LightForce Photon-Pressure Collision Avoidance:
Efficiency Assessment on an Entire Catalogue of Space Debris

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ABSTRACT

The potential to perturb debris orbits using photon pressure from ground-based lasers has been confirmed by independent research teams. Two useful applications of this scheme are protecting space assets from impacts with debris and stabilizing the orbital debris environment, both relying on collision avoidance rather than de-orbiting debris. This paper presents the results of a new assessment method to analyze the efficiency of the concept for collision avoidance. Earlier research concluded that one ground based system consisting of a 10 kW class laser, directed by a 1.5 m telescope with adaptive optics, can prevent a significant fraction of debris-debris collisions in low Earth orbit. That research used in-track displacement to measure efficiency and restricted itself to an analysis of a limited number of objects. As orbit prediction error is dependent on debris object properties, a static displacement threshold should be complemented with another measure to assess the efficiency of the scheme. In this paper we present the results of an approach using probability of collision. Using a least-squares fitting method, we improve the quality of the original TLE catalogue in terms of state and co-state accuracy. We then calculate collision probabilities for all the objects in the catalogue. The conjunctions with the highest risk of collision are then engaged by a simulated network of laser ground stations. After those engagements, the perturbed orbits are used to re-assess the collision probability in a 20 minute window around the original conjunction. We then use different criteria to evaluate the utility of the laser-based collision avoidance scheme and assess the number of base-line ground stations needed to mitigate a significant number of high probability conjunctions. Finally, we also give an account how a laser ground station can be used for both orbit deflection and debris tracking.

1. INTRODUCTION

This paper presents a new assessment of the efficiency of the LightForce space debris collision avoidance concept. This assessment is based on the publicly available orbital data of all tracked space objects for a given time frame and uses the change in probability of collision as an efficiency metric. The LightForce concept envisions reducing the risk of collisions by slightly changing the orbits of objects that are predicted to have a conjunction (a close approach). The means to change orbits is photon pressure from ground-based, industrial strength lasers. Earlier publications have introduced the concept and demonstrated the general viability of the scheme for a significant fraction of conjunctions [1,2,3].

Most conjunctions happen at relative velocities of the order of km/s and hence pose the risk of a catastrophic collision. Fifty years of space missions have left more than ten thousand traceable objects in orbit, building a population of (mostly) debris, which poses a risk of collision (and failure) for active satellites that is higher than that caused by the natural meteoroid background. A 2010 study investigates the cost of operating three different satellite constellations for 20 years [4]. It is based on the 2009 debris population (including debris from the catastrophic Iridium33/Cosmos 2251 collision). The study concludes that in the most congested orbits, the cost of replacing satellites which go out of operation because of debris is increased between four and fourteen percent compared to a no-debris scenario. Depending on the properties of the modeled constellation, that translates into costs between seven hundred million and 1.4 billion US$ for each of the investigated satellite constellations over 20 years [4]. These numbers demonstrate the need for corrective measures, even looking at today's debris environment.

Long-term projections of the debris environment strengthen the argument for corrective measures, because they show an exponential growth of debris population over the next centuries, even if no further space launches occur [5].

This increase is caused by collisions between debris and intact spacecraft and collisions between debris objects themselves, both being sources for additional debris and such causing a cascading effect, first described by Kessler [6]. If no corrective measures are taken, this self-sustaining growth in the debris population would further increase the cost of space operations. The discussion on corrective measures mostly focuses on stabilizing the debris environment by active debris removal (ADR) of four or five of the most massive objects per year, in order to remove sources of new debris. Monte-Carlo simulations have shown that this approach would stabilize the number of debris in Low Earth Orbit (LEO)[7]. However, cost projections for the ADR approach range between 140 and 500 million USD, per piece removed [8]. If one wanted to remove 5 pieces per year this would result in annual costs in the order 700 to 2,500 million USD.

The potential price tag for ADR makes its implementation difficult, especially as there will be no measurable immediate short term effect on collision risk, as the debris flux in LEO would remain virtually unchanged. In both regards, the LightForce concept has considerable advantages. LightForce aims to reduce the risk of collisions by targeting conjunctions on warning (something ADR cannot do), and, because LightForce is a ground-based technology, annual costs will be orders of magnitude lower. By tackling high risk conjunctions it addresses potential collisions directly. Taking part in stabilizing the debris environment (by preventing additional collision debris) is a secondary benefit. LightForce would use tracking data and orbit prediction to continuously compile and update a list of high risk conjunctions and would then engage those. As illustrated in Fig.1, photon pressure from ground based lasers would be used to alter the in-track velocity of space objects. Over time, that translates to an in-track displacement. Earlier research has shown that even if one restricts the analysis to currently available industrial lasers, the approach has the potential to impact a significant fraction (several tens of percent) of conjunctions. The earlier assessments compared achievable displacement to a threshold [2], and to simulated orbit prediction accuracies [3], looking at one ground station only. While those metrics were sufficient to demonstrate the potential of the concept, it is difficult to use displacement to estimate of the efficiency of LightForce in a global application. In an operational setting LightForce would engage objects in conjunction as long as it is useful and simultaneously (and continuously) update orbital data. The goal of the presented research is to provide insight into how efficient LightForce is in reducing the risk of collisions. Hence we choose probability of collision as an efficiency metric for each engaged conjunction and assess a simulation of the full public catalogue of space objects tracked by the US Strategic Command's Joint Space Operation Center (JSPoC) to assess the overall effect on conjunctions occurring today. We do not aim to make claims on the long-term effect on the general debris environment. This aspect needs further study.

The paper is divided into five parts. After this introduction, we outline our simulation approach. We then present the results of several case studies, followed by some considerations for future work and a conclusion.
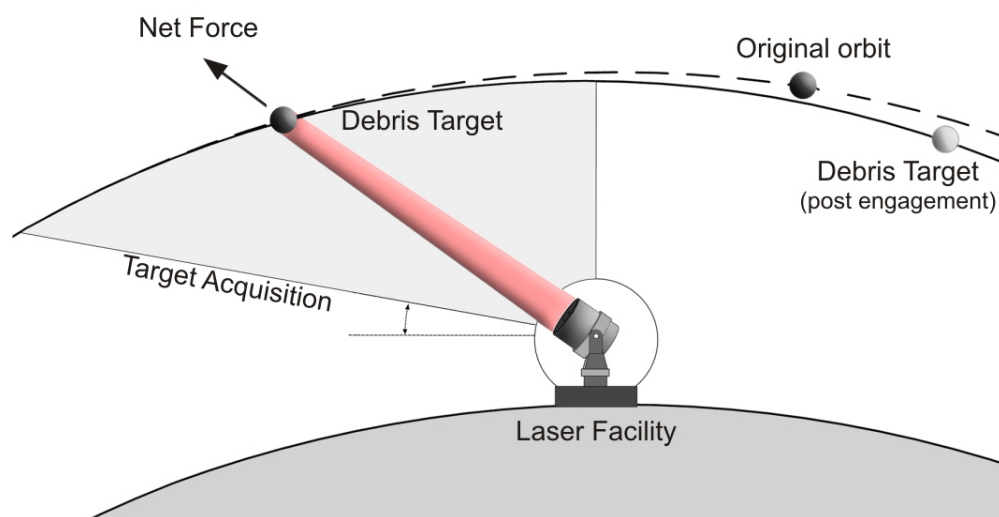

Fig.1:   Schematic view of a laser facility and the operations for nudging space debris using photon pressure. Slowing down the debris results in loss in orbital energy, hence in a lower orbit with a higher velocity.

2. DEVELOPMENT OF A BENCHMARK SIMULATION FOR LASER COLLISION AVOIDANCE

2.1 Goal of the analysis

The goal of the presented analysis is to benchmark the utility of the LightForce laser collision avoidance concept for space operations today. Our past papers [1,2,3] focused on the in-track displacement achievable by a LightForce station for single objects, and permitted the conclusion that LightForce groundstations could divert a significant fraction of debris from potential collisions. However, it is challenging to draw conclusions about the effects on the space environment and space operations from that data, because the link to actual occurring conjunctions is missing. Even if we know what fraction of objects we can divert, it is not obvious whether the same fraction will also be involved in conjunctions. In addition, the risk of collision is not a binary function. Hence it is difficult to draw a conclusion from an in-track displacement to how much of an improvement in regard to probability of collision that actually represents. Finally, it is challenging to draw conclusions from a limited number of cases. Our goal is to overcome these challenges, by implementing a simulation of the entire catalogue of tracked space objects and analyze, what global effect on probability of collision a given LightForce network of ground stations would have. The scale of that analysis required us to switch to a custom-made simulation software we developed. We validated the accuracy using STK and the software package developed during the research presented in [2].

2.2 Steps of the analysis

We analyze the probability of collision for all tracked space objects with and without LightForce active. The analysis follows three steps:
1) The simulation software refines the publicly available two-line element (TLE) orbital data from the JSpOC for a given analysis period using a TLE fitting scheme and produces higher accuracy initial states.
2) The simulation software propagates these initial states for a given time frame, analyzes conjunctions and assembles a list of high risk events above a certain probability of collision.
3) The simulation software re-propagates the initial states of the objects involved in the high risk conjunctions, but this time an additional force is added when the objects pass over the LightForce groundstations. That force represents the photon pressure induced by the laser. The probability of collision is assessed again and compared to that of step 2.

In the following, we describe the three steps in more detail.

Step 1: Refine orbital data
As original input, we use the publicly available catalog of Two Line Elements (TLEs). The catalog is updated by the US Strategic Command on a daily basis and available for download [9]. For each object the catalog provides a unique identifier and the orbital elements at a given epoch. Unfortunately, the catalogue does not directly provide an area-to-mass ratio. Also, single TLEs are error prone and have limited accuracy. To enable the best possible results (with reasonable efforts), we use least-squares fitting of TLE data as described by Levit and Marshall [1] to obtain an improved state vector, an area-to-mass ratio and a covariance uncertainty matrix.

We obtain an initial guess on the area to mass ratio via semi-major axis decay by comparing the latest TLE to one taken approximately 100 days prior. We then convert the latest 5 days of TLEs (where available) via the SGP4 propagator and utilizing them as pseudo-observations. These pseudo observations are then utilized in a high precision propagator (described in step 2) to perform a non-linear least-squares fit of the orbital parameters.
The solver iteratively updates the initial state vector guess (taken from the latest TLE) and area-to-mass ratio and converges to a least-squares fit and produces an uncertainty covariance matrix [10, Ch. 10]. For orbits where objects show low sensitivity to atmospheric drag (e.g. perigee > ~1000km), we keep the initial guess for area-to-mass ratio. To derive data on the object's cross-Sectional area, we use radar cross-Section (RCS) data and convert it to a physical cross-Section using the method given in [11].

The algorithm results in an object database consisting of state vectors, area-to-mass-ratios and object areas. During the time interval chosen for our simulations[1] the catalog was made up of about 12,200 objects consisting of both active spacecraft and space debris. About 11,400 of the objects were in LEO at an altitude below 2,000km. The fraction of active satellites in LEO was 4.4%, equivalent to about 500 satellites. An overview of the objects is given in Fig.2 where we plot the Area-to-Mass Ratio (AMR) of the objects as a function of altitude.

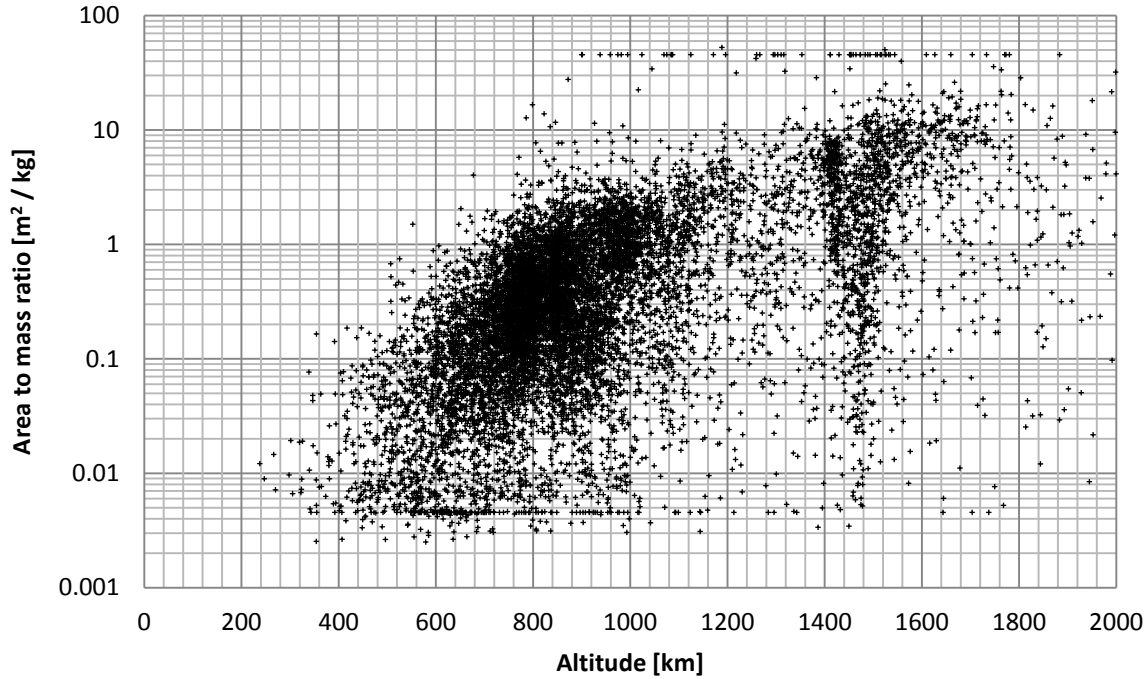[1] All our simulations used TLE's issued between June and December 2012.

Fig.2: Result from TLE fitting (Step 1): Area-to-Mass ratio as a function of the altitude for catalogued objects in LEO.

Step 2: Find conjunctions and determine probability of collision

Using the state vectors derived in step 1, we now simulate the orbits of the objects during the simulation time-frame and perform an all-on-all conjunction assessment. This gives us a sample of conjunctions based on real world data.

The scheme used by the propagator for the numerical integration is a 4th/5th order Runge-Kutta scheme with variable time step [12,13]. The forces taken into account during the propagation include Earth's gravitational field, the gravitational perturbations from the Moon and the Sun, atmospheric drag and the solar radiation pressure. The numerical implementation is built around the NAIF SPICE Toolkit [14] and the physical model used for each force is referenced in Table 1. We validated our propagator against STK's HPOP, an industry standard.

For one second time intervals, we perform an all-on-all conjunction analysis of n space objects (in our case n=11400). To reduce the order of the n^2 problem of that analysis, the traditional approach is to apply various filters that, based on criteria such as apogee, perigee, node location, etc., can rule out the possibility of a conjunction between two objects. We take an alternative approach that reduces the problem to order n*log(n) without the need for filters. At each time step under analysis (e.g. every 1 sec), we sort the x-coordinates of all objects from smallest to largest (an operation of order n*log(n) using the Quick Sort algorithm). We then run through the sorted list and compare neighboring objects that have the x-coordinates within a certain range (e.g. < 25km), an operation of order ~n.

Table 1: Forces taken into account in the dynamical modeling of the debris and the models used for their numerical implementation.

Force	Numerical implementation	Reference
Earth's Gravitational Field	Earth Gravitational Model 1996 (EGM96)	[15]
Luni-Solar Perturbations	NASA JPL Planetary Ephemerides	[16]
Atmospheric Drag	NRL-MSISE-00 model	[17]
Solar Radiation Pressure	Debris modeled as a sphere, eclipses taken into account	[10]
Laser Radiation Pressure	In-house model	[2]

For objects that meet this criterion, we then compare their y-coordinates for proximity, and if true, compare their z-coordinates. If all three coordinates of an object pair are within this pre-defined range, we bound the time of closest approach to within one second using buffered propagated states. We then solve for the time of closest approach (TCA) via interpolation in this one second interval.

Once the TCA is known for a pair of objects the associated state and co-state information is used to calculate the probability of collision. We follow the method described by Patera [18]. For each conjunction we determine both the real and the maximum probability of collision [10, §11.7.2]. The real probability of collision takes into account the actual uncertainties we determined in step 1, while the maximum probability of collision is a value obtained by varying over all possible uncertainty ellipsoids. To be on the safe side, we evaluate the performance of the laser photon pressure against the maximum probability of collision for subsequent calculations. It is the maximum probability of collision we commonly denote as P_c. Fig.3 shows the distribution of conjunctions with different P_c detected over a period of 30 days.

If P_c for a given conjunction exceeds a threshold T_c, we save the data (object IDs, TCA, P_c) in a list of high risk conjunctions. This list is evaluated in the next step.
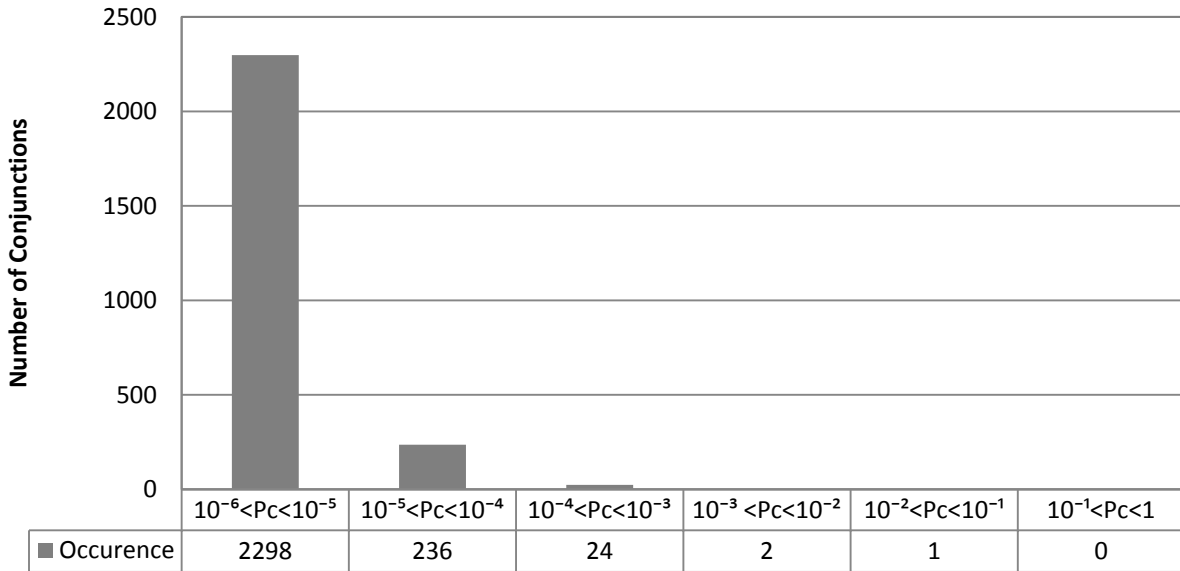

	$10^{-6}{<}Pc{<}10^{-5}$	$10^{-5}{<}Pc{<}10^{-4}$	$10^{-4}{<}Pc{<}10^{-3}$	$10^{-3}{<}Pc{<}10^{-2}$	$10^{-2}{<}Pc{<}10^{-1}$	$10^{-1}{<}Pc{<}1$
Occurence	2298	236	24	2	1	0

Fig.3:   Distribution of conjunctions with maximum probability of collision $P_c{>}10^{-6}$ detected over a 30 day period (June 15 to July 15, 2012)

Step 3: Activate LightForce and re-evaluate the probability of collision
Step 2 produces a list of conjunctions for a given time frame, derived from real world data. In the final step, we activate LightForce and re-evaluate the probability of collisions after LightForce engagements. Using this data, it is possible to evaluate the utility of the concept and optimize the approach, as described in Section 2.3.

In order to re-evaluate the probability of collision, we re-propagate the objects involved in conjunctions. We use the same time-frame, and the same propagator as presented in Step 2 but this time have the option to activate the force induced by laser ground stations. The force of the photon pressure from the ground based lasers is activated when certain conditions are fulfilled. The conditions for laser activation are:

a) There is a line of sight between the object and the laser and the elevation angle is >10 degrees.
b) The time remaining to the time of closest approach for the specific conjunction is less than a set engagement time t_e.
c) Laser activation is beneficial for the chosen optimal collision avoidance strategy, which is either to slow the object down, or to accelerate it.

The first condition is self evident, as laser energy travels (approximately, while passing through the atmosphere) in a straight line. The condition on the elevation angle arises because increased absorption and turbulence make engagements close to the horizon inefficient. The choice of engagement time t_e will drive both the number of objects that have to be engaged (potentially at the same time) and the change in probability of collision. A sensible choice in t_e will also depend on the quality of orbit prediction. In the case studies presented below, we have chosen t_e=48h, however, there is still room for optimization and additional research. The optimal collision avoidance strategy for a pair of objects depends on the encounter geometry and other specifics of the conjunction. LightForce only induces minimal orbital changes (on the order of mm/s delta-v), which are most effective if induced aiming for maximum in-track displacements. The situation is similar to a situation on the highway, where two cars try to enter a one-lane section at the same time. To avoid a collision, ideally one driver accelerates and the other one hits the brakes. If both drivers accelerate or slow down, the risk of collision might not be reduced. For collision avoidance with LightForce, this roughly[2] translates to a requirement that one object should only be illuminated during the first half of its passes of laser ground stations, and the other one only during the second half of its passes over ground stations. The question remains, which object should be accelerated and which one slowed down. To investigate the maximum potential of the LightForce concept, we have chosen to use a brute-force approach: We simulate both options and choose the one which minimizes the probability of collision. We are also working on an algorithm that predicts the optimal engagement strategy which will be presented elsewhere. That algorithm will also include the option of only illuminating one object in order avoid wasting resources.

Laser illumination entails four additional force components. Three of them are caused by conservation of photon momentum (photon pressure), a fourth is induced by temperature gradients in the surface of the illuminated object. The first force component is parallel to the incoming laser beam and caused by the momentum of all incoming photons. Specular reflected photons add an additional force parallel to their outgoing direction (but with a negative sign). The direction depends on Snell's law of reflection. The best case would be a laser beam hitting the object perpendicular to a 100% reflective surface. This would result in a force with twice the magnitude compared to that of a completely absorbing surface. Diffuse reflection adds another force. Finally, temperature gradients on the surface could result in a net force through thermally emitted photons. However, surface reflectivities, as well as object orientation are not very well known for most of the objects. In addition, most objects over 600 km are assumed to be tumbling fast, which would result in cancelling the latter three effects for most cases [19]. Hence we ignore those additional effects and go with the conservative assumption of a debris object with zero reflectivity for the analysis presented in this paper.[3]

Under this assumption, the additional force F on the object is [20]

$$F(t) = \frac{1}{c} \int I(x,y,t)dA \ , \tag{1}$$

where c is the speed of light, I is the irradiance at a point on the cross-section of the illuminated object at the time t. We update the irradiance for each time step. The irradiance I is calculated taking multiple effects into account. These effects are beam spread by diffraction, beam spread by atmospheric turbulence, and power losses by atmospheric absorption and scattering. All depend on the specific path between the laser ground station and the space object (determining distance and atmospheric conditions) and the technical specifications of the ground stations. Table 2 in Section 3 (simulation results) summarizes those specifications. We assume a ground station with adaptive optics and a laser guide star to compensate some of the effects of turbulence. As assumption for the performance of the adaptive optics system we use the results of 1998 benchmark experiments on an adaptive optics system for a directed energy weapon system, compiled in a study of the American Physical Society [21]. Combining the different effects result in the irradiance and the force on the object. The details of the calculations are complex, please see references [2,3,22] and references therein for a step-by-step description.

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[2] It is only a rough analogy, because slowing down the object will result in a loss in orbital energy and hence a lower orbit. In that lower orbit, it finally reaches a higher in-track velocity than before the engagement.

[3] We have investigated the effects of these assumptions and will present the results in detail in a forthcoming paper. In summary, we come to the conclusion that effects of thermal gradients and specular reflections can be significant for high precision simulations of actual maneuvers, but their influence is comparably minor and would not change the general utility assessment of LightForce presented here.

The final result is a time-dependent additional force to be included for the propagator, resulting in a reduced probability of collision for most (>99%) cases.

2.3 Metrics to assess the results of the analysis

Our analysis results in a list of reduced probabilities of collisions for each of the high risk conjunctions investigated. While this allows an assessment of the utility of LightForce for each conjunction, a metric is needed to assess the utility of the scheme in general. Such a metric is also needed to optimize the LightForce concept, e.g. the number and placement of ground stations. The location of the ground station impacts visibility of objects, but local turbulence and average cloud cover determine the expected force, since they impact the effects on the laser beam.

We try to answer two different questions, resulting in two different metrics:
1) What fraction M of conjunctions can a LightForce system mitigate, meaning, what fraction of high risk conjunctions can be mitigated to low risk conjunctions?
2) By how much can a LightForce system influence the number of expected collisions?

For 1), we define the mitigation factor

$$M = 1 - \frac{\text{Number of conjunctions with } P_c > T_c \text{ after LightForce activation}}{\text{Number of conjunctions with } P_c > T_c \text{ without LightForce}} . \tag{2}$$

M can be derived directly from the simulation data when a reasonable threshold T_c is set.

However, while the mitigation factor M is easily defined, it is not ideally suited to answer the second question of the effect on the number of expected collisions. That second question might actually be more important, as it determines the effect on the space environment in general. For example, if a conjunction with a probability of collision of 10^{-1} is mitigated to 10^{-5}, but we set T_c to 10^{-6} it would be counted as failure in regard to the mitigation factor M, even though the risk for a collision is considerably lower than before. Hence for our second metric, we use a metric similar to *a change in Expected Value* in order to obtain a global measure of the reduction in probability of collision. We define a reduction factor R for expected number of collisions caused by high risk conjunctions:

$$R = 1 - \frac{\sum\limits_{\text{all conjunctions with } P_c > T_c \text{ after LightForce activation}} P_c}{\sum\limits_{\text{all conjunctions with } P_c > T_c \text{ without LightForce}} P_c} . \tag{3}$$

The sum of P_c represents the expected value of the number of collisions caused by the assessed conjunctions with $P_c > T_c$ during the simulation time frame. Summing up P_c of different conjunctions is the same approach as one would use to sum up the individual probabilities for "heads" of a stack of loaded (unfair) coins, if one were to calculate the expected value of the number of heads for a game where all the coins are thrown. Recall that the expected value is the result one expects "on average", hence a quantity suitable for optimizations. In our case, the parameter R represents the reduction of the expected value of number of collisions for the case when LightForce is activated, compared to the situation when it is not. For practical reasons, R is dependent on T_c. We only analyze the effect on conjunctions above a the threshold T_c as for the limit $T_c \rightarrow 0$ we would approach 50 million "conjunctions" per investigated time interval, most of which would not represent a close approach at all and hence would likely be outside the area of validity of "probability of collision" as defined by [18,10].

Combining the simulation approach with the introduced metrics for analysis, we are now able provide some analysis of LightForce's efficiency.

3. SIMULATION RESULTS FOR LASER COLLISION AVOIDANCE

3.1 <u>Common parameters for all cases</u>

In the following we present our current simulation results on the efficiency of a network of LightForce ground stations for space debris collision avoidance. All presented cases use a set of shared parameters which are introduced in this section.

For the orbit propagation, we used the force models summarized in Table 1. The start date of our simulation was June 15, 2012 (a random choice) and 5 TLEs for fitting were acquired before that date, reaching back 5 days. The resulting state vector was computed for June 15 at 00:00:00 UTC. We restricted the analysis to orbits with a perigee below 1800 km, where more than 93 percent of space objects are present. The next important region for collision avoidance would be GEO, but engagements to geosynchronous orbits are unrealistic because of the prohibitive laser beam spreading over such a long distance.

To assemble the initial list of conjunctions, we chose a threshold T_c of 10^{-6} and performed the described all-on-all conjunctions analysis every one second interval since it appears to be the standard value at which major international space players, commercial and institutional, start to get interested in the PoC metric. Actual collision avoidance maneuvers (using satellite maneuvers) will not be initialized until P_c is orders of magnitude higher [23]. To make sure that we are not just delaying a potential collision, we investigate P_c during a 20 minute interval centered on the original time of closest approach. This is sufficient as LightForce only delays these TCA on the order of a fraction of a second. For a limited case study, we propagated objects involved in the detected conjunctions of one specific day for an additional month. For all cases where LightForce mitigated the conjunctions, no further high risk conjunctions were detected during that time frame involving those objects.

The input parameters for the laser force model are stated in Table 2. We aim for commercial off-the-shelf technology where possible, to cut down the cost of a potential system. For the same reason the assumptions about the adaptive optics technology is based on 1998 benchmarks. The engagement time t_e is 48h, meaning that objects will only be engaged if the time remaining to the time of closest approach for the specific conjunction is less than a 48 hours.

Tracking and acquisition of the objects is a technical challenge. Experiments conducted by EOS Space Technologies in collaboration with NASA Ames indicate that initial acquisition both for objects in darkness and under terminator conditions (the object is sun illuminated, the ground station is in the dark) is achievable with today's commercial technology, while initial acquisition in daylight is still problematic. However, as we envision a network of ground stations, handover of high-precision laser tracking data between those stations would vastly simplify re-acquisition in daylight. An optimized distribution of a few stations would ensure that at least one ground station is in darkness for each pass and could transfer tracking data in real time to the other stations which would use that data for re-acquisition and update the orbital data in the process. For that reason, we do not constrain our analysis to certain sun illumination conditions, but assume a laser engagement for each pass over a ground station.

Table 2: Laser ground station parameters used for efficiency simulations

Laser	IPG YLS-10000-SM	Telescope diameter	1.5 m
Power	10 kW continuous	Atmosphere model	US Standard 1976
Wavelength	1070 nm	Aerosol model	MODTRAN rural (VIS=23 km)
Beam quality	M^2=1.3	Turbulence model	Hufnagel/Valley 5/7
Engagement time t_e [*]	48 h	Adaptive optics	performance according to [21], Fig.21.1; additional beam degradation by tip/tilt anisoplanatism, see[21], appx. D4.4

[*] Each object is engaged while passing over a ground station in a 48 h window before the time of closest approach of the specific conjunction.

Table 2a: Laser ground station locations for efficiency simulations

Location	Latitude	Longitude	Altitude [km]
Antarctica (Ant.)	-80.4	77.4	4.1
Peru	-14.9	-74.2	3.6
Hawaii (HI)	20.7	-156.3	3.0
Australia (Aus.)	-35.3	149.0	0.8
Alaska (AK)	64.9	-148.5	0.5

3.2   Simulation Results

In this Section we present some results of our recent simulation efforts. Fig. 4 shows the effect of a 4 station LightForce network (Antarctica, HI, Aus, AK, see Table 2a) with one 20 kW laser at each location. We analyze the effects on conjunctions with $P_c>10^{-6}$ detected in a 30 day period, as presented in Fig. 3. Fig. 4 is a scatter plot of all conjunction events, where the x-axis shows the original P_c and on the y-axis we plot the resulting P_c, when the LightForce network is active. Events on the line y=x do not encounter any change in P_c, everything below that line indicates a decrease. The plot indicates significant improvements for a majority of conjunctions. The probability of collision for the conjunction with the highest risk on the far right of the plot was reduced from $3.2*10^{-2}$ to $1.4*10^{-6}$.

Further analysis shows that after LightForce was activated, for 69% of the conjunctions, P_c has been reduced to a value smaller $P_c<10^{-6}$, hence for $T_c=10^{-6}$ the mitigation factor M is 69%. In Table 3 we list the mitigation factors for a couple of different groundstation configurations, again for $T_c=10^{-6}$. For cases presented in Table 3, the analysis was restricted to 72 hours, to reduce computation times. During 24 hours, conjunctions are listed, leaving 48 hours engagement time for each conjunction. We investigate placing lasers at different geographical locations around the globe. At each location we assume a cluster of beam directors (telescopes), where one 10 kW laser is connected with each beam director. We present results for 1, 2, 10 and 20 beam director/laser combinations per cluster at each location.
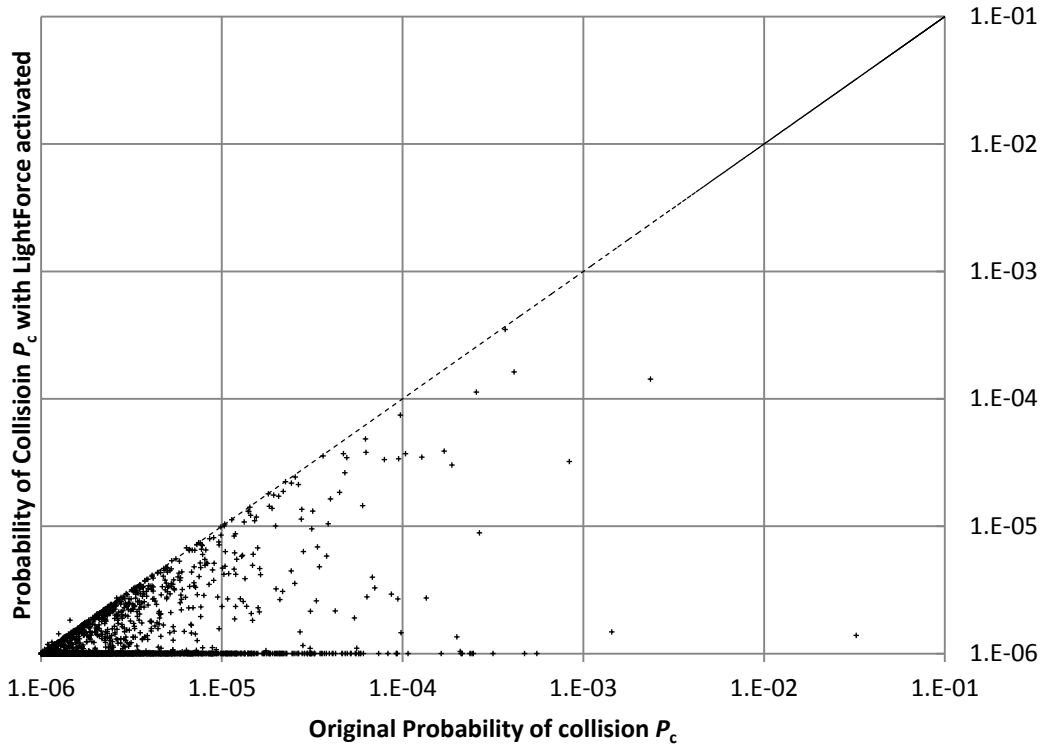

Fig. 4:   Potential reduction of probability of collision for 30 days of conjunctions. Conjunction plotted with a remaining $P_c=10^{-6}$ represent events with $P_c<=10^{-6}$.

With increasing number of clusters and increasing number of lasers per cluster the mitigation factor increases to 95% for the chosen maximum configuration simulated, using 4 ground station clusters with twenty 10 kW lasers each. While 95% is impressive, such an installation would be complex and costly. Fortunately, looking at reduction in expected number of collisions paints a more optimistic picture.

Table 4 presents results for the same ground station configurations, but this time looking at the reduction factor R, representing the reduction in expected number of collisions from high risk conjunctions, as defined in Section 2.3. The stated error bounds arise because conjunctions below $P_c < 10^{-6}$ slip through the conjunction filter and all we know at this point is that their P_c is between 10^{-6} and zero. The uncertainty is bounded by using both extremes and give the average and error range in Table 4. Looking at the results, it is apparent that even a low fidelity system can be efficient in reducing the expected number of collisions arising from the investigated conjunctions with $Pc > 10^{-6}$: One station in a convenient location achieves 72% reduction.

The 91% reduction factor of the most powerful network of 4 stations is lower than the 95% mitigation factor for the same system (Table 3). This can be explained by the fact that the relative impact of LightForce on the low risk conjunctions is smaller than on high risk conjunction. For example, adding a couple hundred meters miss distance to a conjunction that already has several kilometers miss distance does not change P_c much relative to the original P_c. Therefore, for those low risk conjunctions, the impact of increasing the number of lasers on the reduction factor F is lower than on the mitigation factor M, where a small change in P_c might push the conjunction over the threshold into the "mitigated" category.

For both metrics, regardless of the numbers of lasers per cluster, the 1-cluster configuration located in Antarctica delivers results that are close to the more complex, distributed configurations, because at that location the engagement geometry is favorable and the placement at high altitude allows for better beam propagation with fewer losses. Still, Table 3 illustrates that there are a number of conjunctions that a single station at Antarctica would not mitigate, because the objects just do not pass over that station. In addition, one might also need some "tracking-only" stations to hand-over high-precision orbital data to a single LightForce station to enable daylight illumination. Future research will have to optimize between acquiring the capability to mitigate as many conjunctions as possible (say to protect assets against most potential impacts), being most effective on reducing the expected number of collisions and, finally, the cost of a potential system.

Table 3: Mitigation factor M (as defined in Section 2.3) for different LightForce configurations. Conjunctions count as mitigated as their Pc is reduced below 10-6.

Network configuration		Mitigation factor M vs. number of 10kW lasers per ground station cluster in [%] - Threshold $T_c = 10^{-6}$			
cluster(s)	locations	1 laser	2 lasers	10 lasers	20 lasers
1	Antarctica	48	58	83	84
2	Antarctica, Peru	56	67	87	91
4	AK, HI, Ant., Aus.	58	70	92	95

Table 4: Reduction factor R in expected value for number of collisions (as defined in Section 2.3) for different LightForce configurations

Network configuration		Reduction factor R for expected number of collisions vs. number of 10 kW lasers per ground station cluster [%]			
cluster(s)	locations	1 laser	2 lasers	10 lasers	20 lasers
1	Antarctica	72 ± 4	79 ± 4	88 ± 6	89 ± 7
2	Antarctica, Peru	75 ± 4	81 ± 5	89 ± 7	90 ± 7
4	AK, HI, Ant., Aus.	78 ± 4	84 ± 5	90 ± 7	91 ± 7

4. CONSIDERATIONS FOR FUTURE ASSESSMENTS OF LASER COLLISION AVOIDANCE

There are several points to consider for future assessments of the LightForce system. For the immediate future, we plan to integrate a simulation of station duty cycles (i.e. oversubscription of stations) and optimize engagement strategies. In regard to duty cycles, we do not expect a large impact on the R-factor, because there are only a small number of high risk conjunctions with $P_c > 10^{-5}$ (see Fig. 3). Still, analyzing duty cycles is essential for a complete end-to-end simulation.

In regard to optimization, we plan to take the following points into consideration:
Station locations and cloud cover: we have already prepared a simulation for cloud coverage, however it only makes sense to use it in an optimization problem, as one would place stations in locations with low average cloud cover. The task is to find optimal locations in regard to turbulence, cloud cover and engagement geometry.

Engagement strategy: Especially after implementing station duty cycles, the decision of which objects to engage will be crucial to reach optimal *R*-factors for each LightForce network configuration.

Tracking capabilities: Each LightForce station will also provide high precision orbit determination capabilities through laser ranging. This will also impact the engagement strategy. Rather than engage each conjunction until the last minute, for a lot of low risk conjunctions, a single tracking engagement will determine that a collision is highly unlikely and that future engagements with the LightForce network or satellite maneuvers are not even necessary.

Costs and benefits: Increasing the number of LightForce stations around the globe would allow pushing the mitigation factor close to 100%. However, the costs would be prohibitive. The goal here will be to find the optimal solution for given mission requirements, be it satellite protection or general debris environment mitigation.

Finally, we have investigated the utility of LightForce for today's debris environment. The big remaining question is what effect LightForce would have on the Kessler syndrome. To answer this question, a brute force approach as described by Nikolaev would be a likely approach [24].

5. CONCLUSION

We investigated the efficiency of the LightForce photon pressure collision avoidance concept using the entire catalogue of tracked space objects. We assembled a list of occurring conjunctions for the simulation time frame, investigated the utility of several different LightForce configurations and developed two different metrics to assess the utility of the system. The first metric is used to assess the fraction of conjunctions that can be mitigated. This approach is useful if one wants to optimize for the protection of assets, e.g. gain the capability to protect one satellite against as many potential impacts as possible. The second metric assesses the reduction of the expected value of collisions if the system is active. This metric is useful for optimizing the effect on the debris environment in general. LightForce can be used to achieve both goals. With one 20 kW laser placed in Antarctica, a fraction of 58% of conjunctions can be mitigated, resulting in 79% reduction in expected number of collisions (for now neglecting effects of station duty cycles). More sophisticated systems improve those numbers (see Tables 3,4). These results illustrate why we believe that LightForce is a suitable solution to provide immediate benefits for space operations and also would be an extremely beneficial supplement to any long-term active debris removal efforts.

6. ACKNOWLEDGEMENTS

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