A LASER-OPTICAL SYSTEM TO REMOVE LOW EARTH ORBIT SPACE DEBRIS

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Abstract. Collisions between existing Low Earth Orbit (LEO) debris are now a main source of new debris, threatening future use of LEO space. As solutions, flying up and interacting with each object is inefficient due to the energy cost of orbit plane changes, while debris removal systems using blocks of aerogel or gas-filled balloons are prohibitively expensive. Furthermore, these solutions to the debris problem address only large debris, but it is also imperative to remove 10-cm-class debris. In Laser-Orbital-Debris-Removal (LODR), a ground-based pulsed laser makes plasma jets on LEO debris objects, slowing them slightly, and causing them to re-enter the atmosphere and burn up. LODR takes advantage of recent advances in pulsed lasers, large mirrors, nonlinear optics and acquisition systems. LODR is the only solution that can address both large and small debris. International cooperation is essential for building and operating such a system. We also briefly discuss the orbiting laser debris removal alternative.

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1 MOTIVATION

Debris Events are increasingly frequent. Early this year, a piece of the Chinese Fengyun-C satellite collided with the Russian BLITS nanosat, rendering it inoperative. On October 16, 2012, a Russian "Breeze M" rocket spontaneously exploded in orbit, threatening the Space Station and other assets. In 2007, the Iridium/Kosmos collision and the Fengyun 1C anti-satellite test nearly doubled the LEO debris load, prompting concerns about the safety of the final Hubble servicing mission. The instability predicted by Kessler and Cour-Palais [1] has now reached the point where collisions are on track to become the most dominant debris-generating mechanism. While improved debris tracking and orbit prediction can temporarily improve threat avoidance via maneuvering [2,3], effective debris-clearing strategies will be necessary.

Four catalogued events have now occurred in which a debris collision terminated an active satellite. Thirty-five catalogued satellite breakups are of unknown cause, and many of these are surely due to collisions with untracked debris. However, the main urgency is to mitigate future risks. More than one hundred 1360-kg "Tsyklon" third stages with up to 300kg of residual propellant are still in LEO and MEO orbits, waiting to spontaneously explode, as they have five times. The most important ticking time bomb is ENVISAT. Based on [4], we estimate the cumulative probability of its debris-induced failure is 8%/decade. ENVISAT's catastrophic failure would jeopardize use of sun-sync orbits, and threaten the region below 766 km in the long term. It will require a decade to take action on the debris threat, at which time the problem will be much worse.

2 PROBLEM: BOTH LARGE AND SMALL DEBRIS

More attention has been given to re-entering the large debris, such as one-ton spent rocket bodies, than to re-entering the small ones, because that problem seems more amenable to aerospace vehicles. But the threat of large debris is less serious than that of 1 – 10 cm debris because the larger debris are much fewer, are tracked and can so far be avoided by maneuvering. Large debris do need to be removed, because they are a major source of additional debris when hit. But this is not enough. Small debris must also be removed: the chance that small debris will

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damage one of our valuable space assets is 45 times as high as the chance of large-object collisions because of their much greater number.

At typical closing velocities of 12 km/s, debris as small as 1 cm can punch a hole in the Space Station and a 100-gram bolt would be lethal if it hit the crew compartment.

3 PROPOSED SOLUTIONS

3.1 Physical Interaction

Solutions that have been proposed include chasing and grappling the object, attaching deorbiting kits, deploying nets, attaching an electrodynamic tether and deploying clouds of frozen mist, gas or blocks of aerogel in the debris path to slow the debris. Each of these can be shown to be problematic in implementation and cost [5]. For example, an aerogel “catcher’s mitt” solution designed to clear the debris in two years would require a slab 50 cm thick and 13 km on a side [6]. Such a slab would weigh 80-kilotons, and cost $1T to launch. A further problem is the steady 12 kN average thrust required to oppose orbital decay of the slab against ram pressure.

Few concepts have progressed to the point where accurate costs can be calculated, but Bonnal [7] estimated a cost of 27M$ per large object for attaching deorbiting kits. Any mechanical solution will involve a comparable Δv, so we take Bonnal’s estimate as representative of removal cost per large item with mechanical methods.

3.2 Laser-induced Removal

Laser-based methods can be divided into three general categories distinguished by their goals and laser beam parameters. At the lowest intensities, below the ablation threshold, lasers have been proposed to divert debris through light pressure [8]. Depending on duty cycles, this approach has laser momentum transfer efficiency as much as four to five orders of magnitude less than pulsed laser ablation. Furthermore, the proposed hardware arrangement will deliver at most a few times the intensity of the sun to the debris, and that only during a few minutes’ time while the debris passes above the laser site, rather than all day. Focused on diversion, this method does not effectively address the debris growth problem. At higher laser intensity, we can consider continuous (CW) laser ablation, but the slow heating and decay characteristic of CW thrust on tumbling debris will normally give an ablation jet whose average momentum contribution cancels itself. CW heating causes messy melt ejection rather than clean jet formation, possibly adding to the debris problem, and CW lasers cannot reach the required intensity for efficient coupling to targets at the ranges involved without a very small illumination spot size, requiring an unacceptably large mirror. This is why we have chosen pulsed lasers for the problem (Figure 1).

A NASA headquarters concept validation study [9] concluded that the idea of using pulsed lasers to remove essentially all dangerous orbital debris in the 1 – 10-cm range between 400 and 1100 km altitude within two years was feasible, and that its cost would be modest compared to that of shielding, repairing, or replacing high-value spacecraft that could otherwise be lost to debris.

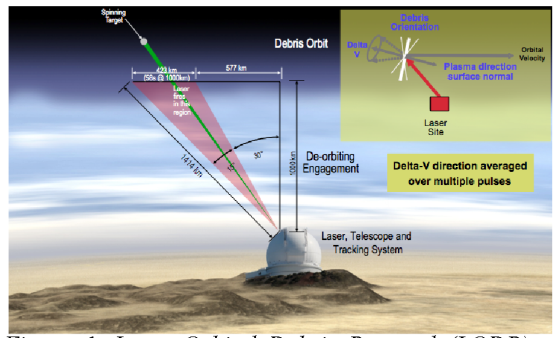

Figure 1. Laser Orbital Debris Removal (LODR). A focused, 1.06-µm, 5ns repetitively-pulsed laser beam makes a jet on the object, slowing it and lowering its perigee and cause it to re-enter the atmosphere. In cases of interest, pushing “up” on the object also lowers its perigee.

4 LASER ORBITAL DEBRIS REMOVAL

4.1 Theory

The figure of merit for this pulsed interaction is the mechanical coupling coefficient C_m,

$$C_m = p/I = p\tau/\Phi \text{ N/W} \quad (1)$$

where p is the ablation pressure on the surface by intensity I, τ is the laser pulse duration and Φ is the laser fluence (J/m^2) per pulse delivered to the debris surface. Typical C_m values are of order 1 – 10mN-s/J, so the effect of the momentum of light ($C_{mv} = 2/c = 6.7$ nN-s/J) is relatively ignorable.

As the intensity I increases, C_m rises to a maximum, then decreases, because more energy goes into reradiation, ionization, breaking chemical bonds, etc. It is important to be able to predict this maximum and its variation with wavelength λ, pulse duration τ and material properties. This maximum is approximately located at the vapor-plasma transition. An approximate relationship for the transition fluence Φ_{opt} for a range of metallic and nonmetallic materials is given by (see [10 – 12]):

$$\Phi_{opt} = 7.6\text{E}8\ \sqrt{\tau}\ \text{J/m}^2 \tag{2}$$

The spot diameter d_s of the beam which can be delivered to a target at range z is

$$d_s = aM^2\lambda z/D_{eff}. \tag{3}$$

where M^2 is the beam quality factor (≥1) and D_{eff} is the illuminated beam diameter inside the telescope aperture D for calculating diffraction. A hypergaussian with index 6 coming from a LODR system with corrected beam quality M^2=2.0 (Strehl ratio = 0.25) gives D_{eff}/D = 0.9 and a = 1.7.

The product WD_{eff}^2 required to deliver fluence Φ to the target is given by [5]

$$WD_{eff}^2 = \frac{\pi M^4 a^2 \lambda^2 z^2 \Phi}{4T_{eff}}. \tag{4}$$

where W is laser pulse energy incident on the target and T_{eff} is the product of all system transmission losses, including apodization, obscuration by internal optics and atmospheric transmission.

W is not arbitrary, but is bounded above by the fluence that excites nonlinear optical losses in the atmosphere while the beam is still close to the source. This limit is (primarily set by stimulated Raman scattering) [5, 13]

$$W/D^2_{eff} = 3\text{E}4\ \lambda\tau \tag{5}$$

for $\tau > 100$ ps. Combining all these relationships gives the interesting result that

$$W = 5.4\text{E}15\ aM^2\lambda^2 z\ \tau^{3/4}/T^{1/2}_{eff}, \tag{6}$$

Therefore, W increases less than linearly with pulse duration and linearly, (as against the simple expectation that it vary quadratically, with range).

4.2 Typical Case

With λ = 1.06 µm, z = 1000 km, T_{eff} = 0.5 and M^2 = 2.0, τ = 8 ns and a = 1.7, we find that W = 25 kJ and, from Eq. (5), D_{eff} = 10 m. These are typical numbers for the ground-based laser approach to ODR.

As a simple approximation to the precise laser-ablation induced orbit change calculations given in [5], we use an efficiency factor η_c for the combined effects of improper thrust direction on the target, target shape, tumbling, etc. in reducing the laser pulse efficiency in producing the desired velocity change,

$$\Delta v_{||} = \eta_c C_m \Phi/\mu. \tag{7}$$

In Eq. (7), μ is the target areal mass density (kg/m^2). This formulation takes account of laser beam "overspill" for small debris, without having to specify the actual size and mass of each target. We take η_c = 0.3 after Liedahl et. al. [14]. A detailed treatment of debris shape factors and their effect on coupling appears in [14] and [15].

In the typical case of LEO debris, $|\Delta v_o|$ = 150 m/s for re-entry, μ = 10 kg/m^2 for a small target [16] and C_m = 75 µN-s/J, and $\Delta v_{||}$ = 12 cm/s for each laser shot. C_m can range from 50 to 320 µN-s/J for various surface conditions of aluminum [17]. Taking target availability to be T=100 s during an overhead pass, repetition frequency for the 10.9 kJ laser pulse is $(\Delta v_o/\Delta v_{||})$/T = 12.5 Hz, giving a time-average laser power of 136 kW. If the target were as big as the beam focus, it would have 0.75 kg mass. Smaller targets of whatever mass with this mass density would also be re-entered in a single pass, even though the beam spills around them.

4.3 Pushing "Up" on Small Targets

In cases of interest, modeling has shown the counterintuitive result that pushing "up" on the debris (when it is near apogee) can lower its perigee, as well as pushing "back" against the direction of travel. This means that the useful range of target zenith angles for applying the laser beam can extend past the vertical (to +30° in Figure 2).

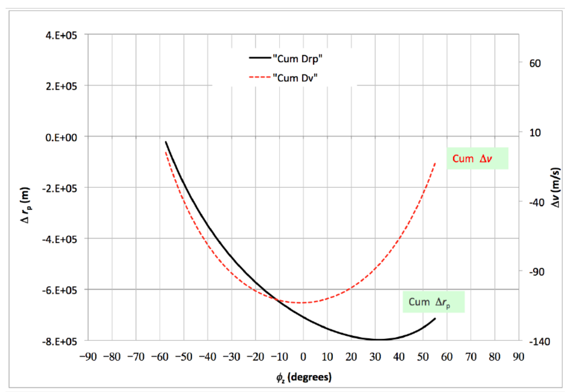

Figure 2. Perigee reduction and velocity change vs. zenith angle. Target re-entry is achieved in one pass for any target smaller than the 31-cm diameter laser spot at 1000 km range, with areal mass density 10 kg/m^2 or less. The largest target re-entered has 0.75 kg mass. System parameters: wavelength 1.06µm, 10.9 kJ pulse energy, repetition rate 14 Hz, average power 153 kW, pulse duration 5 ns, beam quality factor 2.0, mirror diameter 13 m, C_m = 75 µN-s/J, efficiency factor η_c = 30%, initial perigee altitude 1000 km, apogee altitude 1015 km, eccentricity 0.001, re-entry for Δr_p = – 8E5 m. Initial orbit perigee is -120 degrees geocentric (upstream) relative to laser site, 2010 pulses applied over 144 s to achieve minimum perigee.

4.4 Pulsed LODR Can Re-enter 1-ton objects

It has been claimed that lasers cannot de-orbit large, one-ton debris objects that are of concern. Indeed, single-pass re-entry of these objects is not economically practical. However, given many overhead passes, Table 1 shows calculated performance of a 5 Hz, 125 kJ, 1 μm laser re-entering a 1000 kg target in an orbit similar to ENVISAT's. Calculations are described in detail in [5]. A 4-minute interaction period combines with opportunities averaging once per ten days to give 3.7 years for re-entering each target. With less effort, lasers can be used to lower or raise orbits to avoid high risk regions without re-entry. Even for the 8 ton ENVISAT, a 20 month effort with the parameters listed in the lower half of each cell in Table 1 will lower its orbit 40km, reducing the risk of catastrophic destruction by a factor of four. The larger mirror is necessary to avoid nonlinear optical effects in the atmosphere. It is possible to address at least 100 different targets each day. Therefore, 2,000 such one-ton targets can also be re-entered in about four years.

4.5 Stabilizing the LEO Debris Environment

More importantly, it is only necessary to re-enter 15 of these large objects annually to *stabilize* the debris environment [16]. From this standpoint alone, the pulsed LODR system is a good investment.

Table 1. LODR System Parameters for Large Targets (Case A = re-entry/CaseB = 40km lowering)

Target Parameters		**Optical System Parameters**	
Mass [nonspecific target]/ ENVISAT (kg)	1,000/ 8,000	Wavelength λ (μm)	1.06
Perigee (km)	770	Pulse Length τ (ns)	8.0
Apogee (km)	770	Target Spot Size [deliberately defocused] (m)	1.25/ 1.33
Repeat Period [nonspecific orbit] / [ENVISAT] (days)	10/ 35	Pulse Energy (kJ)	125/ 140
Number of Interactions for Re-entry/ or 40km Lowering	68/ 19	Repetition Frequency (Hz)	5/ 10
Time to Re-enter one Target / or to Lower ENVISAT 40km (yrs)	3.7	Push Efficiency η_c	0.30
Primary Mirror Diameter (m)	25	Fluence on Target (kJ/m^2)	75
Average Interaction Duration (s)	250	Beam Quality Factor	2.0

4.6 Acquisition and Tracking

A crucial ingredient of LODR is an acquisition and tracking system capable of reducing the position uncertainty of a debris object from the present level to a value on the order of meters. In [5], we describe a system that can achieve this. For atmospheric turbulence correction, this system will probably use a combination of classic adaptive optics and Brillouin-enhanced Fourwave Mixing (BEFWM) [18], which can provide automatic compensation of atmospheric phase distortions.

4.7 Lasers and Large Optics

There is a lot of synergy between the system required for LODR and a laser driver for Laser Inertial Fusion Energy (LIFE) now being designed at Lawrence Livermore National Laboratory (LLNL) and with lasers being built at several European Laboratories. The high-repetition rate (10-20 Hz), high-efficiency (~12-18%) diode-pumped LIFE system will produce ~10 kJ in a single beam at 1053 nm [19]. The laser output has linear polarization, so it is easy to combine two beams into a 20 kJ per pulse laser system [20].

Techniques for making light-weight segmented mirrors have already produced the large, lightweight mirrors we require, and 39-m primaries are planned [21].

4.8 Cost

By applying an approximate cost model outlined in [5], we estimate cost per small debris object re-entered at a few k$, and that for large objects at about 1 M$ each, roughly 20 times less than the cost of using other techniques.

5 SYSTEM LOCATION

It is worth noting that a polar location, for example, at the Alert Station, Nunavut, Canada, 817 km (8°) from the North Pole would be ideal for increasing the interaction frequency for polar-orbiting, multi-ton debris. A majority of these types of orbits lie within 8° of the pole. The concentration factor for the overhead areal density of observed debris objects would be 8 times that for an equatorial location, and would lead to a proportional decrease in re-entry time. Wind speeds at Alert rarely exceed 25m/s.

6 SPACEBASED ALTERNATIVE SYSTEM

In 1991, Schall proposed a space based pulsed laser debris removal system based on the same principles as LODR [22]. There are distinct advantages. Because the station is physically sweeping out space at 7 km/s, the laser range required to attain the same target interaction rate as LODR is much smaller, perhaps only 100km. Over time, the station in an eccentric equatorial orbit can access all debris orbits. Also, the interaction geometry and target access are much more favorable. However, in contrast with LODR, the cost of this approach has never been studied. Even a much smaller system may cost more because of the current 10 k$/kg cost of placing mass in LEO [23].

7 INTERNATIONAL COOPERATION

The most salient argument against LODR is not technical, but political. Building and operating a LODR system will require international cooperation to avoid concerns that it is actually a weapon system. Also, cooperation in its operation will be needed to get permission for its use to remove specific debris objects.

8 CONCLUSIONS

We have shown that ground based, pulsed Laser Orbital Debris Removal (LODR) is a more effective alternative than other techniques. It can handle tumbling objects, difficult for mechanical systems. It is the only approach that can deal with both small and large debris objects, and it will work on multi-ton objects. We believe it is less costly per object removed. A space based laser alternative deserves further study.

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