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


by
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for
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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)

Conventional Large Components [after Forward]
- Sol
- GW Laser
- 1000 km Transmitter
- Accelerate under beam
- Outer solar system
- Interstellar Medium

High Thrust Small Components [after Lubin]
- Earth Orbit Vicinity
- MW Laser
- < 100 m Transmitter
- Small Sailcraft
- coast

Distributed Small Components [after Kare/Andrews]
- < 339 m Transmitter
- GW Laser
- Stream of 88 million tiny (<1m) sails
- Magnetic momentum coupling

Distributed Moderate Components [Montgomery]
- Inside Venus Orbit
- Solar Laser 10-100 MW
- 100-1000 m Transmitters
- 5-30 Transmitters and/or relay stations along trajectory
- 100-1000 m Sail
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.


### SLS ETO launch capacity

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

Easily Sufficient to Launch Beamed Energy Infrastructure to Orbit

1 MW Space Laser System Weight

<table>
<thead>
<tr>
<th>Components</th>
<th><strong>Supersonic CO</strong></th>
<th><strong>Subsonic CO</strong></th>
<th><strong>Supersonic CO</strong></th>
<th><strong>Direct CF₃I</strong></th>
<th><strong>Indirect Static CO₂</strong></th>
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</thead>
<tbody>
<tr>
<td>Laser Loop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ducts, Nozzle, Diffuser, Cavity, Mirrors, Window Cooling Subsystem</td>
<td>1,574</td>
<td>1,662</td>
<td>6,292</td>
<td>600</td>
<td>600</td>
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<tr>
<td>Radiator and Heat Exch.</td>
<td>445</td>
<td>240</td>
<td>5,023</td>
<td>874</td>
<td>2,070</td>
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<tr>
<td>Flow Loop Compressor</td>
<td>250</td>
<td>275</td>
<td>1,216</td>
<td></td>
<td></td>
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<tr>
<td>Gas Make-up Purification</td>
<td>250</td>
<td>258</td>
<td></td>
<td>250</td>
<td></td>
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<tr>
<td>Recuperator</td>
<td>(N/A)</td>
<td>(N/A)</td>
<td></td>
<td>(N/A)</td>
<td></td>
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<td>Collector and Heat Exch.</td>
<td>(N/A)</td>
<td>(N/A)</td>
<td></td>
<td>(N/A)</td>
<td></td>
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<tr>
<td>Power Source:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine/Recuperator/Compressor</td>
<td>4,350</td>
<td>4,700</td>
<td>7,199</td>
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<tr>
<td>Radiator and Heat Exch.</td>
<td>4,163</td>
<td>4,500</td>
<td>8,565</td>
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<td>Collector/Concentrator/Cavity Absorber</td>
<td>5,670</td>
<td>8,600</td>
<td>15,889</td>
<td>58,560</td>
<td>3,200</td>
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<tr>
<td>Power Conditioner</td>
<td>260</td>
<td>205</td>
<td>(N/A)</td>
<td>(N/A)</td>
<td></td>
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<tr>
<td>Black Body Cavity</td>
<td>(N/A)</td>
<td>(N/A)</td>
<td>(N/A)</td>
<td>(N/A)</td>
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<tr>
<td>Total Weight (kg)</td>
<td>16,962</td>
<td>20,440</td>
<td>64,626</td>
<td>60,284</td>
<td>8,270</td>
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</table>

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

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

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

<table>
<thead>
<tr>
<th>Power [kw]</th>
<th>5 kg/kw</th>
<th>10 kg/kw</th>
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<tr>
<td>1</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>100</td>
<td>500</td>
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<td>5E+08</td>
<td>1E+09</td>
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<tr>
<td>SLS Initial</td>
<td>140000</td>
<td>kg</td>
</tr>
<tr>
<td>SLS Block 2</td>
<td>310000</td>
<td>kg</td>
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</table>

Perspective: HELLADs – General Atomics
- 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

U.S. Army
High Energy Laser Mobile Demonstrator
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
Laser Beamed Energy Propulsion has a Logical Evolutionary Path to Interstellar Grand Challenge

<table>
<thead>
<tr>
<th>Beamed Propulsion Architectures</th>
<th>ETO Mass</th>
<th>Trip Time</th>
<th>Nuclear Power</th>
<th>Solar Pump Laser</th>
<th>Relay Systems</th>
<th>Large Beam Director</th>
<th>Large Sail</th>
<th>Relevance to ISM Roadmap</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Tech Demo 1-10 AU</td>
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<tr>
<td>Ground Based Transmitter - Nano S/C with Sail</td>
<td>Small</td>
<td>Long</td>
<td>No</td>
<td>No</td>
<td>Yes&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Yes</td>
<td>Yes</td>
<td>Small Explorers 5-100 AU</td>
</tr>
<tr>
<td>Earth Orbit Transmitter - Nano S/C with Sail</td>
<td>Large</td>
<td>Long</td>
<td>Yes&lt;sup&gt;1&lt;/sup&gt;</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Medium Missions 200-300 AU</td>
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<tr>
<td>Solar Orbit Transmitter - Nano S/C with Sail</td>
<td>Medium</td>
<td>Medium</td>
<td>No</td>
<td>Yes&lt;sup&gt;2&lt;/sup&gt;</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Large Missions 500-600 AU</td>
</tr>
<tr>
<td>Solar Transmitter with Relays - Nano S/C with Sail</td>
<td>Medium</td>
<td>Short</td>
<td>No</td>
<td>Yes&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>1000 AU Challenge</td>
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<tr>
<td>Nuclear Transmitter with Relays - Nano S/C with Sail</td>
<td>Medium</td>
<td>Short</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

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 (3 km)

Technology Demonstration, Science Discovery
- Technology Demonstration Missions 1 – 10 AU
- Small Explorers LISM and Helisphere Multi-Prebes 5 – 100 AU
- Medium Scale Missions 200 – 300 AU
- Large Scale Missions 500 - 600 AU

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
  - $\lambda=1$ 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.)

$$a = \frac{(100*100)}{(q*\lambda)} = 4.1 \times 10^6 \text{ km}$$
(note: diffraction limit range to capture 1st airy diameter spot)
TREMENDOUS LEVERAGE ON IMPROVING DEPARTURE TRAJECTORIES AND OR LAUNCHING MORE MASSIVE SAILS

characteristic acceleration

\[ a_c = \frac{2 P_{out}}{m_{sail} c} \]

Collected Irradiance \( P_{out} \) = [kilowatts]
Distance from the Sun = [meters]

- \( d=D=100 \text{ meter} \)
- No jitter
- 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

Mercury
Venus

\( y = 2E-27x^2 - 6E-16x^2 + 5E-05x - 2E+06 \)
\( R^2 = 0.9694 \)
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

Graph showing power output in kilowatts from different solar system positions, including Inner solar system Relay #2, Outer solar system Relay #12, Heliosphere Relay #30, and Jupiter, Relay #3.
Figure 5. SEP/Solar Sail Performance Comparison
Some Current Laser System Technology Candidates

- Power Generation
  - Solar (Optical rectenna, photovoltaic, thermal cycle)
  - Nuclear
  - Electrodynamically Tethered

- 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
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
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.

<table>
<thead>
<tr>
<th>Incident Angle alpha (deg)</th>
<th>Solar Force Ratio, f</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10.0</td>
</tr>
<tr>
<td>0</td>
<td>129.22</td>
</tr>
<tr>
<td>-5</td>
<td>130.53</td>
</tr>
<tr>
<td>-10</td>
<td>130.81</td>
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<tr>
<td>-15</td>
<td>130.05</td>
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<tr>
<td>-20</td>
<td>128.22</td>
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<tr>
<td>-25</td>
<td>125.34</td>
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<tr>
<td>-30</td>
<td>121.35</td>
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<tr>
<td>-35</td>
<td>116.29</td>
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<tr>
<td>-40</td>
<td>110.16</td>
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<tr>
<td>-45</td>
<td>102.96</td>
</tr>
<tr>
<td>optimum</td>
<td>134.21</td>
</tr>
</tbody>
</table>


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

<table>
<thead>
<tr>
<th>Incident Angle alpha (deg)</th>
<th>Solar Force Ratio, f</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>10.0</td>
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<tr>
<td>0</td>
<td>419.47</td>
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<td>341.49</td>
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<tr>
<td>optimum</td>
<td>439.39</td>
</tr>
</tbody>
</table>

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

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

$$f = \frac{2P_0 A}{4\pi GMmc}.$$  

(4)