Solar Sail Propulsion: A Roadmap from Today's Technology to Interstellar Sailships

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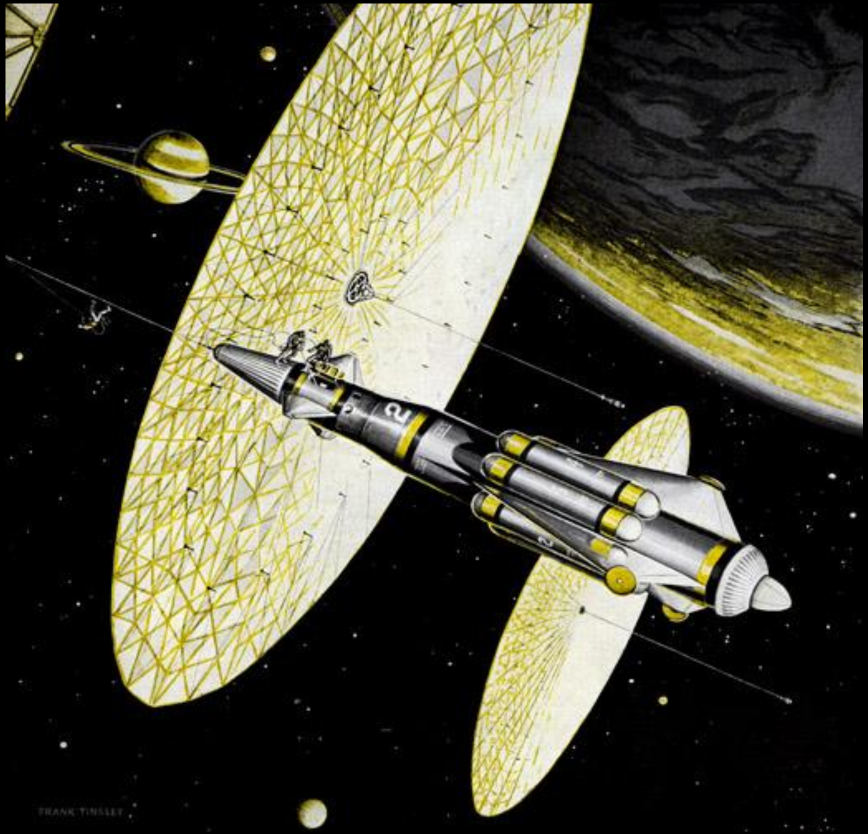
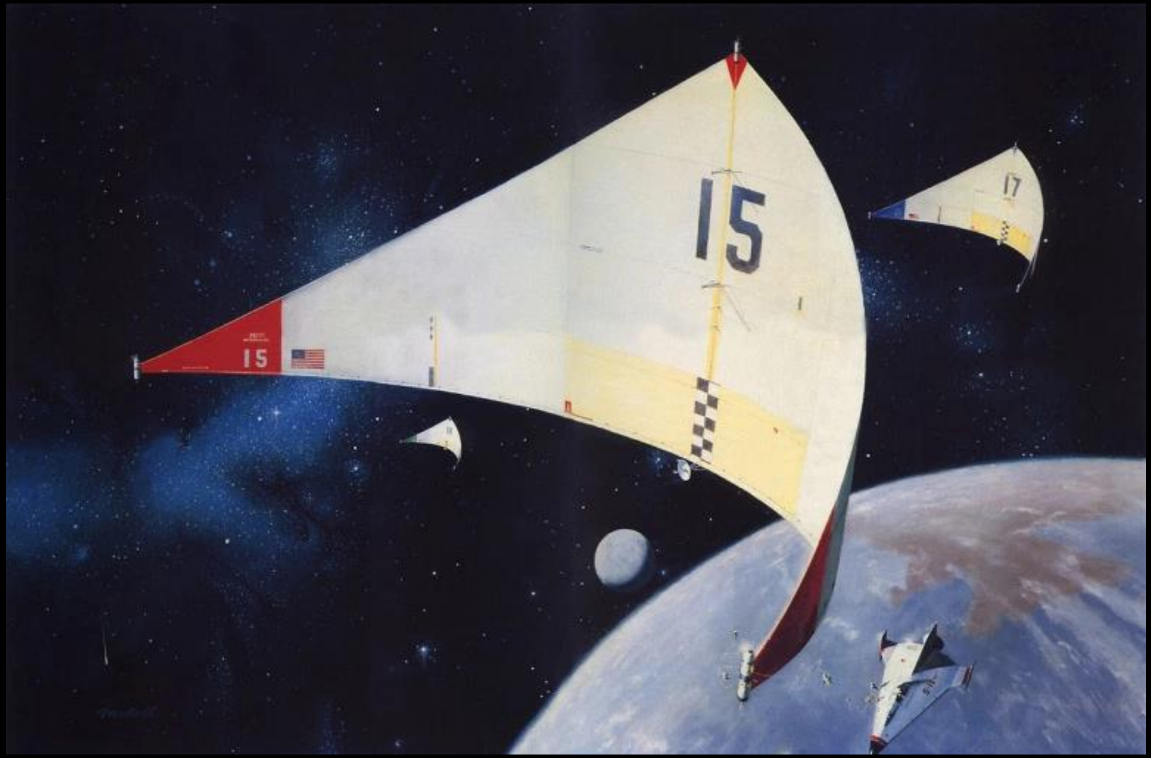
Background - Solar Sail Propulsion Technology

- Maturing rapidly –
  - Matloff & Mallove (1981), MacInness (1999), Cosmos I (2005), NanoSail-D & IKAROS (2010)
  - LightSail(2015-17), NASA Near Earth Asteroids Scout(2018)
- Next generation of sails
  - Out to the solar system and beyond the edge,
  - out to distances of 1000 Astronomical Units, or more.
- Further generation sails
  - may augment their thrust by using high power lasers
  - travel to nearby stellar systems with flight times less than 100 years .
- A notional solar and beamed energy sail technology maturation plan (with performance metrics) is outlined.
  - Comparison Technology Development Paths to 3 Interstellar Capabilities:
    - Solar Sail
    - Laser Sail
    - Break Through Starshot

Solar Sails



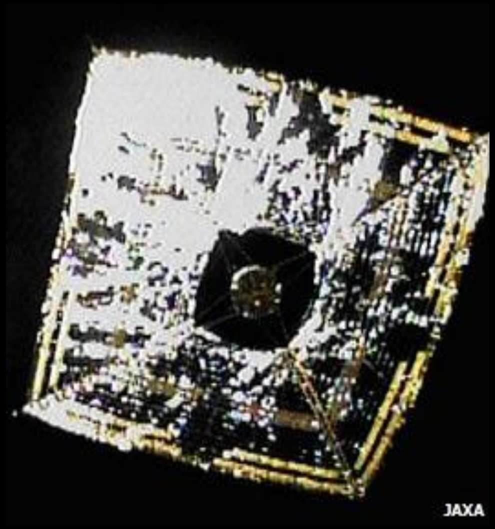
Frank Tinsley

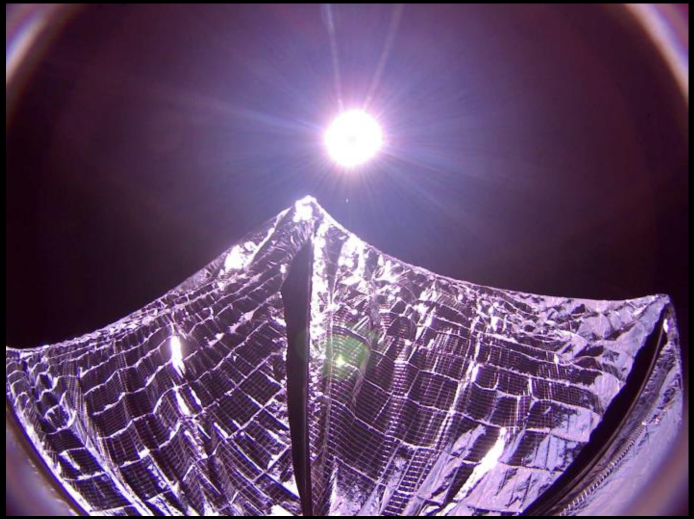


Robert McCall

Major Performance Parameter

Sailcraft	Areal Density [g/m^2]
IKAROS	1535
NanoSail-D	355
Cosmos 1	167
LightSail	143
NEA Scout	158
Sunjammer	45.5
JPL NIAC Study Concept	2.7
JPL ISM Mission Study Concept	1.4
JPL Halley Comet Reendezvous Design	1.4

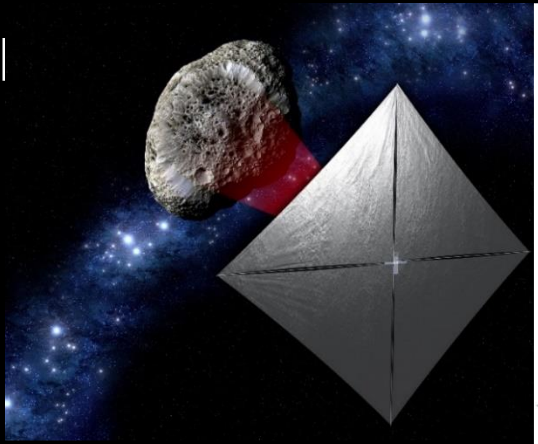


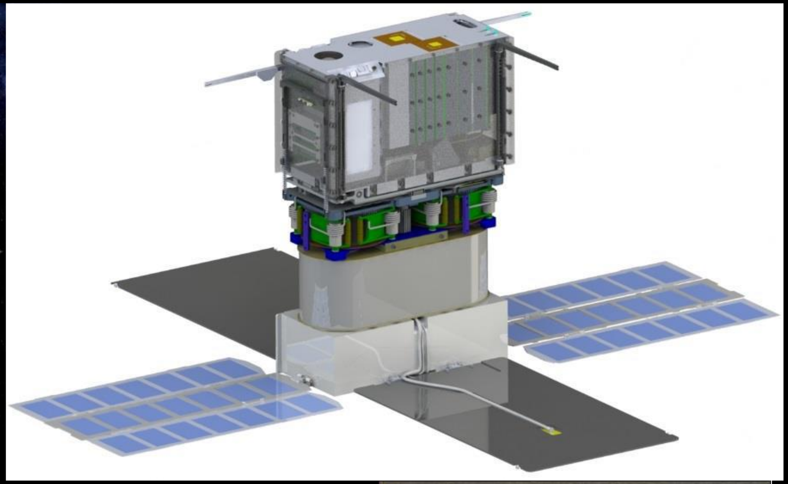


Near Earth Asteroid Scout

The Near Earth Asteroid Scout Will

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





Key Spacecraft & Mission Parameters

- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~85 m^2 solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2017)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

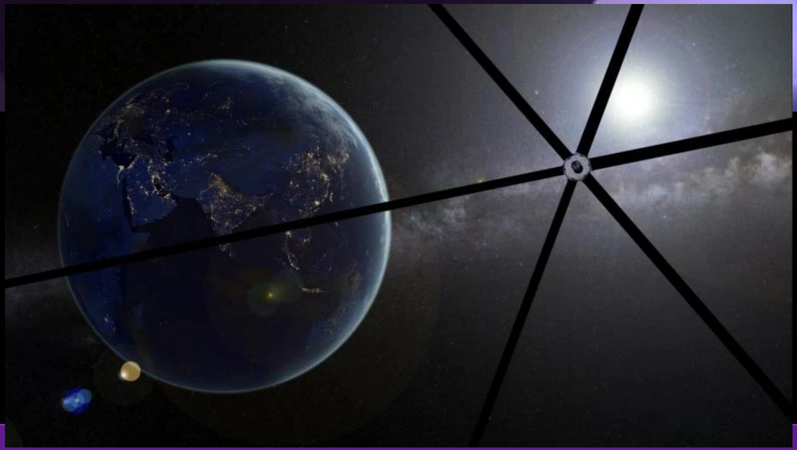
Solar Sail Propulsion System Characteristics

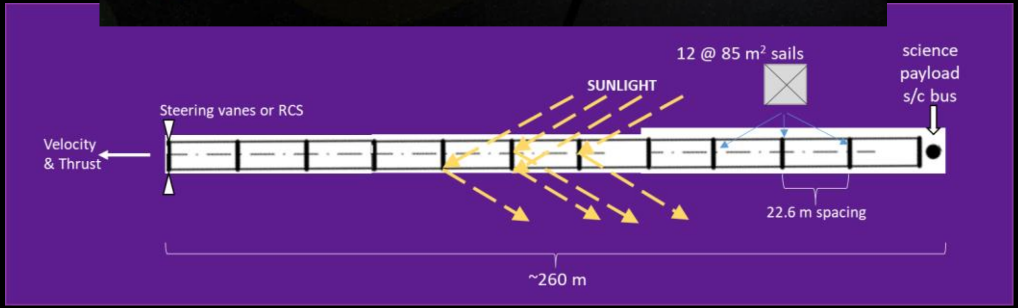
- ~ 7.3 m Trac booms
- 2.5μ aluminized CP-1 substrate
- > 90% reflectivity

The Sails We Eventually Need*

- The Sails We Eventually Need
  - Size: 1 km^2
  - Areal density: 0.1 g/m^2
  - Thermal & Structural Loads
    - Low perihelion: 0.2 AU
  - Automated Manufacturing in space (?)

- Are not close to what we currently have
  - Size: 30-200 m^2
  - Areal density: 25-300 g/m^2
  - Thermal & Structural Loads
    - Lowest perihelion: 0.7 AU (Venus)
  - Manufactured by hand in 1g, 1 atm clean rooms





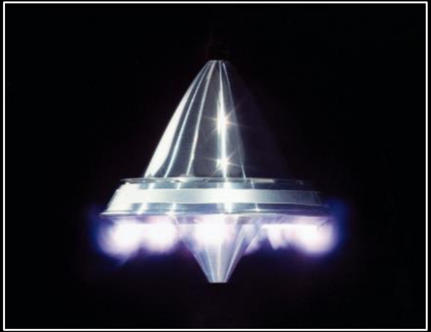
Laser Sails

(not included: laser electric, laser thermal, laser launch, laser detonated fusion/fission, laser photon recycle, or laser ablation)

Background – Beamed Energy Propulsion Technology

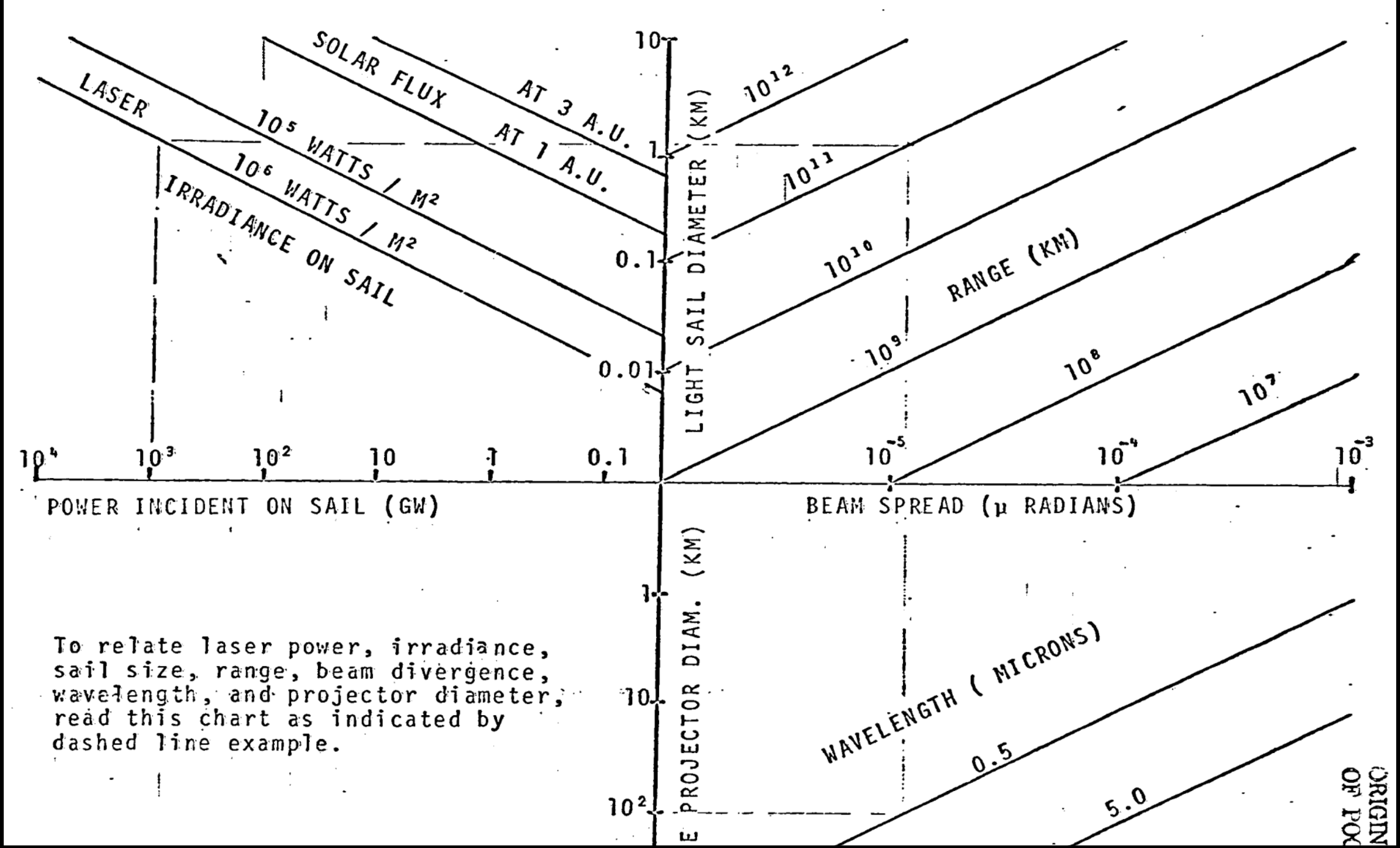
- JPL microwave experiments on ground, 1972
- WSMR Laser Launch experiments
  - Myrabo Lightcraft – USAF 2000
  - DARPA Parkin & Myrabo 2014
- Aircraft
  - Brown – 200 W, 2.45 GHz Helicopter 1964
  - Canada – SHARP, 1 kW, 4.5 meter wingspan
  - NASA – Small UAV flights in hangar at Dryden
- Rocket - MINIX, Japan, ionosphere, 2.4 GHz between stages 1983
- Elevator –Centennial Challenge cable climber, 1 km with 4 kW laser, 2009
- SELENE – NASA study and component technology development, 1990’s

- Earth-to-Orbit Beamed Energy Experiment – NASA MSFC, currently active





Fundamental Power and Propagation Relationships are Simple and Well Known



from "LASER DRIVEN LIGHT SAILS, AN EXAMINATION OF THE POSSIBILITIES FOR INTERSTELLAR PROBES AND OTHER MISSIONS", December 1976, JPL contract 644778, by John D. G. Rather, Glenn W. Zeiders, Karl R. Vogelsang, W. J. Schafer Associates, Redondo Beach, CA

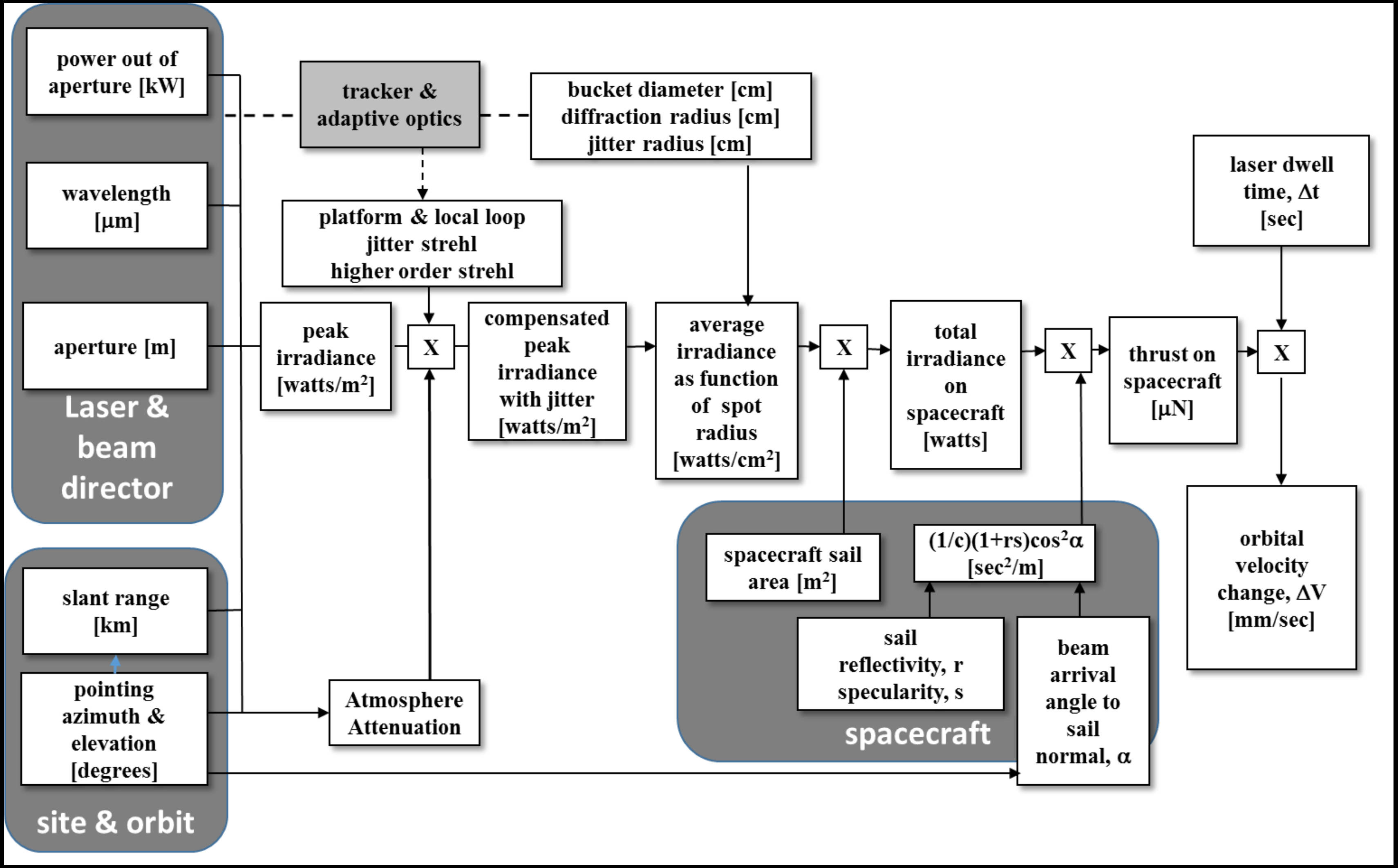
EBEX, Earth-to-Orbit Beamed Energy Experiment Mission Concept Study

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

Let $\sigma^2 = \sigma_D^2 + \sigma_j^2$

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

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

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

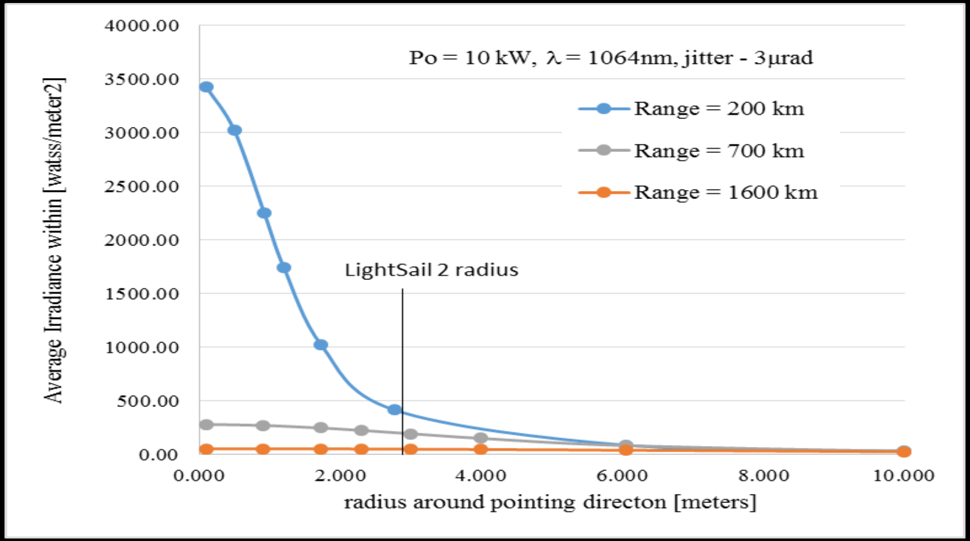
Power in spot, P = I_{ave} * Area

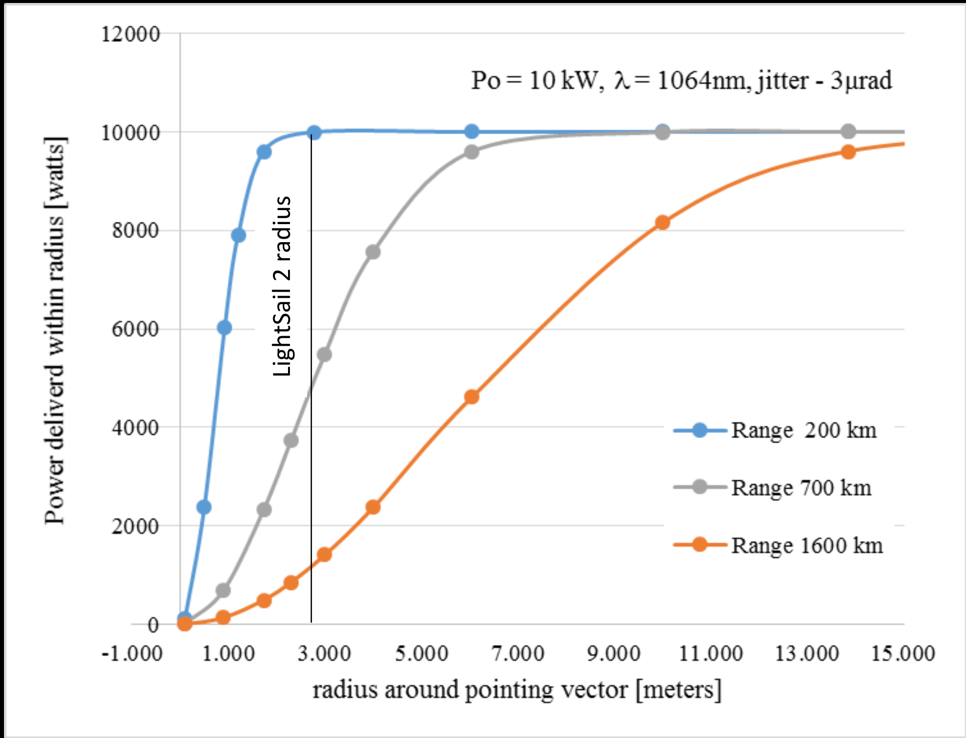
where Area = p r_A^2

s_j = jitter

s_D = diffraction

$I_{pj} = I_{peak} * s_j$



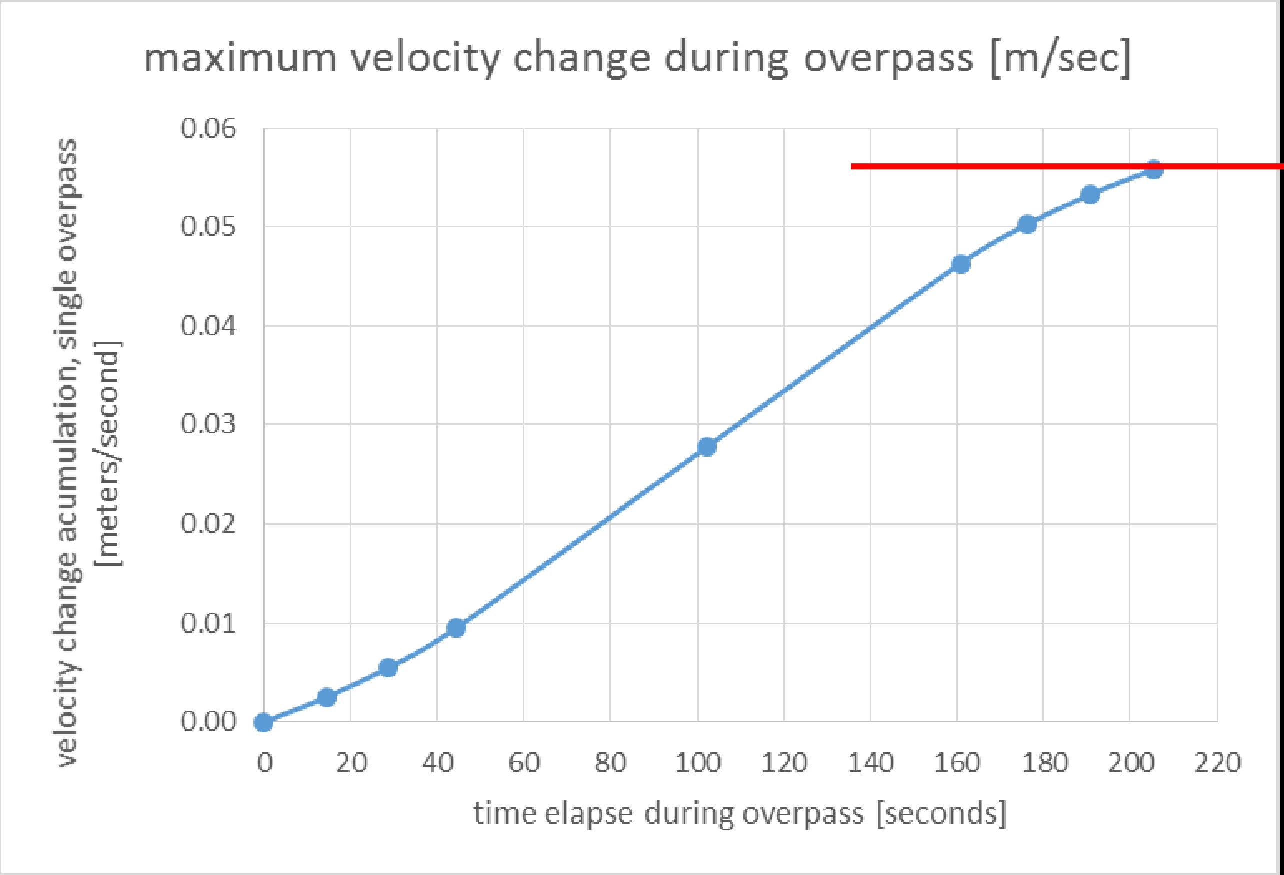


Diffraction and jitter combine to “spill” ~50% of energy past LightSail 2 at 700 km orbit altitude

Max ΔV 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
- $\sigma_{DIFF} = R * 0.45\ \lambda/D$



Single overpass max cumulative $\Delta V = 0.056$ 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

Space Based Laser Legacy
Aperture and Mass

0.5 m
1500 kg

High Energy Laser Mobile Demonstrator

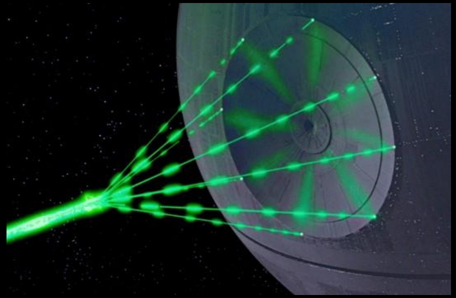
2.4
2920

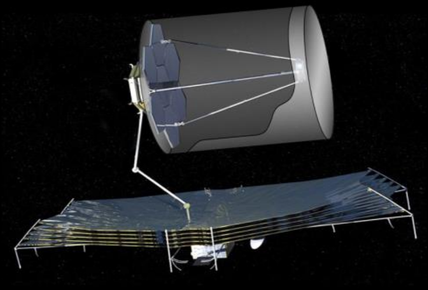
Hubble Space Telescope

8.0
6500

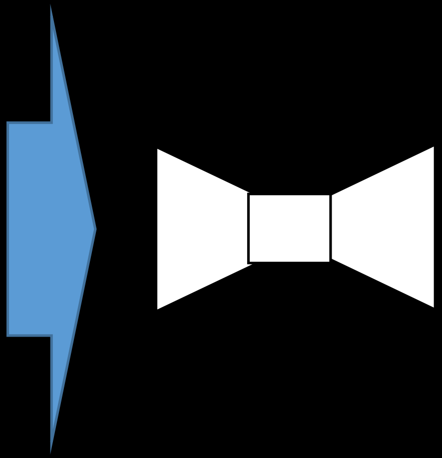
James Webb Space Telescope

20
36,000



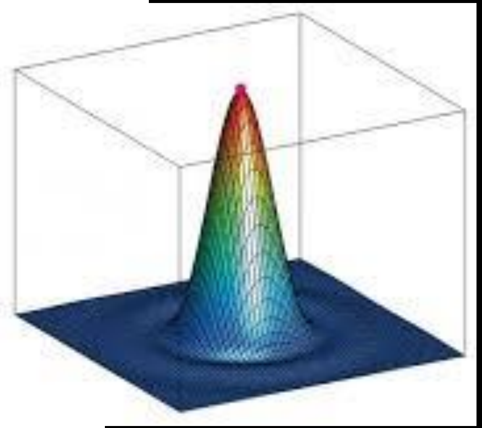


Advanced Large Aperture Space Telescope Concept



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

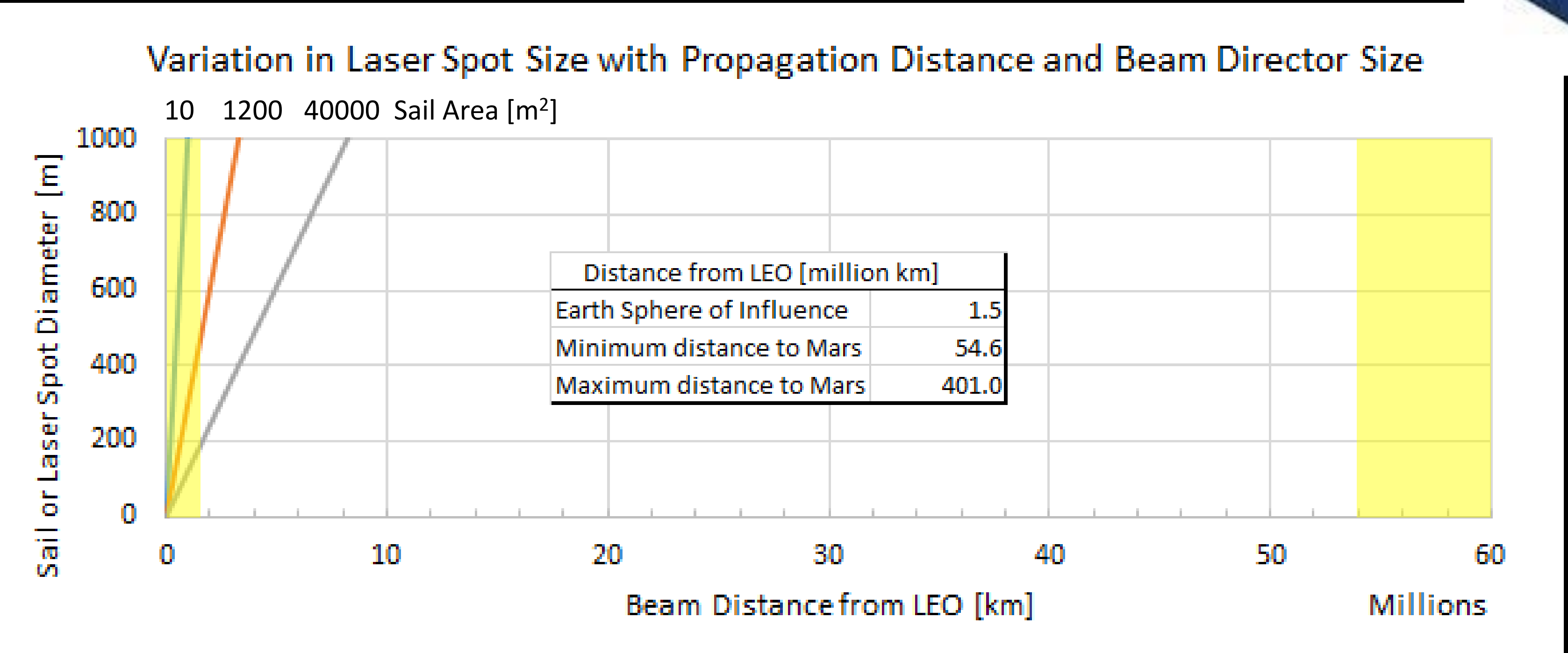


$d = 2.44\, R\, \lambda / D$ ← Independent of laser power level

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

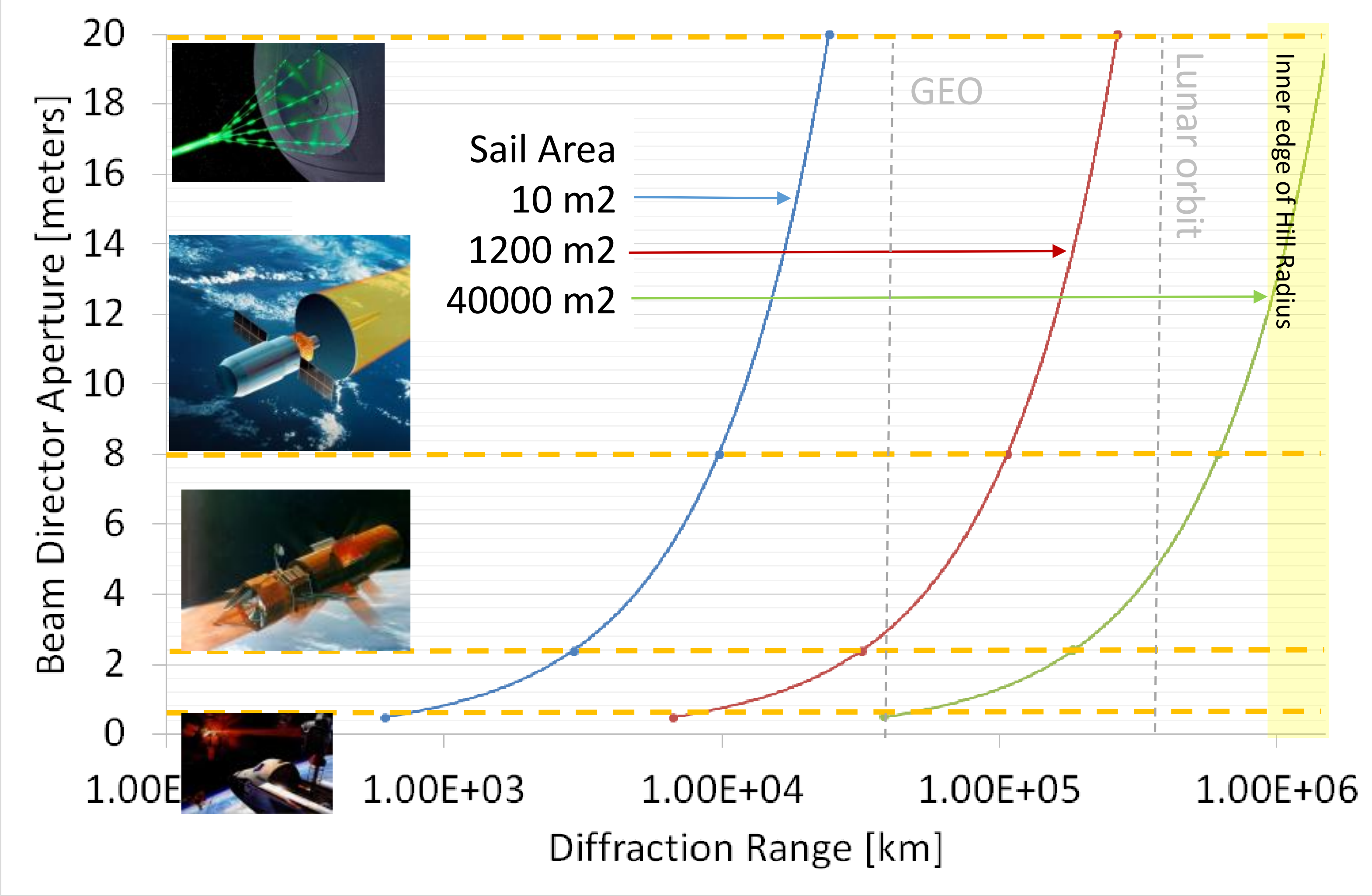
See next chart



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

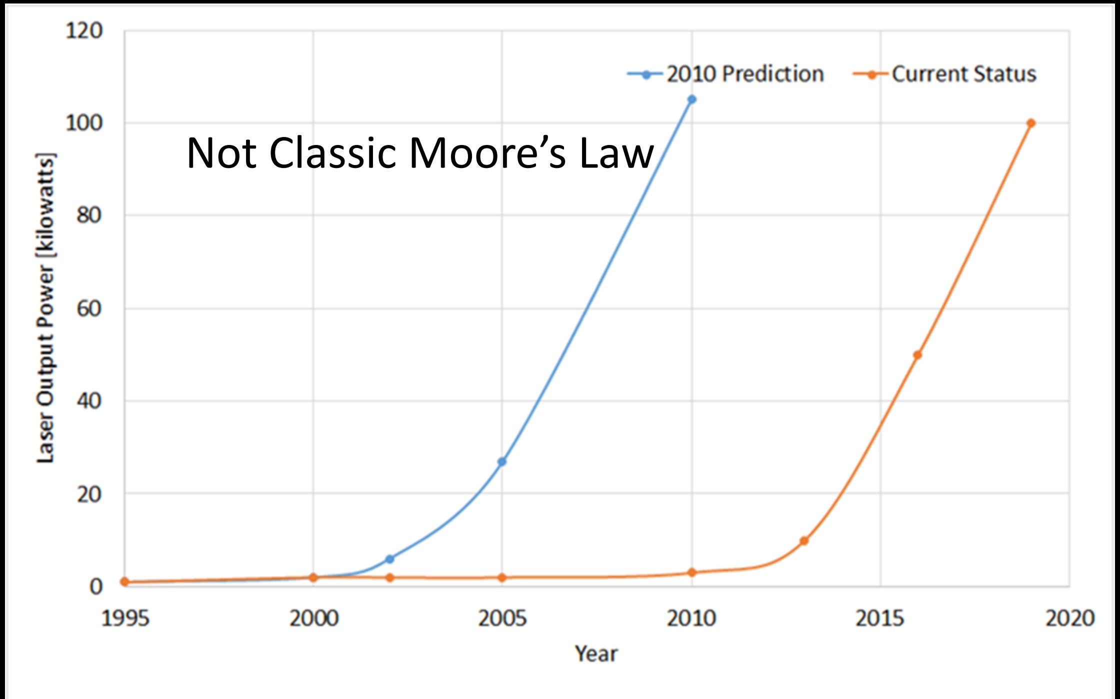
Even Largest Beam Director Considered Does Not Fill Sails Beyond the Earth's Gravitational Sphere of Influence (Hill Radius)

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



Optimal Laser Sail Trajectories to Outer Solar System and Beyond

- To Be Determined – Much Trajectory Optimization 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
- Lasers needed
  - High Duty Cycle [200 sec – 200 days]
  - High Power levels [10 kw – 100 MW]
  - Low Consumable [no reacants]
  - Efficiency (10 - 50 %]
- Space Infrastructure Orbital Mass Density
  - Laser & Beam Control [5-10 kg/W]
  - Power/thermal Mass [5-10 kg/W]
  - Delivery Upper Stage ΔV [6:1 kg]



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.

Break Through Starshot (BTS)

Breakthrough Starshot – Beamed Energy Propulsion 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) downloaded from Cornell University Library website https://arxiv.org/ftp/arxiv/papers/1604/1604.01356.pdf

3 Path Comparison

- Solar Sail
- Laser Sail
- Break Through Starshot

Comparison of Key Performance Parameters

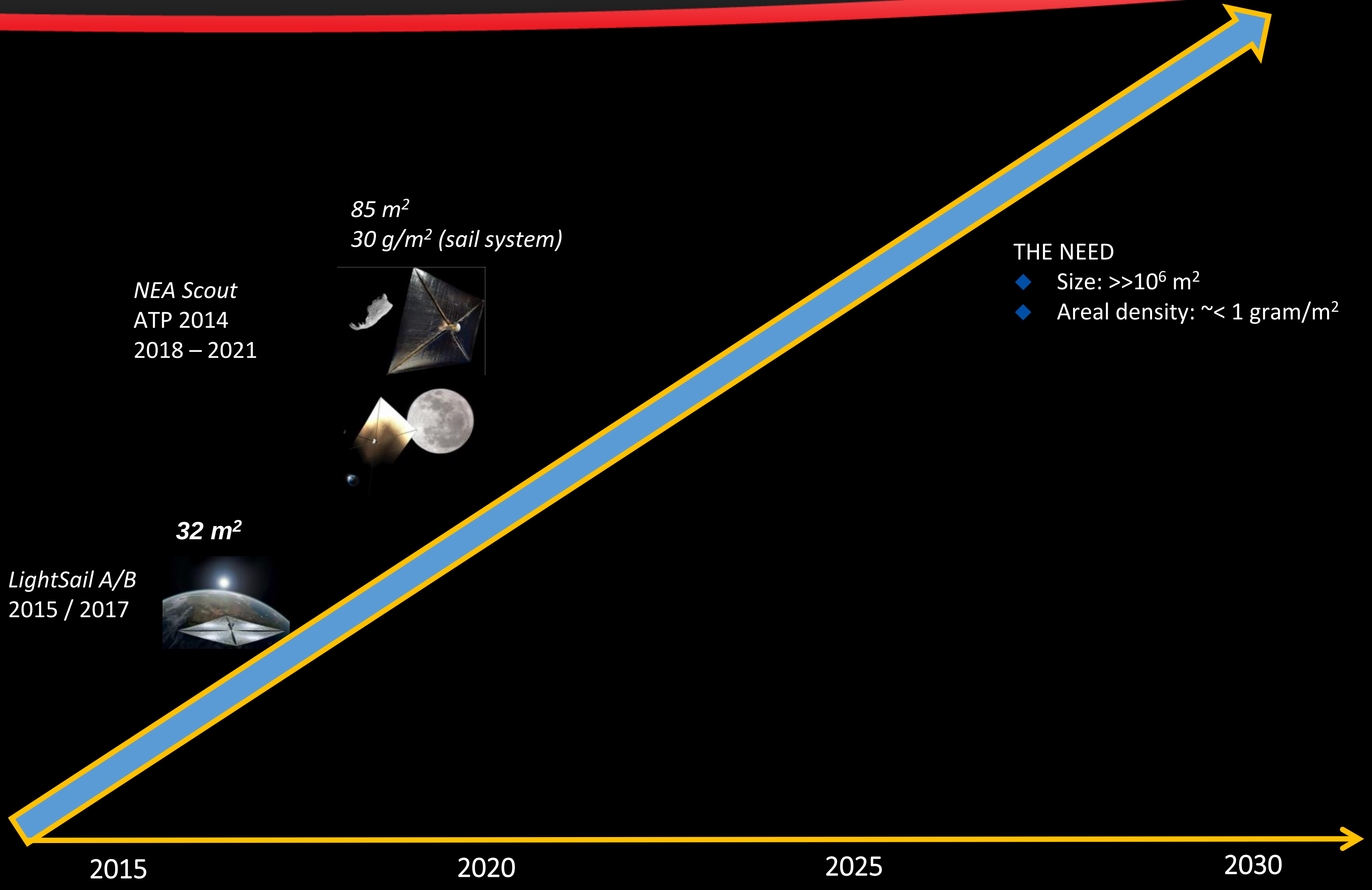
	Solar Sail						Laser Sail Propulsion						Break Through Starshot				
	Earth Orbit		Solar System		Interstellar		Earth to Orbit		Solar System		Interstellar		Earth to Orbit		Solar System		Interstellar
	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	70 GW wafersat
Characteristic Acceleration [mm/s^2]	0.06	0.08	0.06	3	4	1450	0.09	4.77	4.4	595	780	2000					$2x10^8$
Maximum Sail Loading [µN/m2]	9.1	10.9	9.2	34	35	218	16	678	678	6705	6705	$7x10^5$					$4.7x10^8$
Sail Area [m^2]	80	200	100	$4x10^4$	$4x10^4$	$1x10^6$	80	200	100	$4X10^4$	$4x10^4$	$1x10^6$					1
Sail Areal Density [g/m^2]	42	26	38	10	7.0	0.1	42	26	38	10	7.0	0.1					1.4
Sail Flux Damage Threshold [W/cm^2]	0.14	0.16	0.16	0.52	0.52	3.20	0.24	10	10	100	100	$1X10^4$					$7x10^{10}$
Laser Power Delivered [MW]							0.001	0.1	0.1	1	1	100	0.01	1			$7x10^4$
Laser Mass [kg]							-	-	5000	$5x10^4$	$5x10^4$	$5x10^6$	-	-			$7x10^9$
Laser pointing accuracy [µrad]							3	3	1	0.1	0.1	0.1	3	0.1			$2.4x10^{-4}$
Power source [kg]							-	5000	5000	$5x10^4$	$5x10^4$	$5x10^6$	-	$5x10^6$			$7x10^9$
Sail Mass [kg]	3.6	5.2	3.8	401	294	100	3.6	-	3.8	401	294	100					0.0014
Mission Payload[kg]	2.2	6.9	3.4	10	10	10	2.2	6.9	3.4	10	10	10					0.00014
Spacecraft Power[kg]	2.3	4.9	2.5	12	12	12	2.3	4.9	2.5	12	12	12					0.00014
Spacecraft Thermal [kg]	0.5	1.0	0.5	2	2	2	0.5	1.0	0.5	2	2	2					0.00014
Spacecraft ACS/GN&C [kg]	1.9	4.0	2.2	10	10	10	1.9	4.0	2.2	10	10	10					0.00014
Spacecraft Communications[kg]	1.0	2.1	1.0	10	10	10	1.0	2.1	1.0	10	10	10					0.00014
Spacecraft Structure & Mechs [kg]	2.0	4.2	2.0	5	5	5	2.0	4.2	2.0	5	5	5					0.00014
Spacecraft Command/Data [kg]	0.1	0.1	0.1	1	1	1	0.1	0.1	0.1	1	1	1					0.00014
Probe Total Mass [kg]	13.5	28.4	15.4	451	344	150	13.5	28.4	15.4	451	344	150					0.0024
Infrastrucure Mass to Orbit[10^3 kg]	0		0	0	0	12.8	0	0	10	100	1800	$2x10^5$	0	$1x10^4$			$1.4x10^7$

Roadmap Synthesis

- Sails
  - Development of high flux damage tolerance is common across all
    - BTS much higher though 10^{10} vs 10^4 W/cm^2 for solar & laser
    - Current technology sufficient for earth and near interplanetary solar & laser
  - Decrease areal density [g/m^2]
    - All need beyond current SOTA ~ 42 g/m^2
    - Solar and laser incremental goals to 25 > 10 > 7 > 0.1
    - BTS immediate goal: = 1.4
  - Manufacturing in Orbit eventually solar & laser, BTS?
- Laser
  - All need quality power and beam control beyond current SOTA ~ 60 kW
  - BTS ultimate goal higher power than laser, 70 GW vs 100 MW
  - Pointing accuracy & stability 10^{-1} μrad almost SOTA, 10^{-4} μrad for BTS
  - Nuclear power eventually needed to support lasers in outer solar system and beyond, BTS?
- Launch
  - All paths eventually lead to orbit and require significant infrastructure mass to be launched
  - Solar and Laser roadmaps have near term science/exploration missions supportable from ground

Roadmap

No Sail Missions Yet Approved Beyond 2018



Support for Interstellar In US Congress

- In May 2016, Rep. John Culberson of Texas
  - directed the U.S. space agency to start drawing up a conceptual plan for interstellar travel,
  - whether by directed laser energy, nuclear fusion or a ramjet that would scoop up hydrogen from the ISM.
  - Goal": launch an interstellar mission in 2069, the 100th anniversary of the Apollo 11 mission to the Moon.

[From "Breakthrough Starshot", by Patricia Daukantas, Optics & Phtonics Magazine, OSA, May 2017]

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- As chair the Subcommittee on Commerce, Justice, and Science, has jurisdiction over science, NASA..

- "encourages NASA to study and develop propulsion concepts that could enable an interstellar scientific probe with the capability of achieving a cruise velocity of 0.1c [10% of the speed of light]." The report language doesn't mandate any additional funding, but calls on NASA to draw up a technology assessment report and conceptual road map within 1 year.

[from "U.S. lawmaker orders NASA to plan for trip to Alpha Centauri by 100th anniversary of moon landing", by Daniel Clery, ScienceMagazine, May. 23, 2016, DOI: 10.1126/science.aag0558]

Conclusions

While Earth Orbit and Interplanetary missions are not incremental goals to BTS, the capability to do such missions with solar sails and laser sails will be matured while pursuing BTS technologies.

As a roadmap to interstellar mission, BTS eliminates only large area sail manufacturing – but it does so at the cost of 1000X higher sail loading, 10^6 X higher laser damage tolerance, 1000X more accurate pointing, >100X higher power lasers, and 80X more mass launched from Earth.

Parameters not covered here are trip time, stopping at destination, and hardware survival.

- Some Commonality in Technology Advancement Needs exist
  - High Energy, Efficient, Lightweight Lasers
  - Lightweight, High Flux Tolerant Sails
  - Trajectory Optimization
  - 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

Backup

BTS has requirements ?

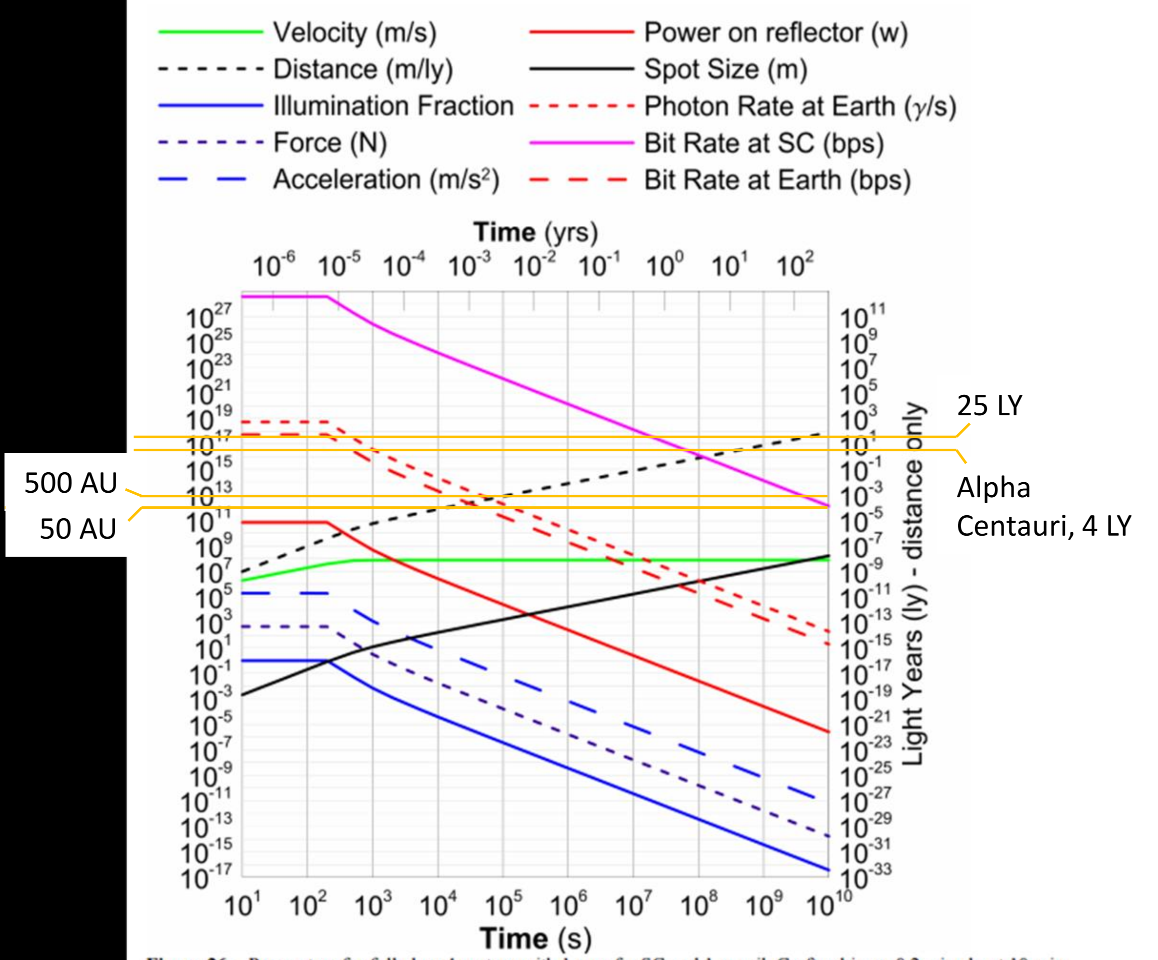

Figure 26 - Parameters for full class 4 system with 1 g wafer SC and 1 m sail. Craft achieves 0.2 c in about 10 min (assuming an extended illumination) and takes about 20 years to get to Alpha Centauri. Communications rate assumes class 4 drive array is also used for reception with a 1 watt short burst from a 100 mm wafer SC. Here we use the 1 meter drive reflector as the transmit and receive optical system on the spacecraft. We also assume a photon/bit ratio near unity. In this case we get a data rate at Andromeda of about 65 kb/s. In the previous figure for the same wafer scale spacecraft the **only optical system on the spacecraft was the 100 mm wafer**. The data rate received at the Earth from Alpha Centauri is about 0.65 kbs during the burst assuming we can use the DE-STAR 4 driver as the receiver and only the wafer itself for the transmission optic. The plot above shows a much more conservative photon/bit ratio of 40 while unity has been achieved but

- Multi layer dielectric on metalized plastic film
  - 50 ppm reflectivity tuned to 1060 nm laser wavelength - NOT suitable for broad solar spectrum sails
  - suitable for large scale "roll to roll" production. Note the reflectivity is tuned to the narrow laser line and
  - that these reflectors are NOT suitable for solar sails which use the broad spectrum of the sunlight to
  - propel them
- Multi layer dielectric on metalized glass
  - 10 ppm reflectivity
- Multi layer dielectric on glass
  - 1 ppt reflectivity
  - Required for high flux, WaferSat cases
- a “boot strap” approach where a ground DE driver with an ablation booster (or high Q photon recycling) is used for ground launches to enable the
- deployment of the DE orbital driver using purely photon thrust