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

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ABSTRACT

NASA's Space Technology Mission Directorate (STMD) is developing a new generation of compactly packageable composite booms designed specifically for small spacecraft applications where volumes for deployable structures are limited. NASA's Advanced Composite Solar Sail System (ACS3) will be the first spaceflight application of this boom technology. ACS3 will also be NASA's first practical solar sail. Objectives of the ACS3 project are to deploy an 80 m^2 composite boom solar sail in low Earth orbit, and as an extended goal, demonstrate controlled solar sailing flight, including orbit raising and lowering. An overview of the ACS3 project and objectives, including descriptions of ACS3's solar sail structures and materials technology, 12U CubeSat spacecraft systems, and flight concept of operations, is provided here. Scalability of the ACS3 solar sail to future, near-term smallsat solar sailing mission requirements will also be discussed. Launch of ACS3 is currently anticipated for mid to late 2022.

INTRODUCTION

Solar sailing is a form of spacecraft propulsion that uses momentum transfer from reflected photons to produce thrust.[1] In principle, this is "propellantless" propulsion. In practice, structures and materials engineering challenges have prevented widespread use of solar sails for scientific space applications. Historically, most solar sail mission concepts have required very large solar sails; a consequence of the high mass scientific instrument payloads and systems used on traditional spacecraft, and the very small forces produced by solar radiation pressure (a perfectly reflecting solar sail would experience pressures of only 9 x 10^{-6} Pa at a heliocentric distance of 1 AU). Recent advances in small spacecraft avionics and instrument technologies are now enabling lighter and smaller space vehicles and science payloads, which in turn permits significantly smaller, and less costly, solar sails to be used for many mission applications.[2-4] Packaging the deployable solar sail structure within the tightly constrained, limited volumes available in Cubesats has now become the major barrier for implementation of solar sails for smallsat propulsion.

Most rigid structure, non-spinning, solar sail architectures use deployable booms to support triangular or square reflective thin-film membranes. Deployable boom structures technologies that are relatively easy to package, e.g, metallic tape springs, or Tubular Rollable And Collapsible (TRAC) booms, tend to be heavy, low rigidity (particularly in torsion) and very sensitive to thermal-elastic deflections when deployed. These deflections can result in asymmetric or warped solar sail surfaces that are difficult or impossible to control in flight.[5,6] Carbon fiber reinforced polymer (CFRP) composite booms are a potentially superior alternative to metallic booms for these applications. CFRP booms can be very stiff and lightweight, and, with their very low coefficients of thermal expansion, are insensitive to large thermally-induced deflections. Unfortunately, coiling, rolling, and flattening of the booms during packaging can produce very high mechanical strains that can damage the boom composite laminates. This can be mitigated by using larger coiling diameters, but this results in larger stowage volumes, which becomes problematic for volume-constrained Cubesats and smallsats.

To address these disadvantages, NASA has developed a new generation of compactly packageable composite booms designed specifically for small spacecraft applications where volumes for deployable structures are limited.[7] NASA's Advanced Composite Solar Sail System (ACS3) will be the first spaceflight application of this boom technology. ACS3 will also be NASA's first practical solar sail, capable of controlled solar sail flight. Objectives of the ACS3 project are to deploy an 80 m^2 composite boom solar sail in low Earth orbit, and as an extended goal, demonstrate controlled solar sailing flight, including orbit raising and lowering.

In this paper, we will provide an overview of the ACS3 project and objectives, including descriptions of ACS3's solar sail structures and materials technology, 12U CubeSat spacecraft systems, and flight concept of operations. Scalability of the ACS3 solar sail to future, near-term smallsat solar sailing mission requirements will also be discussed. Launch of ACS3 is currently anticipated for mid to late 2022.

THE ADVANCED COMPOSITE SOLAR SAIL SYSTEM PROJECT (ACS3)

The ACS3 spacecraft will demonstrate NASA deployable composite boom technology in a solar sailing application in the LEO space environment. The ACS3 solar sail system is a 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 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. Sail membrane quadrants are metallized polyethylene naphthalate (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.

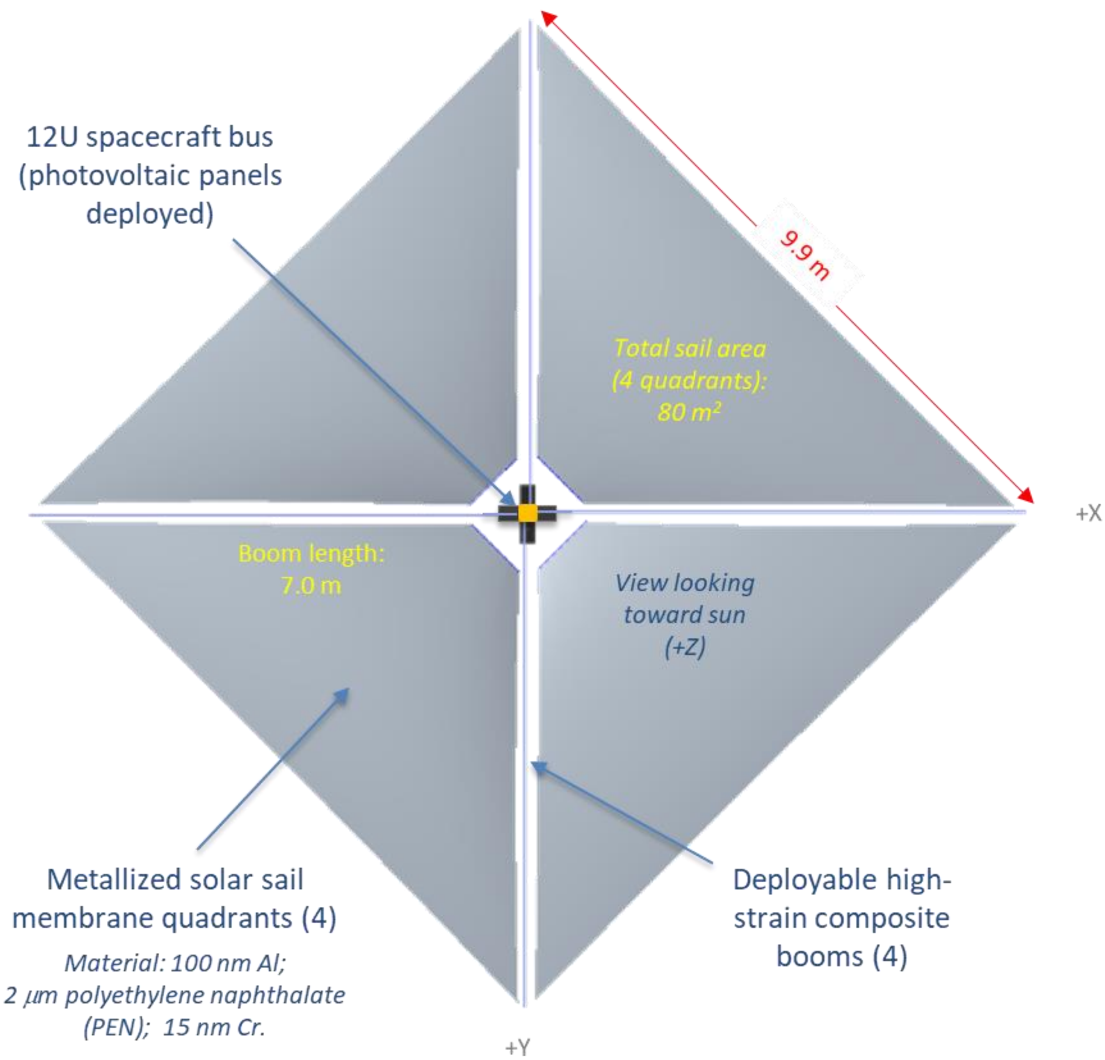

Figure 1. ACS3 Solar Sail.

Primary objectives of the ACS3 flight demonstration will be to deploy and characterize the ACS3 deployable composite boom technology solar sail. This will be conducted through photogrammetry analysis of images obtained with an on-board camera system. 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.

Deployable Composite Boom Technology

The ACS3 solar sail 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.[7,9] 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. 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.

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. The ACS3 7.0-meter 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.

ACS3 SOLAR SAIL 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.

Figure 2. NASA Deployable Composite Booms (DCB).

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. General properties of the complete ACS3 solar sail spacecraft are summarized in Appendix A.

The most complex element of the ACS3 spacecraft is the Sail-Boom Subsystem (SBS), shown in Figure 5. 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. 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.

The ACS3 solar sail membrane quadrants consist of a 2.0 μm polyethylene naphthalate (PEN) plastic film substrate, coated on one side with a very thin (0.1 nm) vapor deposited aluminum layer for reflecting solar photons, and on the other side with a thinner (0.015 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.[8]

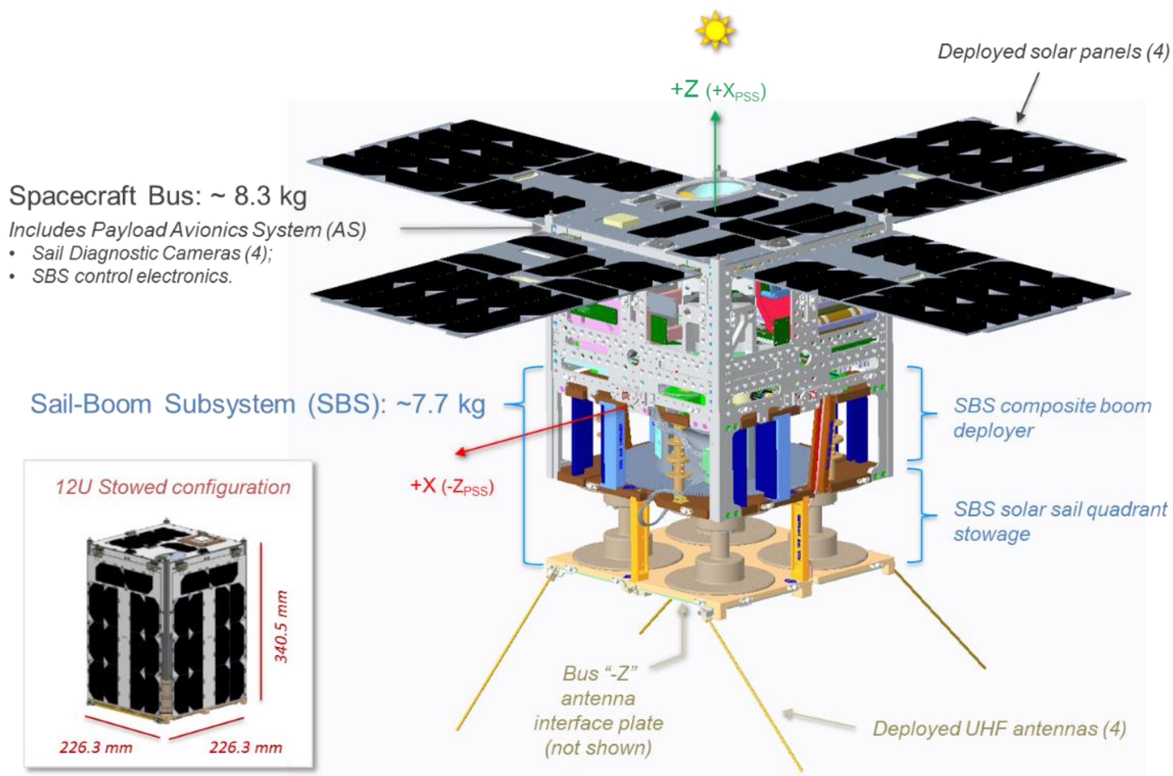

Figure 3. ACS3 12U Spacecraft with Solar panels and UHF Antennas Deployed. Side Panels, Sail Membranes, and Booms Omitted for Clarity.

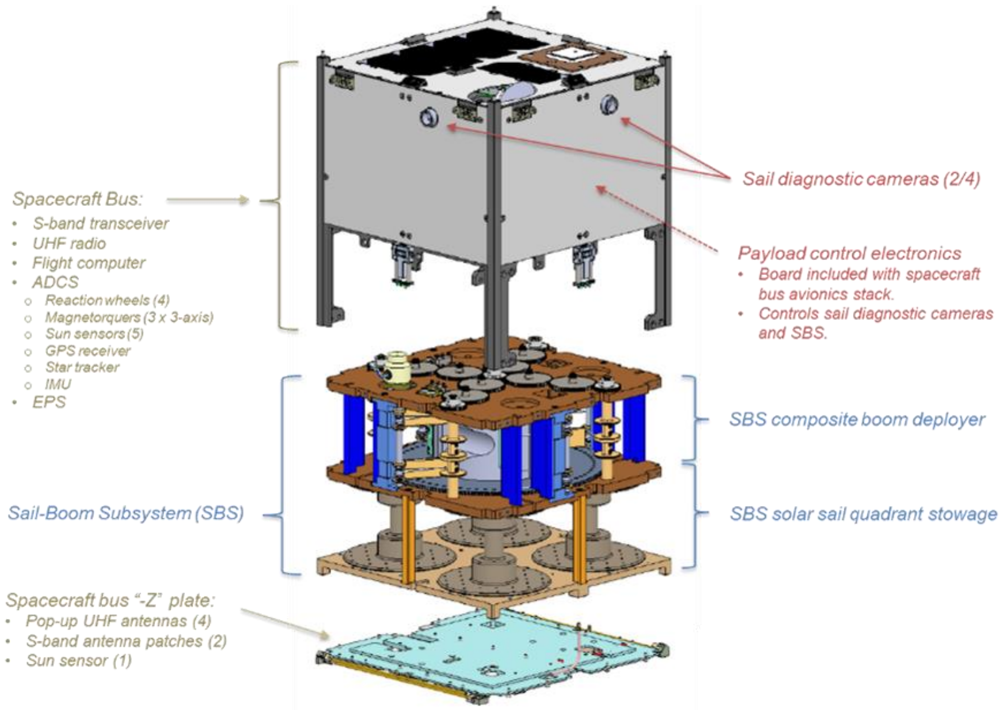

Figure 4. ACS3 12U Spacecraft Major Assemblies and Sub-Systems. Solar Panels, Sail Membrane Quadrants and Composite Booms Have Been Omitted for Clarity.

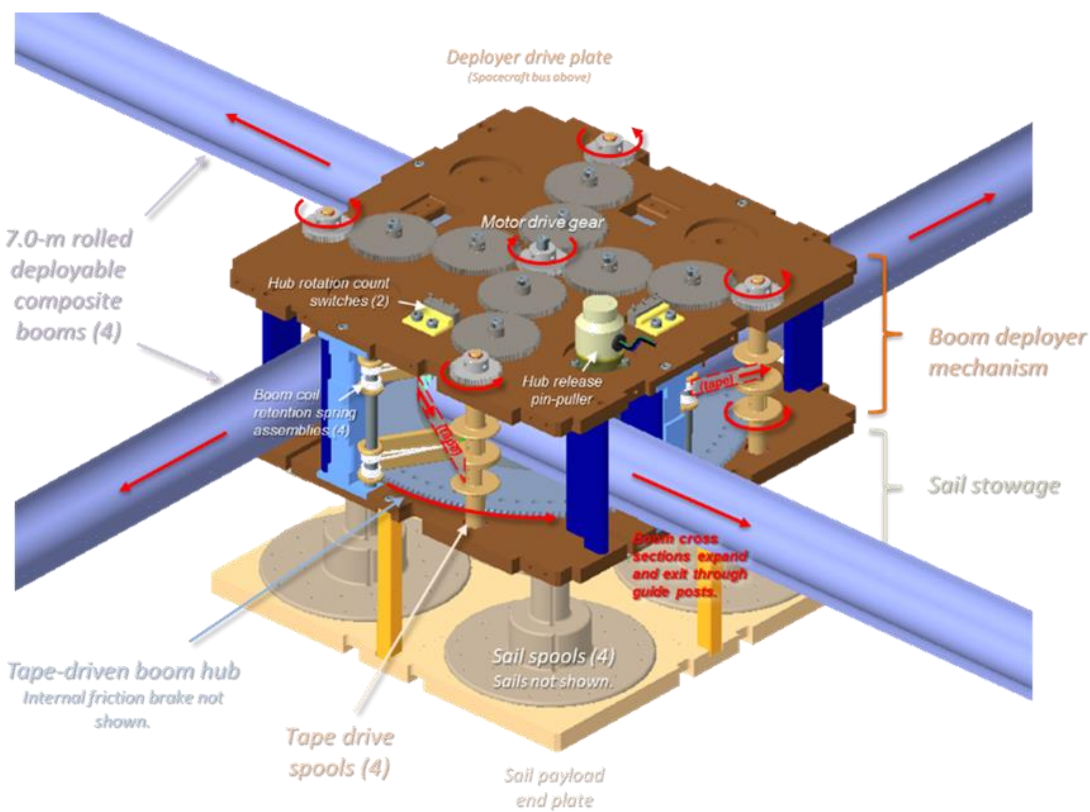

Figure 5. ACS3 Sail-Boom Subsystem (SBS). Deployed Sail Membranes Have Been Omitted for Clarity.

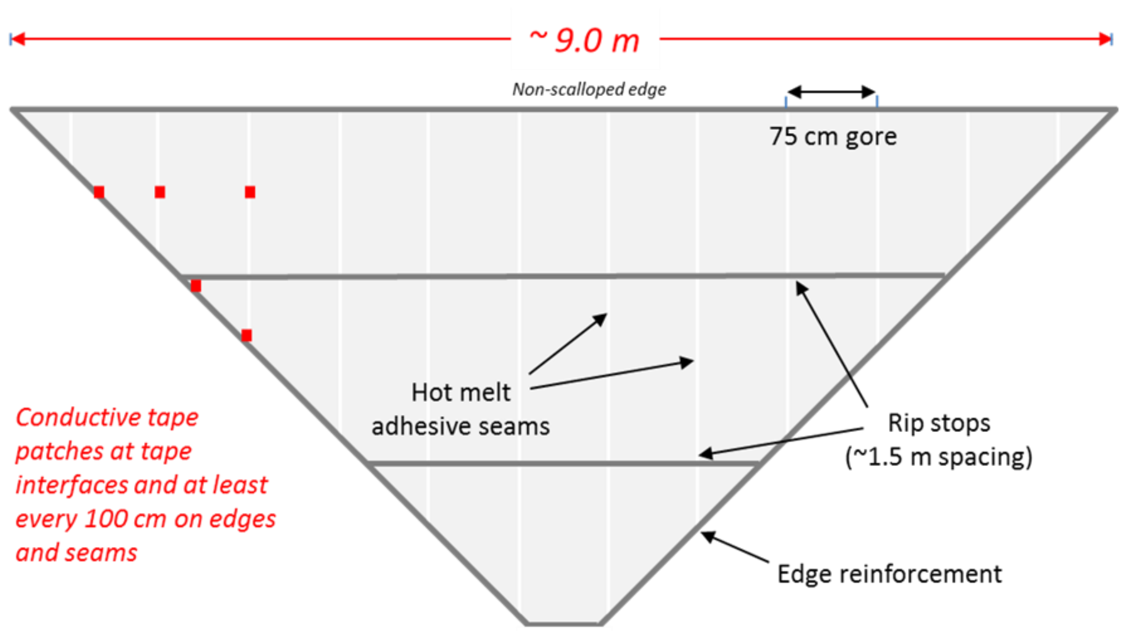

Figure 6. ACS3 Solar Sail Quadrant Planform and Construction.

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). Deployments are computer-controlled, with a nominal duration of 20-30 minutes, corresponding to the anticipated on-orbit deployment duration. A sequence of images from a recent full system deployment test of the SBS prototype unit is shown in Figure 7. The final deployed configuration is shown in Figure 8. Sail quadrants used during this deployment test are slightly smaller than the flight ACS3 sail membranes (8.8 m vs. 9.0 m hypotenuse length). Composite booms, sail folding, sail stowage, sail-to-boom attachment, and sail root spring tensioning are representative of the flight SBS design. Loading of the booms due to sail tensioning at the end of deployment stabilizes the sail structure in its final deployed configuration.

ACS3 CONCEPT OF OPERATIONS

Flight demonstration objectives

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 is 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.

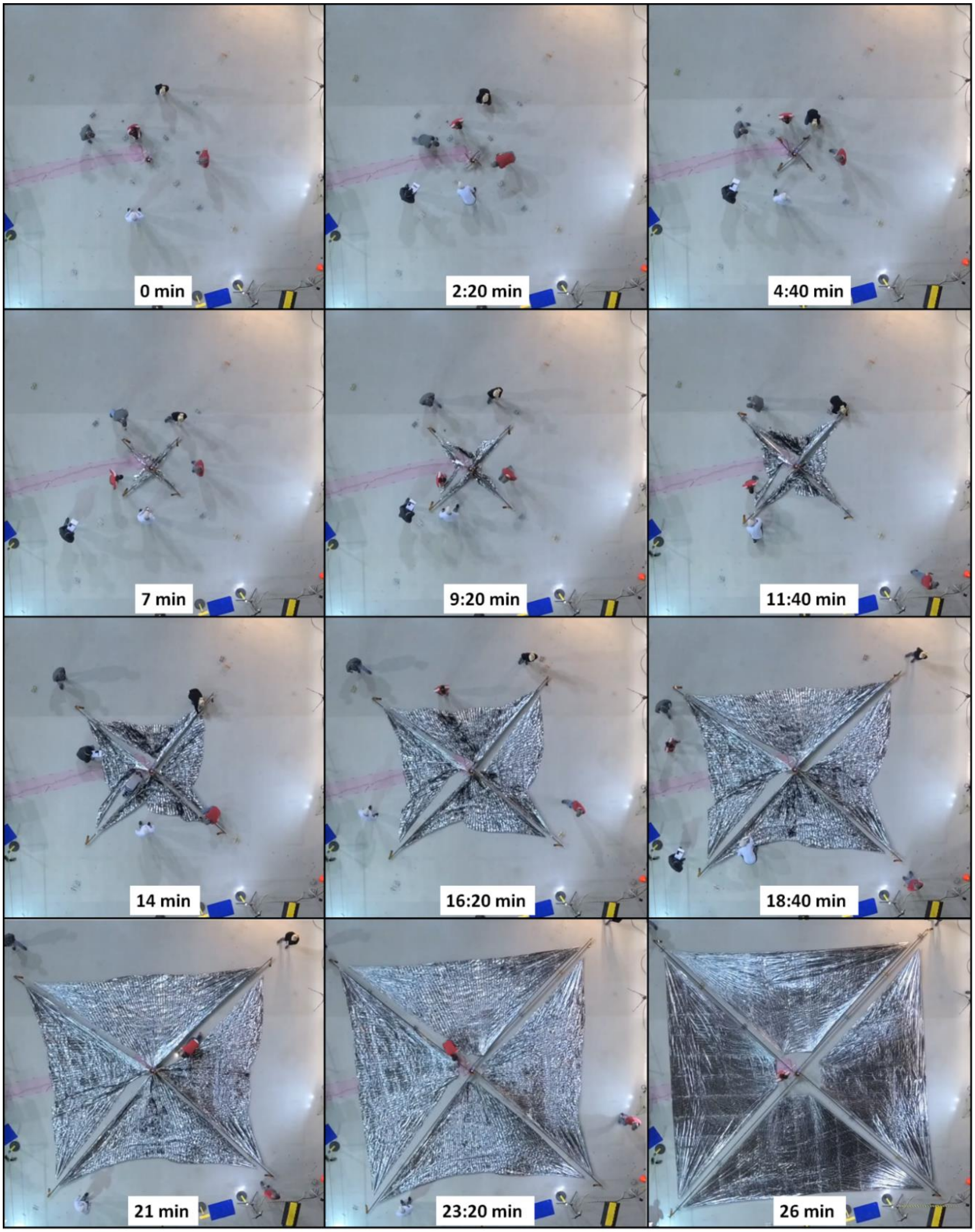

Figure 7. Full System Ground Deployment Test of the ACS3 Sail-Boom Subsystem (SBS) Prototype Unit.

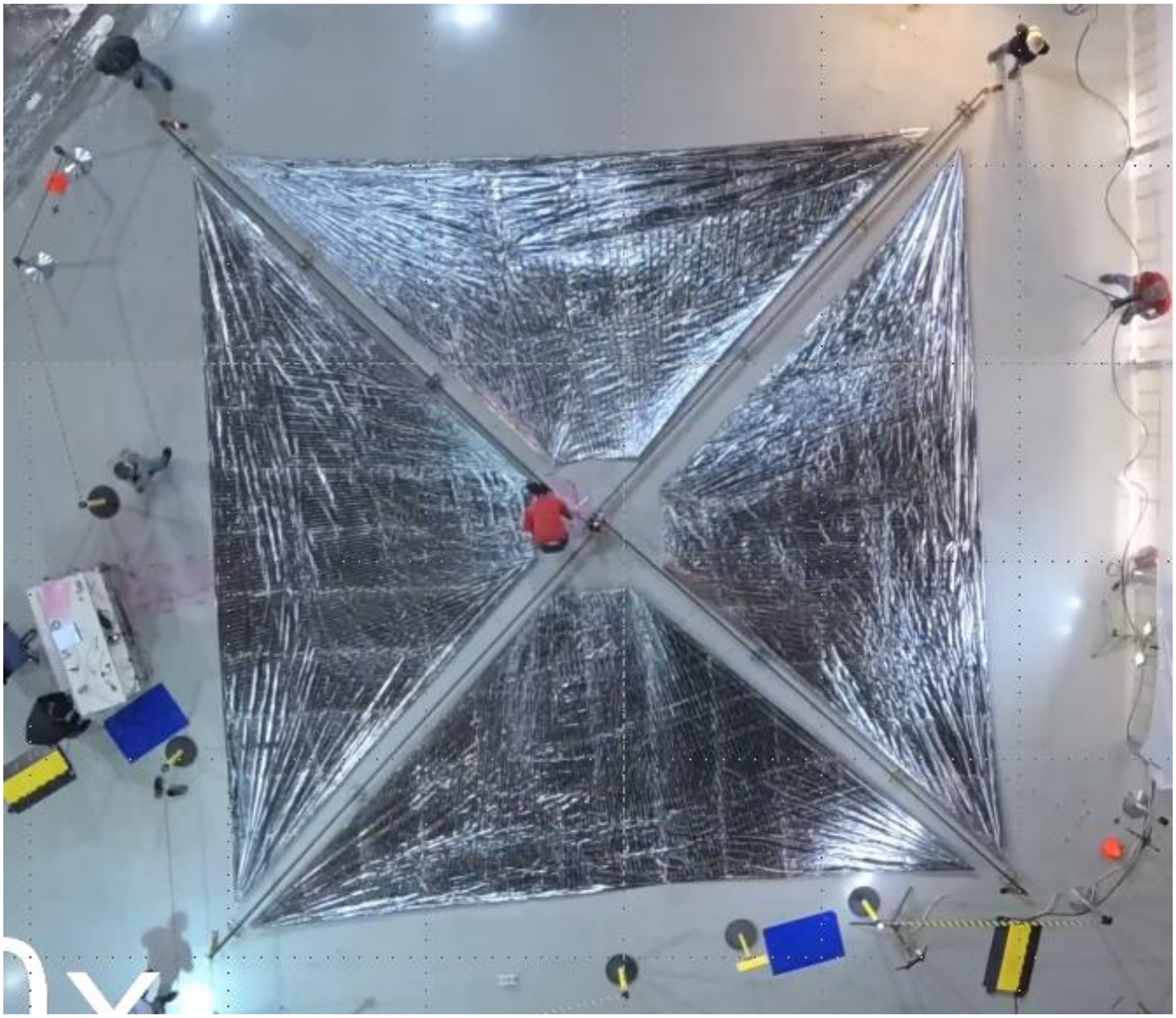

Figure 8. Prototype Sail-Boom Subsystem (SBS) ground deployment test: fully deployed configuration.

Flight demonstration timeline

A timeline illustrating the ACS3 flight demonstration concept of operations is shown in Figure 9. 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 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. 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.

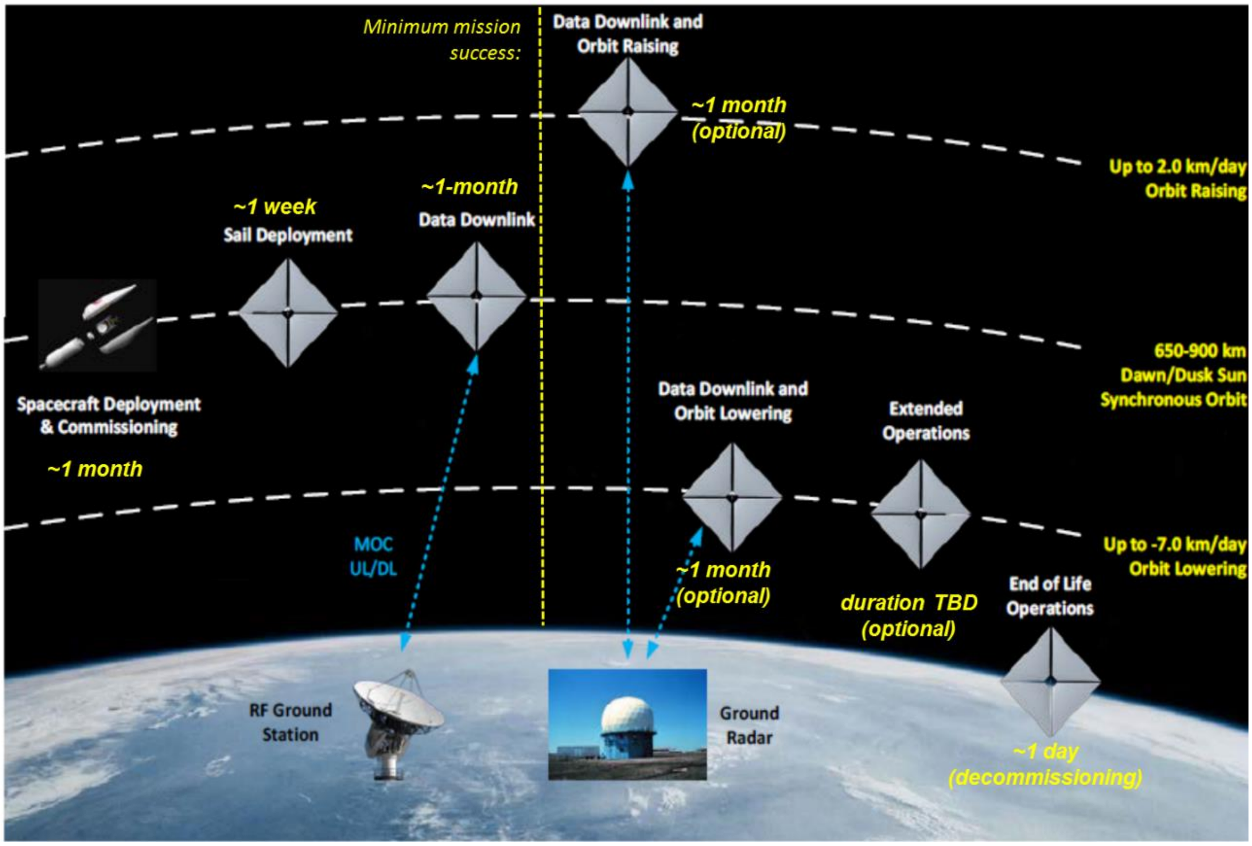

Figure 9. ACS3 Concept of Operations Diagram

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). 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.

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 less constrained, mid-inclination orbit has been adopted as a more general, 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 10. 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 average rates-of-change in orbit semi-major axis (δSMA) of approximately 0.4 km per day should be achievable for initial orbit altitudes of 715 km or higher, with a total increase in SMA of +12 km achievable over 30 days of operation in this steering mode. Estimated orbit changing rates for a 45 degree mid-inclination orbit are shown in Figure 11. These simulations assume a moderately conservative atmospheric density profile consistent with ACS3's anticipated flight dates (mid to late 2022). 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.

Orbit raising and lowering performance estimates for noon-midnight sun-synchronous orbit cases are substantially similar to the mid-inclination orbit cases, and are provided in Appendix B.

ACS3 EXTENSIBILITY TO FUTURE SMALLSAT SOLAR SAIL TECHNOLOGY

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 12. 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.[9,10] The boom and deployer system shown is sized to be compatible with a 27U CubeSat spacecraft.

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 (equivalent to a lightness number, β, of 0.025) when including all spacecraft systems and science instrument payload. 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 β = 0.03-0.035 range. Higher lightness numbers (β ~ 0.04-0.045) may also be attainable using growth DCB-based technology, for solar sail missions with lower mission payload mass requirements.[11] Several examples of potential near-term solar sail mission applications using ACS3-*HIPERSail* technology are shown in Figure 13.[12-16]

SUMMARY AND FUTURE WORK

The Advanced Composite Solar Sail System (ACS3) solar sail technology demonstrator has completed design and fabrication phases and is now undergoing assembly, integration and testing at NASA Langley Research Center. Additional work to optimize orbit-raising steering laws in the presence of atmospheric drag effects is also underway. ACS3 project flight objectives may be met with either a sun-synchronous or mid-inclination orbit with perigee of 700 km or greater. Rideshare launch opportunities to sun-synchronous and mid-inclination orbits at these altitudes are expected within ACS3's anticipated launch time frame; currently mid to late calendar year 2022.

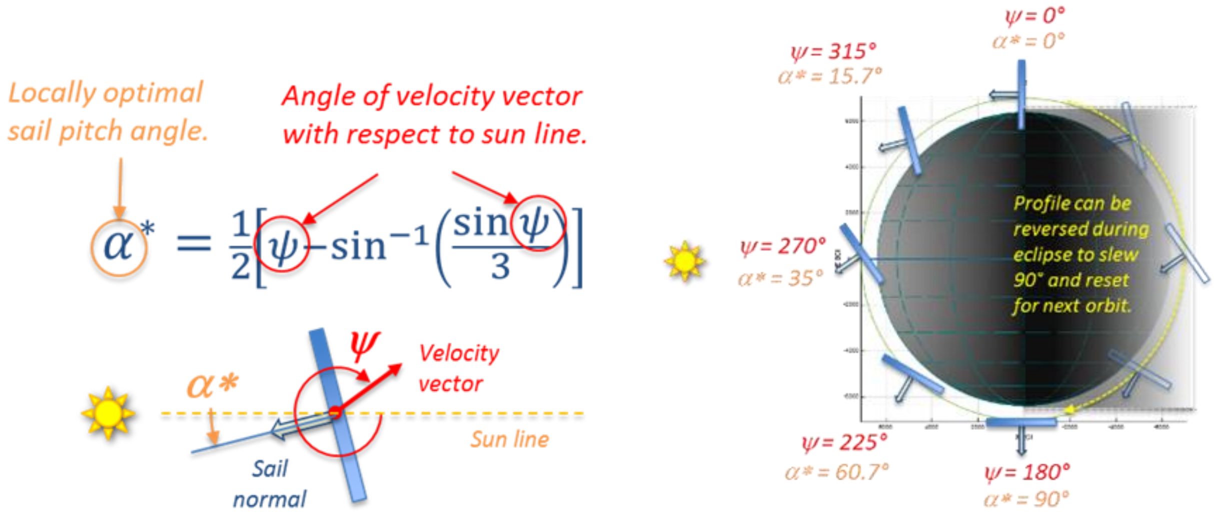

Figure 10. Idealized Locally Optimal Steering Law for SMA Raising.[1]

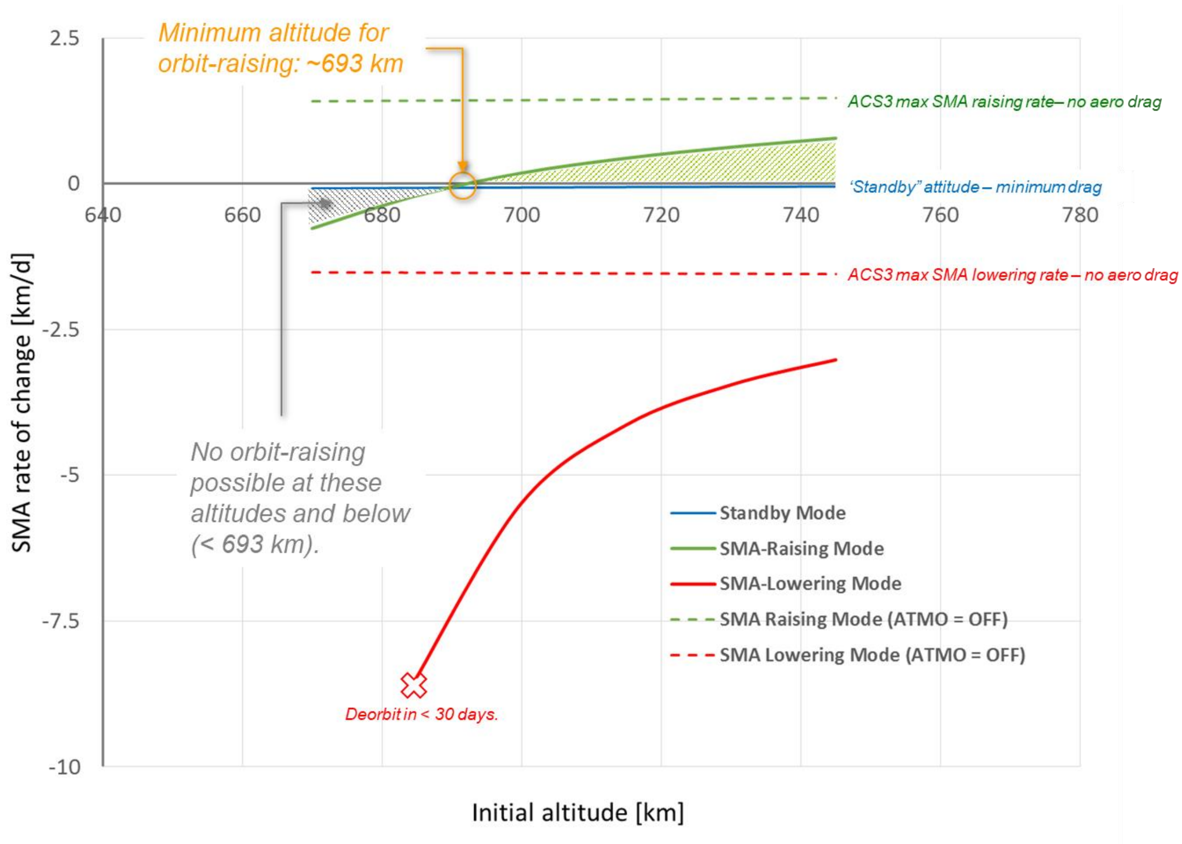

Figure 11. Estimated ACS3 Orbit Raising and Lowering Capabilities for 45-Degree Inclination, Circular Low Earth Orbits with Initial Altitudes Between 670 km and 745 km.

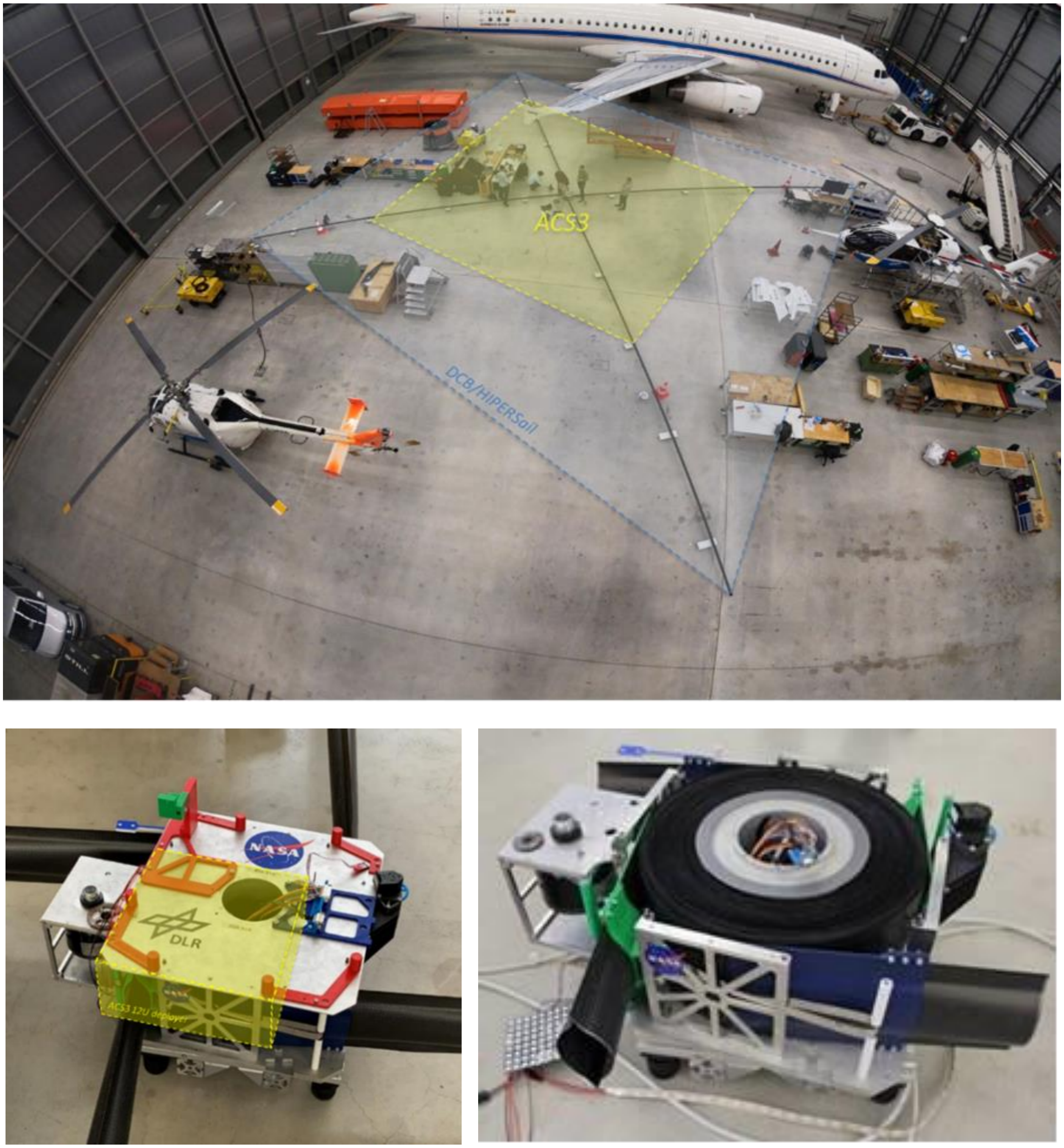

Figure 12. NASA-DLR 16.5-Meter Booms, 520 m^2 "HIPERSail" Solar Sail System Engineering Development Unit. ACS3 Solar Sail and SBS Deployer Shown for Scale. [9,10]

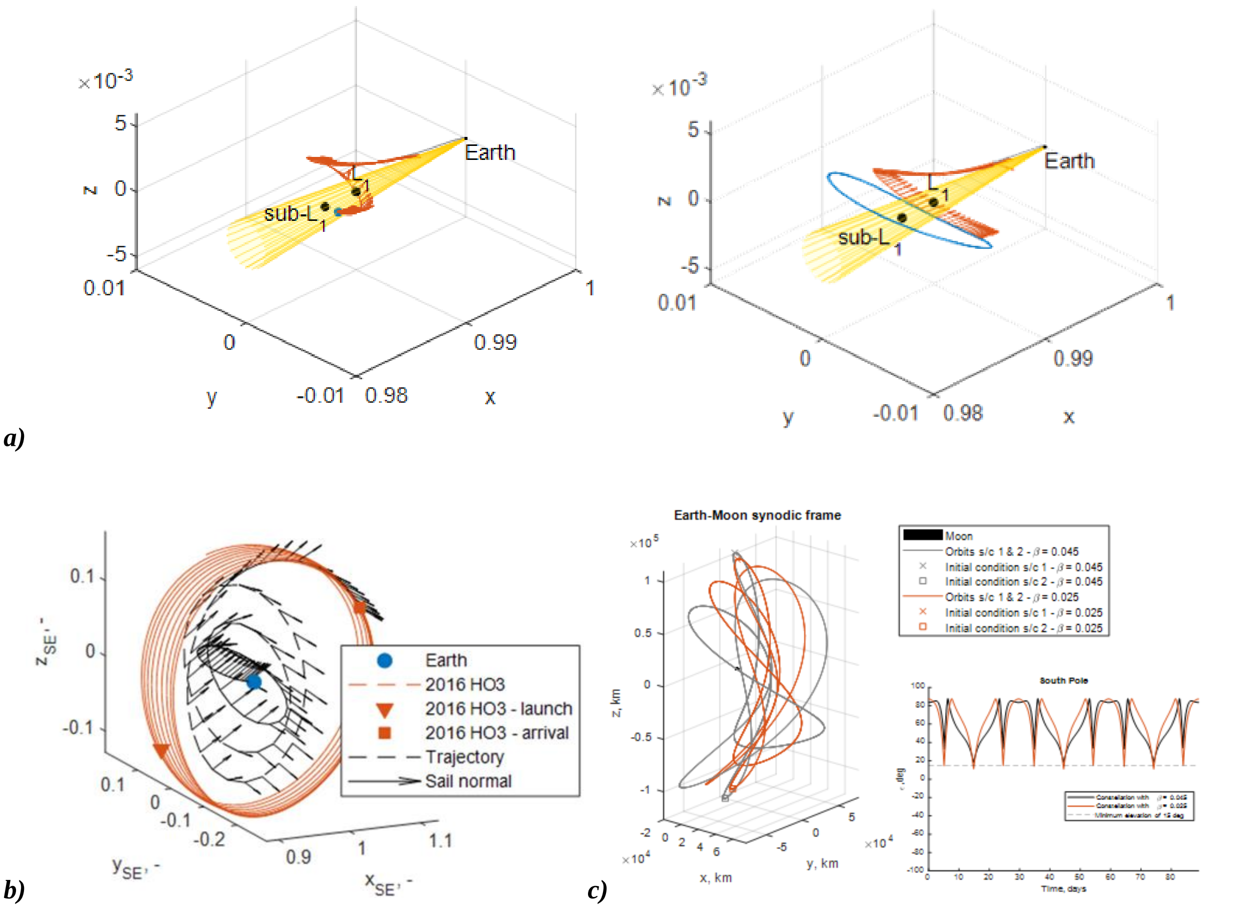

Figure 13. Near-Term Solar Sail Mission Examples Using DCB Deployable Composite Boom Technology. a) Sub-L1 Station-Keeping and Halo Orbit Space Weather Early Warning Sentinels; b) Near-Earth Asteroid Rendezvous (Asteroid 469219 Kamo‘oalewa (2016 HO3)); c) Lunar South Pole Surface Observation and Communications Relays. [12-16]

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APPENDIX A

Table 1. General Properties of the ACS3 Solar Sail Spacecraft

Property	Value	Units
Total spacecraft mass, including sail	16	kg
Spacecraft mass moments of inertia, sail deployed (I_{xx}, I_{yy}, I_{zz})	8.0, 8.0, 15.6	kg-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 x 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-s^{-2}
Effective lightness number, β	0.0077	-

APPENDIX B

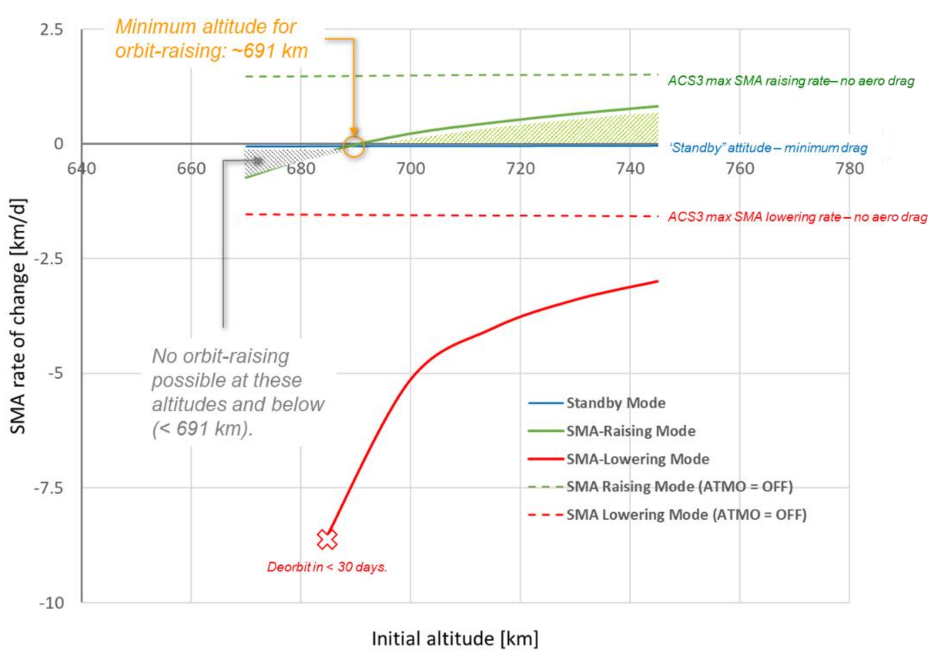

Figure 14. Estimated ACS3 Orbit Raising and Lowering Capabilities for Noon-Midnight Sun-Synchronous Orbits with Initial Altitudes Between 670 km and 745 km.