Interstellar Flight and Recycling Light: A Bilateral Study

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The impossible task of traveling 25.6 trillion miles to Alpha Centauri, our closest star, is now possible. Using a Directed Energy System for Targeting of Asteroids and exploRation (DE-STAR), a versatile, scalable phased-array laser system, it can be reached in a short 16 years. Our project entails carrying out both computational and experimental studies of specific uses of DE-STAR to investigate photon recycling and spacecraft propulsion. Photon recycling is a unique term used to describe a form of energy conservation relative to this project. This effect will greatly improve the efficiency of spacecraft, making interstellar flight more plausible. What lies beyond our solar system is one of the biggest mysteries of mankind and it finally has the potential to be solved.

Keywords: DE-STAR, photon recycling, laser propulsion

I: INTRODUCTION

When you look in a mirror, a reflection stares back. When you stand in-between two mirrors, a tunnel of infinite reflections appear until the speck that is you is no longer visible. This is the concept behind DE-STAR's idea of photon recycling. DE-STAR uses laser technology to propel extremely lightweight spacecraft, called wafer-sats, to incredible speeds. For example, we propose propelling a one-gram spacecraft to 25% the speed of light. However, like any proposal that has to do with sending something to space, it's expensive. This led to DE-STAR's next mission to make this form of interstellar flight more efficient and the birth of photon recycling came to be.

These wafer satellites are miniature probes typically proposed to be 1 meter in diameter. They include cameras, bi-directional optical communications, power, and other sensors that can all be achieved on the gram scale. These lightweight crafts are coupled with laser sails for propulsion to relativistic speeds. [1]

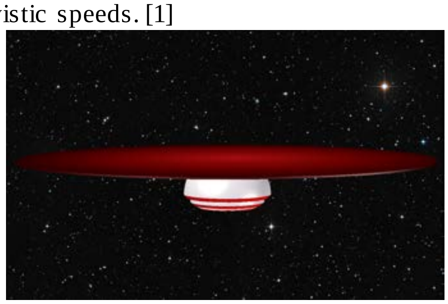

FIG.1. (Color Online) Wafer Scale Spacecraft with laser on reflector. The red depicts the laser light.

Lasers are concentrated streams of photons that are projected as a beam. Although photons are massless, they still carry momentum and therefore, they can transfer their momentum. Although, when a photon hits a reflective surface it bounces back rather than being absorbed. This is due to radiation pressure; twice the amount of momentum is transferred rather than when the photon is just absorbed.

Lasers are not perfect beams, the further they are shined the more they diffract. When they shine through different types of geometric slits, there are different types of diffraction patterns. Specific to our project, we deal with circular slit diffraction. The beam is directed through a hole in one mirror and hits another. When shown through the hole, the laser forms a pattern called airy disks. It forms a bullseye like pattern on the surface and reflects back an expanded form of the same pattern. Since it keeps expanding, the beam diameter is eventually larger than the diameter of the spacecraft and the beam "walks off". This is called the Diffraction Limited Case and is the reason we cannot have an infinite amount bounces. Nevertheless, more bounces means more force against the spacecraft. The purpose of this project is not only to accelerate the spacecraft faster by hitting it with more force in a smaller amount of time, but also potentially spending less money on more powerful lasers when we can hit with the same amount of force using a weaker one.

FIG.2. (Color Online) Artistic rendition of a laser driven spacecraft

II: METHODS

For our experiment we are using 2in. x 2in. square 800nm-1100nm broadband dielectric laser mirrors. They have a 99.99% reflectivity rate for beams with an angle of incidence between 0 and 45 degrees. They maintain a damage threshold of 0.50J/cm 210nm pulse, 10Hz at 1064nm.

Before any testing with the laser could begin, it was vital to test and analyze the noise levels of the new torsion balance. This is done because vibrations occur due to the vacuum pump system and results in adding or subtracting displacement from the detector. In order to combat noise levels we added a magnetic dampener underneath the torsion balance. This worked and our noise levels were negligible.

To begin our experiment, we started by testing the thrust that just one mirror exhibited when hit with the laser. This process required attaching the mirror to a torsion balance inside of a vacuum chamber. Prior to our experiment, the torsion balance was designed to measure the thrust induced by ablation of basalt samples (similar material to asteroids). We altered the set up and machined new "arms" to the balance that would specifically hold a dielectric laser mirror with a fitted counterweight on the other side. The torsion balance is attached to a nickel chrome alloy torsion fiber enclosed in a vacuum tube. This is connected to an angular micrometer to center the readout beam on the readout detector.

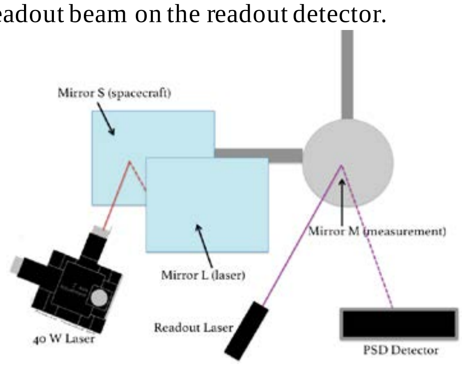

FIG. 3. (Color Online) Drawing of torsion balance mirror alignment set up.

Next a 19 element, 40 Watt laser array is mounted to a set of thermoelectric coolers that is then fed through a 127 micrometer diameter fiber optic cable. This is attached to an anti-reflection coated lens that directs the laser beam to the center of mirror S. When thrust is applied to mirror S the readout laser reflects off of mirror M onto a PSD detector. This detector outputs a voltage proportional to the displacement of the measurement laser beam. These measurements are inputted through a data acquisition system that then, through further software, outputs the final thrust measurement.

<insert figure of lab set up>

Photon recycling is an effect that occurs when a laser beam is reflected back and forth between multiple mirrors. The bounces continuously transfer the photon's momentum until either the beam diffracts to an extent where its impact becomes negligible on the mirrors or the laser is angled to reflect back and forth until it falls off the side of the mirror. To simulate this effect our lab angled the laser ___ degrees to hit mirror S and bounce back on mirror L. The laser reflects back from mirror L to hit mirror S one more time until it is reflected back past the diameter of mirror L. This gives us a second bounce.

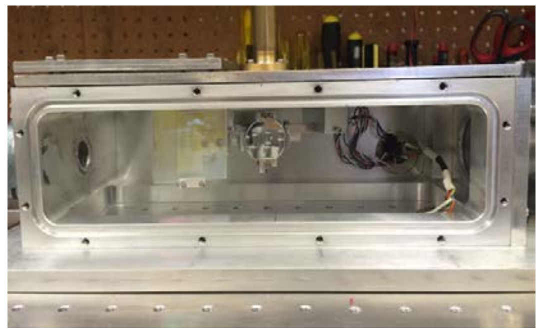

FIG. ?. New torsion balance with dielectric laser mirror and readout mirror.

III: THEORETICAL RESULTS

Theoretical results for infinite bounces of the photons were modeled by multiple equations.

L_0= maximum length between spacecraft and laser array before beam diameter is greater than the diameter of the spacecraft. = $\dfrac{dD}{2\lambda}$

d=diameter of spacecraft, 1 meter

D=diameter of laser array, 10 kilometers

λ= wavelength of the light emitted from the array $1x10^{-6}$ m

c=$3.00x10^{8}$ meters/second

P_0=Power of laser array, $50x10^{9}$ W

α_1= reflectivity of reflector on laser array, 0.99

α_2= reflectivity of spacecraft, 0.99

$$\Gamma_0 = (\frac{L_0}{L})^2$$

FIG.4. Defined variables for equations 1, 2, 3, and 4.

$$F_{NR} = \frac{1+\alpha_2}{c} P_0 \quad (1)$$

$$F_T = \frac{1+\alpha_2}{c} P_0 \frac{1}{1-x} \qquad x = \alpha_1 \alpha_2 \quad (2)$$

When $L<L_0$, the force from the laser onto the spacecraft, with only one reflector, is modeled by equation 1. With multiple reflectors, the force is modeled by equation 2. By keeping measurements constant, as referenced in figure 4, the results were graphed and depicted in figure 5.

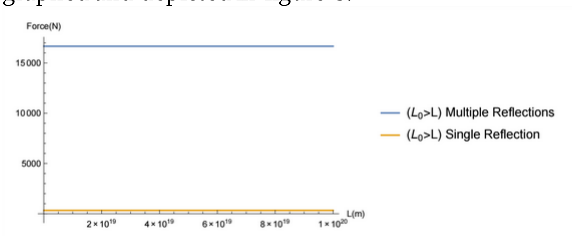

FIG.5. (Color Online) Theoretical results of total force of laser on spacecraft with given constants when $L<L_0$.

With a single reflection, using a 10 km sized laser array and 1 m sized spacecraft, the force is calculated to be approximately 165 Newtons compared to with a second reflector the force is around 16,700 Newtons. These results are strictly ideal and calculated for infinite bounces. In reality the beam would diffract on every bounce and we are put in the Diffraction Limited Case. When this happens the force quickly becomes negligible.

$$F_{NR} = \frac{1+\alpha_2}{c} P_0 \Gamma_0 \qquad (3)$$

$$F_T = \frac{1+\alpha_2}{c} P_0 \Gamma_0 \frac{1}{1-x} \qquad x = \alpha_1 \alpha_2 \left(\frac{L_0}{L}\right)^4 \qquad (4)$$

When $L>L_0$ the force from the laser, with only one reflector, is modeled by equation 3. With multiple reflectors, the force is modeled by equation 4. The results yielded were graphed in figure 6 shown below.

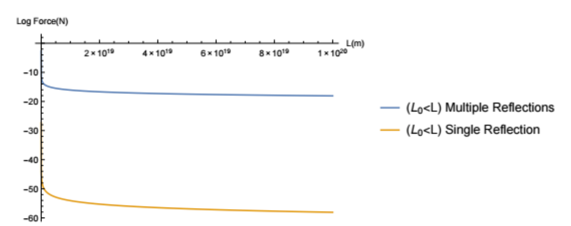

FIG.6. (Color Online) Theoretical results of total force of laser on spacecraft with given constants when $L>L_0$.

With values of force in the E-10's it is clear that force becomes extremely negligible once the beam "walks off" the parameter of the spacecraft. This is highly relevant to the Diffraction Limited Case; once the beam is too big then force becomes increasingly smaller.

EXPERIMENTAL RESULTS

next few paragraphs will include results and discussion from lab testing with graphs displaying the force of one reflector vs two reflectors as well as a table displaying all the computer calculated thrust values for different laser power levels

DISCUSSION

FUTURE RESEARCH

This project is still in the process of being tested and researched. Future methods include measuring the thrust resulted from multiple laser bounces between mirrors by directing the laser through mirror L. When the laser is turned on, it shines through a small hole drilled into mirror L and is reflected off of mirror S which initiates photon recycling. This will give us multiple bounces rather than just one.

CONCLUSION

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