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Earth to Orbit Beamed Energy Experiment

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Abstract

As a means of primary propulsion, beamed energy propulsion offers the benefit of offloading much of the propulsion system mass from the vehicle, increasing its potential performance and freeing it from the constraints of the rocket equation. For interstellar missions, beamed energy propulsion is arguably the most viable in the near- to mid-term. A near-term demonstration showing the feasibility of beamed energy propulsion is necessary and, fortunately, feasible using existing technologies. Key enabling technologies are large area, low mass spacecraft and efficient and safe high power laser systems capable of long distance propagation. NASA is currently developing the spacecraft technology through the Near Earth Asteroid Scout solar sail mission and has signed agreements with the Planetary Society to study the feasibility of precursor laser propulsion experiments using their LightSail-2 solar sail spacecraft. The capabilities of Space Situational Awareness assets and the advanced analytical tools available for fine resolution orbit determination now make it possible to investigate the practicalities of an Earth-to-orbit Beamed Energy eXperiment (EBEX) – a demonstration at delivered power levels that only illuminate a spacecraft without causing damage to it. The degree to which this can be expected to produce a measurable change in the orbit of a low ballistic coefficient spacecraft is investigated. Key system characteristics and estimated performance are derived for a near term mission opportunity involving the LightSail-2 spacecraft and laser power levels modest in comparison to those proposed previously. While the technology demonstrated by such an experiment is not sufficient to enable an interstellar precursor mission, if approved, then it would be the next step toward that goal.

Keywords: LightSail, Solar Sail, CubeSat, Laser Propulsion, Beamed Energy Propulsion

Acronyms/Abbreviations

Advanced Maui Optical System (AMOS)
Earth To Orbit (ETO)
Earth-to-orbit Beamed Energy eXperiment (EBEX)
Eglin Air Force Base (EAFB)
Geostationary Earth Orbit (GEO)
Kwajalein Missile Range (KMR)
Lockheed Martin Company (LMCO)
Marshall Space Flight Center (MSFC)
Near Earth Asteroid (NEA)
Redstone Arsenal (RSA)
Resident Space Objects (RSO)
Starfire Optical Range (SOR)
Two Angle Pairs Initial Orbit with Conjunction Analysis (TAPIOCA)
United States Air Force (USAF)

1. Introduction

The Planetary Society’s LightSail-2 spacecraft will deploy a 32 square meter solar sail in Low Earth Orbit (LEO) sometime in early- to mid-2018. The results of recent achievements in high power solid state lasers, adaptive optics, and precision tracking have made it possible to access effective and low cost laser systems. Combined with renewed interest by the space science and space exploration communities in developing technologies that could eventually send a probe to the Kuiper Belt and beyond into interstellar space, a study team was formed to examine the feasibility of using this confluence of emerging technologies and mission pull to define a low-cost, near-term, Earth-To-Orbit (ETO) Beamed Energy (propulsion) eXperiment (EBEX).

In support of the NASA Near-Earth Asteroid (NEA) Scout mission, NASA’s Marshall Space Flight Center (MSFC) established a Space Act Agreement with The Planetary Society for cooperating on their LightSail 2 mission. LightSail 2 is currently planned for launch no earlier than April 2018 on the USAF Falcon Heavy launch as a secondary payload. LightSail 2 is a 3U cubesat from which the solar sail will be deployed. The spacecraft and sail weigh approximately 5 kilograms. The launch operations plan is to deliver LightSail 2 to a 720 kilometer circular orbit at 24 degrees inclination [1,2]. The orbital elements of right ascension, true anomaly, and argument of perigee are closely tied to exact date and time of day. Those elements and the exact timing of when LightSail 2 will appear over a laser site on the ground will remain uncertain until after the launch.

The first two weeks on-orbit will be spent in check-out of the spacecraft systems. The primary mission of LightSail 2 is solar sailing. Experiments in orbit shaping will be conducted for another 28 days. The final orbit is to be determined experimentally and is therefore uncertain. For the EBEX study, it is assumed that the spacecraft is still in the initial orbit 42 days after launch. At that time, the LightSail 2 will be made available for the EBEX.

2. Measuring the Propulsive Effect

Propulsive effect is indicated via Kepler's laws by a change in a spacecraft's orbital velocity. Two methods were the considered for determining orbital velocity change. The first was to outfit LightSail 2 with an extremely sensitive accelerometer to directly detect spacecraft dynamical response to laser illumination. Resolution on the order of a fraction of micro-g was required. That is slightly beyond the current state of the art and would have required some design changes on LightSail 2 -- incurring expense to the program. A second method would involve design changes, the incorporation of improved GPS signal processing on-aboard the spacecraft and an additional data downlink burden. After further investigation Garber determined that the systems under consideration would likely provide enough propulsive effect that orbital parameter changes could be determined by existing ground tracking assets [3].

The same optical tracking systems that are needed to control the high power laser beam will also provide information sufficient to determine orbital elements with a high degree of accuracy. Determination of low thrust maneuvers from short overpass optical observations from ground-based observatories is a well-developed science for Geostationary Earth Orbit (GEO) satellites. Optical tracklets consist only of measured and time-stamped telescope azimuth and elevation angles from several telescopes located around the globe have been used to determine precise GEO satellite position and velocity. Kelecy and Jah have reported good results using the Two Angle Pairs Initial Orbit with Conjunction Analysis (TAPIOCA) to detect and estimate orbital maneuver events by non-cooperative Resident Space Objects (RSO)s [4]. The Orbit Determination Tool Kit has been used by Hujsak to predict maneuver thrust components as low as 0.01 millimeters/second. [5], which is shown here to be sufficient for the subject near term LEO laser thrust demonstration. This study investigates the feasibility of a proposed key performance parameter of creating laser-induced orbital velocity change greater than 0.01 millimeters per second over a few days of access opportunities from the ground.

3. Ground Based Laser Options

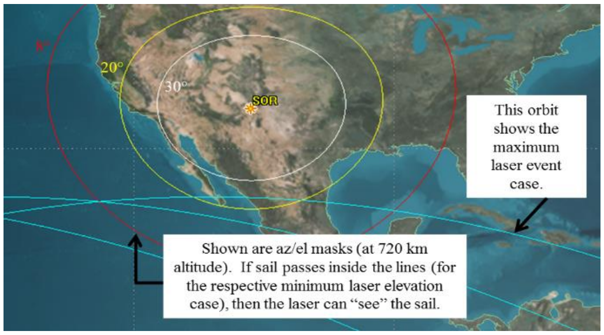
Candidates for the location of the laser on the ground are limited to those with well-developed safety facilities and cultures including air space deconfliction, range access control, and satellite avoidance. Initial investigations into astronomical guide star and satellite ranging laser sites indicated that existing laser power output levels were insufficient. At the bottom of the list of candidate sites in Table 1 is a figure (Fig. 1) showing the 24 degree inclination ground track of LightSail 2. Note that only a few of the sites are actually under the ground track. This illustrates the major challenge with accessing the LightSail 2 orbit. Typical higher inclination orbits would provide much more frequent, longer duration accesses at shorter ranges. In addition to those sites listed, a ship-based laser could theoretically allow optimum access.

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

Table 1. Candidate locations for the ground based laser to illuminate LightSail 2.

Fig. 1 The LightSail 2 ground track is well below the ability of most sites in the continental United States to achieve sufficient laser dwell time.

Figure 2 depicts the ground track geometry between the spacecraft in orbit and a ground site near Albuquerque, New Mexico. Included on the figure are circles indicating the cone of coverage extending up from the ground that would intersect the orbit of LightSail 2 at an altitude of 720 km. The blue lines indicate several successive orbits it as the earth rotates and precesses the ground track. At closest approach, it can be seen that below 30 degrees minimum elevation, the spacecraft could never be accessed from this site. Even at 20 degree minimum elevation, the spacecraft would only be accessible for a very short period of time at very long range.



This orbit shows the maximum laser event case.

Shown are az/el masks (at 720 km altitude). If sail passes inside the lines (for the respective minimum laser elevation case), then the laser can "see" the sail.

Figure 2. The LightSail 2 can only be engaged by the SOR laser at low elevation, likely violating range safety requirements.

Figure 3 Indicates that only three of the candidate sites can offer access times over 200 seconds at laser pointing angles above 30 degree elevation: the Kwajalein Missile Range (KMR) in the Marshall Islands, the Advanced Maui Optical System(AMOS) facility atop Mt. Haleakala on Maui, and Eglin Air Force Base (EAFB) at Santa Rosa Island in Florida on the Gulf Coast of the United States. The frequency at which these overpasses occur is important also. Frequency also tends to favor lower latitudes. On a repeating cycle of approximately every 50 days, the number of accesses could range from once to seven times per day.

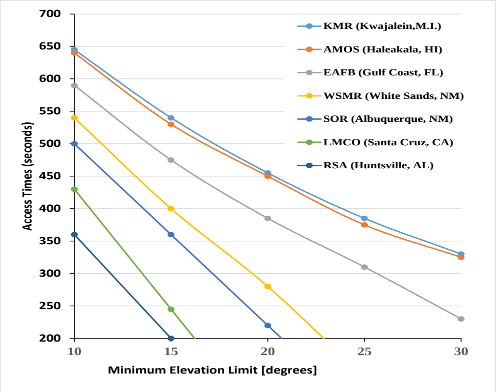


Fig. 3. Duration of laser access to LightSail 2 from candidate ground sites and minimum elevation limits.

Laser power levels in the range of 10-100 kilowatts are powerful enough to have a measurable effect but low enough to only illuminate spacecraft with negligible thermal transfer. There are a number of industrial lasers available at this and higher power levels, but their beam quality is not suitable. The long propagation path from ground to space requires near diffraction limited projection. Single mode fiber lasers such as those based on a 10 kilowatt laser owned by Lockheed Martin Area Defense Anti-Munitions Systems and Boeing Defense and Energy Systems are good candidates. The lasers must be accompanied by high precision beam directors with at least moderately sized apertures (>20 centimeter diameter).

The highest altitude sites AMOS (3055 meters) and North Oscura Peak on White Sands Missile Range (2643 meters) above sea level offer reduced beam extinction. Most atmospheric transmission losses in the laser beam are a result of scattering of aerosols that exist predominately in the first 3 kilometers above the earth's surface. Starfire Optical Range (SOR) at 2280 meters is comparatively high in altitude, but that is mostly the result of mid-continent bulge and the aerosol layers rise above local ground height. The Redstone Arsenal (RSA) location in Huntsville, Alabama and the Lockheed Martin Company (LMCO) range at Santa Cruz, California are the lowest altitude site at a few hundred meters above sea level. RSA has frequent morning fog, high humidity levels, and biological particulates. Because the radius of the earth is so much longer than height of any mountaintop site, position of the laser at altitude doesn't make much difference in dwell time. Latitude of the ground site is a far more important parameter, as that determines the elevation angle of overpass and the number of overpasses occurring per day.

4. Dwell Time

In addition to the geometry between the ground site, the spacecraft and the sun, the slant range, and the actual amount of light that is shining upon the sail, the amount of orbital velocity change produced in LightSail 2's orbit will depend on the length of time the satellite is illuminated (dwell time). Amateur radio operators have developed a working understanding of the relationship between elevation and dwell time. For a spherical earth and a direct overpass, a satellite would be within a line of sight below 10 degrees elevation for 30% of the entire overpass duration. Similarly it would spend another 20% of the total time between 10 and 20 degrees elevation. Between 20 and 30 degrees elevation would encompass another 10%, so that only 40% of time a spacecraft would be within LOS is available for lasing when the minimum elevation imposed is 30 degrees. [6]. Most overpasses with not be directly overhead.

5. Thrust and Acceleration

McInnes has shown that momentum transferred from the laser beam into the spacecraft is dependent on the specularity, s, and total reflectivity, r, of the spacecraft. Solar sails are typically coated to provide high reflectance across the solar spectrum of wavelengths. [7] A typical value of the rs product is 92%. Because the momentum of photons is not only brought to rest in interaction with the sail, but also assumed to be reflected directly backward the multiplier is (1+rs). Thrust from photon momentum transfer is calculated:

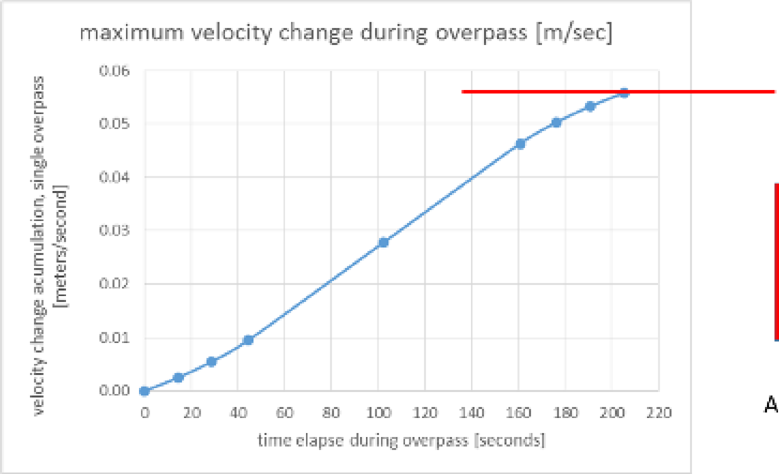
Thrust [Newtons] = (1+rs) * PIB [watts] /c [meters/second], c = speed of light [meters/second^2]

Laser access would occur nominally twice per day, except for AMOS, which may be up to 6 times per day. Its latitude near the equator gives AMOS access to more orbital inclinations. Acceleration is calculated by dividing the thrust by the 5 kilogram mass of LightSail 2. Velocity change is the product of acceleration and dwell time.

6. Anticipated Results

As shown in Figure 4 below, the single access during opportunity one from a 10 kilowatt laser at EAFB would not reach the desired 0.1 millimeter per second goal. However, two or more like accesses would exceed it.

- 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

Fig. 4. Results of the analysis show that, in general, a measurable DV can be achieved with two or more passes and engagements over the laser site.

7. Conclusions

Demonstration of laser photon momentum exchange propulsion from the Earth surface to LEO is technically feasible with existing, commercially available high energy lasers located at operational government test facilities with fully mature range control to meet safety regulations. It appears feasible to produce a measureable effect in a 1-3 accesses over an even unfavorable combination of ground site latitude and orbital inclination. Multiple passes over several during a typical 50 day cycle should reduce the uncertainty in distinguishing between solar pressure and atmospheric drag effects. The state of the art in orbit change determination is increasing steadily and will only become easier and more practical. The proliferation of small spacecraft with high ballistic coefficients will provide a regular supply of opportunities for an EBEX. Availability of the capable ground sites will need to be coordinated, but with 24 months lead time there is reason to believe that could be accomplished. The launch date of payloads such as Light-Sail 2 will not be flexible so that scheduling of the ground site will have to be as flexible as possible. As more powerful solid state laser systems mature over the next few years, even more robust experiments will be possible with mobile platforms carrying self-contained power and thermal control for 50 kilowatt lasers of high beam quality and half meter beam directors with precision NIR and MWIR acquisition and track capability.

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