LIGHTFORCE: AN UPDATE ON ORBITAL COLLISION AVOIDANCE USING PHOTON PRESSURE

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We present an update on our research on collision avoidance using photon-pressure induced by ground-based lasers. In the past, we have shown the general feasibility of employing small orbit perturbations, induced by photon pressure from ground-based laser illumination, for collision avoidance in space. Possible applications would be protecting space assets from impacts with debris and stabilizing the orbital debris environment. Focusing on collision avoidance rather than de-orbit, the scheme avoids some of the security implications of active debris removal and requires less sophisticated hardware than laser ablation. In earlier research we concluded that one ground based system consisting of a 10 kW class laser, directed by a 1.5 m telescope with adaptive optics, could avoid a significant fraction of debris-debris collisions in low Earth orbit. This paper describes our recent efforts, which include refining our original analysis, employing higher fidelity simulations and performing experimental tracking tests. We investigate the efficacy of one or more laser ground stations for debris-debris collision avoidance and satellite protection using a physics-based simulation to investigate multiple case studies. The approach includes modeling of laser beam propagation, the debris environment including actual trajectories and physical parameters, and resulting photon pressure. In contrast to earlier research the focus is now on satellite protection. We also present the results of experimental laser debris tracking tests. These tests track potential targets of a first technical demonstration and quantify the achievable tracking performance.

I. INTRODUCTION

Orbital debris poses a risk to spacecraft operations, already reducing satellite's average life time by a couple per cent. With no countermeasures in place, models project a growing numbers of debris and hence an increasing risk of collisions. This cascading increase is caused both by collisions between debris objects and active spacecraft, as well as collisions between debris objects and is known as the Kessler syndrome [1]. Even for the most conservative scenario, assuming no-future launches, current models predict a catastrophic increase of debris for the most congested (and therefore most useful) orbits [2].

Most debris mitigation proposals focus on active debris removal (ADR) of a few massive objects per year employing sophisticated space missions. Models show that this would stabilize the number of debris [3]. However, this approach has two major drawbacks: 1) it would require a sustained effort of costly ADR space missions to stabilize the debris regime and 2) ADR space missions are not suitable to prevent impending collisions on a short notice.

An alternative to ADR is active collision avoidance (COLA). While de-orbit maneuvers typically require delta-v impulses in the order of 100 m/s, collision avoidance is feasible with cm/s or even mm/s delta-v, depending on how much in advance these maneuvers are executed. However, debris cannot maneuver and not all active satellites have maneuvering capabilities. Even for satellites with maneuvering capabilities, spending fuel on collision avoidance and not for the primary mission reduces the spacecraft's lifetime and is risky, as firing thrusters can have unintended consequences.

Hence, an external capability to maneuver debris objects, or even active satellites is necessary. This would be useful for satellite protection, and might even be part of a solution to curb the Kessler syndrome, if multiple maneuvers per day are possible.

In a 2011 publication, the general feasibility of a COLA scheme employing photon pressure from ground based lasers was investigated by a subset of the authors of this paper [4]. It was shown that a significant part of debris objects can be influenced sufficiently to prevent impending collisions, even if one restricts the technology to commercially-of the shelf lasers and one ground station. Over the past months, a team represented by the authors of this paper has refined the original research. This paper gives an overview of this work. More details will be presented in forthcoming publications.

In this paper, we begin by introducing the concept of using photon pressure to maneuver space objects and summarizing the results of the original paper. After that, we give a survey of our latest results. We expand our original statistical analysis and present first results of experimental tracking tests.

II. LIGHTFORCE: THE CONCEPT AND LEGACY EFFICACY ASSESSMENT

II.I LightForce: A Concept to use Photon Pressure to Maneuver Space Objects

LightForce is a proposed a laser system using only photon momentum transfer for collision avoidance. Illuminating the debris from the ground results in the application of a small Δv in the along-track direction. This changes the orbit's specific energy, thus lowering or raising its semi-major axis and changing its period (illustrated in Fig 1). Changing the period is important, as large displacements may be accumulated from very small perturbation forces. The change in period allows an object to be re-phased in its orbit, allowing rapid along-track displacements to grow over time. This causes the two objects to miss each other in time, even if the orbital elements remain essential unchanged. For the application of this to collision avoidance, a Δv of 1 cm/s, applied in the anti-velocity direction results in a displacement of 2.5 km/day for a debris object in LEO. This growing along track displacement is far larger than the typical error growth encountered in the orbit projections of catalogued debris objects.

Delta-vs in the 1 cm/s order of magnitude can feasibly be imparted through photon momentum transfer, greatly reducing the required power and complexity of a ground based laser system compared to other proposals focusing on laser ablation (for an update see [9]) for de-orbit maneuvers. In addition to the reduced complexity and cost, it also reduces the potential for the laser system to accidentally damage active satellites or to be perceived as a weapon.

In order to avoid pending collisions on short notice, there are three requirements. 1) The collision partners have to be tracked, 2) collisions have to be predicted with sufficient accuracy, and 3) a sufficient displacement has to be induced by the laser ground station.

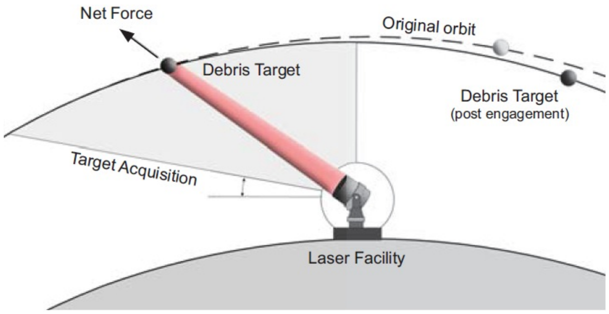

Fig. I: Schematic of laser system for orbital debris collision avoidance.

Tracking is routinely achieved for approximately 30.000 objects today, reaching down to about 10 cm size objects in LEO today. A planed upgrade will lower that threshold further and increase the number of objects. Regardless of these large numbers, modern computer systems can easily predict close conjunctions for all trackable space objects for days in advance. To make sure that the collision can be avoided (and no active satellite maneuvers are necessary), the induced displacement has to be larger than the prediction errors of the orbit propagator including, initial tracking errors. These prediction errors depend on a number of object and environmental factors, which will be introduced in section III.I.

In general, LightForce operations would be conducted as follows: Comprehensive all-on-all conjunction analysis would identify potential collisions involving debris and prioritize them according to collision probability and impact. Usually, the protection of active spacecraft would have priority; however, in some cases the prevention of massive debris clouds might trump that. In addition one would also filter out conjunctions for which this approach is insufficient (e.g. those involving two very massive objects, each >100kg)

For conjunctions with collision probabilities above a certain "high risk" threshold (e.g. 1 in 10,000) one would then have the option of choosing the more appropriate debris object (typically the lower mass, higher Area to mass ratio (A/m) object) as the illumination target or illuminate both. Objects of lower mass will be perturbed more for a given force per unit area.

In order to assess the efficacy of the scheme, we chose a mix of orbit simulations and statistical approach in our earlier paper [4]. It will be summarized in the next section.

II.II Summary of earlier efficacy assessment

The goal of our earlier assessment was to find out, what fraction of LEO debris objects can be significantly displaced with only one ground station, given a 48h collision warning period. The approach was to modify a standard high precision orbital propagator by adding the additional photon pressure. Then a baseline laser system is defined and the orbits of a set of illuminated debris is compared to those of identical objects without illumination. The following sections describe this approach in further detail

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II.II.I Assessing the effects of radiation pressure

Radiation pressure is the small, but significant accumulation of the transfer of photon momentum when a space object absorbs or reflects incoming photons.

As described in the literature [11], the resulting additional force is

$$F = C_r / c \int I(x,y)\, dA$$

where A is the illuminated cross section, I(x, y) is the intensity distribution of the radiation at the piece of debris, C_r is the radiation pressure coefficient of the object and c is the speed of light. C_r can take a value from 0 to 2, where $C_r = 0$ means the object is translucent and $C_r = 2$ means that all of the photons are reflected. An object which absorbs all of the incident photons (i.e. is a black body) has $C_r = 1$.

The intensity distribution I(x, y) at the space object depends on the employed laser, its output power and optics, and the atmospheric conditions between the laser facility and the targeted piece of debris. In the simplest, idealized case, I(x, y) will be axisymmetric I = I(r) and follow a Gaussian distribution [12].

In the case of a real laser facility the atmosphere has two major effects on beam propagation. First, different constituents will absorb and/or scatter a certain amount of energy. Second, atmospheric turbulence leads to local changes in the index of refraction, which increases the beam width significantly. In addition, the resulting time-dependent intensity distributions might not resemble a Gaussian at all. However, in our case laser engagements will take place over time frames of minutes so a time-averaged approach is adopted. As common in this field, an extended Gaussian model is chosen, where the minimum beam width is increased by a beam propagation factor, leading to a reduced maximum intensity. It has been shown that this "embedded Gaussian" approach is valid for all relevant intensity distributions, allowing simplified calculations [13]. Even if the Gaussian model might not resemble the actual intensity distribution, the approach ensures that the incoming time-averaged total intensity is correct [14]. The intensity is updated for each time step as the debris crosses the sky over the ground station. The standard atmospheric physics tool MODTRAN 4 (Anderson, 2000) was used to account for scattering and absorption. The calculations employed to assess turbulence effects are described in detail in the original paper, the theoretical background and details of the numerical approach are described elsewhere [15, appendix A], [16, chapter 2], including additional references therein on atmospheric optics and turbulence.

The cited calculations show that turbulence reduces the effectiveness of the system by an order of magnitude - principally by increasing the effective divergence. To counter those effects, it is assumed that an adaptive optics system with a point-ahead guide star is used. In the calculations, it is assumed that the system's capabilities for turbulence compensation are comparable to the system used in 1998 benchmark experiments [17, 18], which were conducted to test the proposed adaptive optics for the Airborne Laser missile defense project. The American Physical Society has compiled those results into a relationship of Strehl ratio vs. turbulence [19, p. 323] and we use this relationship in our numerical calculations to set the upper limit of the assumed adaptive optics performance. This upper limit is then reduced to account for tip/tilt correction errors that appear because of light travel time and cannot compensated by a employing a guide star. The effect is known as tip/tilt anisoplanatism.

The spin state of a debris object introduces a degree of randomness into the response to directed photon pressure. The momentum transferred from absorbed photons will be in the incident beam direction. For a tumbling target the force vector due to reflection will be varying during the engagement, since there will be a component of the force orthogonal to the laser incidence vector, and for most targets the laser will also induce a torque about the center of mass. In the past we followed the ORION study on the use of laser ablation for de-orbiting debris and assume that collision and debris fragments above 600 km will be rapidly spinning [22]. On average, for quickly tumbling objects, orthogonal force vectors (due to specular reflection) will be zero and the net force vector due to diffuse reflection will be directed parallel to the laser beam.

Target objects are propagated in the orbits using a high precision propagator in STK, a standard software for orbit calculations. In the used configuration, it accounts for higher-order gravitational terms, uses a Jacchia-Roberts atmospheric model, and observed solar flux and spherical solar radiation pressure. Laser engagements are modeled by utilizing the MATLAB-STK scripting environment, allowing the evaluation of the laser intensity and resulting photon pressure at each time step.

II.II.II Baseline System and Chosen Targets

Table 1 summarizes the assumptions for a baseline laser ground station. The parameters are chosen to represent a system which relies on commercial of the shelf technology, where possible. For further details on the selection of these parameters, please see [4]

Table I: Scenario input parameters for laser ground station.

Laser	IPG YLS-10000-SM
Power	10kW (cw)
Wavelength	1070 nm
Beam quality	M2=1.3
Telescope Diameter	1.5 m
Atmosphere	US Standard (1976)
Aerosol content	MODTRAN rural (VIS=23)
Turbulence	Hufnagel/Valley 5/7

A random subset of 100 debris objects from the U.S. TLE catalog with inclinations between 97 and 102 degrees and orbit altitudes between 600 and 1100 km is chosen. This is the regime with the highest congestion today. Characteristic sizes were assigned to these objects to give a representative size distribution, shown in comparison to the ESA MASTER2005 statistics in Fig II.

In order to derive mass values for the set, a method was implemented as described by [20]. It uses the ballistic drag coefficient B, defined as the product of the dimensionless drag coefficient Cd and the area to mass ratio A/m, for an object [21]:

$$B = Cd \times A/m$$

The decay of the semi-major axis of an object is observed over a long period and, using an accurate atmospheric model and a high accuracy orbit integrator, B can be derived. This method was implemented by downloading 120 days of Two-Line-Element (TLE) tracking data provided by U.S. Strategic Command (USSTRATCOM) for each debris object and then using a standard high precision orbit propagator to fit the ballistic coefficient to the observed decay of semi-major axis. Assuming Cd = 2.2, a reasonable value for the A/m ratio of an object can be estimated. At this point mass and area for each object are set. For more details on this approach, see [4]. For the albedo a conservative assumption was made by chosing C_r=1, ignoring the additional force by reflected photons.

II.II.III Summary of results

Simulated lasers at four different locations were tasked with illuminating the target for the first half of each pass for 48 hours and the resultant displacement (from the unperturbed orbital position) was generated for the next five days.

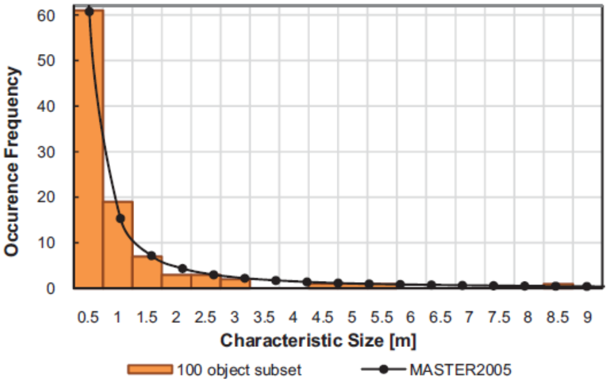

Fig. II: Size distribution for 100 debris objects in sun-synchronous LEO, generated using MASTER2005's characteristic size distributions.

After a two day laser campaign it was found that for a 10 kW laser, 56 objects where perturbed more than 200m and 34 more than 500 m. A number of other "success rates", defined as the number of objects displaced by more than x m/day, are shown in Table II, also for different locations of laser ground stations.

Table II: Success Rates for a 10kW laser system, compared for different sites. The Success Rates are defined as the number of objects displaced more than 50, 100, 200 or 500 m/day

Site		**Success rates (daily displacements)**			
Loc.	**Alt.**	**50m**	**100m**	**200m**	**500m**
ANT	4 km	89	74	56	34
HI	3 km	42	30	13	5
AUS	.7km	29	12	4	4
AK	.5km	48	31	12	4

Locations: ANT: PLATO, Antarctica; HI: AMOS Hawaii, S: Mt. Stromlo, Australia, AK: Eielson AFB

II.II:IV Shortcomings of legacy assessment

The summarized results of [4] give a very strong indication that the LightForce concept can play an important part in future LEO space activities. Even for the current debris environment, a significant fraction of debris objects in SSO could be influenced by one ground station only. In the future, the number of debris objects is projected to increase, hence the necessity for satellite protection maneuvers is going to increase and the motivation to stop more debris-debris collisions might be higher than today

However, the summarized research has several shortcomings, which we will address in the next section:

1) The success rates shown in Table II are meant to give a qualitative estimate of the campaign's effectiveness at avoiding collisions. A better assessment would look at more than 100 objects, ideally enough that no assigned sizes were necessary to reach a representative sample. Instead of success rates, laser displacement should be compared to orbit propagation uncertainty. Also, restricting the assessment to only one ground station artificially cuts down the efficacy of the scheme. Finally, an assessment of actual (past) conjunctions would give a true measure of the efficacy of the scheme.
2) The practical implications of tracking and acquisition have to be assessed.

III. ONGOING RESEARCH EFFORTS

The research described in this section is work in progress. Detailed descriptions will be published in forthcoming articles.

III.I Refined LightForce efficacy assessment

A major uncertainty in the previous assessment is the limitation to daily displacements as criteria for a successful engagement. In practice, a collision avoidance maneuver would be successful if the maneuver is creating sufficient displacement to overcome orbit prediction uncertainties. Only in that case, a collision avoidance maneuver could be counted as 'successful' with a given confidence level.

Orbit prediction uncertainties depend on atmospheric uncertainties and debris properties. The density of the upper atmosphere fluctuates and can only be predicted to a certain accuracy. Ultimately, these fluctuations will lead to along-track prediction uncertainties, competing with the displacement caused by the laser engagement. Both effects depend on area to mass ratio. A higher area to mass ratio leads to increased laser displacement, as debris is usually smaller than the beam diameter and more photon momentum is absorbed per unit mass. At the same time, a higher area to mass ratio also increases prediction uncertainty, as the influence of atmospheric fluctuations on trajectory predictions increases as well. However, this effect diminishes with increasing debris altitude, as the influence of atmospheric fluctuations decreases with decreasing average density.

At this point, we have implemented the following approach:

1) **Simulation of in-track prediction uncertainties for spherical bodies of a given area to mass ratio.** We calculate these uncertainties assuming High Accuracy Satellite Drag Model (HASDM) like density predictions with a accuracy of 3 percent at 1 sigma.
2) **Calculation of number of laser pushes needed to overcome in-track variation.** We calculate the number of laser engagements needed to overcome the prediction uncertainty for a given area to mass ratio and a given altitude. At this point, full laser intensity simulations with atmospheric turbulence, absorption and scattering are not implemented. As compromise, we assume a intensity of one solar constant.
3) **Compile number of objects which have to be pushed a certain amount in order to overcome in-track uncertainties**. The A/m ratios and orbits of 7366 LEO objects below 2000 km are analyzed to create a histogram

of number of pushes to overcome in-track variations vs. number of debris objects (fig. III). A/m ratios have been derived fitting the decay of the objects' semi-major axis over time. For 7366 objects, valid A/m ratios could be derived. This represents approximately 70% of LEO objects 10cm or larger.

3) **Assessment of campaign efficiency.** Assuming a certain number of ground stations and different constraints, it has been assessed, how many objects could be successfully engaged. The results are compiled in table III. Constraints are acquisition capabilities, depending on sun illumination status at the time of a pass over the ground station.

Table III does not include a minimum displacement for successful engagements. If that was set to 10 m or 100 m (depending on the size of a potential collision partner), the values would be worse. It also becomes clear that acquisition capabilities are crucial. Ideal would be daylight tracking, or at least the possibility to re-acquire objects which have been acquired during an earlier pass. Dependency on terminator passes only would considerably hurting efficiency.

While 40% successful engagements for one station are not that impressive please note that the assumption of one solar constant is conservative and Mount Stromlo is not ideally located.

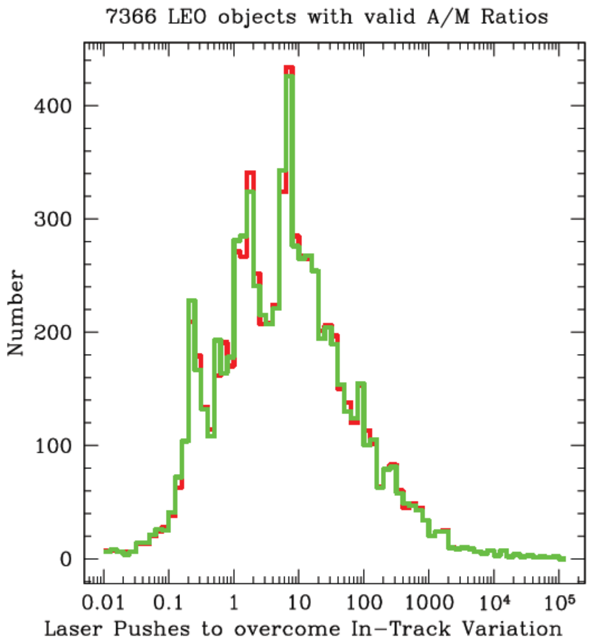

Fig. III: Histogram showing the number of objects vs the number of laser pushes need to overcome their in-track prediction uncertainties.

Table III: Campaign efficiency for 7366 objects for a *laser representing 1 solar constant on target*

Site(s)	**Acqu.**	**Access**	**Succesful engaged**
AUS	Always	7244 (98%)	2933 (40%)
	Dark	6916 (94%)	2112 (29%)
	Terminator	2978 (40%)	1008 (14%)
10@45	Always	7152 (97%)	5612 (76%)
	Dark	7031 (96%)	4905 (67%)
	Terminator	4381 (60%)	3088 (42%)

Acqu.: Acquistion capabilities constraint to darkness or terminator, or unconstraint ("always")

Sites: AUS = Mt. Stromlo, Australia, 10@45 = 10 latitude 45 degree stations.

III.II Optical Debris Tracking Experiments

In an operational scenario, a LightForce ground station would be tasked to engage a specific piece of debris as soon as a conjunction between two space objects extends a certain threshold. This might be based on low accuracy data, e.g. Two-Line-Elements. The first challenge would be to laser track this object. At that point, the incoming data could be used to refine the orbit and, should the conjunction risk be confirmed, a LightForce maneuver would start. While the first track might happen in terminator conditions, ideally, all follow up passes over the ground station should be used to for further engagements. As quantified in table III, re-acquisition out of terminator is highly desirable, especially if the number of ground stations is limited.

Ongoing tracking experiments aim to quantify todays capabilities and future requirements both for first acquisition, and out of terminator re-acquisition. To that regard EOS Mount Stromlo Satellite Laser Ranging facilities are used to track debris objects. The facility offers a 1.8m fast slew telescope, as well as laser ranging, wide field of view and narrow field of view cameras. For further details please see [78,79].

A first tracking campaign has tracked numerous debris objects. Figure IV shows a picture of object 21801, satellite debris in a 600km orbit. It re-affirmed that terminator acquisition of debris objects based on TLE is possible with the current system. Orbit determination was performed using the image of the objects in front of the star field, and first results indicate that re-acquisition would be possible. Experiments to confirm this are ongoing.

Fig. III: Picture of EOS Mt Stromlo Satellite Ranging System tracking object 21801 in front of the starfield.

IV. CONCLUSION

We have shown the theoretical potential of the LightForce concept to modify the orbits of a significant fraction of space objects in low Earth orbit. This method, if appropriately developed, could be used for satellite protection and might also play a role in remediating the deteriorating space environment.

Our legacy simulation approach is sufficient to prove the potential of the concept, however modeling simplifications have several shortcomings.

Ongoing work has reaffirmed the potential of the scheme. Extended simulations with several thousand debris objects have shown the potential to effectively modify a significant fraction of their orbits for collision avoidance. This research will be expanded to assess past conjunction events to assess LightForce efficacy for realistic conjunction scenarios.

Ongoing optical debris tracking experiments have improved our understanding of the technical requirements for tracking and acquisition of debris objects. At this point, we cannot see any insurmountable challenges. Acquisition of debris objects with TLE data is possible, and out of terminator acquisition is most likely possible, with currently available technology.

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