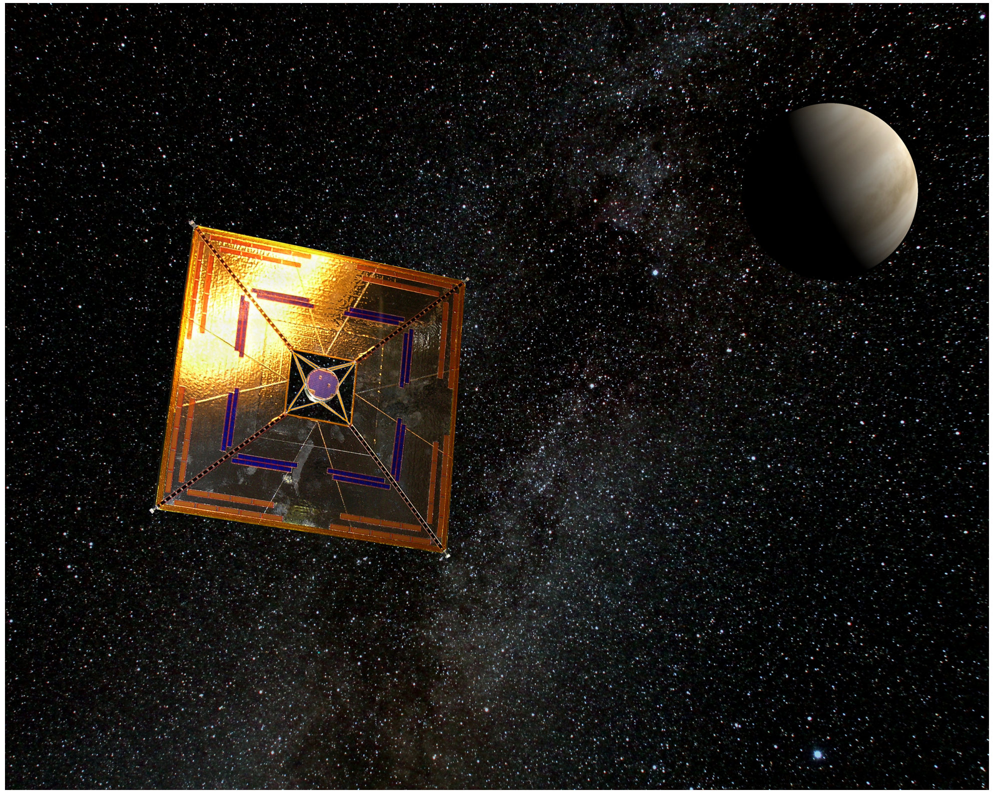
AA283
Aircraft and Rocket Propulsion

Space Sailing – Photon propulsion



STANFORD AERONAUTICS & ASTRONAUTICS

Properties of light

- Momentum

$$p = \frac{h}{\lambda}$$

- Energy

$$E = h\nu = h\frac{c}{\lambda} = pc \quad ; \quad \begin{aligned} h &= 6.63 \times 10^{-34} \text{ Joule} - \text{sec} \\ c &= 3.00 \times 10^{8} \text{ M / sec} \end{aligned}$$

Reference - *Space Sailing* by Jerome L. Wright, Gordon and Breach Science Publishers 1994

Much more current - https://en.wikipedia.org/wiki/Solar_sail

STANFORD AERONAUTICS & ASTRONAUTICS

Properties of sunlight

- Energy flux

$$W = \left[\frac{\text{Joules}}{\text{photon}}\right] \bullet \left[\frac{\text{photons}}{M^2 - \text{sec}}\right] = h\nu \bullet \left[\frac{\text{photons}}{M^2 - \text{sec}}\right] = \left[\frac{\text{Joules}}{M^2 - \text{sec}}\right]$$

At the earth's radius from the sun

$$W_{earth} = 1368 \ \text{Joules} / M^2 - \text{sec}$$

$$W_{earth} / c = 4.56 \times 10^{-6} N / M^2$$

STANFORD AERONAUTICS & ASTRONAUTICS

Properties of sunlight, cont'd

- Light pressure on a perfectly reflecting surface normal to the incidence direction of light

$$P = 2W / c$$

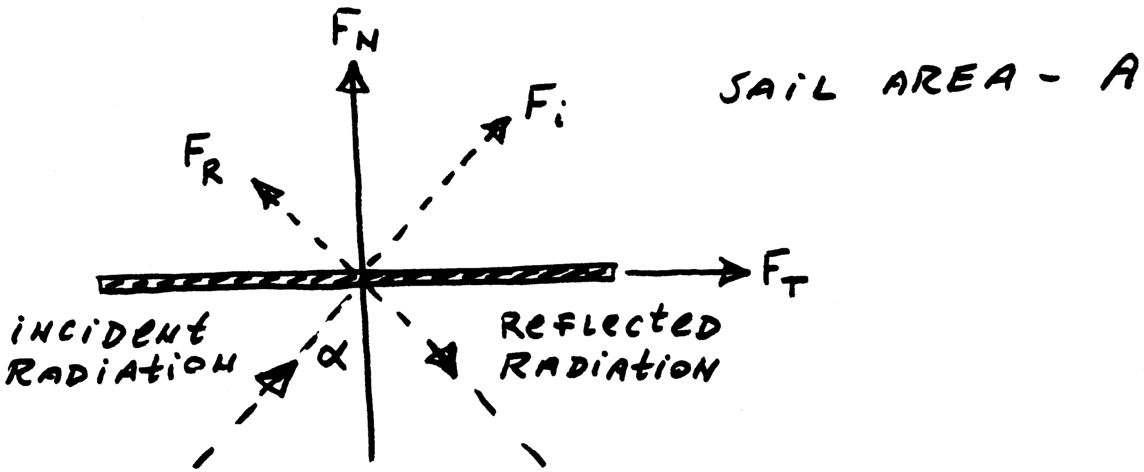
At the earths radius

$$P_{earth} = 9.12 \times 10^{-6} \ \ N / M^2$$

At other radii

$$P = \left(9.12 \times 10^{-6} \ \ N / M^2\right)\left(\frac{r_{earth}}{r}\right)^2 \quad ; \quad \frac{r}{r_{earth}} = \text{radius in AU}$$

Light Force on a Sail



$$F_N = F_i \cos\alpha + F_R \cos\alpha \quad ; \quad F_T = F_i \sin\alpha - F_R \sin\alpha$$

- Perfect reflection

$$F_i = \frac{W}{c} A \cos\alpha \quad ; \quad F_R = \frac{W}{c} A \cos\alpha$$

$$F_N = 2\frac{W}{c} A \cos^2\alpha \quad ; \quad F_T = 0$$

STANFORD AERONAUTICS & ASTRONAUTICS

Light Force on a Sail, cont'd

- Taking account of reflected, absorbed and radiated energy

$$\frac{F_N}{\left(2\frac{W}{c}A\right)} = \frac{(1+rs)\cos^2\alpha + B_f r(1-s)\cos\alpha + \frac{B_f e_f - B_b e_b}{e_f + e_b}(1-r)\cos\alpha}{2}$$

$$\frac{F_T}{\left(2\frac{W}{c}A\right)} = \frac{(1-rs)\cos\alpha\sin\alpha}{2}$$

where

r = reflectivity of the front surface for the incident radiation

s = specular reflection coefficient

ef, eb = front and back surface IR emission coefficients for wavelength of emitted radiation based on sail temperature.

B_f, B_b = Non-Lambertian coefficients for front and back surfaces.

STANFORD
AERONAUTICS &
ASTRONAUTICS

Sail acceleration

The size of a sail is determined by the mass of the payload and the characteristic acceleration required for a particular mission.

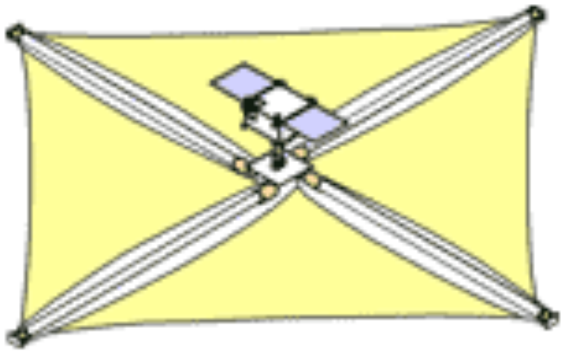
$$a_c = 2\eta \frac{W}{c}\left(\frac{A}{m_{total}}\right)$$

where m_{total} is the total mass of the ship and η is the sail efficiency (typically about 0.9). The key factor limiting the acceleration available is the mass loading of the sail.

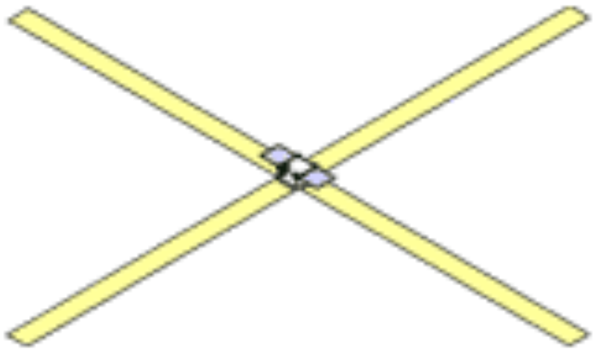
$$\sigma = \frac{m_{total}}{A}$$

The lowest available mass loading using currently available materials is about 5 gm/M^2

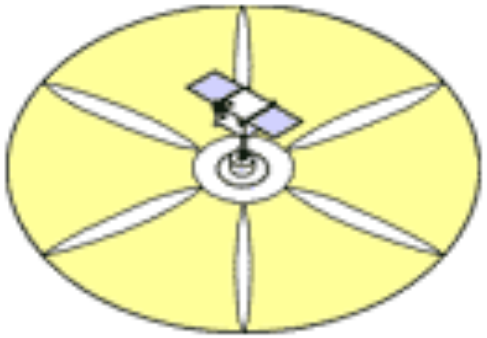
Sail design concepts



Square Sail (not to scale)



Heliogyro (not to scale)



Spinning Disk Sail
(not to scale)

Reference - *Space Sailing* by Jerome L. Wright, Gordon and Breach Science Publishers 1994

Typical mission times - Earth to Moon

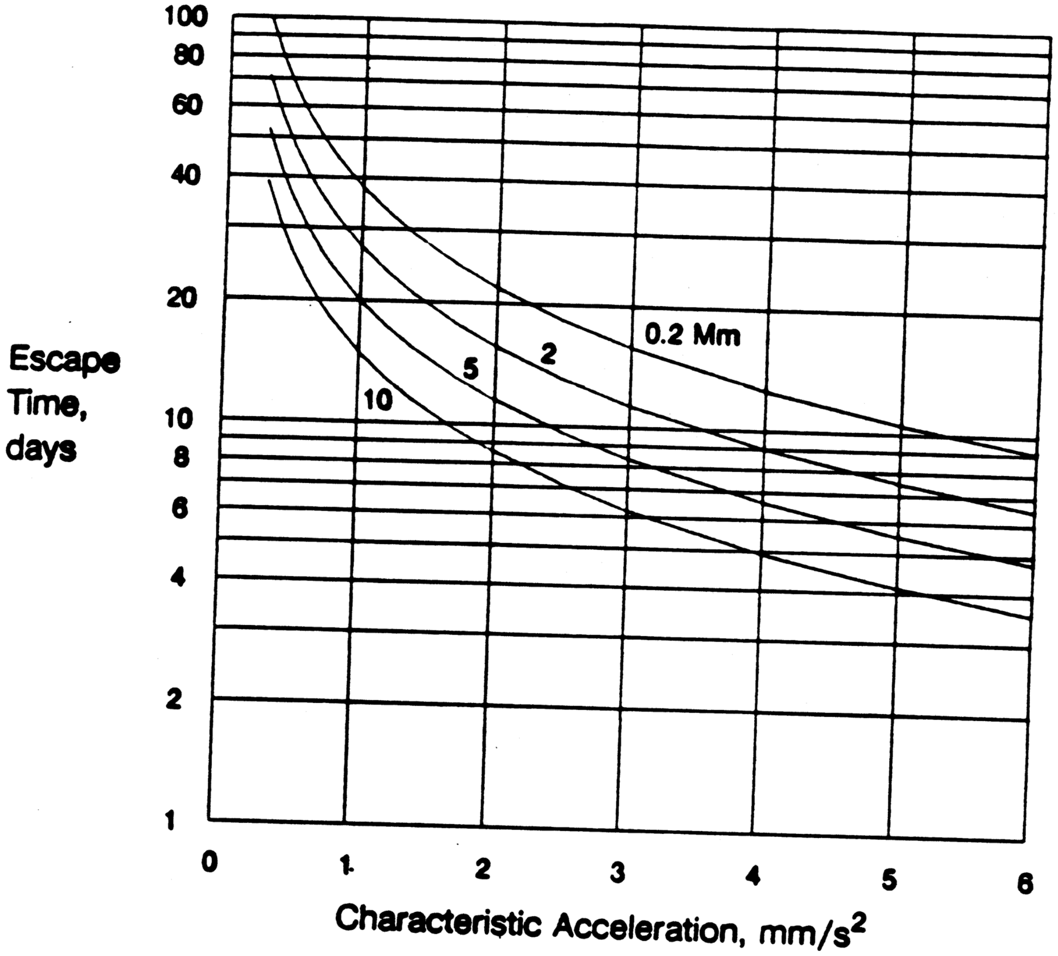


FIGURE 2.2 Lunar Spiral Times.

Mm - Megameters

Typical mission times - Earth Escape

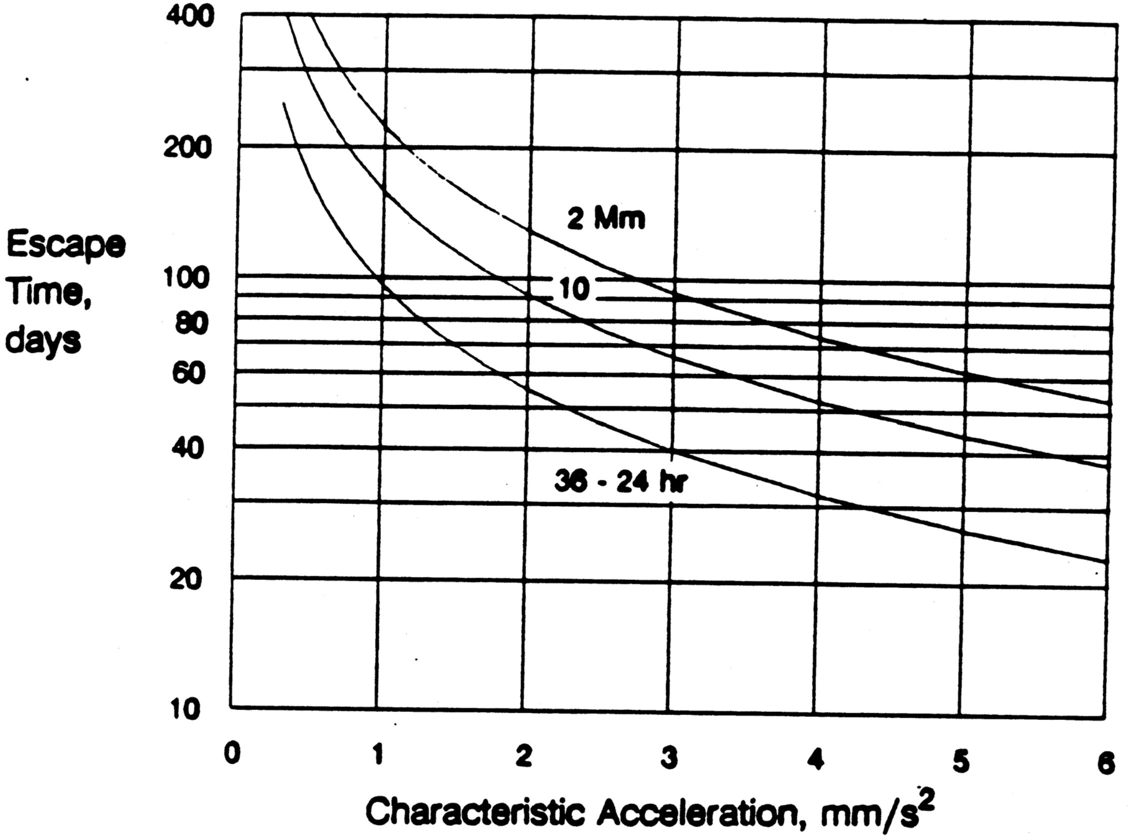


FIGURE 2.1 Earth Escape Times From Various Orbits.

Mm - Megameters

Typical mission times - Missions to the Planets

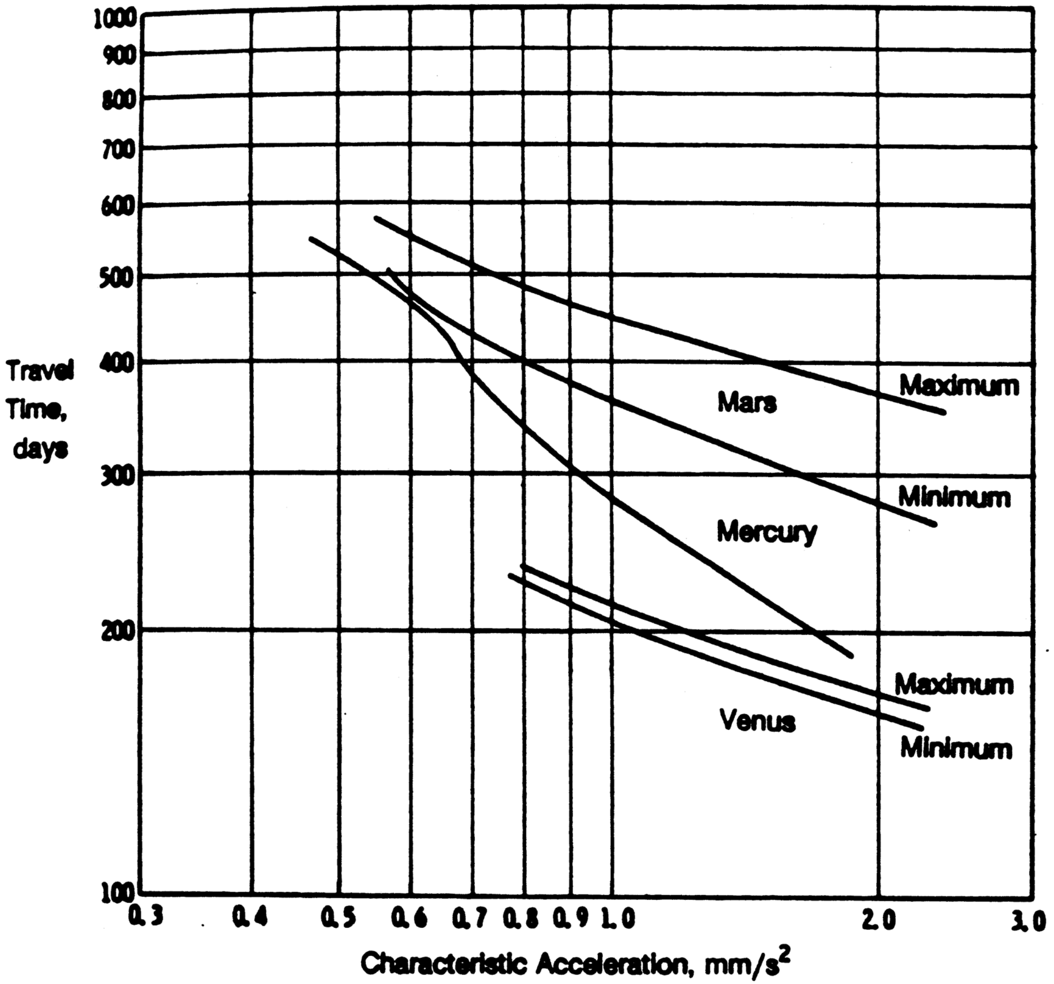


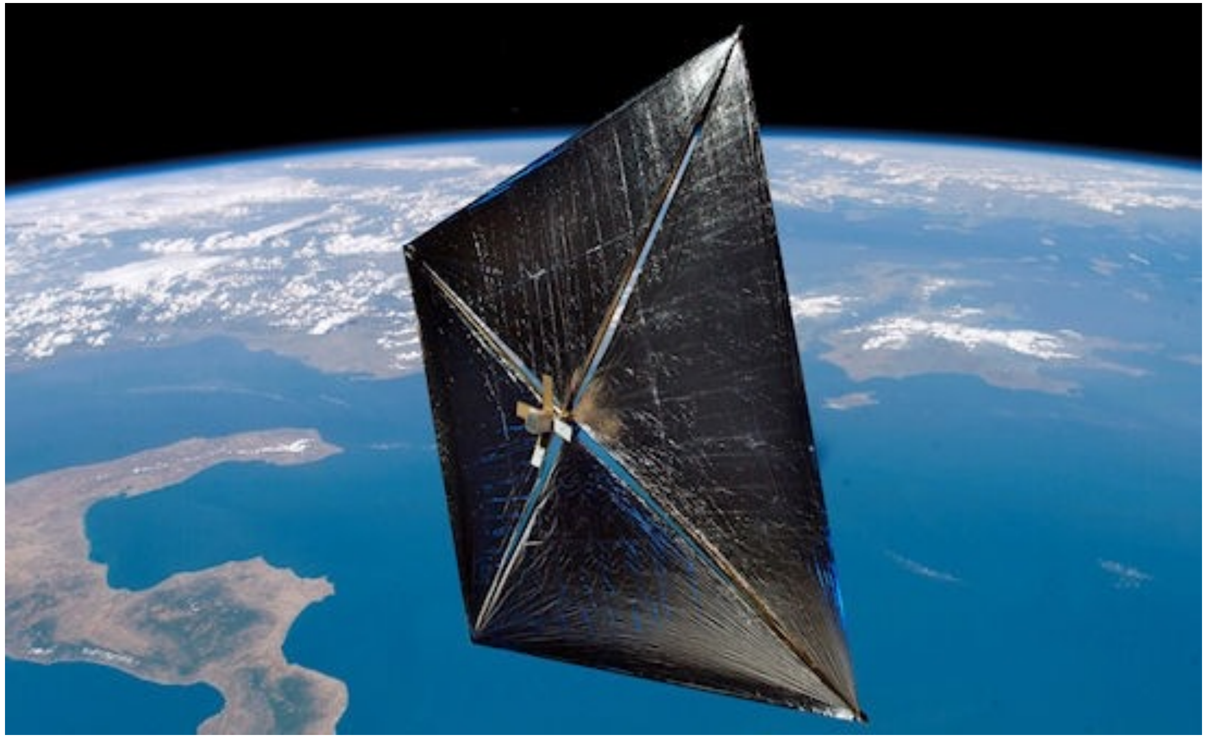
FIGURE 2.4 Typical Travel Times to the Inner Planets.

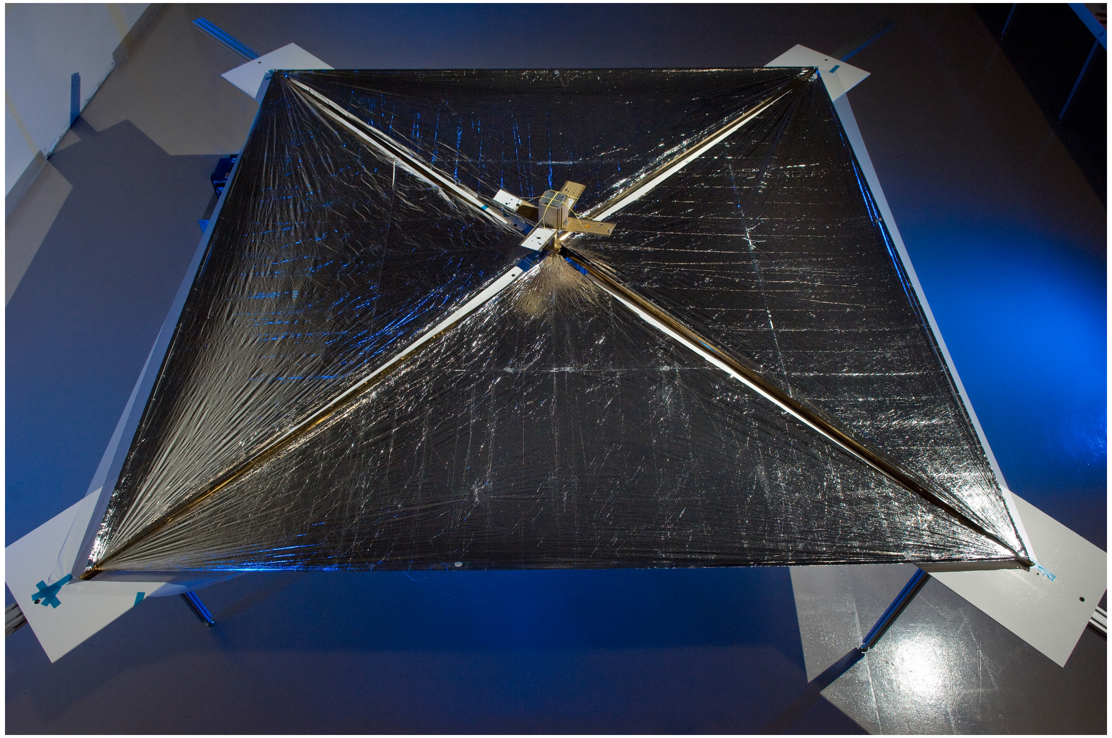
Mm - Megameters

Recent successful missions

NanoSail-D2 - NASA - Second try launched Nov 19, 2010
Mission complete - 240 days (tumbling) in Near Earth Orbit

Area = 10 m^2

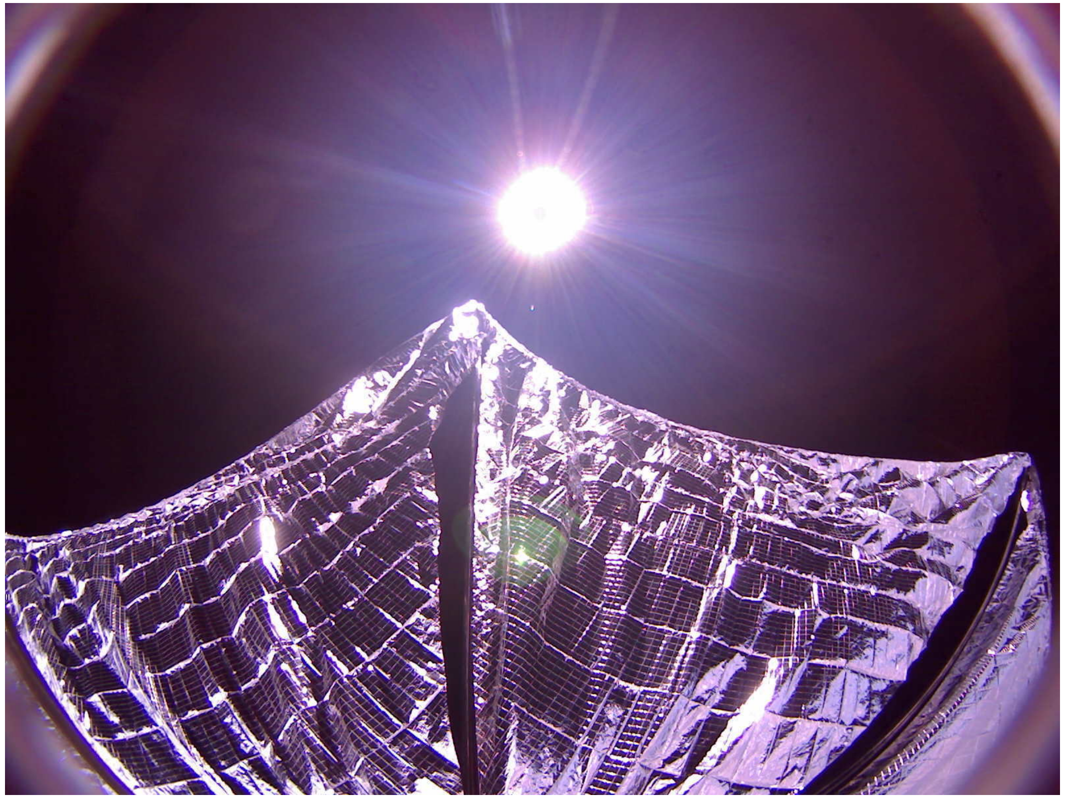


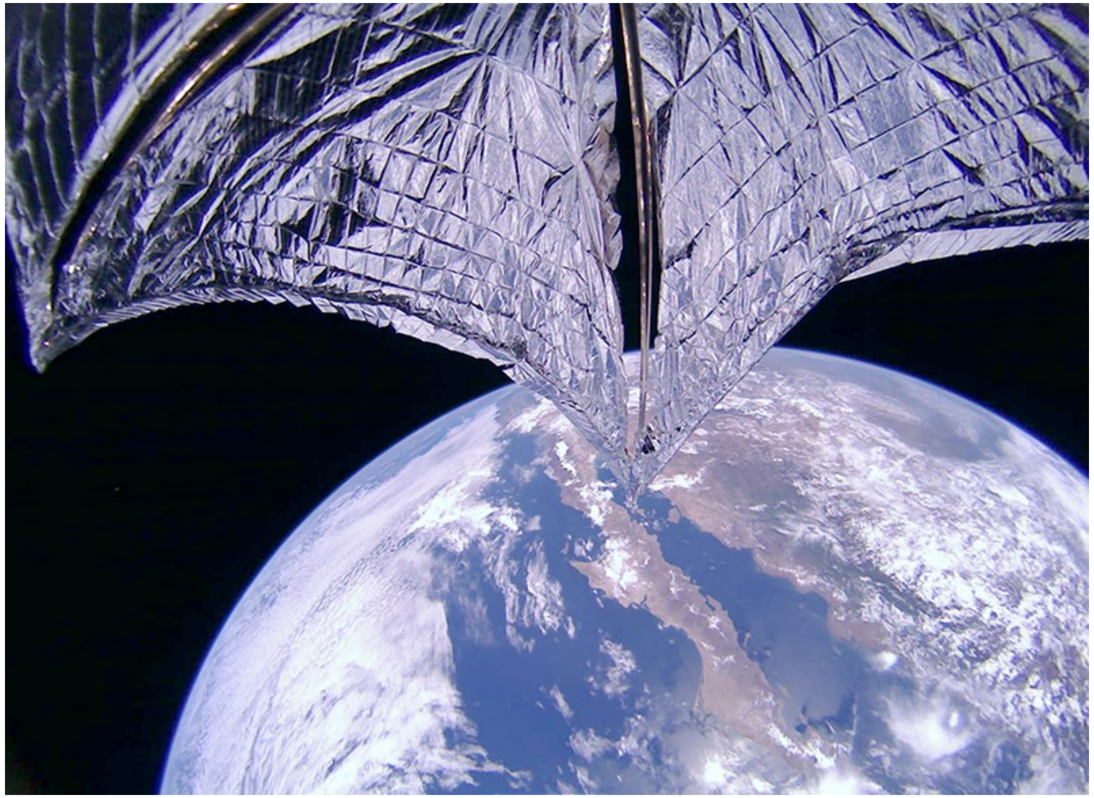


STANFORD
AERONAUTICS &
ASTRONAUTICS

LightSail 1 and 2 – Launched by the Planetary Society in 2015 and 2019. LightSail 2 re-entered Nov 17, 2022 after demonstrating the use of light thrust to slow its orbital decay.

Area = 32 m^2

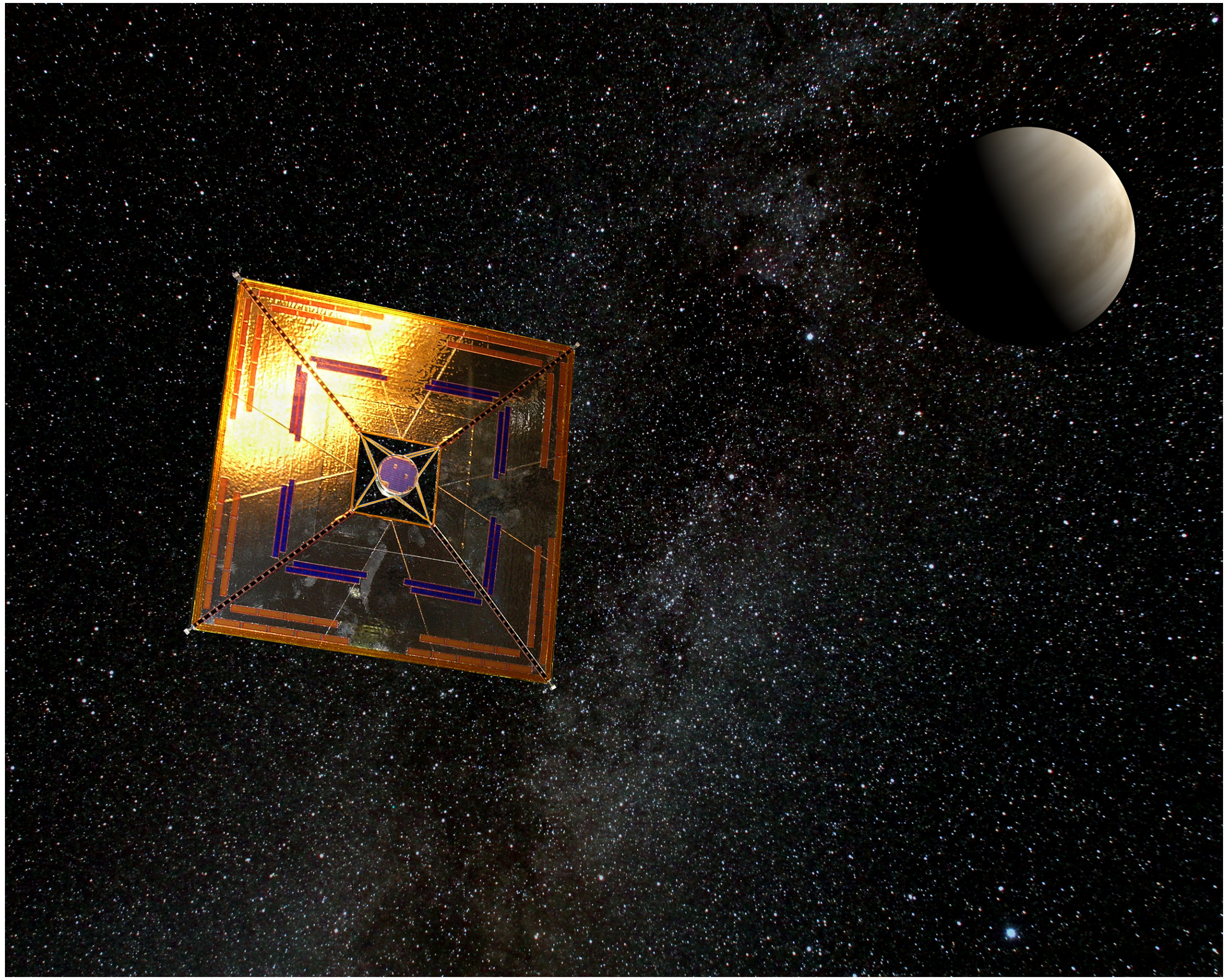




The sails are made of Mylar

IKAROS – Launched by JAXA in 2010 reached Venus in 2015
First successful planetary mission using a solar sail!

Artist rendering of IKAROS

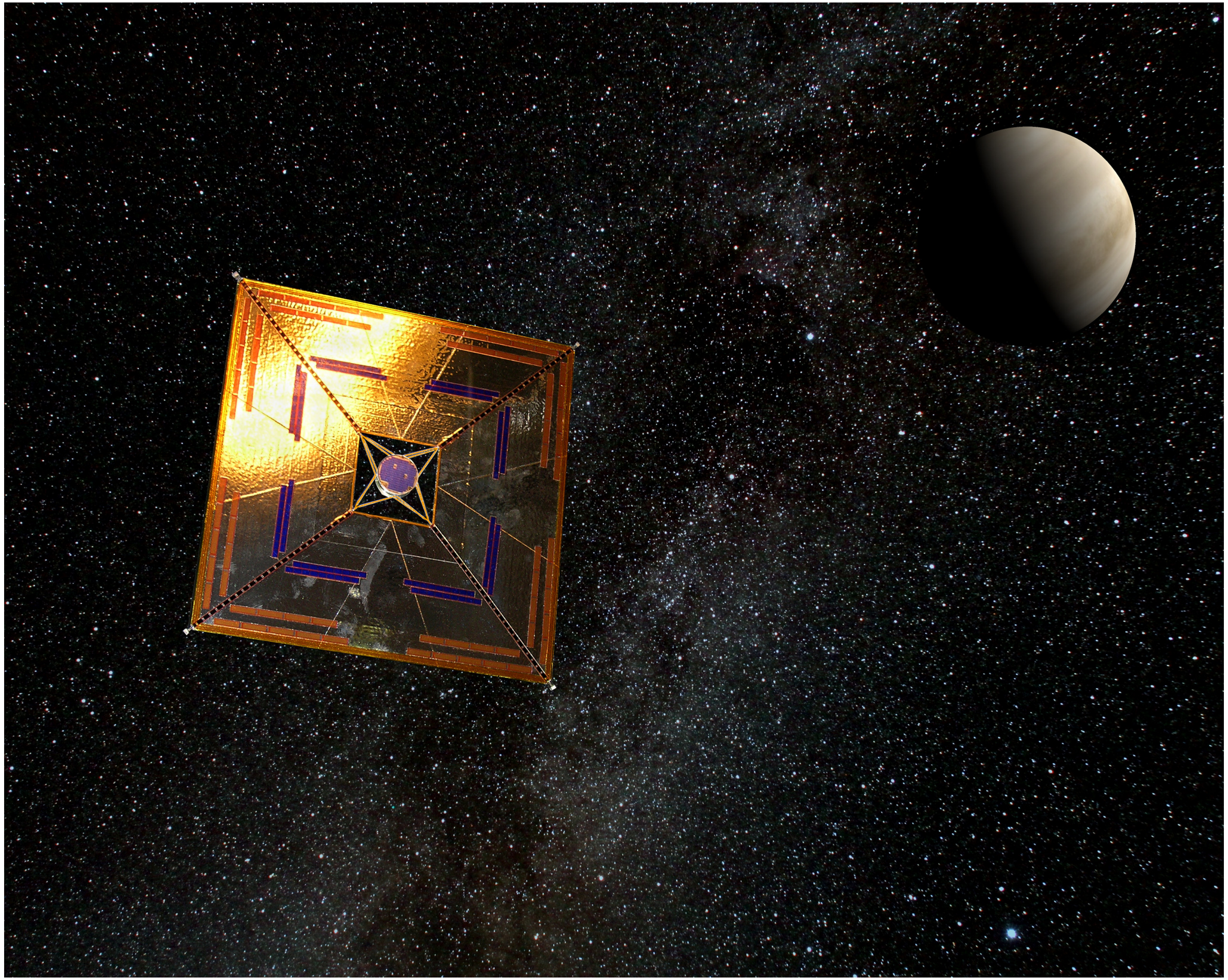


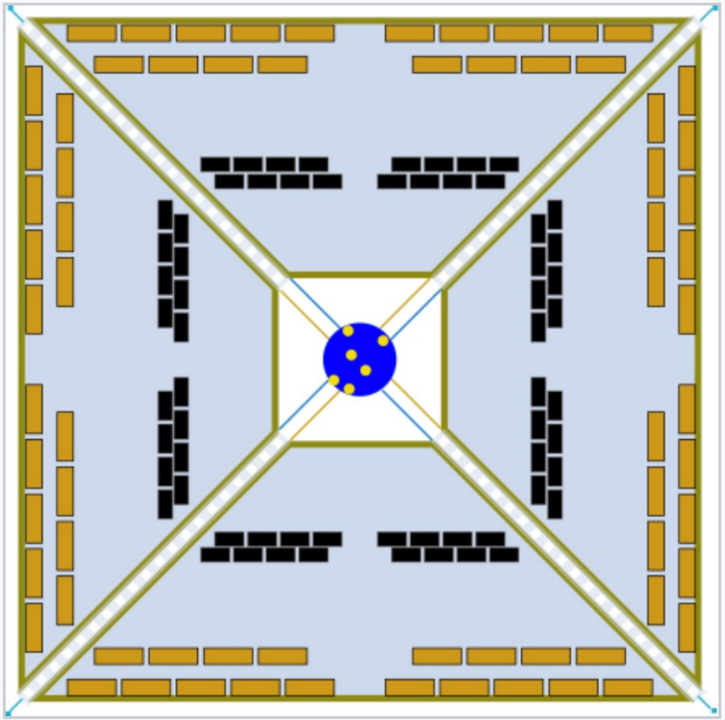
Sail Area 196 m^2,
Thrust 1.12 milliNewtons

IKAROS – Launched by JAXA in 2010 reached Venus in 2015
First successful planetary mission using a solar sail!

Sail Area 196 m^2,
Thrust 1.12 milliNewtons

Artist rendering of IKAROS

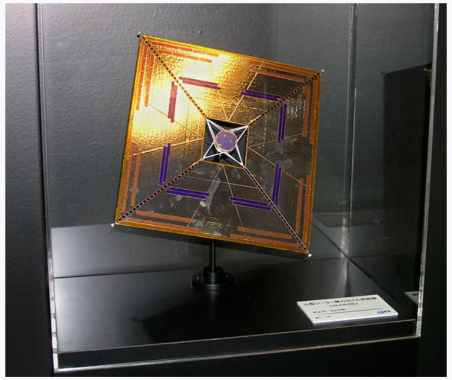




Sun-facing IKAROS diagram without key

1 Tip mass 0.5 kg
2 Liquid crystal device
3 Membrane 7.5 um thick
4 Solar cells 25 um thick
5 Tethers
6 Main body
7 Instruments

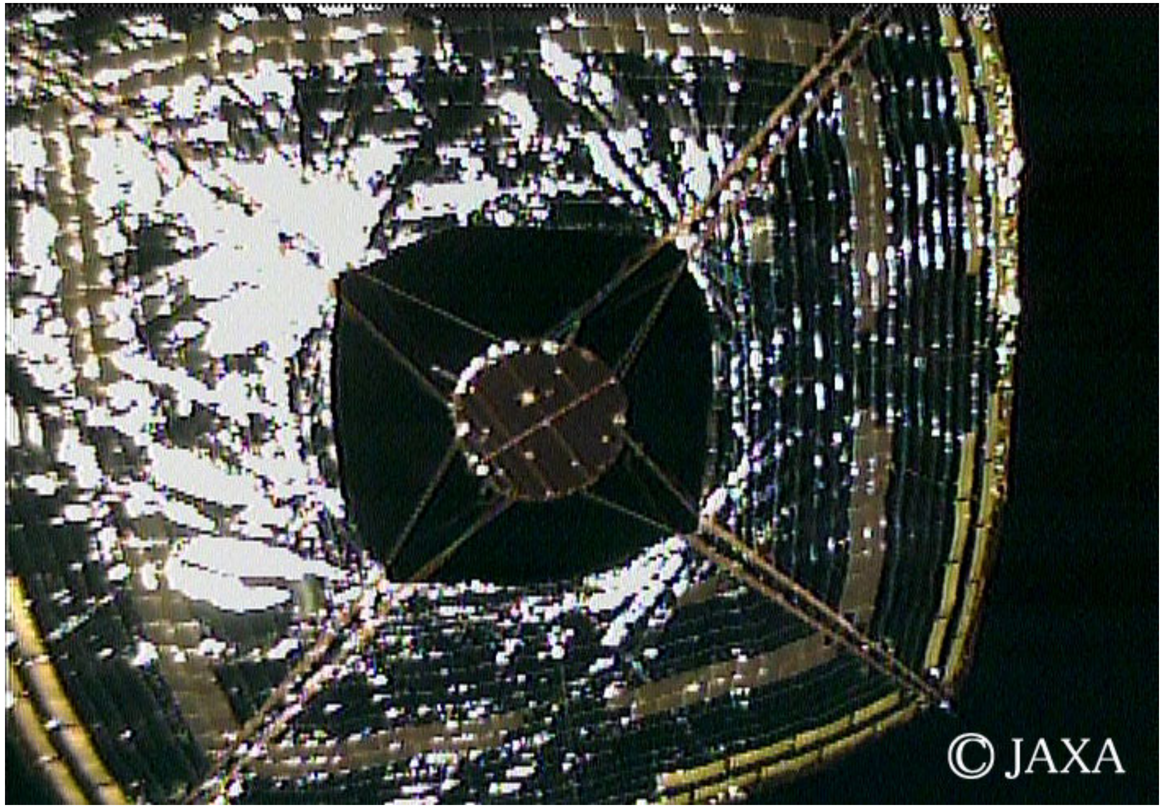
IKAROS

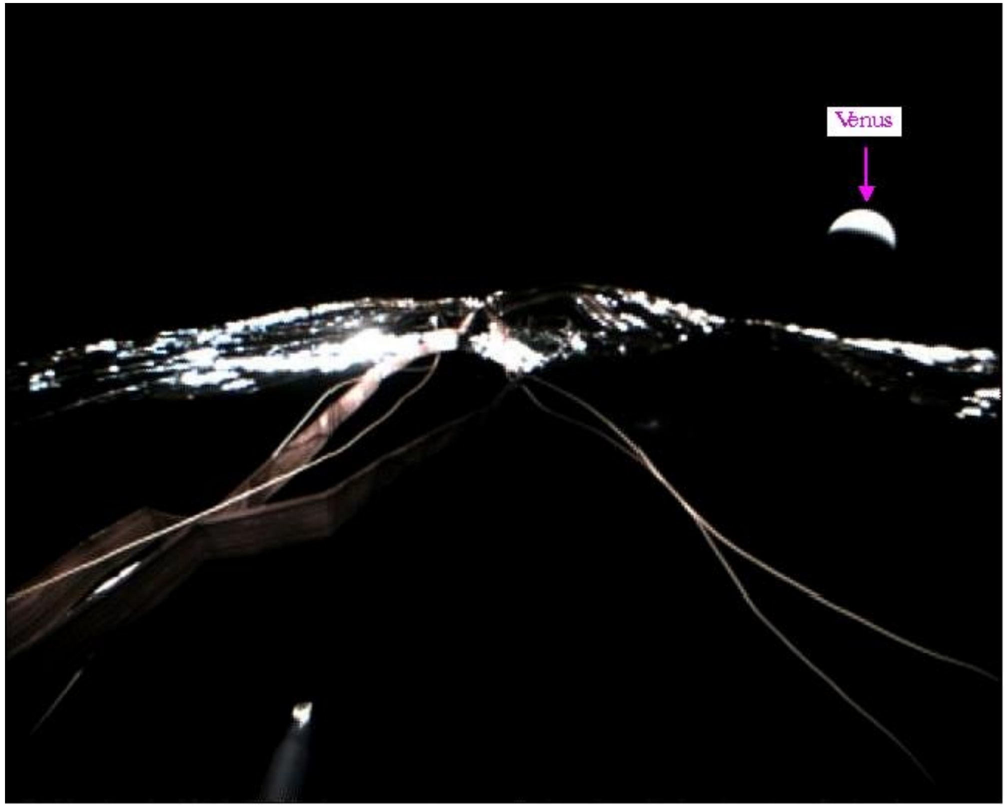


A 1:64 scale model of the IKAROS spacecraft

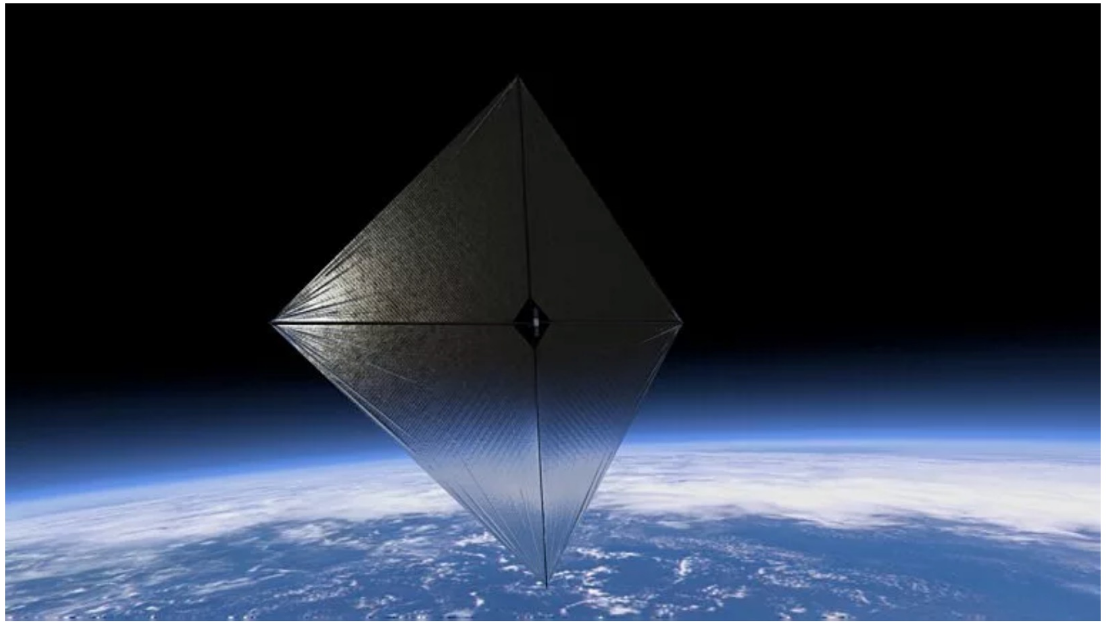
Mission type	Solar sail technology
Operator	JAXA[1][2][3][4]
COSPAR ID	2010-020E
SATCAT no.	36577
Website	global.jaxa.jp/projects/sas/ikaros/
Mission duration	5 years launch to last contact in 2015
Spacecraft properties	
Launch mass	315 kg (694 lb)
Dimensions	Solar sail: 14 m × 14 m (46 ft × 46 ft) (area: 196 m^2 (2,110 sq ft))[5]
Start of mission	
Launch date	21:58:22, 20 May 2010 (UTC)
Rocket	H-IIA 202
Launch site	Tanegashima, LA-Y
End of mission	
Last contact	20 May 2015[6]
Orbital parameters	
Reference system	Heliocentric orbit
Flyby of Venus	
Closest approach	8 December 2010
Distance	80,800 kilometers (50,200 mi)

Self images of IKAROS in space



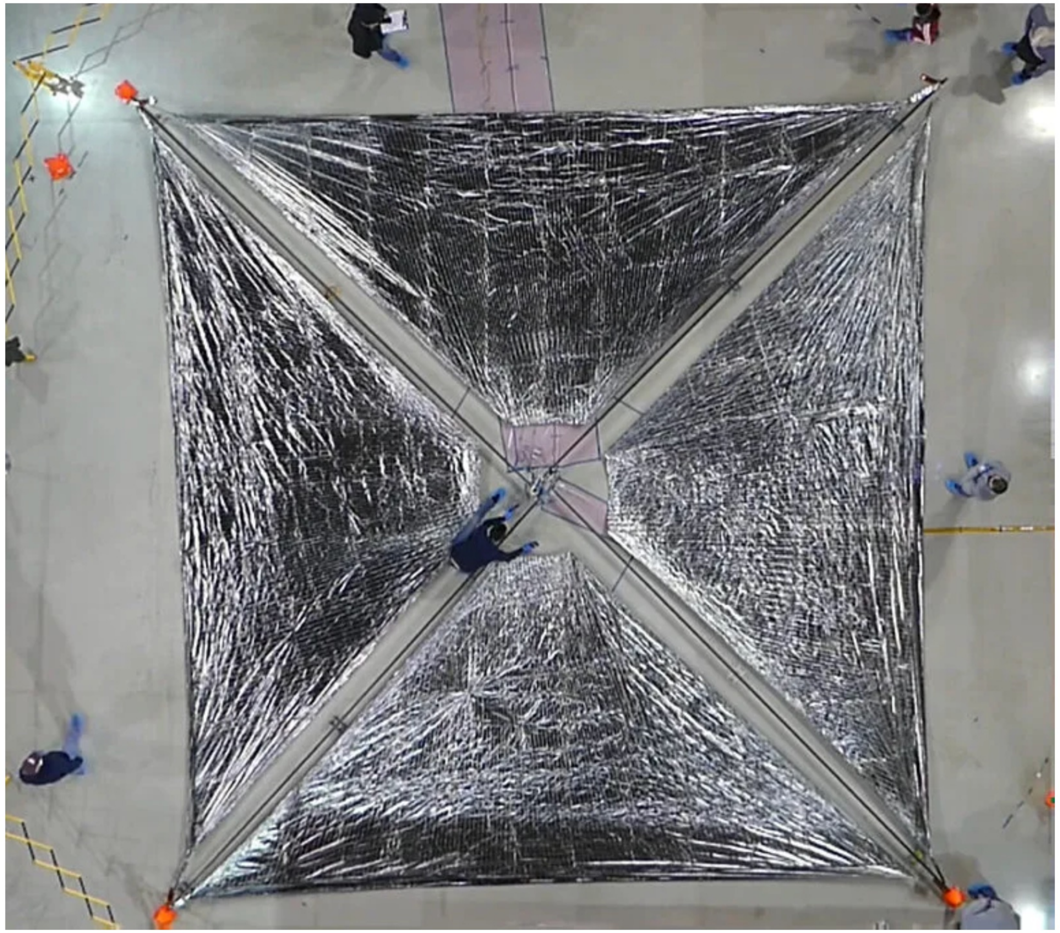


NASA Advanced Composite Solar Sail System, ACS3, launched on a Rocket Lab Electron April 23, 2024



ACS3 SOLAR SAIL An artist's concept of NASA's ACS3 solar sail spacecraft in Earth orbit. *Image: NASA*

Advanced Composite Solar Sail System's, or ACS3's, 12-unit (12U) CubeSat spacecraft bus undergoing assembly and testing. The complete ACS3 spacecraft measures approximately 9 inches x 9 inches x 13 inches (23 centimeters x 23 centimeters x 34 centimeters), or about the size of a small microwave oven.

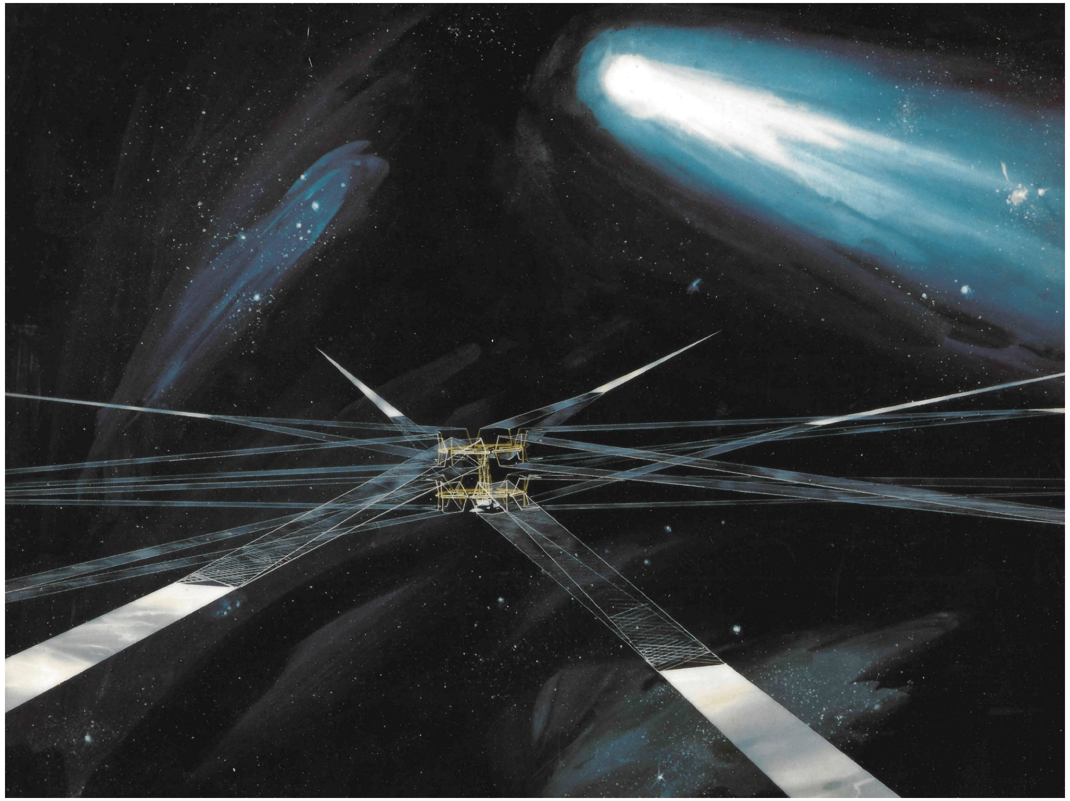


ACS3 DEPLOYMENT TEST Engineers at NASA's Langley Research Center test deployment of the Advanced Composite Solar Sail System's solar sail. The unfurled solar sail is approximately 30 feet (about 9 meters) on a side. *Image: NASA*

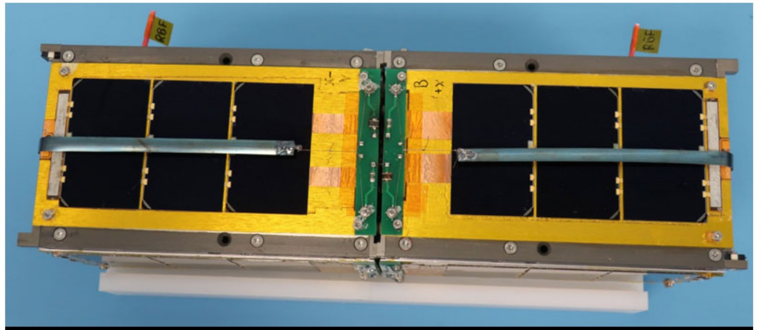
Two more mission/spacecraft concepts

UIUC CubeSail A and B attempted demonstration of the UltraSail concept

Artist's 1986 concept of a heliogyro, proposed to visit Halley's Comet. Each blade would be 8 m (26 ft) wide and 6.2 km (3.9 mi), for 0.6 km^2 (0.23 sq mi) of sail area.

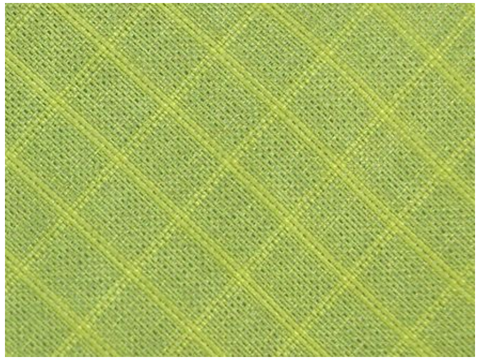


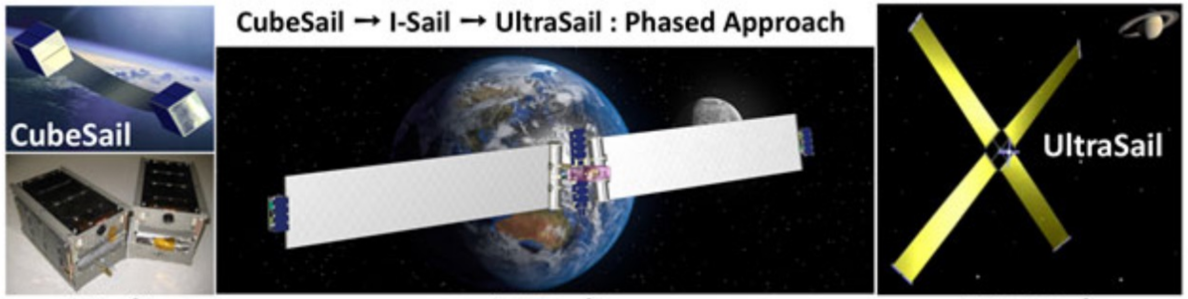
Launched Dec 16, 2018. Beacon detected Dec 18 but signal was very weak. No further communications were received, never deployed the solar sail.



CubeSail before launch-pod integration with stowed antenna.

Each blade made of a polyimide film, eg. Kapton, coated with ripstop.

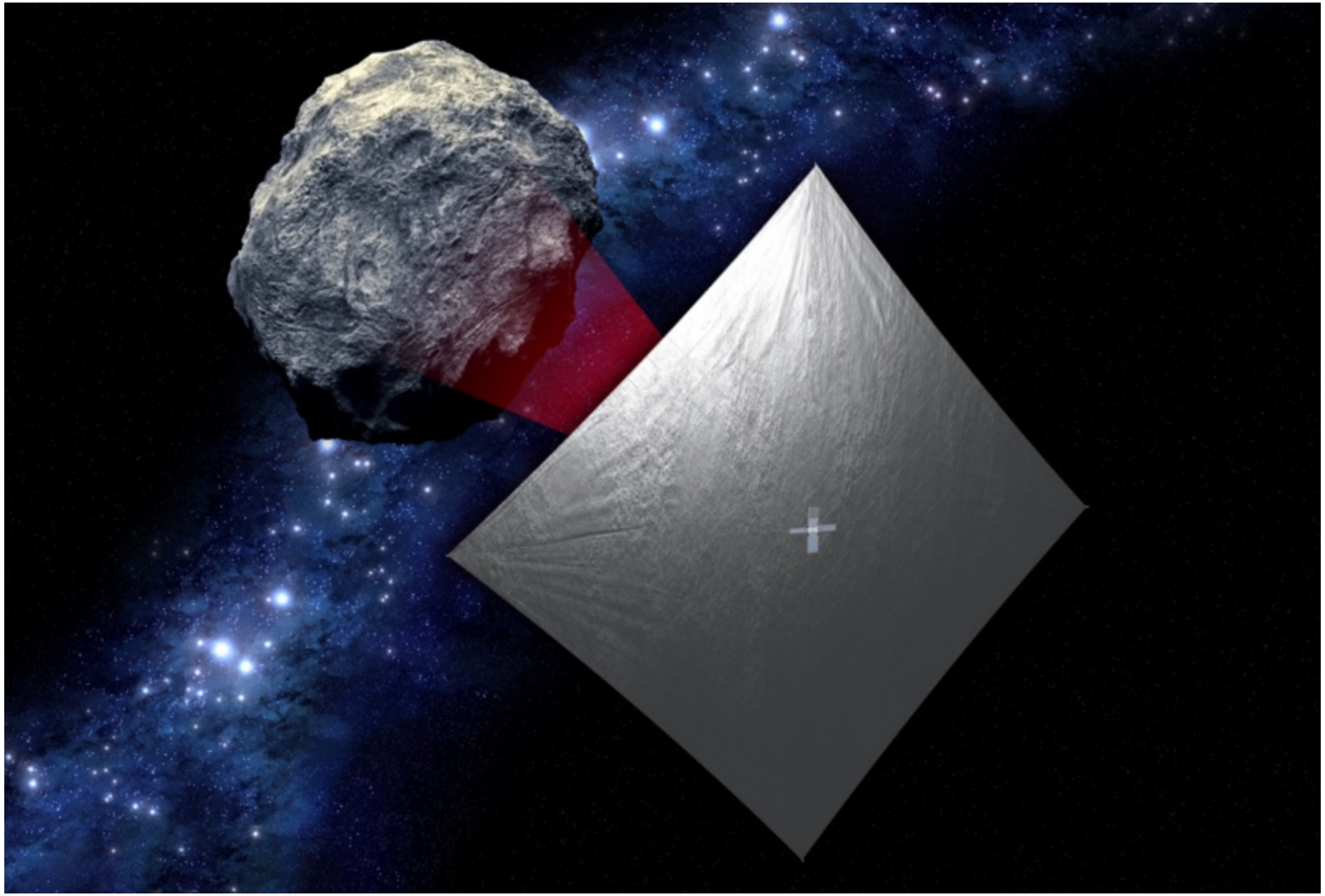




(20 m^2) Fabricated and Manifested for Launch 6/2018	(3,800 m^2) Proposed I-Sail Demonstrator for UltraSail Risk Reduction	(100,000 m^2) Theoretical Viability to Interplanetary Destination Established (2003 – 2006)

STANFORD
AERONAUTICS & ASTRONAUTICS

NEA Scout – SLS Pathfinder Launch date Nov 2021, eventually launched aboard Artemis Moon mission in Nov 2022 but all efforts to communicate with the spacecract failed.



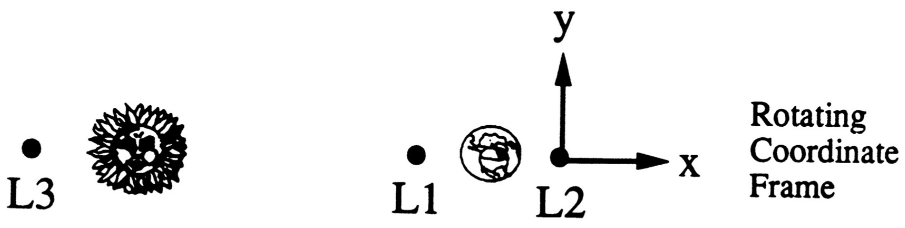
Was supposed to launch on SLS in 2018.

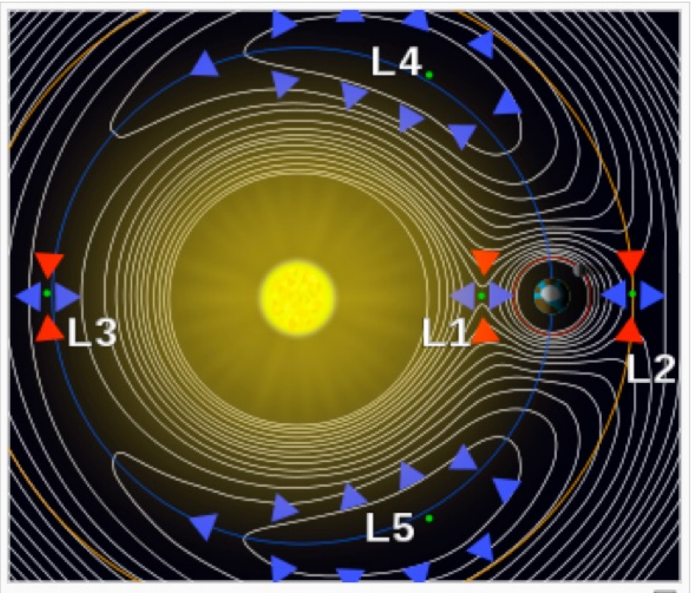
Several Advanced Mission Concepts

Mission to L2 – PhD thesis Sun Hur 1992

STANFORD
AERONAUTICS &
ASTRONAUTICS

What is L2 Libration Point?





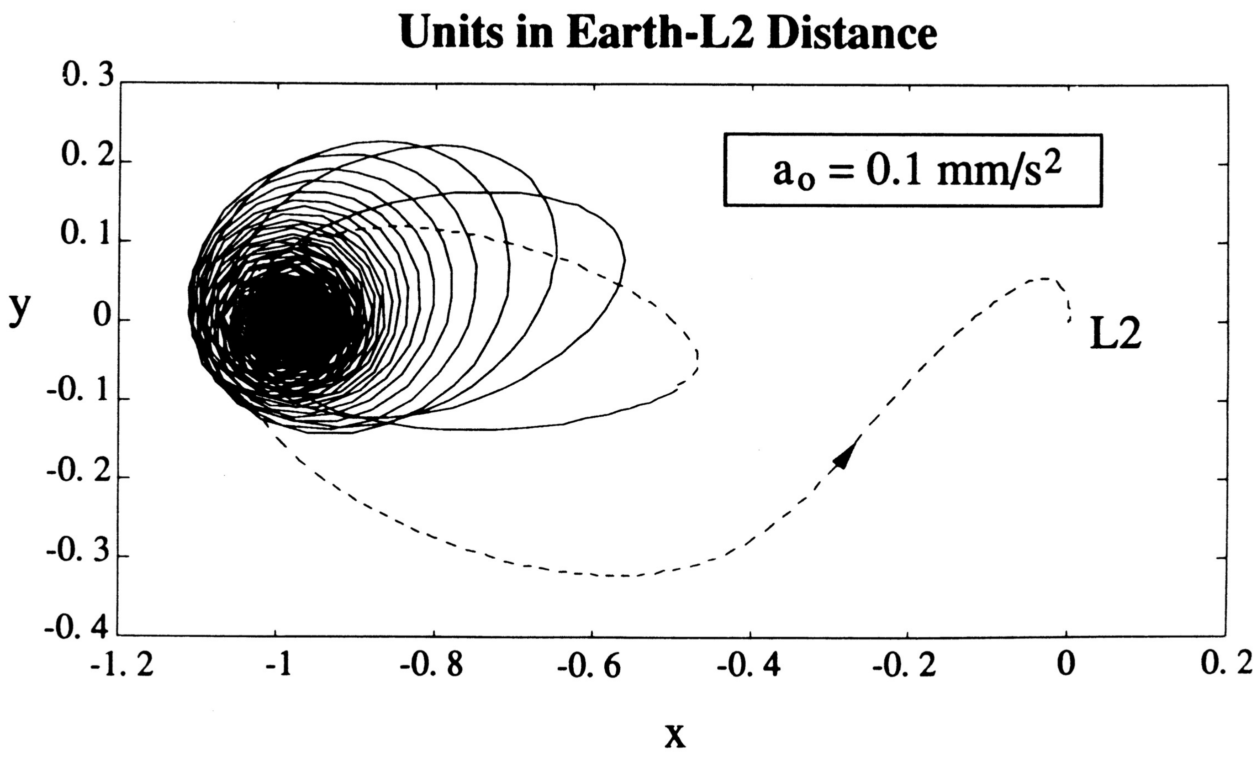
Gravitational potential

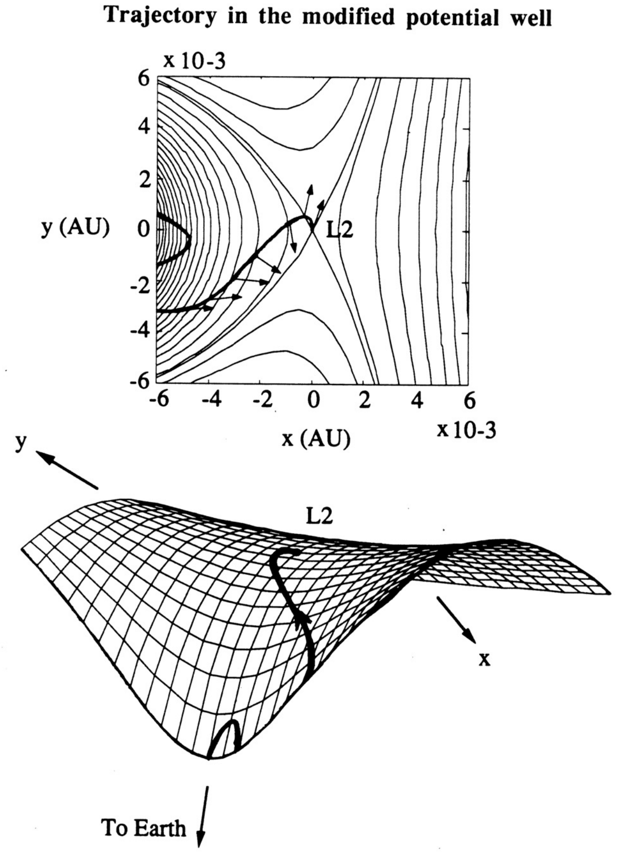
The L2 point is one of five equilibrium points the rotating Sun-Earth system where the gravitational force equals the centrifugal force is an unstable equlibrium point.

CENTRIFUGAL = GRAVITATIONAL

STANFORD
AERONAUTICS &
ASTRONAUTICS

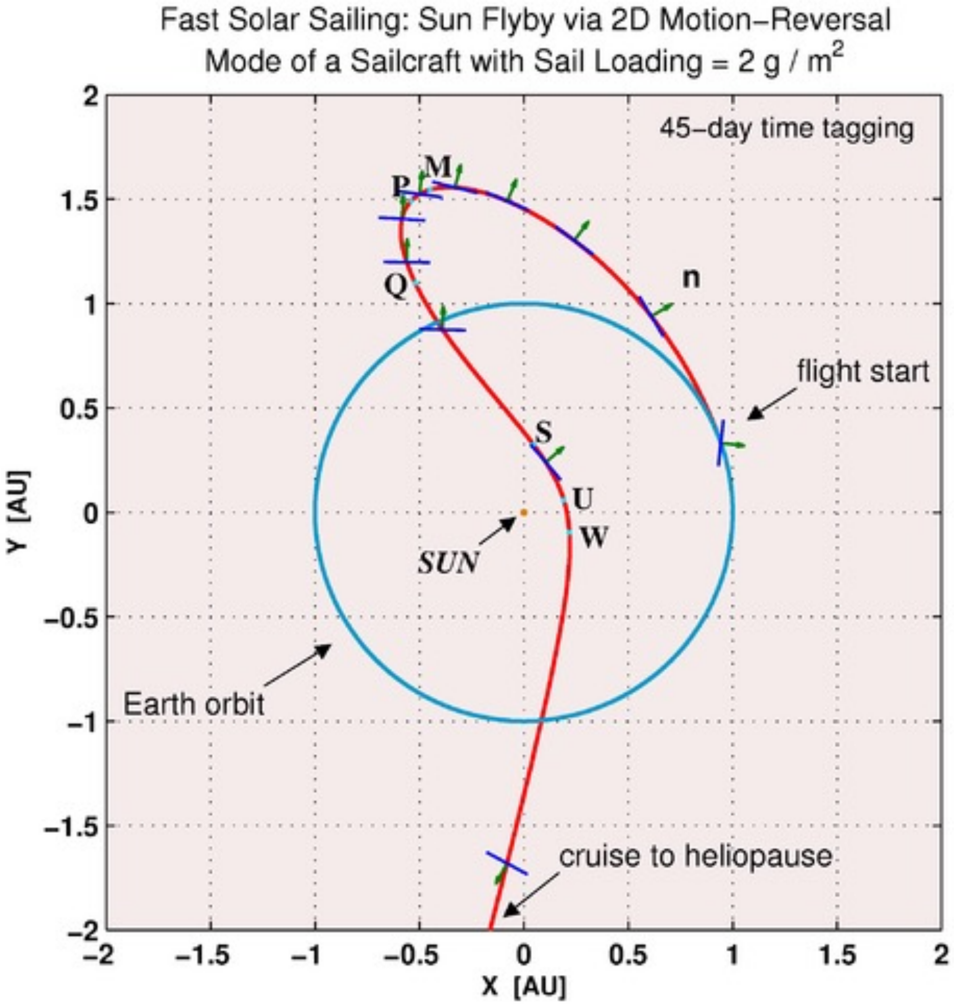
Feasible Trajectory



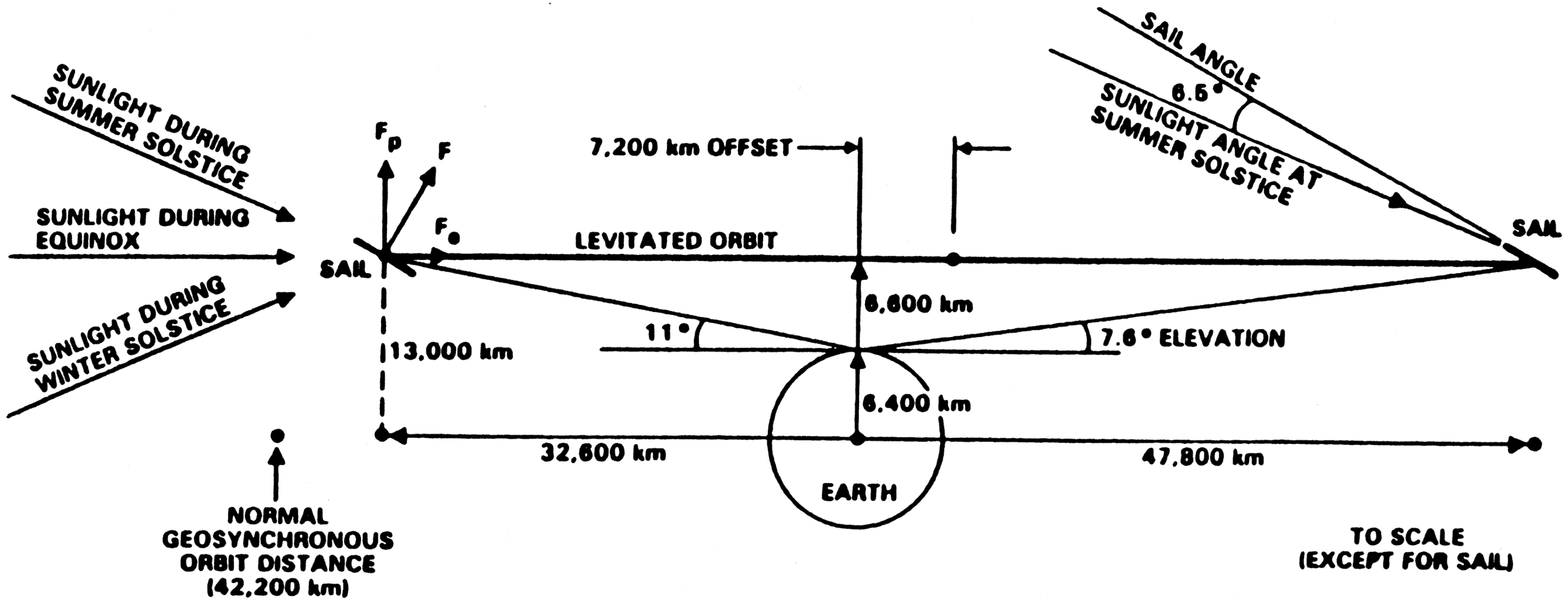


STANFORD AERONAUTICS & ASTRONAUTICS

Mission Toward the Sun



Mission example - levitated orbit



Mission example - solar watchers

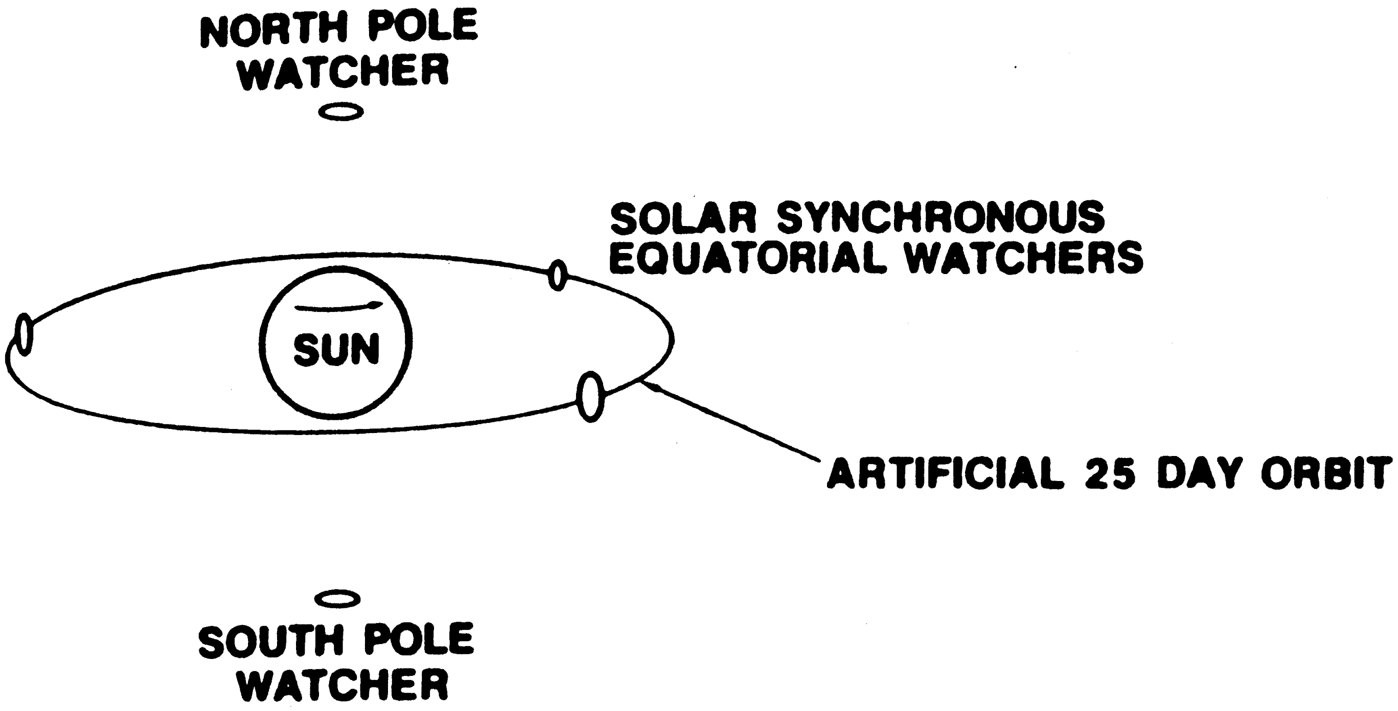


FIGURE 2.21 Synchronous Solar Orbits. (R.L. Forward/Hughes)

Beamed Power Missions

Microwave Thrust

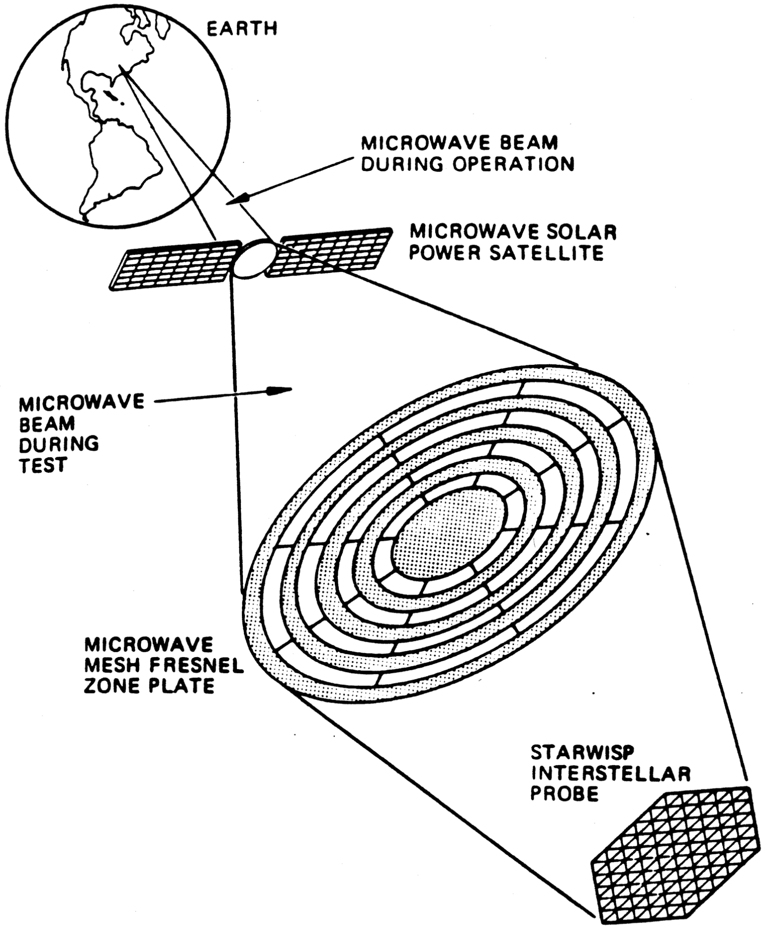
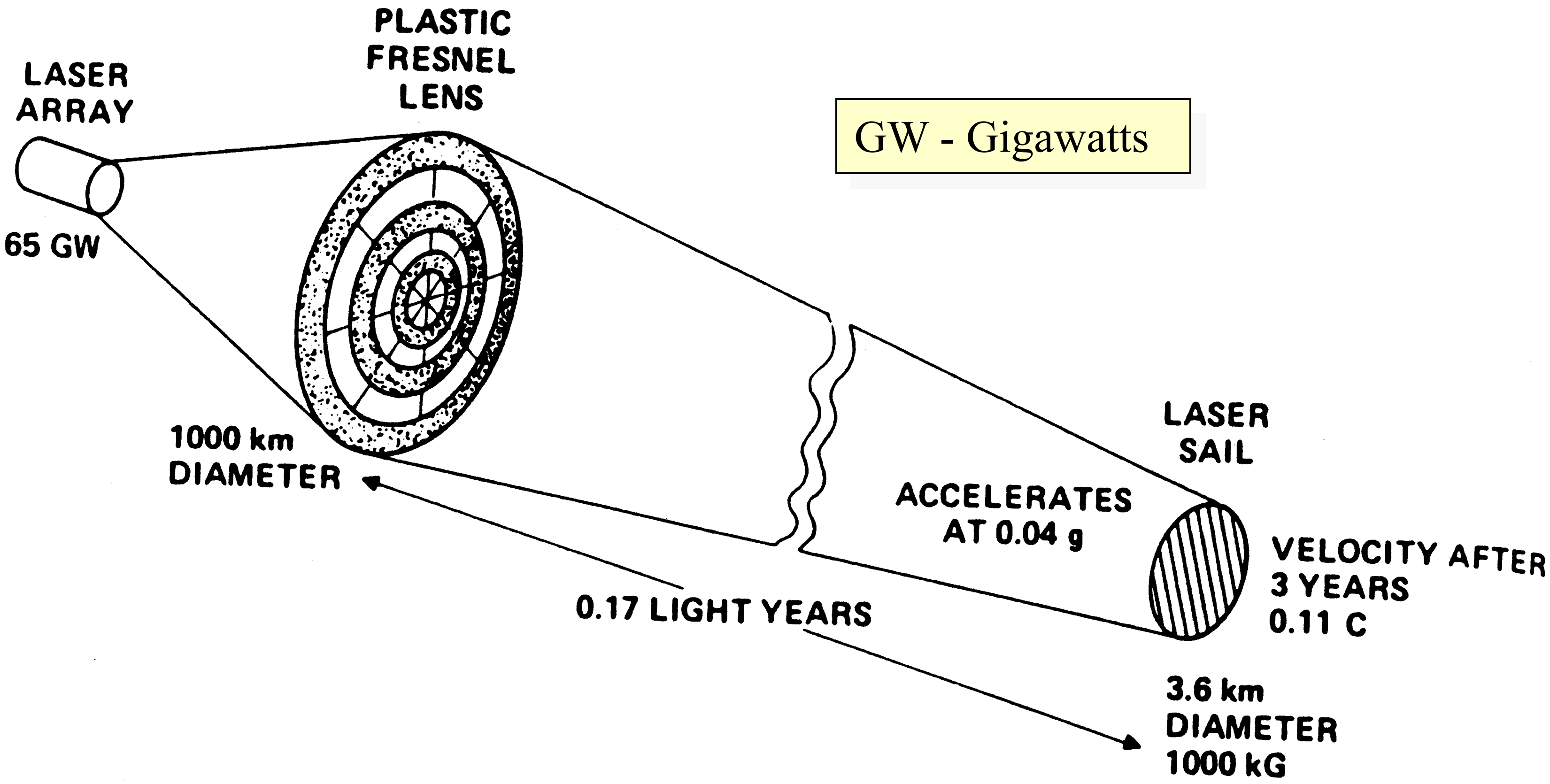


FIGURE 7.10 Operation of a Starwisp Probe. (R.L. Forward)

Mission example - interstellar fly-by



GW - Gigawatts

FIGURE 7.6 Profile of an Interstellar Fly-By Probe. (R.L. Forward)

Mission example - one-way interstellar flight

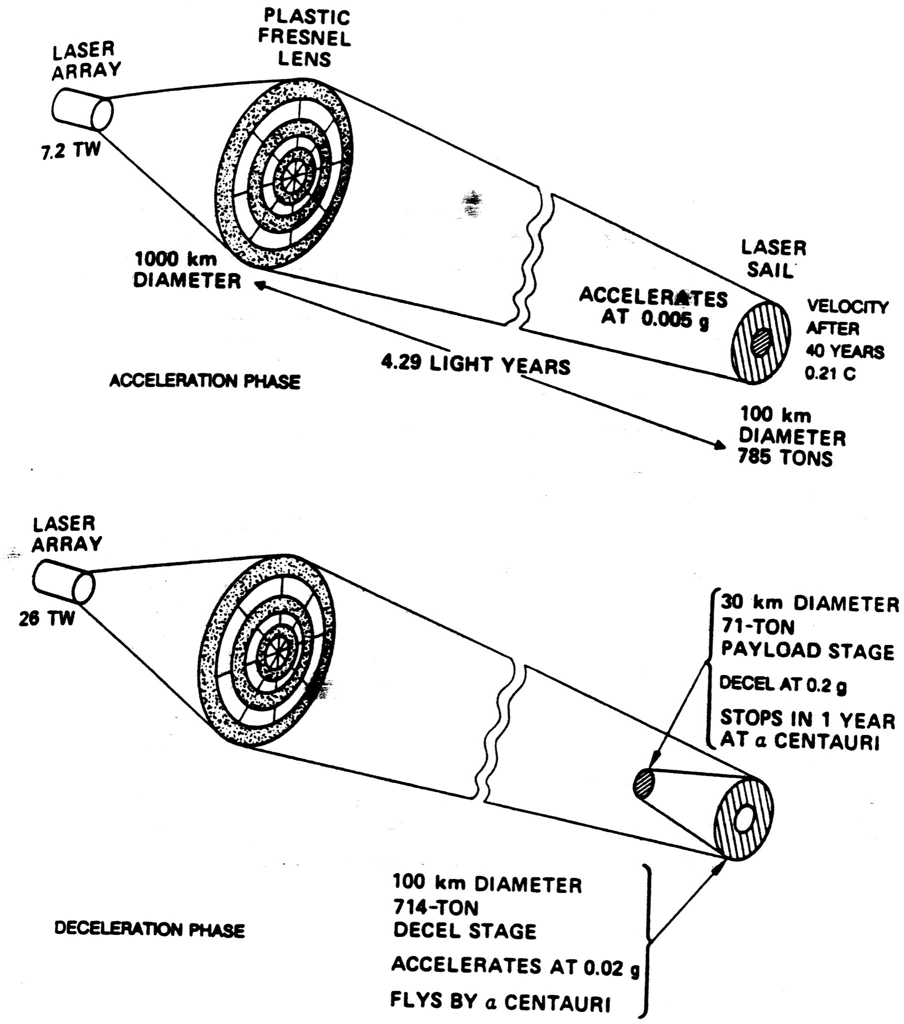


FIGURE 7.7 Profile of a Voyage to Alpha Centauri. (R.L. Forward)

TW - Terawatts

Mission example round-trip interstellar flight

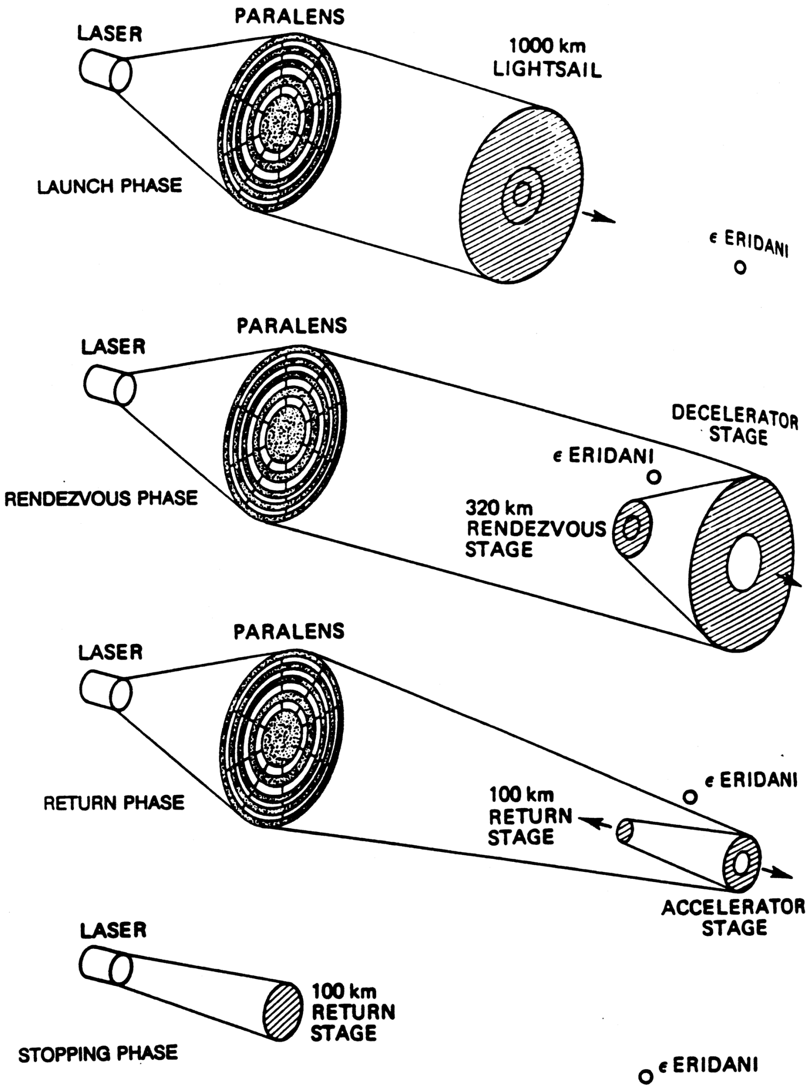
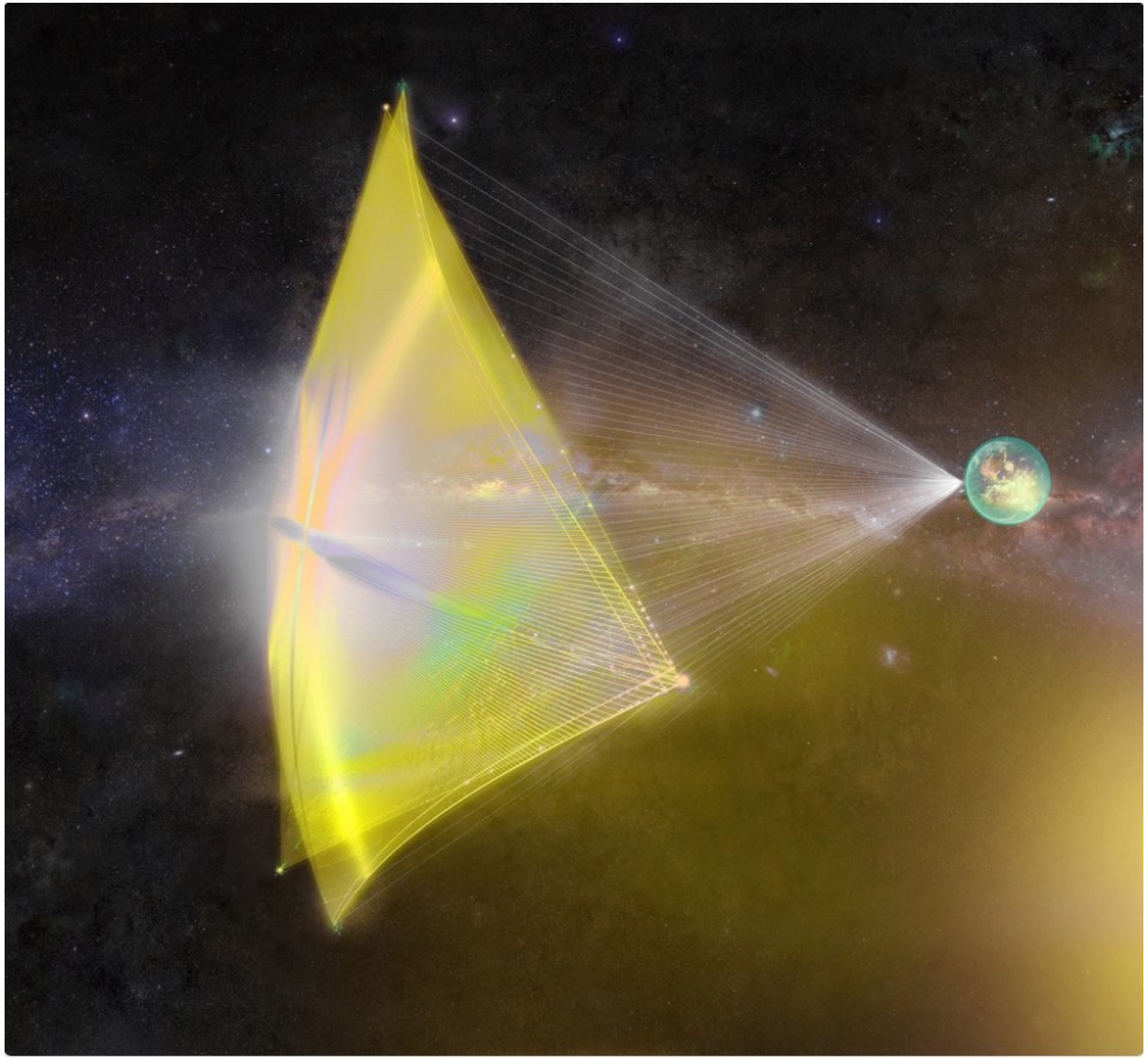


FIGURE 7.8 Profile of a Roundtrip Voyage to Epsilon Eridani. (R.L. Forward)

STANFORD
AERONAUTICS & ASTRONAUTICS

Breakthrough – Starshot - 2018



Use a Gigawatt scale laser to accelerate a 1 gram nano-sized spacecraft to 20% of the speed of light.

Reach the Alpha Centauri system 4.37 light years away in 20 years.

The *StarChip* – camera, photon thruster, power, navigation and communication.

The *LightSail* – several meters in diameter, only a few hundred atoms thick.

The *LightBeamer* – 100 Gigawatt laser tuned to maximize reflectivity from the sail.

The plan

Path to the stars

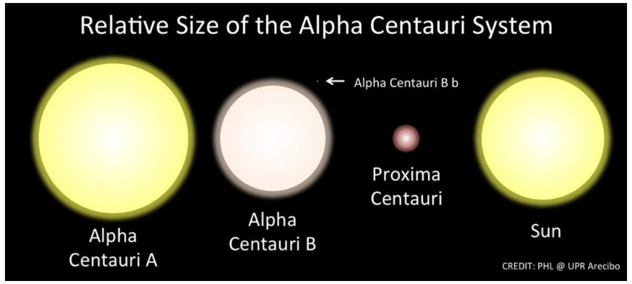
The research and engineering phase is expected to last a number of years. Following that, development of the ultimate mission to Alpha Centauri would require a budget comparable to the **largest current scientific experiments**, and would involve:

- Building a ground-based **kilometer-scale** light beamer at high altitude in dry conditions
- Generating and storing **a few gigawatt hours** of energy per launch
- Launching a 'mothership' carrying **thousands** of nanocrafts to a high-altitude orbit
- Taking advantage of **adaptive optics** technology in real time to compensate for atmospheric effects
- **Focusing** the light beam on the lightsail to accelerate individual nanocrafts to the target speed within minutes
- Accounting for **interstellar dust collisions** en route to the target
- **Capturing images** of a planet, and other scientific data, and transmitting them back to Earth using a compact on-board laser communications system
- Using the same light beamer that launched the nanocrafts to **receive** data from them over 4 years later.

Potential Planets in the Alpha Centauri system

Astronomers estimate that there is a reasonable chance of an **Earth-like planet** existing in the 'habitable zones' of Alpha Centauri's three-star system. A number of scientific instruments, ground-based and space-based, are being developed and enhanced, which will soon identify and characterize planets around nearby stars.

A separate Breakthrough Initiative will support some of these projects.



STANFORD
AERONAUTICS & ASTRONAUTICS

What would it take to reach the speed of light in a few minutes?

Spacecraft mass = 0.001 kg

Acceleration time to c/3 = 1000 sec

Final speed = 10^8 m/sec

Acceleration = 10^5 m/sec^2

Force = 10^2 kg-m/sec^2

Sail Area = 10 m^2

Required light pressure

$$P = \frac{2W}{c} = 10\ N/m^2$$

$$W = 1.5 \times 10^9\ J/m^2 - \mathrm{sec}$$

The *LightBeamer* – 100 Gigawatt laser tuned to maximize reflectivity from the sail.

How much power does the sail have to dissipate? Assume 99.9999% of the incident energy is reflected by the sail. Only one part in a million is absorbed by the sail.

$$W_{absorbed} = 1.5 \times 10^3 J/m^2 - \sec$$

$$Power_{absorbed} = 10 \times W_{absorbed} = 1.5 \times 10^4 J/\sec$$

How fast will the sail heat up? Assume the heat capacity of water (very conservative – for metals C is much lower). C=4.184 J/gram-K

$$Power_{absorbed} = 1.5 \times 10^4 J/\sec = Cm\frac{dT}{dt}$$

$$C = 4.184 \times 10^3 J/kg - K$$

$$m = 10^{-3} kg$$

$$\frac{dT}{dt} = 3.58 \times 10^2 K/\sec$$

How far away is the spacecraft at the end of the acceleration?

$$r = a\frac{t}{2}^2 = 0.5 \times 10^5 \times 10^6 = 5 \times 10^{10} m = 0.33 AU$$

Estimate of drag caused by the cosmic microwave background

Photons per unit volume = 10^9 photons/m^3

Peak wavelength = $10^{-6} m$

Light sail final speed = 10^8 m/sec

Photon flux = 10^{17} photons/m^2 – sec

Energy per photon = $hc/\lambda = 6.6 \times 10^{-34} \times 3 \times 10^8 / 10^{-6} = 2 \times 10^{-16} J$

Momentum per photon = $h/\lambda = 6.6 \times 10^{-34} / 10^{-6} = 6.6 \times 10^{-28} kg - m / \text{sec}$

Drag force on a ten square meter sail = $6.6 \times 10^{-28} \times 10^{17} \times 10 = 6.6 \times 10^{-10} N$

Acceleration of a one gram light sail = $6.6 \times 10^{-7} m / \text{sec}^2$

ΔV over 1000 sec = $6.6 \times 10^{-4} m / \text{sec}$

ΔV over 20 years = $20 \times 365 \times 24 \times 3600 \times 6.6 \times 10^{-7} m / \text{sec} = 416 m / \text{sec}$

This does not account for the blue-shift in the wavelength of the background in the frame of reference of the spacecraft

Photon Thrust

AIAA SPACE 2007 Conference & Exposition
18 - 20 September 2007, Long Beach, California

AIAA 2007-6156

Check for updates

Photonic Laser Thruster (PLT): Experimental Prototype Development and Demonstration

Young K. Bae*
Bae Institute, Tustin, California, 92780

JOURNAL OF PROPULSION AND POWER
Vol. 37, No. 3, May–June 2021

Check for updates

Photonic Laser Thruster: 100 Times Scaling-Up and Propulsion Demonstration

Young K. Bae*
Y.K. Bae Corporation, Corona, California 92883

https://doi.org/10.2514/1.B38144

JOURNAL OF PROPULSION AND POWER
Vol. 38, No. 3, May–June 2022

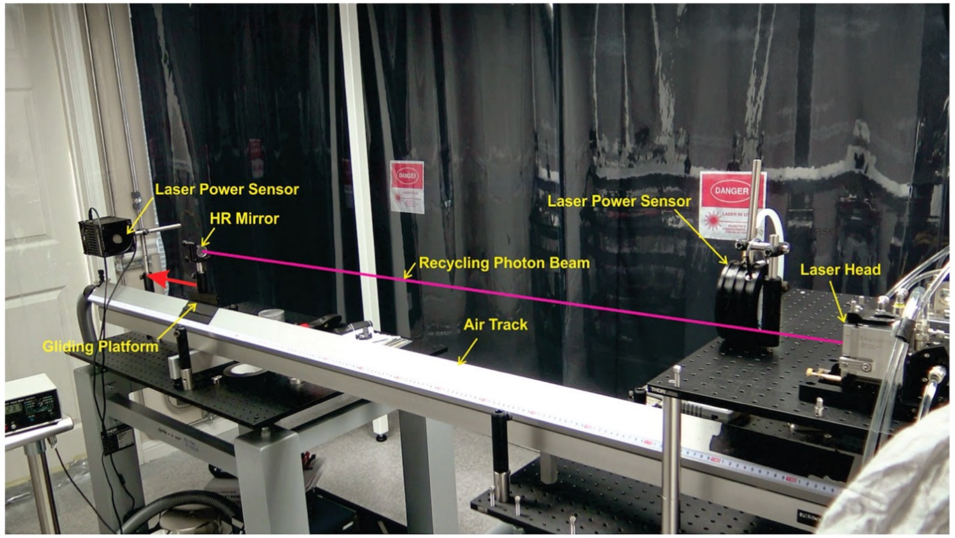
Check for updates

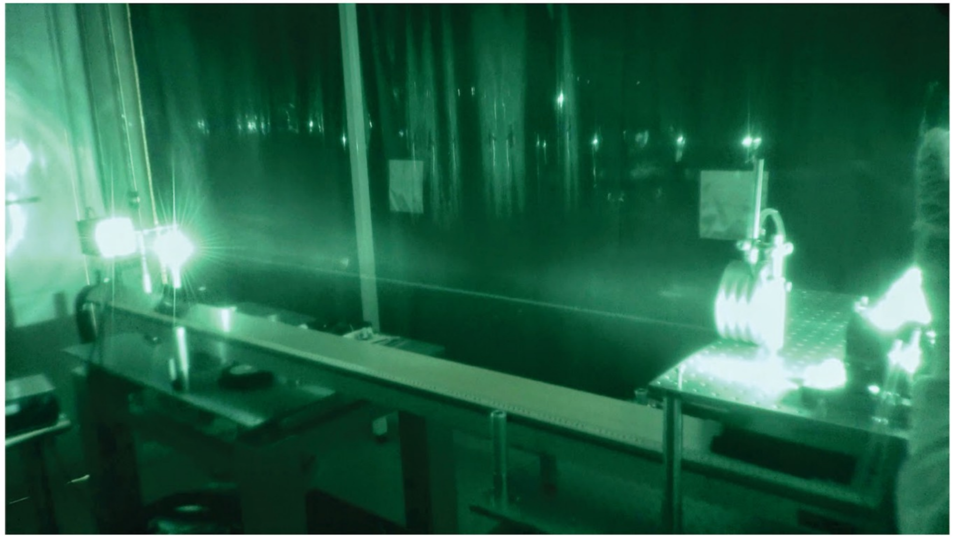
Photonic Laser Thruster: Optomechanical and Quantum Electronical Analyses

Young K. Bae*
Y. K. Bae Corporation, Corona, California 92883

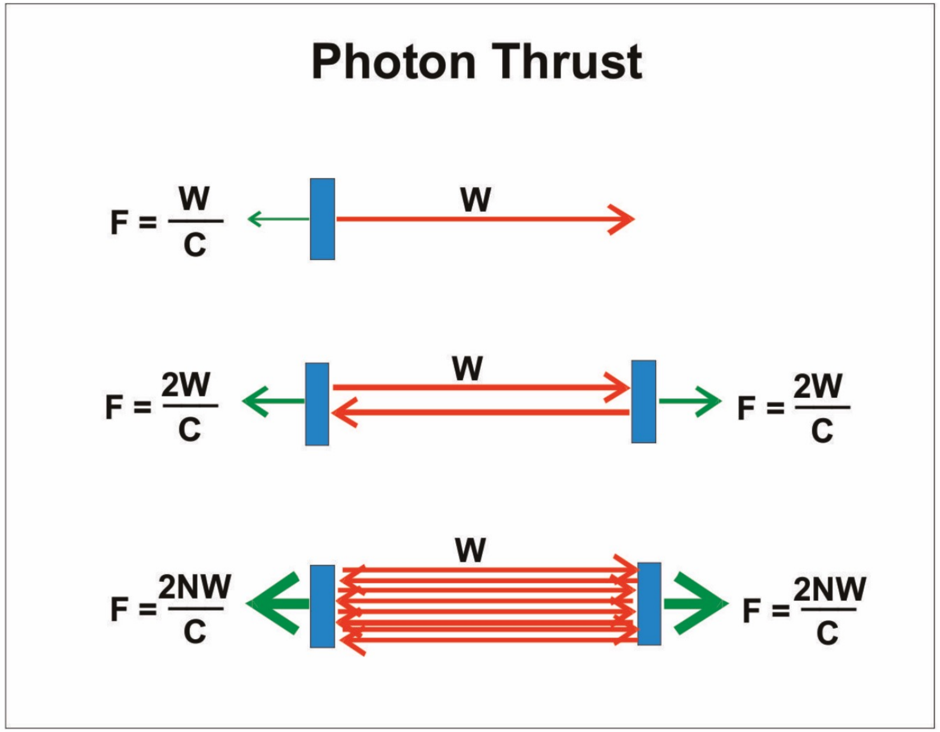
https://doi.org/10.2514/1.B38634

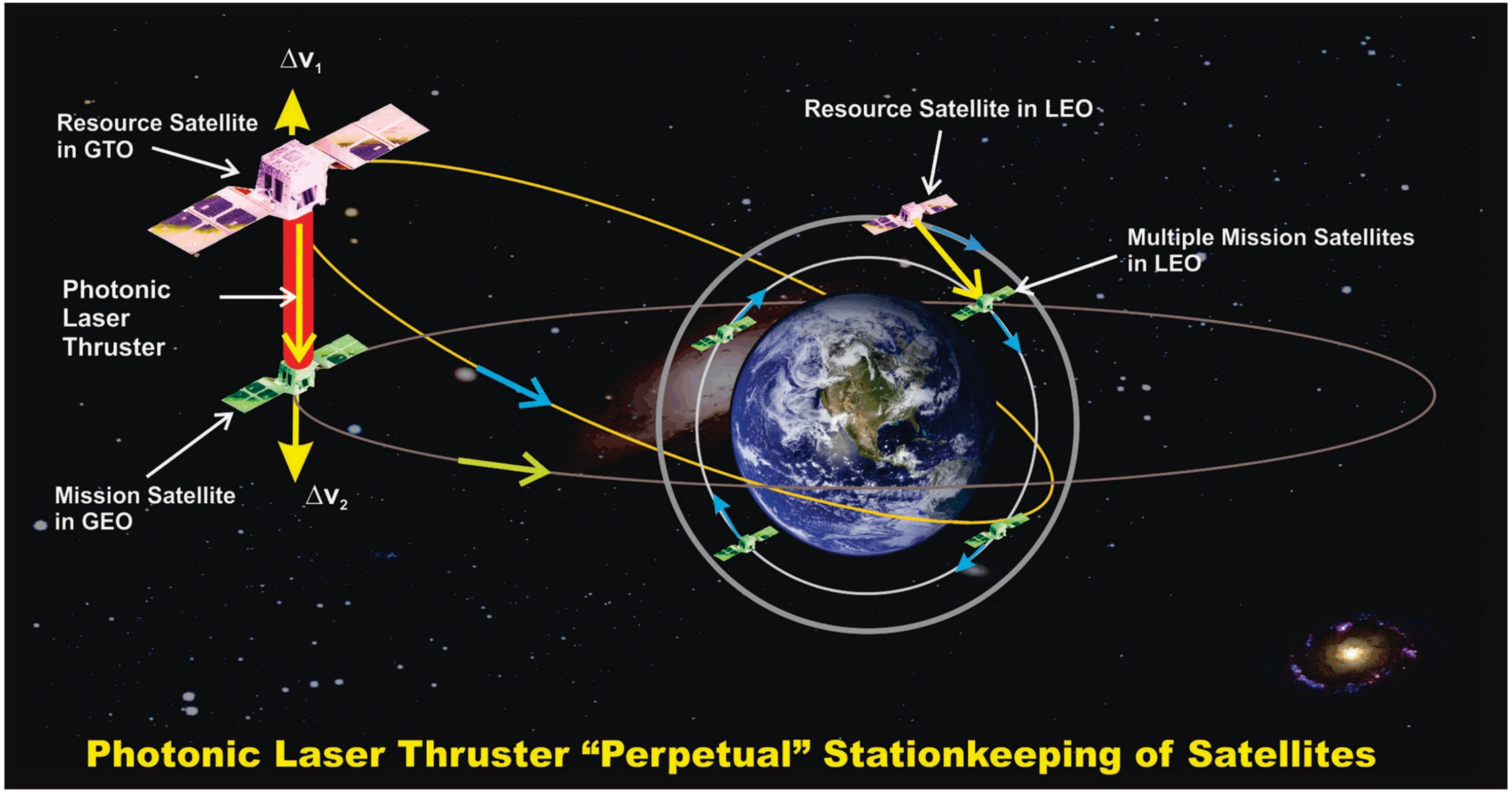
STANFORD
AERONAUTICS & ASTRONAUTICS





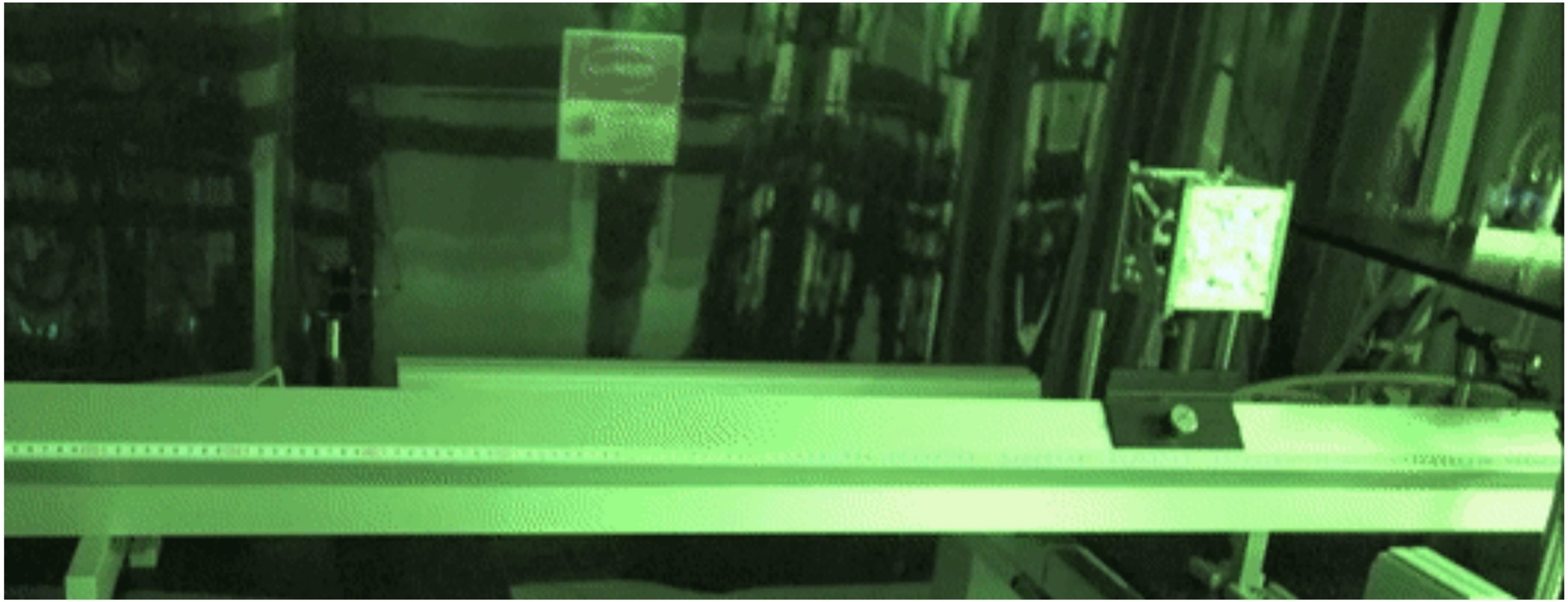
75 to 150 kilowatt laser





Δv_1
Resource Satellite in GTO
Photonic Laser Thruster
Mission Satellite in GEO
Δv_2
Resource Satellite in LEO
Multiple Mission Satellites in LEO
Photonic Laser Thruster “Perpetual” Stationkeeping of Satellites

Photonic Propulsion



https://www.youtube.com/watch?v=eHCb-ty3EBU https://www.youtube.com/watch?v=eHCb-ty3EBU