2018 Technology Demonstration Industry Day

Technology Title: HIPERSail: High-Performance Small Spacecraft Solar Sail System

Affiliation: NASA Langley Research Center; NASA Ames Research Center

Assumptions: Technology required to be at TRL 5 by 2021

Technology Description, Current Performance Metrics, and Performance Goals

HIPERSail is a lightweight, compact, multi-mission-capable solar sail propulsion system payload compatible with low-cost 12U to 27U CubeSat-class or small ESPA spacecraft. Performance can provide a low-thrust propulsion capability for small spacecraft deep space missions with 3-5 year lifetimes.

- HIPERSail performance target: *lightness number*, β (ratio of solar radiation pressure force to gravitational force) 0.02 – 0.025
- Deliverables: Mission-capable small spacecraft solar sail system (booms, deployer, sail, sail stowage, sail trim control system) capable of flight ca. 2024.

Current TRL

3

TRL By May 2021

5-6

Industry State of the Art Technology Performance

- Current state-of-the-art: β = 0.008-0.009 (ref: NEA Scout).
- STMD-DLR DCB high-strain composite booms currently at TRL 3. *Booms and deployment mechanisms to be at TRL 5 by project end in 2020.*
- 6U-scale high-strain composite booms solar sail LEO risk reduction flight in formulation under HEOMD/AES for launch ca. 2020. *DCB-composites-based solar sail system will be at TRL 6.*
- *HIPERSail performance will be a 2.5x - 3x improvement over NEA Scout solar sail technology state-of-the-art (SoA).*

Technology Development Challenges to Meet TRL Goal

- Scaleability: Scale-up of current deployable composite booms to 14-16.5 m lengths. *Being addressed under ongoing STMD Deployable Composite Booms project (DCB) with the German Aerospace Center (DLR).*
- Packageability: System must stow within existing or anticipated rideshare-class small spacecraft form factors with volume for avionics and instrument payloads. *To be addressed during proposed AES Advanced Composites-Based Solar Sail System (ACS3) sub-scale flight demonstration, ca. 2020.*
- Sub-scale system validation: 40-50% scale zero-g flight validation of solar sail and deployment system. *To be addressed during ACS3 LEO flight, ca. 2020.*

Potential HPD Science Application (Optional)

Near-term mission (2024):

- Low-cost Sun-Earth sub-L1/L5 spacecraft for heliophysics science, solar weather modeling and early warning (β > 0.02 required).
- Can be demonstrated as part of TechDemo mission.

Potential TechDemo compatible instruments:

- Magnetometer (e.g., MAGIC)
- Plasma detector (e.g., SWAN, ChaPS).

Medium-term missions (2024-2030):

- Low-cost multi-spacecraft constellations also possible (e.g., L1 Diamond).

Contact Information

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Additional Comments

Potential for non-SMD partnerships:

- HEOMD/Advanced Exploration Systems – space weather early warning for cislunar human operations.
- NOAA/SWPC, DoD - space weather early-warning, modeling and prediction.

HIPERSail: High-Performance Small Spacecraft Solar Sail System *Technology Overview*

Keats Wilkie, Johnny Fernandez, Olive Stohlman, Jay Warren, Geoff Rose, Nigel Schneider, Todd Denkins, Phil Brown

NASA Langley Research Center

Darin Foreman, Mina Cappuccio

NASA Ames Research Center

Jeannette Heiligers

TU Delft

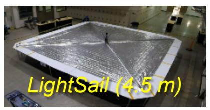
May 30th, 2018

National Aeronautics and Space Administration

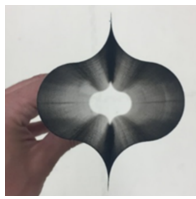
www.nasa.gov

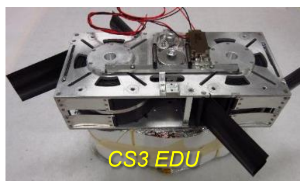
Small Spacecraft Composites-Based Solar Sail Systems Technology Development Roadmap

'TRAC' metallic boom solar sails (SoA)

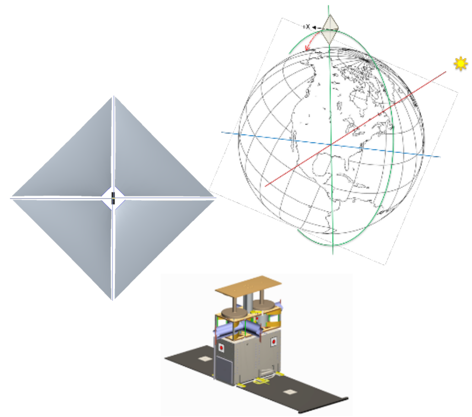


Deployable Composites Boom Technology (DCB)

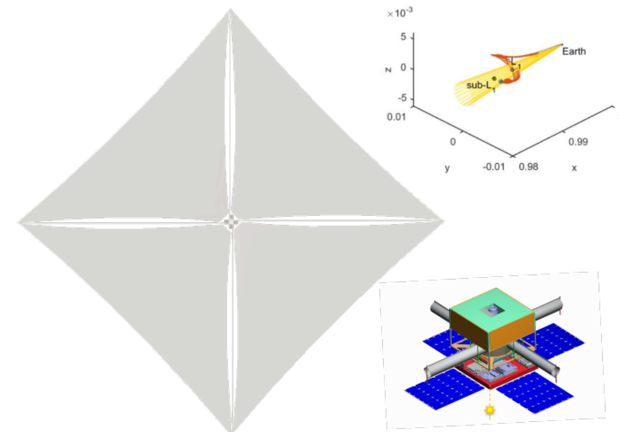




9-m sub-scale LEO deployment demonstration (ACS3)



20-m-class mission-capable solar sail system (HiPERSail)

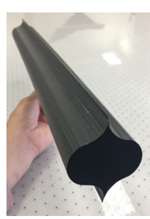


Metallic TRAC boom solar sail architectures:

NanoSail-D2 | LightSail A | NEA Scout

Roadmap addresses solar sail technology gap...

2010 | 2015 | 2020 | 2025 | 2030



Deployable Composite Booms (DCB) — *Zero-g parabolic flight boom deployment demo (w/DLR)*

Advanced Composites-Based Solar Sail (ACS3) — *LEO sub-scale sail deployment demo*

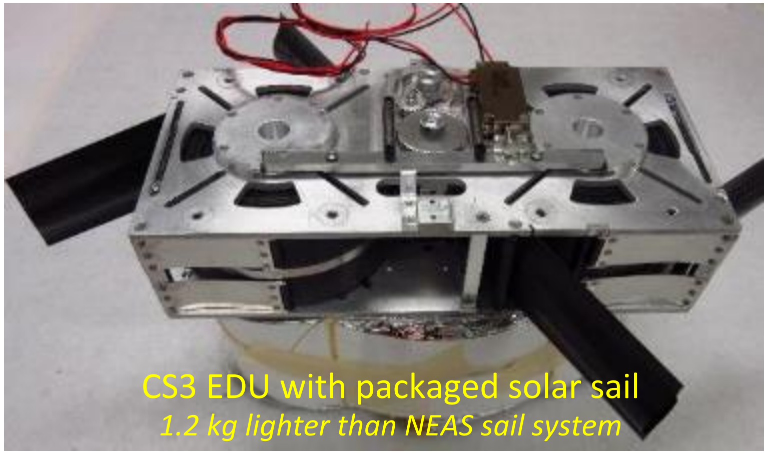
HIPERSail (as proposed) — *Opportunity for early flight in 2024 under SALMON-3 HPD TechDemo AO*

TRL 3

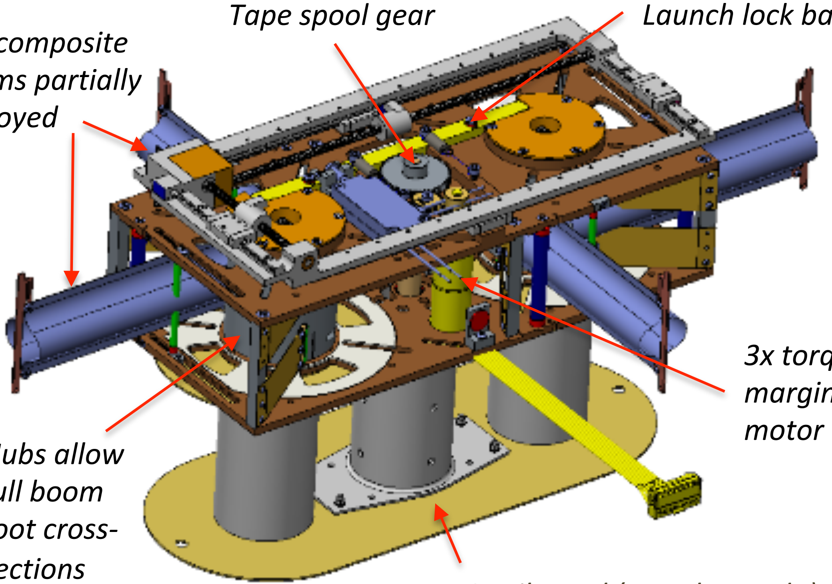
TRL 5-6

- FOR DISCUSSION PURPOSES ONLY -

AES Composites-Based Solar Sail System (CS3) ca. 2016



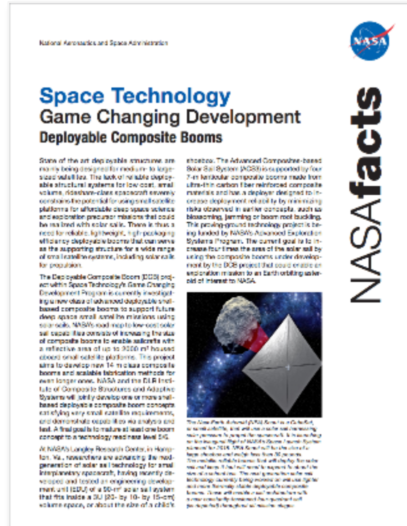
- CS3 unit is a drop-in replacement for NEAS metallic TRAC boom deployer. - *1.2 kg lighter than NEAS* -
- CS3 deployer based on flight-qualified DLR/Surrey *DeorbitSail* deployer.
  - Boom deployment via tape reel "puller" system instead of gear-driven "pusher".
    - Minimizes risks of boom blooming, boom root buckling and potential jamming during deployment.
- Pin pusher/puller locks spools & motor gears for launch and after deployment.
- CS3 EDU validated in ground deployment testing, launch vibrations, and thermal vacuum testing.



Click to play movie.

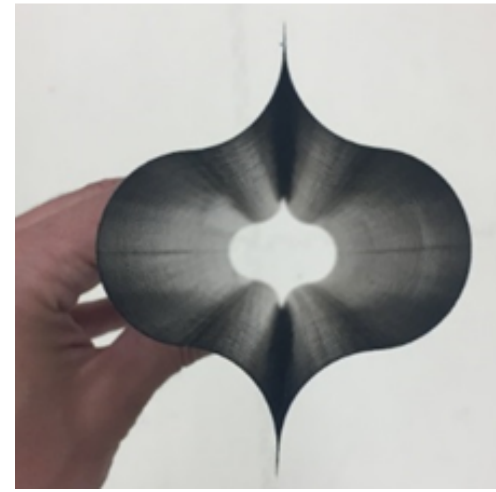
14+ meter composite booms sized for 12U-27U solar sail systems are currently under development in STMD

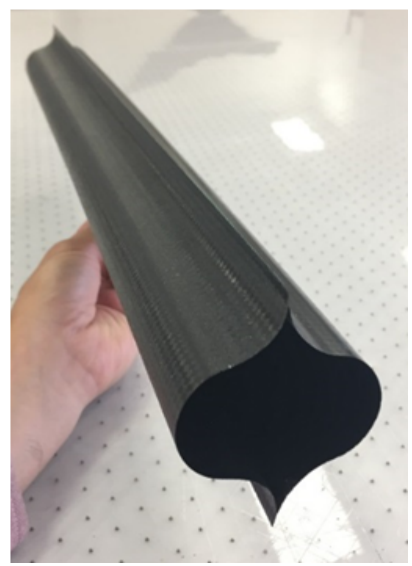
- EDU booms under development by GCDP Deployable Composite Booms project (DCB):
  - 3-year ($3M) joint effort between NASA and German Aerospace Research Agency (DLR).
  - Goal is to develop (to *TRL 5*) 14-16.5 m deployable booms suitable for NASA and DLR small spacecraft applications.
- Two experimental deployable composite boom designs being considered for a 6U ACS3 flight demonstration:
  - Two (2) *high-E*I composite booms
    - [±45/0-90] laminate
  - Two (2) *lower-EI* composite booms
    - [±45/0] laminate
- Both boom designs are being considered for future 12U to 27U-class solar sail missions.


National Aeronautics and Space Administration

Space Technology
Game Changing Development
Deployable Composite Booms

NASAfacts



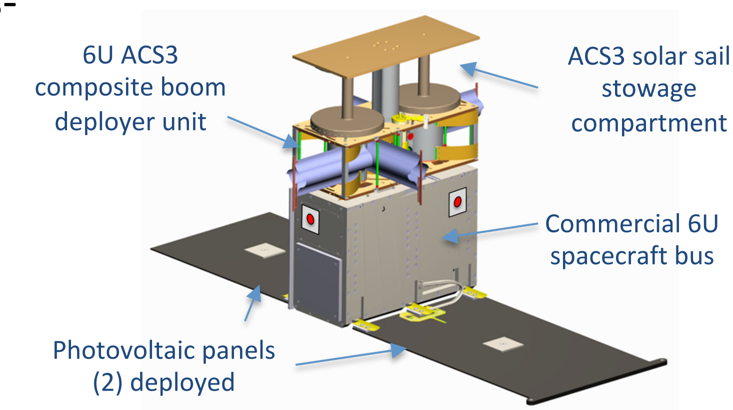


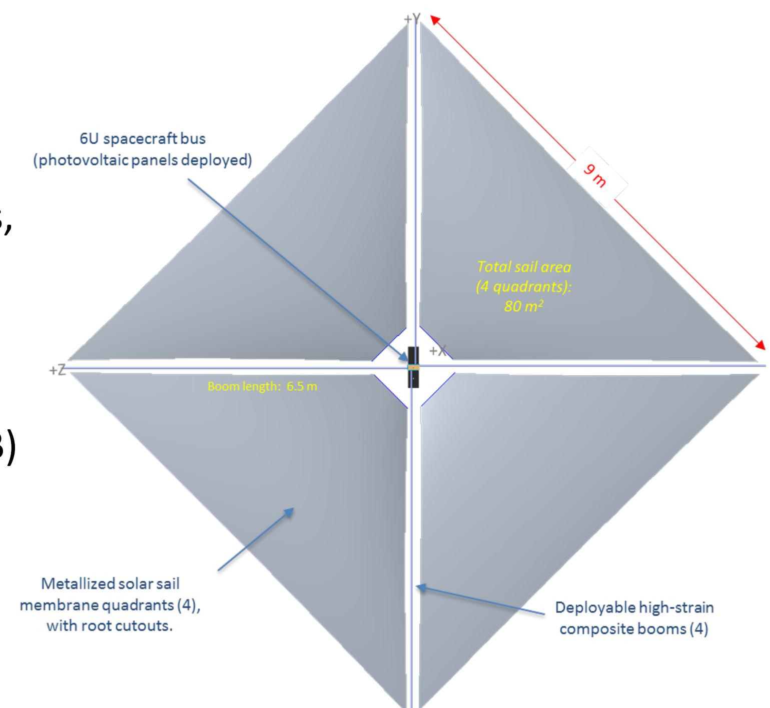
https://gameon.nasa.gov/projects/deployable-composite-booms-dcb/

- FOR DISCUSSION PURPOSES ONLY -

Advanced Composites-Based Solar Sail (ACS3) LEO Risk Reduction Mission AES, 2018 (proposed)

- **Concept**: Low-cost sub-scale (40-50%) composites-based solar sail system deployment validation experiment in LEO.
  - Partnership between LaRC, ARC, Santa Clara University.
  - Leverages STMD DCB project for booms.
- **LaRC** to deliver 6U-compatible ACS3 solar sail system payload.
  - 6U ACS3 design allows deployment testing of two unique composite boom designs for future 12U-27U class solar sail missions.
  - Two (2) “strong” composite booms
    - [±45/0-90] laminate
  - Two (2) “softer” composite booms
    - [±45/0] laminate
- **ARC** to oversee bus procurement, ACS3 payload avionics, including deployment validation cameras, and FSW.
  - Turnkey commercial 6U CubeSat bus to be used.
- **Santa Clara University Robotic Systems Lab** to provide CubeSat operations support.
- **STMD/GCDP** Deployable Composite Booms project (DCB) technology for booms.
- **CSLI**-provided launch opportunity anticipated.
  - 500 km LEO minimum altitude required.
    - No inclination constraint.
  - Polar LEO preferred, but not required.





- FOR DISCUSSION PURPOSES ONLY -

Small Satellite Solar Sail Technology Trends

Ref: Macdonald, McInnes, 2011

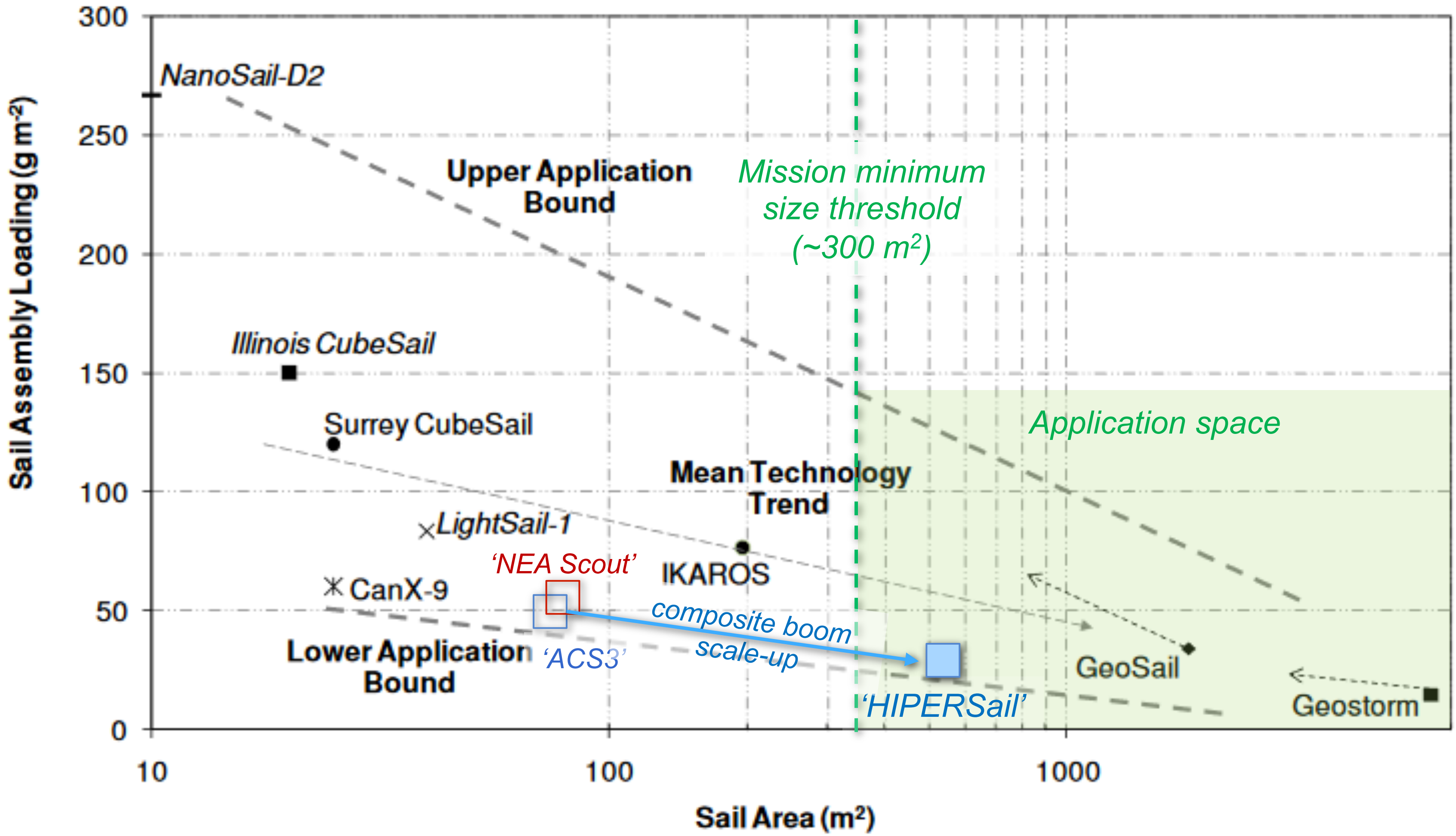
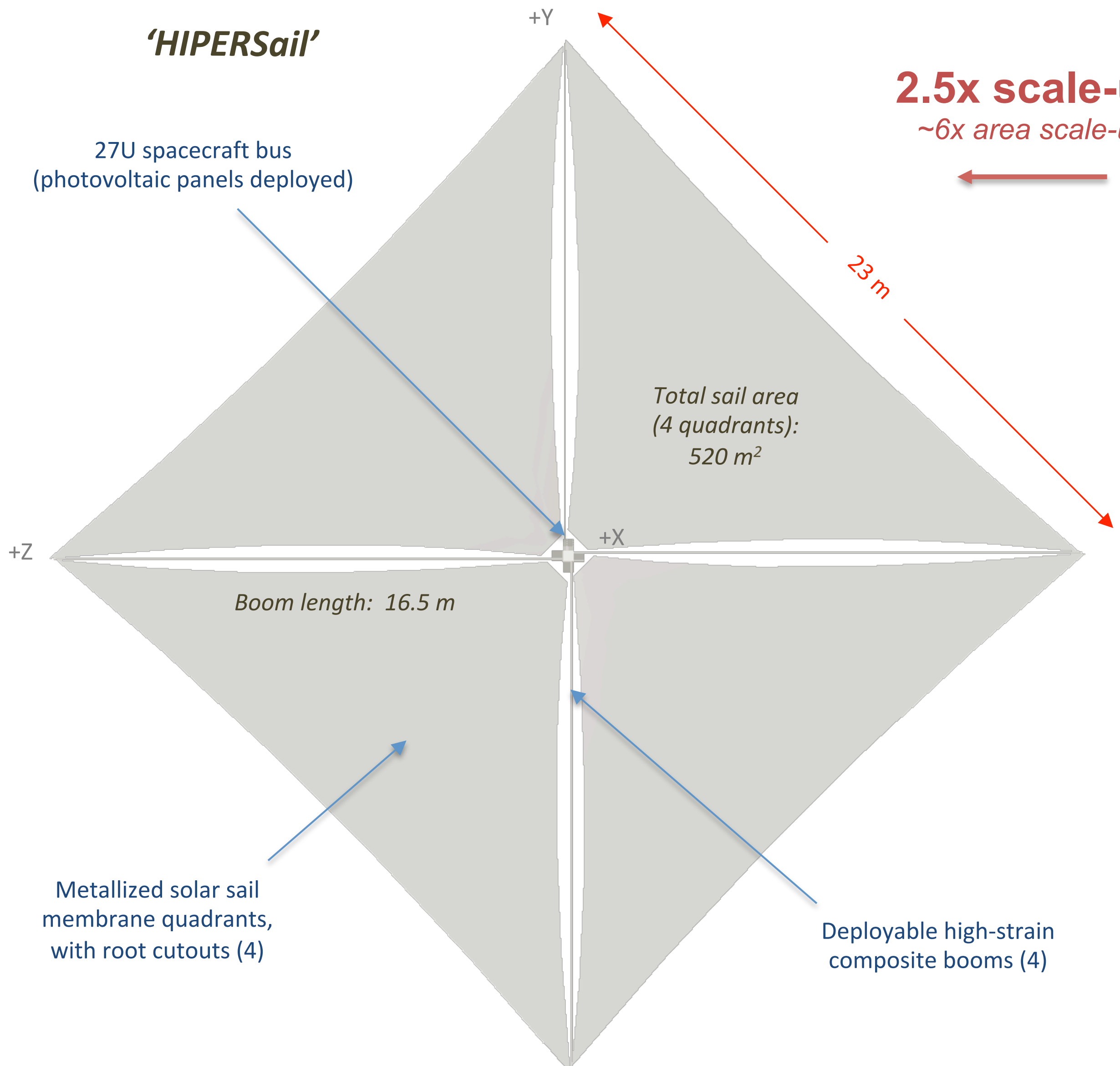


Fig. 5 CubeSat Solar Sail design space. Note, labels in italics indicate assumptions were used to gain sail assembly loading value due to the absence of data within the open literature.

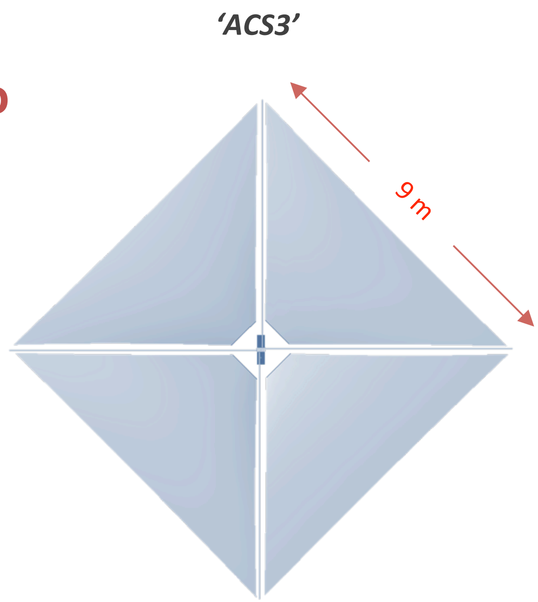
- FOR DISCUSSION PURPOSES ONLY -

'HIPERSail' and 'ACS3' Size Comparison



2.5x scale-up

~6x area scale-up

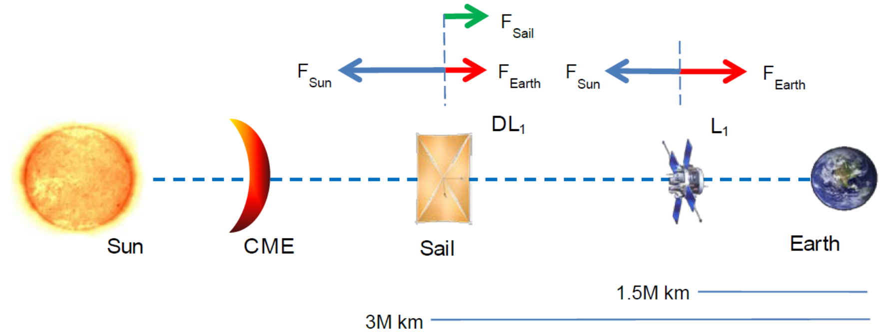


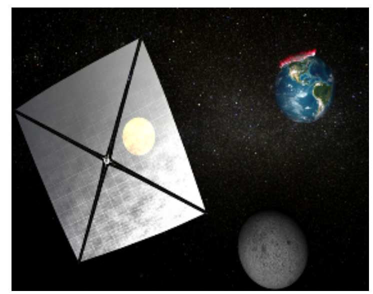
27U 'HIPERSail' Characteristics	
Sail system mass [kg]	14.8
Total space vehicle mass, including contingency [kg]	30
EOL power, 1 AU [W]	50+
Total sail area [m^2]	520
Lightness number, β [-]	0.025
Characteristic acceleration, a_c, 1 AU [mm/s^2]	0.15

- FOR DISCUSSION PURPOSES ONLY -

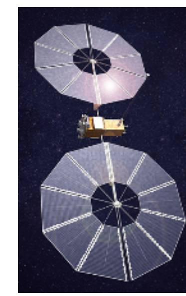
Solar Sails are an enabling technology for enhanced space weather early warning missions

- Permits station-keeping at sub-L1 locations to increase CME warning times.
  - No fuel constraint on operations.
- Constant thrust station keeping operations are not feasible using chemical propulsion.
- Station keeping operations possible using SEP, but for limited durations (< 5 years).
- For constant thrust missions durations more than 5 years (e.g., ACE at 10 years) solar sails are an enabling propulsion technology.





vs.

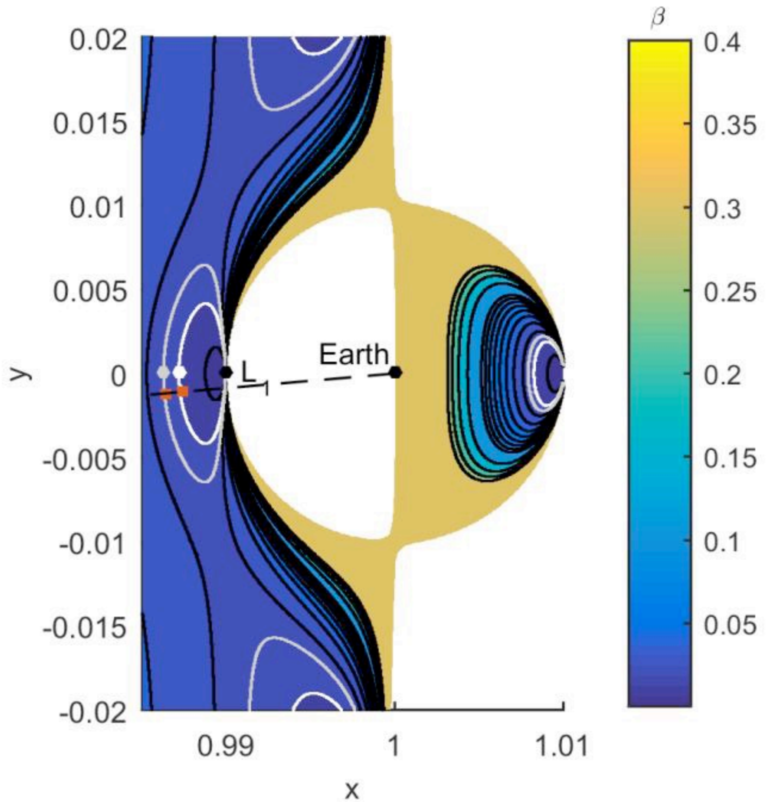


Mission duration (yrs)	Effective Δv (ms^{-1})	Chemical mass ratio	SEP mass ratio
1	9,467	0.05	0.72
2	18,935	0.002	0.53
5	47,336	-	0.20
10	94,673	-	0.04

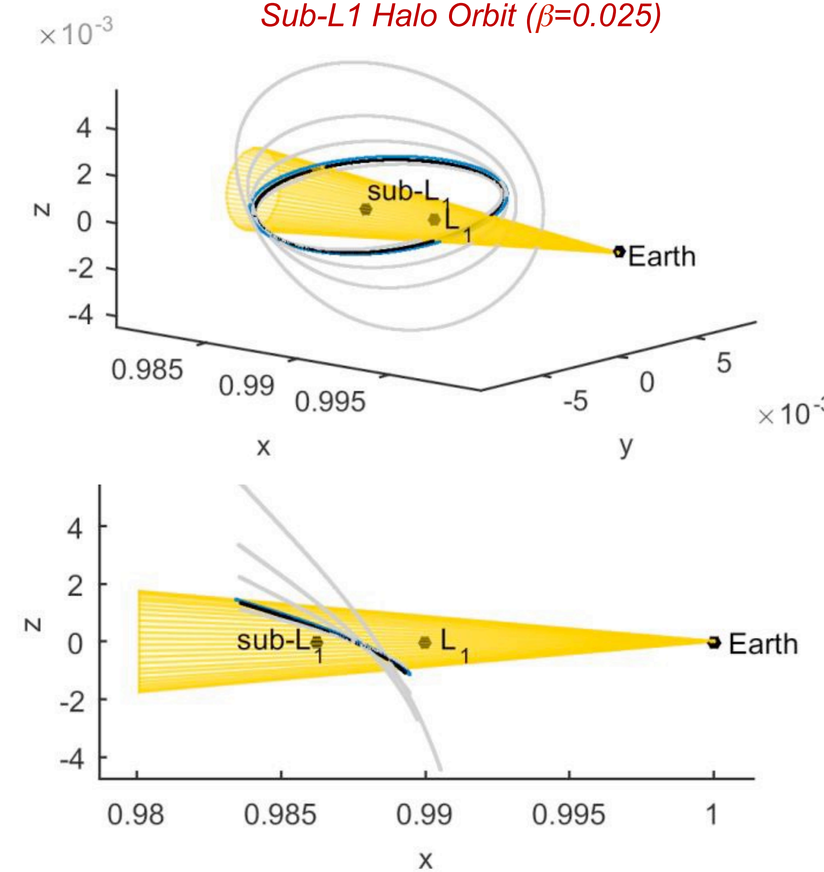
Ref: McInnes, C., et al., "Gossamer Roadmap Technology Reference Study for a Sub-L1 Space Weather Mission," in: Macdonald, M. (Ed.), Advances in Solar Sailing, pp. 227-242, Springer-Praxis, Springer Berlin Heidelberg, 2014.

Mission Example: ACS3 Sun-Earth Sub-L1 Space Solar Weather Early Warning Sentinel [Heiligers, Wilkie, 2015]

Achievable Artificial Lagrange Point (ALP) Contours



Sub-L1 Halo Orbit (β=0.025)

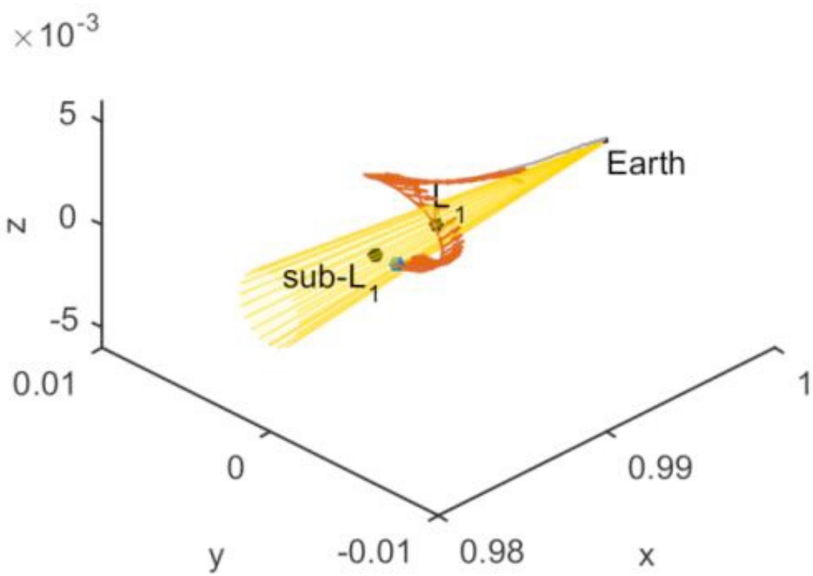


Warning Time Increase for 5°SEZ Sub-L1 ALP

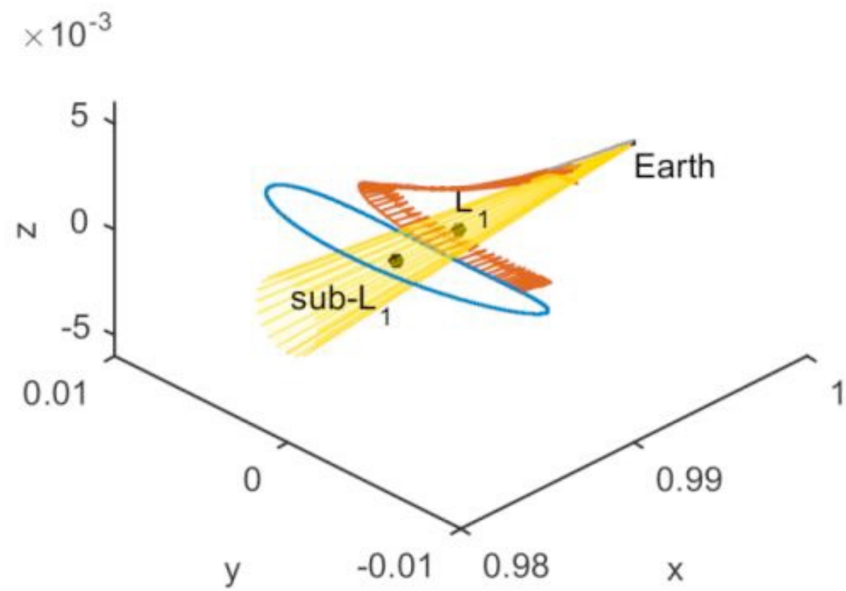
	x-position AEP	y-position AEP	Distance from Earth, km	Increase in warning time over L_1
$\beta = 0.02$	0. 98729	-0.00108	1,907,476	1.274
$\beta = 0.025$	0. 98636	-0.00116	2,047,473	1.367

Optimal Solar Sailing Transfers to Sub-L1 Targets

5°SEZ Sub-L1 ALP



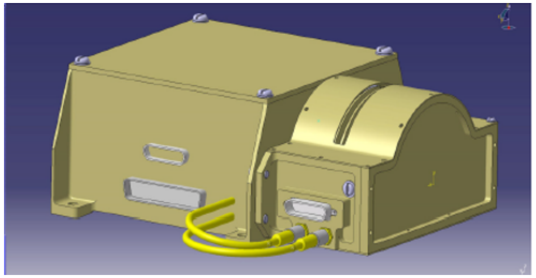
Sub-L1 Halo Orbit



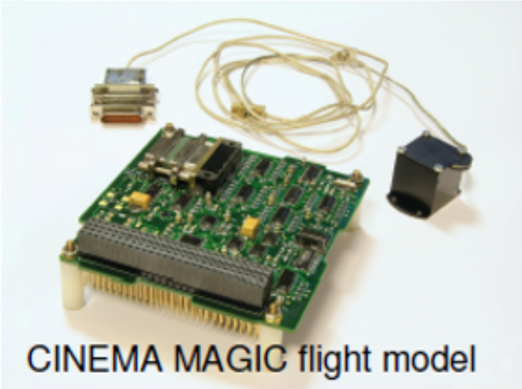
	$\beta = 0.02$		$\beta = 0.025$	
	5 deg trailing AEP	**Solar sail halo orbit**	**5 deg trailing AEP**	**Solar sail halo orbit**
ΔV_{GTO}, **m/s**	747.8	747.5	746.9	747.7
Transfer time, days				
- **Ballistic phase**	7.1	4.4	7.2	4.9
- **Solar sail phase**	191.3	129.1	185.7	125.8
- **Total**	**198.4**	**133.5**	**192.8**	**130.7**

Potential HIPERSail-Compatible Space Weather Early Warning Instruments (examples)

- SWAN (*Solar Wind ANalyzer*)
  – High voltage electrostatic optic measuring solar wind ions
  – Built by Mullard Space Science Laboratory, University College London
  – Based on ChaPS (Charged Particle Spectrometer) on TechDemoSat
- MAGIC (*MAGnetometer from Imperial College*)
  – Magnetometer measuring interplanetary magnetic field and solar wind
  – Sensitivity better than 1 nT over 60 s
  – Flown on CINEMA (UC Berkeley Cubesat)
- Auxilliary S-Band Communications System (option)
  – Extended mission optional package
  – Would permit SSRRM instrument suite to be integrated into existing NOAA real-time space weather monitoring system.



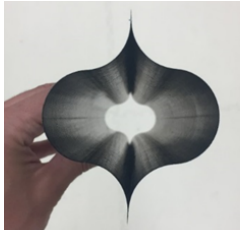
SWAN

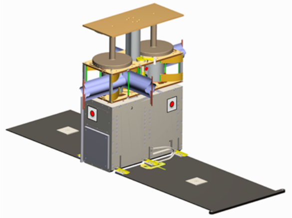


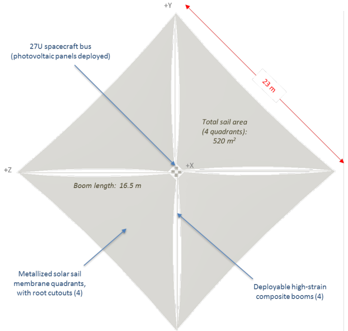
CINEMA MAGIC flight model

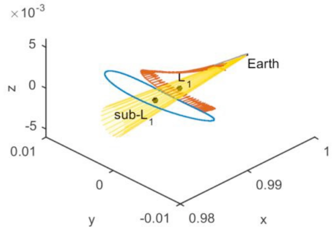
HIPERSail Technology Summary

- Deployable Composite Booms (DCB), deep space CubeSat bus systems, and Advanced Composites-Based Solar Sail System (ACS3) technology to be at appropriate readiness levels for tech demo mission ca. FY21.
  - Avionics systems to be at TRL 9 after InSight (MarCO) and EM-1 (BioSentinel, NEA Scout) missions.
  - STMD/GCDP 14-16.5 m booms at TRL 5 in FY20.
  - Sail system at TRL 6 after proposed 6U ACS3 LEO flight experiment, ca. FY20.
- ACS3 on path to mission capable full-scale solar sail system.
  - Validates *HIPERSail* deployment approach in space environment.
  - Sufficiently large (40% of full-scale) to enable scale-up to full *HIPERSail* mission size.
- Heliophysics TechDemo ideal opportunity to demonstrate mission capability of composites-based small spacecraft solar sail technology.
  - Preliminary analysis indicates Sun-Earth sub-L1 solar sailing space weather early warning tech demo mission feasible with *HIPERSail*.
    - Launch time frame: ca. 2024 (ESPA rideshare on IMAP)
    - Flight time: 5-7 months.









- FOR DISCUSSION PURPOSES ONLY -

NASA

Heliophysics TechDemo SALMON-3 PEA [Released: May 01, 2018]

- https://nspires.nasaprs.com/external/solicitations/summary!init.do?solId=%7B847150E1-67CC-B2B6-C6B6-EA32884560E2%7D&path=open
- Principal Investigator (PI)-led investigations in SMD's Heliophysics programs under a not-to-exceed cost cap.
- Evaluation and down-selection for flight via two-step competitive process:
  1. No more than three TechDemo Investigations to be selected for nine-month, $400K (FY2019) Phase A concept studies.
  2. At least one TechDemo investigation will be selected to continue into Phase B and subsequent mission phases.
- A TechDemo investigation proposed PI-Managed Mission Cost (PIMMC), including all mission phases, is expected to range from **$25M-$65M**.
  – Multiple missions may be selected if their total cost remains below the overall PEA cost cap of $65M.
- **TechDemo investigations must be proposed for flight as a secondary payload with the IMAP mission (launch: ca. 2024)**
  – Up to two ports on an EELV Secondary Payload Adapter (ESPA) will be provided to accommodate this investigation.
  – The ESPA is intended to be an unpowered, non-propulsive, ESPA Grande ring.
  – The TechDemo SCM(s) will be released from the ESPA and/or the IMAP EELV after IMAP injection into a transfer orbit to the Earth-Sun L1 Lagrangian point.

Heliophysics TechDemo SALMON-3 PEA (continued)

- Timeframe to initiate a future research mission achieving the science advancements enabled by the TechDemo investigation must be technically and scientifically plausible **during the next 15 years**.
  - Must advance TRL to 5+ to support inclusion in future Heliophysics Decadal Study.
  - **Science advancements can also be achieved within the TechDemo investigation itself.**
    - Not a factor in the evaluation criteria (although, …)
- The projects are designated as **Category 3**
  - Ref: NPR 7120.5E, *NASA Space Flight Program and Project Management Requirements*.
- The payloads are designated as **Class D (*Tailored*).**
  - Refs: NPR 8705.4, and *NASA Science Mission (SMD) Class-D Tailoring/Streamlining Decision Memorandum*, https://soma.larc.nasa.gov/standardao/ClassD.html
- Proposal timeline:
  - Comments due on this Draft SALMON-3 PEA ... June 1, 2018
  - Release of Final SALMON-3 PEA .... July 9, 2018 (target)
  - Pre-proposal conference .... 2-3 weeks after Final PEA release
  - Mandatory Notification Proposals .... 30 days after Final PEA release
  - Proposals due .... 90 days after Final PEA release