This is a reprint of an article which appears in AIP Conference Proceedings **1464** (2012) available from the American Institute of Physics. It is **NOT** a reprint of C. R. Phipps, K. L. Baker, S. B. Libby, D. A. Liedahl, S. S. Olivier, L. D. Pleasance, A. Rubenchik, J. E. Trebes, E. V. George, B. Marcovici, J. P. Reilly and M. T. Valley, "Removing orbital debris with lasers," Advances in Space Research, **49**, 1283-1300 (2012), which has much greater detail about the system design.

Removing Orbital Debris with Pulsed Lasers

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Abstract. Orbital debris in low Earth orbit (LEO) are now sufficiently dense that the use of LEO space is threatened by runaway collisional cascading. A problem predicted more than thirty years ago, the threat from debris larger than about 1cm demands serious attention. A promising proposed solution uses a high power pulsed laser system on the Earth to make plasma jets on the objects, slowing them slightly, and causing them to re-enter and burn up in the atmosphere. In this paper, we reassess this approach in light of recent advances in low-cost, light-weight segmented design for large mirrors, calculations of laser-induced orbit changes and in design of repetitive, multi-kilojoule lasers, that build on inertial fusion research. These advances now suggest that laser orbital debris removal (LODR) is the most cost-effective way to mitigate the debris problem. No other solutions have been proposed that address the whole problem of large and small debris. A LODR system will have multiple uses beyond debris removal. International cooperation will be essential for building and operating such a system.

Keywords: space debris, laser materials interaction, impulse coupling, adaptive optics; segmented mirror design; phase conjugation

PACS: 79.20.Eb, 42.60.-v, 41.75.Jv, 52.38.-r, 95.55.-n

MOTIVATION FOR LASER ORBITAL DEBRIS REMOVAL

Thirty-five years of poor practice in space launches, plus deliberate as well as accidental spacecraft collisions, have created several hundred thousand space debris larger than 1cm in the 400 -2000-km altitude low Earth orbit (LEO) band, their density reaching a peak in the 800-1,000-km altitude range. Mutual spacecraft

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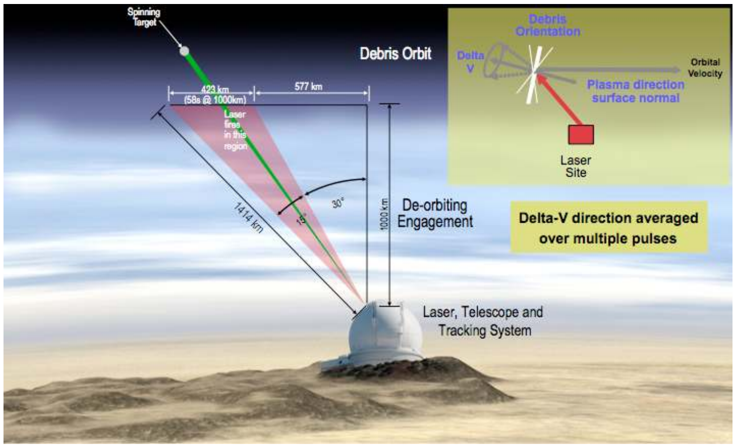

Figure 1. Artist's concept of laser orbital debris removal. A focused, 1.06-μm, 5ns repetitively-pulsed laser beam makes a jet on the object so oriented as to lower its perigee and cause it to re-enter the atmosphere.

collisions are on track to become the dominant source of debris [1]. This runaway collisional cascading, predicted more than thirty years ago [2], threatens the use of LEO space. At typical closing velocities of 12km/s, debris as small as 1cm can punch a hole in the Space Station and a 100-gram bolt would be lethal if it hit the crewcompartment. More attention has been given to re-entering the large debris [3], such as one-ton spent rocket bodies, than to re-entering the small ones, because that problem seems more manageable. But the threat of large debris is less serious than that of 1 – 10cm debris because the larger objects are much fewer, are tracked and can 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 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.

In this paper, we update our earlier proposal [4,5] that laser orbital debris removal (LODR) [Figure 1[1]] is the only way to address both debris classes. LODR uses the impulse generated by laser ablation of the debris surface by a focused, pulsed ground based laser to change the debris orbit and cause it to re-enter the atmosphere. Even with the telescope, the beam spills over small targets, but it is still effective, slowing small debris 10 cm/s for each pulse. Only a few nm of surface are vaporized and the object is not melted or fragmented by the gentle ablation pulse. At a pulse rate of 10 Hz and average power 75kW, the laser can re-enter targets up to 10 cm diameter in a single pass, because the slowing required is only ~100m/s.

New information in this update concerns the urgency of the debris problem, advances in development of pulsed lasers and large lightweight mirrors capable of matching our requirements and improved understanding of the laser-orbit interaction.

A NASA headquarters concept validation study [5] concluded that the capability to use 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.

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OTHER PROPOSED SOLUTIONS

Solutions other than laser-based approaches have been proposed. These have included chasing and grappling the object, attaching deorbiting kits, deploying nets to capture objects, attaching an electrodynamic tether and deploying clouds of frozen mist, gas or blocks of aerogel in the debris path to slow the debris [3]. Each of these can be shown to have severe problems in implementation and cost [6]. For example, an aerogel "catcher's mitt" solution designed to clear the debris in two years would require a slab 50cm thick and 13 km on a side [7]. Such a slab would have 80-kiloton mass, and would cost $1T to launch. A further problem is the steady 12kN average thrust required to oppose orbital decay of the slab against ram pressure.

Few concepts have progressed to the point where costs can be calculated, but Bonnal [8] has 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.

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 [9]. This approach has laser momentum transfer efficiency four to five orders of magnitude less than pulsed laser ablation. Its effects are comparable to the uncertain effects of sunlight and space weather, and do not effectively address the debris growth problem. At higher laser intensity, we can consider continuous (CW) laser ablation, but slow heating and decay of CW thrust on tumbling debris will usually give an ablation jet whose average momentum contribution cancels itself. CW heating causes messy melt ejection rather than clean jet formation, adding to the debris problem, and CW lasers cannot reach the required intensity on target 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.

APPROXIMATE LASER AND MIRROR REQUIREMENTS

When a laser pulse is incident on a target in vacuum, mechanical impulse is produced by the pressure of photoablation at the target surface. The figure of merit for this interaction is the mechanical coupling coefficient C_m,

$$C_m = p/I = p\tau/\Phi \text{ N/W} \tag{1}$$

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) delivered to the debris surface. Typical C_m values are of order 1 – 10μN-s/J, so the effect of the momentum of light ($C_{h\nu} = 2/c$ = 6.7nN-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 working relationship for the transition fluence is given by [10 – 12]:

$$\Phi_{opt} = 4.8E8 \sqrt{\tau}\ J/m^2 \tag{2}$$

For 5ns pulses, precise calculations show Φ_{opt} = 53 kJ/m^2 required for an aluminum target [12], nearly a worst-case target material.

Large mirrors are required to overcome diffraction spreading of the light at a range of 1000km. The spot size d_s which can be delivered to a target at range z is

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

In Eq. (3), 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 [13] 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.

Denoting the product of all transmission losses, including apodization, obscuration by internal optics and atmospheric transmission loss by T_{eff}, and laser pulse energy by W, Eq. (3) shows that the product WD_{eff}^2 is given by

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

In a practical case where D_{eff} = 10m and T_{eff} = 0.5, to deliver 53 kJ/m^2 to a target at 1000km range, $WD_{eff}{}^2$ must be at least 993 kJm², laser pulse energy must be 7.3kJ, and if D_{eff}/D = 0.9, the mirror diameter D must be 13m. If λ=1.06μm and τ = 5ns, avoidance of nonlinear effects in the earth's atmosphere also sets a minimum D_{eff} = 11m. The 13m mirror would give a beam spot size d_s = 31 cm at 1000km range. Lightweight mirrors of this size are now realistic [14]. Examples are the 10-m Keck primary, the 9.8 x 11.1-m South African Large Telescope [15], and the planned 39m European Extremely Large Telescope with a primary mirror composed of 984 segments at very low areal mass density. The quantity M^2 in Eqs. (3) and (4) includes the effects of imperfect atmospheric phase distortion correction, using standard adaptive optics or phase conjugation or a combination of the two (discussed below).

To estimate laser parameters for debris re-entry, 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,

$$\Delta v_{||} = \eta_c C_m \Phi/\mu. \tag{5}$$

In Eq. (5), 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 [16].

If $|\Delta v_o|$ = 150m/s for re-entry, μ = 10kg/m^2 for a small target [1] and C_m = 75μN-s/J, then $\Delta v_{||}$ = 12cm/s for each laser shot. C_m can range from 50 to 320 μN-s/J just for various surface conditions of aluminum [17]. Taking target availability to be T=100s, repetition frequency for the 7.3 kJ laser pulse is $(\Delta v_o/\Delta v_{||})/T$ = 12.5Hz, giving a time-average laser power of 91kW. If the target were as big as the beam focus, it would have 0.75kg 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.

PRECISE LASER- ORBIT CHANGE CALCULATIONS

Figure 2[1] shows shows the geometrical variables for analyzing laser orbit modification. Where the zenith angle $\phi_z = \phi - \delta$, $\delta = -\sin^{-1}(r_E \sin\phi / z)$, and $\beta = \tan^{-1}(v_r / v_\phi)$, range to the target is obtained from

$$z^2 = r^2 + r_E^2 - 2\, r\, r_E \cos\phi. \tag{6}$$

Using the relationships:

$\bar{i}_N \bullet \bar{i}_z = -\cos(\beta - \delta) = -\cos\xi$ and $\bar{i}_T \bullet \bar{i}_z = -\sin(\beta - \delta) = \sin\xi$, and with the Hamiltonian $(E + V)$ expressed in unit mass variables, we have

$$E = \frac{(v_r^2 + v_\theta^2)}{2} \text{ and} \tag{7}$$

$$V = -\, GM/r. \tag{8}$$

The eccentricity

$$e = \frac{r_a - r_p}{r_a + r_p}, \tag{9}$$

where r_a and r_p are the apogee and perigee orbit radii. In the plane of motion, the orbit is described by

$$r(\phi) = [\frac{r_p(1+e)}{1 + e\cos(\phi + \phi_o)}] \tag{10}$$

a definition which means perigee is at $\phi = \phi_o$. Where r_p is the perigee geocentric radius, and the semi-major axis $a = r_p/(1-e)$, ℓ is the angular momentum per unit mass, MG is the Earth's gravitational constant and the quantity

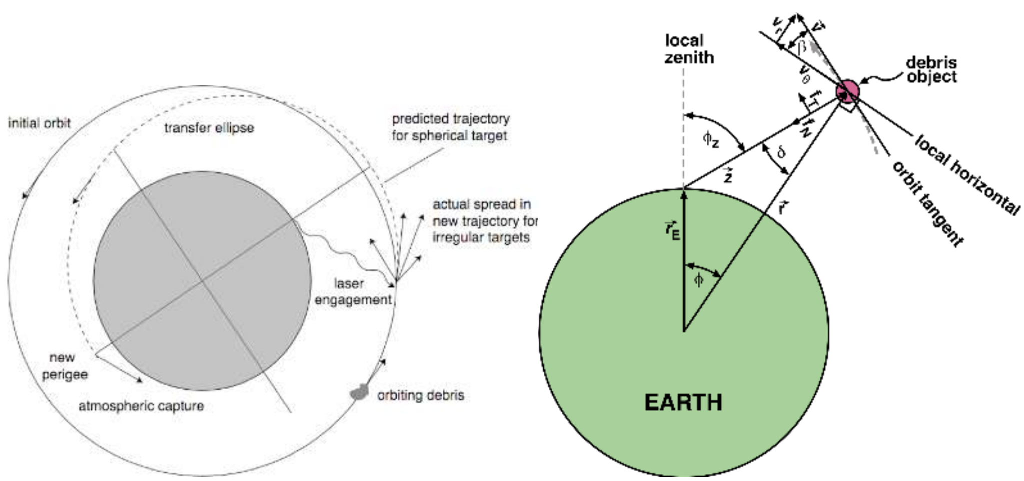

Figure 2. Geometry of the laser-target interaction
a: Schematic of debris de-orbiting concept in low-Earth orbit. For a given energy deposition, the orbital perturbation on a spherical target is predictable. For non-spherical targets, the perturbation can be predicted, if the shape and orientation at engagement are known.
b: Thrust on a debris object is resolved into components f_T and f_N normal to and along the orbit tangent. Since, for LEO debris, range $z \ll$ the Earth's radius r_E, the zenith angle ϕ_z changes rapidly compared to the geocentric angle ϕ.

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$$q = a(1\text{-}e^2) = \ell^2/\text{MG}, \quad (11)$$

the tangential and radial velocity components are

$$v_\phi = \sqrt{\frac{MG}{q}}[1 + e\cos(\phi + \phi_o)] \quad \text{and} \quad (12)$$

$$v_r = \sqrt{\frac{MG}{q}}[e\sin(\phi + \phi_o)]. \quad (13)$$

The total velocity is obtained from $v^2 = v_r^2 + v_\phi^2 = MG(\frac{2}{r} - \frac{1}{a})$. (14)

For externally perturbed orbits, we have

$$\Delta a = \frac{GM}{2H^2}\Delta H, \quad (15)$$

and

$$\Delta v_r = -\Delta J_N = +\Delta J\cos\xi \quad (16)$$

$$\Delta v_\theta = +\Delta J_T = +\Delta J\sin\xi \quad (17)$$

where ξ=β-δ. Also, $\Delta q = 2r\sqrt{p/MG}[\Delta J_T\cos\beta + \Delta J_N\sin\beta]$, (18)

or, in a more useful form, $\Delta q = \frac{2r}{v}[\Delta J_T(1 + e\cos(\phi + \phi_o)) + \Delta J_N e\sin(\phi + \phi_o)]$ (19)

In Eq. (19), ΔJ_T and ΔJ_N are, respectively, the components of $\Delta\bar{J}$ along the orbit tangent, and along the inward normal to the orbit in the orbital plane. This equation makes the point that pushing up on the debris [ΔJ_N] has a major effect on the orbit, not only pushing in the slowing direction [ΔJ_T] as one might intuitively think. When $(\phi+\phi_o) = 0$ [perigee at zenith], Eq. (19) shows ΔJ_N has no effect. This makes sense because $\Delta H = v_r\Delta v_r + v_\theta\Delta v_\theta$ and $v_r=0$ at perigee. The effect of pushing directly upward is to instantaneously tilt the velocity vector upward, so that the orbit can change later.

Now,

$$\Delta H = v_r\Delta v_r + v_\phi\Delta v_\phi, \quad (20)$$

$$\Delta v'^2 = v'^2 - v^2 = 2\Delta H, \quad (21)$$

But, since $\Delta q = (1 - e^2)\Delta a - 2ae\Delta e$, we can write (22)

giving

$$\Delta e = \frac{[(1 - e^2)\Delta a - \Delta q]}{2ae} \quad (23)$$

From which,

$$\Delta r_p=(1-e)\Delta a-a\Delta e \quad (24)$$

and

$$\Delta r_a=(1+e)\Delta a+a\Delta e \quad (25)$$

If e=0, Eq. (23) gives correct results in the limit $e \to 0$.

To apply these relationships, one substitutes ΔJ from Eq. (5) into Eqs. (16) and (17) to obtain the radial and azimuthal components of the laser-induced target velocity change, and the parameter Δq using Eq. (19). Substitute the velocity increments into Eq. (20) to get ΔH, and use this to get Δa in Eq. (15). Now we can compute Δe from Eq. (23) and, using that, Δr_p and Δr_a from Eqs. (24) and (25). This procedure is developed from first principles, and is free of approximations.

For small debris, which can be re-entered in a single pass, apsidal shift during the re-entry is irrelevant. For large debris, it must be taken into account when the object is re-engaged. The preceding analysis allows us to calculate total perigee reduction [Figure 3[1]], and conclude that objects up to 1kg can be re-entered in one pass by a system consisting of a 13m mirror and 80kW average power laser [11Hz, 7kJ].

OPTICAL CONSTRAINTS FROM ATMOSPHERE

We must simultaneously satisfy constraints that arise from diffraction, nonlinear optical effects in the atmosphere and target physics. Beam fluence in the atmosphere is constrained above and below. Using the symbol

$$\zeta = \frac{az\sqrt{\lambda}}{D_{eff}^2} \tag{26}$$

to represent the effects of diffraction, a lower limit for fluence in the atmosphere

$$\frac{\Phi_b}{\lambda} \geq \frac{\beta\zeta^2\sqrt{\tau}}{T} \tag{27}$$

is required to ignite a plasma on the target. With our earlier assumptions, a typical value of ζ is 75. In Eq. (27), T is atmospheric transmission, which we take to be 85%.

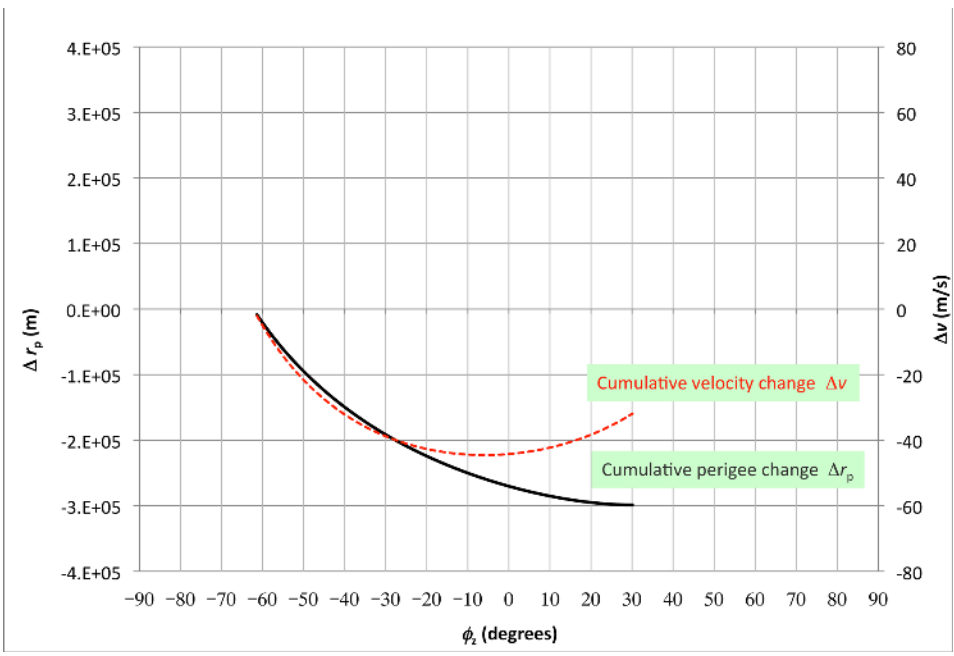

Figure 3. Target re-entry is achieved in one pass for <u>any</u> target smaller than the 31-cm diameter laser spot at 1000 km range, with areal mass density 10kg/m^2 or less. The largest target re-entered has 0.75kg mass. System parameters: 7.3kJ pulse energy, repetition rate 11.2 Hz, mirror diameter 13 m, C_m = 75 μN-s/J, efficiency factor η_c = 30%, perigee altitude 500km, apogee altitude 1073km, eccentricity 0.04, re-entry for Δr_p = -3E5m. Orbit perigee is -120 degrees geocentric (upstream) relative to laser site, 833 pulses applied over 210 s to achieve minimum perigee.

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An upper limit for beam fluence is set by nonlinear optical (NLO) effects including (for short pulses) phase distortions due to nonlinear index (n_2), stimulated rotational Raman scattering (SRS) and stimulated thermal Rayleigh scattering (STRS). For pulses 100ns≤ τ ≤1ms, the NLO effects limit amounts to

$$\Phi_b/\lambda \leq 3E10\ \tau\ \text{Jm}^{-2}\mu\text{m}^{-1}. \tag{28}$$

For shorter pulses, this linear dependence saturates, settling at $\Phi_b/\lambda \leq 100$ J $m^{-2}\mu m^{-1}$ at 100ps. We can obtain solutions to these requirements graphically.

TARGET SHAPE EFFECTS

In general, the impulse and laser propagation vectors are not parallel. Since ablation will be parallel to the local normal, and the impulse is directed opposite to the net ablation vector, we can write

$$m\Delta\bar{v} = -C_m \Phi_L \sum_\alpha A_\alpha \left|\hat{k} \bullet \hat{n}_\alpha\right| \hat{n}_\alpha , \tag{29}$$

summing over all illuminated surface elements A_α. Laser fluence is given by $\underline{\Phi}_L = \Phi_L \hat{k}$. For "smooth" objects, the sum goes to an integral over the illuminated portion of the surface. Figure 4[1] shows the range of perigee change for a variety of shapes and target orientations. In this calculation, we assumed C_m

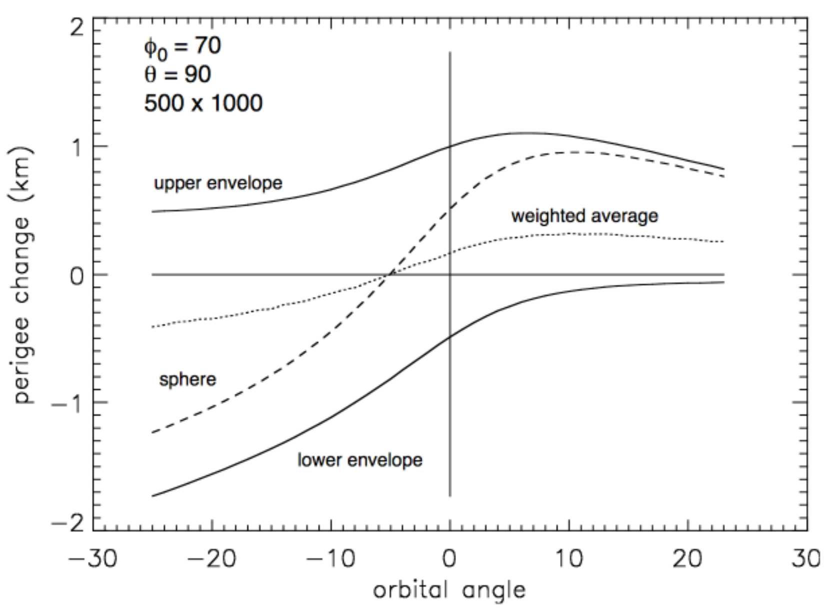

Figure 4. Perigee change is plotted against orbital angle for a 1 gram plate receiving a single 10 J pulse at the indicated geocentric angle. Negative angles correspond to upstream positions relative to the laser position at ϕ=0. The example orbit is characterized by 500 km perigee, 1000 km apogee, perigee angle (ϕ_0) 70 degrees downstream of the laser position (descending), and an orbit intersecting laser zenith. Plotted are the best case ("lower envelope"), worst case ("upper envelope"), the weighted average (dotted), and the result for a spherical target (dashed).

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=100 μN–s/J, and a random distribution of plate orientations in three dimensions. It should be emphasized that a real engagement will involve hundreds or thousands of laser shots, and that each shot will affect the orientation and spin of the target.

ACQUISITION AND TRACKING

An acquisition system reduces the position uncertainty of a debris object from km to the meters required by the "pusher laser" system. A distributed array of broad field of view, staring acquisition telescope using solar target illumination will be a helpful adjunct for the LODR system. Although each unit is limited to about two hours operation per day, it can be small and relatively inexpensive and several such devices around the globe can feed information to the LODR station.

At the station, active acquisition is possible, in total darkness or in daylight [5], using the "pusher laser" to illuminate the target, and the LODR system mirror on Earth to collect the scattered light. The field of view is set by target detection rate. On average, one object per 4 minutes will pass through a 3km field of view at 1000km range, enough input for the system. A large (20m) receiving aperture and 7.3kJ pulses from the pusher laser are required to gather enough scattered photons to see small targets. The system requires a bandwidth of 0.2nm for both the laser and detection system, and a 75 km "range gate." Range gating also gives rough range information, which is needed to compute the "look-ahead" angle.

If we have a 1000x1000 element CCD array with a 3-km field of view, each pixel projects onto a 3-m spot. The telescope primary mirror would be composed of independently steerable segments about 1m in size mounted on three-point mounts. Since the target will be moving at about 1 degree/second and within the field of view for only a half-second, each segment is accelerated rapidly over a small angular range to follow the object while the whole structure comes up to speed.

In standard adaptive optics (AO), phase fluctuations along the beam path through the atmosphere are corrected electromechanically using a deformable element array in the telescope optical train that cancels these distortions moment by moment. A control system bandwidth of about 1kHz is required. A reference wavefront is provided by a laser guidestar at high altitude, creating what is nearly a point source viewed from the ground. Rayleigh beacons, which use scattering from the atmosphere rather than exciting the sodium layer may also be used. The AO system adapts until it sees a point source; the resulting phase shape is recorded and reversed at the deformable mirror.

The finite velocity of light requires dealing with "look-ahead" before an accurately tracked target can be "pushed." At 7.5km/s, the debris is actually as much as 50 m ahead of where the sensor last detected it. Correctly pointed, the laser appears to be shooting into empty space but, when its pulse arrives, the target is there. We literally look in two directions, separated by about 100μrad, sequentially. Two independent adaptive optics systems correct these paths. The acquisition path uses the target itself as guidestar. Meanwhile, a sodium laser guidestar is tilted ahead of the detector by a computed angle, and a separate array uses the signal from that to command the corrector plate to keep the laser focus on its target during the laser pulse.

When the acquisition system has established a track within a 3-km circle, the field of view is narrowed. Ultimately, the computer makes the best focus possible and the pusher laser begins doing its work. The fine tracking signal now becomes very bright and shifts into the blue as plasma is formed on the target.

An alternative to standard adaptive optics is BEFWM (Figure 5[1]), a type of phase conjugation in which distortions are automatically compensated [19-21]. It may be easier to use BEFWM than classical adaptive optics, or perhaps a hybrid system will be best. Phase conjugation operates like holography, but it is a dynamic hologram recorded by interfering waves in a nonlinear optical medium rather than being a static pattern on a glass plate. With a phase conjugate mirror, each ray is reflected back through the system in the direction it came from with reversed phase. This reflected wave "undoes" the distortion, converging to the initial point source. The amplified conjugate signal is automatically concentrated on the space object to an accuracy that is determined not by the turbulent scattering angle (~100 μrad) but, instead by the spacial resolution of the receiving aperture (~ 0.1 μrad for a 10m receiving aperture).

In this technique, the target becomes its own guidestar. Other advantages are that tilt anisoplanatism is eliminated, and the system has extremely narrow acceptance bandwidth for good background noise rejection. The time by which the phase correction is “out of date” is just that required for a double pass through the atmosphere (~100μs), much faster than the 1ms time in which atmospheric phase distortions can typically change. Target lead-ahead in a BEFWM system is computed by a proprietary technique.

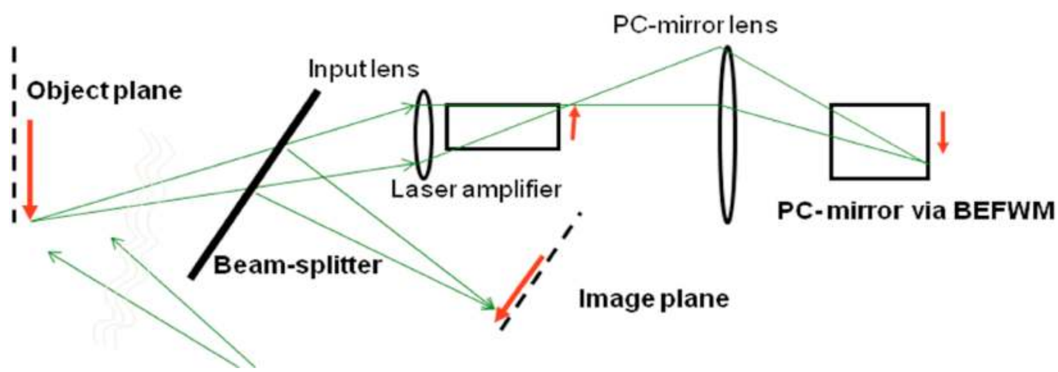

Figure 5. Illustrating the BEFWM process.

ADVANCES IN 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 at the design at Lawrence Livermore National Laboratory (LLNL). This high-repetition rate (10-20 Hz), high-efficiency (~12-18%) diode-pumped solid-state system will produce -10 kJ in a single beam at

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1053 nm.[22].The laser output has a linear polarization and it is easy to combine two beams in 20 KJ per pulse laser system [24].

Techniques for making light-weight segmented mirrors have already produced the 10-m class mirrors we require, and 42-m primaries with 984 segments are planned [20].

INTERNATIONAL COOPERATION

Building and operating a LODR system will require international cooperation to avoid concerns that it is really a weapon system. Also, cooperation in its operation will be needed to facilitate permission for its use to remove large debris objects.

LARGE OBJECT RE-ENTRY

It has been claimed that lasers cannot de-orbit large, one-ton derelict debris objects that are of concern. Indeed, single-pass re-entry of these objects is not possible. However, our calculations show that a single one-ton object can be re-entered in 3.7 years using a 25m mirror and a repetitively pulsed laser with 370kW average power [2.7Hz, 140kJ]. Since 167 different objects can be addressed in one day, 4.9 years are enough to re-enter the whole constellation. Note that it is only necessary [1] to re-enter 15 of these large objects annually to *stabilize* the debris environment. From this standpoint alone, the LODR system is a good investment. A larger mirror is required for the large-target system to avoid nonlinear effects in the atmosphere.

SERENDIPITY

LODR systems would be useful for purposes other than complete re-entry of all large debris, such as:

Increasing ephemeris precision:

A LODR system will use detection and tracking technology that permits location of targets with 1m precision, much better than present practice. This capability by itself will allow more accurate collision prediction.

Orbit modification on demand for large objects:

Even the small-target LODR system would then be able to nudge these objects to avoid collisions, or to provide modest orbit changes, inducing as much as a 35 cm/s velocity change in a 1,000 kg target during a single overhead pass. This is more than required to divert a large target and avoid a predicted collision.

Causing precise re-entry:

Re-entry for selected large derelicts can be altered in a calibrated fashion so the re-entry trajectory will endanger neither resident space objects by creating a new potential conjunction, nor air traffic corridors and population locations.

Moving GEO targets into disposal orbits:

The small target system, coupled with a 10-20m relay mirror just above geosynchronous (GEO) orbit is capable of raising the orbit of a defunct GEO satellite 100km in just 20 minutes.

IMPACT ON DEBRIS REMOVAL COST

We do not claim high accuracy for our cost models. An accurate model requires a thorough engineering study. However, rough system cost estimates based on the algorithms described in [5] are useful to estimate cost per object re-entered. We used this to estimate cost per small object removed at a few thousand dollars, and that for large objects at about $1M each. It is interesting to note that this cost model gives a relatively sharp minimum for total system cost at D = 20m.

FUTURE WORK

A demonstration system should be built using a 9-m mirror and a 4.6-kJ laser to prove LODR works on targets at 400km altitude. We plan to spend a considerable effort on design of the LODR acquisition and tracking system

CONCLUSIONS

We analyzed all the major aspects of laser orbital debris removal, and conclude that laser orbital debris removal will work, even for large debris objects. A LODR system should provide the lowest cost per object removed among all approaches that have been proposed. LODR is the only solution that can deal with both small and large debris. With LODR, target access is at the speed of light, redundant and agile. LODR can handle tumbling objects, while mechanical grapplers cannot. The system has multiple uses aside from general debris clearing, such as preventing collisions, increasing the accuracy of debris ephemerii and controlling where large debris impact the Earth's surface. Development and construction of the laser debris removal system offers the opportunity for international cooperation. Indeed, such cooperation will be necessary to avoid concerns that it is a weapon system and provide a framework for practical use.

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REFERENCES

1. Klinkrad, H. Space Debris – Models and Risk Analysis, Praxis Publishing, Chichester, UK, 2006
2. Kessler D. and Cour-Palais, B. Collision Frequency of Artificial Satellites: The Creation of a Debris Belt, J. Geophys. Res., 83, 2637-2646, 1978
3. Proc. NASA/DARPA International Conference on Orbital Debris Removal, Chantilly, VA, 2009
4. Phipps, C., Friedman, H., et al. ORION: Clearing near-Earth space debris using a 20-kW, 530-nm, Earth-based, repetitively pulsed laser, Laser and Particle Beams, 14, 1-44, 1996
5. Project ORION: Orbital Debris Removal Using Ground-Based Sensors and Lasers, Campbell, J. (ed.) NASA Marshall Spaceflight Center Technical Memorandum 108522, 1996

6. Phipps, C. et al., http://arxiv.org/abs/1110.3835v1
7. Phipps, C., Phipps, C. Catcher's Mitt as an Alternative to Laser Space Debris Mitigation, AIP Conf. Proc. 1278, 509-5142010)
8. Bonnal, C. High Level Requirements for an Operational Space Debris Deorbiter, Proc. NASA/DARPA Orbital Debris Conference… 2009
9. Mason, J., Stupl, J., et al. Orbital Debris Collision Avoidance, arXiv:1103.1690v1 [physics.space-ph], 2011
10. Phipps, C. An Alternate Treatment of the Vapor-Plasma Transition, Int. J. Aerospace Innovations 3, 45-50, 2011
11. Phipps, C., Turner, T., et al. Impulse Coupling to Targets in Vacuum by KrF, HF and CO_2 Lasers , J. Appl. Phys., 64, 1083-1096, 1988
12. Phipps, C., Birkan, M., et al. Laser Ablation Propulsion, J. Propulsion and Power, 26, 609-637, 2010
13. Phipps, C., Thomas S., et al. Effect of nonlinear refraction on beam brightness in laser fusion applications, Proc. Intl. Conf. on Lasers '79, STS Press, McLean VA, 878-887, 1980
14. Egerman, R., De Smitt, S., et al. Low-weight, low-cost, low-cycle time, replicated glass mirrors, Proc. SPIE, 7739, 77390G, 2010
15. http://www.salt.ac.za/
16. Liedahl, D., Libby, S., et al. Momentum Transfer by Laser Ablation of Irregularly Shaped Space Debris, AIP Conf. Proc. 1278, 772-779, 2010
17. Esmiller, B. and Jacquelard, C., Small Debris Removal By Laser Illumination And Complementary Technologies, AIP Conference Proceedings 1402, pp. 347-353, 2011
18. Priedhorsky W. and Bloch, J. Optical detection of rapidly moving objects in space, Appl. Opt. 44, 423-433, 2005
19. MacDonald, K., Tompkin, W., et al. Passive One-Way Aberration Correction Using Four-Wave Mixing, Opt. Lett. 13, 485-487, 1988
20. Kulagin, O., Pasmanik G., et al. Amplification and phase conjugation of weak signals, Sov. Phys. Uspekhi, 35, 506–519, 1992
21. Bespalov, V, Matveev, A., et al. Study of maximum sensitivity of a SBS amplifier and a four-wave hypersound phase-conjugate mirror, Izvestiya, Radiophysics series, 29, 1080–1094, 1986
22. Bayramian, A., Anklam, T., et al. Compact, efficient laser systems required for laser inertial fusion energy, Proc. Conf. Technology of Fusion Energy 2010.
23. Strafford, D., DeSmitt, S., et al. Development of lightweight stiff stable replicated glass mirrors for the Cornell Caltech Atacama Telescope (CCAT), Proc. SPIE, 6273, 62730R, 2006
24. A.Rubenchik et al, "Laser systems for orbital debris removal," International Symposium on High Power Laser Ablation, Santa Fe, N.M., 2010, AIP Conf. Proc.1278, pp. 347-353 (2010)