From Solar Sails to Laser Sails

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Background - Solar Sail Propulsion Technology

- Maturing rapidly – NanoSail-D, IKAROS, LightSail, Near Earth Asteroids Scout
- Solar sail filght demonstrations are incrementally advancing one of the few approaches allowed by physics that may one day take humanity to the stars.
- Continuous solar pressure provides solar sails with propellantless thrust, potentially enabling them to propel a spacecraft to tremendous speeds—theoretically much faster than any present-day propulsion system.
- Next generation of sails will enable us to take our first real steps beyond the edge of the solar system, sending spacecraft out to distances of 1000 Astronomical Units, or more.
- Descendants of first and second generation sails will augment their thrust by using high power lasers and enable travel to nearby stellar systems with flight times less than 100 years – a tremendous improvement over what is possible with conventional propulsion systems.
- By fielding these first solar sail systems NASA is actually developing a capability to reach the stars.

Background – Sail Near Term Technology Maturation

- The Planetary Society's LightSail
- Japanese Aerospace Exploration Agency's IKAROS
- NASA's Near Earth Asteroid Scout
- proposed Earth-to-Orbit Beamed Energy eXperiment (EBEX)
    - will not be quick or easy
    - development paths for solar photon sails and beamed energy sails will quickly diverge.
    - Each order of magnitude improvement in sail size (for solar photon sails) and performance (for both) will require advances
        - in materials science (sails, coatings, structures)
        - packing and deployment design (eventually in-space fabrication)
        - spacecraft attitude dynamics and control during deployment and flight
        - flight guidance, navigation and control
        - Space traffic management

Contents

- A notional solar and beamed energy sail technology maturation plan (with performance metrics) will be outlined.
- A discussion of the real-world engineering challenges facing today's first generation missions and the design and development challenges for those in the next generation will be described.
- Finally, a step-by-step approach for developing sails of increasing capability and performance will be proposed – leading to the sailcraft required for true interstellar travel.

- Focus of this effort: 3 Paths
  - Solar Sail
  - Laser Sail
  - Break Through Starshot

Solar Sails

Roadmap Development Guidelines

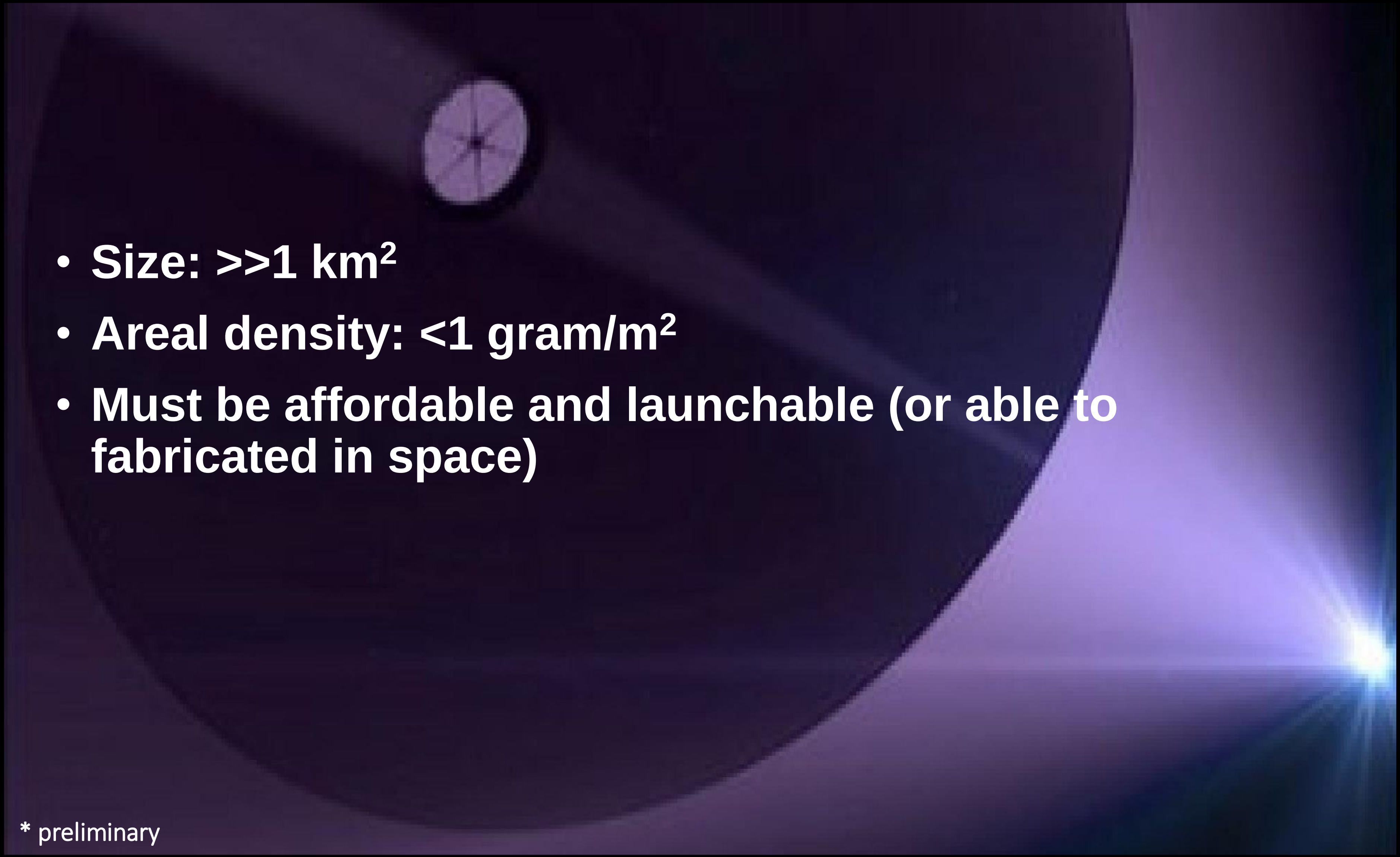
- Dates for Missions to Destinations depend on
  - Science and Exploration Priorities
  - Current state of the art
  - Required technology advancement
  - required technology and infrastructure advancement
- NASA currently has no firm interplanetary or interstellar mission objectives beyond Mars exploration – Missions presented here are authors choice
- Destinations will progress in time by distance
  - Earth-to Orbit
  - Earth Orbit to Solar System
  - Earth Orbit to Interstellar
  - Solar system to Interstellar
  - Interstellar to Solar System

Build/Launch Infrastructure

- Operations will remain Earth-based until launch cost is significantly reduced (to the point they no longer outweigh
  - Fabrication limitations of 1 g
  - Attenuation by atmosphere
  - Rotation of the Earth effect on Duty Cycle
- Lasers are only useful within local planetary space (diffraction limit and realistic apertures)
- Availability of High Power Photon Stream
  - Sun: 10^{14} TW
  - Earth-Based
    - 18 TW Earth total usage, 10^{5} TW incident solar,
    - Hydro - Largest plants (hydro): Three Gorges @ 22.5 GW, US Grand Coulee at 6.8 GW
    - Nuclear - Largest Plant Kashiwaleaki-Kariwa* @8.2 GW (7 reactors), US Palo Verde @ 4.4 GW
  - Space Based
    - ISS PV @ 120 kW
    - Nuclear (NASA Technology Roadmap)
      - Fission – 10-100 kW, <10 MW — Mars Surface Operations, 2033
      - Fission >10 MW — Nuclear Electric Propulsion, 2033
      - Fusion ~10 GW — >2033
- Key Infrastructure Masses
  - Sail Manufacturing
  - Laser+Power+Thermal+Beam Control
  - Spacecraft+Payload

Currently inoperable due to Earthquake damage.

The Sails We Need*



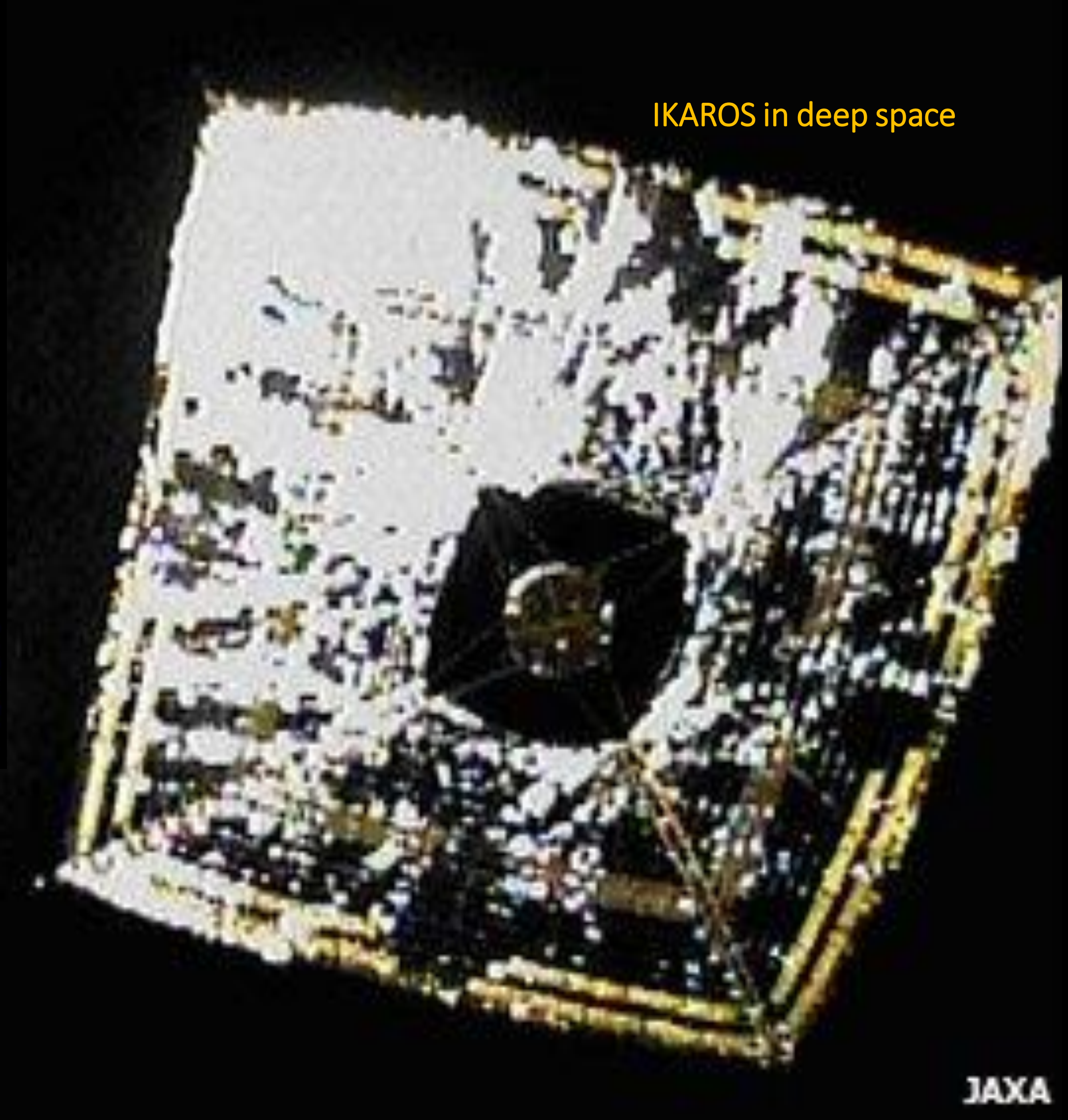
- Size: >>1 km^2
- Areal density: <1 $gram/m^2$
- Must be affordable and launchable (or able to fabricated in space)

* preliminary

The sails we have are not close to what we need

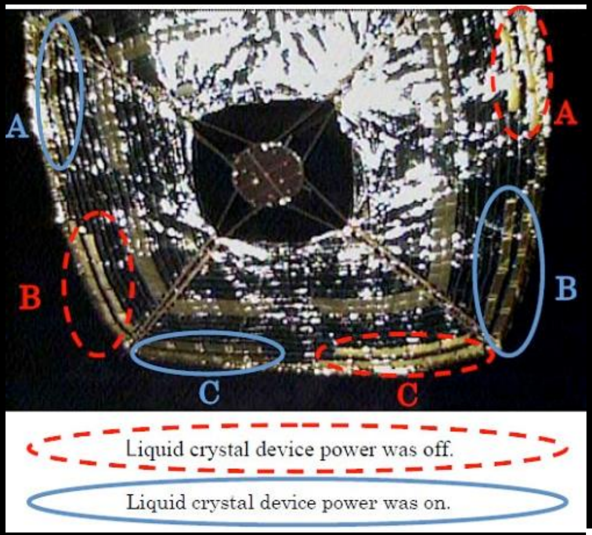
NanoSail-D as seen from the ground

IKAROS in deep space

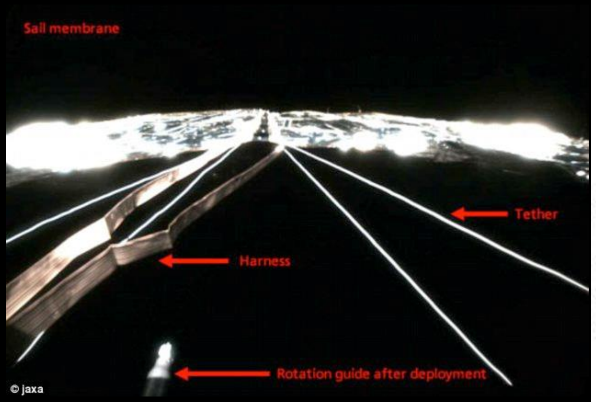


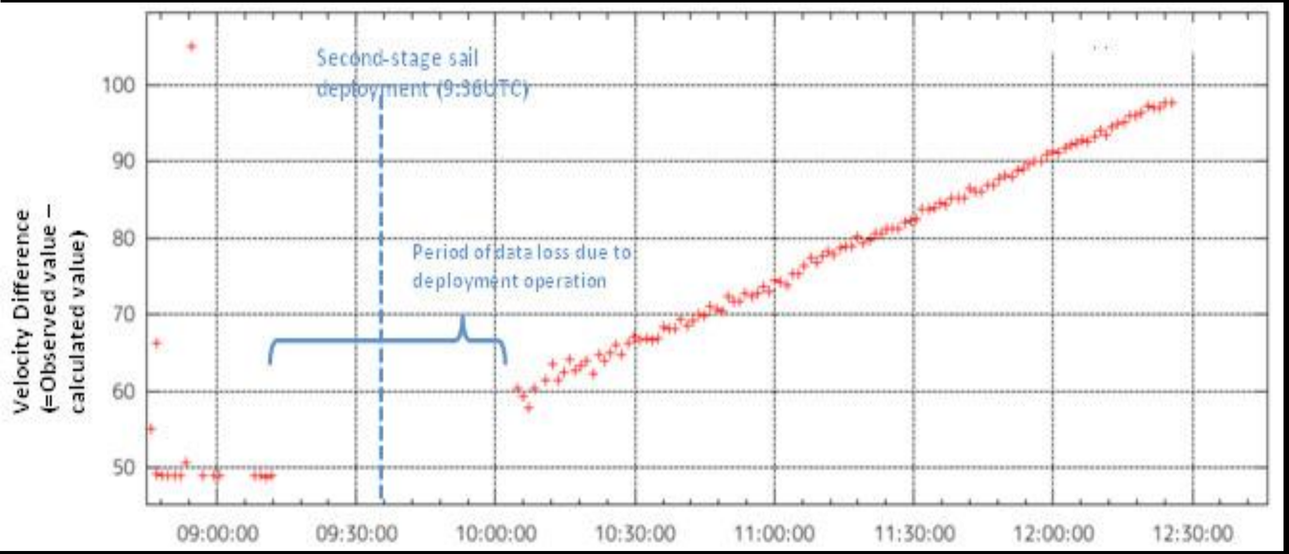
- **Size: ~100 m^2 to ~200 m^2**
- **Areal density: 25 - 300 g/m^2**

Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)

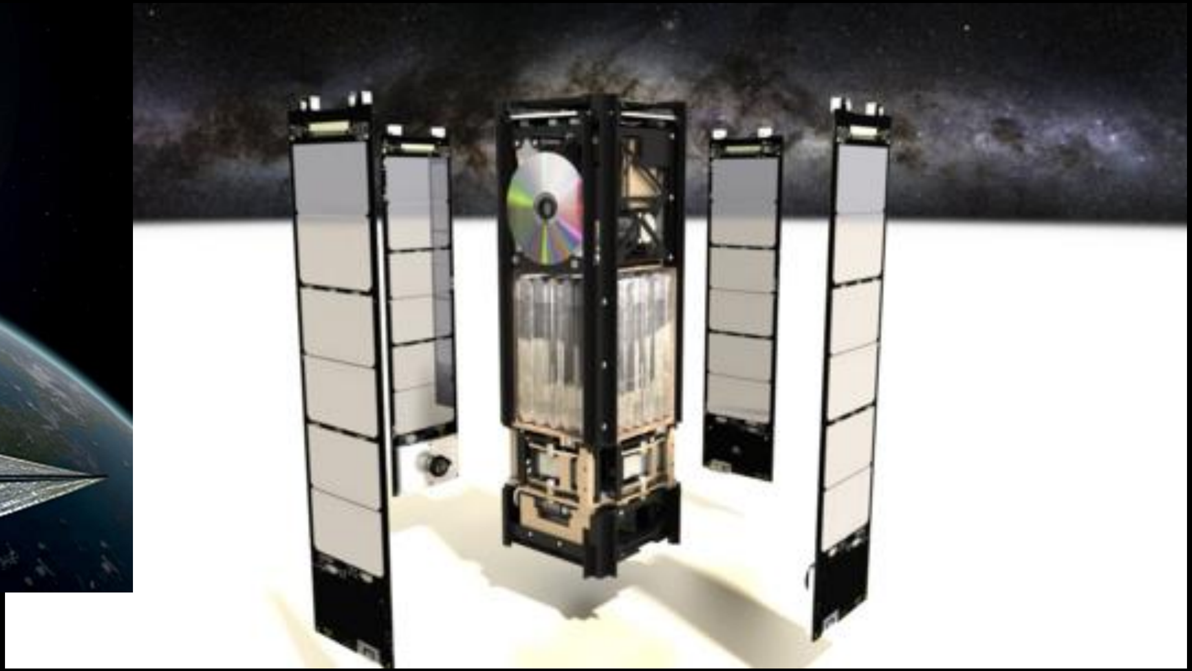


Configuration / Body Diam.	1.6 m x Height 0.8 m (Cylinder shape)
Configuration / Membrane	Square 14 m and diagonal 20 m
Weight	Mass at liftoff: about 310 kg





LightSail-A and -B

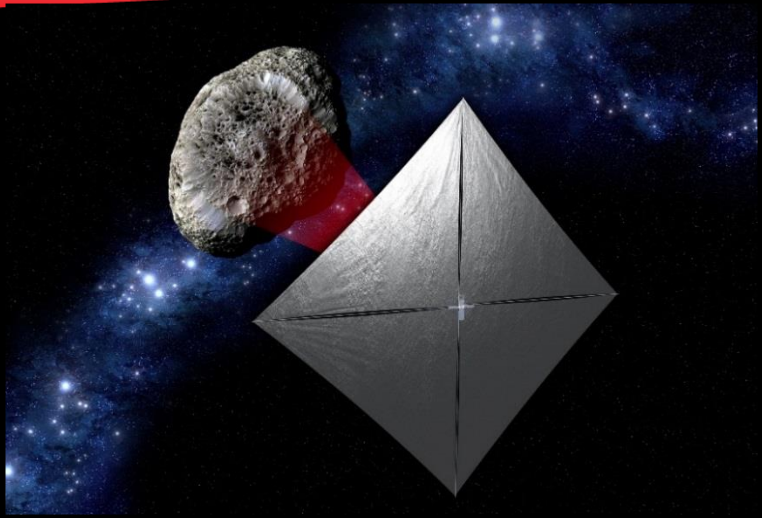


- 3U Cubesat design
- Sail Material: aluminized 4.5 micron Mylar film
- 32 square meters solar sail area fully deployed
- LightSail-A (flew 2015) and LightSail-B (2016)

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

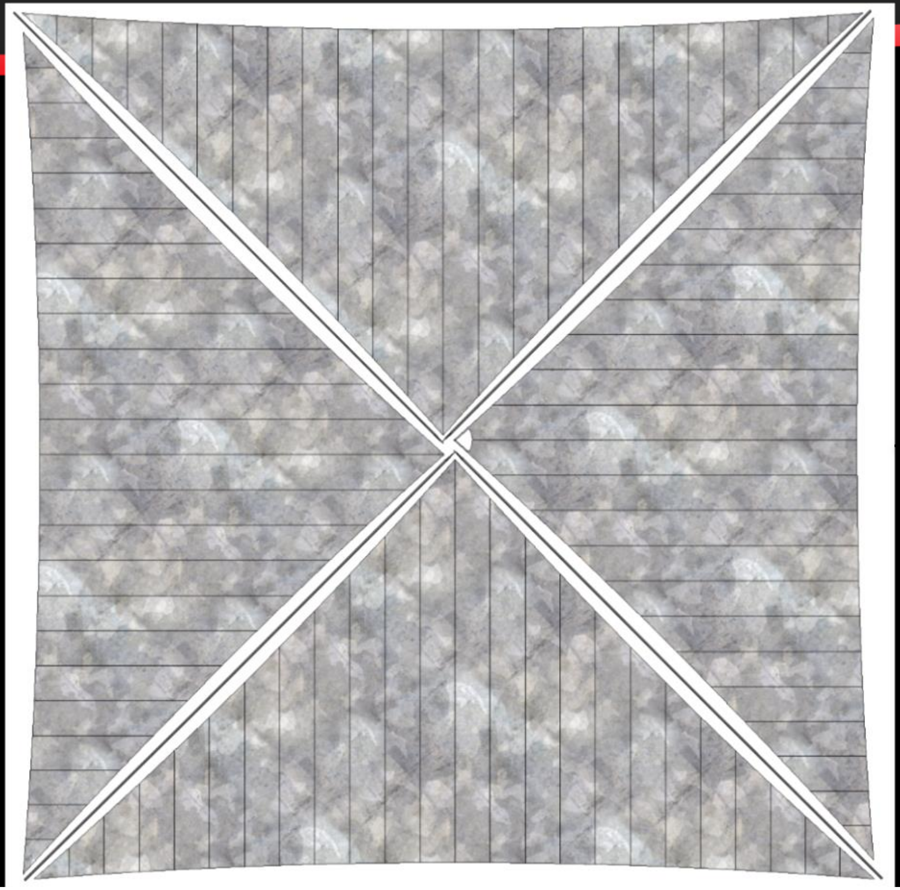
- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~86 m^2 solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2019)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

Solar Sail Propulsion System Characteristics

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

NEA Scout SAIL Approximate Scale

Deployed Solar Sail



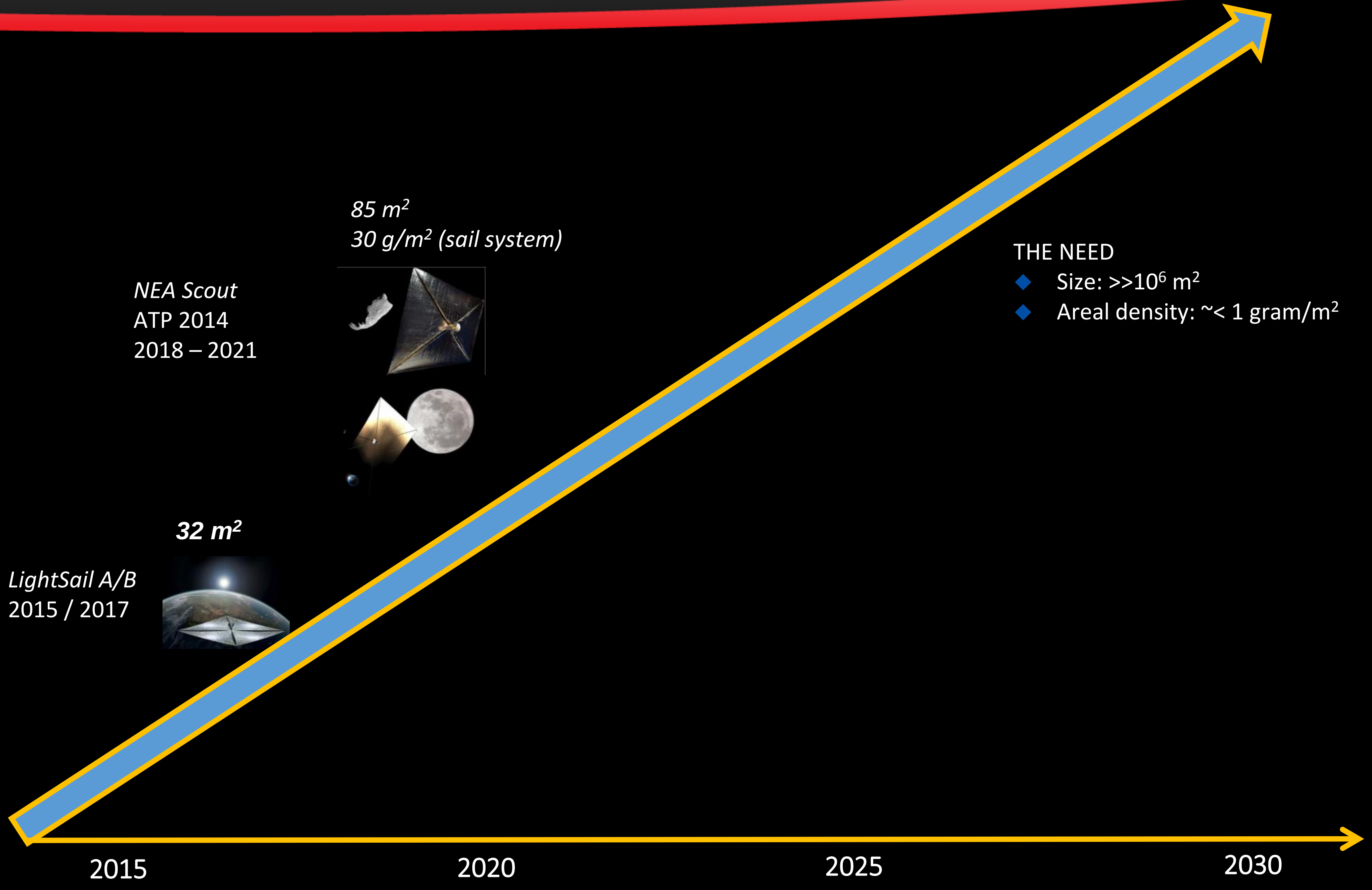
School Bus

Human

6U Stowed Flight System

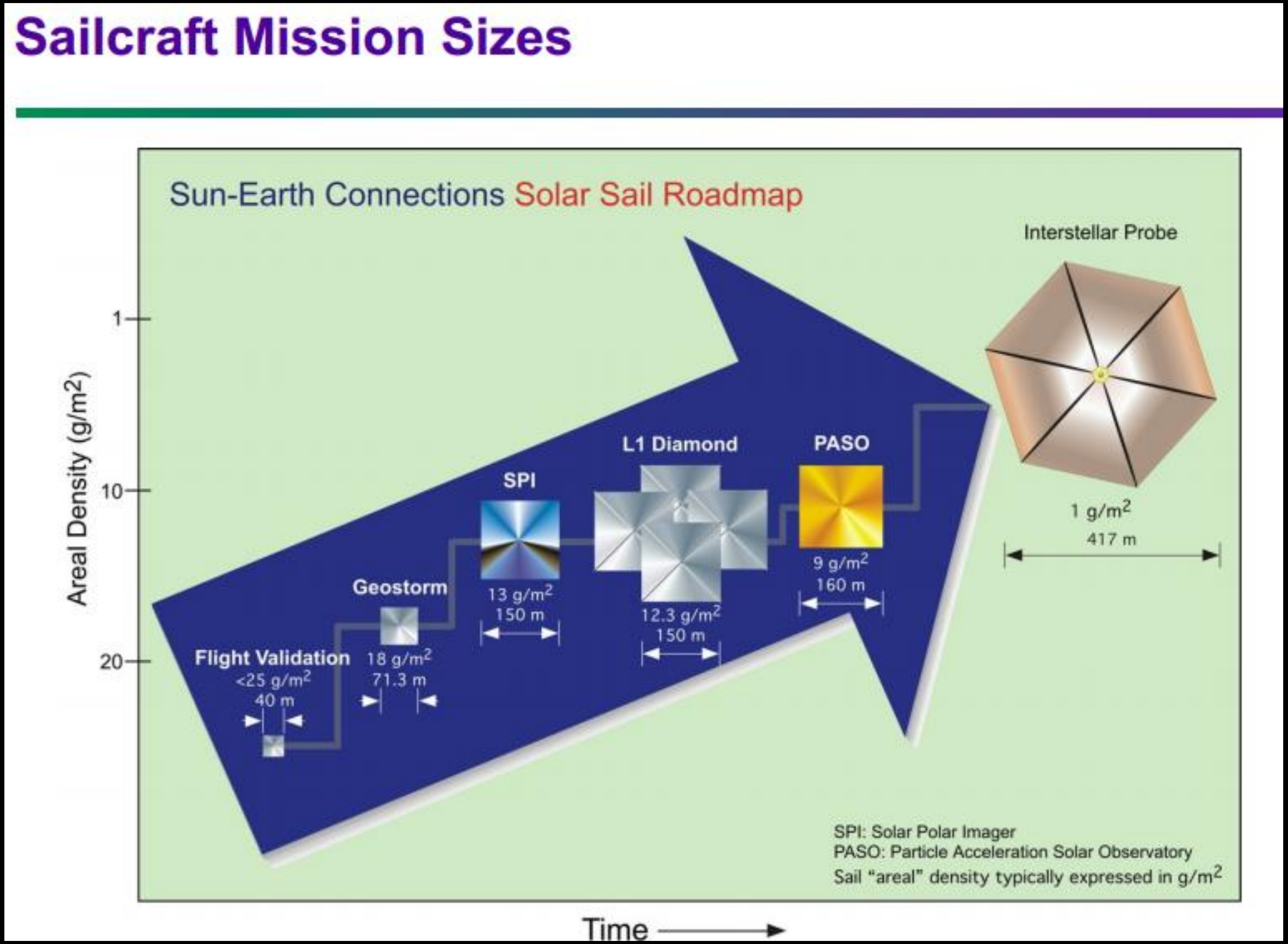
Folded, spooled and packaged in here

No Sail Missions Yet Approved Beyond 2018



Solar and Beam Energy Maturation Plan

NASA Solar Sail Roadmap (circa 2005)



Optimal Solar Sail Trajectories to Outer Solar System and Beyond

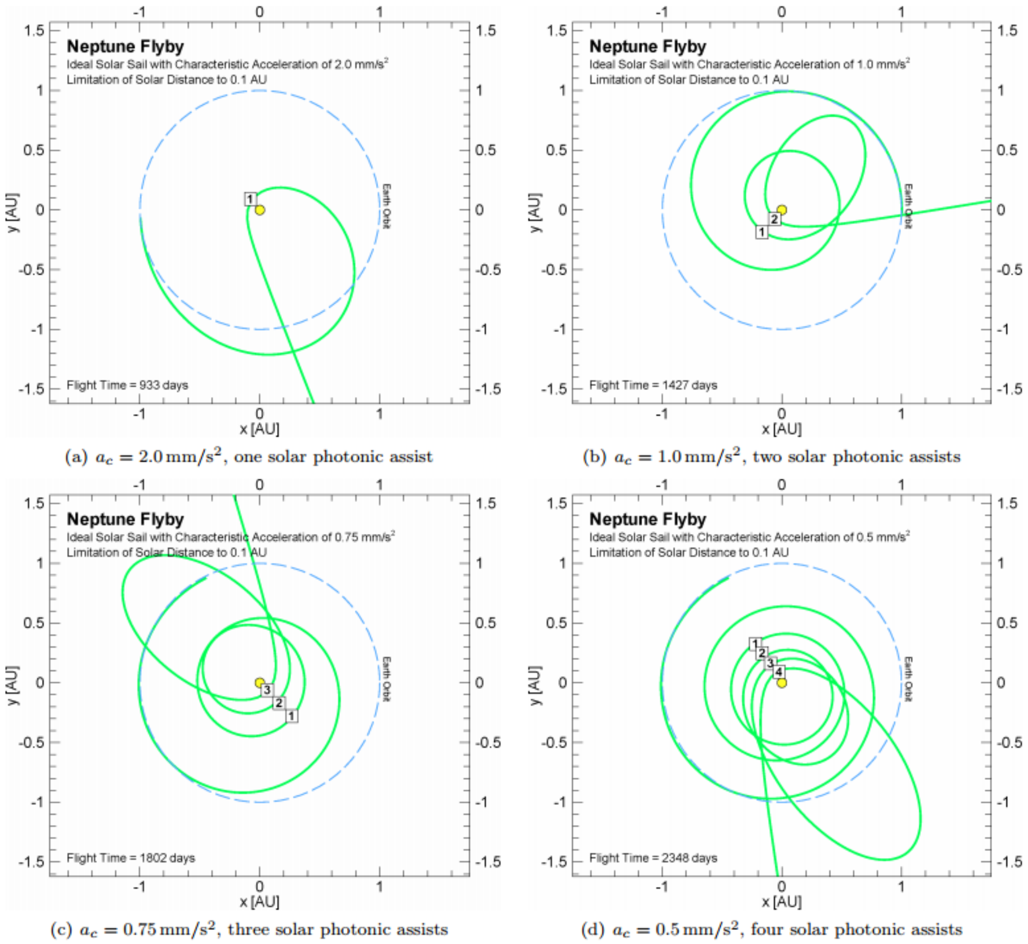
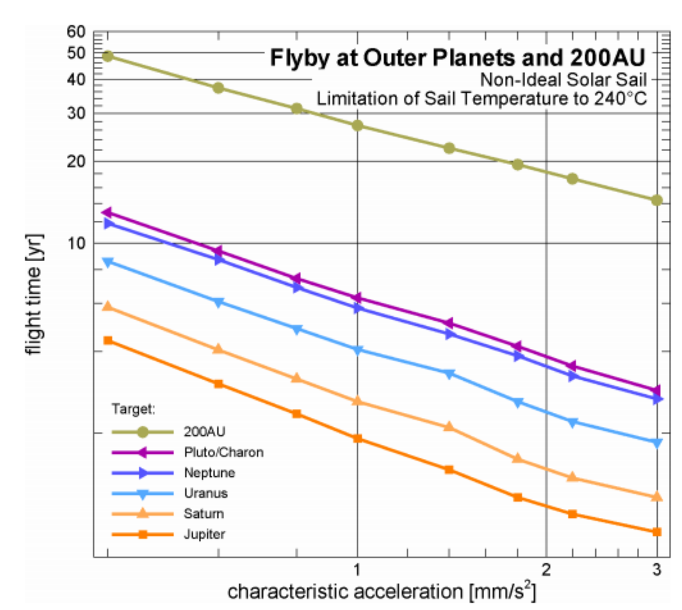


Figure 6. Topology of optimal Neptune flyby trajectories for different characteristic accelerations (ideal sail, $r_{\mathrm{lim}} = 0.1$ AU)

Faster trip times come with higher characteristic acceleration (a_c) and sail temperature limits

NEAS-type sail

$a_c = 8.3 \times 10^{-6}$ * (sail area/sailcraft mass)



From "Optimal Solar Sail Trajectories for Missions to the Outer Solar System", by Bernd Dachwald, German Aerospace Center (DLR), Cologne, Germany, AIAA/AAS Astrodynamics Specialist Conference and Exhibit, AIAA 2004-5406, 16 - 19 August 2004, Providence, Rhode Island

Laser Sails

Optimal Laser Sail Trajectories to Outer Solar System and Beyond

- To Be Determined – Much study needed

- Laser photons in addition to solar photons will increase characteristic acceleration for the same sail area and sailcraft mass – as long as sail can withstand additional thrust loads and heating
- Laser in low Solar orbit (beaming tangential to sun)
  - Optimal place to add energy to an orbit is at its closest approach to central body (sun).
  - At perihelion, the sail attitude should be edge on to the sun to reduce thermal load (while still benefiting from gravity assist)
  - Before and After perihelion, the sail should orient to more normal with the sun to capture high flux for thrust .
  - Located near sun, laser would enjoy ample power harnessed from solar energy
- Laser in Solar Orbit
  - Action distance of laser is small on interplanetary scale, even for very large sails and beam directors
  - Cycler orbits may be possible to allow multiple conjunctions between laser and sail craft
  - Nuclear Fusion Power likely necessary for lasers based or orbiting in outer solar system to be effective

Background – Laser Near Term Technology Maturation

- FEL – scalable due to vacuum media, large footprint, highest power achieved ~11 watts, minimal current research
- Chemical
  - CO_2, COIL – USAF Airborne Laser , Boeing 747, MW class, scrapped 2014
  - Deuterium Fluoride – MIRACL, MW class, last operational 1997
- Solid State
  - Diode pumped
    - Solid State – JHPPSL – US Army – 100kW in lab, GBAD
    - Fiber – US Army RELI in HELMTT, 10 kW, 60 kw in 2018
      - Tiled Arrays – LaWS in USS Ponce – 30 kW, 150 kW in 2018
      - Phased Arrays – DARPA lab – Excalibur – 21 kW, currently ?
        - Spectrally Combined
        - Coherently Combined
    - Rare Gas and alkali lasers, TRL 1-3 lab experiments
    - Direct Diode – commercially available up 8 kW, beam quality a challenge
  - Atom (BEC) Laser – TRL 2

On-Orbit Beam Directors
Aperture and Mass

0.5 m
1500 kg


High Energy Laser Mobile Demonstrator

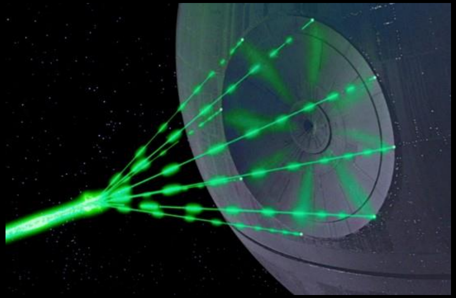
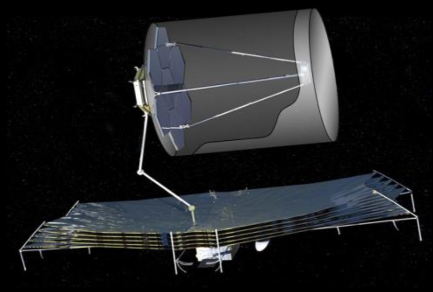
2.4
2920


Hubble Space Telescope

8.0
6500

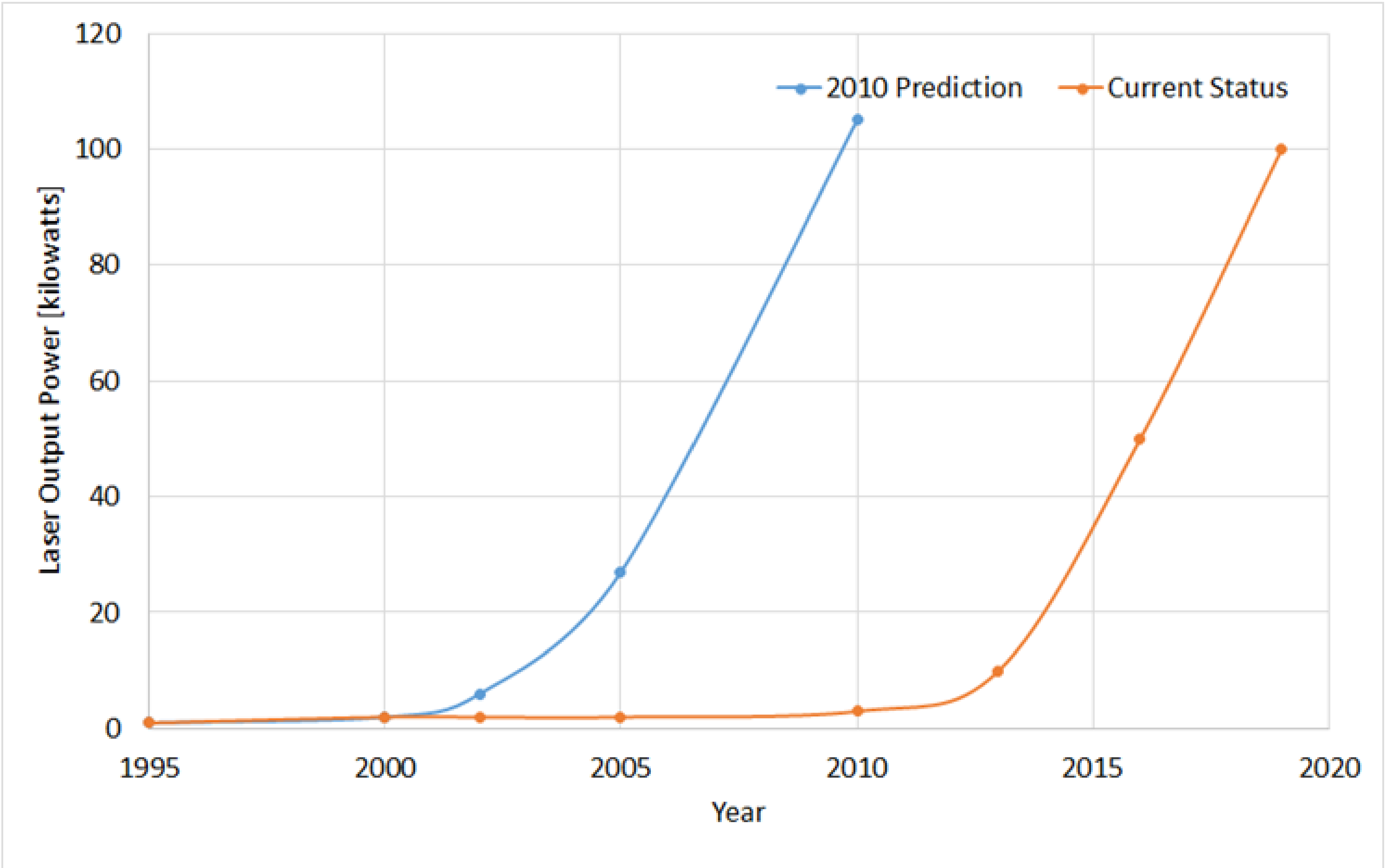

James Webb Space Telescope

20
36,000

Advanced Large Aperture Space Telescope Concept

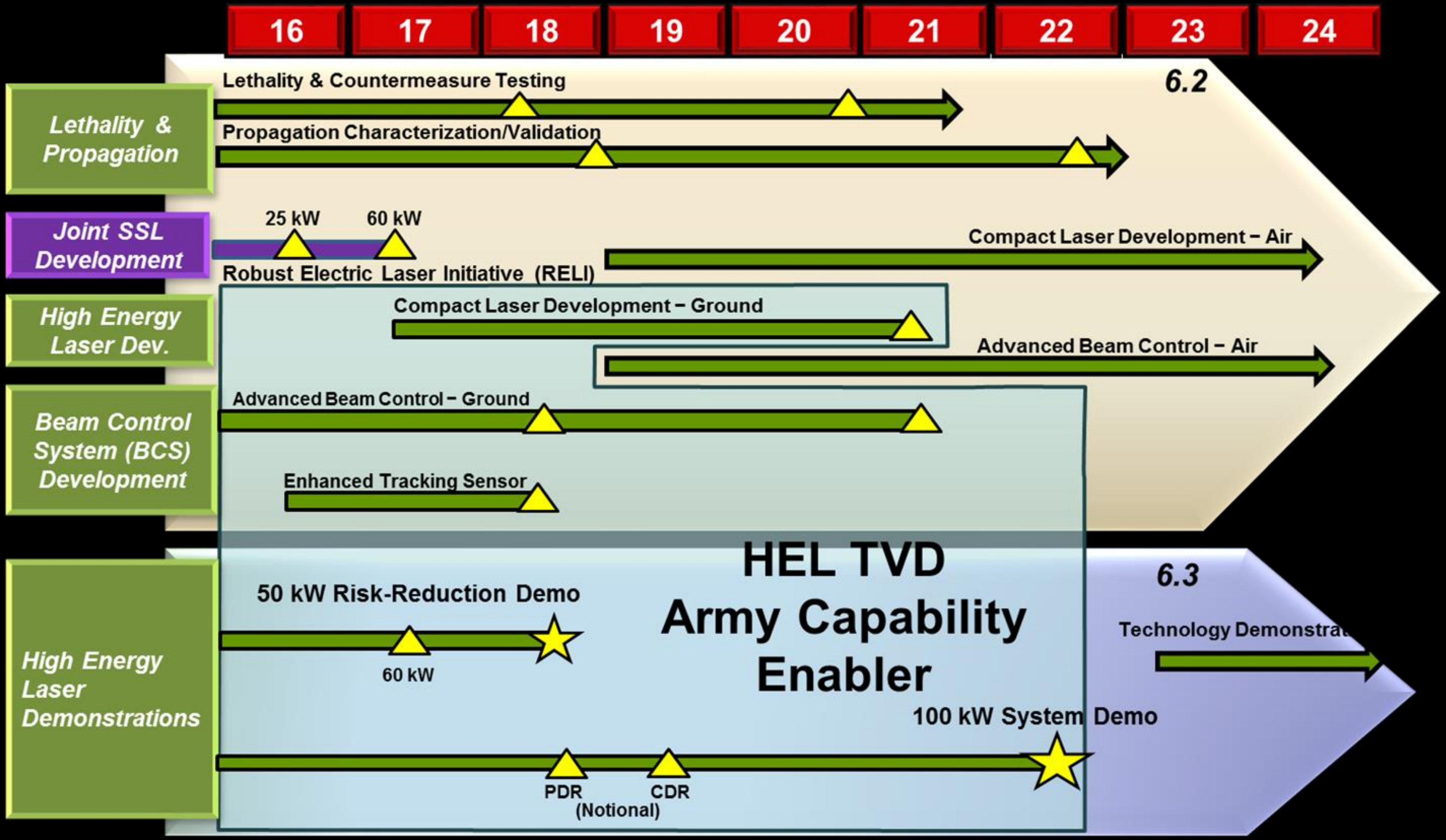
Update to 2010 BEP Symposium Presentation: Exponential Growth of Continuous Working Solid State Lasers



2010 Prediction Source: “Solid-State Laser Weapon Systems, Bridging the Gap — or Bridge Too Far?”, by Andrew Krepinevich, Tom Ehrhard, and Barry Watts, Center for Strategic & Budgetary Assessments (CSBA), May 20, 2009.

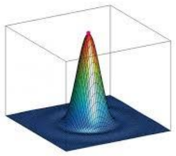
US Army High Energy Laser Roadmap

(as of May 2017)



Beaming Interplanetary distances

The diameter of the sailcraft d, is set equal to the diameter of the first Airy ring at a range R from a circular beam director aperture D. Assuming a 1 micron wavelength LEO-based laser, perfect beam and optics, no atmosphere, and no jitter, that relationship follows from the Fraunhofer Diffraction equation[1] to be

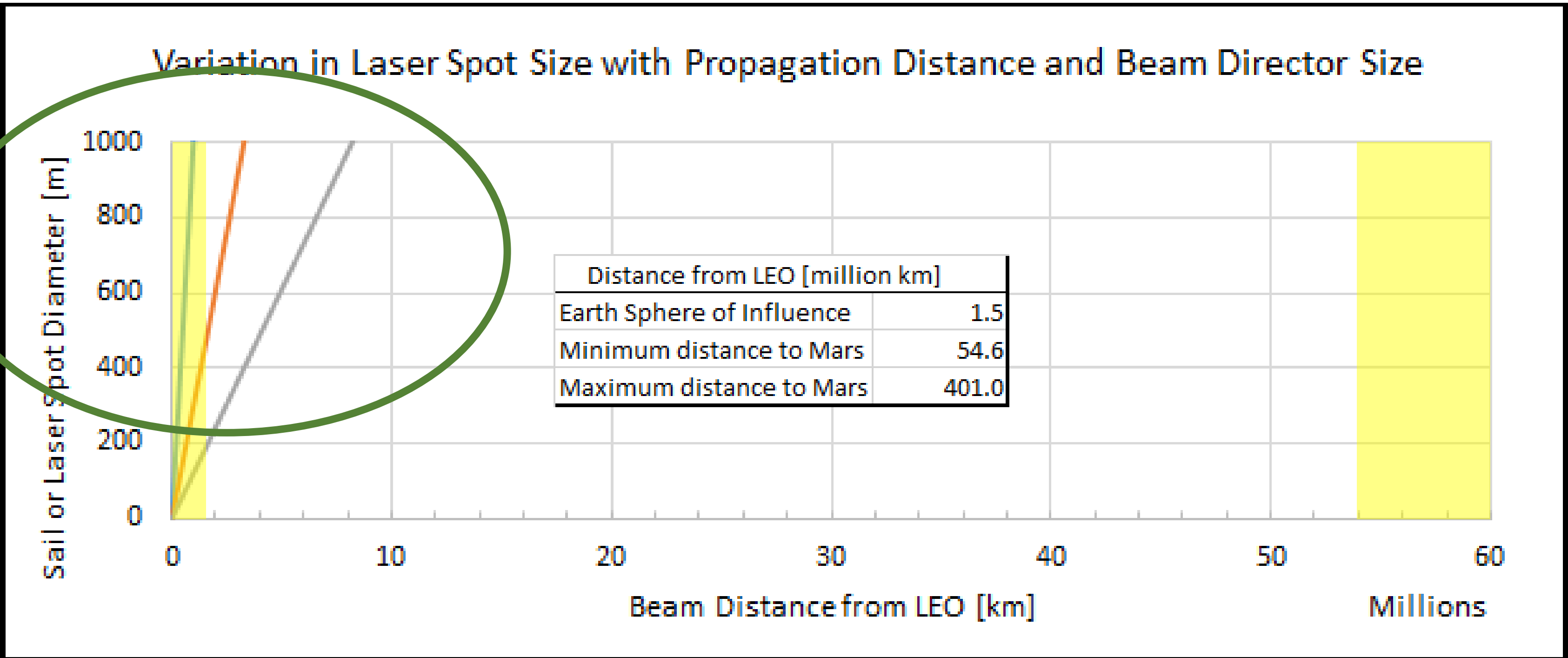


$d = 2.44\, R\, \lambda / D$ ← Independent of laser power level

The total power ($\mathcal{P}$) within the first Airy ring projected onto a surface from a laser with power $\mathcal{P}_o$ is:

$\mathcal{P} = 0.838\, \mathcal{P}_o$ ← Independent of propagation distance

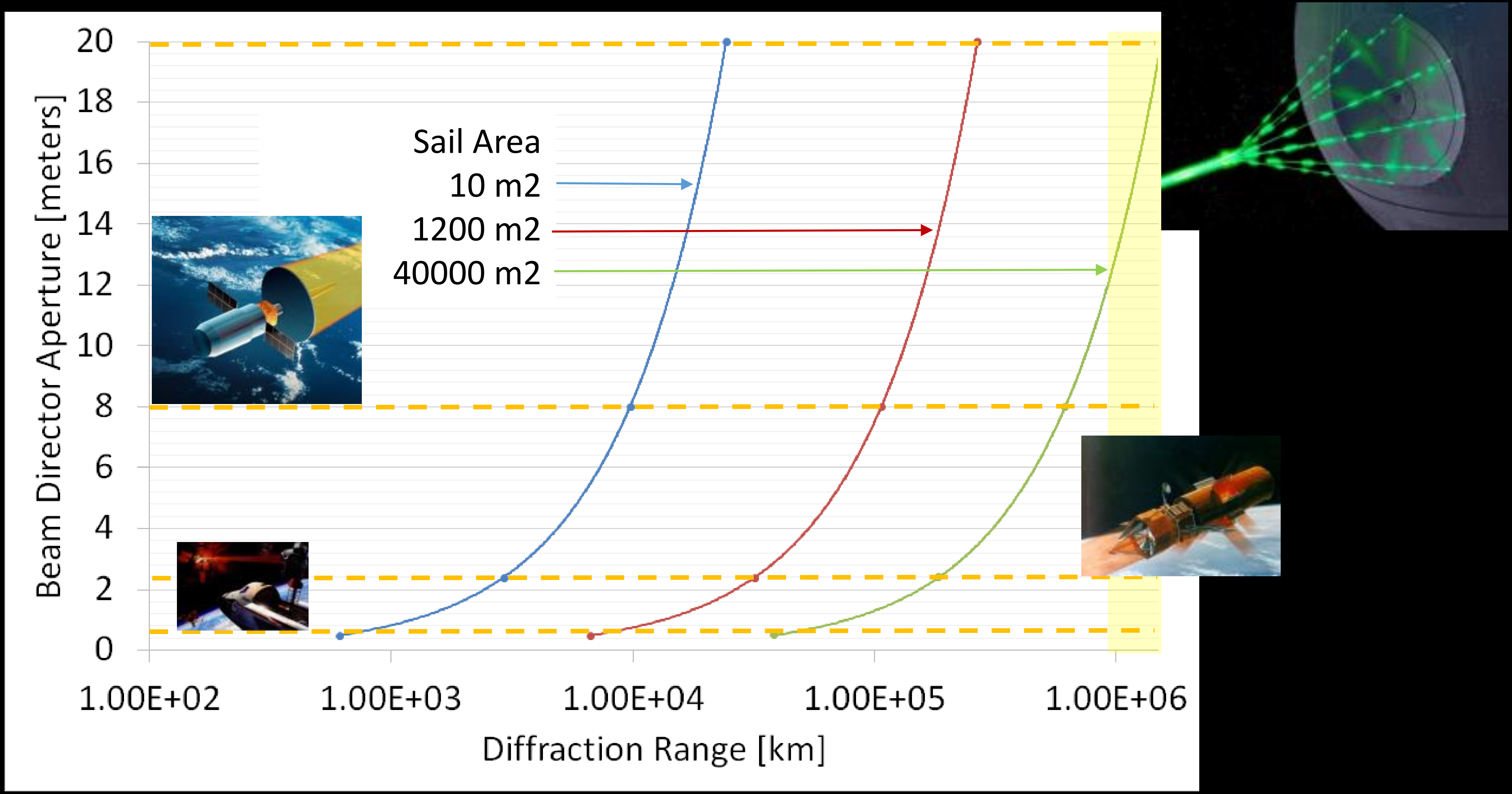
See next chart



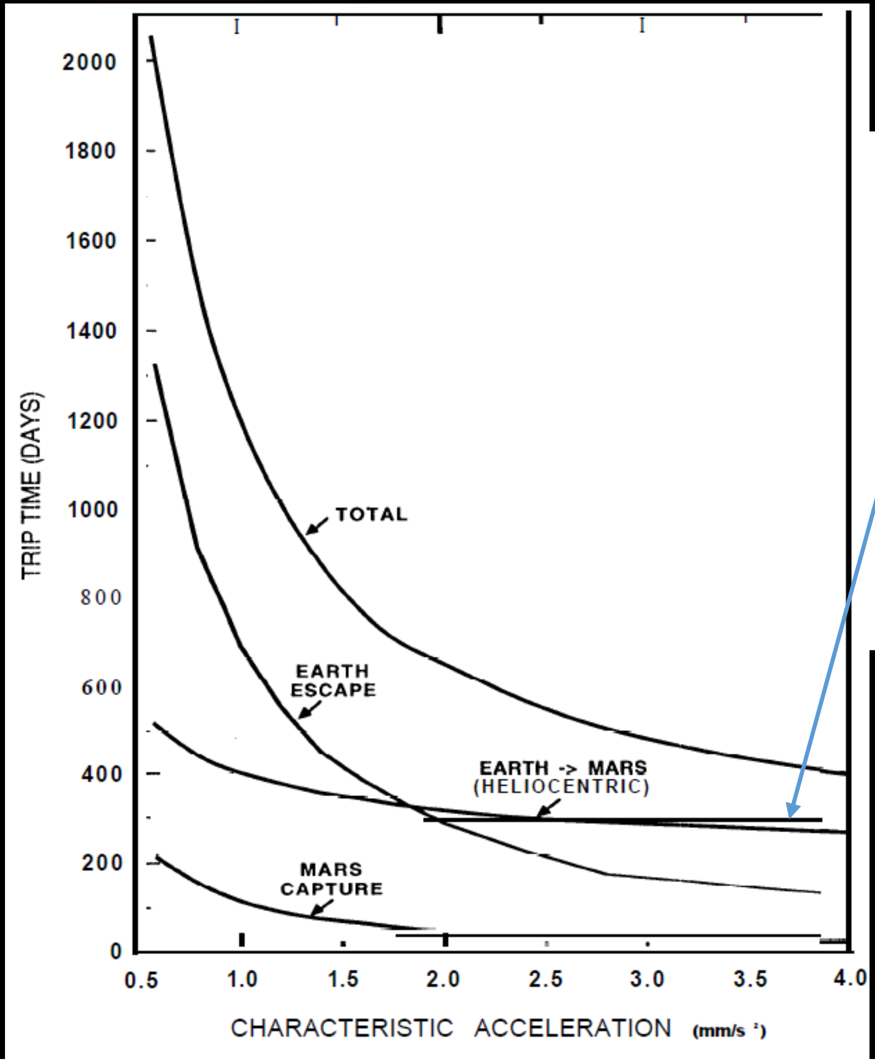
[1] M. Born and E. Wolf, Principles of Optics (Pergamon Press, New York, 1965)

Even Largest Beam Director Considered Does Not Fill Sails Beyond the Earth's Gravitational Sphere of Influence (Hill Radius)

1 micron wavelength, diffraction-limited laser in LEO @ 200 km



Earth to Mars Trip Time Shortened by Increasing Characteristic Acceleration of the Sailcraft



[after Robert H. Frisbee and John R. Brophy, Jet Propulsion Laboratory, “Inflatable Solar Sails for Low-Cost Robotic Mars Missions”, AIAA 97-2762, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 6-9, 1997, Seattle, WA]

Radiation Pressure (α=0 maximum)

Solar Distance	μPa (μN/m^2)
0.20 AU = close	227
0.39 AU = Mercury	60.6
0.72 AU = Venus	17.4
1.00 AU = Earth	9.08
1.52 AU = Mars	3.91
3.00 AU = asteroid	1.01
5.20 AU = Jupiter	0.34

[after, Wright, Jerome L. (1992), Space Sailing, Gordon and Breach Science Publishers]

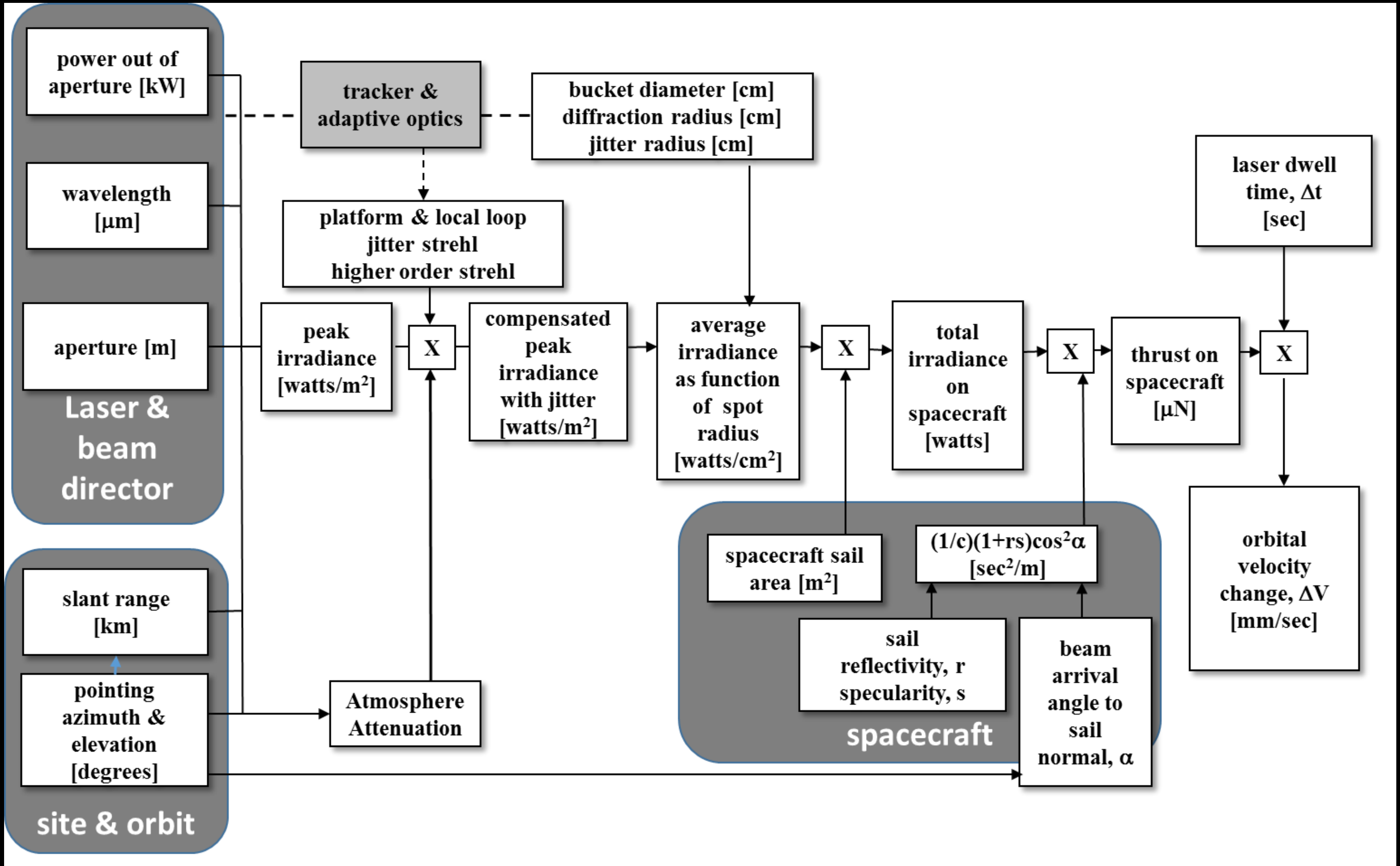
EBEX, Earth-to-Orbit Beamed Energy Experiment Mission Concept Study

Ground Site Candidates

- For this assessment only considered sites that had previously hosted outdoor HEL operations or were controlled-access, space observation installations
- Site latitude with respect to orbital inclination important

Ground Site	Latitude (deg)	Longitude (deg)	Altitude (km)
Haleakala	20.7085	-156.258	3.057
Huntsville, AL	34.6064	-86.6557	0.171
Kwajalein	8.71955	167.719	0.05904
North Obscura Peak, NM	33.7522	-106.372	2.400
Santa Cruz	37.1399	-122.202	0.710
Santa Rosa Island, FL	30.3979	-86.7291	0.000
Starfire Optical Range	34.9642	-104.464	1.871
White Sands	32.6325	-106.332	1.205

EBEX Performance Analysis Method



- Method based on:
- "Beam Control for Laser Systems", by Dr. Paul Merritt, published by the Directed Energy Professional Society, Albuquerque, N.M., 2012, Library of Congress Control Number: 2010929641]
- "Linear Photonic Thrust Model and its Application to the L'Garde Solar Sail Surface", by Gyula Greschik, 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 8-11, 2013, Boston, Massachusetts

Power Delivered to Orbit

$$\text{Let } \sigma^2 = \sigma_D^2 + \sigma_j^2$$

$$I_{ave}(r_A) = \frac{1}{\pi r_A^2} \int_0^{2\pi} \int_0^{r_A} I_{PJ} e^{\frac{-r^2}{2(\sigma_D^2+\sigma_j^2)}} r dr d\theta$$

$$I_{ave}(r_A) = \frac{1}{\pi r_A^2} \int_0^{2\pi} \int_0^{r_A} I_{PJ} e^{\frac{-r^2}{2\sigma^2}} r dr d\theta = \frac{I_{PJ}}{\pi r_A^2} \int_0^{2\pi} d\theta \int_0^{r_A} e^{\frac{-r^2}{2\sigma^2}} r dr = \frac{I_{PJ} 2\pi}{\pi r_A^2} \int_0^{r_A} e^{\frac{-r^2}{2\sigma^2}} r dr$$

$$I_{ave}(r_A) = \frac{2 I_{PJ} \sigma^2}{r_A^2} \left[1 - e^{\frac{-r_A^2}{2\sigma^2}} \right] = \frac{2 I_{PJ} (\sigma_D^2 + \sigma_j^2)}{r_A^2} \left[1 - e^{\frac{-r_A^2}{2(\sigma_D^2+\sigma_j^2)}} \right] \quad (2.10)$$

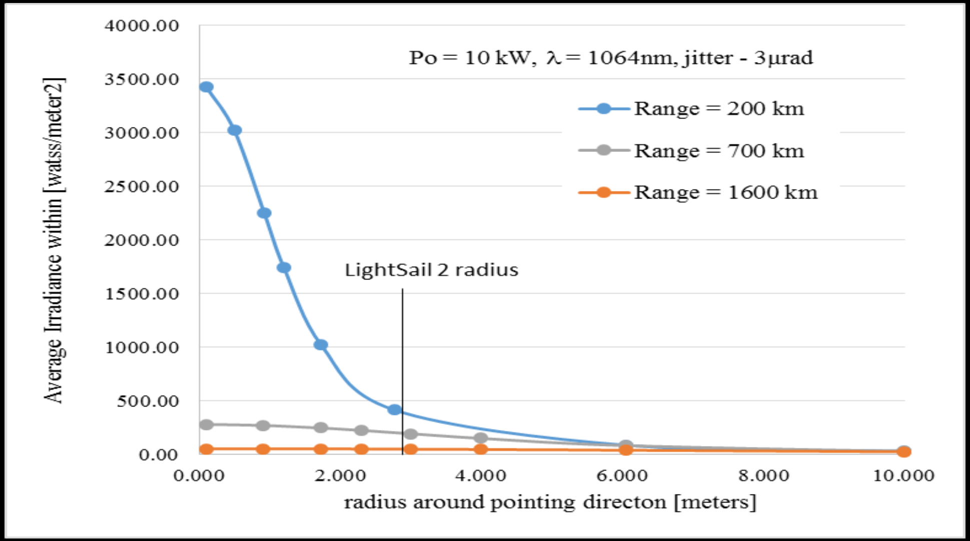
Power in spot, P = I_{ave} * Area

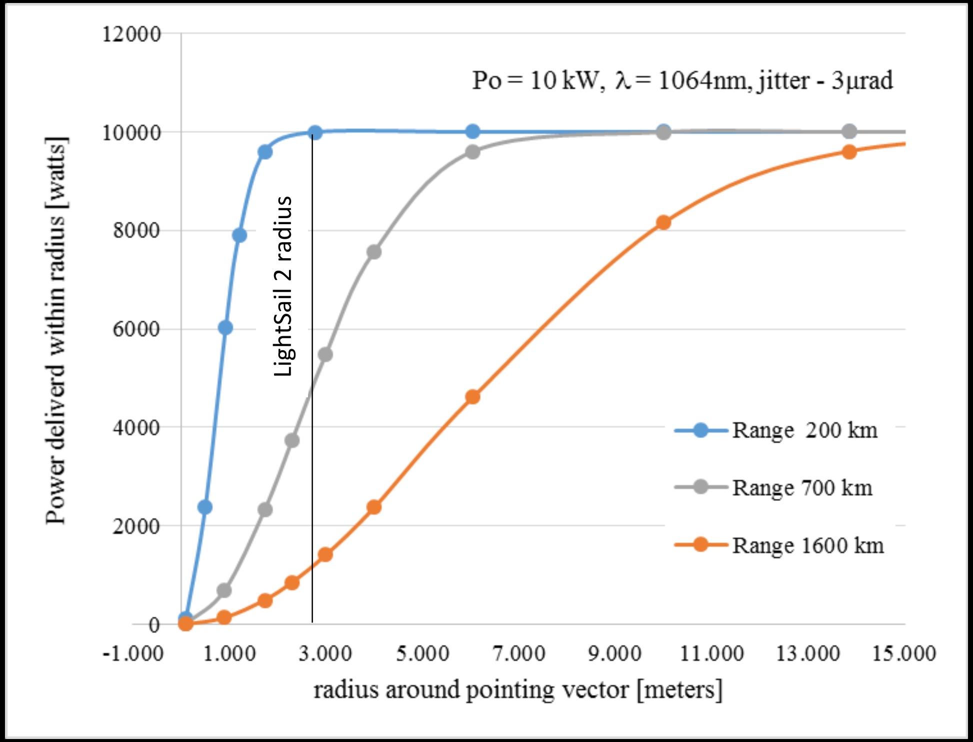
where Area = p r_A^2

s_j = jitter

s_D = diffraction

I_{pj} = I_{peak} *s_j



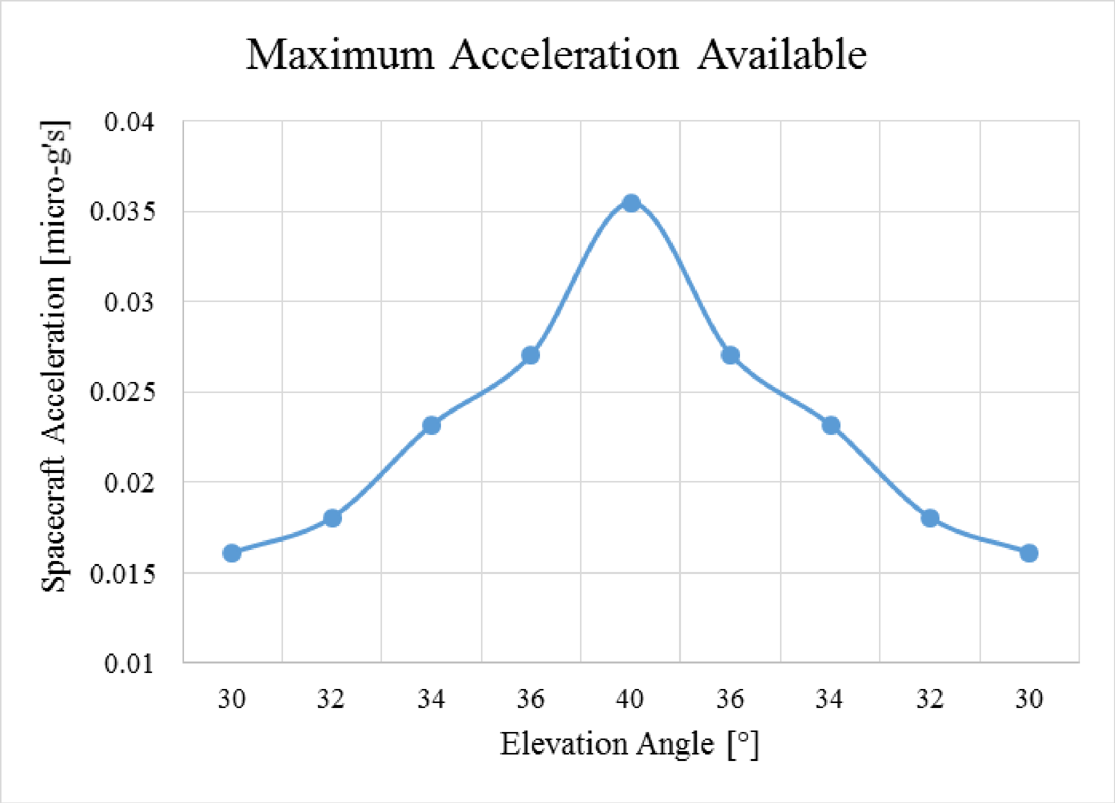


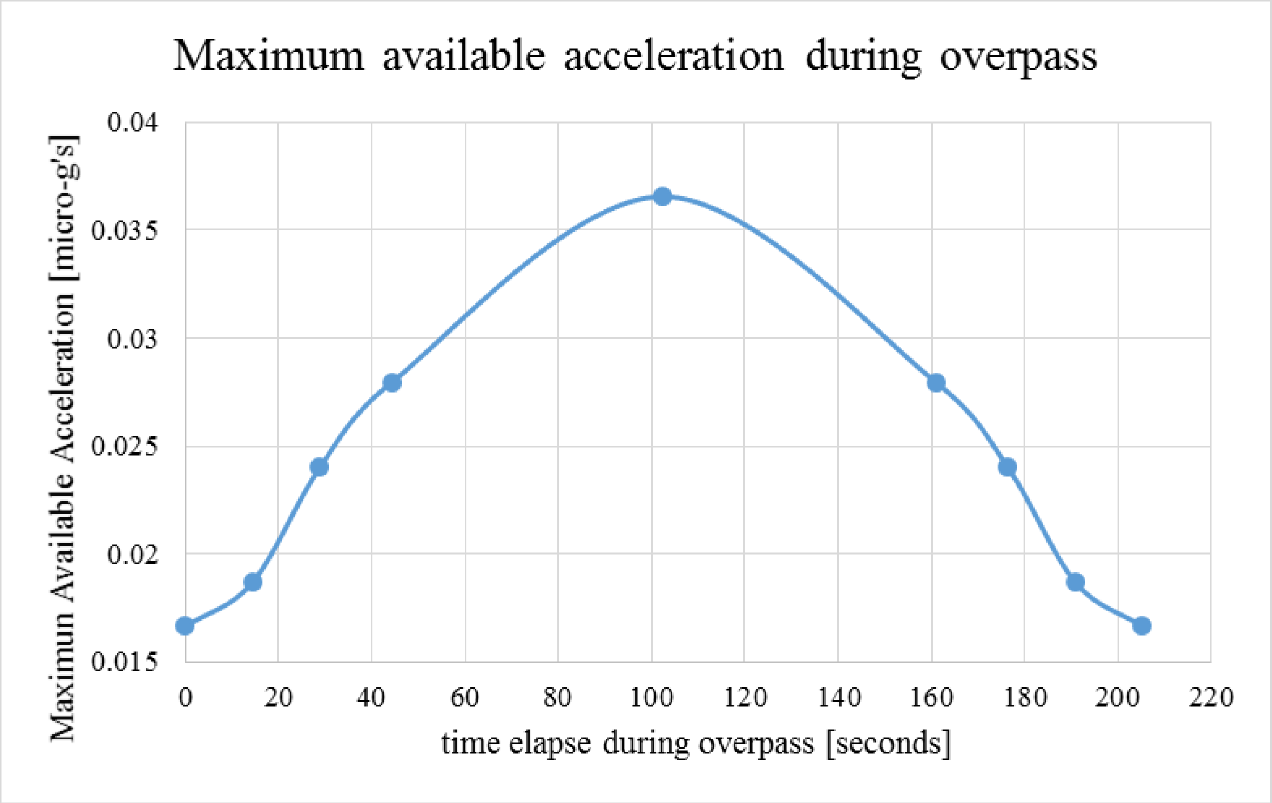
Diffraction and jitter combine to “spill” ~50% of energy past LightSail 2 at 700 km orbit altitude

Max Effect of Laser on LightSail 2

[for 13 May 2017 Opportunity 1]

- 10kw, 1064 nm cw laser
- 30 cm beam director aperture
- 3 μrad jitter, $M^2 = 1.1$
- 32 m^2 Sail Area, 0.92 specular reflection
- 5 kilogram spacecraft mass
- 720 km circular orbit @ 24 ° inclination
- Ground site: Eglin AFB, FL
- 0.71 transmittance factor
- $\sigma_{DIFF} = R * 0.45\ \lambda/D$





Max ΔV of Laser on LightSail 2

[for 13 May 2017 Opportunity 1]

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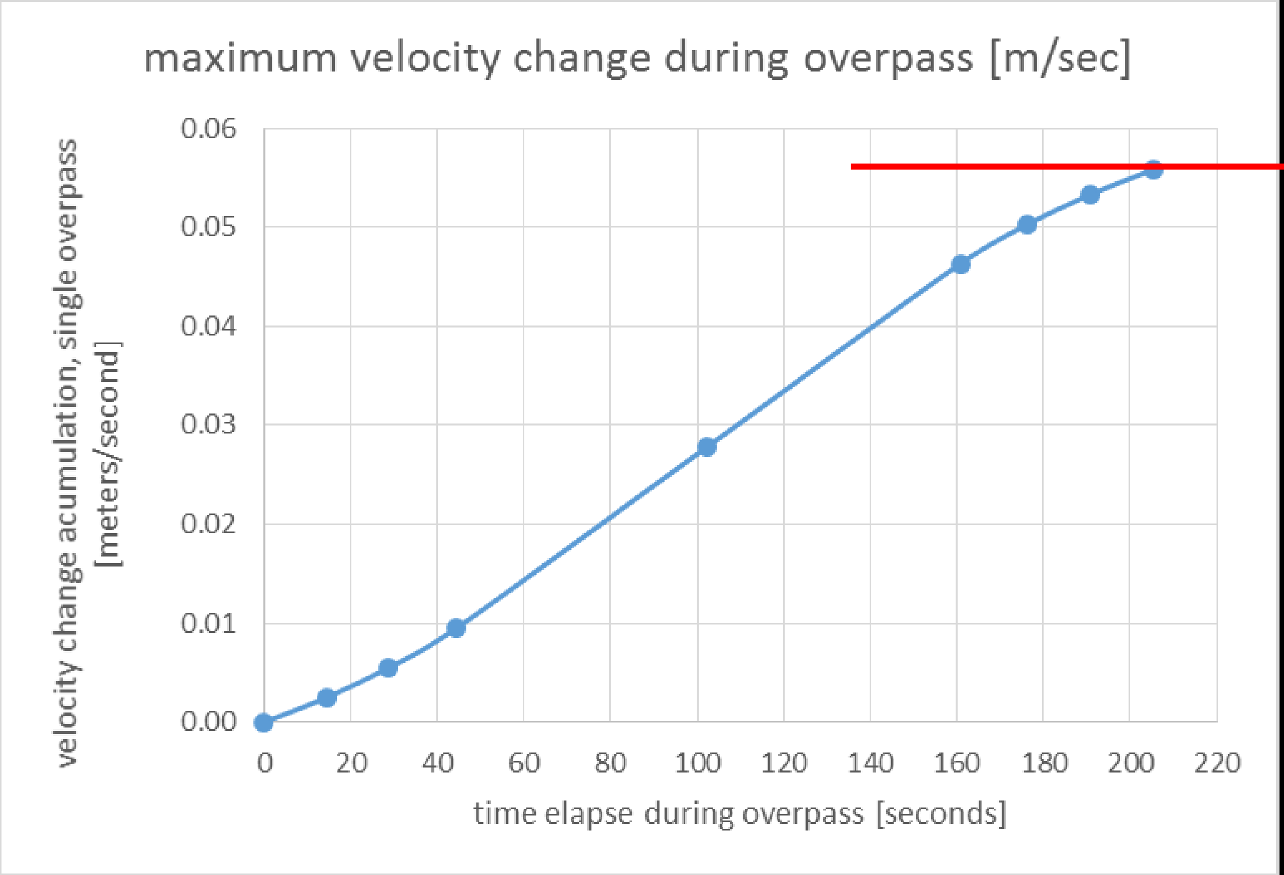

Single overpass max cumulative ΔV = 0.056 m/sec

0.1 m/sec ΔV goal may be exceeded with two or more accesses

An optimum spacecraft attitude program required to achieve max results

Break Through Starshot

Breakthrough Starshot – Beamed Energy Proulsion Workshop

- Step 1 - Ground based - Small phased array (~ 1m), beam targeting and stability tests - 10 kw
- Step II – Ground based - Target levitation and lab scale beam line acceleration tests - 10 kw
- Step III – Ground based - Beam formation at large array spacing (10m-10km) with sparse array
- Step IV – Ground based - Scale to 100 kW with arrays sizes in the 1-3 m size – Possible suborbital tests
- Step V – Ground based - Scale to 1 MW with 10-100 m optics. Explore 1 km ground option.
- Step VI – Orbital testing with small 1-3 class arrays and 10-100kw power – ISS possibility
- Step VII – Orbital array assembly tests in 10 m class array
- Step VIII – Orbital assembly with sparse array at 100 m level –
- Step IX – Orbital filled 100 m array
- Step X – Orbital sparse 1km array
- Step XI – Orbital filled 1 km array
- Step XII – Orbital sparse 10 km array
- Step XIII – Orbital filled 10 km array

[1] "A Roadmap to Interstellar Flight", by Philip Lubin, Physics Dept, UC Santa Barbara, JBIS Vol. 69, pp. 40-72 Feb 2016, Current version 15–w7-4 (10/18/16) downladed from Cornell University Library website https://arxiv.org/ftp/arxiv/papers/1604/1604.01356.pdf

Comparison of Key Perfromance Parametrics

Roadmap Development Guidelines

Key Parameters

	Solar Sail						Laser Sail Propulsion						Break Through Starshot					
	Earth to Orbit		Solar System		Interstellar		Earth to Orbit		Solar System		Interstellar		Earth to Orbit		Solar System		Interstellar	
	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper
Characteristic Acceleration [mm/s^2]	0.06	0.3	0.06	3	1.5						50	2000						
Maximum Sail Loading [N/m2]																		
Sail Area [m^2]	80	200	100	$4X10^4$	$5X10^4$	$1X10^6$												
Sail Areal Density [g/m^2]	40	20	40	10	10.0	0.1												
Sail Flux Damage Threshold [W/cm^2]	1361	1634																
Laser Output [kW]																		
Laser Mass [kg/W]																		
Power source [kg/W]																		
Thermal Control [kg/W]																		
Beam Control [kg/m^2]																		
Mission Payload [g, W]																		
Spacecraft Power [kg/W]																		
Spacecraft Thermal [kg/W]																		
Spacecraft ACS/GN&C [g]																		
Spacecraft Communications [kg/W]																		
Spacecraft Structure & Mechs [g]																		
Spacecraft Command/Data [g]																		
Probe Mass																		
Infrastrucure Mass																		

Conclusions

- An evolutionary multi-path roadmap has been derived for the development of photon sail propulsion for near-term Earth Orbit, Interplanetary, and then Interstellar science and exploration missions

- Some Commonality in Technology Advancement Needs exist
  - High Energy, Efficient, Lightweight Lasers
  - Lightweight, High Flux Tolerant Sails
  - Trajectory Optimization
  - Precision Guidance, Navigation, and Control
  - Reduced Launch Cost
  - Space Power/Energy Storage
  - Long Range, Low Power Communication Systems
  - Miniaturized, Robust, Low power Spacecraft Bus

- Significant levels of Technology Development must start now to enable even the most modest missions in the next half century