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

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June 13-15, 2017
Foundations of Interstellar Studies Workshop
New York City College of Technology, Brooklyn, NY
Background - Solar Sail Propulsion Technology

• Maturing rapidly –
• 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
<table>
<thead>
<tr>
<th>Sailcraft</th>
<th>Areal Density [g/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKAROS</td>
<td>1535</td>
</tr>
<tr>
<td>NanoSail-D</td>
<td>355</td>
</tr>
<tr>
<td>Cosmos 1</td>
<td>167</td>
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<td>LightSail</td>
<td>143</td>
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<td>NEA Scout</td>
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<tr>
<td>Sunjammer</td>
<td>45.5</td>
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<td>JPL NIAC Study Concept</td>
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<td>JPL ISM Mission Study Concept</td>
<td>1.4</td>
</tr>
<tr>
<td>JPL Halley Comet Reendezvous Design</td>
<td>1.4</td>
</tr>
</tbody>
</table>
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)
• ~85 m² 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

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

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.

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

Method based on:


Power Delivered to Orbit

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

Power in spot, \( P = I_{ave} \cdot \text{Area} \)

where

- \( \text{Area} = \pi r^2 \)
- \( s_j \) = jitter
- \( s_D \) = diffraction

\( I_{pj} = I_{peak} \cdot s_j \)

\[
I_{ave}(r_d) = \frac{1}{\pi r_d^2} \int_0^{2\pi} \int_0^{\pi} I_{pj} e^{2\pi j r_d^2} r dr d\theta
\]

\[
I_{ave}(r_d) = \frac{1}{\pi r_d^2} \int_0^{2\pi} \int_0^{\pi} I_{pj} e^{2\pi j r_d^2} r dr d\theta = \frac{I_{pj}}{\pi r_D^2} \int_0^{2\pi} \int_0^{\pi} e^{2\pi j r_d^2} r dr d\theta = \frac{I_{pj}}{2\pi r_D^2} \int_0^{2\pi} \int_0^{\pi} e^{2\pi j r_d^2} r dr d\theta
\]

\[
I_{ave}(r_d) = \frac{2I_{pj} \sigma_D^2}{r_D^2} \left[ 1 - e^{-2\pi r_d^2} \right] = \frac{2I_{pj} (\sigma_D^2 + \sigma_j^2)}{r_D^2} \left[ 1 - e^{-2\pi r_d^2} \right]
\]

(2.10)
Max $\Delta V$ of Laser on LightSail 2
[for 13 May 2017 Opportunity 1]

- 10kw, 1064 nm cw laser
- 30 cm beam director aperture
- 3 $\mu$rad 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
- $\sigma_{DIFF} = R \times 0.45 \lambda/D$

Single overpass max cumulative $\Delta V = 0.056$ m/sec

0.1 m/sec $\Delta V$ 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

<table>
<thead>
<tr>
<th>Aperture (m)</th>
<th>Mass (kg)</th>
<th>Aperture (m)</th>
<th>Mass (kg)</th>
<th>Aperture (m)</th>
<th>Mass (kg)</th>
<th>Aperture (m)</th>
<th>Mass (kg)</th>
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</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1500</td>
<td>2.4</td>
<td>2920</td>
<td>8.0</td>
<td>6500</td>
<td>20</td>
<td>36,000</td>
</tr>
</tbody>
</table>

High Energy Laser Mobile Demonstrator
Hubble Space Telescope
James Webb Space Telescope
Advanced Large Aperture Space Telescope Concept
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 Fraunhoffer Diffraction equation\(^1\) to be:

$$d = 2.44 \frac{R \lambda}{D}$$

Independent of laser power level

The total power ($P$) within the first Airy ring projected onto a surface from a laser with power $P_0$ is:

$$P = 0.838 P_0$$

Independent of propagation distance

---

\(^1\) 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)

Sail Area
- 10 m²
- 1200 m²
- 40000 m²

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]

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

3 Path Comparison

- Solar Sail
- Laser Sail
- Break Through Starshot
## Comparison of Key Performance Parameters

<table>
<thead>
<tr>
<th></th>
<th>Solar Sail</th>
<th>Laser Sail Propulsion</th>
<th>Break Through Starshot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Earth Orbit</td>
<td>Solar System</td>
<td>Interstellar</td>
</tr>
<tr>
<td><strong>Characteristic Acceleration</strong> [mm/s²]</td>
<td>lower 0.06 upper 0.08</td>
<td>lower 0.06 upper 3</td>
<td>lower 4 upper 1450</td>
</tr>
<tr>
<td><strong>Maximum Sail Loading</strong> [μN/m²]</td>
<td>lower 9.1 upper 10.9</td>
<td>lower 9.2 upper 34</td>
<td>lower 35 upper 218</td>
</tr>
<tr>
<td><strong>Sail Area</strong> [m²]</td>
<td>lower 80 upper 200</td>
<td>lower 100 upper 4x10⁴</td>
<td>lower 4x10⁴ upper 1x10⁶</td>
</tr>
<tr>
<td><strong>Sail Areal Density</strong> [g/m²]</td>
<td>lower 42 upper 26</td>
<td>lower 38 upper 10</td>
<td>lower 7.0 upper 0.1</td>
</tr>
<tr>
<td><strong>Laser Power Delivered</strong> [MW]</td>
<td>lower 0.001 upper 0.1</td>
<td>lower 0.1 upper 1</td>
<td>lower 1 upper 100</td>
</tr>
<tr>
<td><strong>Laser Mass</strong> [kg]</td>
<td>lower - upper -</td>
<td>lower 5000 upper 5x10⁴</td>
<td>lower 5x10⁴ upper 5x10⁵</td>
</tr>
<tr>
<td><strong>Laser pointing accuracy</strong> [μrad]</td>
<td>lower 3 upper 3</td>
<td>lower 1 upper 0.1</td>
<td>lower 0.1 upper 0.1</td>
</tr>
<tr>
<td><strong>Power source</strong> [kg]</td>
<td>lower 3.6 upper 5.2</td>
<td>lower 3.8 upper 401</td>
<td>lower 294 upper 100</td>
</tr>
<tr>
<td><strong>Sail Mass</strong> [kg]</td>
<td>lower 2.2 upper 6.9</td>
<td>lower 3.4 upper 10</td>
<td>lower 10 upper 10</td>
</tr>
<tr>
<td><strong>Spacecraft Power</strong> [kg]</td>
<td>lower 2.3 upper 4.9</td>
<td>lower 2.5 upper 12</td>
<td>lower 12 upper 12</td>
</tr>
<tr>
<td><strong>Spacecraft Thermal</strong> [kg]</td>
<td>lower 0.5 upper 1.0</td>
<td>lower 0.5 upper 2</td>
<td>lower 2 upper 2</td>
</tr>
<tr>
<td><strong>Spacecraft ACS/GN&amp;C</strong> [kg]</td>
<td>lower 1.9 upper 4.0</td>
<td>lower 2.2 upper 10</td>
<td>lower 10 upper 10</td>
</tr>
<tr>
<td><strong>Spacecraft Communications</strong> [kg]</td>
<td>lower 1.0 upper 2.1</td>
<td>lower 1.0 upper 10</td>
<td>lower 10 upper 10</td>
</tr>
<tr>
<td><strong>Spacecraft Structure &amp; Mechs</strong> [kg]</td>
<td>lower 2.0 upper 4.2</td>
<td>lower 2.0 upper 5</td>
<td>lower 5 upper 5</td>
</tr>
<tr>
<td><strong>Spacecraft Command/Data</strong> [kg]</td>
<td>lower 0.1 upper 0.1</td>
<td>lower 0.1 upper 1</td>
<td>lower 1 upper 1</td>
</tr>
<tr>
<td><strong>Probe Total Mass</strong> [kg]</td>
<td>lower 13.5 upper 28.4</td>
<td>lower 15.4 upper 451</td>
<td>lower 344 upper 150</td>
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<tr>
<td><strong>Infrastructure Mass to Orbit</strong> [10³ kg]</td>
<td>lower 0 upper 0</td>
<td>lower 0 upper 0</td>
<td>lower 0 upper 12.8</td>
</tr>
</tbody>
</table>
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

THE NEED

- Size: >>10^6 m^2
- Areal density: ~< 1 gram/m^2

NEA Scout
ATP 2014
2018 – 2021

LightSail A/B
2015 / 2017

85 m^2
30 g/m^2 (sail system)

32 m^2
• 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 & Photonics Magazine, OSA, May 2017]

• 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]
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
BTS has requirements?

- 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