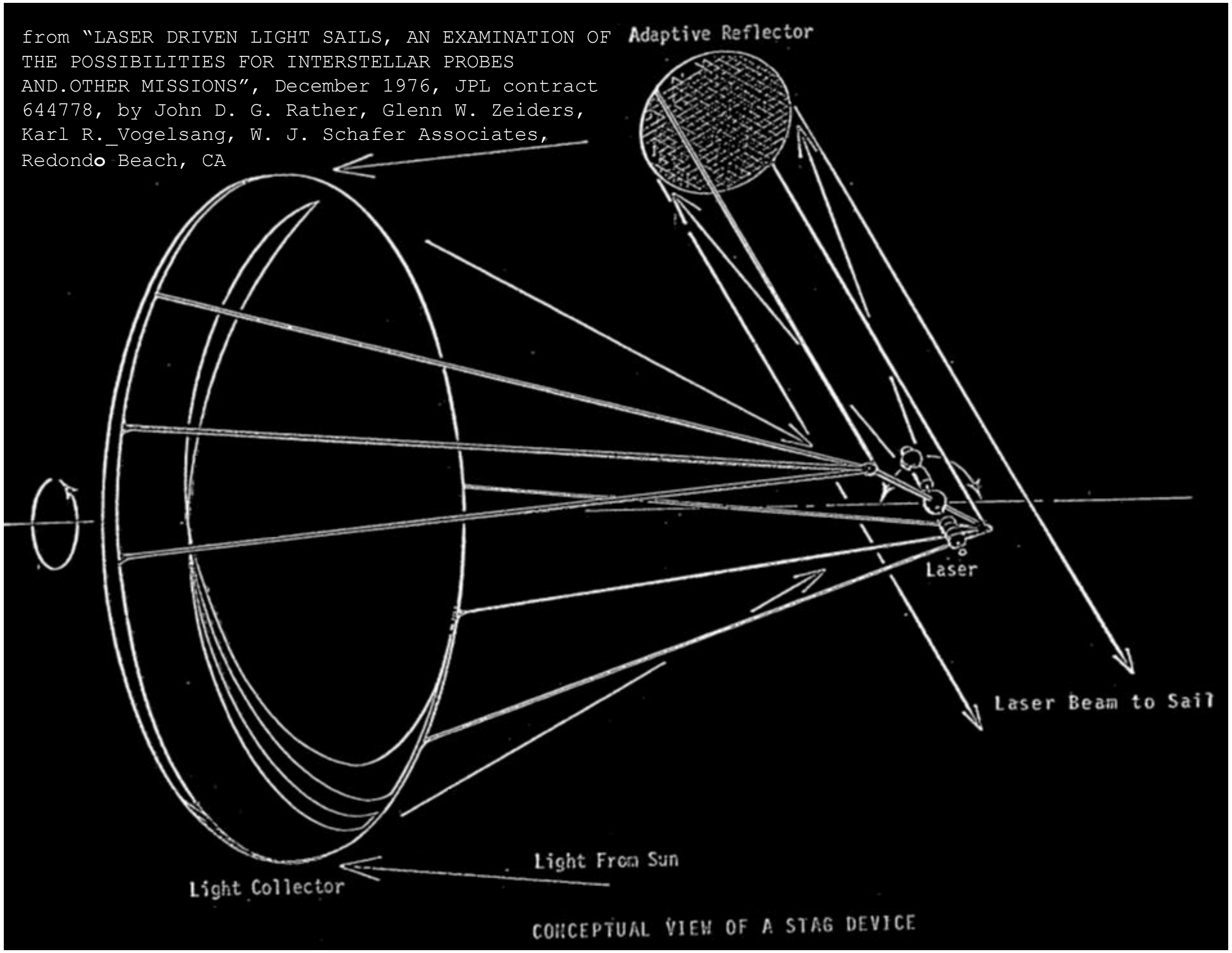
Beamed Energy Propulsion for Missions to the Interstellar Medium (ISM)
Modes and Past Studies



by

Edward E. (Sandy) Montgomery IV

Aerospace Engineer

Huntsville, AL

for

Keck Institute for Space Studies

Workshop on the

"Science and Enabling Technologies for the Exploration of the Interstellar Medium"

13 January 2015

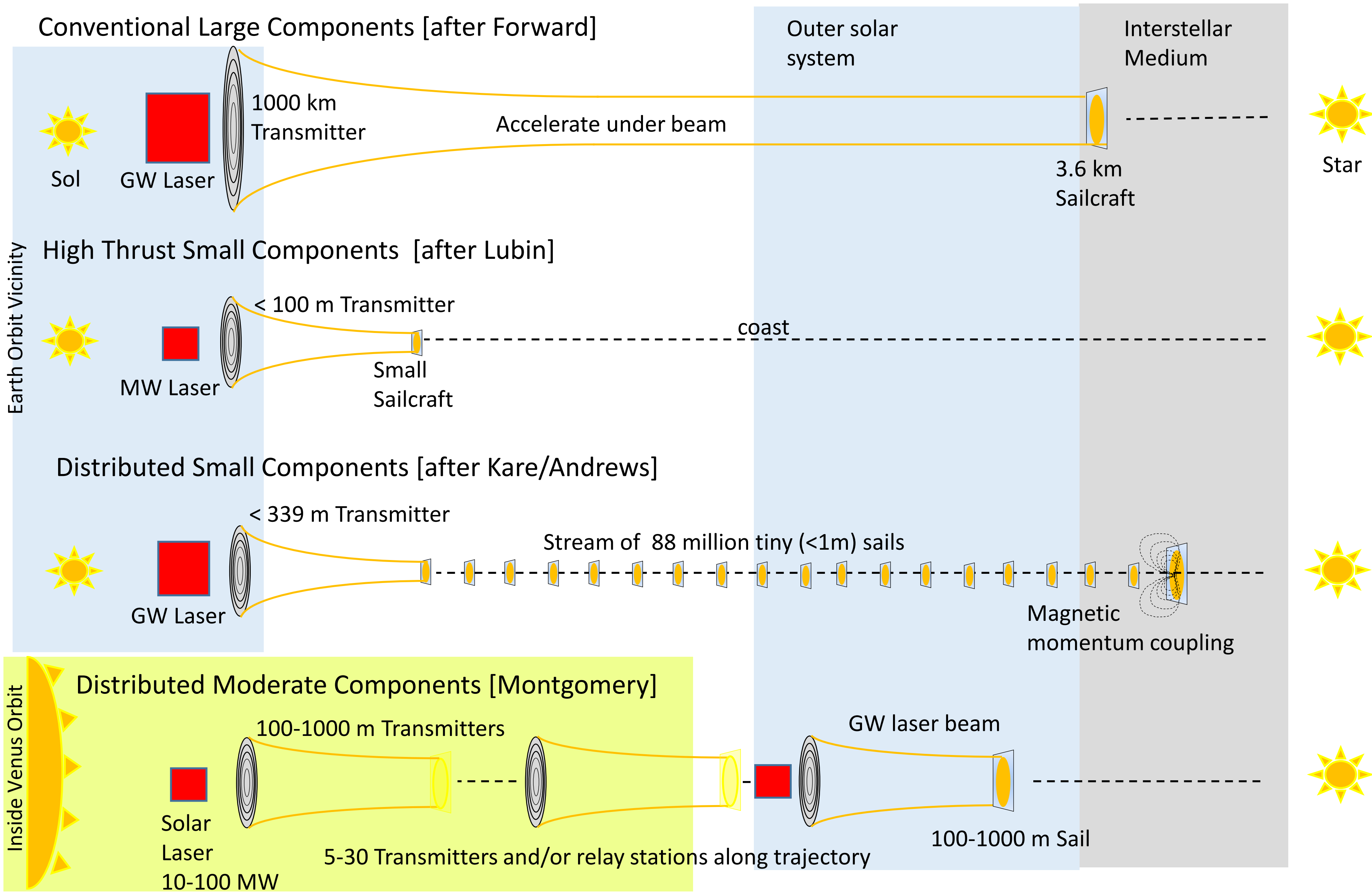
Cal Tech

Pasadena, CA

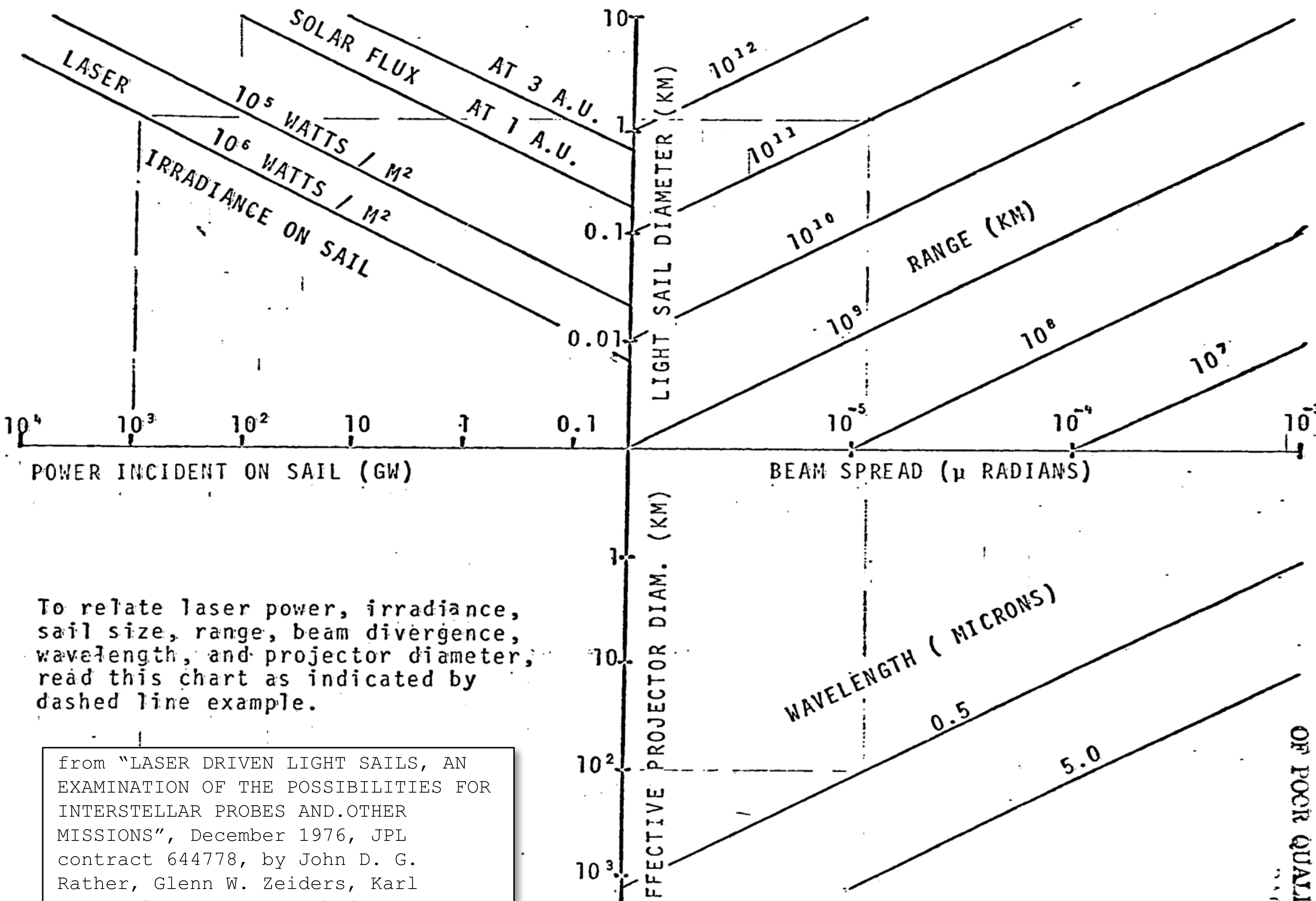
All the information in this presentation was taken from the public domain.

Many Beamed Energy Interstellar Sail Propulsion Modes Exist

(gravity assist and Oberth maneuvers omitted for simplicity)



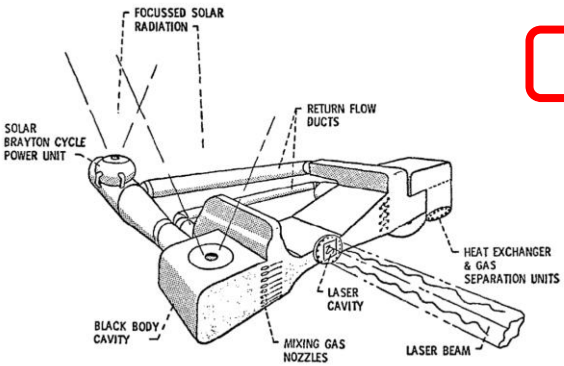
Fundamental Power and Propagation Relationships are Simple and Well Known



To relate laser power, irradiance, sail size, range, beam divergence, wavelength, and projector diameter, read this chart as indicated by dashed line example.

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

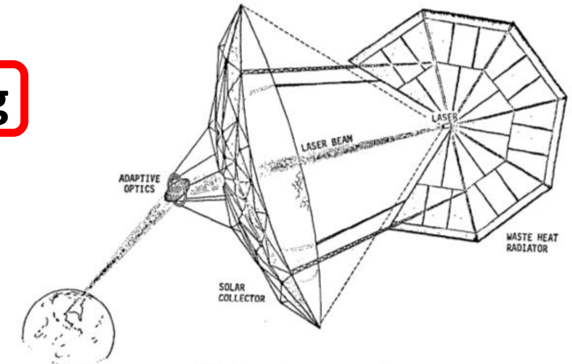
ARTIST'S SKETCH OF CO/CO_2 FLOW-MIXED SOLAR-PUMPED LASER FOR SPACE APPLICATIONS



SLS ETO launch capacity

140,000 kg, Block II = 310,000 kg

Easily Sufficient to Launch Beamed Energy Infrastructure to Orbit



Artist's Concept of 1 MW Solar-Pumped Laser,

1 MW Space Laser System Weight

	Laser Type				
	EDL*		GDL*	OPL*	
Components	Supersonic CO	Subsonic CO_2	Supersonic CO_2	Direct CF_3I	Indirect Static CO_2
Laser Loop					
Ducts, Nozzle, Diffuser, Cavity, Mirrors, Window Cooling Subsystem	1,574	1,662	6,292	600	600
Radiator and Heat Exch.	445	240	5,023	874	2,070
Flow Loop Compressor	250	275	1,216	250	(N/A)
Gas Make-up Purification	250	258	(N/A)		
Recuperator	(N/A)	(N/A)	18,330	(N/A)	
Collector and Heat Exch.			2,112		(N/A)
Power Source:					
Turbine/Recuperator/ Compressor	4,350	4,700	7,199	(N/A)	(N/A)
Radiator and Heat Exch.	4,163	4,500	8,565		
Collector/Concentrator/ Cavity Absorber	5,670	8,600	15,889	58,560	3,200
Power Conditioner	260	205	(N/A)	(N/A)	(N/A)
Black Body Cavity	(N/A)	(N/A)	(N/A)	(N/A)	2,400
Total Weight (kg)	16,962	20,440	64,626	60,284	8,270

*EDL = Electric Discharge Laser
GDL = Gas Dynamic Laser
OPL = Optically Pumped Laser

SLS PRIME, C3 = 13 AU/yr
Payload = 16,857 kg

From " Design Investigation of Solar Pumped Lasers for Space Applications ", Mathematical Sciences Northwest, reviewed by Richard B. Lancashire, NASA Lewis Research Center, Proceedings of "Space Laser Power Ttransmission System Studies" symposium, October 1981.

Compact Power and Thermal Systems Enable High Power Laser System Mass to SLS Launch Capacity

Mass/Power density

Power [kw]	5 kg/kw	10 kg/kw
1	5	10
10	50	100
100	500	1000
1000	5000	10000
10000	50000	100000
100000	500000	1000000
1000000	5000000	10000000
10000000	50000000	1E+08
100000000	5E+08	1E+09
SLS Initial	140000	kg
SLS Block 2	310000	kg

U.S. Army
High Energy Laser
Mobile Demonstrator

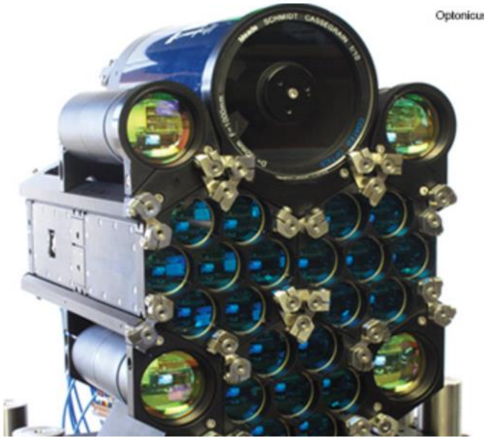
<u>Perspective: HELLADs – General Atomics</u>

- Packaging:
  - Predator C = small car (750 kg)
  - Goal 5 kg/kw
- 150 kw array, <10 km range
- Liquid-cooled, solid state laser array
- One 34kw module has been ground demonstrated

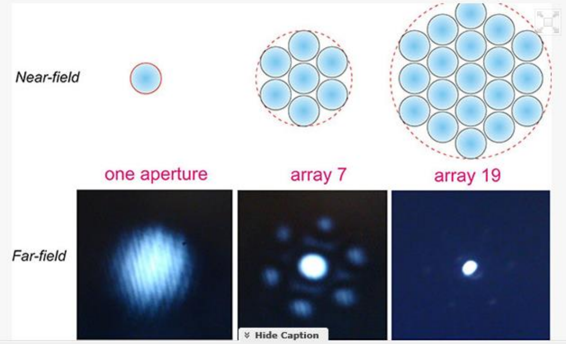
Leverage DoD Technology Development
in Lightweight Power/Thermal Systems
For Mobile High Power Laser Mission

Leverage DoD Technology Development in High Power Lasers

ARL-DARPA
Excalibur - Adaptive Phase Coherent Fiber Laser Array



- single-mode diode lasers and fiber-based amplifiers
- efficiencies greater than 50 percent and 30 percent
- multi-kW single channels
- Phase-locked, coherent optically combined
- multichannel, 7, 19, and 21 fiber laser sub-aperture arrays
- ultimate goals:
  - 100-kilowatt-class laser system
  - scalable size
  - 10 times lighter and more compact than existing high-power chemical laser systems
- Status
  - 21-element low power phased array (OPA) precisely hit a target 7 km away along a high turbulence path.
  - Experiments consisted of three 10 cm diameter clusters of seven lasers
- Key Organizations:
  - DARPA, US Navy, US Army SMDC
  - Army Research Lab, Optonicus, MIT-LL



Results of Coherent Beam Combining

Laser Beamed Energy Propulsion has a Logical Evolutionary Path to Interstellar Grand Challenge

Beamed Propulsion Architectures	ETO Mass	Trip Time	Key Technology Developments Required					Relevance to ISM Roadmap				
			High	Medium	Low	High	Medium	Tech	Small	Medium	Large	1000 AU
			Nuclear Power	Solar Pump Laser	Relay Systems	Large Beam Director	Large Sail	Demo 1-10 AU	Explorers 5-100 AU	Missions 200-300 AU	Missions 500-600 AU	Challenge 1000 AU
Ground Based Transmitter - Nano S/C with Sail	Small	Long	No	No	Yes[3]	Yes	Yes					
Earth Orbit Transmitter - Nano S/C with Sail	Large	Long	Yes[1]	No	No	Yes	Yes					
Solar Orbit Transmitter - Nano S/C with Sail	Medium	Medium	No	Yes[2]	No	Yes	Yes					
Solar Transmitter with Relays- Nano S/C with Sail	Medium	Short	No	Yes[2]	Yes	No	No					
Nuclear Transmitter with Relays- Nano S/C with Sail	Medium	Short	Yes	No	No	No	No					

notes

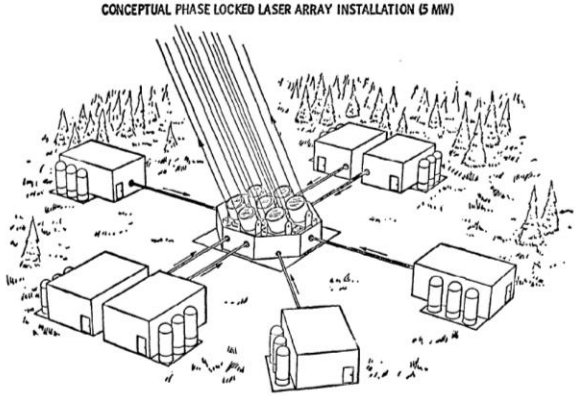
1 - or space solar power

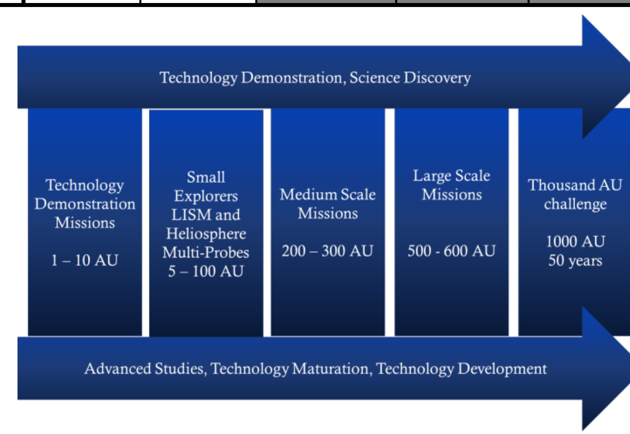
2 or more efficient collection/conversion for electric laser

3 - to increase access to more orbits

S/C = spacecraft

CONCEPTUAL PHASE LOCKED LASER ARRAY INSTALLATION (5 MW)





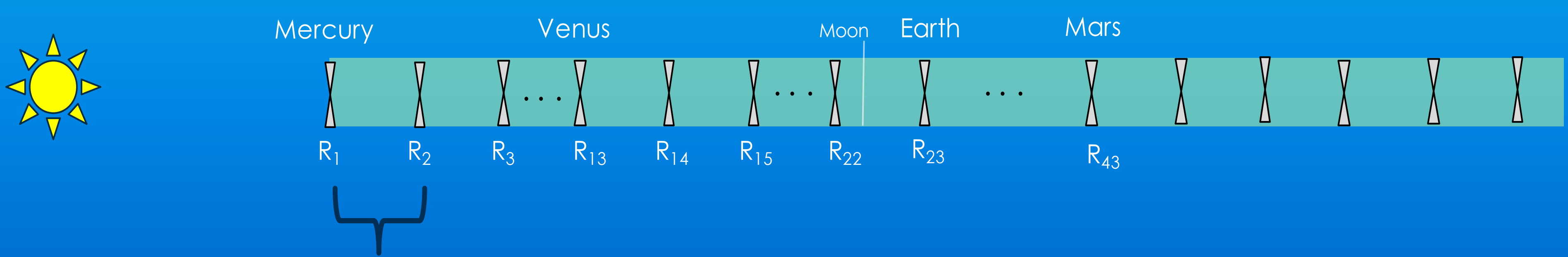
Grand Vision of a Grand Challenge Interstellar Exploration Program

Backup

EXAMPLE CONFIGURATION OF SOLAR POWER PIPELINE USING MODEST SIZED RELAY

- **Modest Aperture = 100 meter diameter, circular**
  - **First Relay is near the orbit of Mercury, Energy output 60 Megawatts**
  - **Four relays reach the orbit of Venus, 95 Megawatts**
  - **23rd Relay is near Earth's Orbit, 49 Megawatts**
  - **Number of relays to reach interstellar destinations = too many**

- **Assumptions**
  - **λ=1 micron for Fraunhofer range calculation**
  - **Collector and beam design is achromatic across solar spectrum**
  - **Losses**
    - **%16 at each relay for power outside first airy disk**
    - **%10 for all other loss (absorption in coatings, optics mis-figure, jitter, etc.)**

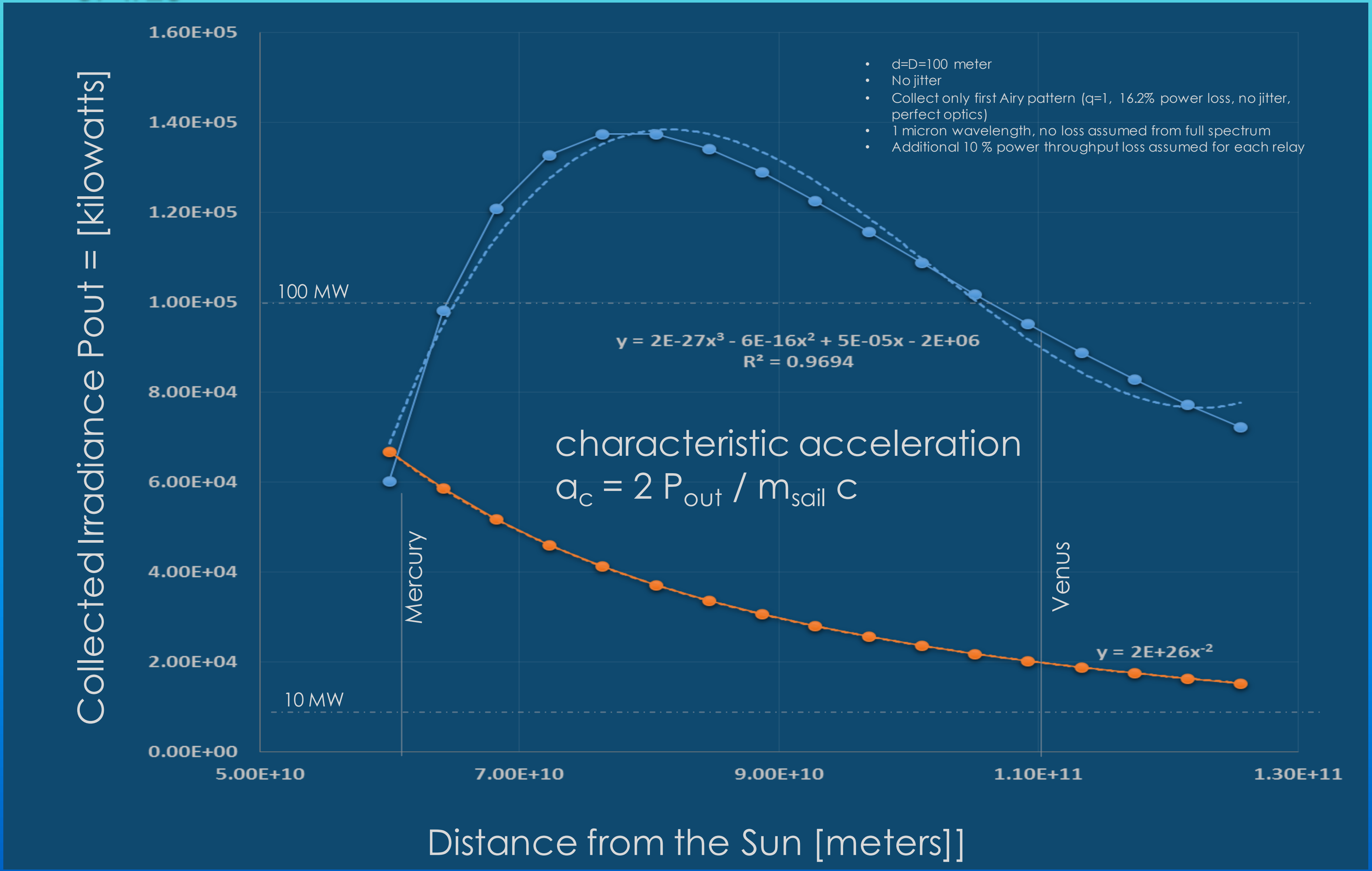


$a = (100*100)/(q*\lambda) = 4.1 \times 10^6$ km

(note: diffraction limit range to capture 1st airy diameter spot)

not to scale

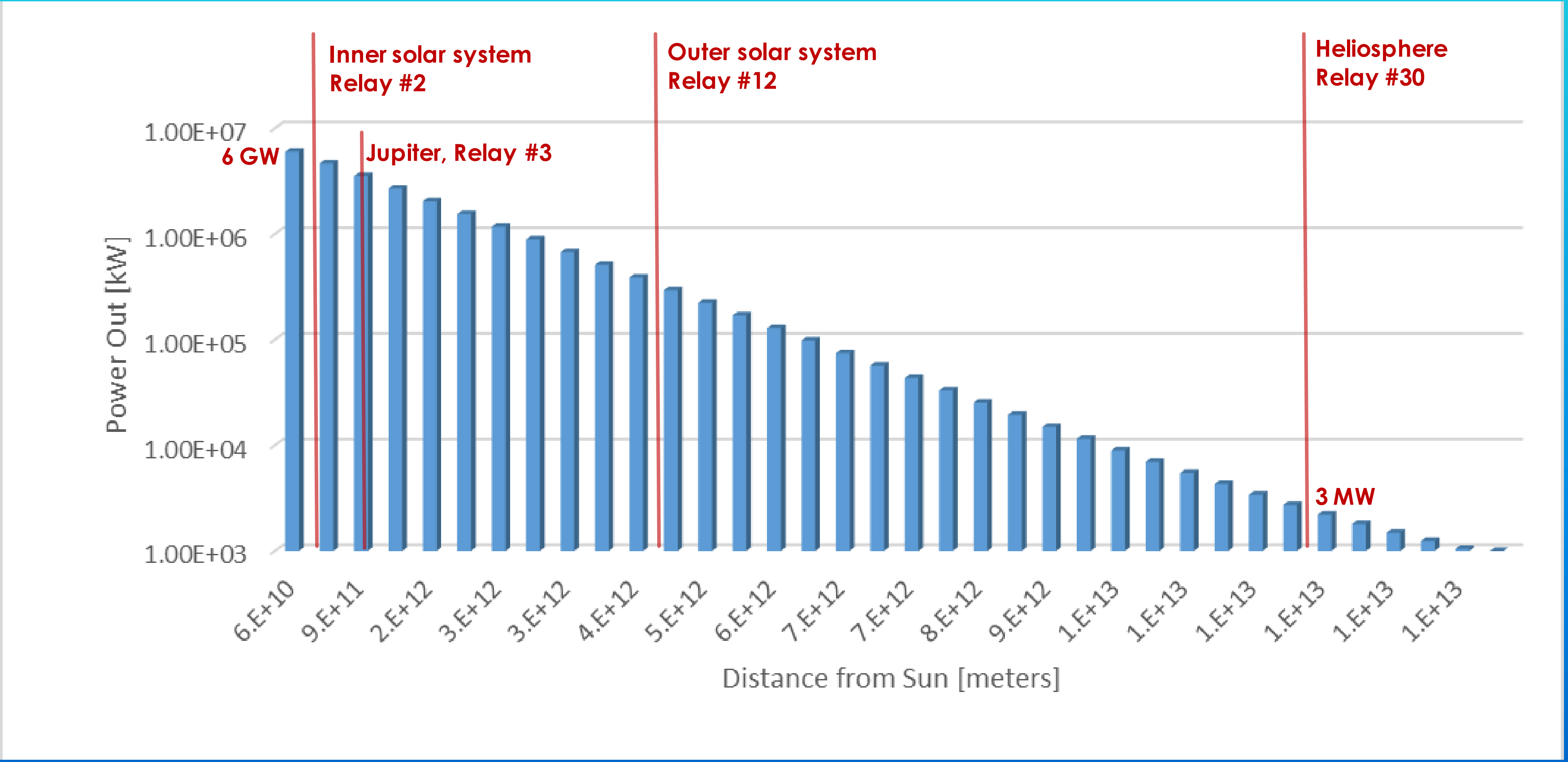
TREMENDOUS LEVERAGE ON IMPROVING DEPARTURE TRAJECTORIES AND OR LAUNCHING MORE MASSIVE SAILS



POWER OUT OF EACH RELAY [KILOWATTS]

- 1000 METER DIAMETER FOR BOTH COLLECTOR AND BEAM DIRECTOR
- CLOSEST STATION TO SUN AT MERCURY ORBIT

- Collect only first Airy pattern (q=1, 16.2% power loss, no jitter, perfect optics)
- 1 micron wavelength, no loss assumed from full spectrum
- Additional 10 % power throughput loss assumed for each relay



[from] “Places Only Sails Can Go”, by Edward E. Montgomery IV, Dr. Gregory P. Garbe, and Andrew F. Heaton, NASA Marshall Space Flight Center, Proceedings of the AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years, *AIAA-2003-2836, 14-17 July 2003, Dayton, Ohio*

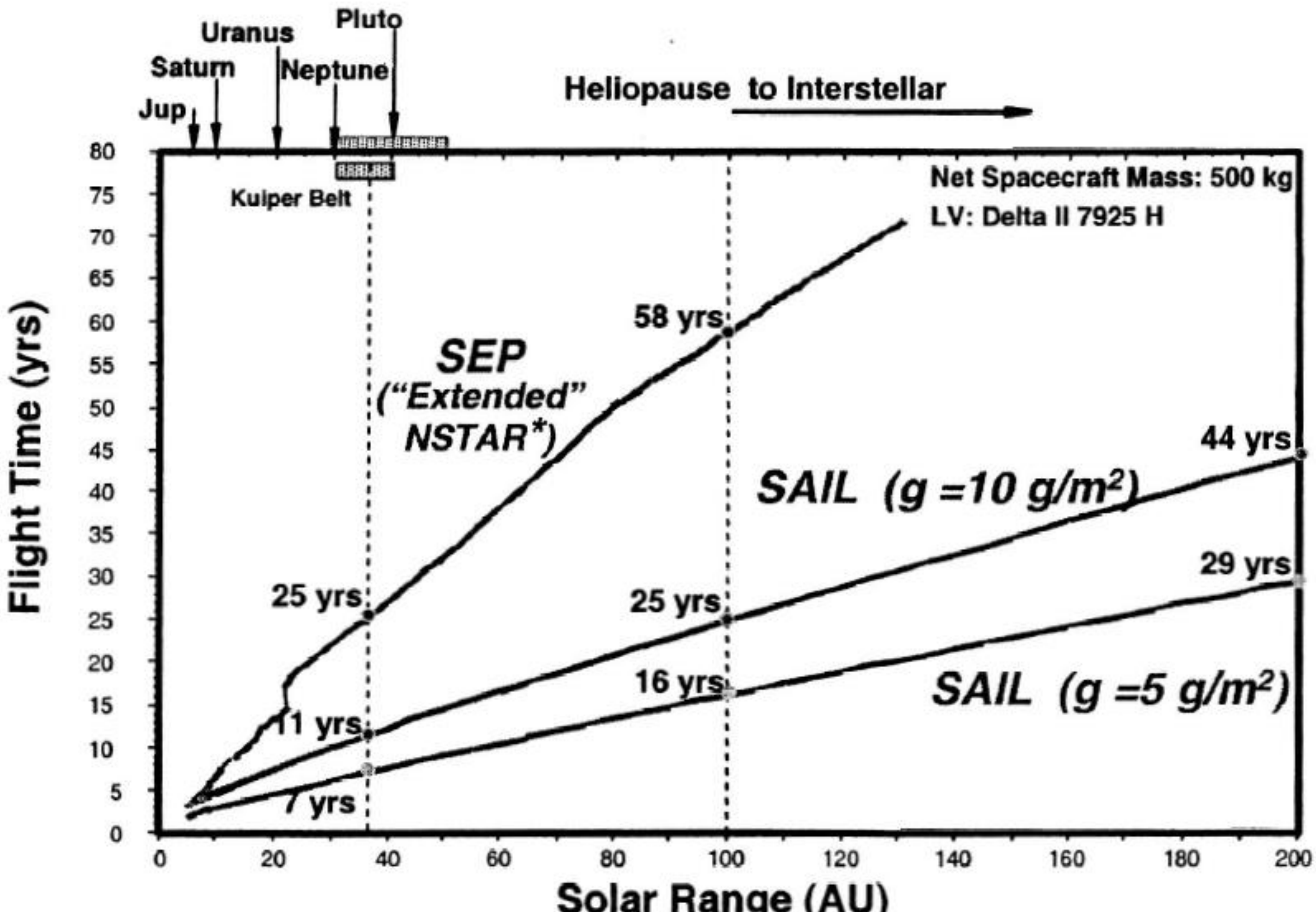


Figure 5. SEP/Solar Sail Performance Comparison

Some Current Laser System Technology Candidates

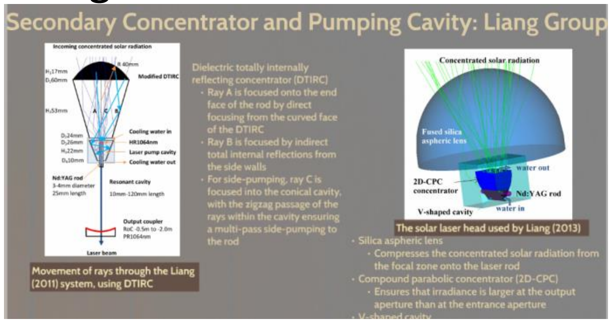
- Power Generation
    - Solar (Optical rectenna, photovoltaic, thermal cycle)
    - Nuclear
    - Electrodynamic Tether
- Laser
    - Solar-Pumped
        - Solid State Slab
        - Semiconductor)
    - Diode-Pumped Fiber Array
    - Diode-Pumped Rare Gas, Alkali
    - Direct Diode Array
    - Superconducting Accelerator FEL
    - Photonic Crystalline Fiber Array
    - Closed loop chemical, gas dynamic, electric discharge
- Beam Director
    - Large Gossamer Space Telescopes
    - Large Fresnel Lens
    - Phased Arrays

Ivanpah developers confident of meeting long-term target

Posted on *Nov 10, 2014*

Ivanpah tower plant in California. Picture credits: BrightSource.

A recent spate of articles makes the claim that Ivanpah, the 277 MW Ivanpah Concentrated Solar Power (CSP) power tower project in California is "not performing as expected."

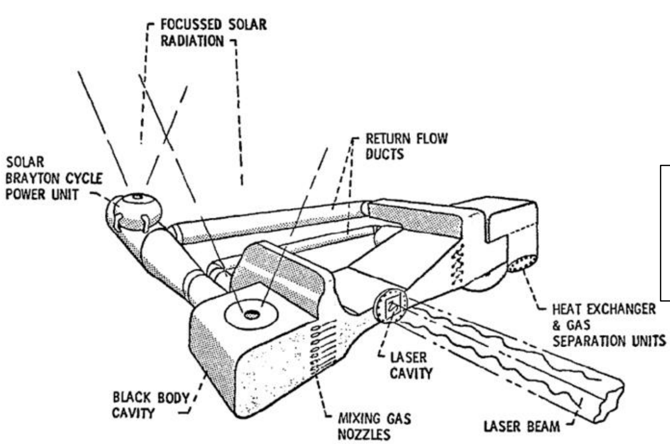


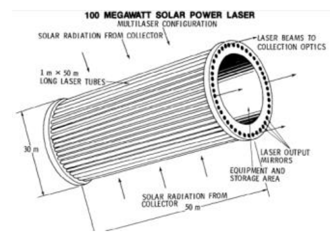
Notional Laser Beamed Power Requirements

- Transmitter
  - Very high output power levels required: > 100-10,000 Megawatts
  - Space-based to avoid atmospheric losses, pointing constraints, and safety
  - Large aperture, high quality beam control: > 100-10,000 meters
  - Shorter wavelengths preferred: < 500 – 2400 microns
  - Transmitter:efficient energy collection/generation and conversion to photons: >50%
  - Low system mass: > 1-5 kW/kg
- Receiver
  - Large Solar (photon) Sail: 500-1500 meter diameter, 5-7 g/m2
  - Small photon Sail: 2-100 cm diameter, high thermal & acceleration tolerance

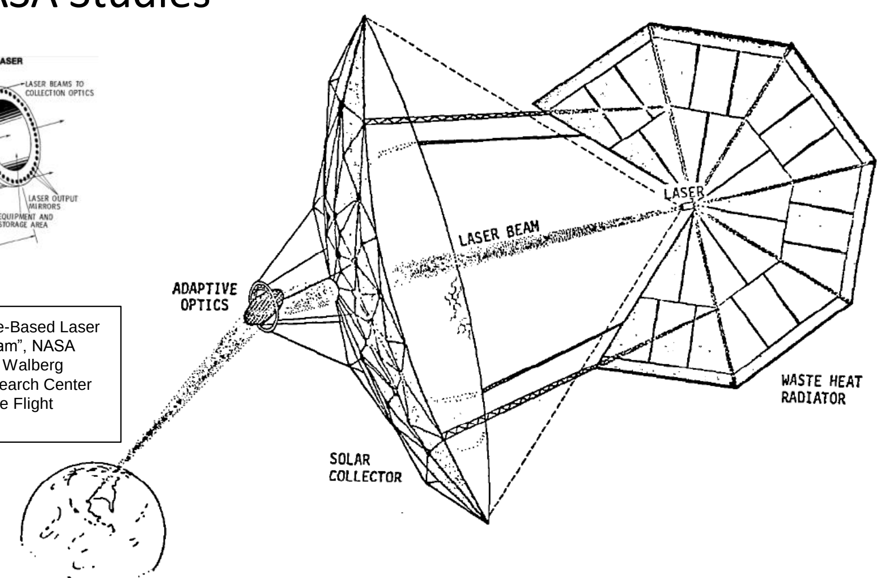
1972-81 NASA Studies

ARTIST'S SKETCH OF CO/CO_2 FLOW-MIXED SOLAR-PUMPED LASER FOR SPACE APPLICATIONS





From "A NASA High-Power Space-Based Laser Research and Applications Program", NASA SP-464, by R. J. De Young, G. D. Walberg And E. J. Conway of Langley Research Center and L. W. Jones of Marshall Space Flight Center



Artist's Concept of 1 MW Solar-Pumped Laser,

Laser System Technology Demonstrations

- Smallsat Demo in Earth Orbit
  - Long distance propagation - yes
  - Measurable thrust - maybe
  - Power density – no
  - New component tech
    - Diode-pumped fiber – yes (array, in ~5 years)
    - Solar pumped solid state – yes
    - Direct conversion – no (yes in 5-10 years)
      - Solar to electric (optical rectenna)
      - Electric to photon (direct diode)

- Ground Demonstration
  - Large Aperture Beam gossamer director - deploy and beam quality
  - Direct conversion technologies in space simulator chambers
  - High Power or phased array thrust measurement (pendulum experiment)

- Adjunct to interstellar NEA Scout
  - Smallsat Burst Laser to chase and engage
  - Send cubesat Fresnel lens to concentrate (Beam) sunlight on to sail from close proximity

Extrapolation from Other Mission Analysis

TABLE 1: *Solar System Escape Velocities (km/s) for 1.00 au Aphelion Launch.*

Incident Angle alpha (deg)	Solar Force Ratio, f 10.0	5.0	2.0	1.0	0.5	0.2	0.1
0	129.22	88.8	51.24	29.53	0	0	0
-5	130.53	90.28	53.00	31.79	9.97	0	0
-10	130.81	90.99	54.14	33.38	13.51	0	0
-15	130.05	90.88	54.65	34.33	15.51	0	0
-20	128.22	89.96	54.52	34.70	16.54	0	0
-25	125.34	88.20	53.75	34.49	16.74	0	0
-30	121.35	85.61	52.33	33.61	16.21	0	0
-35	116.29	82.17	50.26	32.10	14.92	0	0
-40	110.16	77.88	47.54	29.98	12.72	0	0
-45	102.96	72.86	44.16	27.16	9.19	0	0
optimum	134.21	94.22	57.54	37.06	19.18	0	0

From "Optimisation of Interstellar Solar Sail Velocities"
by Brice N. Cassenti, Orbital Technologies Research Center
JBIS, Vol 50, pp. 425-478, 1997

TABLE 2: *Solar System Escape Velocities (km/s) for 0.10 au Aphelion Launch.*

Incident Angle alpha (deg)	Solar Force Ratio, f 10.0	5.0	2.0	1.0	0.5	0.2	0.1
0	419.47	295.37	184.25	127.25	85.57	44.22	12.67
-5	425.02	301.11	189.78	132.51	90.34	48.56	19.48
-10	427.16	304.18	193.39	136.10	93.65	51.58	23.37
-15	425.78	304.35	194.93	138.01	95.55	53.38	25.56
-20	420.83	302.10	194.40	138.22	96.04	54.03	26.40
-25	412.25	296.84	191.77	136.69	95.14	53.54	25.99
-30	400.01	288.72	187.05	133.48	92.86	51.93	24.33
-35	384.12	277.75	180.24	128.57	89.21	49.19	21.24
-40	364.60	263.95	171.39	121.99	84.20	45.28	16.17
-45	341.49	247.35	160.59	113.75	77.83	40.10	5.83
optimum	439.39	314.75	202.23	143.44	99.66	56.36	28.55

Solar System Orbits

- Radius of attraction = 4500 AU
- Radius of Action = 60,000 AU
- Hill Sphere Radius
  - Direct = 230,00 AU
  - Retrograde = 100,00 AU
- Heliosheath = 113 AU
- Sol Gravity Lens Focus = 1000 AU

TABLE 3: *Solar system Escape Velocities (km/s) for 0.01 au Aphelion Launch.*

Incident Angle alpha (deg)	Solar Force Ratio, f 10.0	5.0	2.0	1.0	0.5	0.2	0.1
0	1333.89	942.88	595.55	420.22	295.84	184.40	126.98
-5	1352.11	961.50	613.12	436.17	309.46	194.53	134.83
-10	1352.11	961.50	613.12	436.17	309.46	194.53	134.83
-15	1355.54	972.97	629.23	452.53	324.14	205.95	143.81
-20	1340.20	965.44	627.47	452.83	325.28	207.27	144.98
-25	1313.29	948.89	619.10	447.88	322.32	205.70	143.97
-30	1274.70	923.25	604.17	437.71	315.29	201.29	140.80
-35	1224.45	888.55	582.59	422.38	304.29	194.10	135.54
-40	1162.81	844.84	554.58	402.01	289.31	184.23	128.26
-45	1089.53	792.28	520.21	376.73	270.69	171.81	119.04
optimum	1402.10	1007.47	652.30	469.12	335.99	213.41	149.11

Let f be the ratio of the solar light force to the solar gravitational force for a reflectivity of unity, then

$$f = \frac{2P_0A}{4\pi GMmc}. \qquad (4)$$