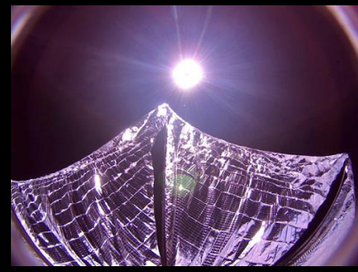
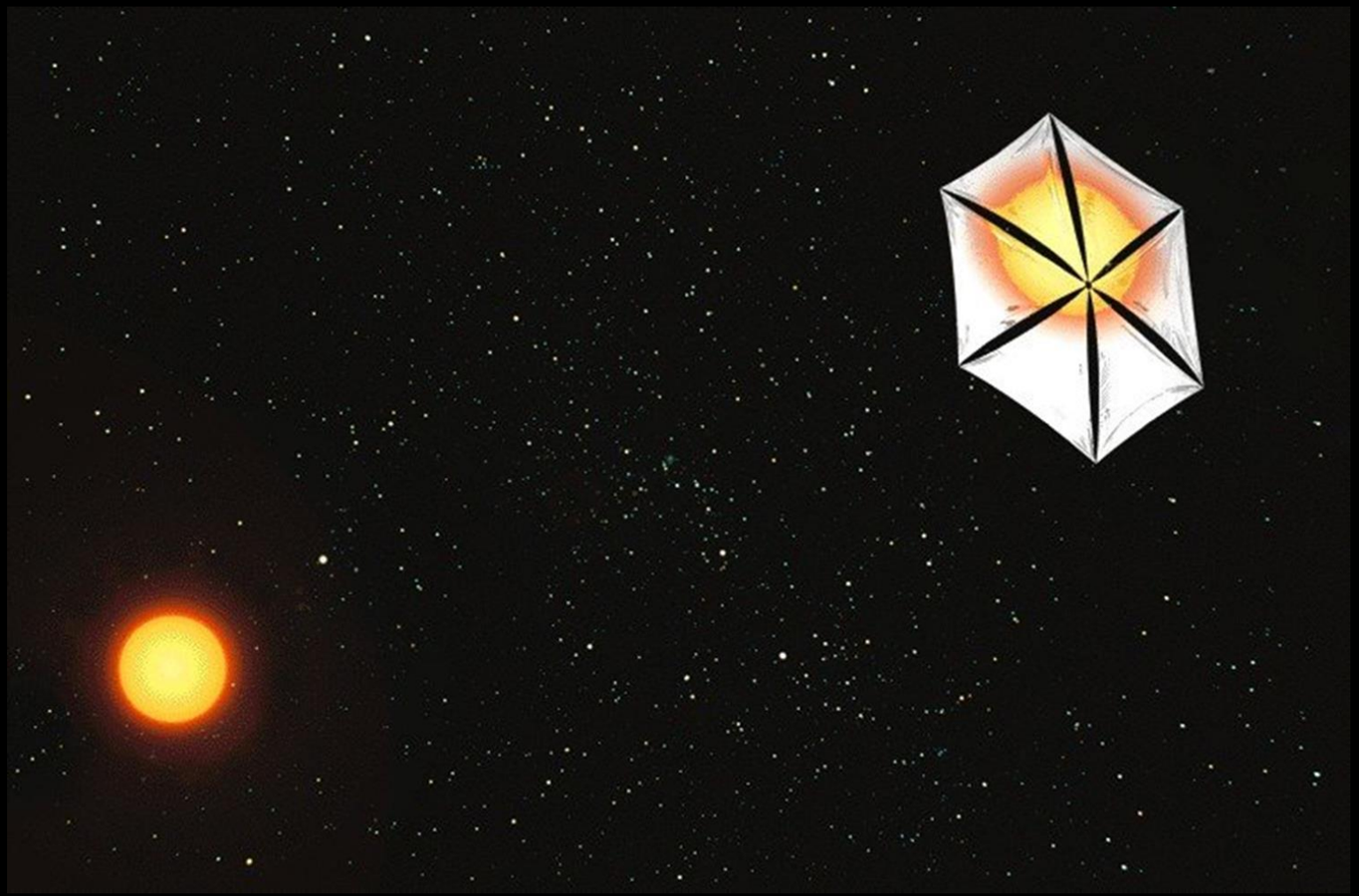
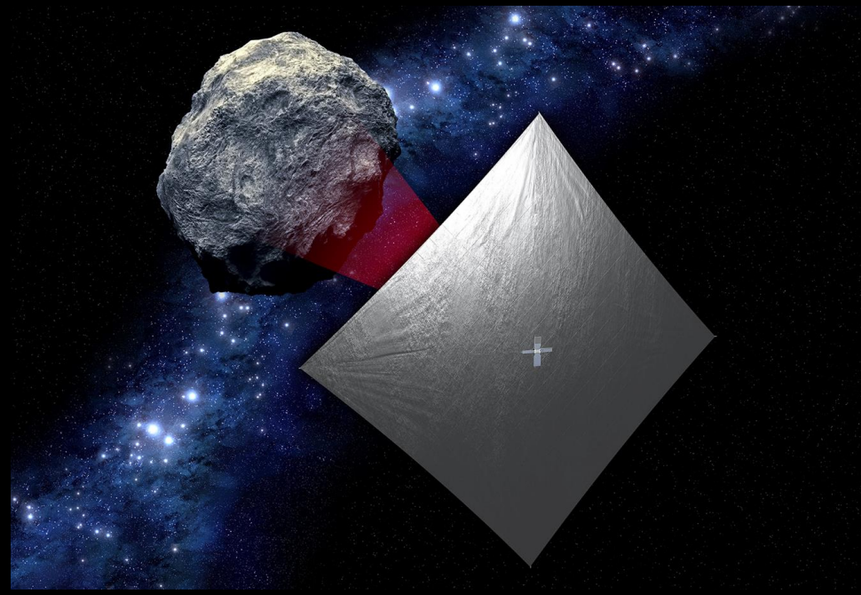
Solar Sail Propulsion
Status and Mission Applications







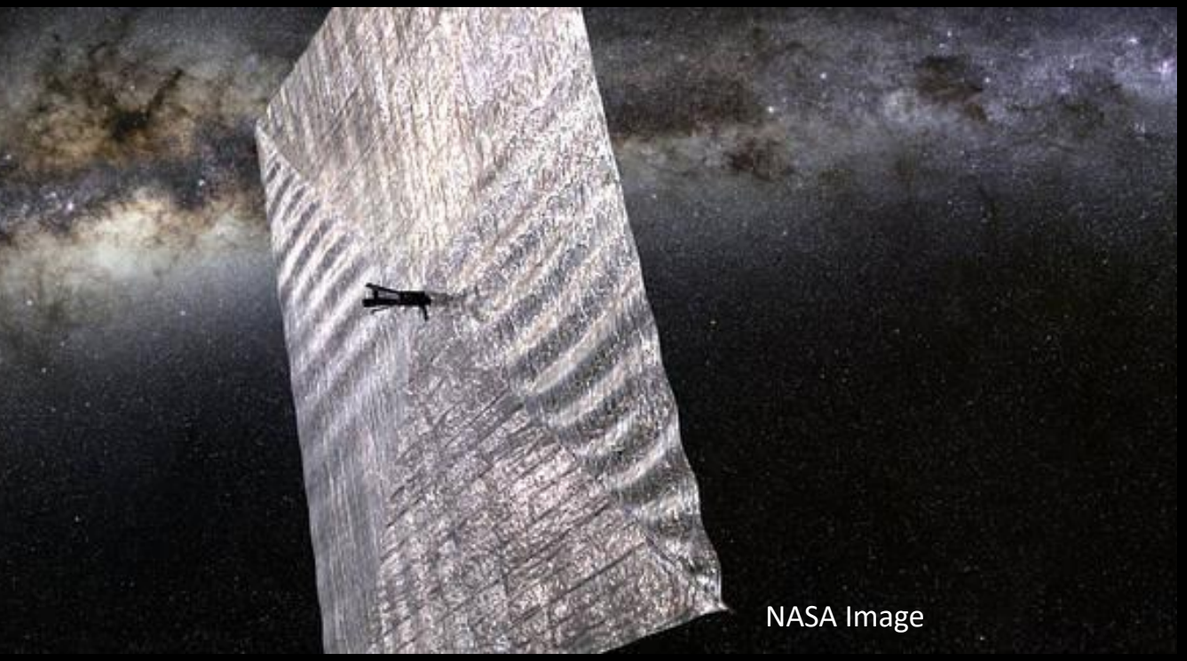
Les Johnson

NASA George C. Marshall Space Flight Center

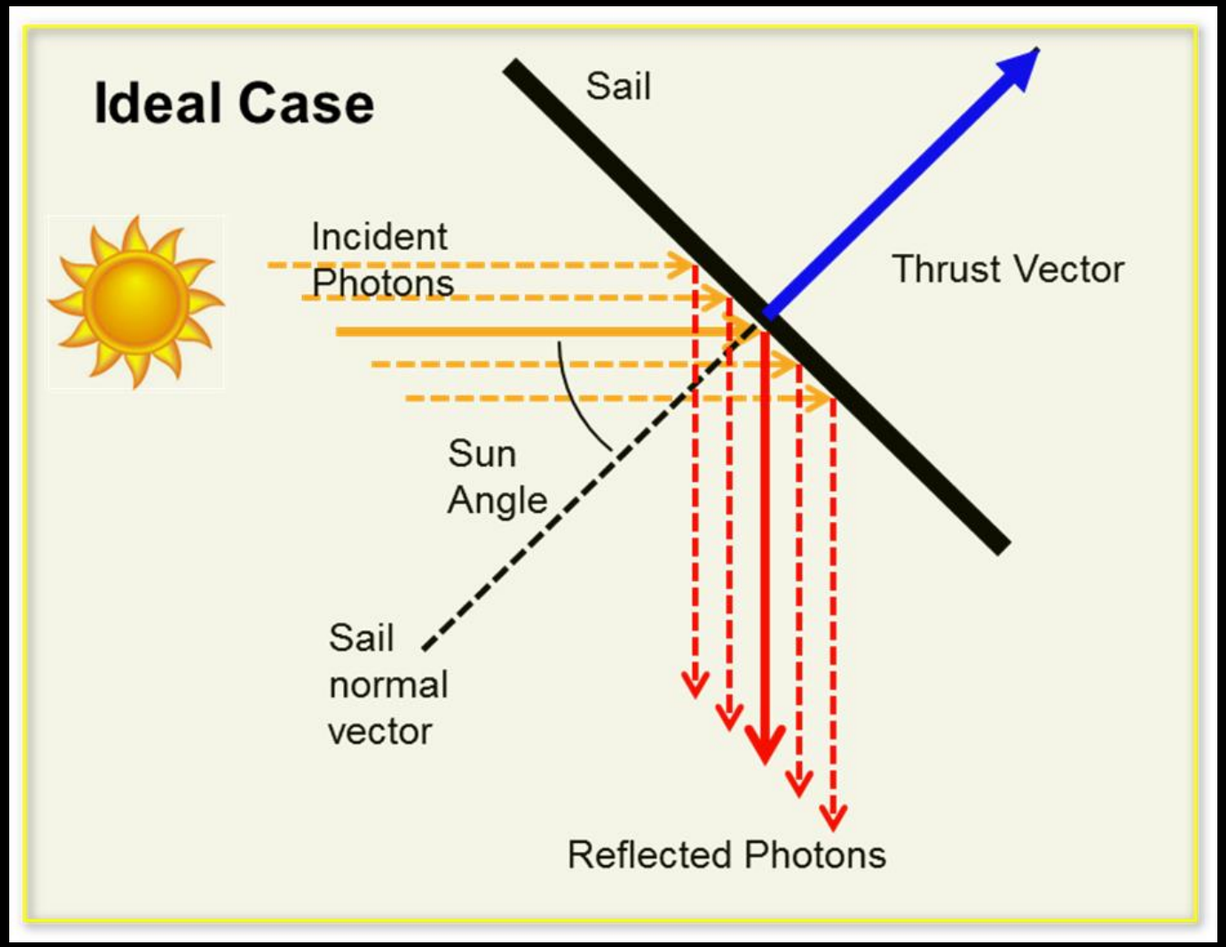
les.johnson@nasa.gov

Solar Sails Derive Propulsion By Reflecting Photons

Solar sails use photon “pressure” or force on thin, lightweight, reflective sheets to produce thrust.

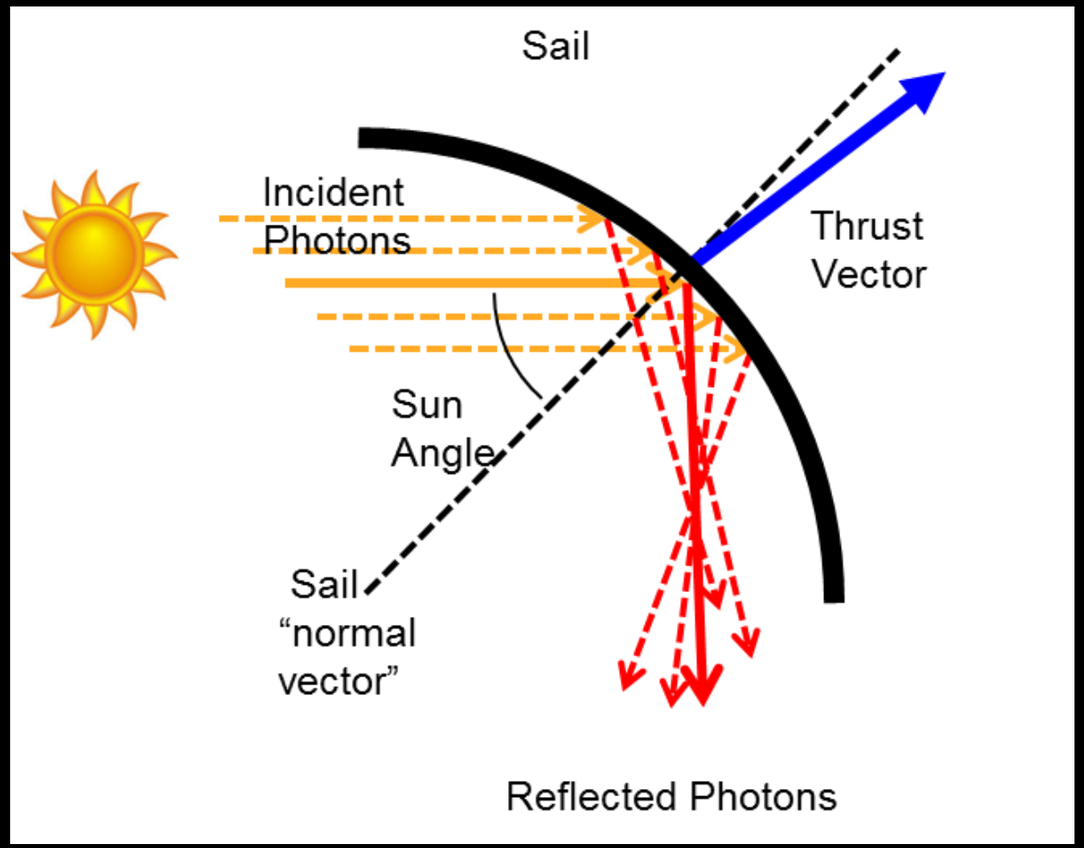


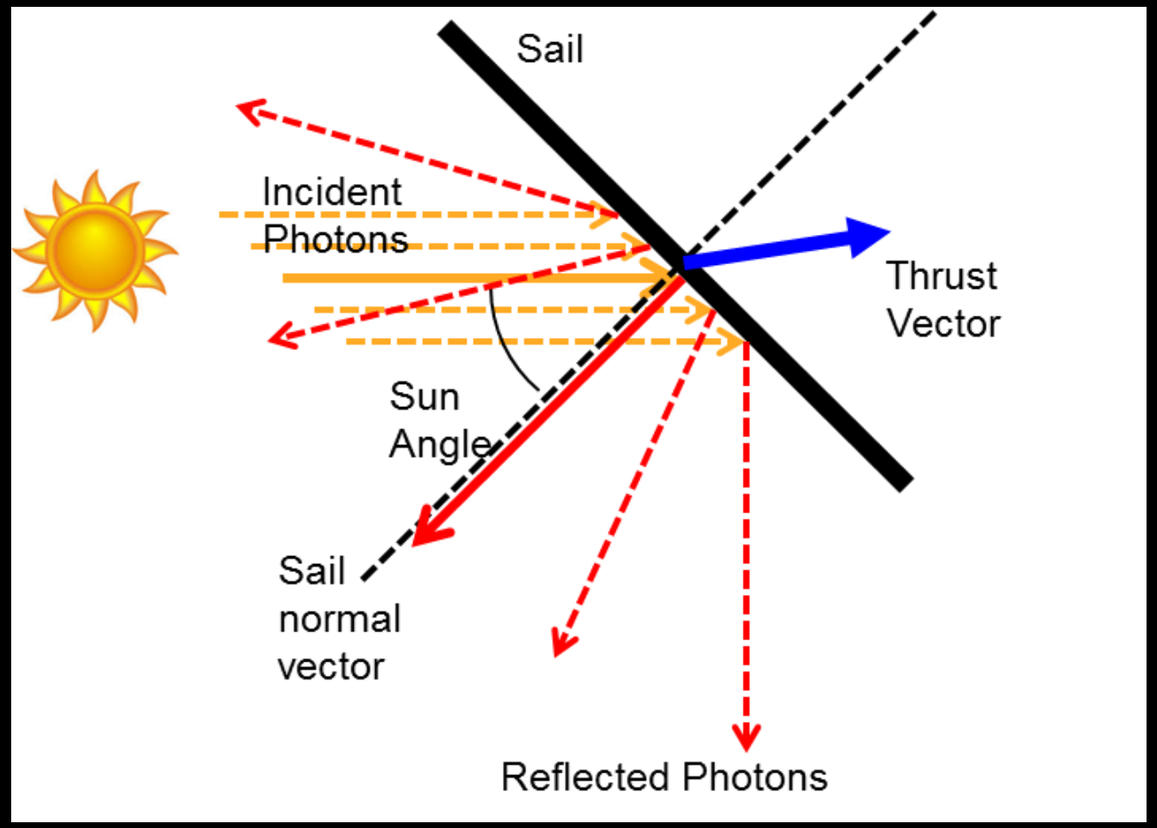
NASA Image



Real Solar Sails Are Not “Ideal”

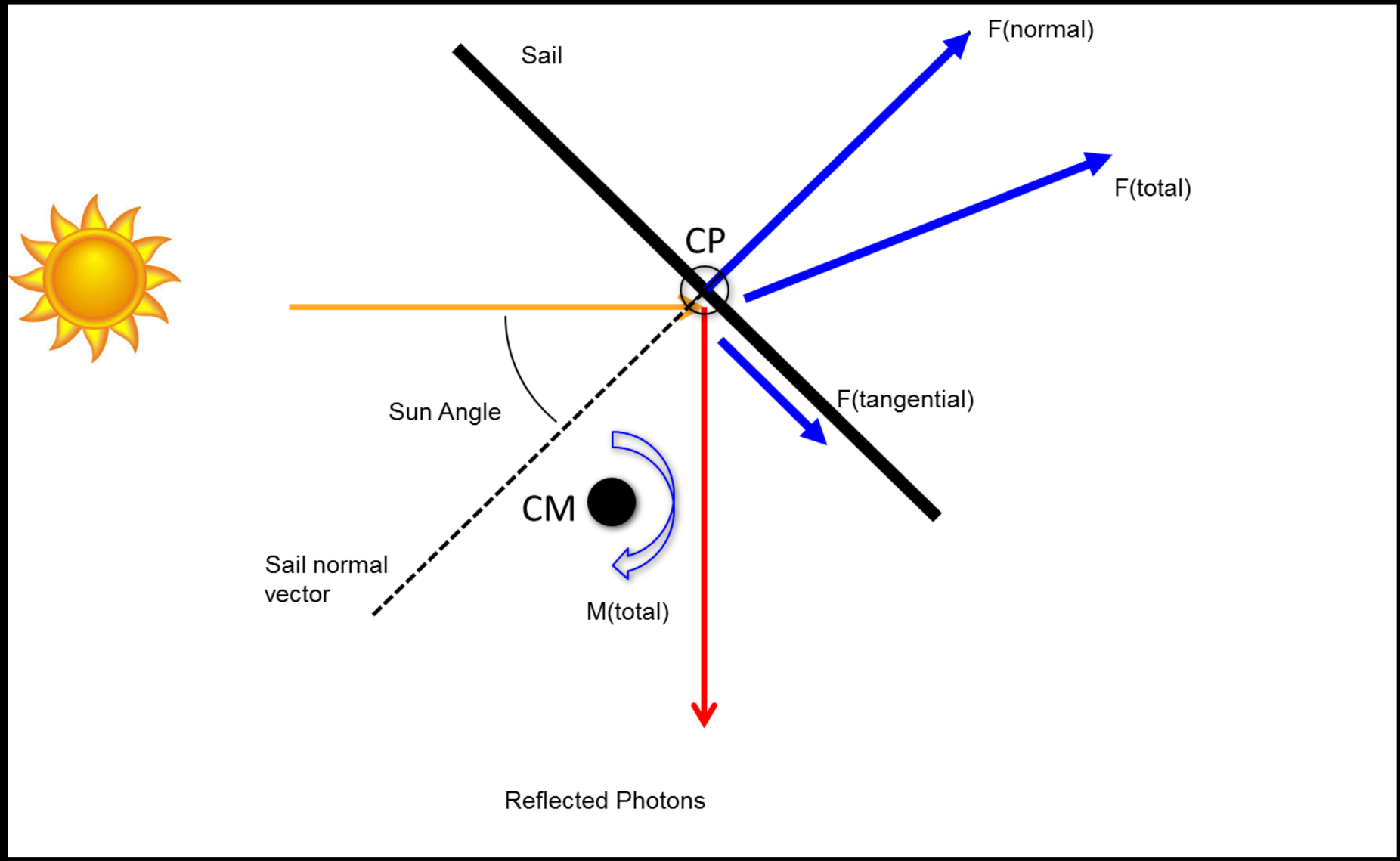
Billowed Quadrant



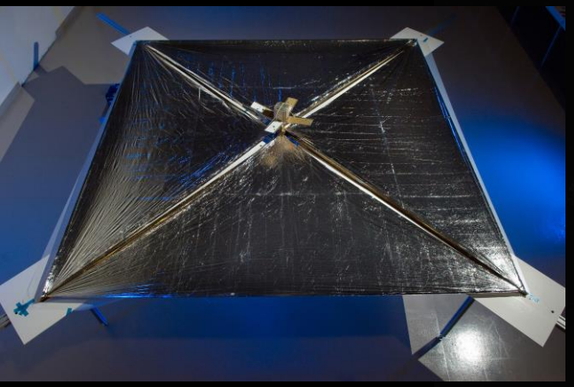


Diffuse Reflection

Thrust Vector Components



Solar Sail Missions Flown (as of May 2018)



NanoSail-D (2010)
NASA

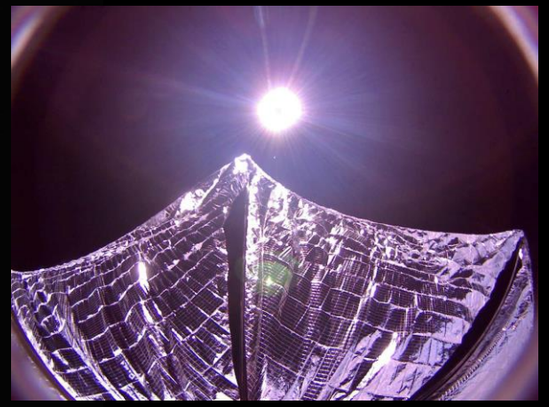
Earth Orbit
Deployment Only

3U CubeSat
10 m^2

IKAROS (2010)
JAXA

Interplanetary
Full Flight

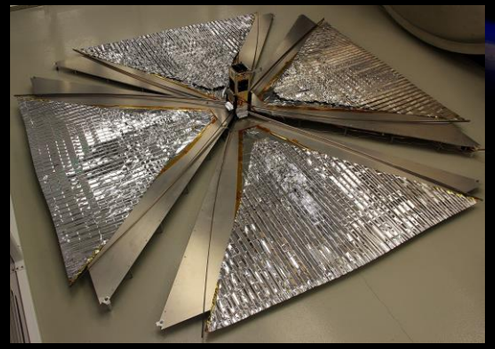
315 kg Smallsat
196 m^2



LightSail-1 (2015)
The Planetary Society

Earth Orbit
Deployment Only

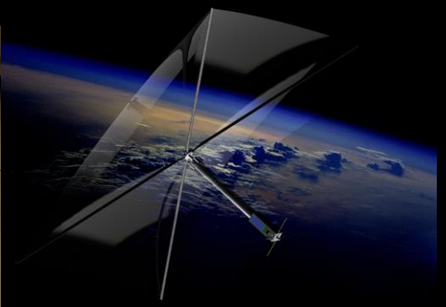
3U CubeSat
32 m^2



CanX-7 (2016)
Canada

Earth Orbit
Deployment Only

3U CubeSat
<10 m^2

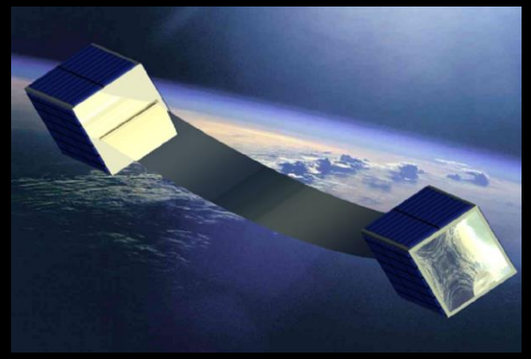


InflateSail (2017)
EU/Univ. of Surrey

Earth Orbit
Deployment Only

3U CubeSat
10 m^2

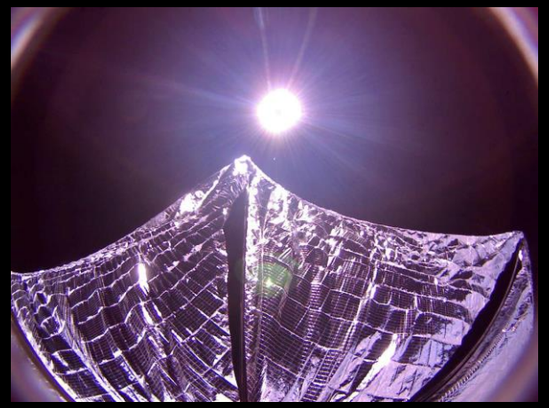
Planned Solar Sail Missions (as of April 11, 2018)



CU Aerospace (2018)
Univ. Illinois / NASA

Earth Orbit
Full Flight

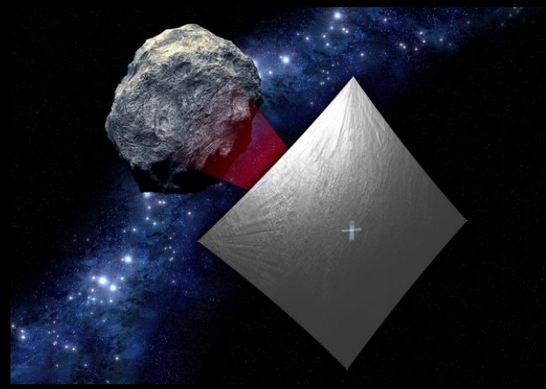
3U CubeSat
20 m^2



LightSail-2 (2018)
The Planetary Society

Earth Orbit
Full Flight

3U CubeSat
32 m^2



Near Earth Asteroid Scout (2020) NASA

Interplanetary
Full Flight

6U CubeSat
86 m^2

NASA's Near Earth Asteroid Scout

The Near Earth Asteroid Scout Will:

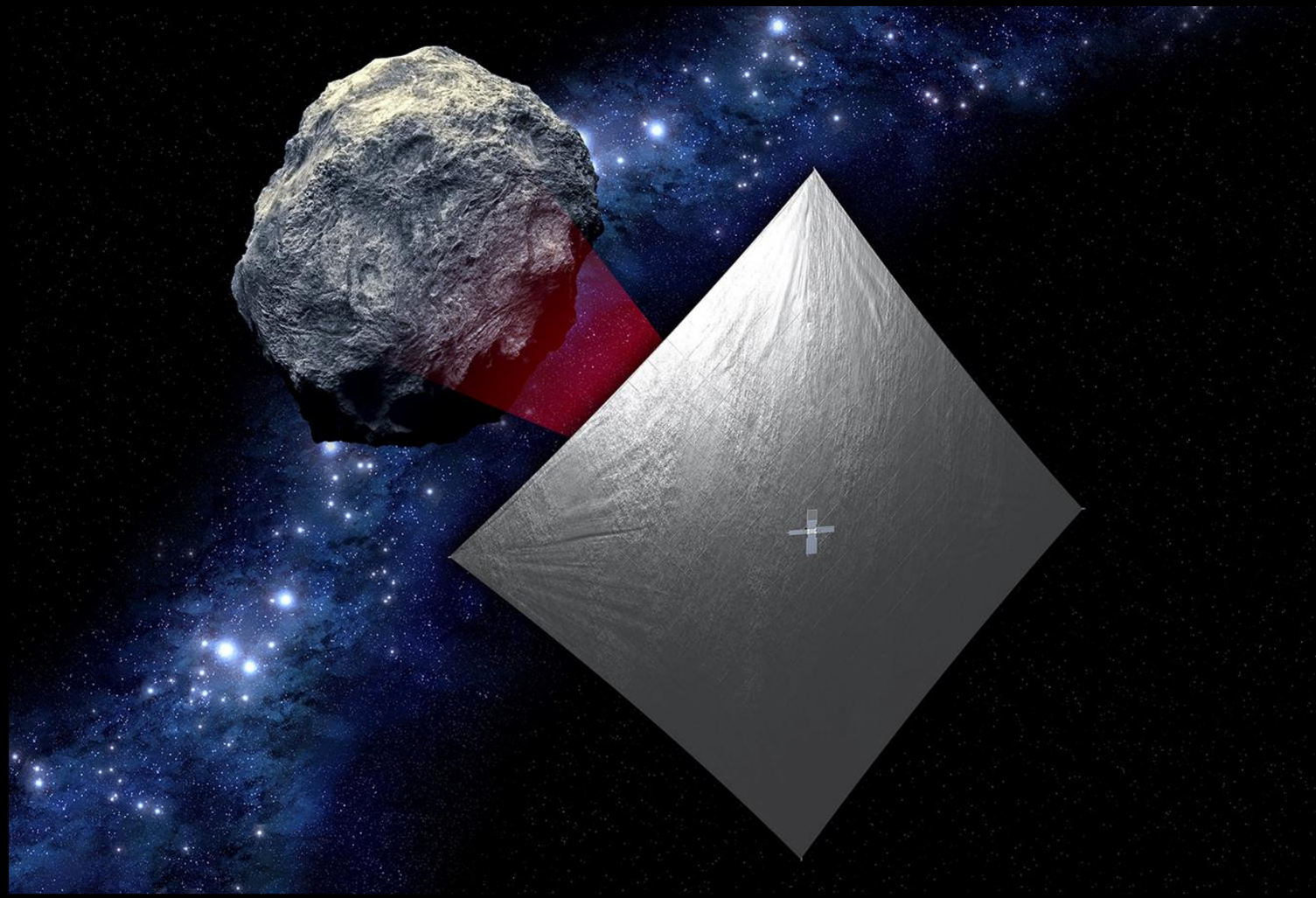
- Image/characterize a NEA during a slow flyby
- Demonstrate a low cost asteroid reconnaissance capability

Key Spacecraft & Mission Parameters

- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~86 m^2 solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2019)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

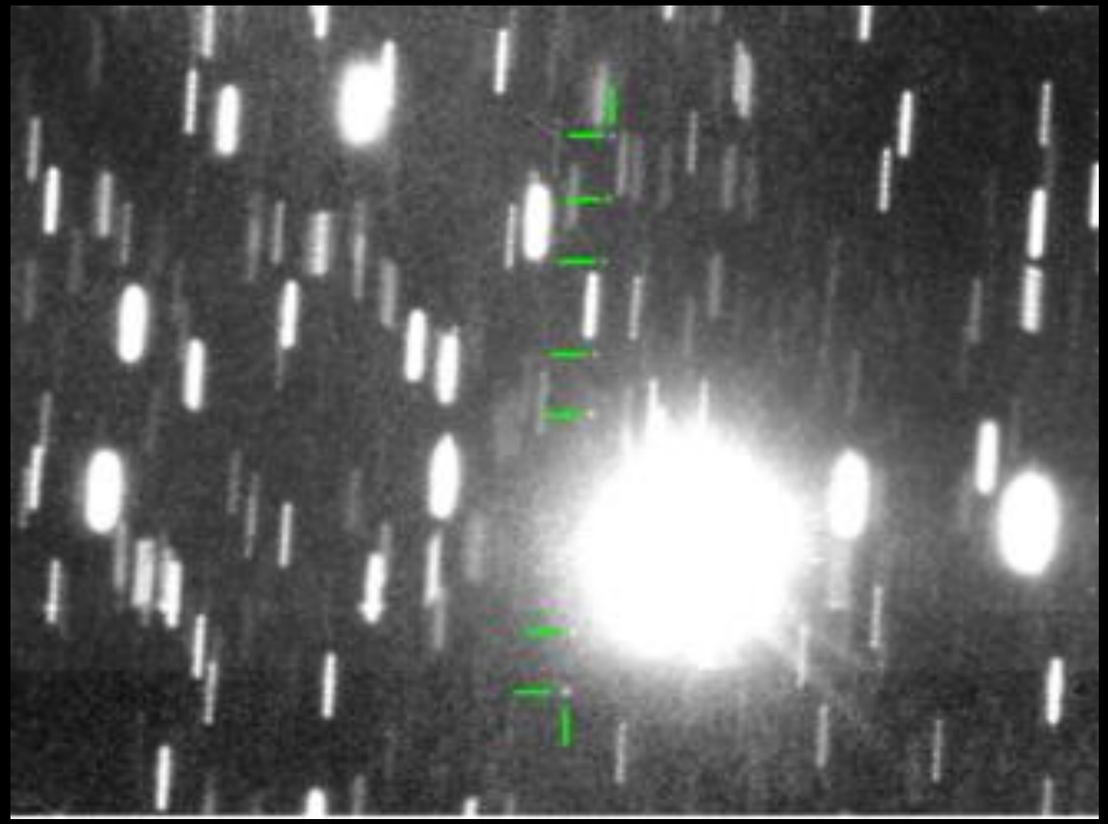
Solar Sail Propulsion System Characteristics

- ~ 7.3 m Trac booms
- 2.5μ aluminized CP-1 substrate
- > 90% reflectivity



NASA Image

Baseline Target Asteroid: 1991 VG

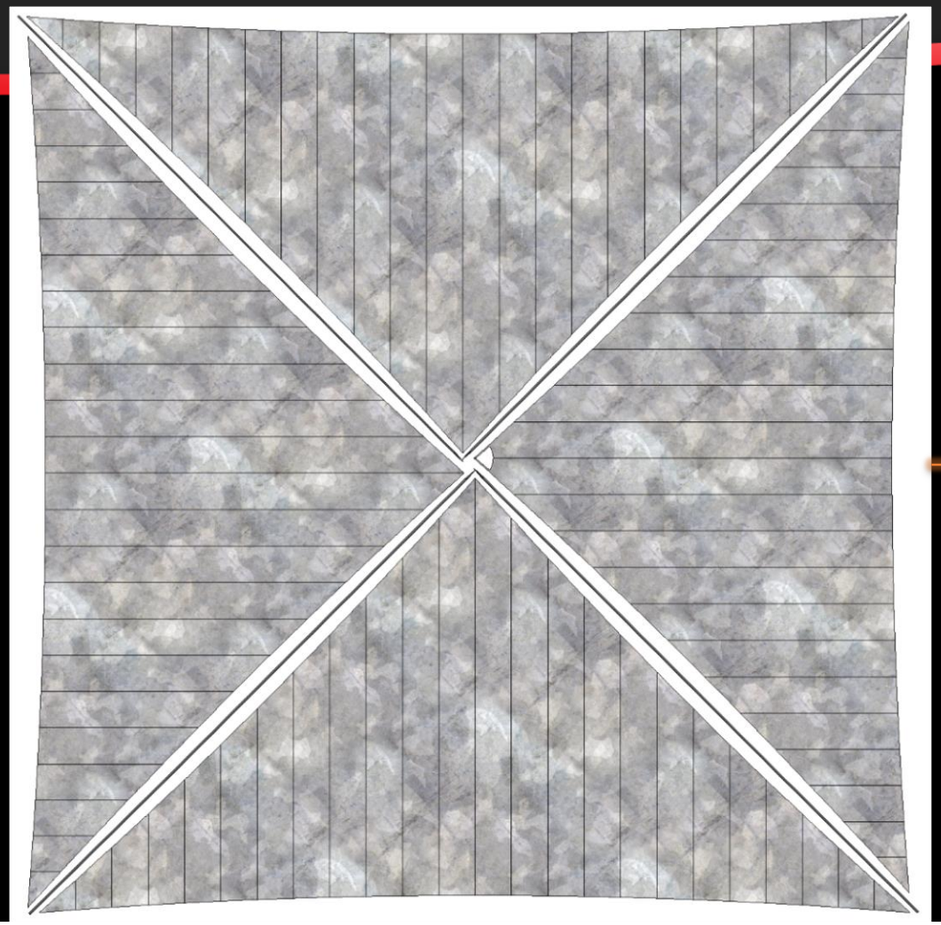


Near-Earth Asteroid 1991VG (marked with green lines) on 2017 May 30. This is a composite of several images obtained with the ESO VLT. The images have been combined in 7 stacks tracking the position of the asteroid, resulting in the object appearing as 7 dots as it moves in front of the background stars. The stars appear trailed due to the motion of the asteroid during each series. Credit Hainaut/Micheli/Koschny

- Diameter ~ 5 -12 meters
- Rotation period between a few minutes and less than 1 hour
- Unlikely to have a companion
- Unlikely to retain an exosphere or dust cloud
  - Solar radiation pressure sweeps dust on timescales of hours or day

NEA Scout Approximate Scale

Deployed Solar Sail



School Bus

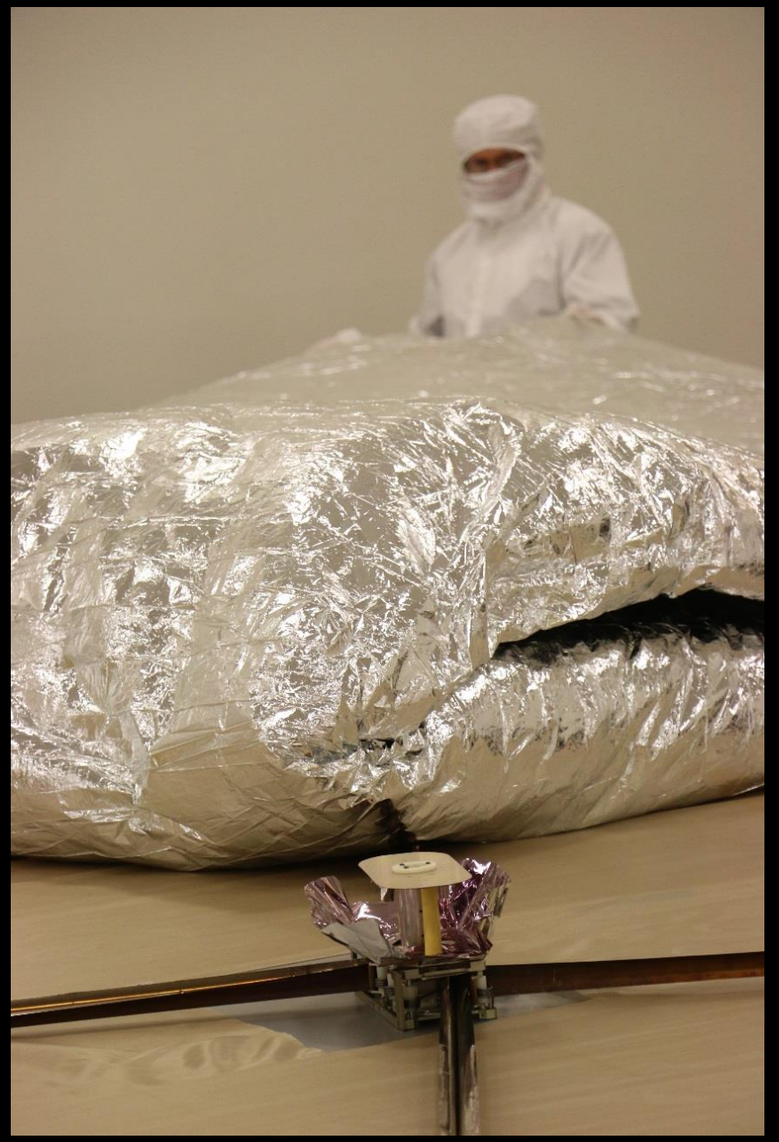
6U Stowed Flight System

Folded, spooled and packaged in here

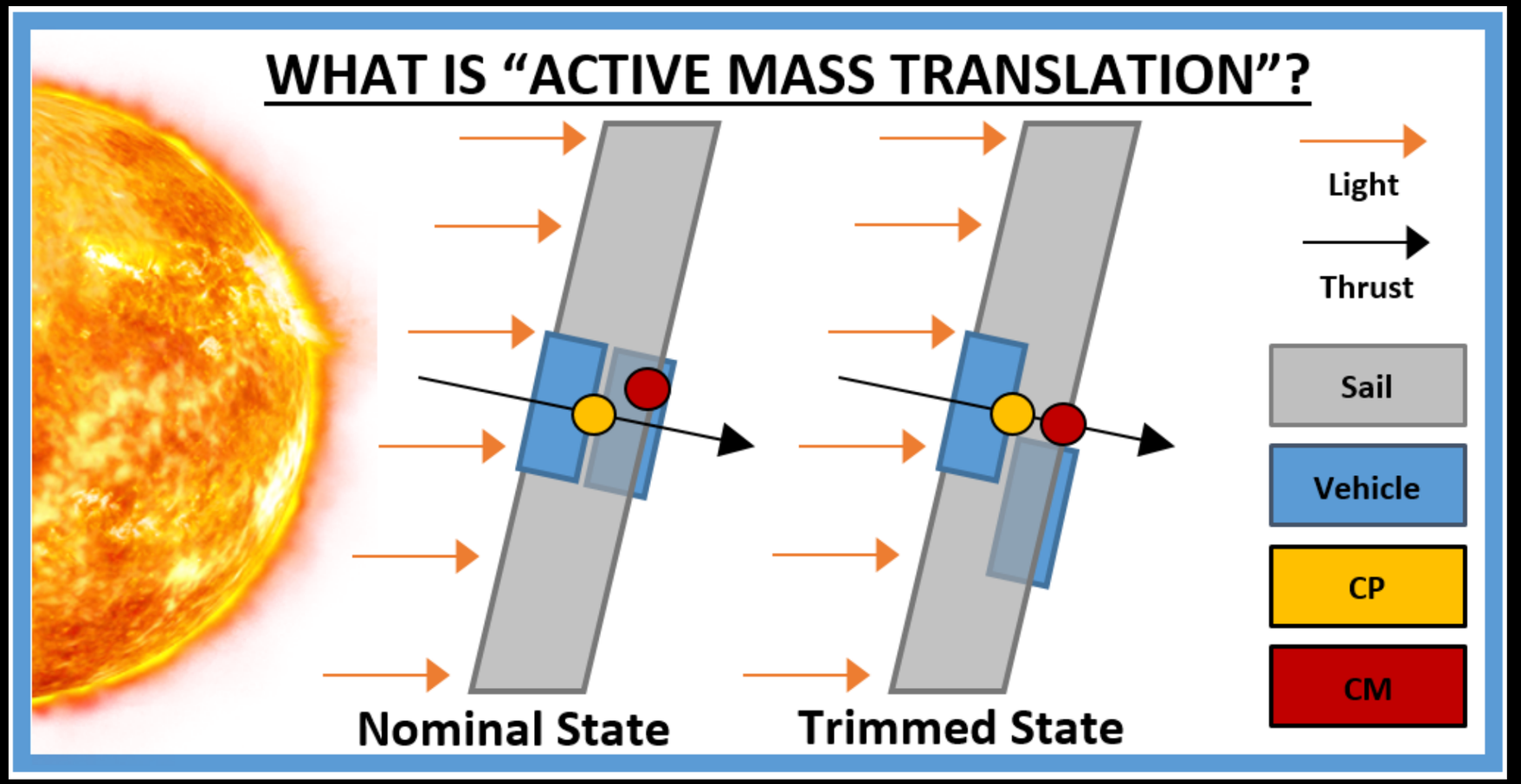
NASA's Near Earth Asteroid Scout Full Scale Successful Deployment

NASA Image

NASA's Near Earth Asteroid Scout Hardware



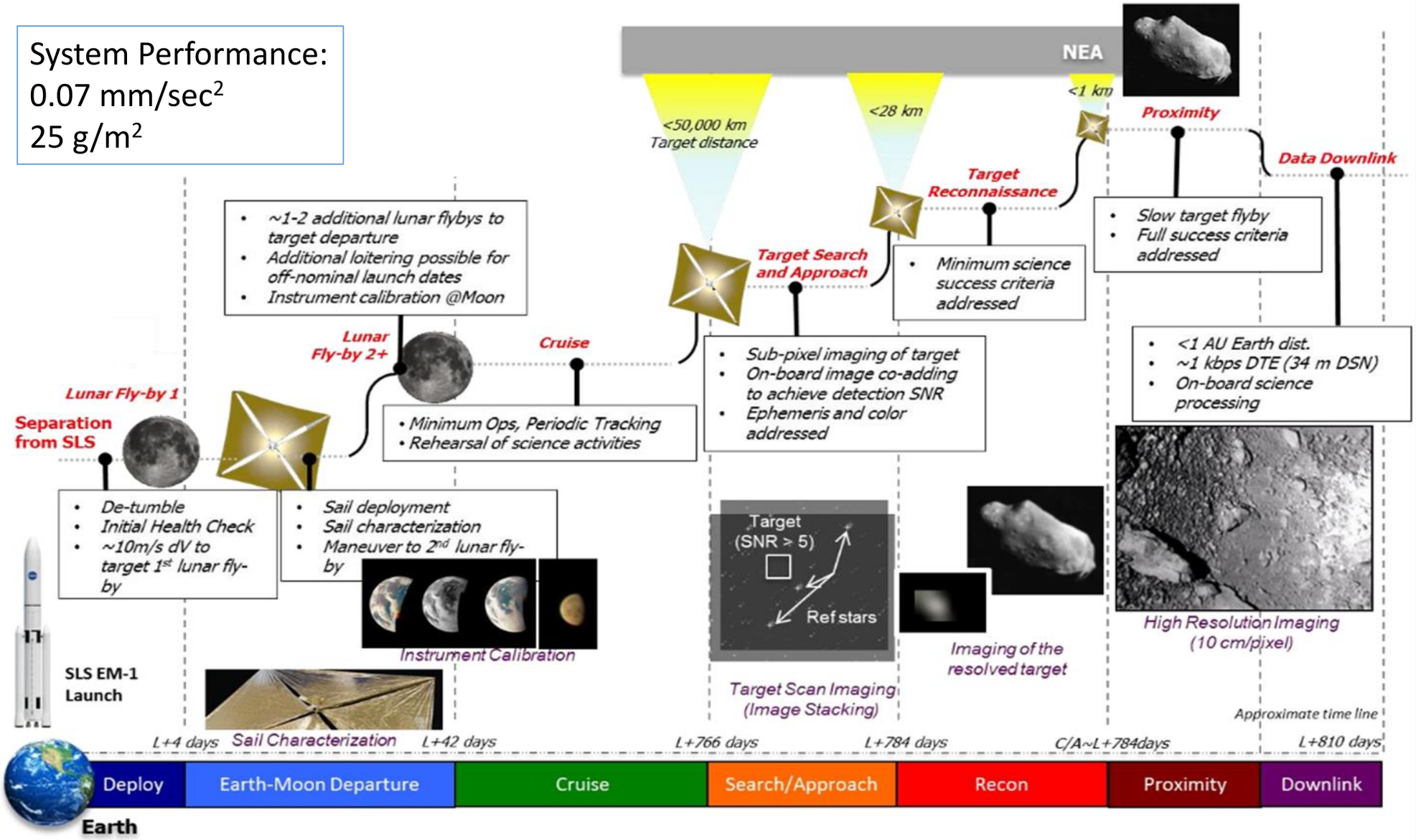
The Need for CM/CP Adjustment



The AMT will move one portion of the NEA Scout relative to the other. This translation of mass will alter the inertial properties of the vehicle and align the CP and CM

NEA Scout – Mission Overview

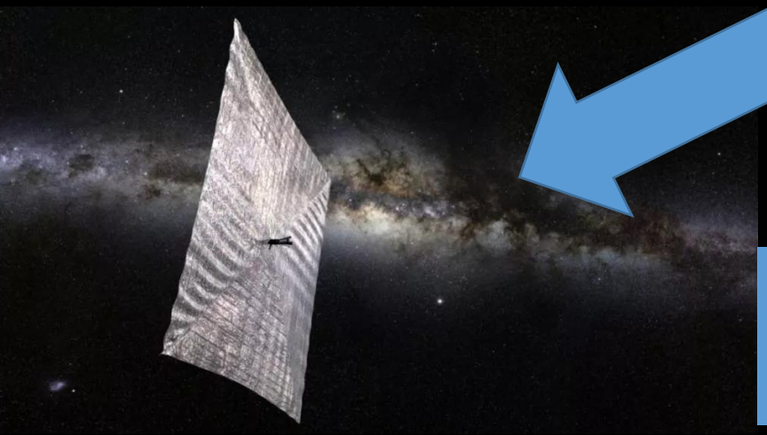
System Performance:
0.07 mm/sec^2
25 g/m^2



SMD AO: SALMON-3 Heliophysics Tech Demo

THIRD STAND ALONE MISSIONS OF OPPORTUNITY NOTICE (SALMON-3)
NNH17ZDA004O-HPTDMO
PROGRAM ELEMENT APPENDIX (PEA) L
2018 HELIOPHYSICS TECHNOLOGY DEMONSTRATION MISSION OF OPPORTUNITY

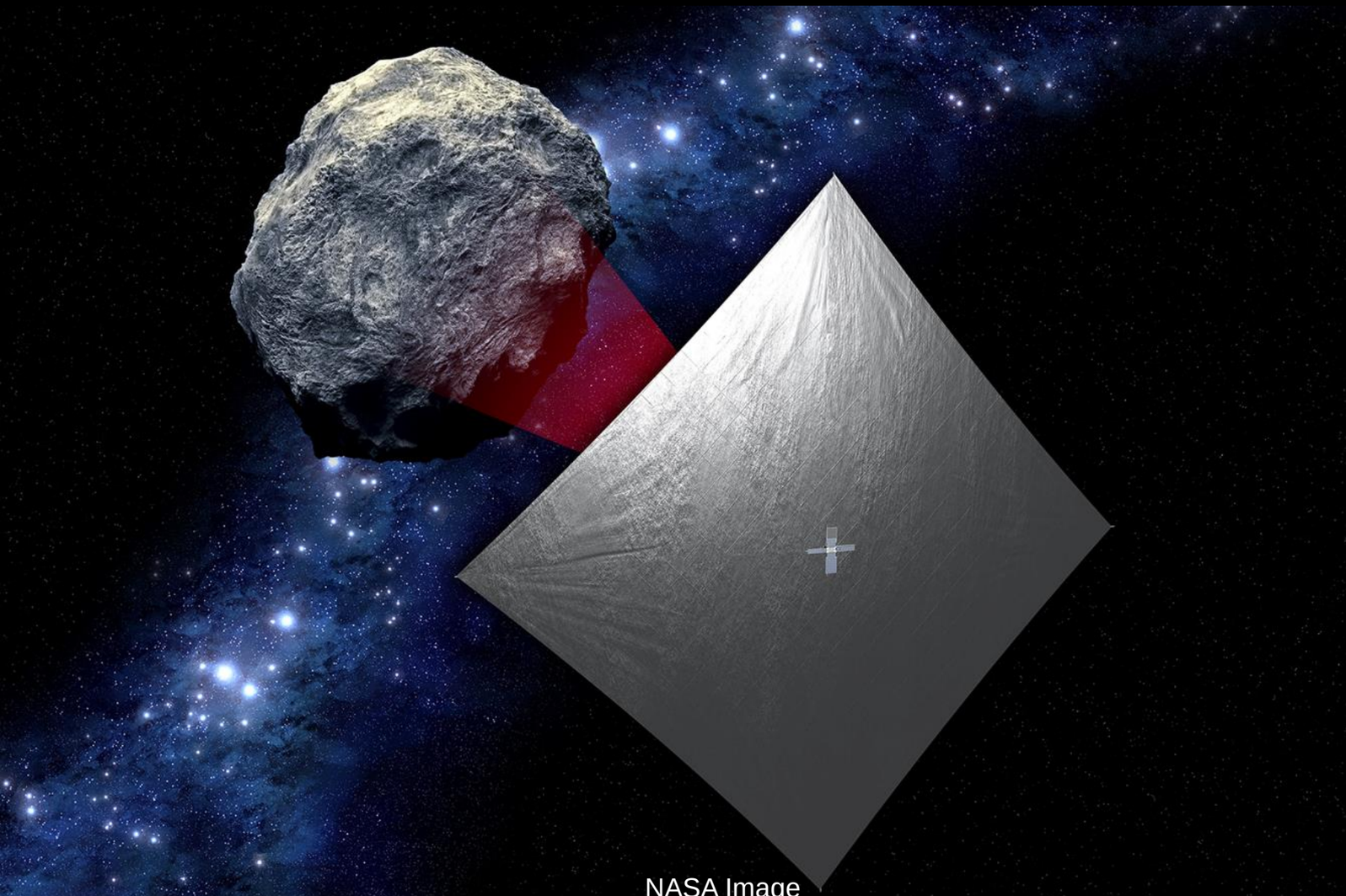
NOTICE: Amended August 28, 2018. This amendment makes the following changes to this PEA: in Section 9 it is noted that the dates for Notification Proposal, Final PEA Full Proposal Due (NSPIRES), and Final PEA Full Proposal Due (CD ROMs) have been changed. New text is in bold and deleted text is struck through.



- SMD release of the SALMON-3 AO
  - Release of Final SALMON-3 PEA: August 6, 2018
  - **Proposals Due: November 30, 2018**
- Mission of Opportunity Parameters
  - Principal Investigator (PI) managed mission cost cap for all mission phases is $65M
  - No more than 3 Tech Demos will be selected for a 9 month, $400K (FY19) Phase A concept study (streamlined Class D)
  - 1 Tech Demo will be selected to continue to Phase B and subsequent mission phases
- The AO solicits Small Complete Mission (SCM) proposals for space flight demonstrations of innovative medium TRL enabling technologies to address Heliophysics Scientific Objectives and Goals in a 15 year timeframe
- Proposal merit determined by magnitude of potentially enabling impacts on future Heliophysics science return in operational missions

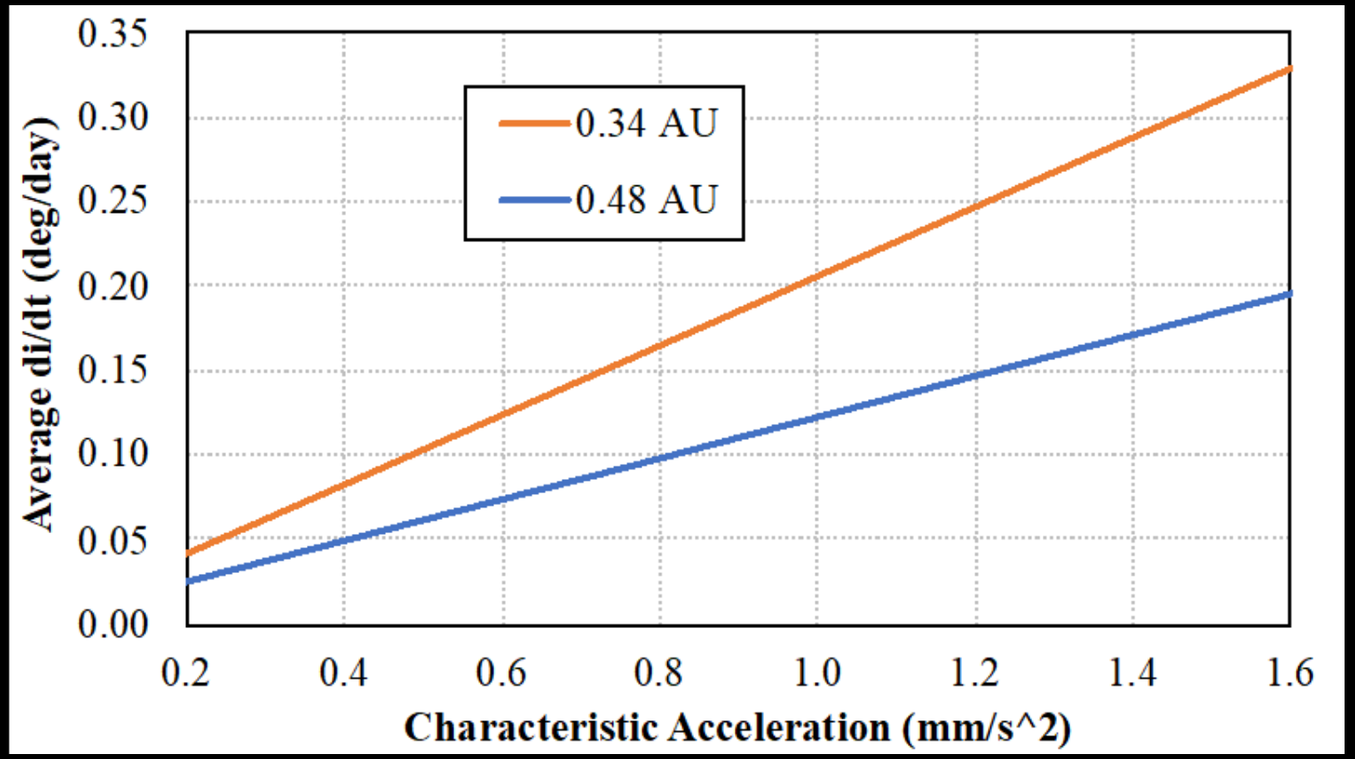
Likely 2-3 solar sail propulsion demonstration proposals of > 0.15 - .020 mm/s^2

Solar Sail Propulsion
Mission Applications



NASA Image

High Inclination Solar Imaging Mission Analysis



In the near-future, sails with Characteristic Accelerations >0.2 – 0.4 mm/s^2 will be feasible.

0.025 deg/day = 9 deg/year
0.05 deg/day = 18 deg/year

Time to Solar Polar Orbit =

0.025 deg/day = ~10 years
0.05 deg/day = ~5 years

High Inclination Solar Imaging with Solar Electric Propulsion

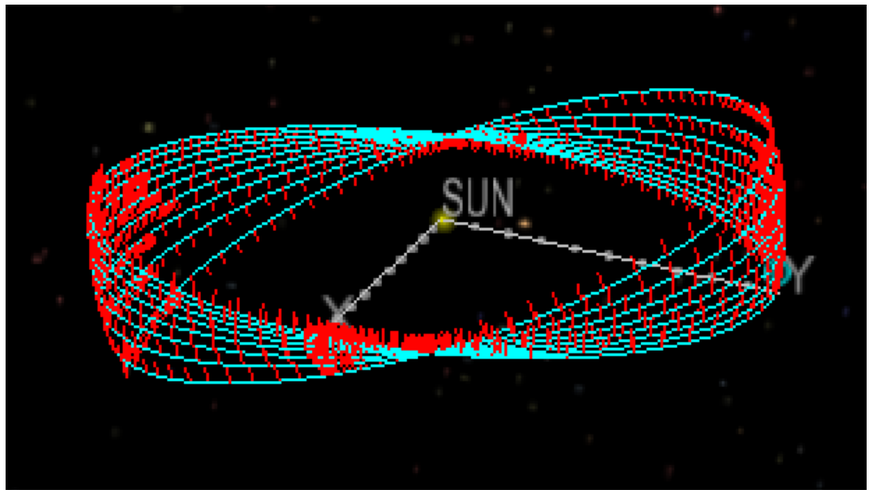
Begin at 1 AU, C3 of 0, and perform the maximum plane change.

Configuration	Power	Isp	Efficiency (nominal)	BB	DD	Thrust 1AU	Duty Cycle	r_inc	m0	m_inert	mf	inc final	A0	ideal DV
	(W)	(sec)				(N)	(%)	(AU)	(kg)	(kg)	(kg)	(deg)	mm/s/s	(km/s)
H200	200	1375	0.458	0.7	-1000	0.014	100%	1	322	153	153	12.4	0.043	10.03
H600	600	1500	0.485	0.7	-1000	0.041	100%	1	322	164	164	12.5	0.127	9.92
H1500	1500	1895	0.548	0.7	-1000	0.0914	100%	1	322	188	188	13	0.284	10.00

Assumes ESPA Heavy 322 kg mass limited spacecraft

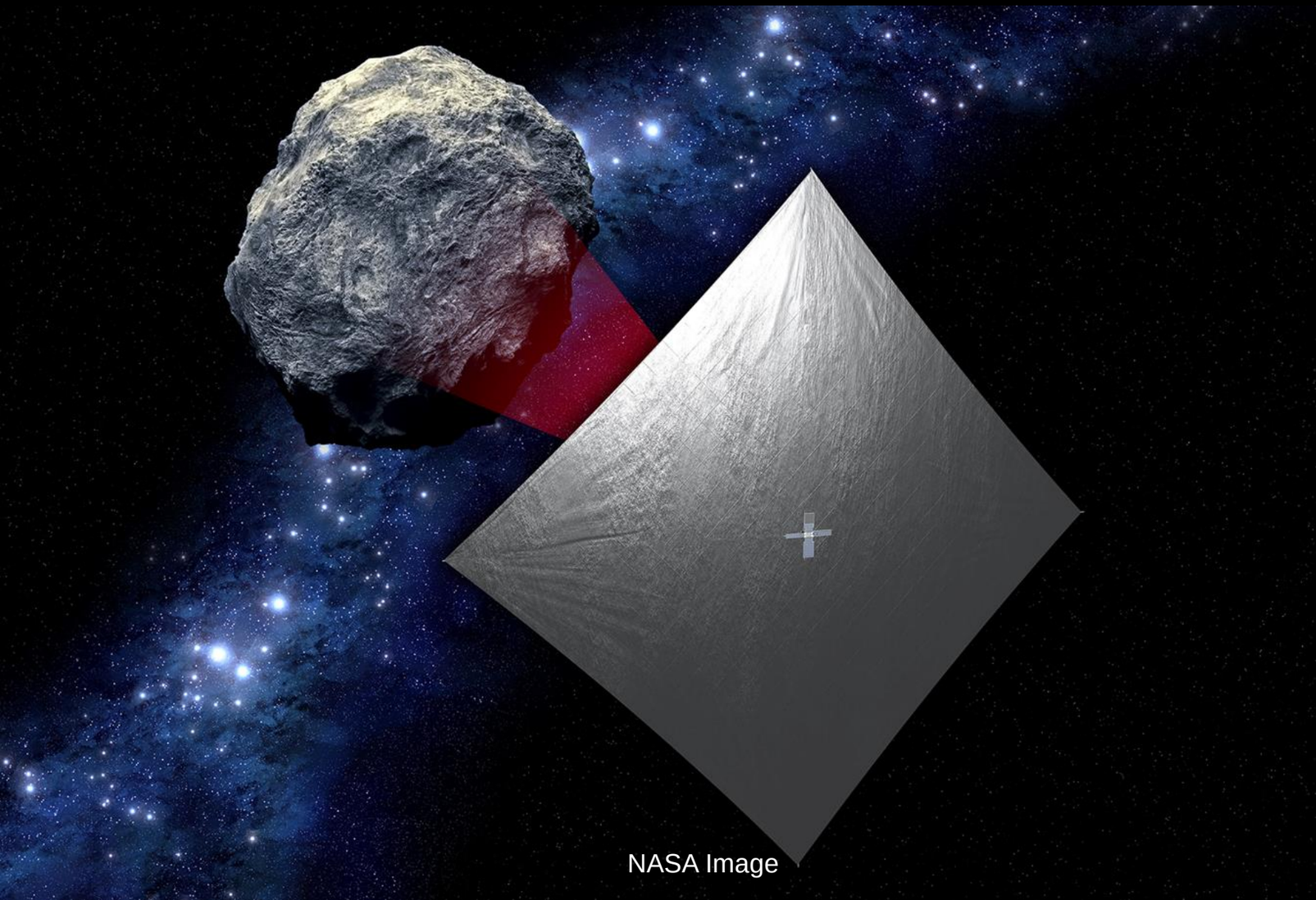
No propulsive benefit from starting sunward of 1 AU - plane change begins at 1 AU distance.

Maneuver continues until all propellant is expended.



For the configuration analyzed, the maximum inclination reached is around 13 degrees

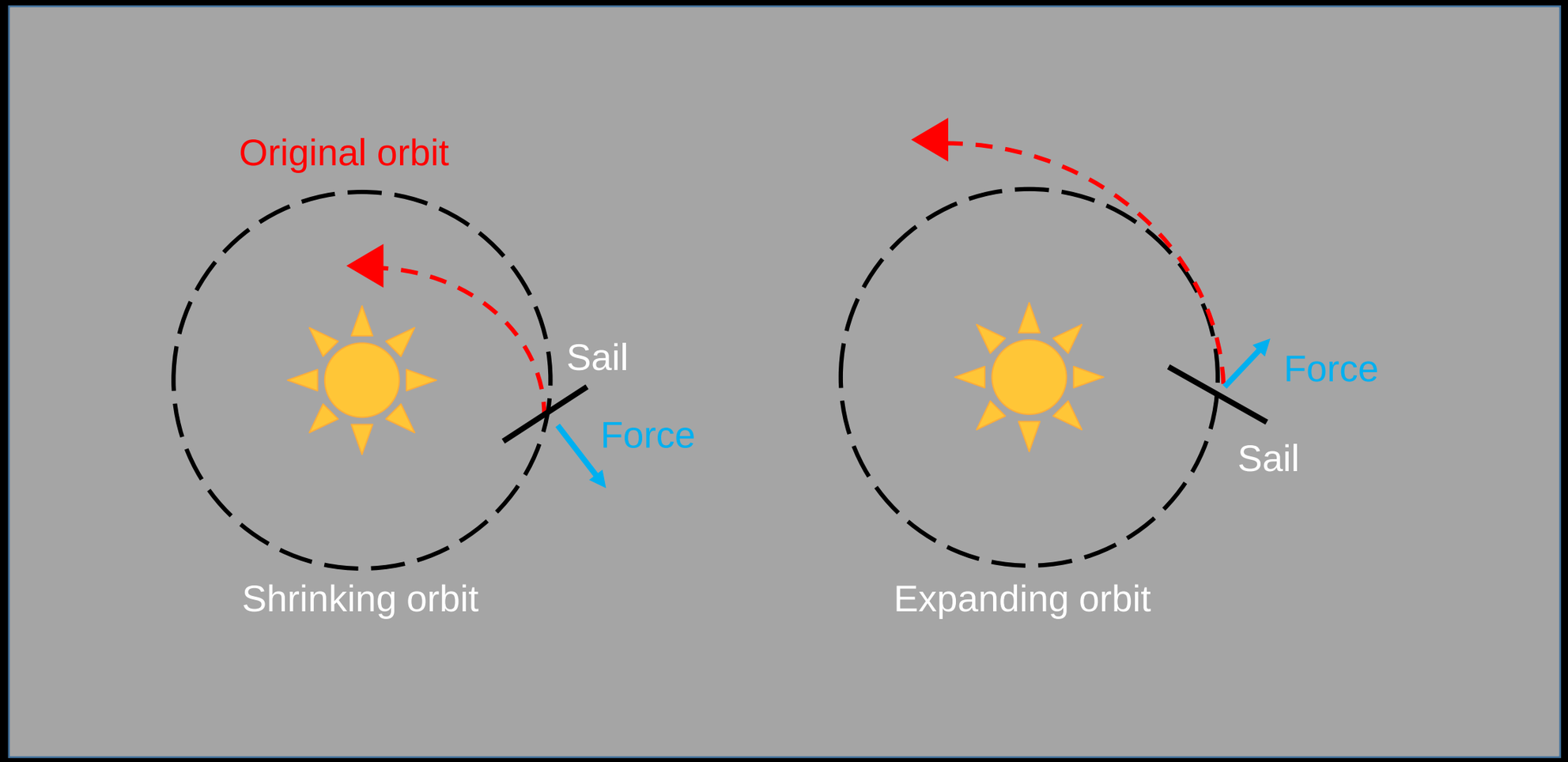
Solar Sail Propulsion
Backup Charts



NASA Image

Solar Sail Trajectory Control

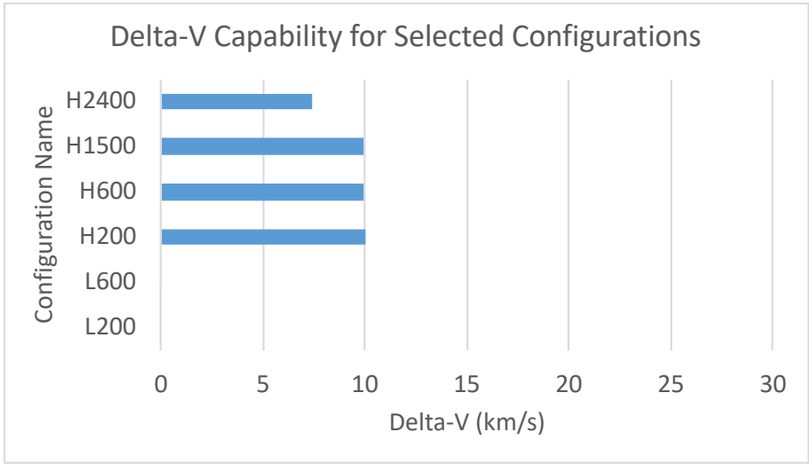
- Solar Radiation Pressure allows inward or outward Spiral



SEP MEL and Capability

(Detailed MEL in backup section)

Name of Configuration	L200	L600	H200	H600	H1500	H2400	units
Total Mass Allocation	**83.3**	**83.3**	**322**	**322**	**322**	**322**	**kg**
Thruster class	200	600	200	600	1500	1500	W
Base spacecraft + science (no sail)	**56.6**	**56.6**	**56.6**	**56.6**	**56.6**	**56.6**	**kg**
Thruster Type	Hall Effect	Hall Effect	Hall Effect	Hall Effect	Hall Effect	Hall Effect	
Vendor example	Busek BHT-200	Busek BHT-600	Busek BHT-200	Busek BHT-600	Busek BHT-1500	Busek BHT-1500 (@2400W)	name
Isp (nominal)	1375	1500	1375	1500	1895	1735	s
Total Thruster and PPU Mass	**12.62**	**17.23**	**12.62**	**17.23**	**28.77**	**33.09**	**kg**
Total Solar Array Mass	**13.45**	**23.57**	**13.45**	**23.57**	**46.34**	**69.10**	**kg**
Total tank mass (includes prop)	**0.60**	**0.00**	**239.33**	**224.60**	**190.29**	**163.21**	**kg**
TOTAL MASS	**83.3**	**97.4**	**322.0**	**322.0**	**322.0**	**322.0**	**kg**
Maneuver propellant	0	0	169	158	134	114	kg
Inert Mass	83	97	153	164	188	208	kg
Ideal Delta-V Capability	**0.00**	**0.00**	**10.01**	**9.94**	**9.95**	**7.44**	**km/s**



Naming convention

H600

"L" = 83.3 kg
"H" = 322 kg

SEP power (W)

Next step: determine the capability that is required for the 3 SEP missions: L1 to Earth trailing, heliocentric plane change to solar polar, and 45 deg heliocentric hover.