overview of the nasa advanced composite

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

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An overview of the NASA Advanced Composite Solar Sail System (ACS3) technology demonstration project is presented. Descriptions of the ACS3 solar sail design, spacecraft systems, concept of operations, and ground testing are provided, along with a discussion of the extensibility of the ACS3 composite solar sail system technology to future small spacecraft solar sails and missions.

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I. Nomenclature

a_c = characteristic acceleration at 1.0 AU, mm/s^2
AU = astronomical unit, 149.6 x 10^6 km
β = lightness number, ratio of solar radiation pressure force to solar gravitational force
U = CubeSat 10 cm x 10 cm x 10 cm "unit" of volume, 1 liter

II. Introduction

The National Aeronautics and Space Administration (NASA) is currently developing a range of deployable composite space structures technologies for small spacecraft applications.[2, 3] One application of particular interest is for use in solar sailing propulsion systems for future deep space CubeSat and small satellite missions.[4] A solar sailing propulsion system sized for small spacecraft would be an enabling technology for low-cost deep space scientific missions based on CubeSat, or small Evolved Secondary Payload Adapter (ESPA), rideshare spacecraft. Alternative low-thrust propulsion technologies, such as solar electric propulsion, have been particularly difficult to scale downward to small spacecraft form factors, requiring either cryogenic propellant storage or, if using more easily-stored propellants, having relatively limited operational lifetimes due to erosion of electrode surfaces. Previously developed solar sail systems are designed for larger and heavier spacecraft systems and missions. These solar sail technologies, although potentially viable for larger, more elaborate -- and more expensive -- missions, do not scale well to the smaller packaging volumes required for CubeSat and ESPA class rideshare spacecraft.

The majority of solar sail flight demonstration projects conducted to date have been 3U CubeSat-class rideshare spacecraft (e.g., Betts et al[5]). Available volume within this spacecraft form factor is very limited, which severely restricts the deployed area of the solar sail system contained within. These small deployed sail areas result in relatively low radiation pressure induced thrust capabilities, and little volume remains in the 3U CubeSat chassis for related mission systems and scientific instrument payloads, restricting the use of 3U class solar sails primarily to technology demonstrations in low Earth orbit (LEO). 6U-class solar sail spacecraft (e.g., Near Earth Asteroid (NEA) Scout[6]) are similarly constrained by small volumes with little space available for large-area solar sails once space is allocated for necessary spacecraft systems and scientific instruments.

Until recently, the state-of-the-art in high packaging efficiency deployable booms suitable for small CubeSat solar sails was the Triangular Rollable And Collapsible (TRAC) boom, developed by the Air Force Research Laboratory (AFRL)[7]. These booms have been used for the NASA NanoSail-D solar sail mission, and The Planetary Society Lightsail 1 and Lightsail 2 solar sail missions. The TRAC boom is also being used for the upcoming NASA NEA Scout mission. Although TRAC boom technology has excellent packaging efficiency, their metallic structure is relatively heavy, has poor torsional rigidity, and is very sensitive to thermal-elastic deformation on-orbit.[8] These limitations make TRAC boom technology most suitable for applications requiring short boom lengths or non-load-carrying applications with low deployed dimensional precision requirements.

Newly developed NASA deployable composite boom technologies are now being used for the next generation of small spacecraft solar sail systems.[2] These deployable composite booms use ultra-thin carbon fiber reinforced polymer (CFRP) composite plies to maximize boom packaging efficiency in very small volumes, while significantly reducing weight and thermal-elastic distortion sensitivity compared with metallic materials. They can also be formed into closed cross-section, tubular structures for much higher torsional rigidity. This also helps minimize the risk of boom collapse and buckling when subjected to eccentric loads due to solar sail membrane tensioning.

An overview of the NASA Advanced Composite Solar Sail System (ACS3) technology demonstration project will be presented here. Descriptions of the ACS3 solar sail design, spacecraft systems, concept of operations, ground and deployment testing will be provided, along with a discussion of the extensibility of the ACS3 composite solar sail system technology to future small spacecraft solar sails and missions.

III. The Advanced Composite Solar Sail System (ACS3) Project

A. ACS3 technology demonstration

The ACS3 solar sail system is an approximately 40% sub-scale version of a future composite solar sail system sized for near-term CubeSat class deep space solar sail missions. The ACS3 solar sail spacecraft will demonstrate NASA deployable composite boom technology in a solar sailing application in the LEO space environment.

The ACS3 solar sail consists of four approximately triangular metallized polymer membrane quadrants supported by four deployable composite booms. The planform of the deployed ACS3 solar sail is shown in Figure 1.

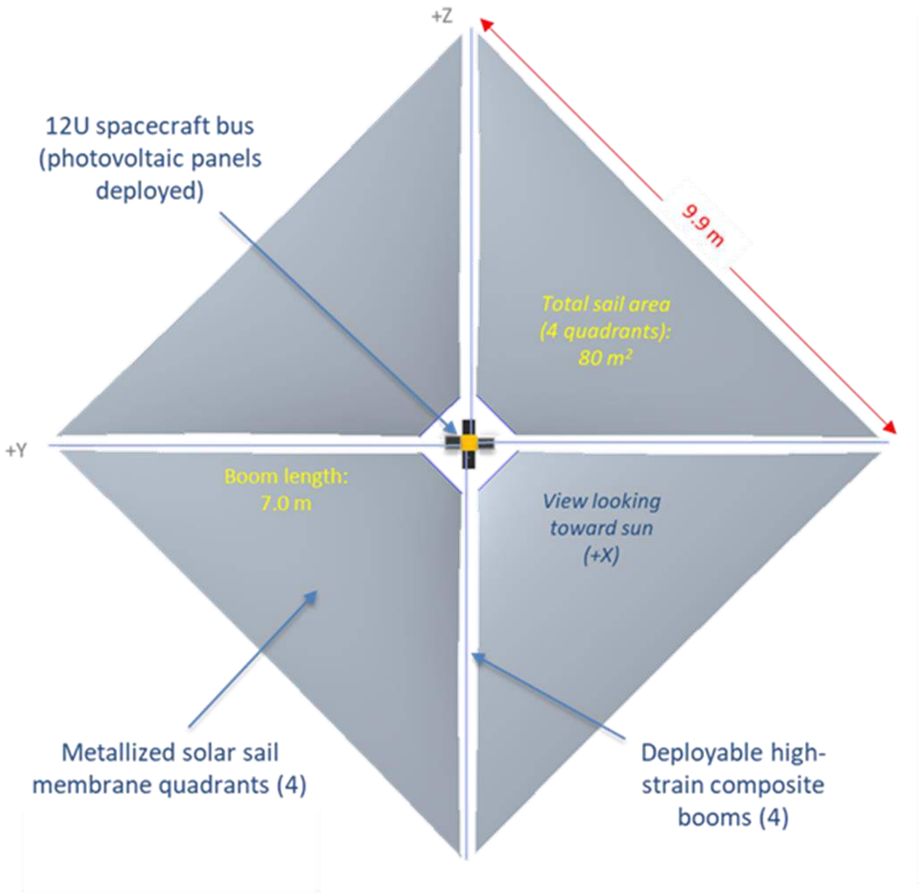


Figure 1. ACS3 solar sail. Sail membrane quadrants are metallized polyehtylene napthalate (PEN) thin films. Film thickness including metallization is 2.115 μm. Tip-to-tip distance between adjacent booms is 9.9 m. Sail quadrant hypotenuse length is 9 m. Total deployed sail area is 80 m^2.

B. ACS3 technology demonstration objectives

The primary objectives will be to deploy and characterize the ACS3 deployable composite boom technology solar sail. This will be accomplished through photogrammetry analysis of images obtained with an on-board camera system. The extended ACS3 project goals are to characterize the solar radiation pressure thrust of the deployed solar sail via controlled orbit raising and lowering, and to attempt to identify the fundamental flexible body structural dynamic vibration modes of the deployed solar sail.

C. NASA Deployable Composite Booms (DCB) technology

One of the fundamental objectives of the ACS3 project is to demonstrate NASA deployable composite boom technology in a spaceflight application. The ACS3 solar sail structure uses booms developed by the NASA Space Technology Mission Directorate (STMD) Deployable Composite Booms Project (DCB). The DCB project is a collaboration between NASA Langley Research Center and the German Aerospace Center (DLR) to advance compact deployable boom technology for future small spacecraft applications. DCB has been primarily focused on advancing design methodologies and manufacturing methods for closed cross-section, collapsible lenticular composite booms, and development of the associated mechanical systems needed for stowing and deploying them. Examples of typical DCB booms are shown in Figure 2. One of the most difficult challenges is stowing these booms in very limited, compact volumes, such as within CubeSats. DCB booms use very thin carbon fiber plain-weave and unidirectional ply technology to minimize wall thicknesses and minimize bending radii needed for compact rolling stowage of the booms.

Figure 2. NASA Deployable Composite Boom (DCB) booms. DCB boom technology uses very thin carbon fiber composite plain-weave and unidirectional plies for maximizing the curvature strain tolerance of the boom wall laminates when flattening and rolling for stowage. This enables stowage of very long load-carrying booms in very small volumes in CubeSat form factor spacecraft.

IV. ACS3 spacecraft

The ACS3 spacecraft uses a 12U CubeSat payload form factor to take advantage of rideshare launch capabilities and minimize costs. Selection of a 12U size was done primarily to simplify engineering of the ACS3 spacecraft bus. The 12U form factor also permits a more symmetric cross-section footprint for the ACS3 solar sail subsystem, which is a more realistic configuration for future ACS3-derived solar sails. The larger volumes available for sail subsystem package also permits the use of higher stiffness composite boom laminates, which are also more applicable to future, larger scale deployable composite boom solar sails. The general arrangement of the ACS3 spacecraft is shown in Figure 3. The ACS3 spacecraft has three major assemblies, as shown in Figure 4: The spacecraft bus, containing the majority of the spacecraft avionics systems; the Sail-Boom Subsystem (SBS), which contains and deploys the packaged solar sail membranes and composite booms; and the "-Z" plate, which primarily serves as a mounting surface for the ACS3 UHF and S-band communications antennas.

V. ACS3 Sail-Boom Subsystem (SBS)

A. ACS3 composite booms

The 7.0-meter ACS3 composite boom design is derived from a 16.5-meter "full-scale" solar sail boom developed under the DCB project. Boom design methodology, thin-ply composite laminate materials, and boom manufacturing processes are the same as those used for DCB booms. A schematic of the ACS3 boom cross-section is shown in Figure 5.

1. Boom Manufacturing

ACS3 deployable composite booms are manufactured at NASA Langley Research Center (Figure 6). Manufacturing methods are derived from those used with the DCB full-scale 16.5 m deployable composite booms. ACS3/DCB booms consist of two curved composite shell laminates that are bonded along the narrow web regions of the cross-section. Laminate curing and bonding occur inside an oven using a single out-of-autoclave process. Carbon foam mold tooling minimizes thermal mismatches between the carbon fiber ply boom material and the mold tooling, minimizing curvature in the final boom part. For ACS3, the acceptable as-built curvature of the booms is defined as less than 1%, or less than 7 cm over the full 7-meter length of the boom. A manufacturing rate of one to two booms a week is typical for ACS3 booms.

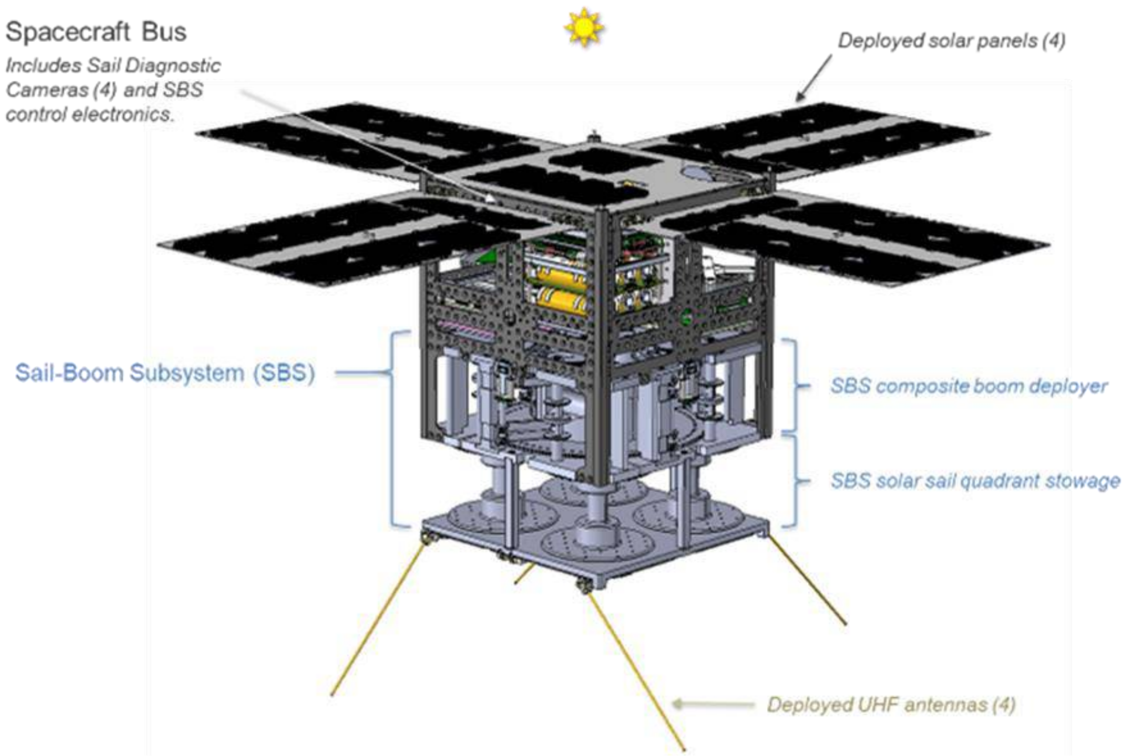


Figure 3. ACS3 12U spacecraft. Solar panels are shown deployed. Avionics compartment side panels, sail membranes, and booms have been omitted for clarity.

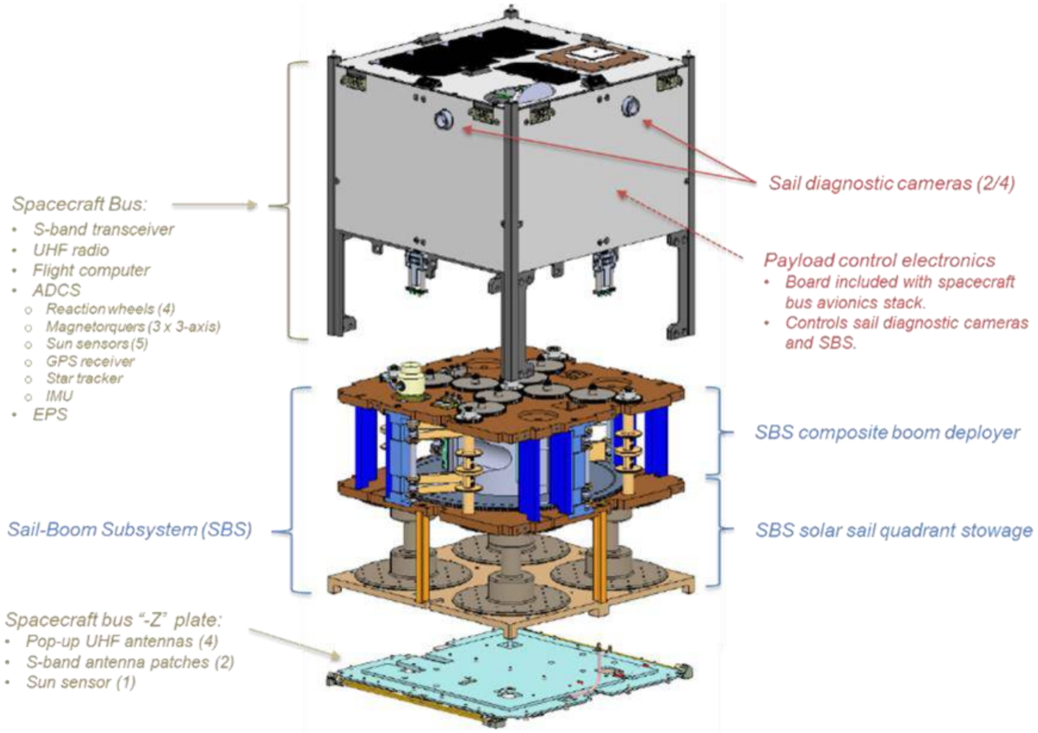


Figure 4. ACS3 12U spacecraft major assemblies and sub-systems. Solar panels, sail membranes, and booms have been removed for clarity.

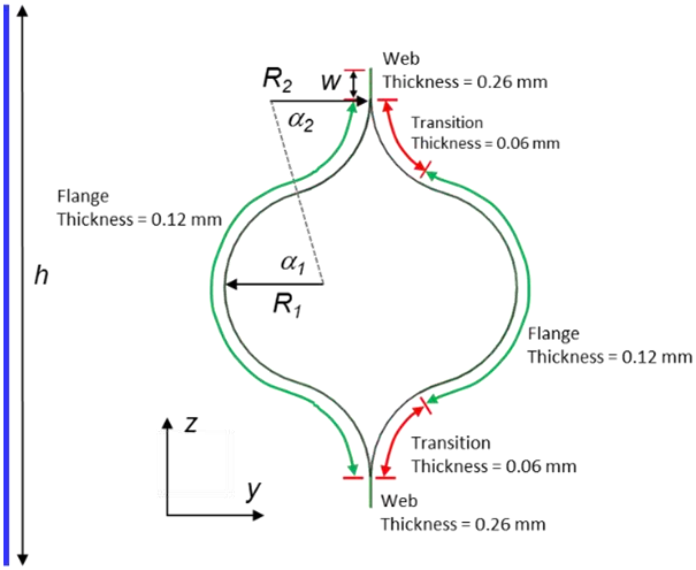


Figure 5. ACS3 deployable composite boom cross-section and laminate details. When flattened for rolling, the ACS3 boom cross-section is approximately 65 mm high (dimension h). The deployed cross-section is approximately 50 mm high by 33 mm wide when fully developed. Ply drop-offs (red) are used on the inner shell laminate (compressed side when rolled) to improve boom rolling tolerance.

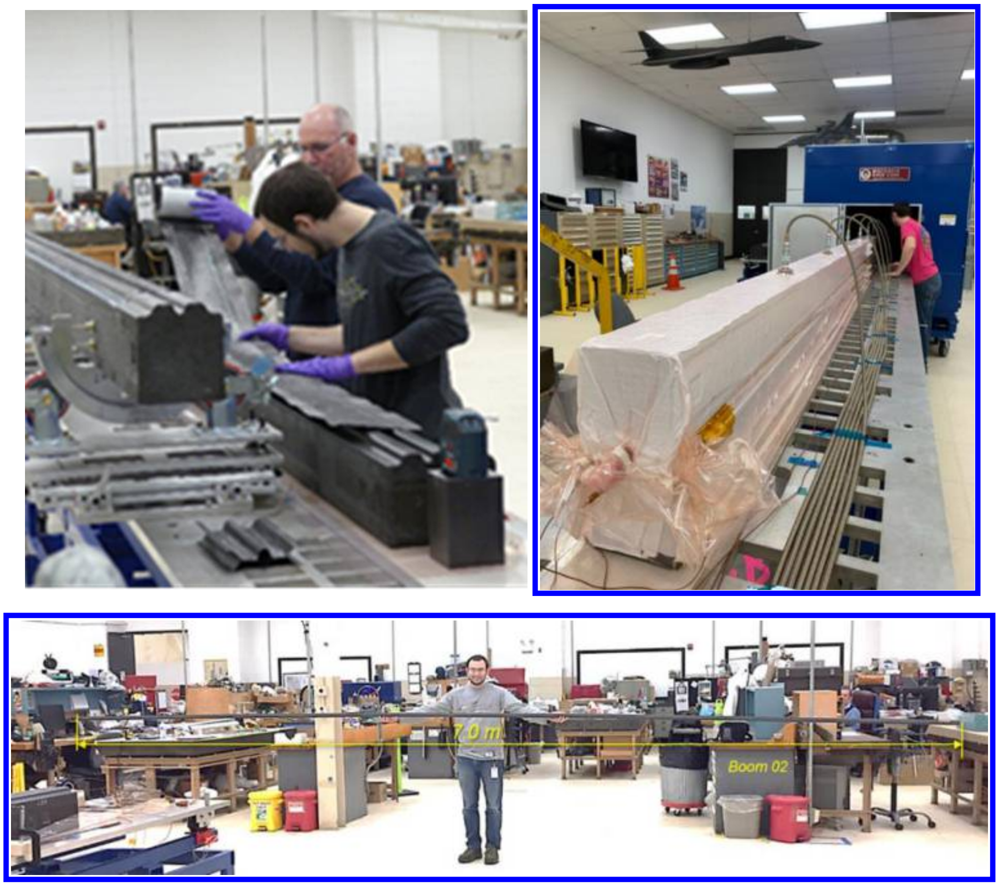


Figure 6. Manufacturing ACS3 deployable composite booms.

B. SBS boom deployer

The most complex element of the ACS3 spacecraft is the Sail-Boom Subsystem (SBS), shown in Figure 7. The SBS stows the composite booms and solar sail quadrants for launch, and deploys the booms and sail membranes on-orbit. The SBS deployer mechanism design is an evolution of the "tape-puller" concept, developed originally by the German Aerospace Center (DLR) and Surrey Space Centre (Figure 8).[9] This deployer design, developed originally for a 3U CubeSat deployable solar sail, was adapted by NASA Langley Research Center for use in a 6U CubeSat form factor solar sail system, and by DLR for a 27U CubeSat solar sail system. A 12U version of the tape-puller deployer design is used for ACS3. The tape-puller architecture deploys the solar sail boom elements by motorized retraction of several metallic tapes co-wound with the composite booms during stowage. This approach has several reliability advantages to driving the boom coil hub directly to "push" the booms out of the deployer. In the tape-puller system, the metallic tapes act to restrain the boom coil, which minimizes the risk of the deployer mechanism jamming due to booms unwinding inside the deployer during deployment.

C. Sail membrane quadrants

1. *Materials and material properties*

The ACS3 solar sail membrane quadrants consist of a 2.0 μm polyethelene napthalate (PEN) plastic film substrate, coated on one side with a very thin (100 nm) vapor deposited aluminum layer for reflecting solar photons, and on the other side with a thinner (15 nm) chromium metal layer for increasing overall thermal emissivity of the sail. PEN material was chosen primarily for its low-cost, acceptable space durability when metallized, and commercial availability in small thickness and large width rolls. Optical and thermal-mechanical testing of metallized film coupons have also shown that PEN-based sail should be acceptable for short flight durations (less than one year) at or near 1.0 AU heliocentric distances.[10]

2. *Design and Fabrication*

Layout and dimensions of a typical ACS3 sail quadrant are shown in Figure 9. Sail quadrants are approximately triangular in shape, with a 9-meter long outermost edge, and a 1-meter long inboard cutout. Each quadrant is assembled from 0.75-meter wide gores using a polyester melt-adhesive seaming technique. The melt-adhesive seams are stronger than the base PEN material, thinner and tack-free relative to Kapton or transfer tape seaming, and function as built-in mechanical ripstops. Kevlar reinforcing threads are incorporated along all seams and edges for additional mechanical reinforcement.

3. *Folding and stowing*

ACS3 sail quadrants are folded and then rolled onto individual spools for stowing inside the sail stowage compartment of the SBS. The folding and spooling process can typically be performed in a single day per quadrant. A "biased" Z-fold pattern is used with the sails, as shown in Figure 10. This pattern is designed so that the outer wrap of the spooled sail remains in tension and constrains the inner wraps during the deployment process. The approximately radial direction of the folds also minimizes stackup of sail seams, which helps minimize the stowed volume of each quadrant. The fold lines also run more nearly perpendicular to the sail tension forces during deployment, which facilitates unfolding and flattening of creases in the sail.

D. Boom Packaging

Rolling and stowing the ACS3 booms is accomplished in a two-step process, as shown in Figure 11. The first step consists of hand flattening and simultaneously rolling each boom onto an individual, large-diameter spool. The individual spooled booms are then mounted to a tabletop apparatus that feeds all four flattened booms synchronously onto the common boom reel within the ACS3 Sail-Boom Subsystem deployer mechanism. An external, non-flight motor is used to directly drive the SBS deployer hub in reverse to reel the booms onto the hub. The metallic puller tapes are co-wound with the booms on the hub during this operation. Pneumatic mechanical ground support equipment (MGSE) actuators keep the booms compressed and constrained onto the SBS deployer hub during the reeling process. Once completely stowed, all packaging MGSE is removed and tension in the co-wound metal tapes is sufficient to constrain the flattened boom coil within the deployer.

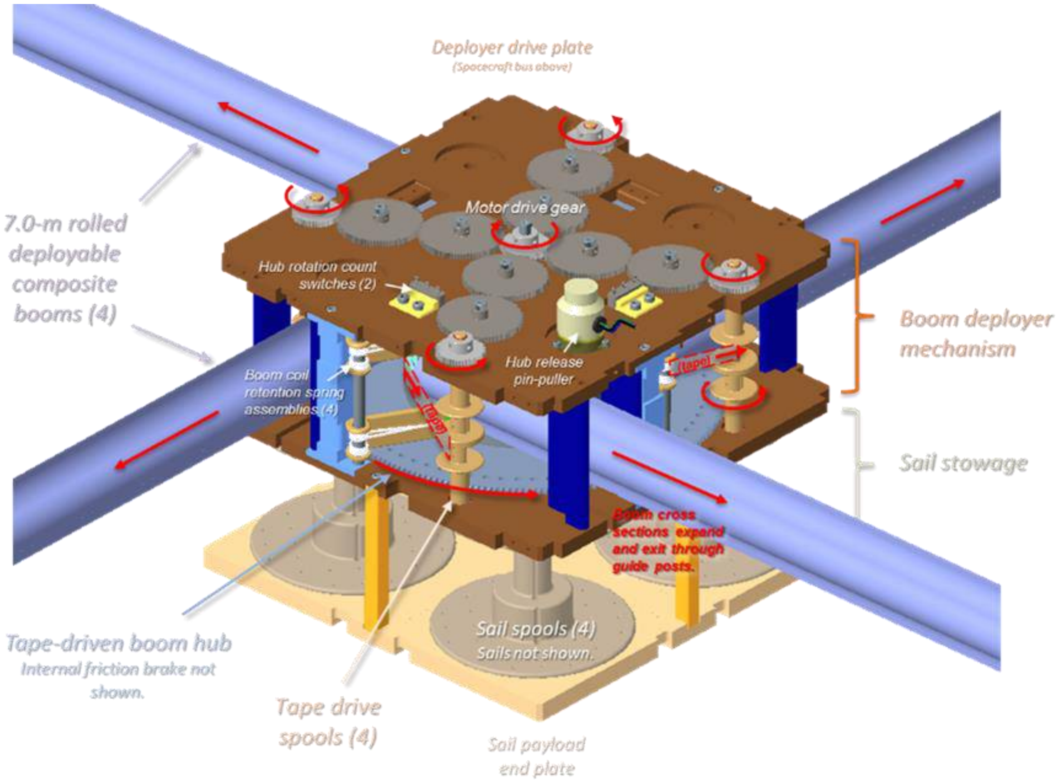
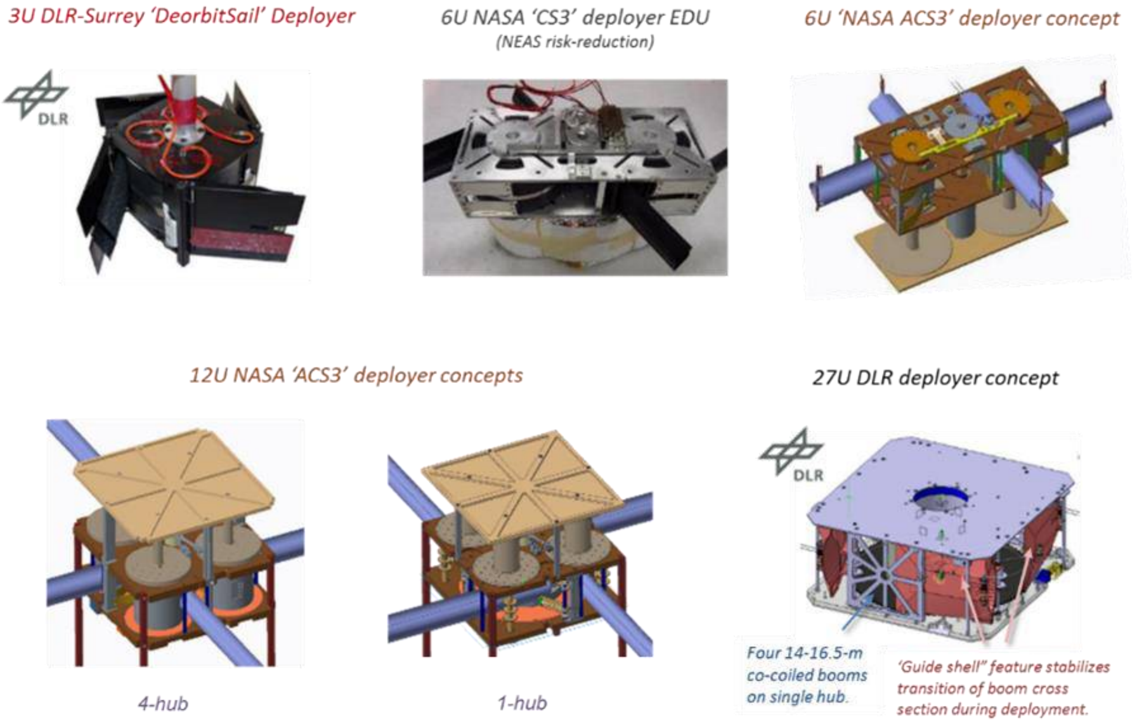


Figure 7. ACS3 Sail-Boom Subsystem (SBS). Sail membranes have been removed for clarity.


3U DLR-Surrey 'DeorbitSail' Deployer

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

6U 'NASA ACS3' deployer concept

12U NASA 'ACS3' deployer concepts

27U DLR deployer concept

4-hub

1-hub

Figure 8. Heritage and evolution of the "tape-puller" boom deployer design for solar sail applications. A single-hub, 12U-sized tape-puller design (middle bottom) was adopted for the ACS3 SBS.[9]

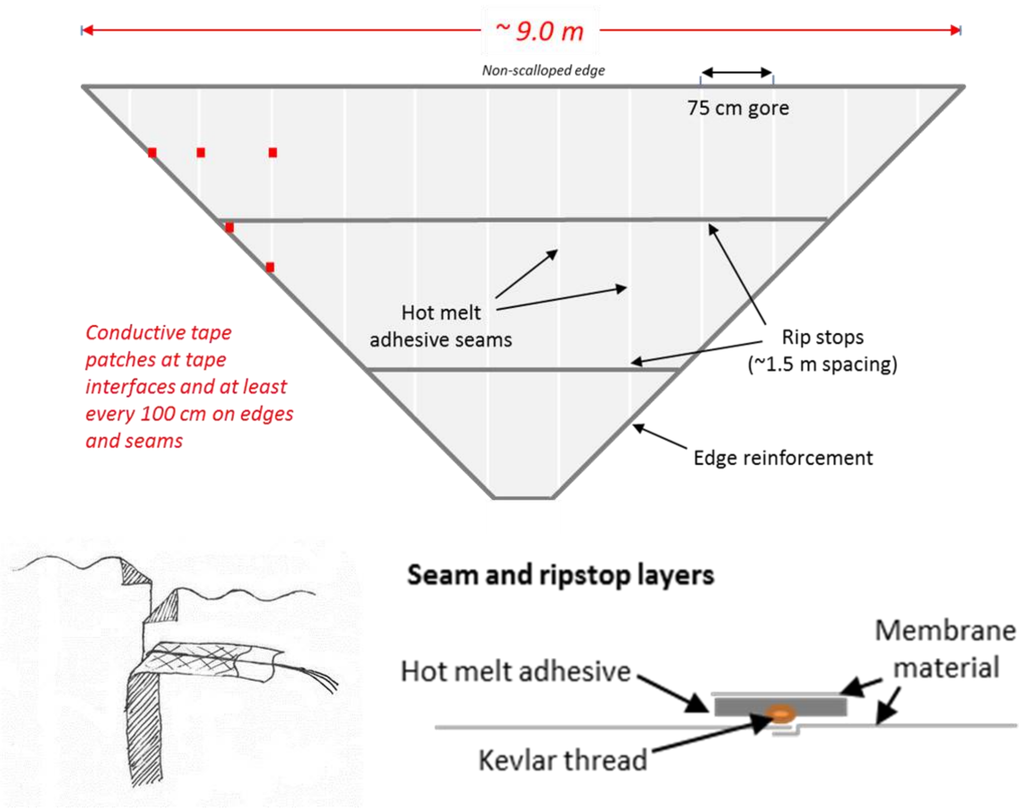


Figure 9. ACS3 solar sail quadrant design and seam construction.

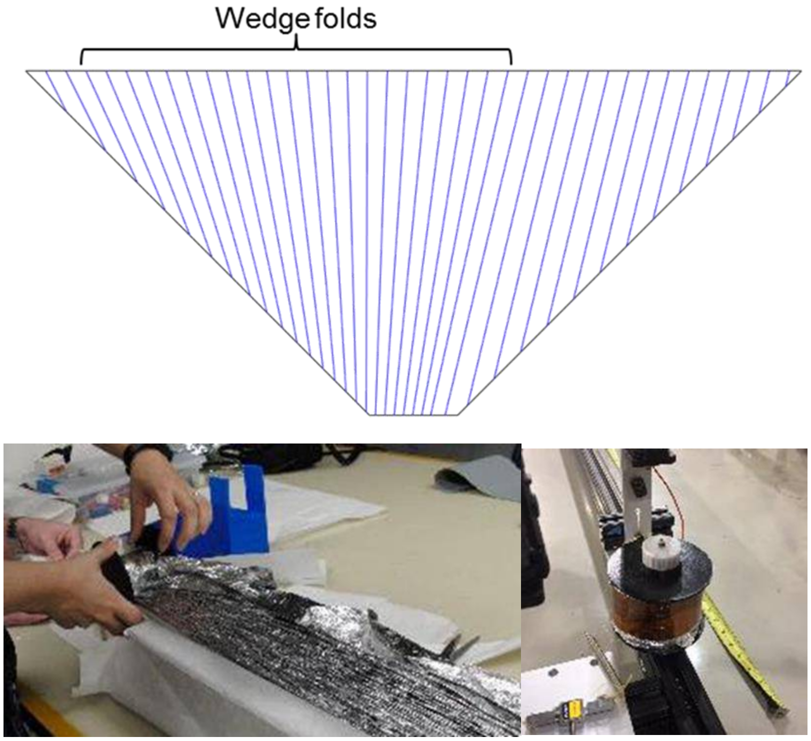


Figure 10. ACS3 sail quadrant folding scheme and spooling process.

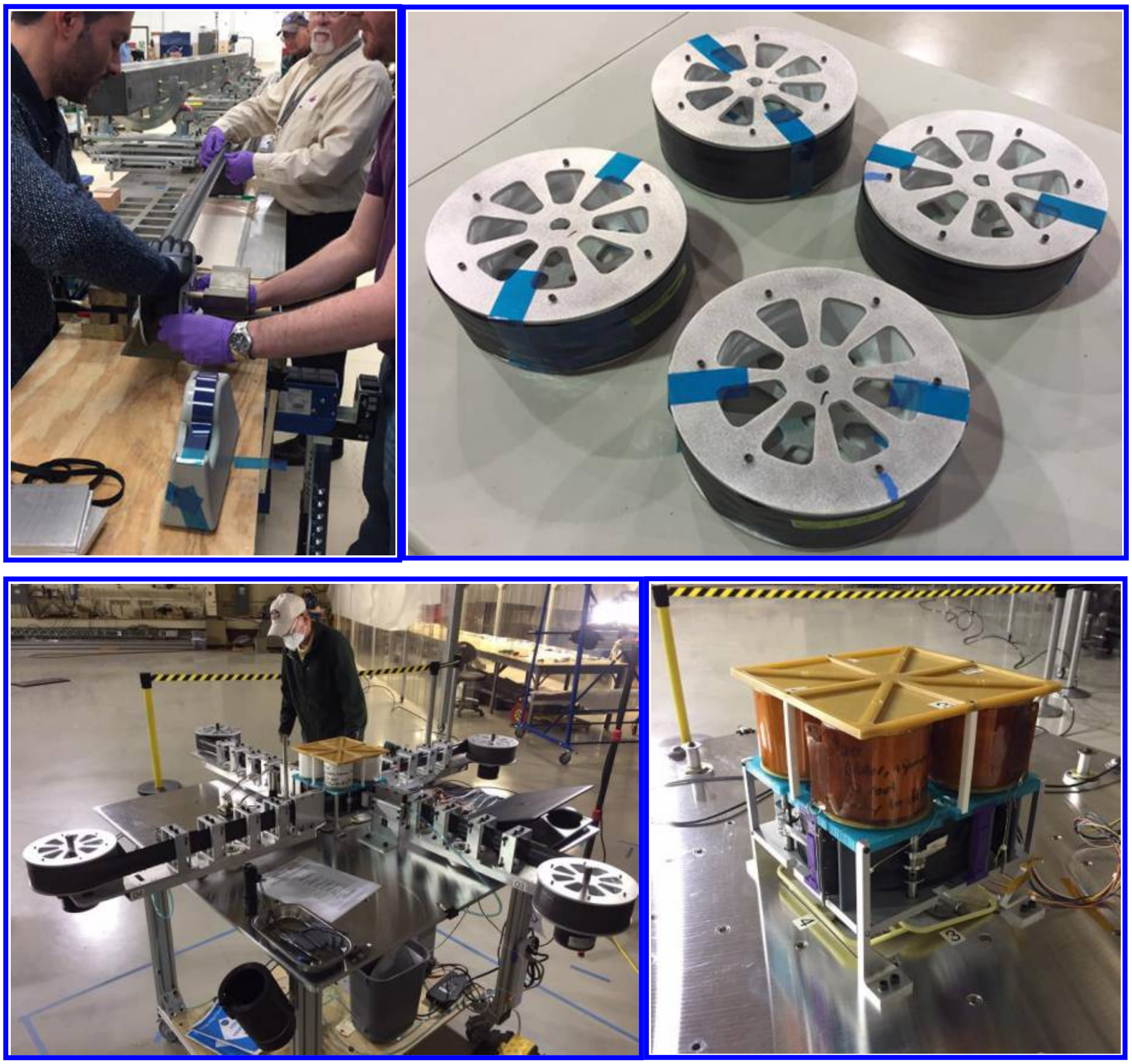


Figure 11. ACS3 boom reeling and packaging process. Development booms here are being stowed onto the ACS3 Sail-Boom Subsystem functional prototype deployer unit.

E. Ground deployment testing

Ground deployment tests of the ACS3 Sail-Boom Subsystem (SBS) deployer with booms only, booms and simulated sail quadrants (cables with tensioning springs), and booms with spooled sails are performed on the flat floor of the Spacecraft Structures and Dynamics Laboratory at NASA Langley Research Center (Figure 12). Deployments are computer-controlled, with a nominal duration of 20-30 minutes, corresponding to the anticipated on-orbit deployment duration.

One technique to simulate loading of the booms by tensioning of the sail membranes is to use a network of spring-tensioned Kevlar cables attached to the boom tips and central bus structure. This approach was used to demonstrate that the booms can successfully tension the sail membranes at the end of deployment with margin (greater than 150% of nominal tension load), as shown in Figure 13. Loading of the booms also pulls the sail structure into its desired deployed configuration, with all booms perpendicular to the square faces of the central deployer and bus structure.

Ground deployment testing of the complete solar sail system - sails, booms, and deployer - under gravity loading is significantly more complicated. In particular, vertical and in-plane loads caused by dragging of the partially furled sails tends to disrupt the natural paths of the boom tips during deployment. This testing is useful for verifying proper initial unspooling of the sails and final loading of the booms due to sail membrane tensioning. A sequence of images from a recent full system deployment test of the SBS prototype unit is shown in Figure 14. The final deployed configuration is shown in Figure 15. Sail quadrants used during this test are slightly smaller than the final flight sail designs. As with the simulated sail quadrant deployment tests, loading of the booms at the end of deployment stabilizes the sail structure in its final deployed configuration. Frictional loads between the sail membranes and the test floor are still present and prohibit a completely interference-free full-system ground deployment test.

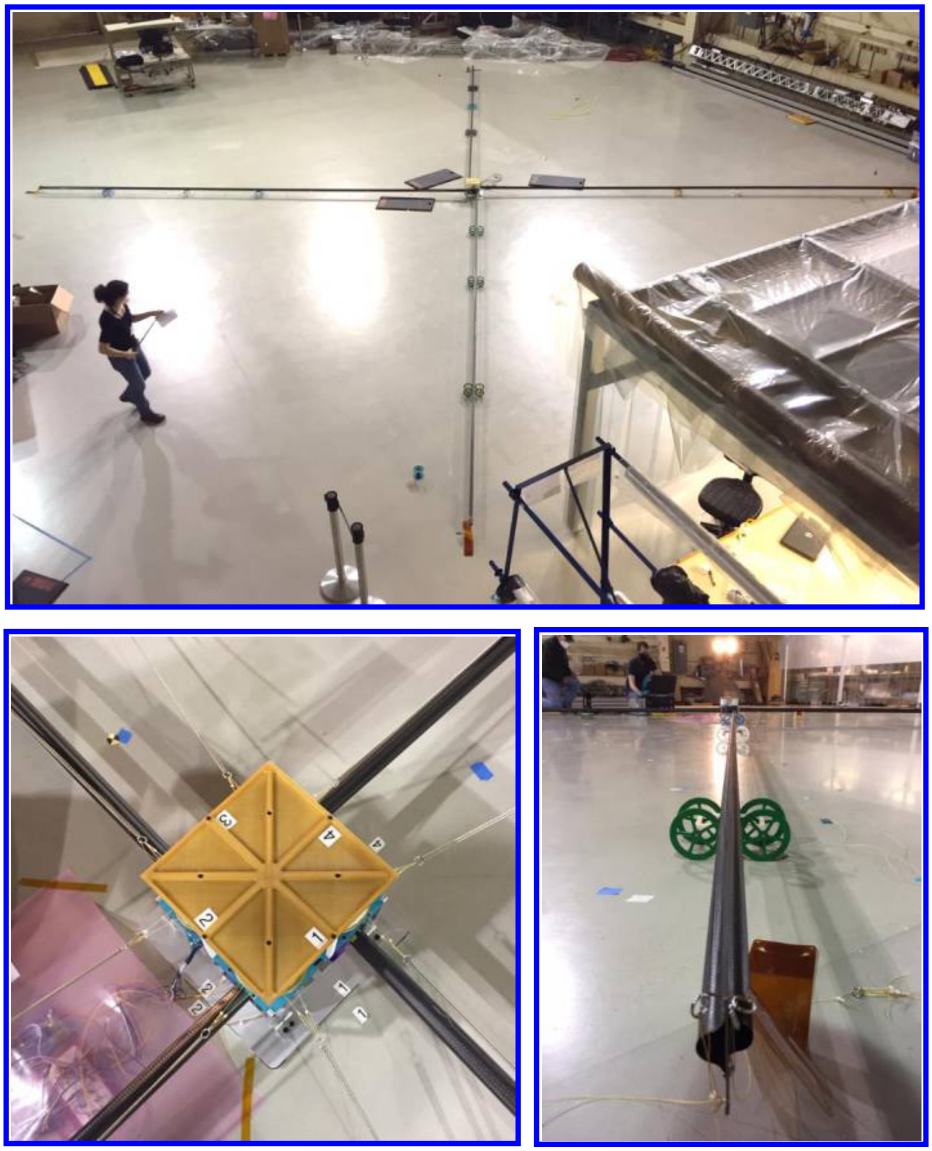


Figure 12. Ground deployment testing of the ACS3 Sail-Boom Subsystem (SBS) prototype unit. A network of Kevlar cables and tensioning springs are used to simulate sail membrane loads. Cables are attached to all four booms and at the central deployer structure (lower left). Connections at the boom tips and tensioning springs at the roots simulate the geometry and loading of the flight sail membranes. Gravity offloading of the booms during deployment is accomplished using small free-rolling 3-D printed plastic carts spaced periodically along the length of each boom (lower right). ACS3 offloading carts are based on a DLR design developed for testing the 16.5-meter full-scale DCB solar sail booms and deployer system.

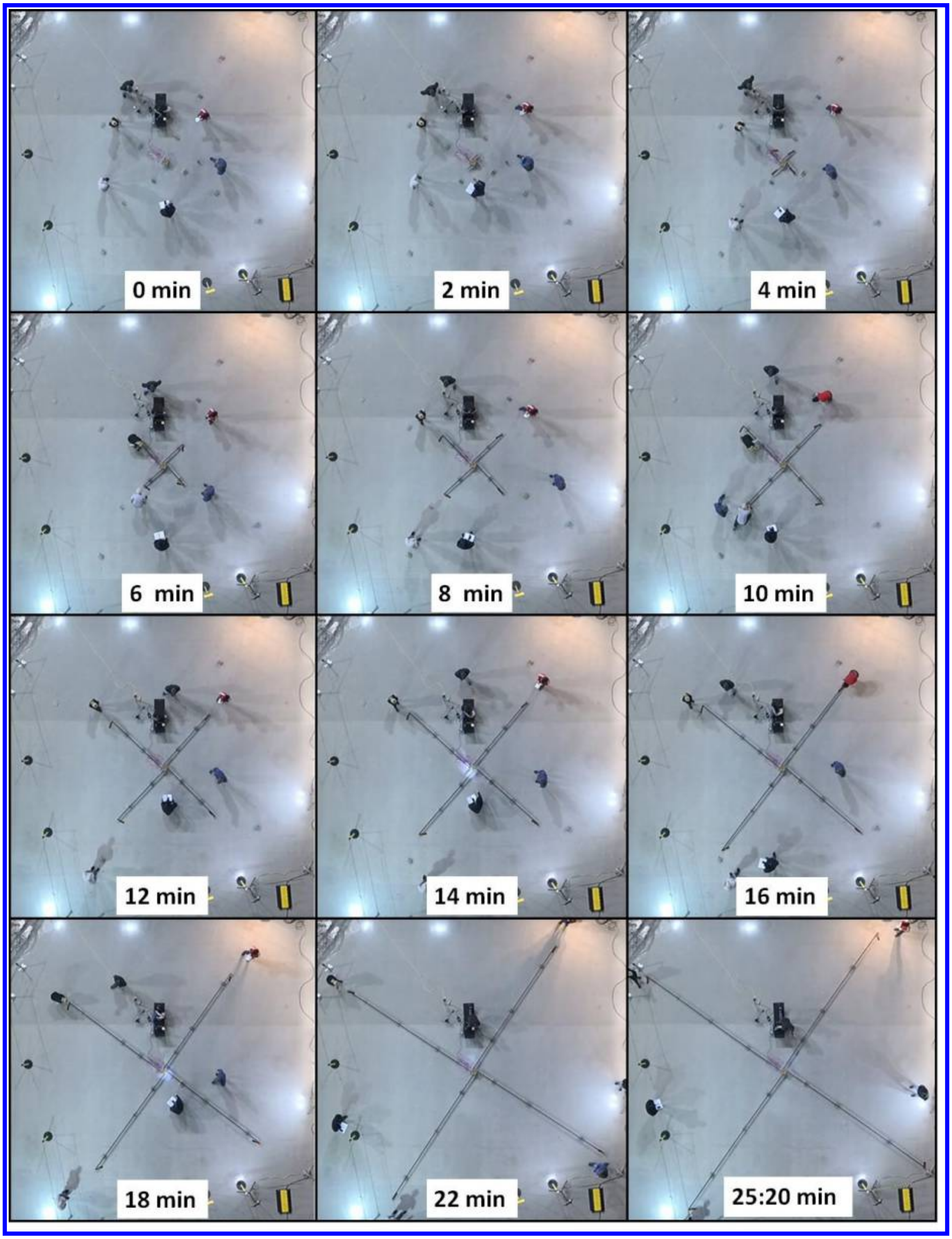


Figure 13. Simulated sail quadrant testing of the ACS3 Sail-Boom Subsystem (SBS) prototype using tensioned cables. The simulated quadrants are attached to the boom tips for the final meter of deployment.

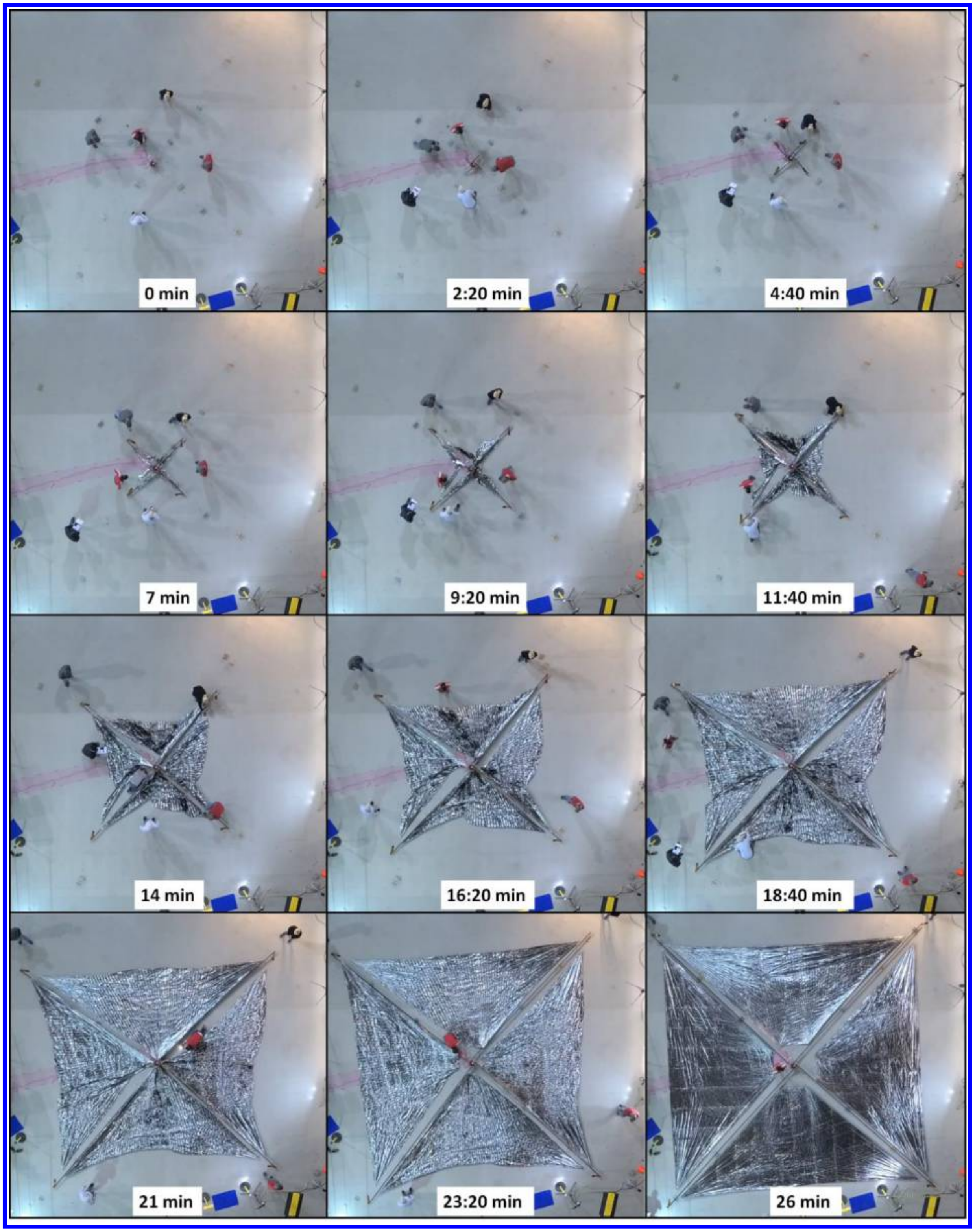


Figure 14. Full system ground deployment test of the ACS3 Sail-Boom Subsystem (SBS) prototype unit. Development sails shown are slightly smaller than the flight ACS3 sail membranes. Composite booms, sail folding, sail and boom stowage, sail-to-boom tip attachment, and sail root spring tensioning are representative of the flight SBS design.

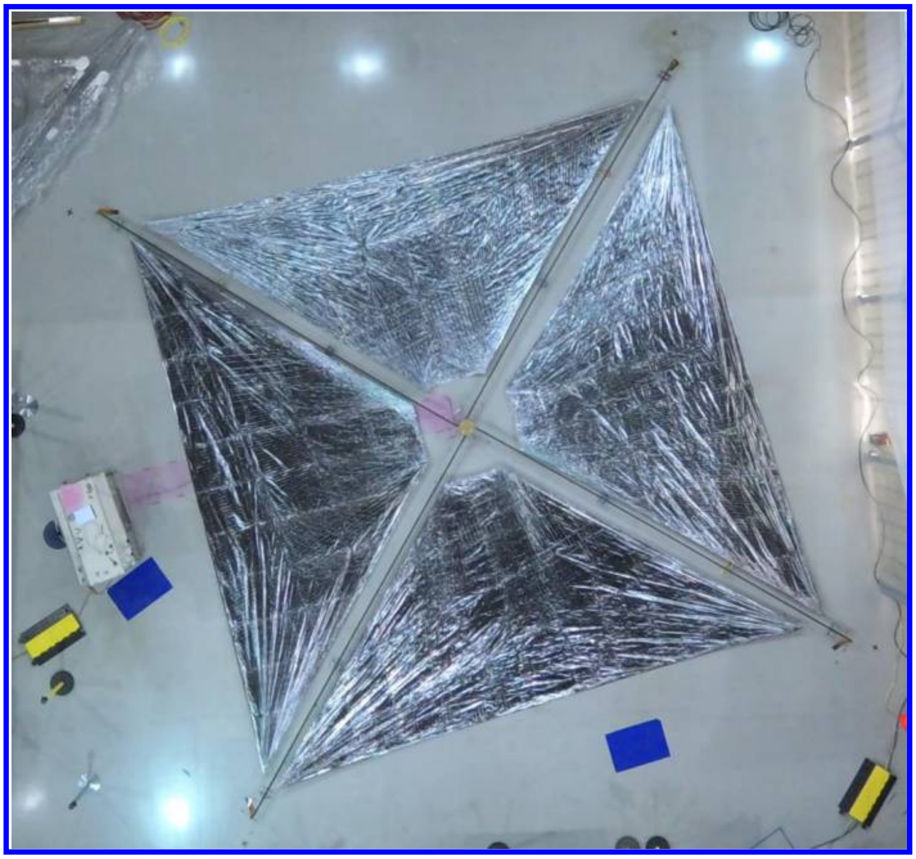


Figure 15. Sail-Boom Subsystem (SBS) prototype ground deployment test: final deployed configuration.

VI. ACS3 flight demonstration concept of operations

A. Flight demonstration timeline

A timeline illustrating the ACS3 flight demonstration concept of operations is shown in Figure 16. After launch and ejection from the rideshare launch vehicle, the ACS3 spacecraft will deploy solar panels and detumble using magnetorquers. This will be followed by commissioning operations. Commissioning is expected to take approximately 28 days, at which point ACS3 will be ready to deploy its solar sail.

The primary objective of the ACS3 project is to deploy and characterize the ACS3 experimental composite boom structure solar sail in space. A suite of four high-definition onboard cameras will record deployment of the solar sail. Camera imagery will be downlinked and processed to characterize the deployed shape and uniformity of the sail. Approximately one week is allocated for ACS3 sail deployment operations, including pre-deployment checkouts of the SBS system. Deployment of the sail will take between 20 to 30 minutes.

A secondary objective of ACS3 will be to characterize the thrust characteristics of the deployed solar sail. This will be attempted by orienting the deployed sail to maximize solar radiation pressure-induced thrust in the direction of flight, resulting in a gradual change in the semi-major axis of the orbit. An altitude change of up to 1-2 km/day should be achievable with the ACS3 solar sail, depending on orbit altitude and final mass of the ACS3 spacecraft. Camera imagery data obtained and stored during the previous deployment and shape characterization operations will also be downlinked during this time. A minimum of 30 days is allocated for ACS3 orbit raising operations, followed by an additional 30 days of orbit lowering.

A final objective of the ACS3 experiment will be to assess the fundamental structural dynamic properties of the deployed solar sail structure. This will be attempted via system identification analysis of attitude determination and control sensor data from the spacecraft bus.

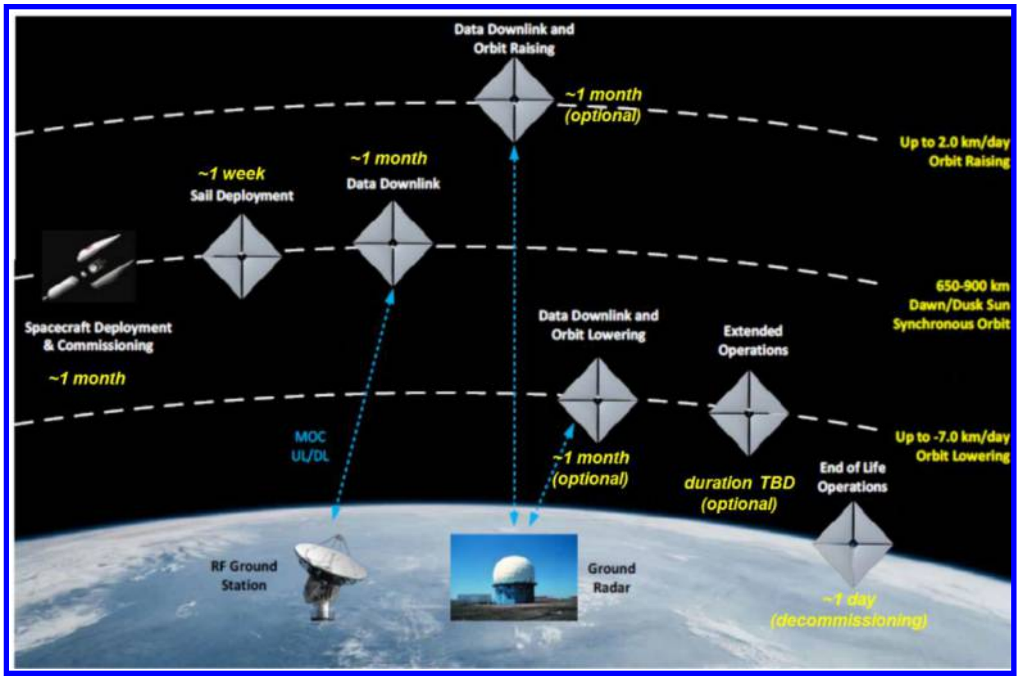


Figure 16. ACS3 Concept of Operations diagram. Nominal flight duration from launch to decommissioning is approximately 120 days, with an option for extending operations after all primary and secondary technology demonstration objectives have been achieved.

After completion of all mission success criteria, ACS3 will use the solar sail to further lower altitude through aerodynamic drag and solar radiation pressure forces. Attitude control of the spacecraft will be maintained as long as possible, until aerodynamic forces and moments begin to overpower the attitude control system. At this point, the spacecraft will be commanded to passivate and power-down prior to a complete loss of attitude control authority. The deorbiting phase and burnup should be completed within two to three months depending on atmospheric density conditions and the initial orbit altitude.

B. Orbit selection

Aerodynamic drag is the greatest complicating environmental factor for conducting a low earth orbit solar sail technology demonstration. Orbit altitude needs to be relatively high to minimize aerodynamic disturbance forces and torques, which, for a large area solar sail, can cause rapid deorbiting or loss of vehicle control. Furthermore, if an objective is to demonstrate propulsion via solar radiation pressure, it is desirable that aerodynamic drag forces are smaller than solar radiation pressure forces acting on the sail.

A dawn-dusk sun-synchronous orbit (DD-SSO) simplifies many solar sail flight operations, by permitting the plane of the solar sail to be kept in the plane of the orbit, thereby minimizing aerodynamic drag, while allowing the sail normal to be directed toward the sun, maximizing solar radiation pressure effects. As a DD-SSO is non-eclipsing, power management of the spacecraft can be simplified, which has advantages for small spacecraft. Thermal-elastic distortions of the sail structure are also minimized as the sail operates at a nearly constant temperature.

If the nominal DD-SSO altitude is sufficiently high, drag forces acting on the sail will be less than radiation pressure forces for non-edge-on flight. In this situation, the sail can be rotated about the nadir axis to a fixed sun angle that will maximize energy gain of the orbit due to solar radiation pressure, and raise altitude. Similarly, the sail can be rotated to fixed angles that maximize orbital energy loss, lowering altitude via solar radiation pressure.

Despite the advantages for solar sailing, DD-SSO launches for rideshare payloads to altitudes of 700 km or higher are relatively scarce. Lower altitudes are more common, but the higher aerodynamic forces acting on the solar sail would restrict operations to edge-on flight, precluding an orbit raising demonstration. Increased drag also increases risks of rapid loss of altitude during an attitude control anomaly, which would shorten the flight duration, severely limiting the volume of camera imagery data that can be downlinked. To increase rideshare opportunities to acceptable orbits, ACS3 is designed to operate in any orbit with perigee 700 km or higher, and apogee up to 900 km. Apogee is mainly constrained by the desire to deorbit in less than 25 years. This should be achievable with a partially deployed sail (25% or greater boom deployment) as shown in Figure 18. Sun-synchronous orbits are still preferred, to simplify operations, but are not strictly required. Thermal design of the sail structure and inclusion of electrical heater elements in the deployer mechanism allow eclipsing orbits to also be considered.

C. Orbit raising and lowering performance

Orbit raising and lowering simulations for several assumed initial orbits have been conducted. The simplest orbit raising maneuver is for a non-eclipsing, dawn-dusk sun-synchronous initial orbit (DD-SSO). A DD-SSO of 700 km or higher initial altitude would be the ideal, and preferred, orbit for ACS3, although availability of rideshares to these orbits is relatively low. A more general noon-midnight sun-synchronous orbit (NM-SSO) with 12 noon local time of the ascending node (LTAN) has been adopted as a more representative likely orbit for ACS3 simulations. Orbit raising and lowering is more challenging in this case, and requires slewing of the sail by 90 degrees each orbit in order to optimize the net energy gain due to solar radiation pressure. An idealized steering law for this case is shown in Figure 19. This steering law is based on the ideal locally optimal steering law described by McInnes.[1] Time domain simulations for the ACS3 solar sail show that increases in orbit semi-major axis (SMA) of 0.5 to 0.7 km per day on average should be achievable for an initial NM-SSO altitude between 700 km and 800 km, with a total increase in SMA of +20 km achievable over 30 days of operation in this steering mode. (Figure 20.) A similar steering law can be used for optimizing energy loss and lowering SMA. Controlled orbit lowering using this strategy will also be attempted to accelerate deorbiting of the ACS3 spacecraft after all flight demonstration objectives have been achieved.

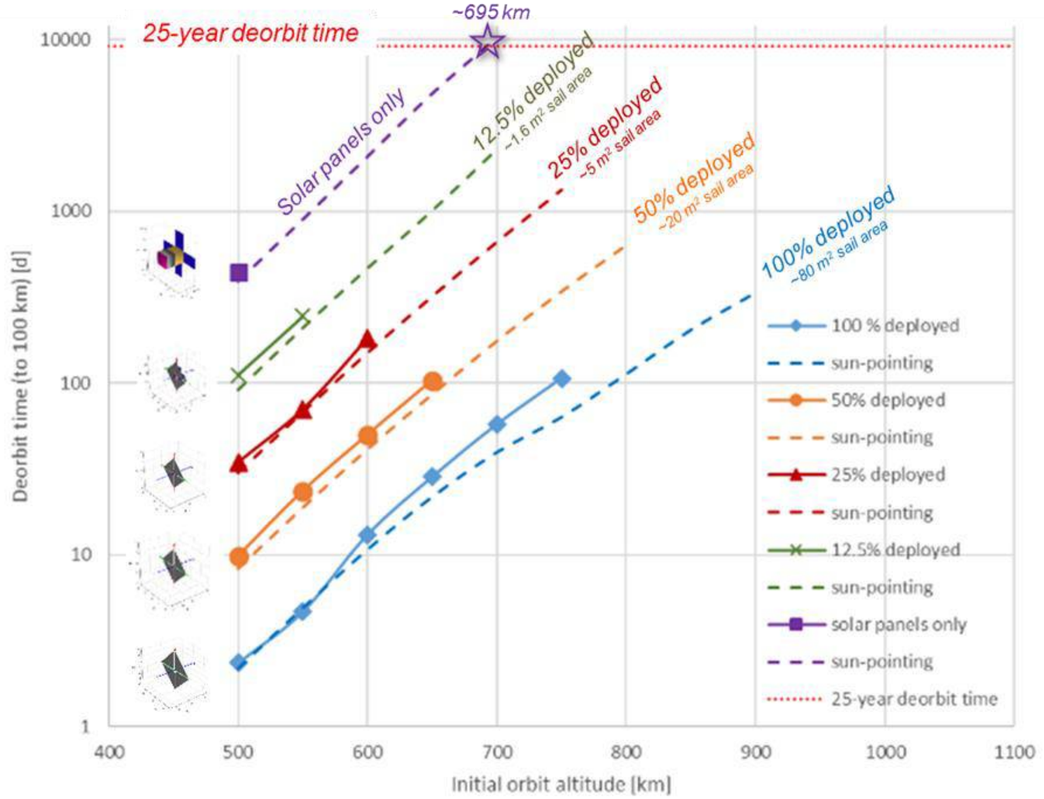


Figure 18. ACS3 deorbiting time in days versus orbit altitude for noon-midnight sun-synchronous initial orbits. Results are based on numerical time domain simulations. Sail configurations between 0% and 100% boom deployment are shown. Solid lines and symbols indicate uncontrolled, tumbling flight cases. Dashed lines are for controlled, sun-pointing flight. Partial sail boom deployments of 25% or greater should be sufficient to deorbit the ACS3 spacecraft within 25 years for orbit altitudes up to 900 km. Deployment of solar panels alone should be sufficient to deorbit ACS3 within 25 years for altitudes below 700 km.

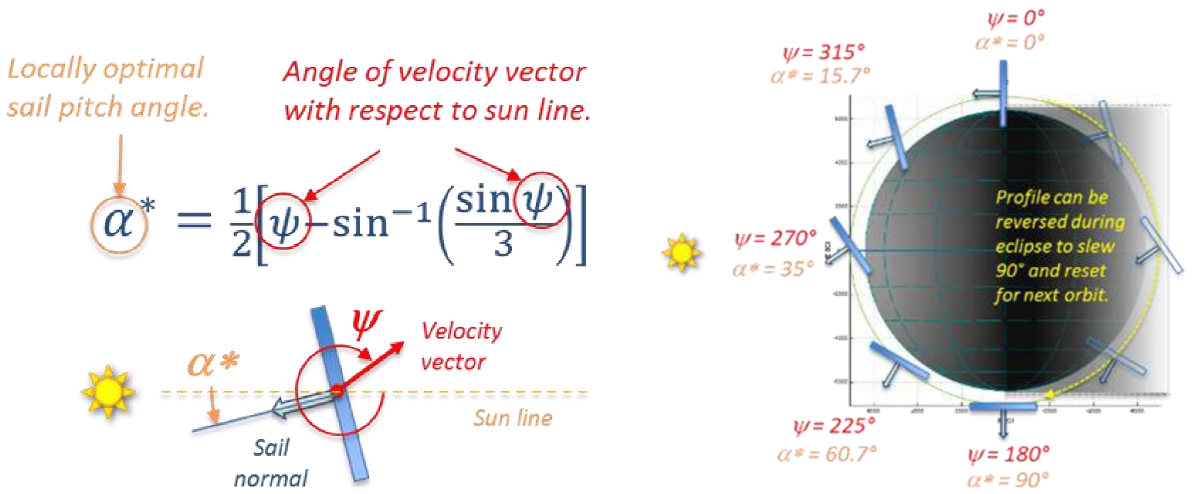


Figure 19. Idealized locally optimal steering law for SMA raising from an initial noon-midnight sun-synchronous orbit. The ACS3 optimal steering laws for orbit-raising and lowering will be optimized for the actual launch orbit and epoch once they are finalized.

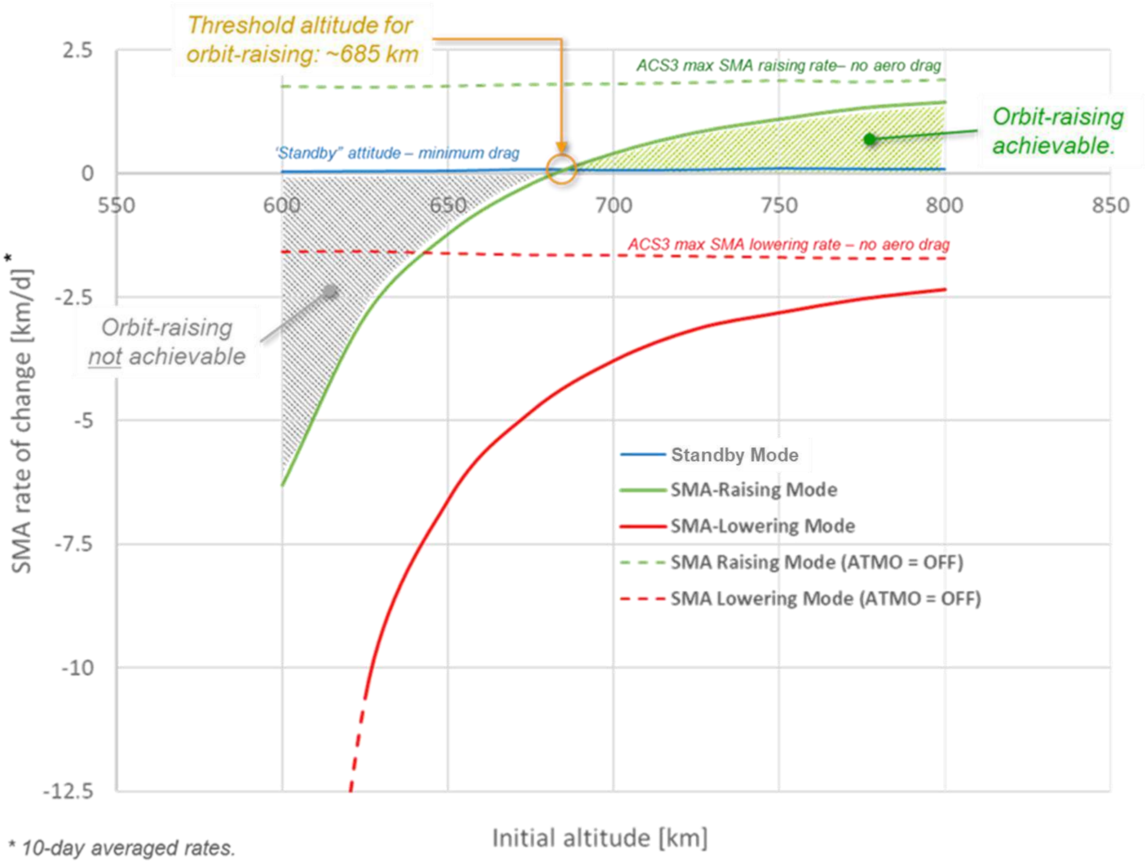


Figure 20. ACS3 orbit raising and lowering capabilities as a function of initial altitude and atmospheric drag. A locally optimal steering law similar to McInnes[1] is assumed for all cases. 10-day average rates of change in semi-major axis (SMA) are shown. Noon-midnight sun-synchronous initial orbits are assumed. In "standby" attitude, ACS3 operates with the –Z axis of the spacecraft nadir pointing at all times.

VII. ACS3 extensibility to future small spacecraft solar sail technology

A. Scalability of ACS3 solar sail structure and future architectures

Ultimately, ACS3 is intended to be a solar sail technology pathfinder for future, larger-scale solar sail systems based on the DCB deployable composite booms technology. The upper size limit for DCB-based solar sails in a CubeSat form-factor chassis is the "HIPERSail" design reference solar sail concept, shown in Figure 21. The HIPERSail solar sail system concept uses 16.5-meter NASA DCB deployable composite booms in an advanced 'tape-puller' design deployer mechanism developed by DLR.[11] The boom and deployer system shown is sized to be compatible with a 27U CubeSat spacecraft. Notional HIPERSail vehicle properties and dimensions are shown in Figure 22. This 27U HIPERSail solar sail vehicle would deploy a solar sail up to 520 m^2, which would be sufficient for a characteristic acceleration of approximately 0.15 mm/s^2 (lightness number, β, of 0.025) when including all spacecraft systems and science instrument payload (Figure 23). This characteristic acceleration, or alternatively, lightness number, performance capability should be sufficient for a number of near-term small-spacecraft science mission applications using solar sail propulsion. Higher performance DCB HIPERSail-based sails ("DCB-2") can extend lightness number capabilities to the $\beta = 0.03$-0.035 range. Higher lightness numbers ($\beta \sim 0.04$-0.045) may also be attainable using growth DCB-based technology, for solar sail missions with lower mission payload mass requirements.

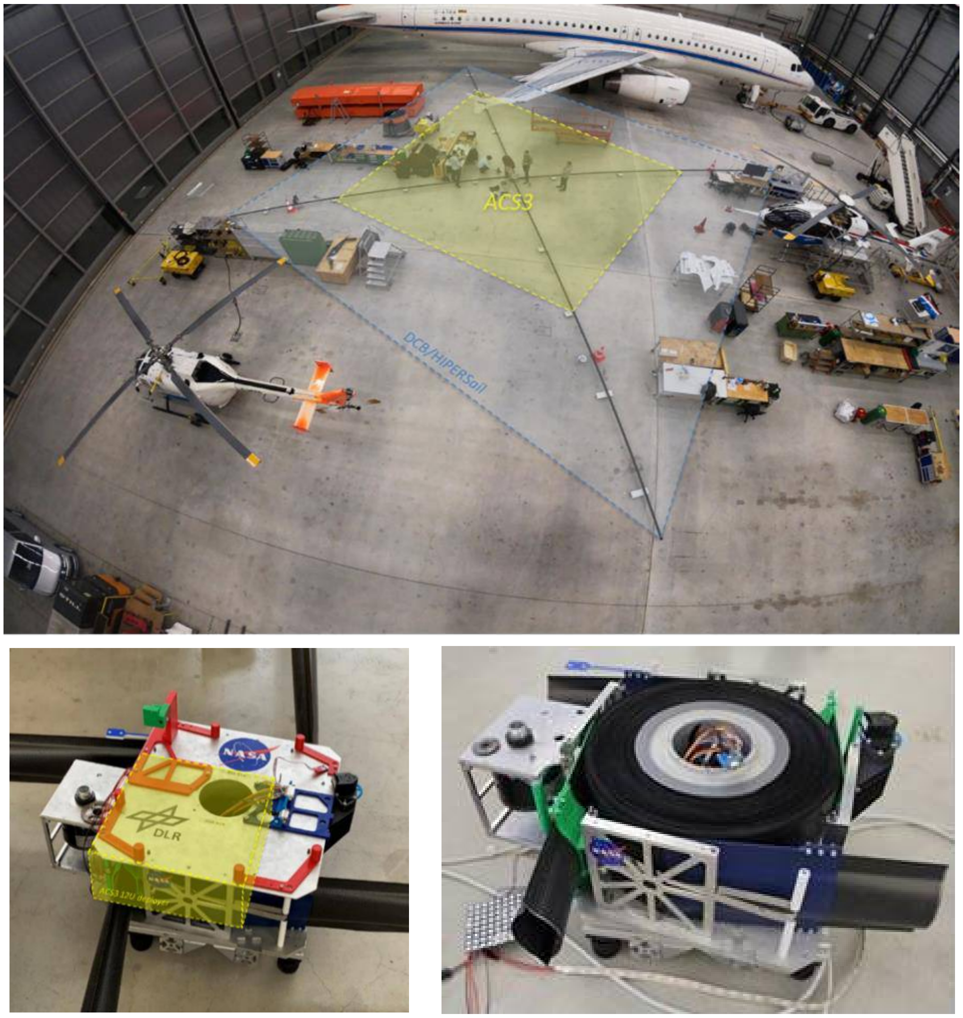
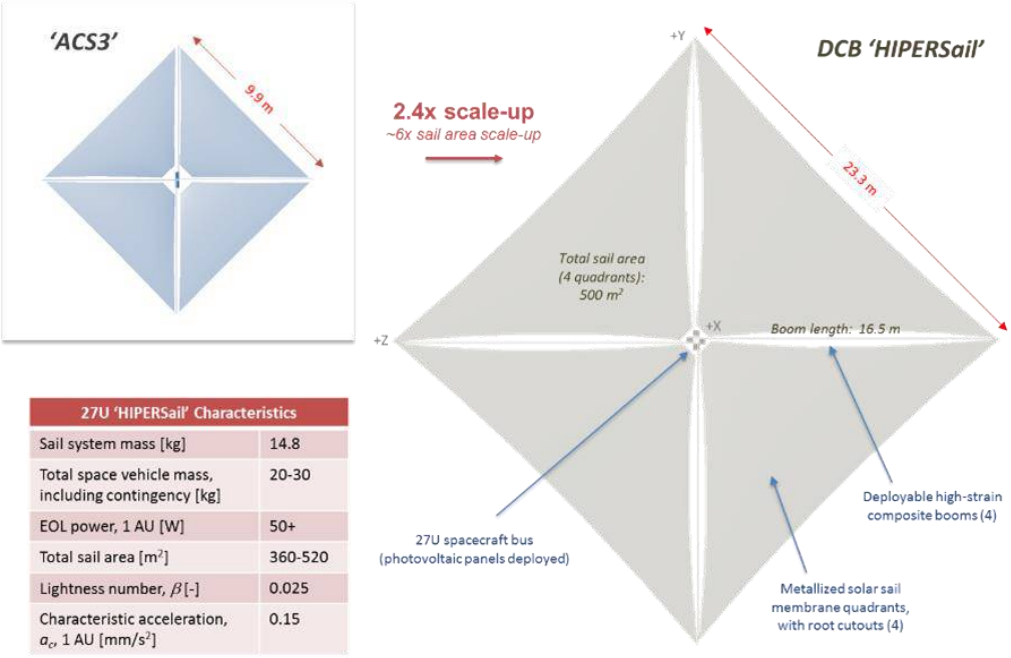


Figure 21. Joint NASA-DLR 16.5-meter booms, 520 m^2, 27U-scaled DCB "HIPERSail" solar sail system engineering development unit. The 12U-scaled ACS3 7.0-m boom, 80 m^2 solar sail technology demonstrator is shown for scale. Both ACS3 and DCB HIPERSail use similar deployable composite boom technology and deployer architectures.[11]



27U 'HIPERSail' Characteristics	
Sail system mass [kg]	14.8
Total space vehicle mass, including contingency [kg]	20-30
EOL power, 1 AU [W]	50+
Total sail area [m²]	360-520
Lightness number, β [-]	0.025
Characteristic acceleration, a_c, 1 AU [mm/s²]	0.15

Figure 22. Straw man 27U DCB "HIPERSail" solar sail spacecraft. ACS3 solar sail is shown to scale. Tip-to-tip distance between adjacent boom tips is indicated.

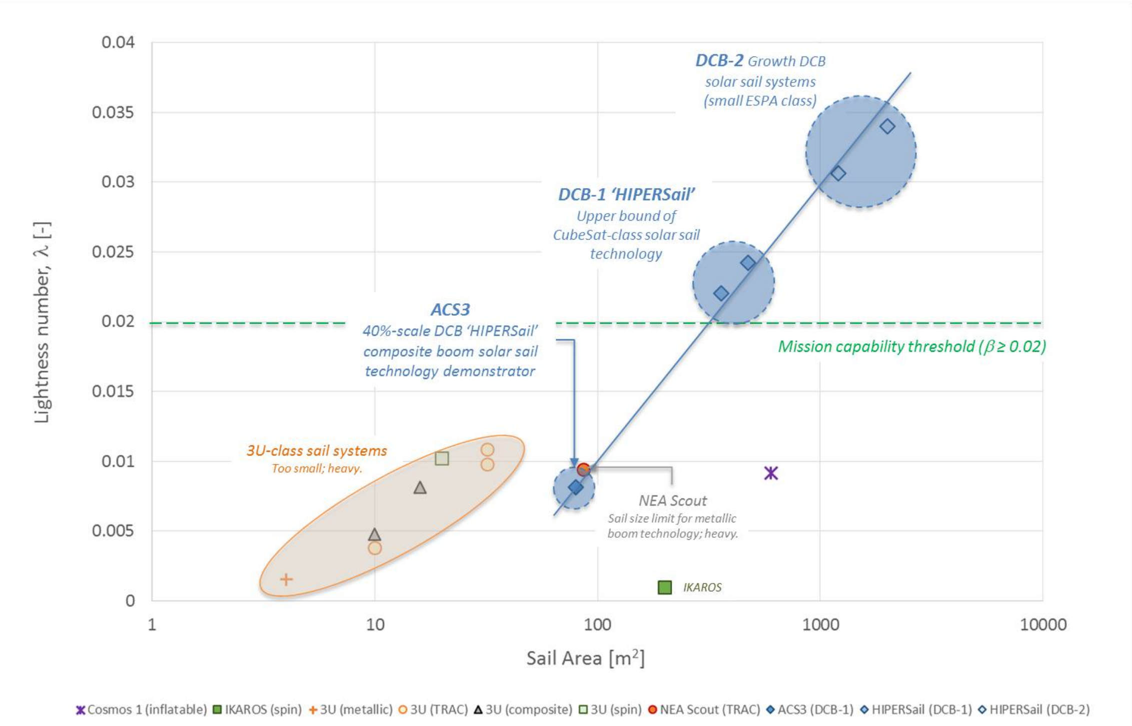


Figure 23. Comparison of CubeSat-scale solar sail capabilities. ACS3 is designed as a sub-scale technology demonstrator for a future DCB "HIPERSail" mission capable solar sail system. Lightness number (ratio of solar radiation pressure forces to solar gravitation forces) is plotted against solar sail size. 3U (ellipse) and 6U (NEA Scout) metallic boom solar sail technology limits are indicated. ACS3 performance and estimated near-term DCB HIPERSail technology capabilities are also shown. Solar sail vehicles with lightness numbers below 0.02 are likely insufficient for most solar sail missions.

B. Potential near-term mission applications using ACS3/DCB HIPERSail technology

To demonstrate the mission enabling capabilities of the ACS3/DCB HIPERSail based technology, several near-term (launch timeframes between 2025 and 2030) deep space mission examples are described in Figures 24 through 27. "Small" spacecraft form factors (27U or small ESPA volumes) are assumed for β = 0.02-0.025 lightness number examples. For β > 0.025, larger-scale solar sail architectures are being considered.[12] These solar sails would incorporate boom structures in the 30 meter length range and sail areas up to 2000 m^2. These expanded DCB solar sail systems ("DCB HIPERSail II") would not be packageable within foreseeable CubeSat spacecraft dimensions, but would be compatible with ESPA class payload volumes.

The first mission scenario provides enhanced south lunar polar region observation and surface operations support, through a constellation of two vertical Lyapunov orbits at the Earth-Moon L_2 point, see Figure 24. By keeping the sail attitude fixed with respect to the direction of sunlight, pitched at 35° in the out-of-plane direction, these orbits can be displaced towards the southern hemisphere of the moon. This displacement enables long residence times over the lunar south pole and scientifically interesting features on the lunar far side, including the Aitken Basin. The displacement also allows moving the "crosspoint" of the natural "figure eight"-shaped vertical Lyapunov orbits away from the Earth-Moon line, enabling continuous communication between the Earth and the spacecraft. For a lightness number in the range of β = 0.025 (results in red in Figure 24), continuous coverage of the aforementioned regions is achieved at a minimum elevation of the spacecraft of 10°, see Figure 24c-d, which, as an upper bound reference, can be increased to a minimum elevation angle of 15° for larger-scale solar sail architectures with β = 0.045 (results in gray in Figure 24). Details on the design of the orbits (through differential correction) in the Earth-Moon circular restricted three-body problem as well as the mission performance in more realistic dynamical environments can be found in Heiligers et al (2018)[13].

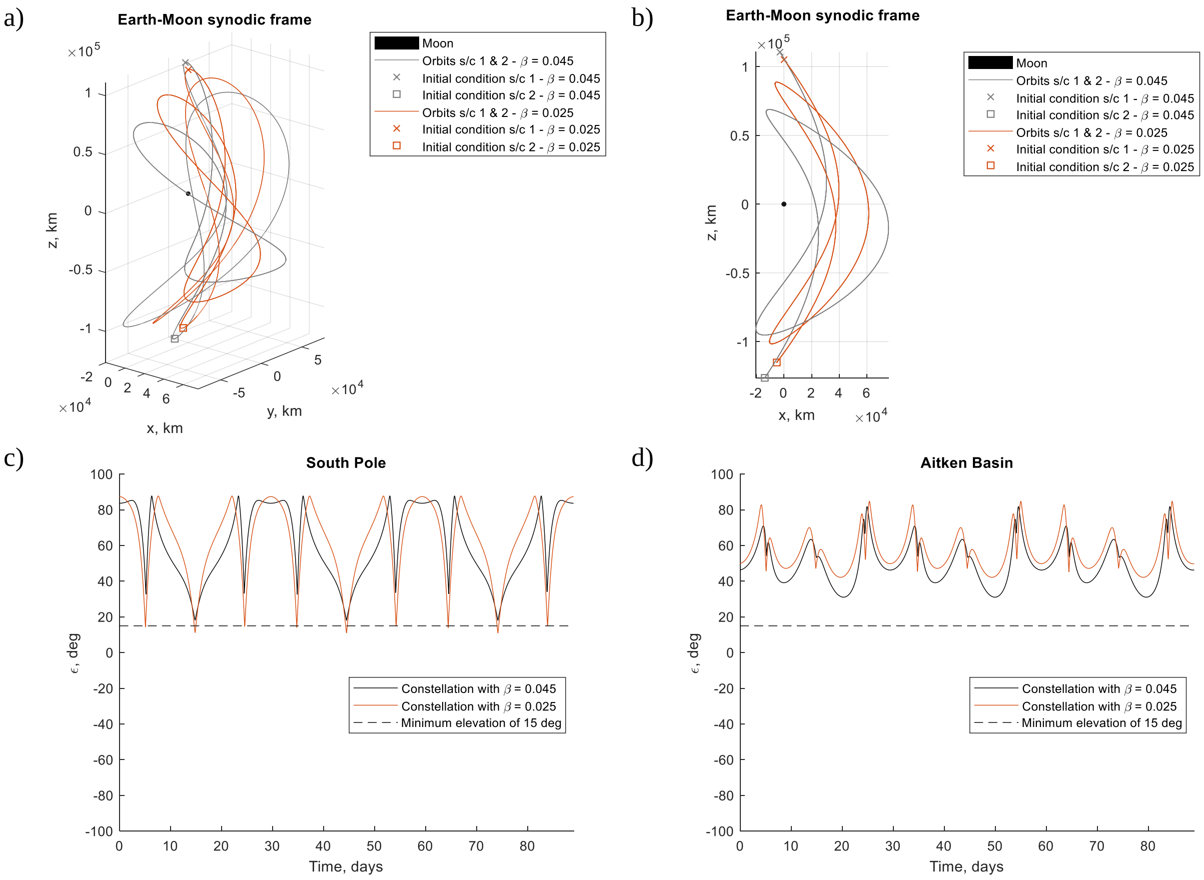


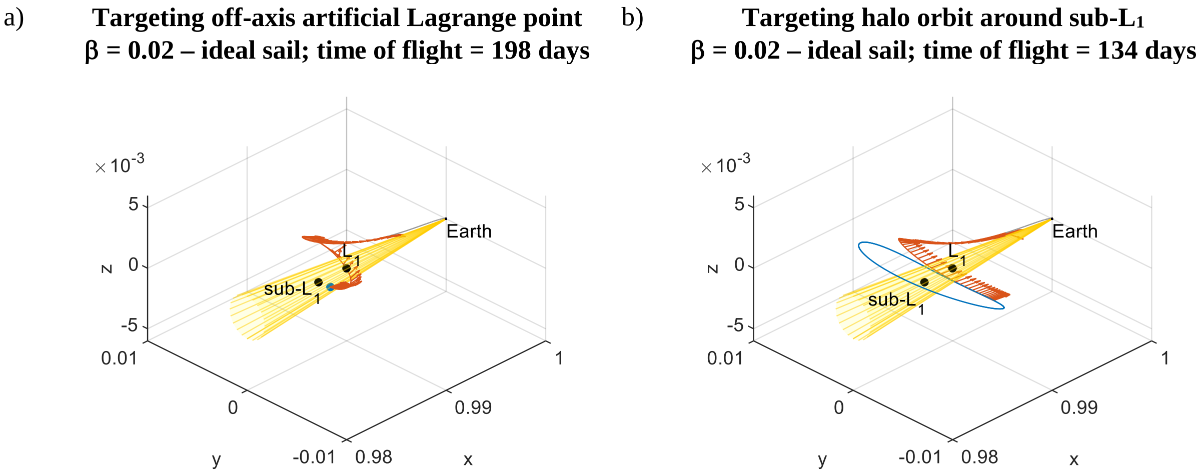
Figure 24. Examples of south lunar polar region observation and surface operations support using solar sailing in vertical Lyapunov orbits. A constellation of two solar sail spacecraft could provide near constant coverage of the lunar South Pole and Aitken Basin regions.[13]

Beyond the Earth-moon system, the ACS3/DCB HIPERSail based technology provides opportunities for enhanced space weather early warning, a widely proposed mission application of solar sailing.[1] The constant thrust of a solar sail permits operation around artificial Lagrange points closer to the Sun than the natural Sun-Earth L_1 point, the so-called sub-L_1 point, allowing early in-situ detection of coronal mass ejection events. Accounting for a 5° solar exclusion zone around the Sun-Earth line for communication purposes, the spacecraft can be placed either at an artificial Lagrange point away from the Sun-Earth line, see Figure 25a, or into a halo orbit around the sub-L_1 point, see Figure 25b. Solar-sail powered transfers from a geostationary transfer orbit to either location are feasible, assuming that an upper stage provides near-escape conditions. A lightness number of $\beta = 0.02$-0.025 can achieve a 30-40% increase in early warning of severe coronal mass ejection events with optimal transfer times in the order of 4-6 months. Details on the design and optimization of these transfers can be found in Heiligers et al (2014)[14].

Examples of using the DCB HIPERSail purely as a means of transfer are shown in Figure 26 and 27. The transfer in Figure 26 builds on the application of enhanced space weather warning and allows positioning instruments for heliophysics at the Sun-Earth L_5 point and upstream of the L_1 point in the Parker spiral. As transfers to the L_5 vicinity require significant ΔV, solar sail propulsion presents an energy efficient alternative to other high- or low-thrust propulsion technologies. The transfer in Figure 26 assumes a rideshare on the IMAP mission to the Sun-Earth L_1 point, where the sail follows IMAP's trajectory just beyond the Earth's sphere of influence before diverging away from IMAP's path to target the L_5 region. By hybridizing several optimization techniques (genetic algorithm, multiple shooting differential correction, and continuation), locally time-optimal transfers are obtained in the circular restricted three-body problem that take 580-658 days to complete for $\beta = 0.02$-0.025.[15]

A final example of the mission enabling capabilities of the ACS3/DCB HIPERSail based technology appears in Figure 27, which presents time-optimal solar sail rendezvous transfers to Asteroid 469219 Kamoʻoalewa (2016 HO_3), a "quasi-satellite" of Earth. With assumptions on the launch window (2022-2023), launch ejection conditions (Artemis-2 rideshare), and sail technology, trajectories taking 2.2-3.5 years are found for $\beta = 0.025$-0.04 using the same hybridization of optimization techniques as for the results in Figure 26.[16] To confirm the mission enabling potential of solar sail technology for this mission scenario, the rendezvous trajectory has also been designed assuming the use of solar electric propulsion (SEP) and optimized for the fuel consumption. The results show that the SEP trajectories take longer to complete than the solar sail trajectories and require a propellant consumption that exceeds the expected available propellant mass capacity onboard a CubeSat.[16]

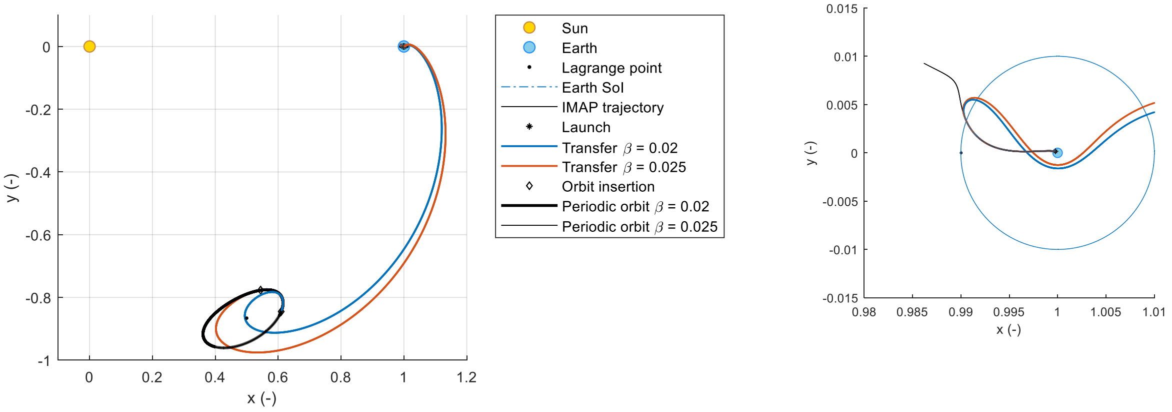
From the mission scenarios presented throughout Figures 24 to 27, the potential of the ACS3/DCB HIPERSail solar sail technology for a range of deep space science missions as well as for lunar exploration support is clear. In addition, through the – in theory – unlimited ΔV capability of solar sail propulsion, it presents a highly efficient means of transportation to reach targets within the Solar System beyond the reach of conventional forms of propulsion.



a) **Targeting off-axis artificial Lagrange point**
$\beta = 0.02$ – ideal sail; time of flight = 198 days

b) **Targeting halo orbit around sub-L_1**
$\beta = 0.02$ – ideal sail; time of flight = 134 days

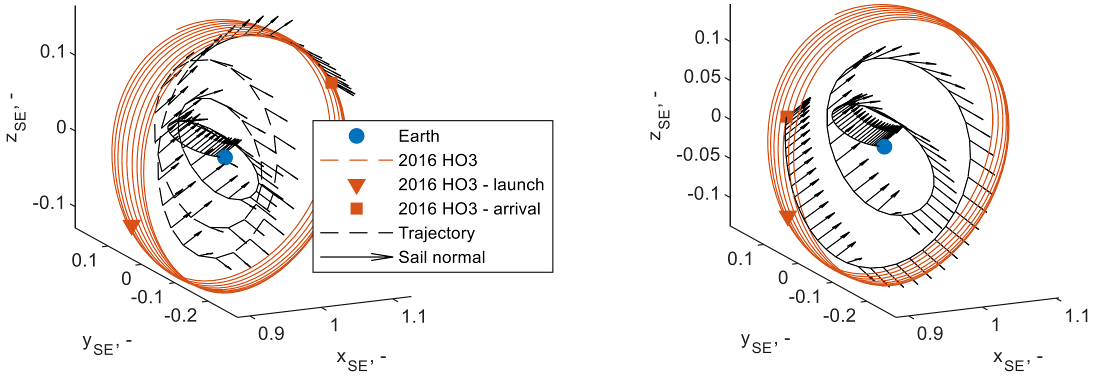
Figure 25. Sun-Earth sub-L_1 solar sailing for enhanced space weather early warning using a DCB "HIPERSail" class solar sail vehicle ($\beta = 0.02$) (presented in a dimensionless Sun-Earth synodic frame). A lightness number of $\beta = 0.02$-0.025 can provide a 30-50% increase in early warning of severe coronal mass ejection events.



a) **IMAP rideshare β = 0.02 and 0.025 – ideal sail**

b) **Close-up of trajectory in Earth's vicinity**

Figure 26. Examples of solar sailing transfers between Sun-Earth (S-E) L1 vicinity and S-E L5 using DCB "HIPERSail" class solar sailing vehicles (β = 0.02-0.025) (presented in a dimensionless Sun-Earth synodic frame). A solar sail can provide an energy efficient means for positioning instruments at S-E L5 or upstream of S-E L1 in the Parker Spiral.[15]



a) **β = 0.025 – ideal sail; time of flight = 3.5 years**

b) **β = 0.04 – ideal sail; time of flight = 2.2 years**

Figure 27. Near Earth asteroid reconnaissance example for DCB *HIPERSail* class solar sail vehicle (β = 0.025) and notional advanced DCB "HIPERSail II" vehicle (β = 0.04) (presented in a dimensionless Sun-Earth synodic frame).[16] **The target body is the recently discovered Asteroid 469219 Kamoʻoalewa (2016 HO3) "quasi-satellite" of Earth.**

VIII. Summary and Future Work

The Advanced Composite Solar Sail System (ACS3) solar sail technology demonstrator has completed design and fabrication phases. The ACS3 flight system is now undergoing assembly, integration and testing. The ACS3 launch will be supported by the NASA CubeSat Launch Initiative (CSLI) in coordination with the NASA Launch Services Program. Launch is anticipated in late CY 2021.

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