Feasibility study for a near term demonstration of laser-sail propulsion from the ground to Low Earth Orbit

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ABSTRACT

This paper adds to the body of research related to the concept of propellant-less in-space propulsion utilizing an external high energy laser (HEL) to provide momentum to an ultra-lightweight (gossamer) spacecraft. It has been suggested that the capabilities of Space Situational Awareness assets and the advanced analytical tools available for fine resolution orbit determination make it possible to investigate the practicalities of a ground to Low Earth Orbit (LEO) 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 by Forward, Landis, or Marx. [1,2,3] A more detailed investigation of accessing LightSail 2 from Santa Rosa Island on Eglin Air Force Base on the United States coast of the Gulf of Mexico is provided to show expected results in a specific case.

1. BACKGROUND

The design and construction of the Planetary Society's LightSail 2 solar sail demonstration spacecraft has captured, in space flight hardware, the concept of small, yet capable spacecraft. The results of recent achievements in high power solid state lasers, adaptive optics, and precision tracking have also made it possible to access the effectiveness and reduced cost of an entry level laser power source. 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 formulate near term mission concepts that would initiate the development of new propulsion methods needed for such a mission. [4] A small scientific probe spacecraft with a lightweight reflective sail to capture momentum from a high energy laser (HEL) was one of the recommended propulsion technology options. [5] Several candidates were considered for a low cost, near term demonstration, then quickly reduced to two mission-system concepts. The first is a fully space-based option involving a small satellite that would have on-board a laser and beam control system that would illuminate a tiny square sail (2-5 centimeters in length on a side) also launched from the small-sat. It is consistent with the concepts put forth by Lubin et al [6]. The other concept which is addressed in this paper involves utilizing existing ground-based high power lasers to illuminate and propel a satellite in LEO. NASA's Marshall Space Flight Center has partly enabled a demonstration mission through an agreement with The Planetary Society for cooperating on their LightSail 2 mission. LightSail 2 is currently planned for launch in Mid-March of 2017 on the USAF STP-2 Falcon Heavy launch as a secondary payload. LightSail 2 is a 3U cubesat from which a 32 square meter reflective membrane sail will be deployed. The whole spacecraft and sail weighs only 5 kilograms. The launch operations plan is to deliver LightSail 2 to a 720 kilometer circular orbit at 24 degrees inclination. [7, 8] 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 this study, it is assumed that the spacecraft is still in the initial orbit 42 days after launch. On May 17, 2017, LightSail 2 will be made available for laser propulsion studies. NASA has given this latter activity a project name and acronym, Earth-to-Orbit Beamed Energy Experiment (EBEX). [9]

2. ANALYTICAL MODELS

Two analytical tools were developed. The first is a model of the fundamental orbital mechanics of LightSail 2 in version 11 of AGI's Orbit Determination Tool Kit (ODTK). An HPOP orbital propagator was selected. It used the World Geodetic System 1984 elliptical earth gravity model, NRLMSISE 2000 atmospheric density model, and third body gravitational effect from the Sun and Moon. Only access times occurring in umbra (total eclipse) were selected as laser propulsion opportunities. A further restriction was that lasing could not occur until the spacecraft was above 30 degrees elevation. This should encompass keep-out-zones due to nearby objects (e.g. buildings, mountainous terrain) and allow for time to acquire and lock a track on the spacecraft with the beam director. Initial values were assumed to be: right ascension = 270 degrees, true anomaly = 90 degrees, and argument of perigee =0 degrees.

The second tool was a spreadsheet implementation of simplified algorithms for laser propagation and photon momentum exchange. For estimating the laser power delivered to orbit, a set of equations based on methods used in the Airborne Laser Program and reported by Merritt [10] was used. The estimate for photon momentum transfer to the spacecraft was based on the linear photonic thrust model by Greschik [11]. A combined flow model for the analysis is depicted in Figure 1. Basic inputs include GBL output power, aperture, wavelength and slant range to the target (in this case, LightSail 2). There are other important inputs that model the degree to which the atmosphere conditions are accommodating (transmittance, higher order strehl). The degree to which the tracker and adaptive optics control loops can reject errors is also an input. Dwell time and elevation affect the accumulation of energy on the spacecraft. A specific overpass case is handled by segmenting the overpass trajectory by equal increments of elevation change (2 degrees). The result is numerically integrated using the Newton-Cotes mid-point rule.

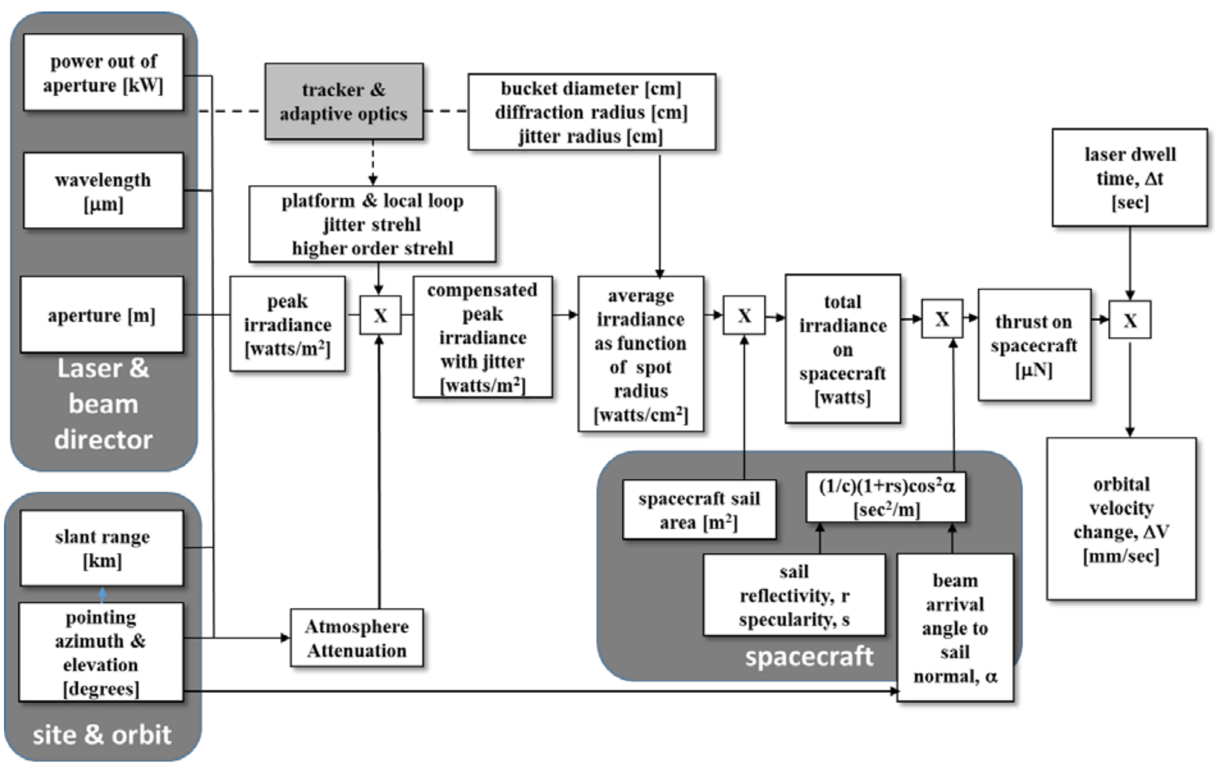


FIGURE 1. Extension of Merritt's method for laser propagation to include Greschik's photon momentum transfer model.

3. MANEUVER MEASUREMENTS

Propulsive effect is indicated via Kepler's laws by a change in a spacecraft's orbital velocity. Two methods were 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 [12] determined that the systems under consideration would likely provide enough propulsive effect that orbital parameter changes could be determined by existing ground tracking assets.

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 (GEO) satellites. Optical tracklets consisting 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).[13] The Orbit Determination Tool Kit has been used by Hujsak to predict maneuver thrust components as low as 0.01 millimeters/second. [14]. Change in velocity will be the product of acceleration caused by thrust from the laser photon pressure and the duration of the lasing event.

4. LASER GROUND SITE

Candidates for the location of the laser on the ground were limited to those with well-developed safety facilities and cultures including air space deconfliction, range access control, and satellite avoidance. Initial investigations into astronomical guidestar and satellite ranging laser sites indicated that existing laser power output levels were insufficient. [15] At the bottom of the list of candidate sites in Table 1 is a figure 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.

Table 1. Candidates for location of HEL ground site

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

5. ACCESS OPPORTUNITIES

The geometry between the ground site, the spacecraft and the sun are important for (1) high signal to background for acquisition and tracking, and (2) extraction laser impulse from a much stronger solar impulse on the spacecraft. More detailed consideration of a ground laser site on the Santa Rosa Island (SRI) range on EAFB follows. Figure 2 shows the access opportunities predicted by the STK model for the assumed launch date and initial conditions. This ODTK case indicates the first repeating ground track cycle has just passed (gray area) and now a second cycle of opportunities is coming between 50 and 75 days after launch. This is an artifact of the assumed orbit insertion parameters and represents very nearly worst case timing.

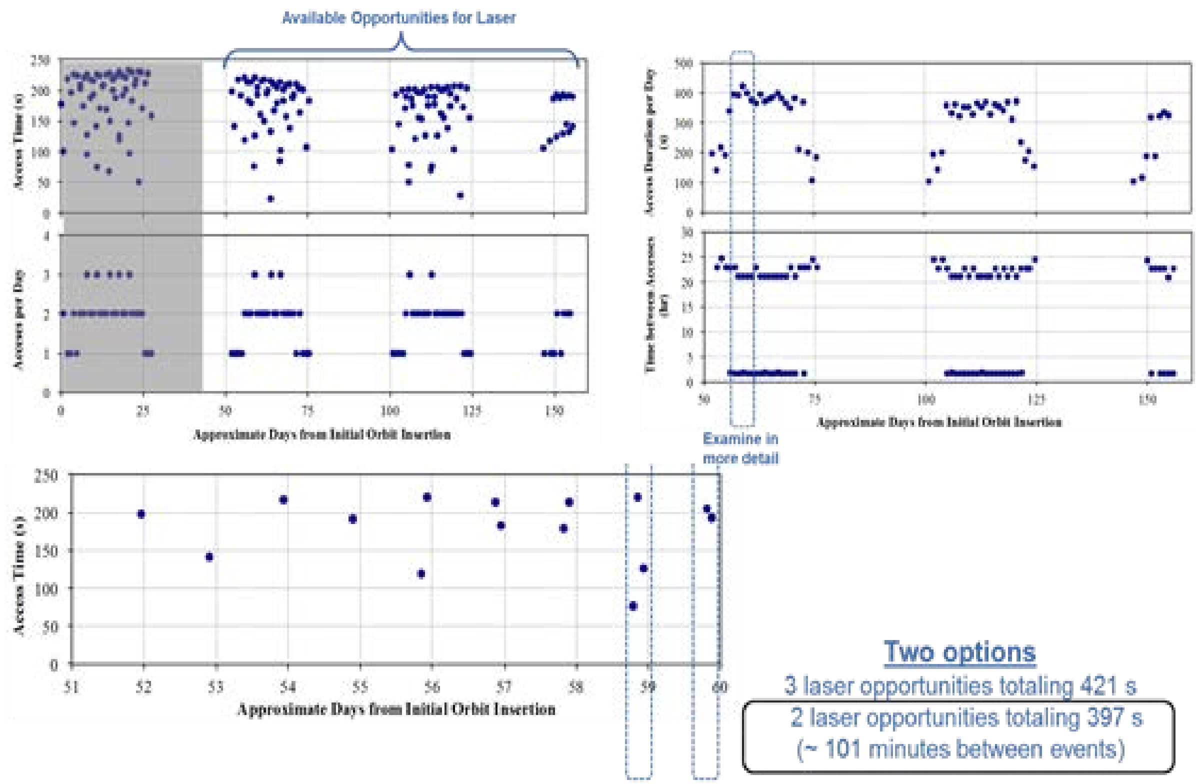


Figure 2. Access opportunities selected for further analysis – SRI to LightSail 2 on May 13-14, 2017

A few observations of broad application on lighting conditions are available to us. The azimuth and elevation track across the sky from SRI vary only slightly from day to day. The sun rises at 5:53 AM, sets at 7:33 PM, and reaches a peak elevation of 78 degrees at 12:43 PM local time. In addition to the 13 hour, 40 minute day are the 3 to 4.5 hour twilight times at dawn and dusk. Compared to that wide window in time, the 200 second overpass event is a relatively narrow, short duration. For this reason, during any particular access event, the position of the sun can be considered fixed in the sky. The actual time of day occurrence of an access (and up to six others) is totally set by the orbital insertion time of day at launch. Good lighting conditions occur when there is a lot of contrast between the spacecraft and the sky. Cubesats in orbits as high as LightSail 2 usually reflect so little light they are very difficult to acquire and track. The best time is when the background temperature in the tracking sensor field-of-view (FOV) is essentially the -450 degrees F of deep space. However, it is the temperature and scattering of light in the intervening atmosphere that determines detectability. The worst conditions occur when the sun is in or near the FOV of the tracker telescope or when the earth is shadowing the spacecraft from the sun. Opportunities in which the sun is not blocked by the Earth and is at least 45 degrees in azimuth or elevation away from the line-of-sight (LOS) to LightSail 2 occur during approximately 9 hours out of every 24 hour day. The best lighting conditions times occur when LightSail 2 is rising (always from the west) when the sun is rising (always in the east) and, conversely, when LightSail 2 is setting in the east while the sun is setting in the west.

6. SLANT RANGE

The degree of orbit velocity change by laser propulsion will depend on the irradiance strength and length of time the beam dwells on the sail. For any given ground site there are a fixed number of overflights of the spacecraft. The number of passes per day and length of time the spacecraft will be in view on each pass is increased for sites at lower geographic latitudes. Atmosphere attenuation increases dramatically when attempting to beam power horizontally. Garber has indicated typical AMOS overflights will last almost five minutes, whereas the New Mexico sites will be approximately three minutes and the Huntsville sites will be two minutes. [12]. The circular diameter of a propagated laser beam begins as the size of the projecting telescope aperture and increases with the power beaming distance over which it is projected. The range will be greatest as the GBL site acquires LightSail 2 at lowest elevation and shortest when LightSail 2 is directly overhead. It will also depend on the orbital altitude of the LightSail 2 spacecraft. Figure 3 was calculated for any generic ground site using the method of Cakaj. [16]. The red lines indicate slant ranges between 720 kilometers and 1621 kilometers will be encountered when attempting to access a 720 kilometer altitude orbit. For comparison, the blue lines indicate the output of the ODTK model. It calculated the slant range to be 1015-1215 kilometers for the access from EAFB at 30-40 degrees elevation.

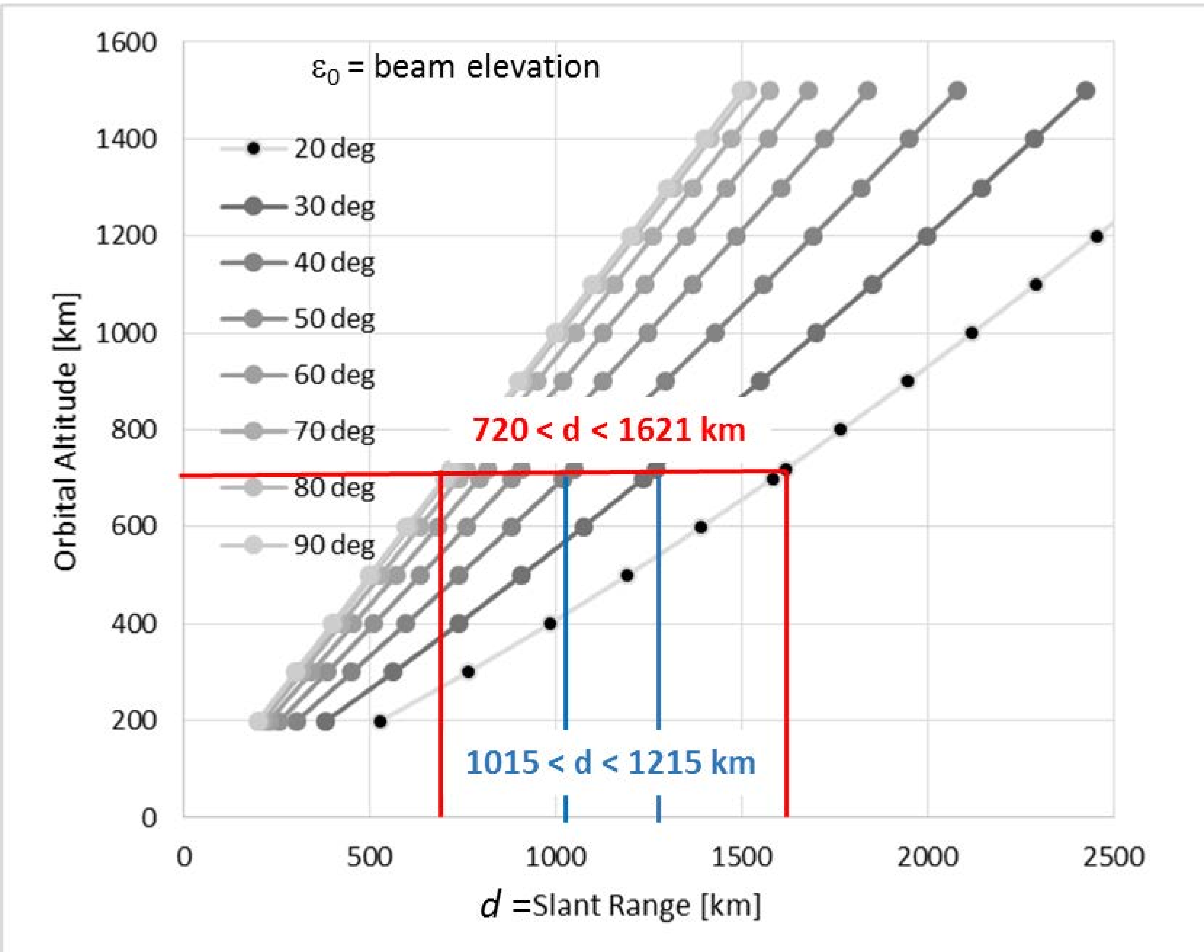
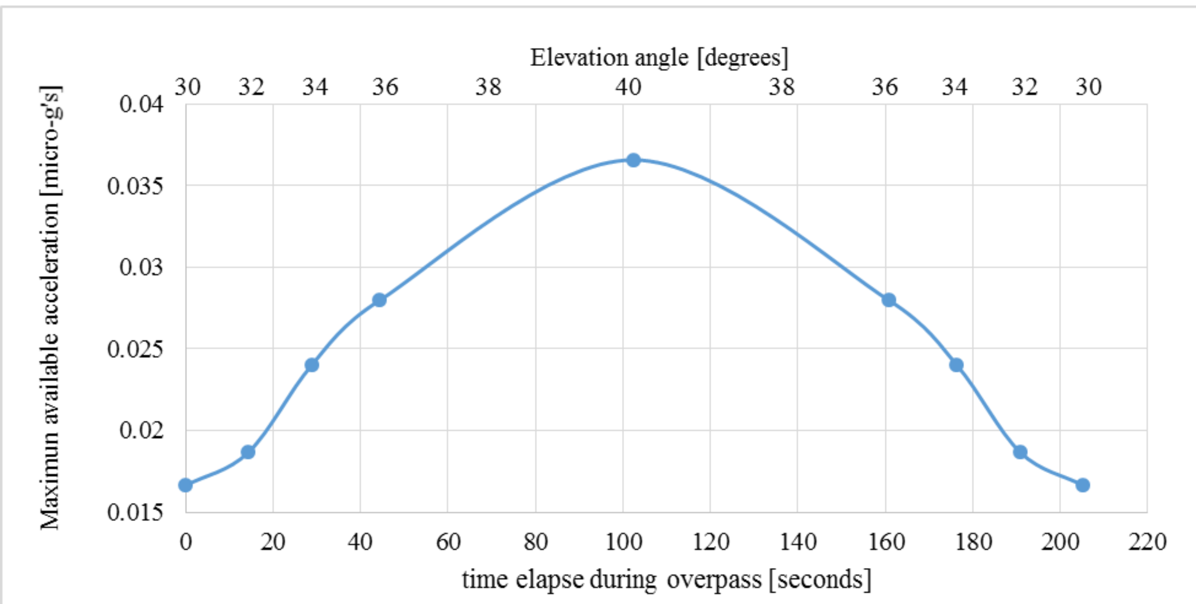


Figure 3. Laser propagation distance from the ground to spacecraft

7. POWER IN THE BUCKET (PIB)

The effectiveness of a system designed to deliver a High Energy Laser system to a target is often described in terms of the encircled power within a specified spot diameter of a propagated laser beam. It is desirable that a bucket diameter that contains most of the beamed energy is the same size or smaller than the target. PIB decreases with diffraction and jitter. It also decreases with the fundamental quality of the source laser and imperfections in the optical elements and their alignment in the beam control system. Integrating the average irradiance over the spot area gives the total power received within the specified bucket. As PIB increases, eventually most of the projected power is recaptured. That is, there is no spillage. When accessing lower altitude (shorter slant range) orbits, the less diverged beams collect the power more effectively. In the design of a practical EBEX, this consideration will be offset by the uncertain effects of atmospheric drag. Also, low ballistic coefficient spacecraft tend to lose altitude precipitously below 300-400 km altitude. The diameter of LightSail 2 (approximated as the 5.66 meter length of a side of the square sail) is indicated in the plot to identify the LEO altitudes at which the sail is insufficient to capture the full spot for given elevation angles and aperture sizes. The planned altitude for LightSail 2 is at the critical point for ground beam director apertures of 50 centimeters or less. At higher orbits, significant beam power will be lost because the sail is smaller than the spread of the beam. Conversely, the larger 3.4 meter aperture beam directors could place more energy in a much smaller sail at a lower orbit altitude (e.g., 30 centimeters at 200 kilometers). Figure 4 results from input of the ODTK trajectory into the spreadsheet. The vertical axis relates to the amount of energy arriving at the 720 kilometer altitude orbit in a bucket the same size as LightSail 2. It is only the maximum available because the attitude of the sail with respect to the beam must also be included to estimate the exact direction and magnitude of momentum transfer. The total access time available for lasing after LightSail 2 rises above the minimum 30 degree elevation is a little over 200 seconds. Because this access occurs when the beam director is pointed in mostly a southerly direction, the trajectory is symmetrical.



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

Figure 4. Maximum effect on LightSail 2 [for 13 May 2017 opportunity 1]

8. DWELL TIME

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 LOS 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. [17]. Most overpasses will not be directly overhead. For example the overpass for 13 May 2017 from the EAFB ground site will only see LightSail 2 at low elevation.

9. CONCLUSIONS

Demonstration of laser photon momentum exchange propulsion from the Earth Surface to Low Earth Orbit 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. A mean value of the acceleration in figure 4 is 0.022 micro-g's and the duration of the over pass of 205.2 seconds. The product of these is 0.045 millimeters per second or a little less than half the objective value (0.1 millimeters/second). This indicates it is unrealistic to expect to measure an effect after one overpass of the kind modelled here. By extension, it proves the feasibility of applying a measureable effect on LightSail 2 across several accesses (even those with 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.

10. FURTHER ANALYSIS NEEDED

Optimizing the attitude of LightSail 2 to capture laser illumination and translate it into measurable orbital velocity change over the effects of solar pressure, atmospheric drag, and residual spacecraft attitude control errors will be of critical importance. The conventional solar sailing approach would angle the sail with respect the incoming beam so that maximum component is added to (or subtracted from) the circular orbit tangential velocity vector. This approach would decrease velocity of the spacecraft as it approached the laser site only to cancel it out by adding an equal effect as the spacecraft moves away from the site. For this reason, as Garber [12] has pointed out only half the short overpass time can be utilized. The sail would not be oriented perpendicular to the incoming laser beam, reducing the effective area of the sail presented to capture the incoming laser beam. The result is a full PIB is not captured on the sail. An angled sail also will present some silhouette area of the sail to velocity vector resulting in atmospheric drag. If the sail were to fly edge-on to the gravitational vector, it would present almost no drag area and would be available to fully capture the laser spot projected from the ground. It may be more or less efficient in producing measureable change to the spacecraft orbit. A detailed study is needed to determine an optimal steering law for LightSail 2 during this segment of its mission.

11. REFERENCES

1. R. L. Forward, "Roundtrip Interstellar Travel Using Laser-Pushed Lightsails," J. Spacecraft and Rockets, Vol. 21, pp 187-195 (Mar-Apr. 1989)

2. "Advanced Solar- and Laser-pushed Lightsail Concepts, Final Report," a 1998 Phase I NIAC Study, by Geoffrey. A. Landis, Ohio Aerospace Institute, Brook Park, OH, May 31, 1999.

3. "Interstellar Vehicle Propelled by Laser Beam," by G. Marx, Nature, Vol. 211, July 1966, pp. 22-23.

4 KISS Workshop on the "Science and Enabling Technologies for the Exploration of the Interstellar Medium," by Leon Alkalai, Ed Stone, Lou Friedman, co-organizer's for the Keck Institute of Space Studies, September 24, 2014

5. "Laser Propulsion Demo Consideration," by Ad-hoc working group: M. Arya, J. Cantrell, L. Friedman, D. Garber, L. Johnson, P. Lubin, E. Montgomery, J. Puig-Suari, Tom Svitek , Presentation to KISS Exploring the Interstellar Medium Workshop 14 January 2014. http://www.kiss.caltech.edu/study/scienceII/Workshop%20Presentation.pdf

6. "Solar lens mission concept for interstellar exploration," by Travis Brashears, Philip Lubin, Slava Turyshev, Michael Shao and Qicheng Zhang, Proceedings of the SPIE Conference *Nanophotonics and Macrophotonics for Space Environments IX*, volume 9616, September 1, 2015.

7. "FORMOSAT-7/COSMIC-2 Progress Update and its Launch Plan," by Nick L.Yen, 4th International Radio Occultation Working Group Workshop (IROWG), Melbourne, Australia, April 16-22, 2015.

8. "LightSail Project Manager Passes Torch," by Jason Davis, web article posted July 7, 2015 on the Planetary Society website: http://www.planetary.org/blogs/jason-davis/2015/20150701-lightsail-project-manager.html

9. "Earth-to-orbit Beamed Energy eXperiment (EBEX)," project kickoff presentation by Les Johnson, NASA Marshall Space Flight Center, Huntsville, AL, April 26, 2016

10. "Beam Control for Laser Systems," by Paul Merritt, Library of Congress Control Number: 2010929641, Directed Energy Professional Society, High Energy Laser Joint Technology Office, Albuquerque, NM, 2012, pp.14

11. "A 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

12. "LaserSail Test: Ground Based Directed Energy Propulsion," by Darren D. Garber Ph.D., NXTRAC report, 25 Aug 2015.

13. "Detection and Orbit Determination of a Satellite Executing Low Thrust Maneuvers," by Kelecy, T. and Jah, M., Acta Astronautica, Vol. 66, No. 5-6, 2010, pp. 798-809.

14. "Orbit Determination During High Thrust and Low Thrust Maneuvers," by Richard S. Hujsak, Analytical Graphics, Inc., Exton, PA, Paper AAS 05-136, *15th AAS/AIAA Space Flight Mechanics Conference*, Copper Mountain, Colorado January 23-27, 2005.

15. "Laser Propulsion Demonstration," by Edward E. Montgomery IV, MontTech, LLC, invited paper at the High Power Laser Ablation Symposium, Santa Fe, NM, April 4, 2016.

16. "The Range and Horizon Plane Simulation for Ground Stations of Low Earth Orbiting (LEO) Satellites," by Shkelzen Cakaj, Bexhet Kamo, Vladi Koliçi, Olimpjon Shurdi, Polytechnic University of Tirana, Albania, International Journal of Communications, Network and System Sciences, 2011, 4, 585-589.

17. Web article by Bob Bruninga, ham radio license, WB4APR. Website for the Automated Packet Reporting System. http://aprs.org/LEO-tracking.html