Assessment Study of Small Space Debris Removal by Laser Satellites

Sang H. Choi and Richard S. Pappa

NASA Langley Research Center
Hampton, VA 23681

Abstract

Space debris in Earth orbit poses significant danger to satellites, humans in space, and future space exploration activities. In particular, the increasing number of unidentifiable objects, smaller than 10 cm, presents a serious hazard. Numerous technologies have been studied for removing unwanted objects in space. Our approach uses a short wavelength laser stationed in orbit to vaporize these small objects. This paper discusses the power requirements for space debris removal using lasers. A short wavelength laser pumped directly or indirectly by solar energy can scan, identify, position, and illuminate the target, which will then be vaporized or slow down the orbital speed of debris by laser detonation until it re-enters the atmosphere. The laser-induced plasma plume has a dispersive motion of approximately 10^5 m/sec with a Lambertian profile in the direction of the incoming beam [1-2]. The resulting fast ejecting jet plume of vaporized material should prevent matter recombination and condensation. If it allows any condensation of vaporized material, the size of condensed material will be no more than a nanoscale level [3]. Lasers for this purpose can be indirectly pumped by power from an array of solar cells or directly pumped by the solar spectrum [4]. The energy required for vaporization and ionization of a 10 cm cube (~ 2700 gm) of aluminum is 87,160 kJ. To remove this amount of aluminum in 3 minutes requires a continuous laser beam power of at least 5.38 MW under the consideration of 9% laser absorption by aluminum [5] and 5% laser pumping efficiency. The power needed for pumping 5.38 MW laser is approximately 108 MW, which can be obtained from a large solar array with 40% efficiency solar cells and a minimal area of 450 meters by 450 meters. This solar array would collect approximately 108 MW. The power required for system operation and maneuvering can be obtained by increasing solar panel size. This feasibility assessment covers roughly the power requirement, laser system, and a potential operational scenario.

Keywords: space debris, laser vaporization, power satellite, laser satellite.

Table of Contents

1. Space Debris

Most man-made space debris larger than 1 cm are closely monitored by space radar and space telescopes. However, objects smaller than 1 cm cannot be identified with current technology and can pose a serious hazard to spacecraft, satellites, and human flights in near earth orbit. Much of the debris in orbit around the Earth was created in the past 50 years. The space debris, scattered over orbiting the earth, are shown in Figures 1 and 2. The majority of this debris are small particles numbering in the tens of millions. This debris includes slag and dust from solid rocket motors, surface degradation products such as paint flakes, coolant released by the Soviet-era Radar Ocean Reconnaissance SATellite (RORSAT) nuclear powered satellites [6], clusters of small needles for creating an artificial ionosphere [7], and objects released by impact of micrometeoroids or small debris into other objects. Impacts by these small objects can cause considerable damage to orbiting spacecraft. The kinetic energy of small orbiting objects are the major component of impact damage due to high velocities. Upon impact, this debris and the impacted surface material vaporize, resulting in plasma ejecting from the impact crater (see Figure 3).

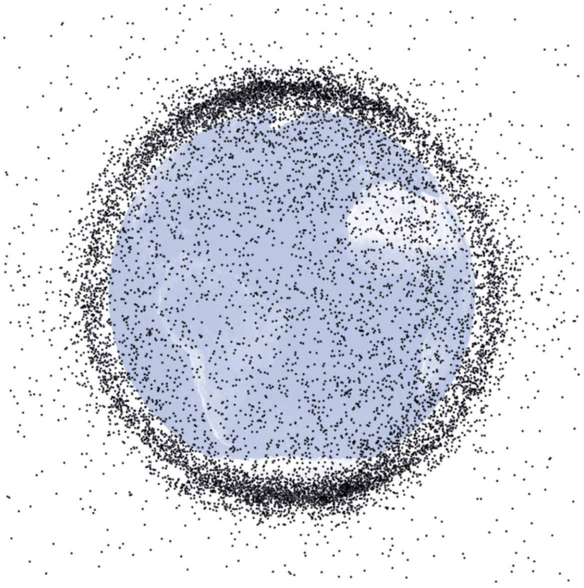

Figure 1. Space debris distribution in low Earth orbit. Image by NASA Earth Observatory.

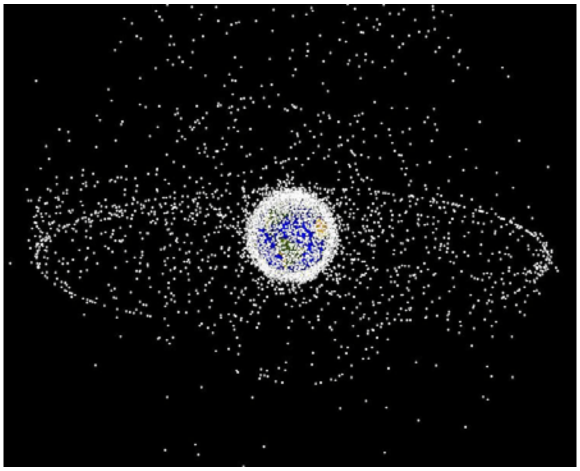

Figure 2. Space debris populations seen from outside geosynchronous orbit (GEO) by NASA. Note the two primary debris fields, the ring of objects in GEO, and the cloud of objects in low earth orbit (LEO).

Impact damage can be mitigated using an additional layer of metal foil on the outside of the spacecraft. However, not all parts of a spacecraft can be protected by such shielding. Only when the size of space debris is less than 1 cm can the protective thin-metal film work effectively. Otherwise, maneuvering of spacecraft in orbit is the only remaining option to avoid collision [8]. This requires accurate position and path information of the small objects in orbital proximity. Currently, radar and space telescopes can track space debris down to about 1 cm (0.4 in) in size in low Earth orbit [9], and about 50 cm (20 in) in size in geosynchronous orbit. However, only about 19,000 objects are tracked out of the total estimated 600,000 objects [10] larger than 1 cm. The orbital accumulation of small size debris mainly attributes to the on-orbit satellite fragmentations [11]. This leads to a wide range of uncertainties on estimating the quantities of debris and their predicted orbital paths.

Collisions with larger debris create numerous fragments in the 1 kilogram (2.2 lb) mass range [12]. These fragments scatter and become new sources of additional collision risks. If the number of debris in orbit is large enough, the increased frequency of collisions among scattered debris can further generate more debris in orbit. This collision generating debris increases the probability of further collisions that accelerate multiplication of debris in a period of years. This possibility is known as the "Kessler Syndrome" [14], and there is debate as to whether or not this critical density has already been reached in certain orbital bands. Although there is no international treaty yet to limit space debris, voluntary guidelines have been published by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) [15]. NASA has its own procedures for limiting debris production in space [16].

Figure 3. Space debris impact on Space Shuttle Challenger's front window on STS-7. [13]

One approach to removing small orbital debris is using a space-based continuous wave (CW) laser beam to render it harmless. This method requires a substantial amount of laser power. Another approach uses powerful laser pulses to create a series of plasma plumes from a targeted surface of debris. The incident pulsed laser beam generates a sequence of detonation plumes opposite the direction of the debris. The laser detonated plume, just like a rocket plume, generates an ejection of evaporated plasma with a velocity of roughly 10^5 m/s [14]. Repeated laser detonations at the leading edge of the debris reduce its orbital velocity and cause it to re-enter Earth's atmosphere and disintegrate.

2. Power Requirements and Sources

Among many approaches to remove small space debris, the laser evaporation or laser detonation (or ablation) of small objects could be plausible since the laser, optics, monitoring and tracking, and steering optics technologies are readily available. However, both approaches require substantial amounts of laser power. For this study, several key laser parameters including the beam power, mode, wavelength, and optics were assessed. The most favorable laser wavelength is ultra-violet (UV), which is most effective for laser-materials interaction [17].

Power Required for Laser Vaporization: Assuming that most man-made debris from rockets, spacecraft, satellites and other sources is aluminum, several parameters such as the energies of vaporization and ionization, laser beam energy, laser-material coupling efficiency, and laser pumping efficiency need to be taken into account. For aluminum, the vaporization and ionization energies are 294 kJ/mol and 577 kJ/mol, respectively. Assuming an 9% laser-aluminum coupling efficiency [5] at ultra violet spectral range, the power required for vaporization varies

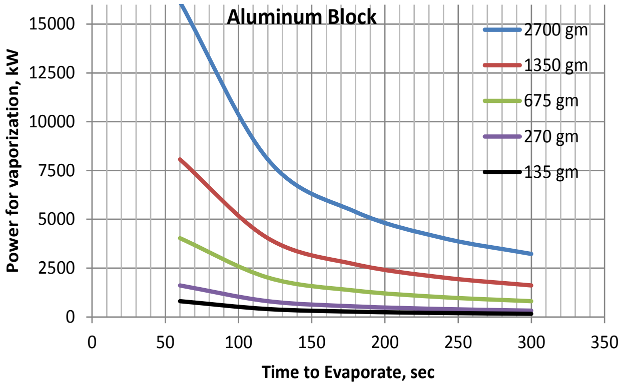

Figure 4. Laser power requirement for vaporization of aluminum blocks according to the exposure times.

with the mass of aluminum and the exposure time as illustrated in Figure 4.

Using only three minutes of laser exposure to vaporize aluminum blocks, the laser power required linearly increases with the debris mass as shown in Figure 5. To raise the laser beam power such levels, the power collected by solar cells must be sufficient to alleviate the poor laser pumping efficiency (in general, $\eta < 5$ %). Assuming a 40% solar cell efficiency [19], the size of an assumed square solar array to generate enough laser power to vaporize aluminum blocks is plotted in Figure 6. The solar array size was determined by laser beam power requirements for the three minute vaporization scenario. The exposure time of laser beam power is a key factor to determine the size of solar cell array. It is clear that shorter exposure times require less power and smaller solar array sizes.

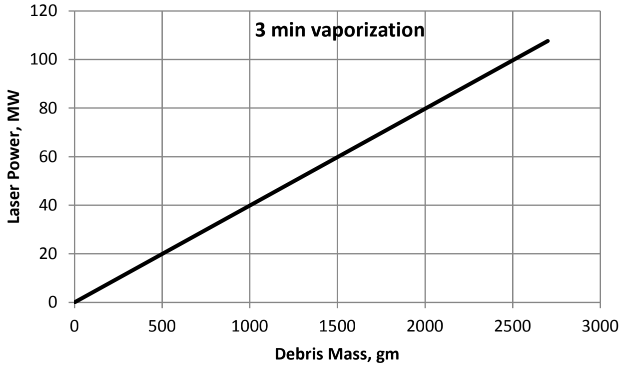

Figure 5. Laser power is linearly increased for vaporization of aluminum blocks when 3 minutes of the exposure time is only allowed.

Power Required for Laser Ablation: The power required for laser ablation is much less than that required for complete laser vaporization because the laser ablation process uses multiple laser pulses to create plasma plumes of laser detonation. The amount of material removed by a single laser pulse is factored by the material's optical absorptivity, laser wavelength, pulse duration, and pulse energy. The selection of a shorter wavelength laser is beneficial for laser-material interaction, but the efficiency of short wavelength lasers is lower. The pulse duration can vary over a wide range from milliseconds to femtoseconds. Very short laser pulses remove material so quickly that small amounts of laser energy is absorbed to heat the surrounding material. Laser pulse energy is an important factor for the ablation process. The pulsewidth after the compression of a laser pulse energy determines the power of laser delivered for interaction. When a laser beam in pulse mode hits the target material, it generates a plume of plasma from the material cavity because the compressed pulse power is high enough to melt and vaporize the material. Additional laser pulses hitting the cavity and plasma plume continuously increase the plasma temperature through inverse Bremsstrahlung absorption [20]. Of course, when the pulse interval exceeds the recombination time of plasma, there is no inverse Bremsstrahlung process. Figure 7 depicts the laser ablation process. When a laser pulse hits the material, a plasma plume from the interaction cavity develops and is ejected with a substantial velocity of 10^5 m/s in vacuum.

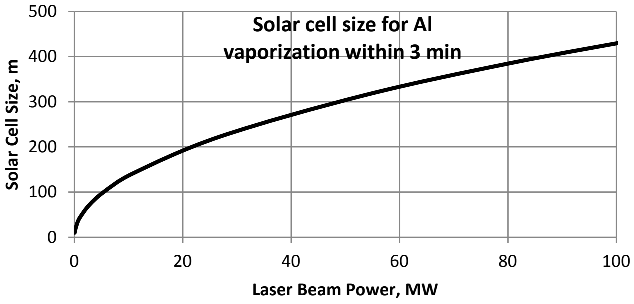

Figure 6. The size of solar cell array was determined by laser beam power requirement for vaporizing aluminum blocks within 3 minutes exposure.

For a laser pulse of 300 ns and 1 or 2 mm diameter focal spot size for laser-material interaction, the threshold of laser supported detonation for aluminum was measured to be ~ 2 x 10^8 W/cm^2 [21]. The detonation wave velocity varies from about 10^4 m/s in air to 10^5 m/s in vacuum. With a CO_2 laser that has a wavelength of 10.6 μm with 100 J energy and 40 ms pulsewidth, the ejection velocity of detonation wave appears to be approximately 10^4 m/s [22].

The momentum vector of laser detonation works against the direction of motion as shown in Figure 7. By repeated laser detonations, the orbital velocity and altitude are changed and the debris can eventually fall into Earth's atmosphere. Figure 8 shows the approximate number of pulses required for stopping a 2.7 kg aluminum block orbiting at 10 km/s using laser pulse energy. In this estimate, a UV laser with 488 nm and 1 μs pulsewidth for an ablation rate of 3 mg per 100 J was used. However, it is not necessary to completely stop space debris; changing the orbital velocity is sufficient for gradual orbital decay and re-entry. Suppose that the orbiting speed of debris is reduced by 30% to 7 km/s, which requires. approximately 26000 laser pulses. The use of higher pulse energy would require fewer pulses. The ablation spot should not be always the same. The laser pulse may hit the debris off from its own center of principal momentum, which will make the target spin. However, the period of rotation caused by the off-center impacts is large compared to the repetition rate of laser pulses, that the pulsed laser beam can repeatiously hit the same approximate area. Regardless of where the laser pulses hit the target, the debris will continuously change its velocity. If the object is decelerated, the debris will continuously decrease its orbit and eventually reenter Earth's atmosphere. Based on this hypothesis, laser ablation is much more favorable than laser vaporization in terms of laser energy requirements and operation.

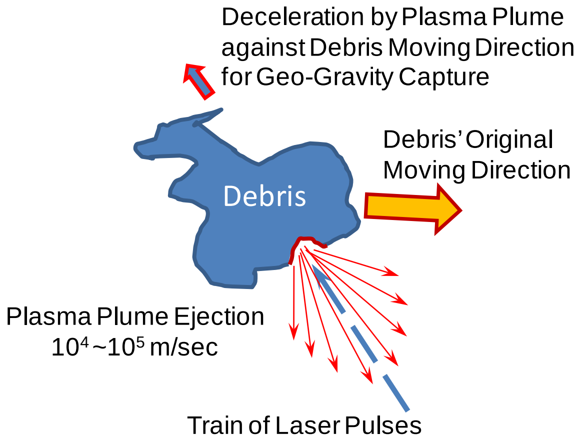

Figure 7. Space debris is ablated after hitting by train of laser pulse. The plasma plume (red arrows) by laser ablation is ejected by approximately 10^5 m/s velocity and decelerates debris for geo-gravity capture.

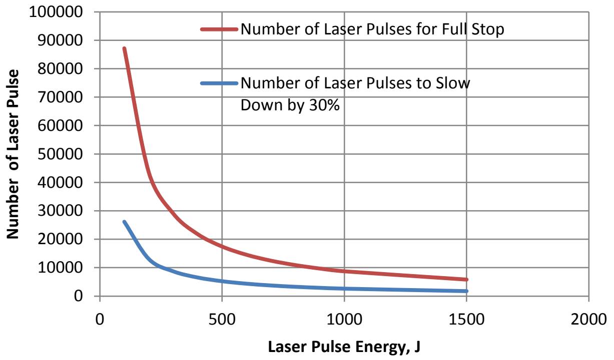

Figure 8. Red line: Number of laser pulses required to stop 2.7 kg aluminum block orbiting with 10 km/s with respect to laser pulse energy. Blue line: Number of Laser pulses to slow down the debris speed by 30%.

3. Laser Satellite

Laser transmission in space is nearly 100% attenuation-free regardless of laser wavelengths. However, the pumping efficiency of a high power UV laser is very low since UV laser pumping process requires a high level transition from the ground state to an upper state of population inversion. The quantum efficiency of laser pumping through laser gain medium is limited by the level transition that leads to a down conversion process. The largest single transition to the first stable state in the level transition process determines the photon energy of the emitted laser beam. The higher the upper level is, the shorter the emission wavelength from pumping medium can be. Otherwise, by Stark splitting [23], the up-conversion process during pumping is facilitated for spectral emission.

Table 1 shows the pumping bands and output power of deep and vacuum UV by second harmonic generator (SHG). Note that the output power of UV pumping by SHG is substantially reduced by almost two orders of magnitude. The

UV laser is favorable for removing space debris in terms of wavelength, but impractical because of the large power requirement by its low efficiency. As we noticed earlier in the laser ablation, near infrared (IR) lasers would perform better for laser detonation than CO$_2$ lasers. Even now fiber lasers are known to have very high pumping power greater than 1 kW level. Among them is the Ytterbium-doped large-core fiber laser that generates 1.36 kW of power at 1.1 μm with 83% slope efficiency and near diffraction-limited beam quality [24]. A proper optical bundling of this type of fiber laser would provide a high power option for laser transmission. Long distance beam transmission from bundled fiber lasers in array is difficult because of the mismatched phases of fiber lasers. However, NASA Langley Research Center has developed a method for correcting the spatial coherence from bundled laser emissions [25]. The dynamic selection of emitting lasers in an array may partially correct the spatial coherence of an array of laser beams. The method trades far-field intensity for simplistic implementation and array lifetime extension, resulting in a quasi-coherent array with features of adaptive optics. Accordingly, because of pseudo coherence achieved by the dynamic selection method [25], the beams from 45% of lasers in array can be collectively concentrated onto a receiver at a farther distance away with far-field intensity.

Table 1. Pumping Band and Output Power of Deep UV by Second Harmonic Generator.

Visible Wavelength	Output power	SHG wavelength	Output power
568.2 nm	225 mW	284 nm	10 mW
528.7 nm	420 mW	264 nm	10 mW
514.5 nm	2400 mW	257 nm	200 mW
501.7 nm	480 nm	250 nm	10 mW
496.5 nm	750 mW	248 nm	30 mW
488.0 nm	1800 mW	244 nm	100 mW
476.5 nm	720 mW	238 nm	10 mW
457.9 nm	420 mW	229 nm	10 mW

Far-field transmission using bundled lasers such as diode or fiber is feasible but requires at least pseudo-coherence of the beam. Under this assumption of pseudo-coherence of bundled lasers, several scenarios of beam power transmission technology in space have been developed at

Figure 9. Power satellite and ground power station are used for wireless power transmission by either laser or microwave.

NASA Langley [4, 25-28]. Recently, an Nd:YAG laser doped with chromium was directly pumped with solar energy [29]. Although the total efficiency of a Nd:YAG solar pumped laser is still low, the directly solar pumped laser is attractive because solar energy is abundant and free.

Figure 9 shows several scenarios of wireless power transmission for space applications. The key challenge for removing debris using the proposed approach is how to provide sufficient electrical power to a laser system in space. The left-hand side of Figure 9 shows a power satellite for deep space using a radioactive thermoelectric generator (RTG). However, solar energy is plentiful near earth and can be harnessed for useful applications. For a large power lasers, the size and cost of the required solar arrays are key concerns. The size of the required solar arrays for this application was plotted at Figure 6.

4. Current & Future Developments

Unfortunately, there are no practical activities for space debris mitigation and removal to date. Only the working group meetings for reviewing the seriousness of space debris have been held numerous times. The most recent one was the meeting organized by the International Science and Technology Center (ISTC) to stress the importance of the continuation of the research in the field of space debris removal in the lower earth orbit taking into account various elements such as the risk of collision and self-decaying of the various objects and to conclude that international cooperation and partnership is essential [30]. The seriousness of man-made space debris has been well addressed but still actual actions for removal of space debris are desperately required while constraining any further increase of debris. The DARPA's Catcher's Mitt report [31] addresses the overall concerns and solutions related to ever increasing space debris.

5. Conclusion

In this feasibility study, wireless power transmission technology is adopted for removing space debris. Two removal scenarios were studied: laser vaporization and laser ablation. The power required for either case can be obtained from solar energy. This study found that the laser ablation approach uses less energy than the laser vaporization approach and is therefore preferred. The reduced energy consumption using laser ablation results from the lower laser pulse energy required for slowing the orbiting velocity of unwanted debris.

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Biographies

Dr. Sang H. Choi is a senior scientist at NASA Langley Research Center. After joining NASA Langley in 1980, Dr. Choi has accumulated his experiences in plasma devices, lasers, microwave, and materials technology, and also pioneered smart optics, bionanobattery, quantum apertures, new bandgap engineering, etc. He received numerous Superior Accomplishment Awards at NASA. He won Nano50 Awards in 2006 and 2007. In 2008, he won a Nano50 Award in "Innovator" category. His team won 2009 R&D100 Award and 2010 SOLAR Metrology/Test Inline Solution Award. He published 169 papers. He has 89 inventions, 18 patents, and 16 patents pending. He gave total 11 plenary or keynote talks. He gave 63 invited talks and has 17 news media captures.

Mr. Richard S. Pappa has 32 years of experience at NASA Langley as both a research engineer and as a structural engineering loads and stress analyst. He is the author of over 120 papers in many areas including structural dynamics, launch vehicle loads analysis, innovative structural test methods, modal and system identification techniques, photogrammetry, and space flight experiments. In his NASA career, Mr. Pappa has worked primarily in the field of structural dynamics and has broad knowledge of structural dynamics as well as the related technologies of vibro-acoustics, quasi-static & coupled loads, transient & frequency response analysis, stress analysis, fatigue, material properties, damping, nonlinear analysis, modal and system identification, and ground and flight tests.