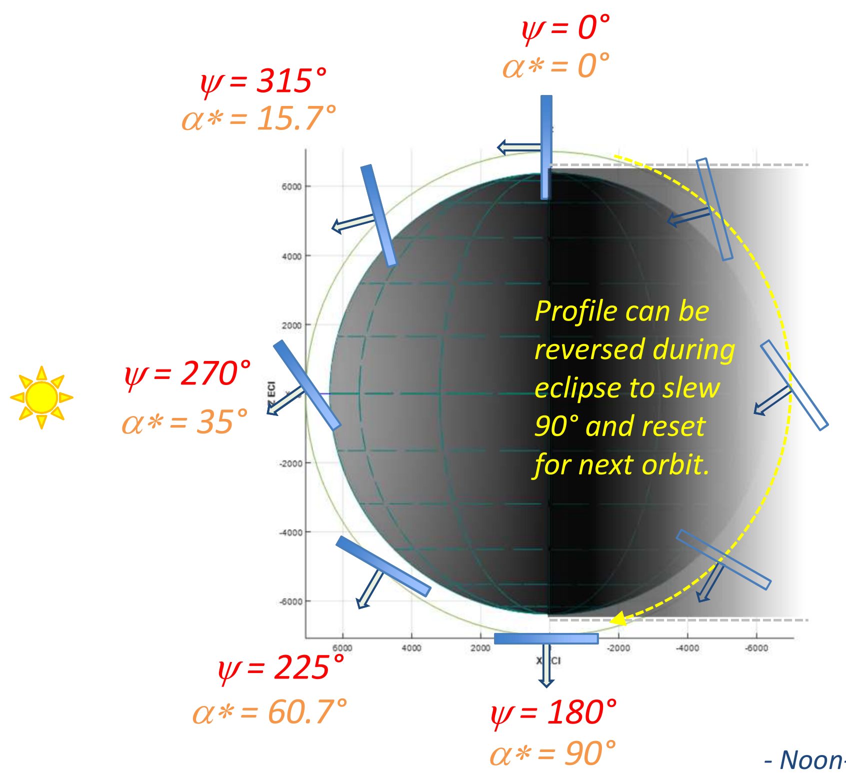
- **Locally optimal steering law for maximum energy gain/loss each orbit.**
  - Sail oriented at all times to maximize solar radiation thrust component in direction of flight.
  - For lowering, thrust component opposite direction of flight is maximized.

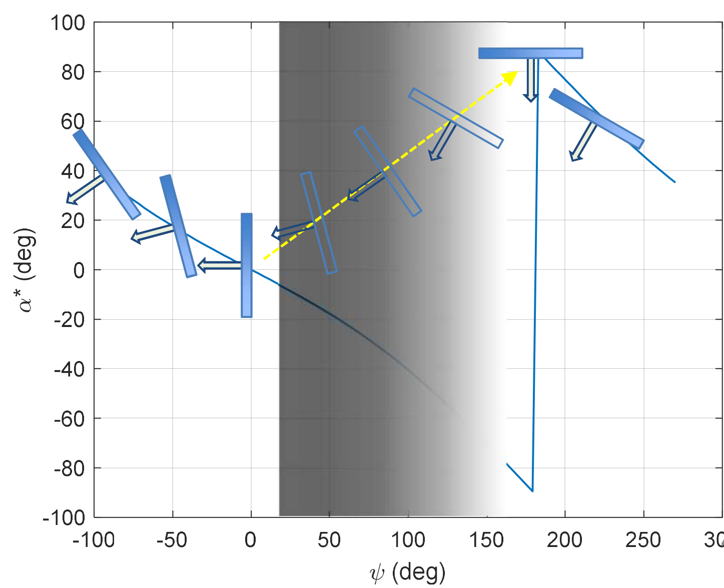
Locally optimal sail pitch angle.

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. -

ACS3: SMA-Raising Mode vs. Standby Attitude – 30 days

[700 km Noon-Midnight Sun-Synchronous Initial Orbit; 9/22/2021 launch date; Model v.16.a]