



**From Iron Horse to Worldship:
Becoming an Interstellar Civilization**

Chattanooga, February 28 - March 2, 2016

Ben Beers

NASA MSFC / Geocent LLC.

benjamin.r.beers@nasa.gov

(256) 544-7628



Propulsion Technology Assessment: Science and Enabling Technologies to Explore the Interstellar Medium

Tennessee Valley Interstellar Workshop (TVIW) 2016
28 February – 2 March 2016

Randy Hopkins, Dan Thomas, Bruce Wiegmann, Andy Heaton, Les Johnson
NASA, George C. Marshall Space Flight Center

Mike Baysinger
Jacobs ESSSA Group

Ben Beers
Geocent – Jacobs ESSSA Group



Interstellar Probe Mission:

Trade and determine the best propulsion system from the following options in order to reach the Heliopause (100 AU) in 10 years:

- ◆ Magnetically Shielded Miniature (MaSMi) Hall thruster
- ◆ Solar sail
- ◆ Electric sail (E-Sail)

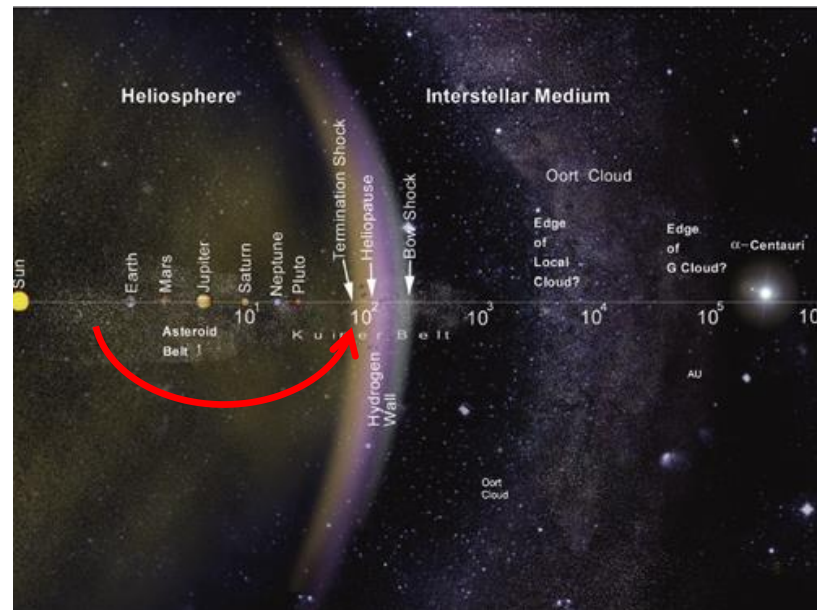
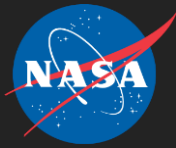
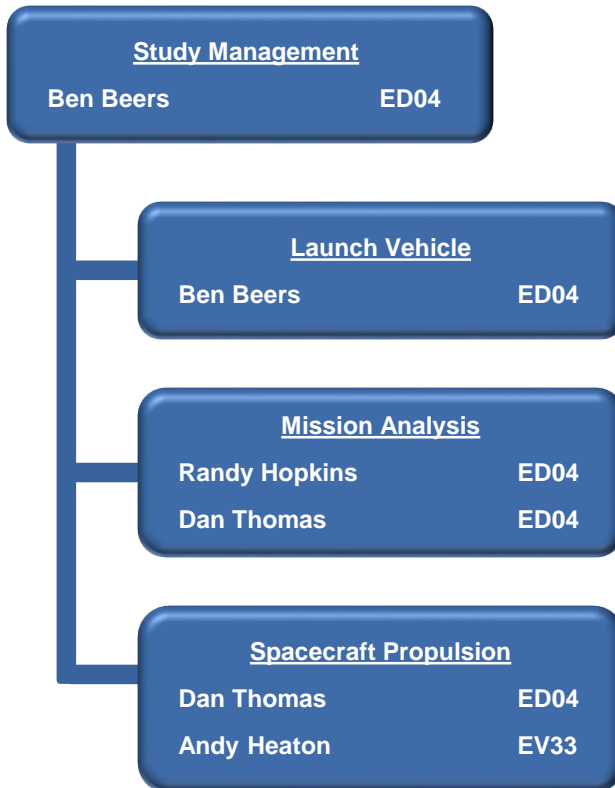


Figure 1. Solar system and interstellar distances.
(Image credit: JHU APL)

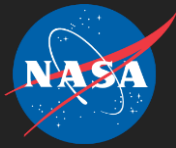


Team Infrastructure



<u>Ground Rules & Assumptions</u>	
Spacecraft	JPL / Cal Tech
Launch Vehicle	MSFC
Propulsion	MSFC

<u>Subject Matter Expertise</u>	
Launch Vehicle	Barney Holt Jessica Garcia
MaSMi Hall thruster	Dan Thomas
E-Sail Propulsion	Bruce Wiegmann Andy Heaton
Solar Sail Propulsion	Les Johnson



Space Transportation Options



- ◆ In-space high-thrust stages:
 - ◆ 1 to 2 solid rocket motors (SRM) in SLS stack
- ◆ Onboard low-thrust Advanced Propulsion Systems (APS):
 - ◆ MaSMi Hall thruster
 - ◆ Solar sail
 - ◆ E-Sail

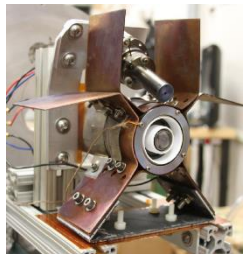


Figure 2. MaSMi Hall thruster.
(Image credit: UCLA)

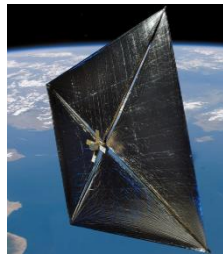


Figure 3. NanoSail-D solar sail. (Image credit: NASA Science News)

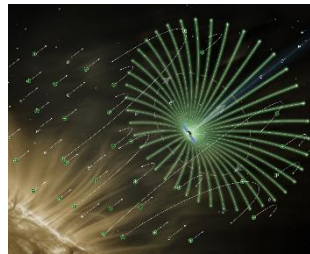


Figure 4. Electric sail (E-Sail).
(Image credit: Szames)

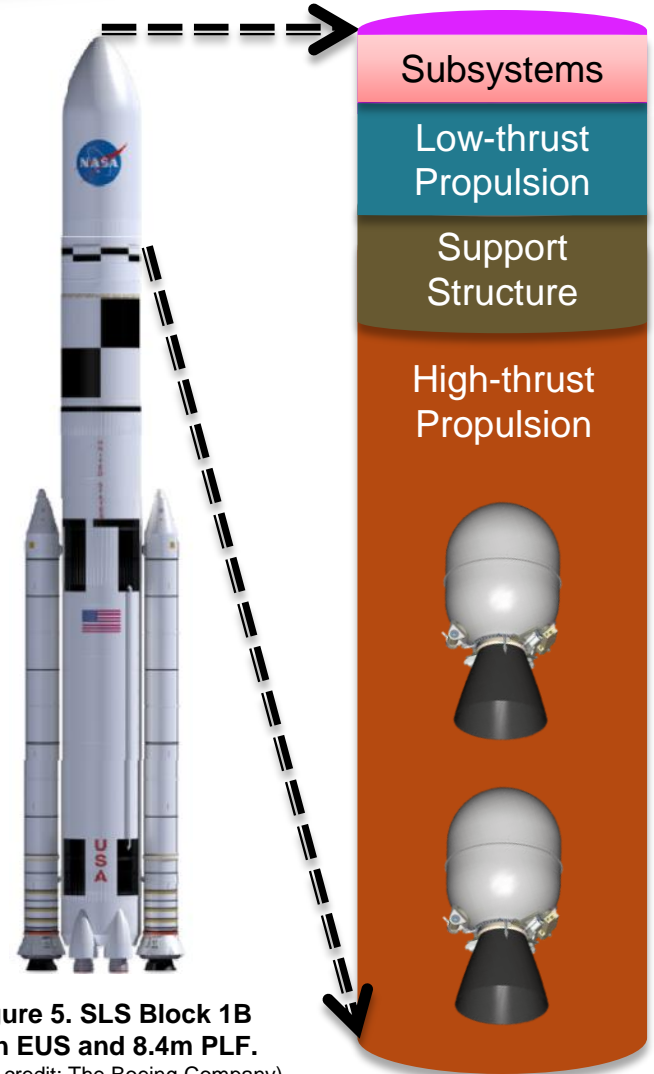
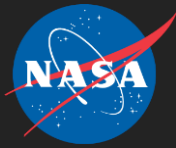


Figure 5. SLS Block 1B with EUS and 8.4m PLF.
(Image credit: The Boeing Company)



Ground Rules & Assumptions (GR&A)



Table 1. Highlighted system-level ground rules and assumptions.

Item	Assumption	Notes
Mission performance	100+ AU in 10 years	
Launch window	2025 – 2030	
Launch vehicle	SLS Block 1B + EUS + 8.4 m PLF	<ul style="list-style-type: none">- C₃ energy for SLS Block 1B + EUS 5.0m Payload Fairing (PLF) was not released until after conclusion of study, so C₃ energy from 8.4m PLF configuration was used out of necessity.- Payload Attach Fitting (PAF) bookkept within net payload mass.
Spacecraft mass	380 kg (838 lb _m)	Includes all components except an onboard low-thrust APS.
Spacecraft heat shield	300 kg (661 lb _m)	Mass scaled from Solar Probe Plus heat shield (with conservatism).
Spacecraft power	450 W	Provided by an Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG).



Figure 6. SLS Block 1B with EUS and 8.4m PLF.
(Image credit: The Boeing Company)



Ground Rules & Assumptions (GR&A)

(cont.)

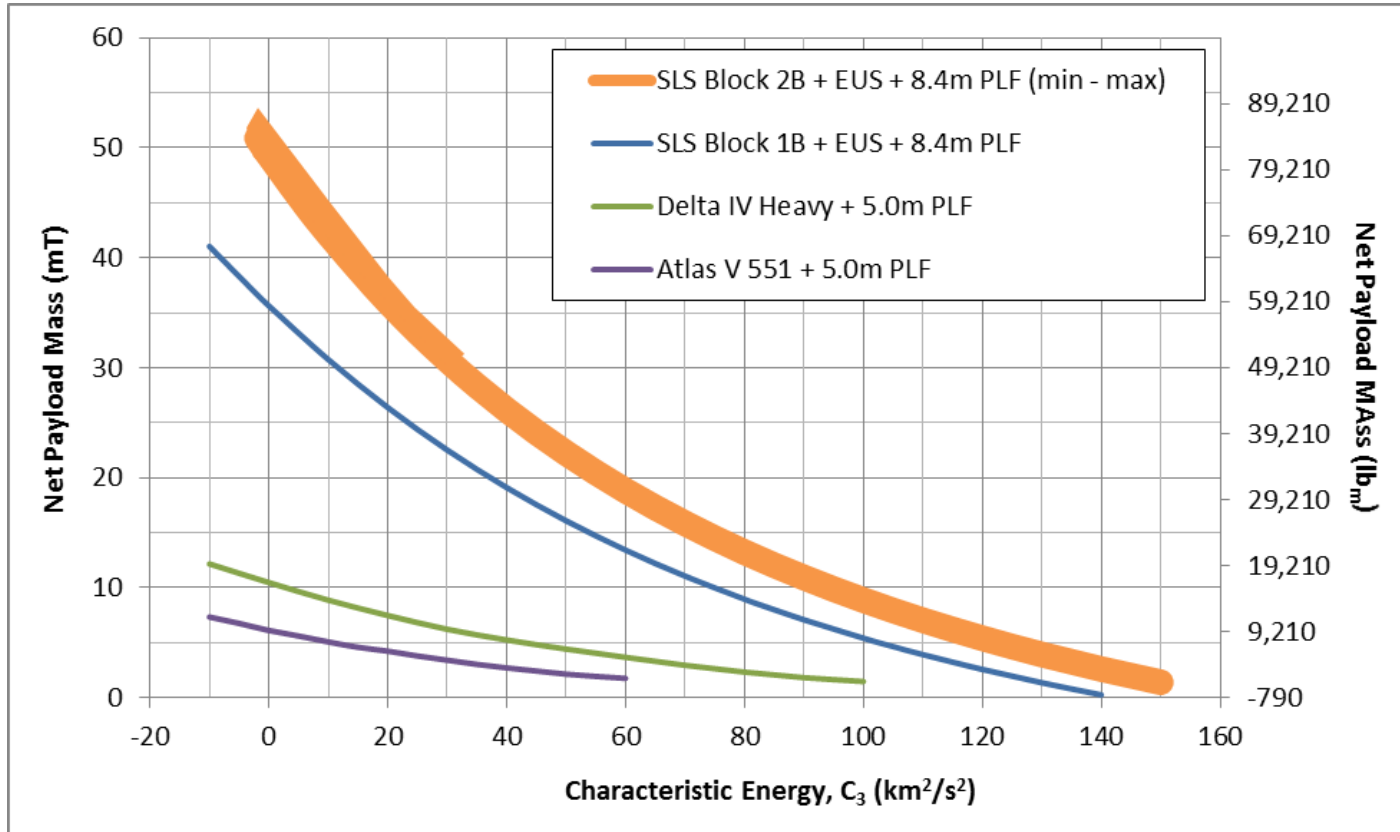


Figure 7. C₃ Energies for SLS and other large launch vehicles. ^{1, 2}

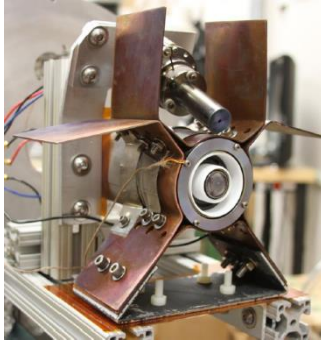


Figure 8. MaSMi Hall thruster.
(Image credit: UCLA)

Table 2. MaSMi Hall thruster GR&A.

Item	Description
Maximum lifetime	50,000 hours
Thrust	19 mN (0.004 lb _f)
Specific Impulse, I_{sp}	1,870 sec

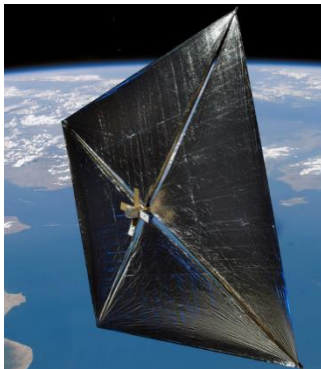


Figure 9. NanoSail-D solar sail.
(Image credit: NASA Science News)

Table 3. Solar sail GR&A.

Item	Description	
Reflectivity	0.91	
Minimum thickness	2.0 μm	
Maximum size (per side)	200 m (656 ft)	
Sail material	CP1	
Aerial density *	3 g/m ²	10 g/m ²
Characteristic acceleration	0.426 mm/s ²	0.664 mm/s ²
System mass	120 kg (265 lb _m)	400 kg (882 lb _m)

* Assumes technology development. Current technology is approximately 25 g/m².



Electric Sail: Concept of Operations & GR&A



- ◆ Wires deployed from main spacecraft bus while spacecraft rotates to keep wires taut.
- ◆ Electron gun used to keep spacecraft and wires in high positive potential.
- ◆ Positive ions in solar wind repulsed by the field and thrust is generated.

Table 4. E-Sail GR&A.

Item	Description	
System mass	120 kg (265 lb _m)	
Wire material (density)	Aluminum (2,800 kg/m ³)	
Wire diameter (gauge)	0.127 mm (36 gauge)	
Characteristic acceleration	1 mm/s ²	2 mm/s ²
Tether quantity	10	20
Individual tether length	20 km (12.4 mi)	20 km (12.4 mi)

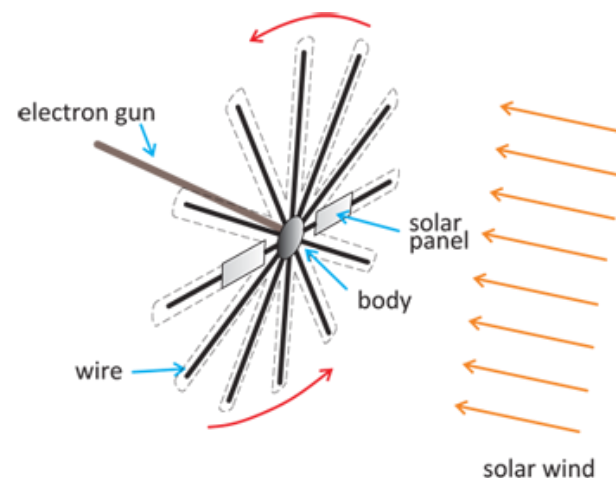
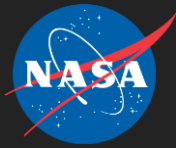


Figure 10. Cartoon schematic of E-Sail propulsion technology.

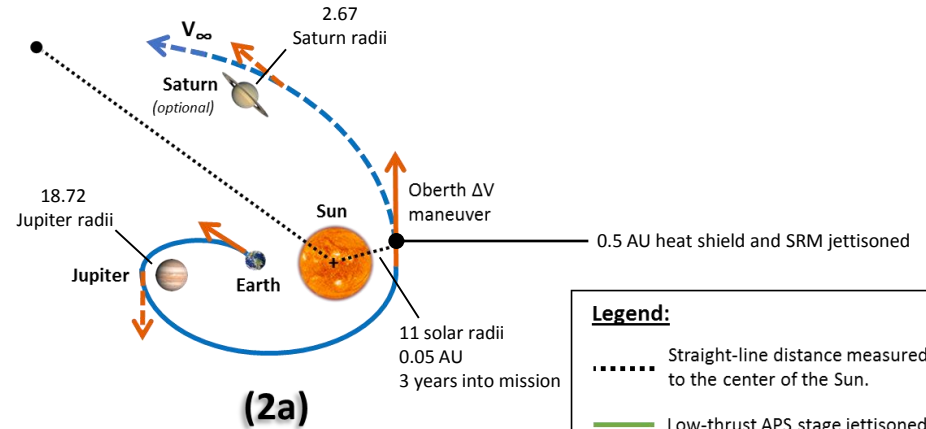
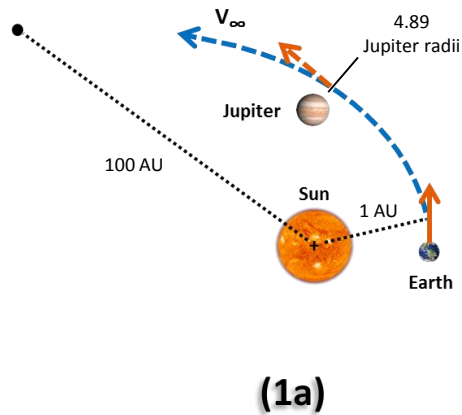
(Image credit: nextBIGFuture.com)



Space Transportation Approaches Used to Compare Onboard Propulsion Options



MaSMi Hall thruster
— and —
E-Sail



Legend:

- Straight-line distance measured to the center of the Sun.
- Low-thrust APS stage jettisoned
- Low-thrust APS stage inactive
- - - Low-thrust APS stage active
- Powered maneuver per SRM kick stage
- - - Unpowered maneuver per gravity assist

Solar Sail

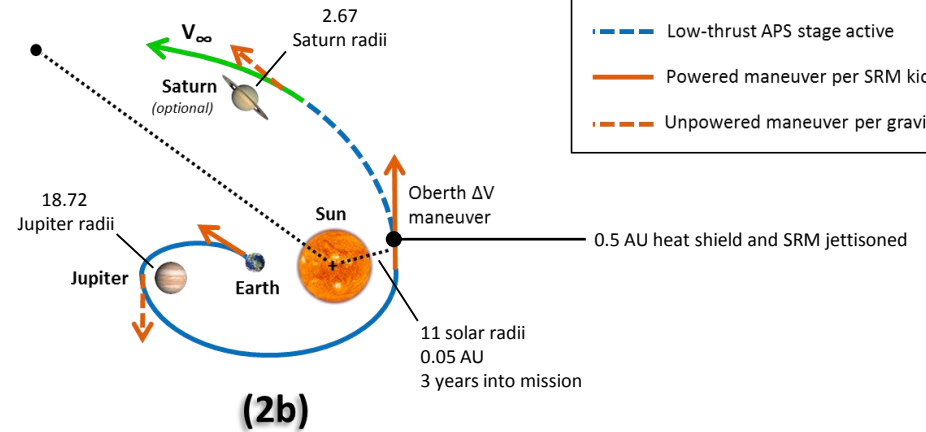
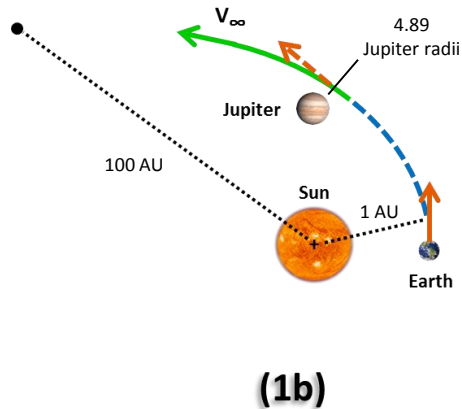
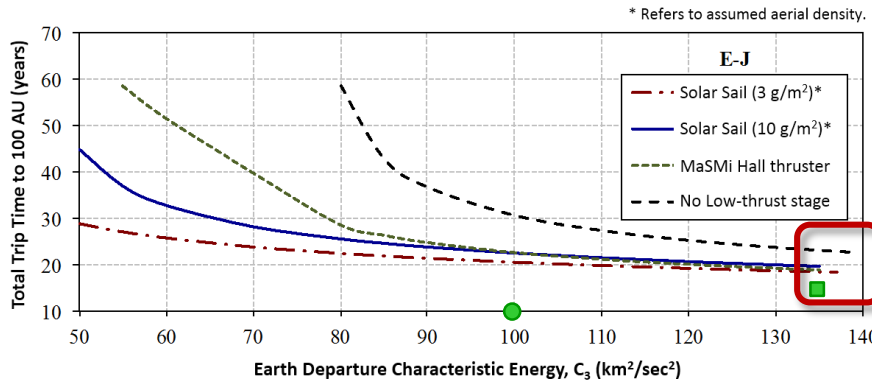


Figure 11. Mission trajectory profile options considered.

Figure 12

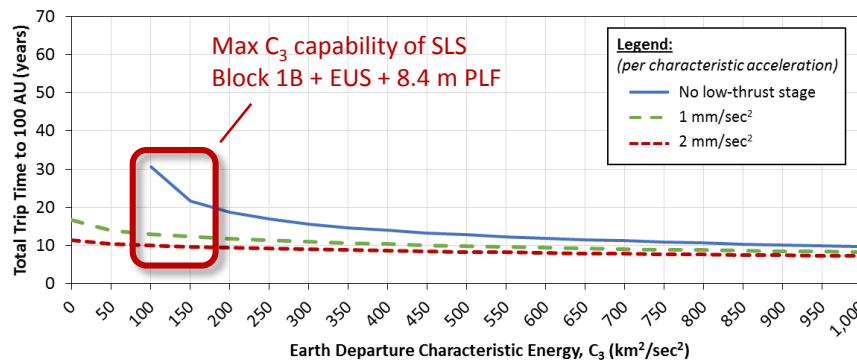


E-Sail Capability: (also see p. 11)

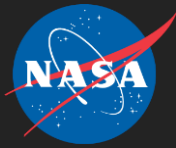
- 9.9 years
 - $C_3 = 100 \text{ km}^2/\text{s}^2$
 - $2 \text{ mm}/\text{s}^2$
- 12.5 years
 - $C_3 = 135 \text{ km}^2/\text{s}^2$
 - $1 \text{ mm}/\text{s}^2$

Max C_3 capability of SLS
Block 1B + EUS + 8.4 m PLF

Figure 13



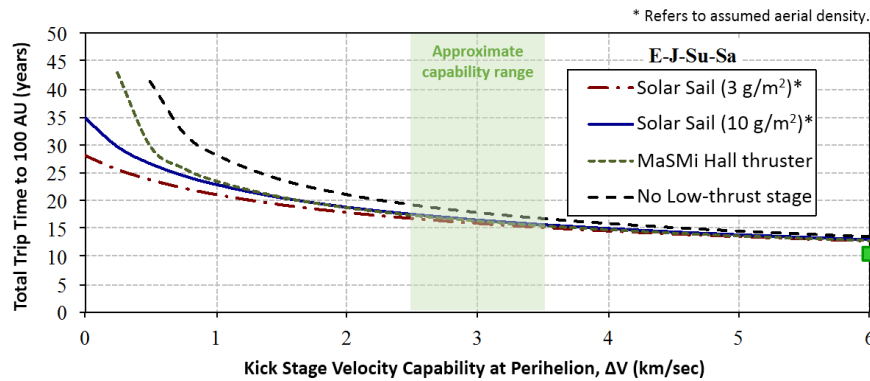
Max C_3 capability of SLS
Block 1B + EUS + 8.4 m PLF



Earth-Jupiter-Sun-Saturn Trajectory Results



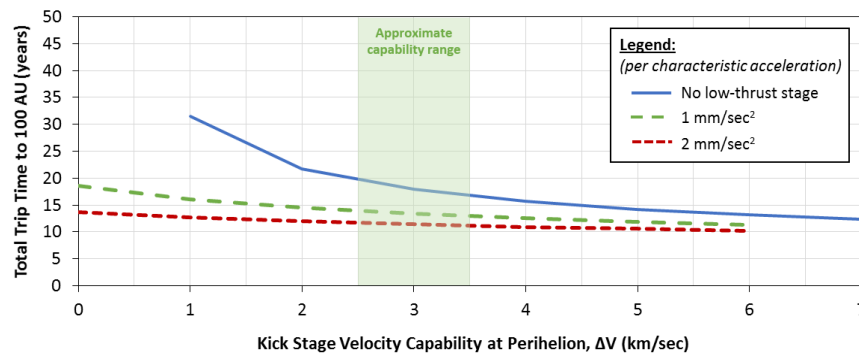
Figure 14



E-Sail Capability:

- 9.9 years
 - ΔV = 7 km/s
 - 2 mm/s²
- 10.9 years
 - ΔV = 6 km/s
 - 1 mm/s²

Figure 15



Total Payload Mass:

Including:

- Spacecraft
- Low-thrust stage
- Heat shield
- SRM kick stage(s)

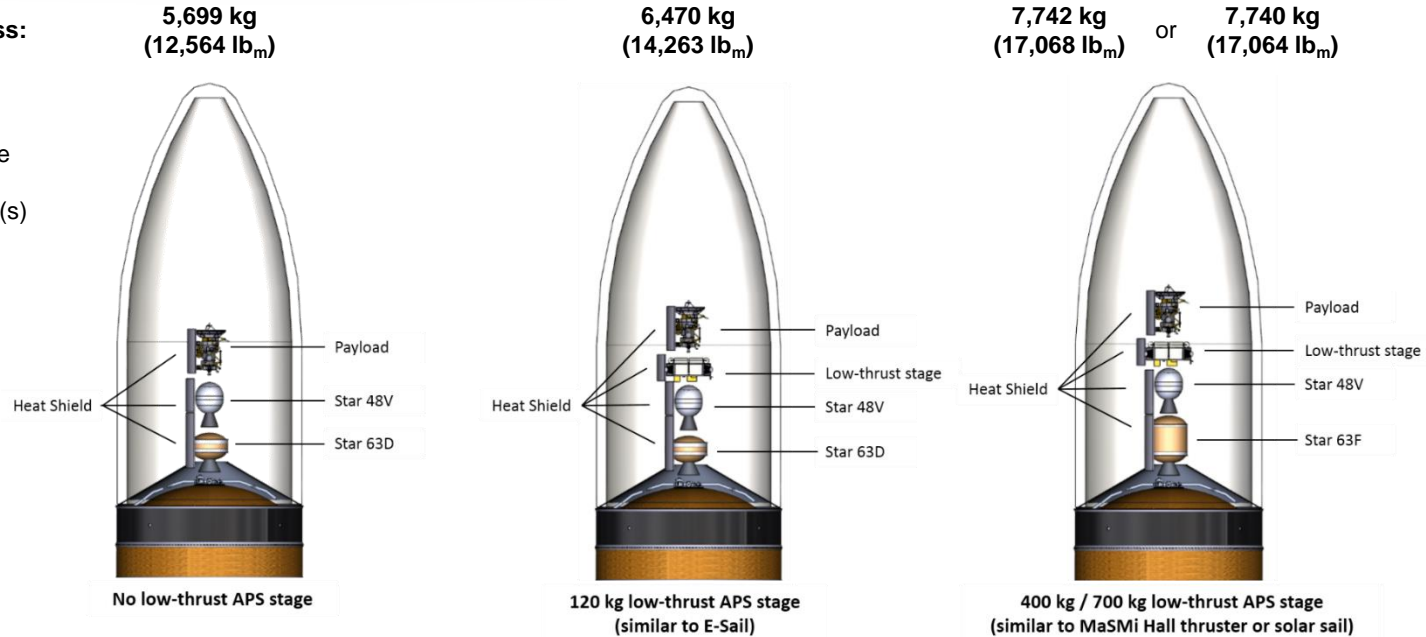


Figure 16. Approximate envelope of payload and SRM kick stages inside SLS 8.4 m PLF per stowed Voyager configuration volume.

Table 5. SRM kick stages chosen for the *E-Ju-Su-Sa* trajectory option.

Low-thrust APS Mass	Impulsive Burn 1 (Earth departure)	Impulsive Burn 2 (Perihelion)	Notes
0 kg (0 lb _m)	Star 63D	Star 48V	Star 63D – 20% of propellant offloaded.
120 kg (265 lb _m)	Star 63D	Star 48V	No propellant offloaded for either SRM
400 kg (882 lb _m)	Star 63F	Star 48V	Star 48V – 5% of propellant offloaded.
700 kg (1,543 lb _m)	Star 63F	Star 48V	Star 48V – 20% of propellant offloaded.



◆ Future work:

- ◆ Analyze trajectories employing an ion thruster propulsion system.
- ◆ Consider C_3 energy curve for SLS Block 1B + EUS + 5.0 m PLF.
 - Would require an additional launch vehicle adapter.

◆ Concerns:

- ◆ Survival of the heat shield closest to the SRM nozzle burning during the impulsive maneuver at perihelion.



Figure 17. SLS Block 1B with EUS and 5.0m PLF (adapted).
(Image credit: The Boeing Company)



REFERENCES



References



- 1) “Space Launch System (SLS) Program Mission Planner’s Guide (MPG) Executive Overview,” SLS-MNL-201, Version 1, NASA MSFC, August 22, 2014.
- 2) Donahue, B., Sigmon, S., “The Space Launch System Capabilities with a New Large Upper Stage,” AIAA 2013-5421, Boing Defense, Space & Security (BDS), 2013.
- 3) Conversano, R. W., Goebel, D. M., Hofer, R. R., Matlock, T. S., Wirz, R. E., “Magnetically Shielded Miniature (MaSMi) Hall Thruster,” University of California, Los Angeles (UCLA), Department of Mechanical and Aerospace Engineering Plasma and Space Propulsion Laboratory.
- 4) Quarta, A. A. and Mengali, G., “Electric Sail Mission Analysis for Outer Solar System Exploration,” University of Pisa, Pisa, Italy.
- 5) McNutt, Jr., R. L., “Enabling Interstellar Probe with Space Launch System (SLS),” IAC-14-D.4.4.2, 65th International Astronautical Congress (IAC), Johns Hopkins University (JHU) Advanced Physics Laboratory (APL) and The Boeing Company, page 6, 2014.
- 6) “Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) Concept,” NASA, URL: https://solarsystem.nasa.gov/rps/docs/eMMRTG_onepager_LPSC20140317.pdf [cited 2 January 2015].



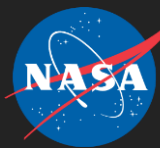
Acronyms & Symbols



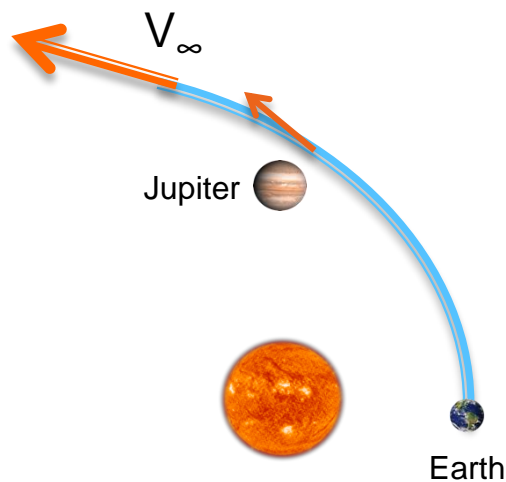
APL	Applied Physics Laboratory	PMF	Propellant Mass Fraction
APS	Advanced Propulsion System	Sa	Saturn
AU	Astronomical Unit	SLS	Space Launch System
BDS	Boeing Defense, Space and Security	SRM	Solid Rocket Motor
C ₃	Characteristic energy	Su	Sun
eMMRTG	Enhanced Multi-Mission Radioisotope Thermoelectric Generator	UCLA	University of California, Los Angeles
E	Earth		
E-Sail	Electric Sail		
EUS	Exploration Upper Stage		
GR&A	Ground rules & Assumptions		
IAC	International Astronautical Congress		
JAXA	Japanese Aerospace eXploration Agency		
JHU	Johns Hopkins University		
JGA	Jupiter Gravity Assist		
JPL	Jet Propulsion Laboratory		
Ju	Jupiter		
MaSMi	Magnetically Shielded Miniature [hall thruster]		
MPG	Mission Planner's Guide		
MSFC	Marshall Space Flight Center		
NASA	National Aeronautics and Space Administration		
PAF	Payload Attach Fitting		
PLF	Payload Fairing		



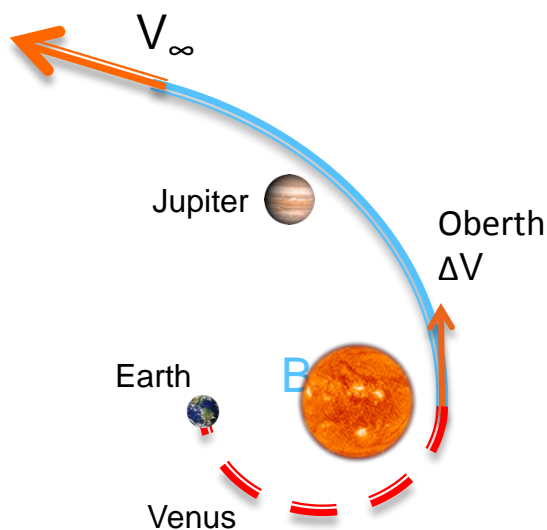
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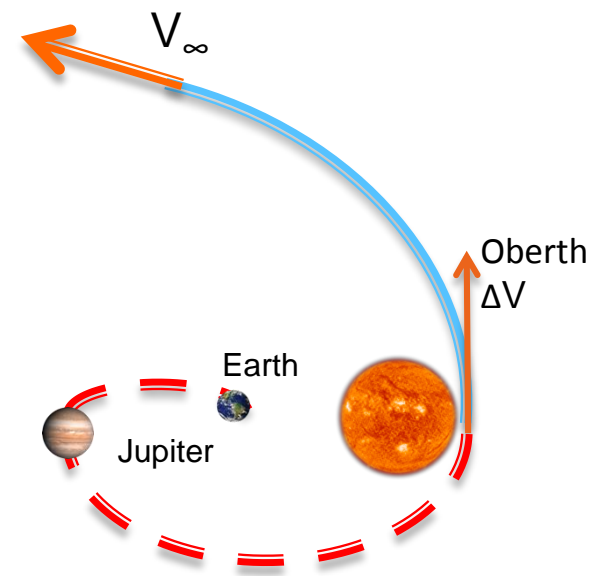
Space Transportation Approaches Used to Compare Onboard Propulsion Options



Direct escape using SLS, Jupiter Gravity Assist (JGA) and onboard in-space propulsion system.



Sun dive using SLS for Oberth maneuver and onboard in-space propulsion system.



JGA to Sun dive using SLS and onboard in-space propulsion system.



- ◆ Optimized solar sail and electric propulsion trajectories to 100 AU
 - ◆ Two-dimensional
 - ◆ Sail angle (and electric propulsion thrust angle) maximizes orbital energy gain
 - ◆ Payload mass = 380 kg
 - ◆ Sail parameters:
 - Reflectivity = 0.91
 - Square sail: side = 200 m
 - Sail aerial density trades:

Aerial density = 10 g/m²

Characteristic acceleration = 0.4256 mm/s²
Sail mass = 400 kg
Total spacecraft mass = 780 kg

Aerial density = 3 g/m²

Characteristic acceleration = 0.6639 mm/s²
Sail mass = 120 kg
Total spacecraft mass = 500 kg

- ◆ MaSMi (assume maximum lifetime = 50,000 hrs)
 - Assume powered by 450 W eMMRTG
 - Total spacecraft initial mass = 800 kg
 - Thrust = 19 mN
 - $I_{sp} = 1870$ s



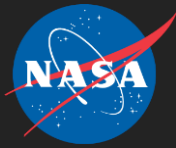
◆ Two mission cases

◆ *E-J-Su-Sa*

- Earth to Jupiter with gravity assist (at 18.72 Jupiter radii) to reduce perihelion to 11 solar radii (~ 0.05 AU).
 - Time from Earth to perihelion = 2.97 years
- Kick stage performs ΔV at perihelion
- Drop stage and heat shield and deploy sail at 0.5 AU (after perihelion passage)
- Drop sail before Saturn flyby
 - Assume circular Saturn orbit at 9.583 AU
 - Flyby radius = 2.67 Saturn radii

◆ *E-J*

- Depart Earth with enough energy to perform Jupiter gravity assist
 - Initial velocity set by given C3 (SLS Block 1B + EUS + 8.4m PLF)
 - Assume circular Jupiter orbit at 5.203 AU
 - Flyby radius = 4.89 Jupiter radii
- Deploy sail at 1 AU
- Drop sail before Jupiter flyby



Previous Interstellar Probe Study



- ◆ Departure velocity at Earth:
 - ◆ Optimal split between SLS and kick stage depends on kick stage PMF.
 - ◆ Plot shows that for a PMF of 0.90, optimal split is to let SLS insert the payload into an escape trajectory with C_3 of $67.766 \text{ km}^2/\text{s}^2$.

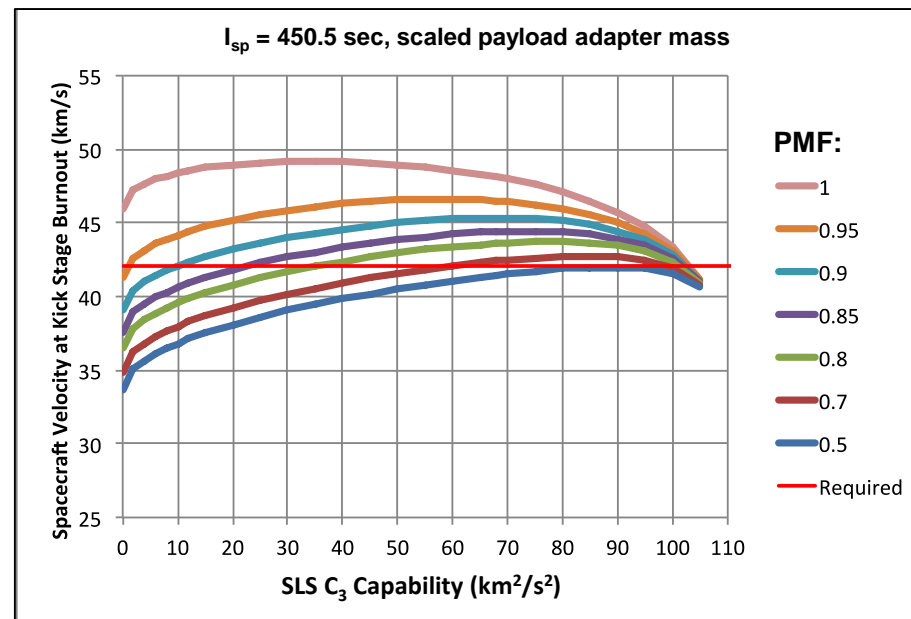


Figure 17. Spacecraft velocity at kick stage burnout for various PMF values.

◆ Why choose Jupiter?

- ◆ It's huge!
- ◆ It's closer than Saturn, so (1) the assist occurs sooner and (2) the spacecraft is going faster, sooner.
- ◆ Table 6 compares possible gravity assist equivalent ΔV values.
 - Data is for skimming the planet's surface and are therefore for comparison only. Data only provides magnitude of ΔV available.
 - Perihelion before flyby is 1 AU for all cases.
 - Circular planetary orbits assumed.

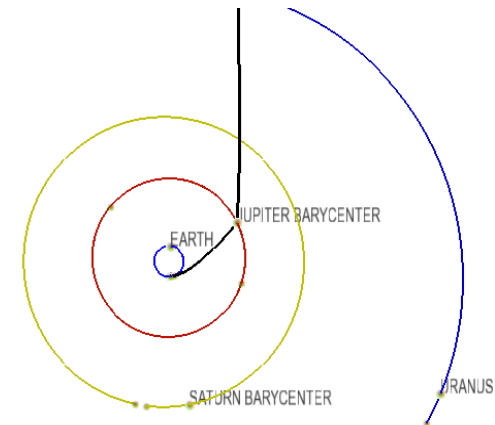


Figure 18. Jupiter trajectory plot from Copernicus.

Table 6. Estimate of maximum ΔV from Planetary Flyby.*

Planet	Earth Masses	Aphelion before assist (AU)		
		10	30	100
Jupiter	318	22.5	27.6	29.0
Saturn	95	11.4	19.3	20.8
Uranus	15	N/A	11.9	14.0
Neptune	17	N/A	N/A	12.7

*** NOTE: A portion of the ΔV goes into turning the trajectory.**

◆ Multiple gravity assist trajectories:

- ◆ Based on planetary alignment at time of launch, only multi-body gravity assist available with gas giants.
- ◆ Probable Jupiter-Saturn opportunity in mid 2030's, but date is out of scope of this analysis.

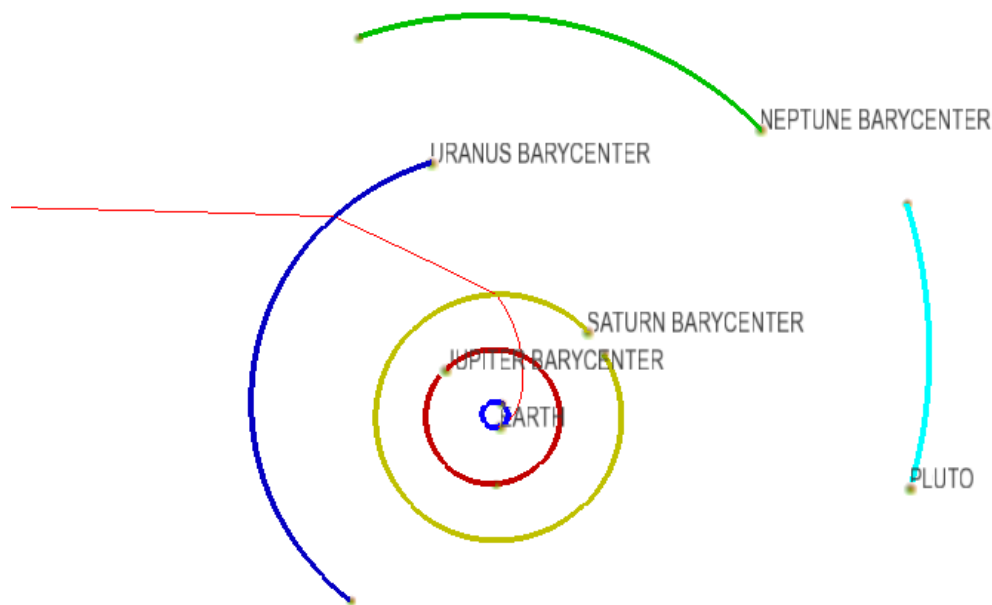
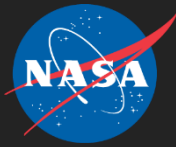


Figure 19. Saturn-Uranus trajectory plot from Copernicus.



The Sails We Need



- ◆ Size: 75,000 m² to 250,000 m²
- ◆ Aerial density: ~ 1 gram/m²
- ◆ Can survive close solar deployment (0.1 – 0.25 AU)



The Sails We Have



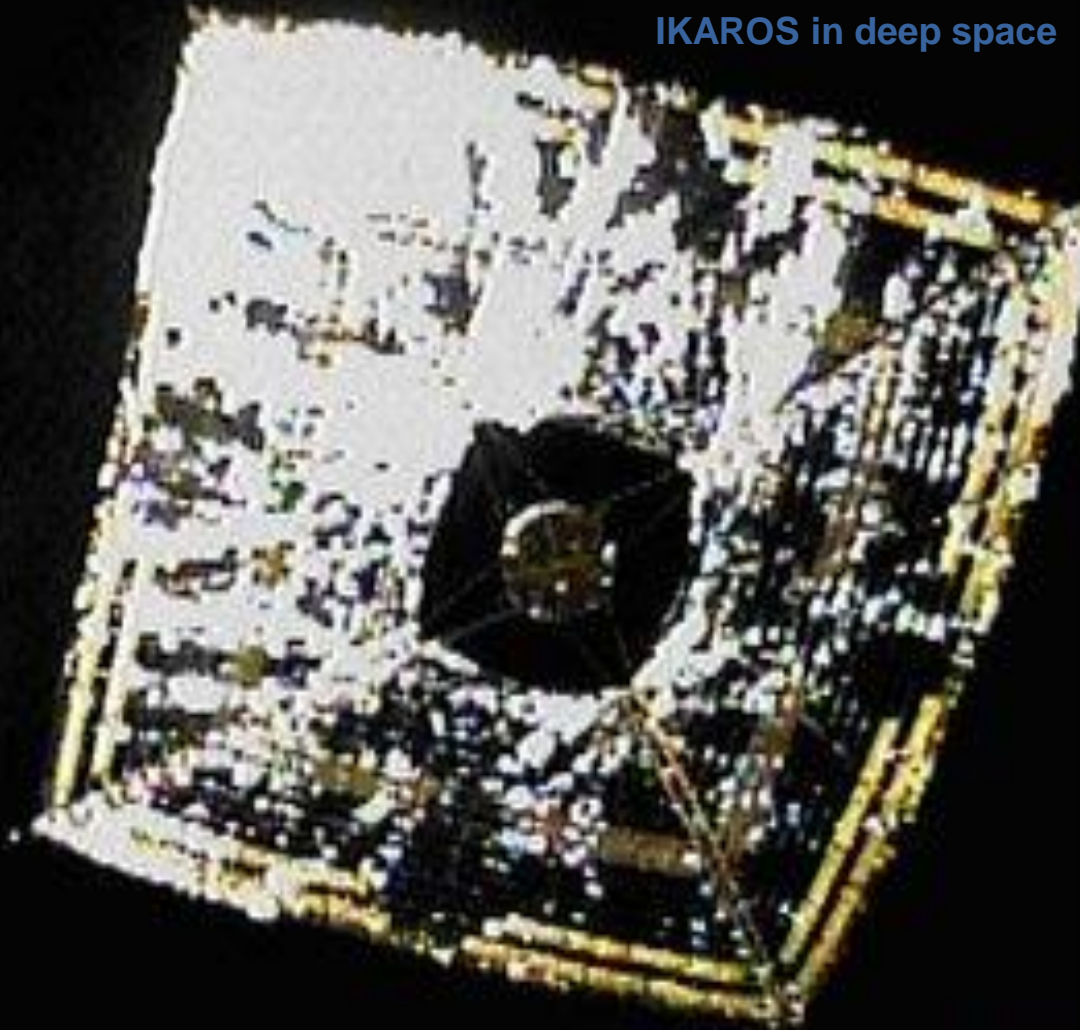
NanoSail-D as seen from the ground

Nanosail-D2 in Orbit August 19 2011 01h 19m 28s UT
Clay Center Observatory at Dexter and Southfield Schools
42.307404N, -71.13722W (WGS84)
www.claycenter.org Focal length: 12,200mm,
Aperture = 640mm Ritchey-Chretien
Contact: Ron Dantowitz (rondantowitz@gmail.com)



- ◆ Size: 100 m² to 200 m²
- ◆ Aerial density: 25 – 300 gram/m²
- ◆ Can survive 0.5 AU deployment

IKAROS in deep space

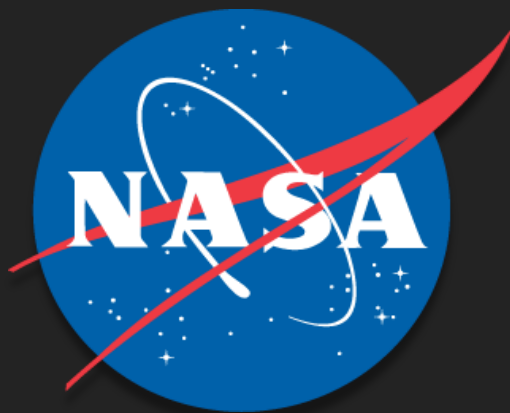




Electric Sail: Technical Justification



- ◆ Has the potential to fly payloads out of the ecliptic and into non-Keplerian orbits, place payloads in a retrograde solar orbit, flyby missions to terrestrial planets and asteroids and position instruments for off-Lagrange point space weather observation.
- ◆ Low mass / low cost propulsion system.
- ◆ Electric sail thrust extends deep into the solar system.
- ◆ Can be packaged in a small spacecraft bus.
- ◆ E-Sail = MSFC interplanetary CubeSat propulsion portfolio
 - ◆ Iodine drive, solar sails, green propellants



Ben Beers

NASA MSFC / Geocent LLC.

benjamin.r.beers@nasa.gov

(256) 544-7628