

# What's New for Laser Orbital Debris Removal

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**Abstract.** Orbital debris in low Earth orbit (LEO) are now sufficiently dense that the use of space is threatened by runaway collision cascading. A problem predicted more than thirty years ago, the threat from debris larger than about 1cm is now a reality that we ignore at our peril. The least costly, and most comprehensive, solution is Laser Orbital Debris Removal (LODR). In this approach, a high power pulsed laser on the Earth creates a laser-ablation jet on the debris object's surface which provides the small impulse required to cause it to re-enter and burn up in the atmosphere. The LODR system should be located near the Equator, and includes the laser, a large, agile mirror, and systems for active detection, tracking and atmospheric path correction. In this paper, we discuss advances that have occurred since LODR was first proposed, which make this solution to the debris problem look quite realistic.

**Keywords:** Diode-pumped Solid State Lasers, Space Debris, Orbital Debris Removal, Laser-plasma Interactions

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## INTRODUCTION: LEO DEBRIS

Fifty years of poor housekeeping in space have created several hundred thousand pieces of space debris larger than 1cm in the 400 – 2000 km altitude band called low Earth orbit (LEO), their density reaching a peak in the 800 - 1,000 km altitude range [1]. Debris in the 1 - 10-cm size range are most hazardous to LEO space vehicles because they are not tracked, but can cause fatal damage. The most probable closing velocity between objects is on the order of 12km/s [2]. At this speed, a piece of debris has ten times the energy density of dynamite, and a few-gram object (like a penny) would likely cause a lethal event on the International Space Station.

The threat is less from larger objects, because they are less numerous, can be tracked and can often be avoided by maneuvering. Even so, in March, 2009, it was necessary for Space Station astronauts to take cover in a docked Soyuz capsule.

The first thing that is new in the space debris problem is that the Kessler & Cour-Palais instability predicted in 1978 [3] is now a reality, collisions among existing debris having become a major source of additional debris [4].

## CLEARANCE STRATEGY

There are about  $N_1 = 2.2E3$  very large objects (diameter  $> 100$ cm, mass of order 1 ton) in low Earth orbit, and  $N_2 = 1.9E5$  small objects (diameter  $> 1$ cm) [5]. The flux for the small ones in the peak density region is about  $R_2 = 1.4E-4 \text{ m}^{-2}\text{year}^{-1}$ . Based on

the relative numbers, one can deduce a flux  $R_1 = 1.6\text{E-}6 \text{ m}^{-2}\text{year}^{-1}$  for the large ones in the LEO band. Taking a  $\sigma = 1\text{m}^2$  cross-section for the large objects, the interval between collisions of type  $i$  on the large ones across the ensemble is

$$T_{i1} = [\sigma N_1 R_i]^{-1} \quad (1)$$

Applying Eq. (1), the chance that a big object will destroy a big object is once in  $T_{11} = 280$  years, whereas the chance a small object will destroy a big object is once in  $T_{21} = 3.2$  years. Just removing the big objects doesn't solve the problem. Any large space asset that is installed in LEO will encounter the same fatal collision rate  $R_{21}$  as before, from the small objects that have not been removed. Lifetime for these small objects at 1000km altitude is of order 100 years [6]. This is why a system that can address small as well as large LEO debris is important. It is also true that the debris growth rate is reduced by removing the big derelict objects which are the source of clouds of debris when hit [7]. However, the main point is that the small debris can turn useful assets, which we do not want to re-enter, into clouds of debris at their present density.

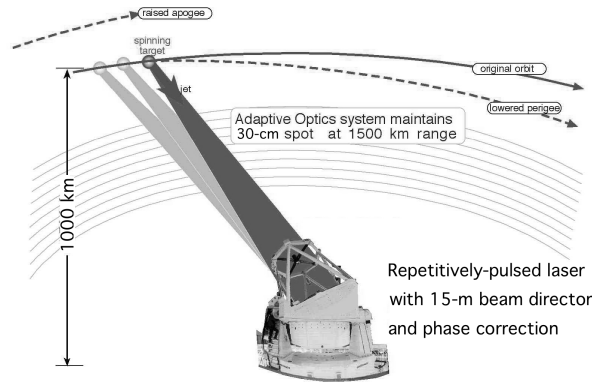
## PROPOSED SOLUTIONS

Solutions to the orbital debris problem which have been proposed include chasing and grappling the object or deploying a net to capture it, attaching deorbiting kits such as electrodynamics tethers, and deploying clouds of frozen mist, gas or blocks of aerogel in the debris path. Each of these solutions has its own difficulty. For example, it has been shown that an aerogel "catcher's mitt" able to clear the debris in two years would be a slab 13 km on a side and 50cm thick [8]. Such a slab would have 80 ktonne mass, and would cost \$800M to launch. More problematic is the steady 12kN average thrust required to oppose orbital decay of the slab over an elliptical orbit ranging between 400km and 1100km altitude. To maintain altitude against ram pressure over a two-year operating lifetime would require 150ktonnes fuel, nearly tripling the cost. Few of these concepts have progressed to the point where costs can be discussed, but Bonnal has estimated 27M\$ per large object re-entered via a de-orbiting kit [9], and we take this cost as representative of the cost of flying to and retrieving an individual, large debris object.

Using a laser combined with a large telescope on the ground was proposed fifteen years ago [2] as a solution to orbital debris removal. At that time, lasers and telescopes with the required performance did not yet exist, although it was understood how to build them. As recently as four years ago, it was considered that "The use of ground based lasers to perturb the orbits of the satellites is not now practical because of the considerable mass of the satellites and the consequent need to deposit extremely high amounts of energy on the vehicles to affect the necessary change." [4]. This statement is now outdated as a result of our better understanding of laser-induced orbit modification, and of advances in laser and mirror technology. The purpose of this article is to show that laser orbital debris removal is now the most practical and economical solution to the debris problem. Calculations we will present support this.

## THE LODR CONCEPT

Figure 1 shows the concept for laser orbital debris removal (LODR). A repetitively-pulsed laser is focused by a 15-m diameter mirror augmented by adaptive optics on the distant target, making a 30-cm diameter spot. During one or more periods of target availability, multiple laser pulses slow the target by 150 - 200m/s, causing its perigee altitude to drop to 200km, sufficient for rapid re-entry.



**FIGURE 1.** Laser ODR concept. This figure is used with permission of the copyright holder, Photonic Associates, LLC

## THEORETICAL MODELS FOR MOMENTUM COUPLING

The mechanical coupling coefficient  $C_m$  gives the efficiency with which laser energy  $W$  is converted to impulse  $J$  by laser ablation of a target surface. For pulsed lasers, typical  $C_m$  values are of order  $1\text{E-}5 - 1\text{E-}4 \text{ N-s/J}$ . The portion due to light pressure ( $C_{hp} = 2/c = 6.7\text{E-}9 \text{ N-s/J}$ ) is smaller by orders of magnitude and ignorable.  $C_m$  is a function of  $I$ , the laser pulse intensity on target, wavelength  $\lambda$  and laser pulse duration  $\tau$  for a given target material in vacuum. As  $I$  is increased, ablation begins in the vapor regime and progresses to the fully-formed plasma regime, causing  $C_m$  to rise to a maximum and then decrease as more energy goes into the plasma jet. The  $C_m$  maximum occurs just as plasma forms, not in the vapor regime. This is why pulsed lasers are needed for this problem. A continuous (CW) laser could not reach the necessary intensity on target at such large range without a very small illumination spot size, which would require an unacceptably large mirror to produce. Using the light pressure from CW lasers to alter orbits (which has been proposed [10]) would only double the natural perturbation from sunlight, which delivers a similar intensity to the debris.

It is important to be able to predict at what fluence the  $C_m$  maximum is found. This requires knowing how to combine vapor and plasma models and determine where the rollover between them occurs. A new result is our development of models that permit this (Figure 2) [11]. For 10ns pulse duration, this optimum fluence is about  $7.5 \text{ J/cm}^2$ .

Advantages of pulsed laser ODR include redundant, agile, speed-of-light access; the ability to handle tumbling objects (which grappling techniques cannot) and the fact

that new debris created are microscopic since only few monolayer's of target surface are removed each shot. The system also has serendipitous applications such as divert-to-protect and controlling the point of entry of a decaying object.

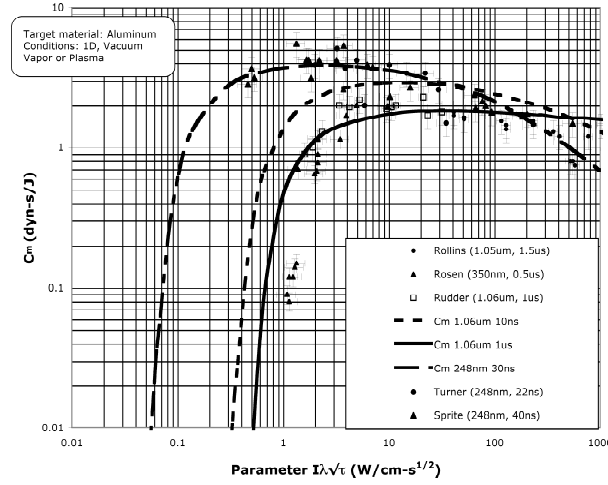


FIGURE 2. Results of the Combined Model for Aluminum at Nd Laser Wavelengths.

## ORBIT MODIFICATION

In an orbit of eccentricity  $e$  described by

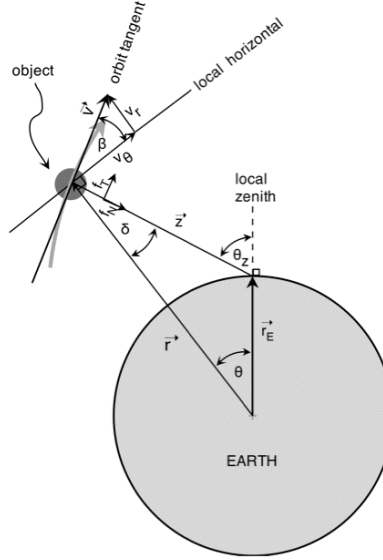
$$r(\theta) = \left[ \frac{r_p(1+e)}{1+e\cos\theta} \right], \quad (2)$$

defining  $q = l^2/MG$ , with  $l$  the angular momentum per unit mass and  $MG$  is the earth's gravitational constant, we can vary  $q$  according to

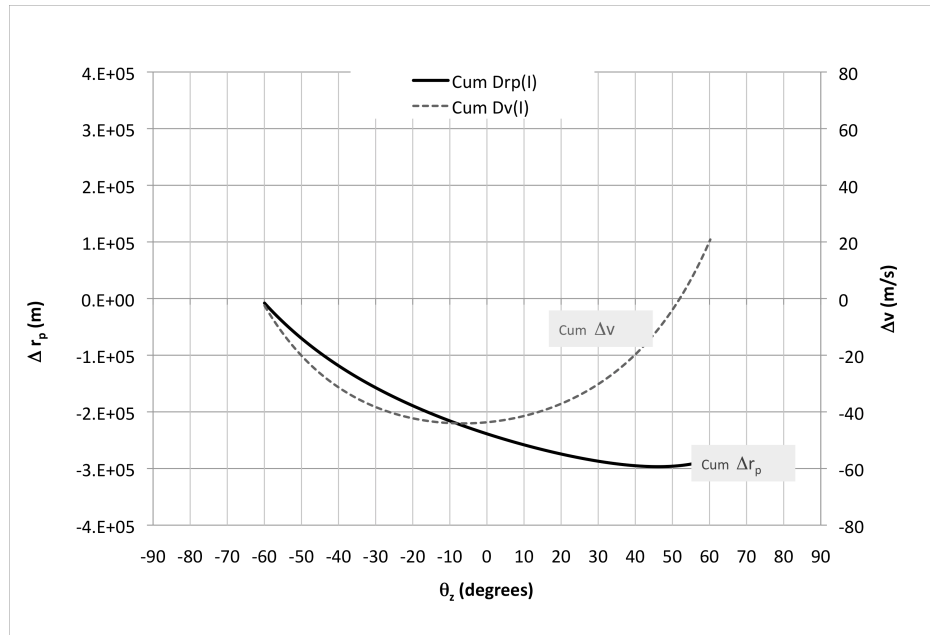
$$\Delta q = \frac{2r}{v} [\Delta J_T(1+e\cos\theta) + \Delta J_N e \sin\theta] \quad (3)$$

In Eq. (3),  $\Delta J_T$  and  $\Delta J_N$  are, respectively, the components of the laser-induced impulse  $\Delta J$  along the orbit tangent, and along the inward normal to the orbit in the orbital plane and  $\theta$  is the geocentric angular coordinate of the orbit. The parameter  $\Delta q$  is directly related to changes in the orbit that cause re-entry. Eq. (3) makes the counterintuitive point that  $\Delta J_N$  also has an effect on the orbit, not  $\Delta J_T$  alone. Figure 3 shows the geometry.  $\Delta J_N$  has no effect in the case where perigee or apogee are at zenith.

A new result is that, in the many cases where perigee or apogee are not directly overhead, we can drop perigee dramatically by pushing directly upward on the object, as well as by pushing against its direction of travel. In fact, the range of zenith angles for which laser action is productive for re-entry can extend from -60 to +45 degrees zenith angle in some cases we have studied. Figure 5 shows an example of one-pass re-entry for a 0.75kg target with orbit eccentricity  $e = 0.04$  and apogee at -90 degrees geocentric relative to the laser site, using a 25kW average power  $1\mu\text{m}$  laser.



**FIGURE 4.** Geometry for orbit modification



**FIGURE 5.** Re-entry produced by 2,200 laser pulses over 245 seconds. Parameters:  $\lambda = 1.06 \mu\text{m}$ , beam quality factor 2.0, beam format hypergaussian with index 6,  $\Phi = 75 \text{ kJ/m}^2$ , 15kJ pulse energy, repetition rate 7.5 Hz, telescope mirror diameter 20 m,  $C_m = 75 \mu\text{N-s/J}$ ,  $\eta_c = 35\%$ , perigee altitude 500km, apogee altitude 1073 km,  $e = 0.04$ , re-entry for  $\Delta r_p = -3\text{E}5\text{m}$ . Orbit apogee is -90 degrees geocentric (upstream) relative to laser site.

## LASER AND OPTICAL SYSTEM DESIGN

The LODR system must simultaneously satisfy constraints caused by diffraction, nonlinear optical effects in the atmosphere and achieving the optimum fluence on the target. Thanks to our new  $C_m$  models, this can now be done on a simple spreadsheet

that implements the procedure in [6]. The main problem to be solved is to launch the beam with large enough cross-section in the atmosphere to avoid nonlinear optical effects, while focusing it to a small enough spot to produce optimum fluence on target.

## SYSTEM COST

For rough estimates of system cost, we use a model similar to that described in reference [6], modified to match modern mirror costs and adjusted for inflation to the year 2010. The model predicts the cost of the National Ignition Facility (NIF) laser fairly well. Rough cost is an important technical input because repeated use of the spreadsheet shows it optimizes sharply at a particular telescope mirror diameter for any particular problem. For most of our cases, this occurs in the 15 – 20 m diameter range [Figure 6]. The most important parameter in the Figure is the target visibility interval, because we are requiring re-entry in one pass for this small-target case. Cost minimizes sharply between two extremes: on the left, a very large laser and small mirror; on the right, the opposite.

New, lightweight construction techniques for mirrors give a mass of 3-4 kg/m<sup>2</sup> for mirror segments of 1.5 m size. Total cost for the 10x11m South African Large Telescope (SALT) with 989 mirror segments was about 50 M\$ [12].

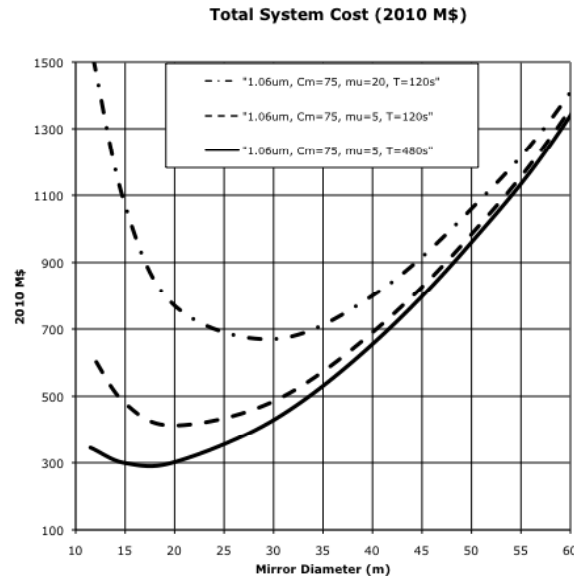


FIGURE 6. Rough system cost vs. mirror diameter for targets <22cm diameter, 1-pass re-entry

## TARGET DETECTION AND TRACKING

Target acquisition and tracking is based on a three-step sequence. First, a wide field-of-view (FOV), sun-illuminated survey instrument establishes the rough ephemeris. Even a 67 km diameter array FOV at 1000km range (a 1Mpixel array) will acquire 20 objects per minute, far more than we need. Second, a narrow FOV precision active tracking instrument using range-gating, parallel processing, narrowband filtering and illumination from the ground establishes and maintains the

position to within 1 m accuracy. Telescopes with the required  $\frac{1}{4}$  arc-sec precision already exist, and it is anticipated to be an ideal application for the Maui Space Surveillance System's coherent 11 $\mu$ m LIDAR called HICLASS, which was shown to be able to detect the smallest LODR targets at 1000km [13].

## ADVANCES IN HIGH AVERAGE POWER PULSED LASERS

Several international efforts are underway now to build a diode-pumped, repetitive solid state laser with capabilities equal to what is required by LODR (Table 1) [14-16].

**TABLE 1.** Planned high average power pulsed lasers

| Laser           | Country | Pulse Energy (kJ) | Pulse width (ns) | Avg. Power (kW) | Rep Rate (Hz) | Status   |
|-----------------|---------|-------------------|------------------|-----------------|---------------|----------|
| DIPOLE [14]     | UK      | 10                | 10               | 100             | 10            | Proposed |
| HiPER demo [15] | EU      | 250               | 5                | 250             | 1             | Proposed |
| HALNA [16]      | JAPAN   | 10                | 10               | 100             | 10            | 2012-15  |
| TERRA [16]      | US      | 36                | 10               | 360             | 10            | Proposed |
| LODR            | US      | 70                | 10               | 100             | 1.4           | Proposed |

## RESULTS

The LODR system for small orbital debris object removal is designed to re-enter the 300k objects 1 – 20 cm in size below 1500 km altitude in two years. These objects can be re-entered in one pass, so they do not have to be tracked after the interaction. The costs in Figure 6 are for this option, and give a cost per object re-entered of \$330. A 28 m diameter telescope is required. We assumed  $C_m = 75 \mu\text{N/W}$ , and pulsed laser fluence on the target  $\Phi = 7.5 \text{ J/cm}^2$ .

**TABLE 2.** System for small object removal

| Wavelength<br>$\lambda$ ( $\mu\text{m}$ ) | Pulse Length<br>$\tau$ (ns) | Pulse Energy<br>(kJ) | Pulse Frequency<br>$f$ (Hz) | Avg. Power<br>(kW) | Spot size<br>(cm) | Range<br>(km) |
|-------------------------------------------|-----------------------------|----------------------|-----------------------------|--------------------|-------------------|---------------|
| 1.06                                      | 10                          | 2.7                  | 8.7                         | 30                 | 22                | 1500          |

A LODR system for large orbital debris object removal is designed to re-enter 2k objects with total mass 3 ktons in 5 years. These cannot be re-entered in one pass and do need to be tracked after the interaction, as they already are. A 25 m diameter telescope is required. Assumed  $C_m = 75 \mu\text{N/W}$ , and pulsed laser fluence on the target is  $7.5 \text{ J/cm}^2$ . This system would cost more than indicated in Figure 6, probably 1.5B\$. Cost per object removed is \$500k, considerably less than so far offered by other published proposals. For comparison, the insurance costs for satellites worldwide is \$850M [17].

**TABLE 3.** System for large object removal

| Wavelength<br>$\lambda$ ( $\mu\text{m}$ ) | Pulse Length<br>$\tau$ (ns) | Pulse Energy<br>(kJ) | Pulse Frequency<br>$f$ (Hz) | Avg. Power<br>(kW) | Spot size<br>(cm) | Range<br>(km) |
|-------------------------------------------|-----------------------------|----------------------|-----------------------------|--------------------|-------------------|---------------|
| 1.06                                      | 10                          | 93                   | 3.0                         | 350                | 125               | 1500          |

Laser Orbital Debris Removal has been shown to have good potential. Estimated costs per object removed are the lowest of any technology. Laser ODR is an opportunity for international cooperation, which is essential to avoid severe problems arising from suspicions about the intent of the system and property damage issues (Russia and the U.S. are together responsible for 83% of the large objects to be removed). It is also essential to facilitate approval for day-to-day operations.

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