

63rd International Astronautical Congress, Naples, Italy. Copyright ©2012 by the International Astronautical Federation. All rights reserved. One or more authors of this work are employees of the U.S. government, which may preclude the work from being subject to copyright in the U.S., in which event no copyright is asserted in that country.

IAC-12.A6.5.11

LIGHTFORCE: AN UPDATE ON ORBITAL COLLISION AVOIDANCE USING PHOTON PRESSURE

Jan Stupl*

SGT Inc. / NASA Ames Research Center, United States, jan.stupl@nasa.gov

James Mason

Universities Space Research Association (USRA), United States

Willem De Vries

Lawrence Livermore National Laboratory, United States

Craig Smith

EOS Space Systems Pty Ltd, Australia

Creon Levit

National Aeronautics and Space Administration (NASA), United States

William Marshall†

San Francisco, United States

Alberto Guillen Salas*

SGT Inc. / NASA Ames Research Center, United States

Alexander Pertica

Lawrence Livermore National Laboratory, United States

Scot Olivier

Lawrence Livermore National Laboratory, United States

Wang Ting

Center for International Security and Cooperation (CISAC), Stanford University, United States

* Part of this work was accomplished while J. Stupl and A. Guillen Salas were employed at Universities Space Research Association (USRA)

† Part of this work was accomplished while William Marshall was working for Universities Space Research Association (USRA) at NASA Ames Research Center

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 and liability 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 simulations to investigate multiple case studies. The approach includes modeling of laser beam propagation through the atmosphere, the debris environment (including actual trajectories and physical parameters), laser facility operations, and simulations of the resulting photon pressure. 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 the average low Earth orbit (LEO) satellite's life time by a couple per cent [1]. With no effective countermeasures in place, models predict a growing number of debris and hence an increasing risk of collisions. This cascading increase is caused both by collisions between debris objects and spacecraft, as well as collisions between debris objects and is known as the Kessler syndrome [2]. Even for the most conservative scenario, assuming no-future launches and responsible operators, current models predict a catastrophic increase for the most congested (and most useful) orbits [3].

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 [4]. 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 for preventing impending collisions at short notice.

Active collision avoidance (COLA) is an alternative approach that does not suffer from these drawbacks. While de-orbit maneuvers typically require delta-v impulses in the order of 100 m/s, COLA 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, COLA is not desirable. COLA maneuvers expend fuel that could be used for the primary mission, reduce the spacecraft's operational lifetime and increases risk, as firing thrusters can have unintended consequences.

Hence, an external capability to maneuver debris objects, or even active satellites is highly desirable. Such a capability 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 this paper's authors [5]. 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 off-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 ongoing 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.1 LightForce: A Concept to use Photon Pressure to Maneuver Space Objects

LightForce is a proposed laser system using only photon momentum transfer for collision avoidance. Illuminating an object in orbit from the ground results in the application of a small Delta-v, with part of this force in the along-track direction. This changes the object's specific orbital energy, thus lowering or raising its semi-major axis and changing its period (illustrated in Fig 1). Changing the period is important, as large along-track displacements may be accumulated over time from very small perturbation forces. When previously two objects were to collide, minutely changing one's period causes it to arrive at the collision point ahead, or behind, schedule; the two objects miss each other in time, even if the orbital elements remain essential unchanged. A delta-v 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, despite an only 0.02 second change in the orbital period and 18 m change to the semi-major axis. This growing along-track displacement is far larger than the typical error growth encountered in the orbit projections of catalogued debris objects.

Delta-v of this order of magnitude can feasibly be imparted through photon momentum. When compared to other proposals focusing on de-orbit through laser ablation (for an update see [6]), these slight COLA nudges greatly reducing the required power and complexity of a ground based laser system. 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 colliding objects 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 facility.

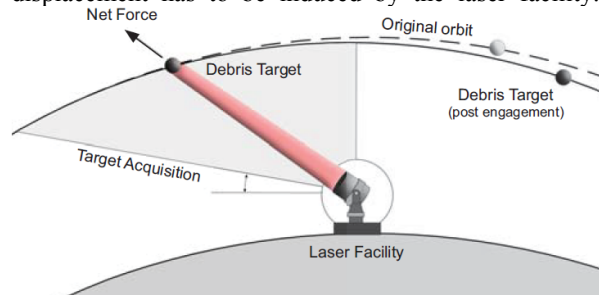


Fig. 1: Schematic of laser system for orbital debris collision avoidance.

Tracking is routinely achieved for approximately 30,000 objects of all sizes, down to about 10 cm for objects in LEO. A planned upgrade of Air Force tracking capabilities 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 be confident that a laser nudge will result in no collision the induced displacement has to be larger than the propagated orbits, 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 environmental impact. Usually, the protection of active spacecraft would have priority; however, in some cases the prevention of a collision that results in massive debris clouds might get higher priority. One would then also filter out conjunctions for which this approach is insufficient (e.g. those involving two very massive objects, each >100kg, or two objects with very low area-to-mass (A/m) ratios)

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 object (typically the lower mass, higher A/m object) as the illumination target or to illuminate both. In order to assess the efficacy of the scheme, we employed a mix of orbit simulations and the statistical approach in our earlier paper [5]. 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. To do this we modified a standard high precision force model propagator by adding the additional photon pressure. A baseline laser system was defined and the orbits of a set of illuminated debris was compared to those of identical objects without illumination. The following sections describe this approach in further detail.

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 [7], 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 [8].

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 [9]. Even if the Gaussian model might not resemble the actual intensity distribution, the approach ensures that the incoming time-averaged total intensity is correct [10]. 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 [11, appendix A], [12, 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 [13, 14], 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 [15, 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 anisoplanatism - the tip/tilt correction errors that appear because of light travel time that cannot be corrected using a guide star.

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. 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 [16]. 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 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 [5]

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. Two Line Element (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 [17]. It uses the ballistic drag coefficient B, defined as the product of the dimensionless drag coefficient C_d and the area to mass ratio A/m , for an object [18]:

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

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 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 $C_d = 2.2$, 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 [5]. For the albedo a conservative assumption was made by choosing $C_r=1$, 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. After a two day laser campaign it was found that for a 10 kW laser, 56 objects were 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.

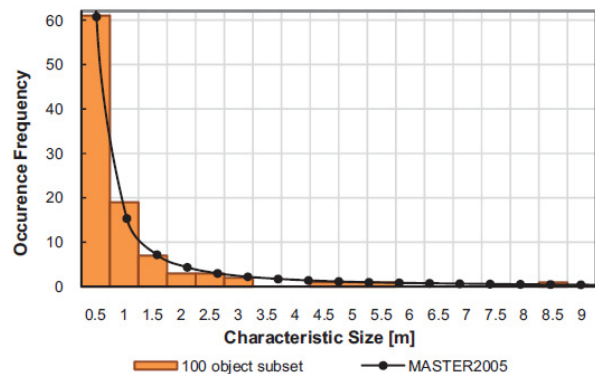


Fig. II: Size distribution for 100 debris objects in sun-synchronous LEO, generated using MASTER2005's characteristic size distributions.

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 [5] give a very strong indication that the LightForce concept can play an important role 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 will grow.

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 creates 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) **Simulations 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 an initial step, we assume a intensity of one solar constant, which is well within the achievable performance of our 10kW baseline station.
- 3) **Generate statistics on the distribution of objects that can be perturbed to overcome in-track uncertainties with some number of 'pushes'.** 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.

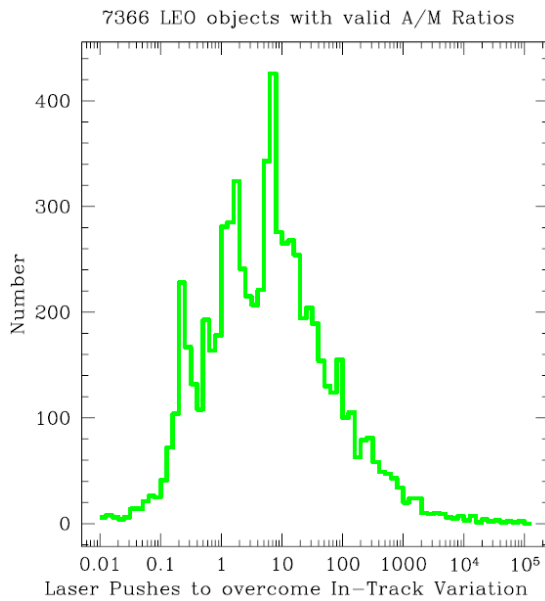


Fig. III: Histogram showing the number of objects vs. the number of laser pushes need to overcome their in-track prediction uncertainties.

4) 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. System performance under different acquisition constraints, which depending on sun illumination status at the time of a pass over the ground station, is investigated.

Table III does not include a minimum displacement for successful engagements, and assumes even the smallest displacements are measurable. If a limit was set to 10 m or 100 m (depending on the size of a potential collision partner and/or the inherent measurement uncertainty of a monitoring system), the values would be worse. It also becomes clear that acquisition capabilities are crucial. Ideally there would be no constraints, and target acquisition would be possible during daylight tracking ("always"), or re-acquisition of objects which have been acquired during an earlier pass would be possible. Employing thermal infrared imaging or using the main laser beam as a search spotlight, "darkness" acquisition should be possible when the sky around the target is dark. Currently acquisition is

[‡] Successfully engaged means only that the object has been perturbed by more than the orbit uncertainty

limited by "terminator" passes, when the target is sun illuminated against a dark sky. This constraint, if not overcome, would keep efficiencies prohibitively low.

It should be noted that these numbers are preliminary, and that they will be refined by accounting for laser propagation through the atmosphere in our modeling and simulation setup, instead of just using the solar constant intensity assumption.

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

Site(s)	Acq.	Access	Successful
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.: Acquisition capabilities constraint to darkness or terminator, or unconstrained ("always")

Sites: AUS: Mt. Stromlo, Australia,

10@45: 10 stations at latitude 45°

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 the probability of collision between two space objects exceeds 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. Once ranged and tracked, this incoming data can be used to refine the orbit and, should the conjunction risk be confirmed, a LightForce maneuver would start with continued engagements. While the first track might happen in terminator conditions, ideally, all follow up passes over the ground station should be used 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 today's capabilities and future requirements both for first acquisition, and out of terminator re-acquisition. For this purpose EOS Mount Stromlo Laser Ranging facilities are used to track debris objects. The facility offers a 1.8m fast slewing telescope, as well as an automated laser ranging system, and both wide and narrow field of view cameras. For further details please see [19,20].



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

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

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 the remediation of the deteriorating space debris 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, critically providing more insight into the uncertainty of debris orbits. Extended simulations with several thousand debris objects have shown the potential to effectively modify a significant fraction of debris orbits for collision avoidance. This research will be enhanced by replacing simplifying assumptions with realistic models or experimental results. We also plan 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. Initial acquisition of debris objects with TLE data is certainly possible, and out of terminator acquisition is most likely possible, with currently available technology.

V. REFERENCES

- [1] W. Ailor, J. Womack, N. Lao, G. Peterson, and E. Murrell, *Effect of Space Debris on the Cost of Space Operations*, Aerospace Corporation, TOR-2010(1106)-9938e, May 2010.
- [2] Kessler, D. and Cour-Palais, B. *Collision frequency of artificial satellites: The creation of a debris belt*. J. of Geophys. Res., 83(A6), 2637–2646, 1978.
- [3] Liou, J.-C. & Johnson, N. *Instability of the present LEO satellite populations*. ASR, 41,1046–1053 2008.
- [4] Liou, J.-C. *An Active Debris Removal Parametric Study for LEO Environment Remediation*. Adv. Space Res., Vol 47, Issue 11, p. 1865-1876, 2011.
- [5] Mason, J., Stupl, J., Marshall, W., Levit, C. *Orbital debris-debris collision avoidance*. *Advances in Space Research*, 48, 1643-1655, 2011.
- [6] Phipps, C. R. et al. *Removing Orbital Debris with Lasers*. arXiv:1110.3835v1, submitted to ASR
- [7] McInnes, C.K. *Solar sailing: technology, dynamics, and mission applications*. Springer, 1999.
- [8] Siegman, A.E., *LASERS*. Mill Valley, CA, USA: University Science Books, 1986.
- [9] Siegman, A. E. *Defining the effective radius of curvature for a nonideal optical beam*. IEEE J. of Quant. Electronics, 27, No. 5, p. 1146-1148, May 1991.
- [10] Siegman, A. E et al. *How to (Maybe) Measure Laser Beam Quality*. DPSS Lasers: Applications and Issues, Optical Society of America, MQ1, 1998.
- [11] Stupl, J., & Neuneck, G. *Assessment of Long Range Laser Weapon Engagements: The Case of the Airborne Laser*. Science & Global Security. 18(1): 1-60, 2010.
- [12] Stupl, J. *Untersuchung der Wechselwirkung von Laserstrahlung mit Strukturelementen von Raumflugkörpern*. München: Verl. Dr. Hut., 2008.
- [13] Higgs, C. et al. *Adaptive-Optics Compensation Using Active Illumination*, Airborne Laser Advanced Technology of SPIE Vol. 3381, pp. 47-56, 1998.
- [14] Billman, K.W., et al. *ABL beam control laboratory demonstrator*. Airborne Laser Advanced Technology II, Proceed. of SPIE Vol 3706, pp.172–179, Orlando, Florida, 5-7 April 1999.

63rd International Astronautical Congress, Naples, Italy. Copyright ©2012 by the International Astronautical Federation. All rights reserved. One or more authors of this work are employees of the U.S. government, which may preclude the work from being subject to copyright in the U.S., in which event no copyright is asserted in that country.

[15] Barton, D. K. et al. *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues*. Rev. Mod. Phys. 76, No. 3, S1-, 2004.

[16] Phipps, C.R. et al. *ORION: Clearing near-Earth space debris using a 20-kW, 530-nm, Earth-based, repetitively pulsed laser*. Laser and Particle Beams 14 no.1 pp. 1–44, 1996.

[17] Pardini, C. and Anselmo, L. *Assessment of the consequences of the Fengyun-1C breakup in low earth orbit*, Adv. Space Res. 44, 545–557, 2009.

[18] Vallado, D.A. et al. *Revisiting Spacetrack Report # 3*. AIAA/AAS Astrodynamics Specialist Conference, Keystone, CO, August 21-24, 2006.

[19] Sang, J., and Smith, C. (2011), *An Analysis of Observations from EOS Space Debris Tracking System*, 2011 Australian Space Science Conference, 26 – 29 September, 2011, Canberra.

[20] Sang, J., and Smith, C. (2012), *Real-Time Tracking of Geostationary Satellites in Sub Arc Second Accuracy*, 2012 AIAA/AAS Astrodynamics Specialist Conference, accepted for presentation, 13 – 16 August, 2012, Minneapolis, Minnesota.