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ORBITAL DEBRIS REMOVAL USING GROUND-BASED LASERS

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INTRODUCTION

Orbiting the Earth are spent rocket stages, non-functioning satellites, hardware from satellite deployment and staging, fragments of exploded spacecraft, and other relics of decades of space exploration: orbital debris. The United States Space Command tracks and maintains a catalog of the largest objects. The catalog contains over 7000 objects.

Recent studies[1,2] have assessed the debris environment in an effort to estimate the number of smaller particles and the probability of a collision causing catastrophic damage to a functioning spacecraft. The results of the studies can be used to show, for example, that the likelihood of a collision of a particle larger than about one centimeter in diameter with the International Space Station during a 10-year period is a few percent, roughly in agreement with earlier estimates for Space Station Freedom.[3] Particles greater than about one centimeter in diameter pose the greatest risk to shielded spacecraft. There are on the order of 10^5 such particles in low Earth orbit.

The United States National Space Policy, begun in 1988, is to minimize debris consistent with mission requirements. Measures such as venting unused fuel to prevent explosions, retaining staging and deployment hardware, and shielding against smaller debris have been taken by the U.S. and other space faring nations.[4,5]

There is at present no program to remove debris from orbit. The natural tendency for upper atmospheric drag to remove objects from low Earth orbit is more than balanced by the increase in the number of debris objects from new launches and fragmentation of existing objects. In this paper I describe a concept under study by the Program Development Laboratory of Marshall Space Flight Center and others to remove debris with a ground-based laser.[6] A longer version of this report, including figures, is available from the author.

LASER ENERGY/TARGET MOMENTUM COUPLING

At low intensity, laser radiation exerts a force on a target by the mechanism of radiation pressure. If the intensity is higher, vaporization occurs at the target surface, resulting in higher laser energy-target momentum coupling, and higher pressure on the target. The greatest coupling occurs when the intensity is high enough to form a plasma in the vapor. The pressure can be much higher than the radiation pressure. Experiments to determine the coupling coefficient have been done which demonstrate coupling on the order of 10 dyne/W.

The pressure exerted on a piece of orbital debris as a result of laser radiation from the ground alters the orbit. The laser should be fired under conditions that cause the perigee altitude to decrease. When this happens, the increased atmospheric drag at lower altitude causes the object to spiral into the atmosphere, where it is destroyed by frictional heating.

CONCENTRATION OF GROUND-BASED LASER ENERGY ON ORBITING TARGET

The feasibility of removing debris with a ground-based laser hinges on attaining a high intensity, on the order of 10^8 W/cm^2, on targets in orbit. Intensity can be increased by keeping the laser beam as narrow as possible. The angular sizes of the largest targets are on the order of 0.1 μrad. A telescope operating at the diffraction limit can deliver a beam of this angular size at visible wavelengths if its aperture diameter is about 5 m. The angular size of the beam increases with increasing wavelength, and decreases with increasing aperture diameter.

Fluctuations in atmospheric density related to convective motion limit the angular size of the beam to about 5 μrad or greater unless adaptive optics are used. With adaptive optics, a pointing system with the phenomenal accuracy of 0.1 μrad is needed to keep the narrow beam on target.

In addition to minimizing the beam width on the target, intensity is maximized by using the highest available pulse energy and minimum pulse duration. If the intensity is too great within the atmosphere, the beam width will be degraded by stimulated rotational Raman scattering (SRS).[7,8] For pulses longer than about 0.1 ns, SRS is a threshold phenomenon whose intensity threshold decreases with increasing zenith angle. In addition, Rayleigh scattering by the atmosphere reduces the energy reaching the target. Atmospheric extinction increases with decreasing wavelength, and increases with increasing zenith angle.

EFFECT OF LASER IMPULSE ON PERIGEE ALTITUDE

The effect of an impulse on the orbit of a piece of debris depends on the magnitude and direction of the impulse, the mass of the object, the geocentric distance and speed at the time of the impulse, and the angle at which the object is climbing with respect to the local horizontal. The effect is not linear, so that doubling the impulse does not necessarily double the effect on the perigee altitude. It is possible for multiple pulses to have an effect on the perigee altitude which is opposite to the effect the pulses would cause individually!

In order to investigate the effects of varying the many parameters, I wrote a spreadsheet, LASER2D. The laser/target geometry is assumed to be two-dimensional in this early work. The laser is assumed to be on the equator of the Earth, and the inclination of the orbit is assumed to be zero degrees.

The user specifies an initial orbit by entering the perigee and apogee altitudes and the time of transit as a fraction of the orbital period. The debris target is specified by its diameter and ballistic coefficient. The laser parameters which are entered are the pulse energy, frequency, diameter at launch, wavelength, and pulse duration. The user also enters the range of zenith angles over which pulses are to be fired. Zenith angles are entered as positive numbers for rising targets and negative numbers for setting targets. The mass of the target is calculated from the diameter and ballistic coefficient. The user may opt to use the ballistic coefficient of a Na sphere of the chosen diameter.

The beam diameter at launch, pulse energy, and maximum zenith angle are used to calculate a minimum pulse duration to prevent the onset of stimulated Raman scattering. The user will generally use this minimum pulse duration in order to maximize intensity. The spreadsheet does not perform any extinction calculations in its present version. The momentum coupling coefficient is calculated from Phipps's empirical formula for aluminum alloys with plasma ignition, which depends on the intensity on the target, wavelength, and pulse duration. It varies with zenith angle because of the intensity dependence.

It is assumed that adaptive optics corrects the beam for atmospheric density variations, and that 84% of the energy is concentrated in an angular radius given by $1.22\ \lambda/D$, where D is the launch diameter. The spreadsheet does not check that the intensity is great enough for plasma ignition, but the user may view the intensity calculations.

The user may view a graph of the perigee change for single pulses as a function of zenith angle. Also available is a graph of the perigee change per zenith angle increment for multiple pulses. The spreadsheet calculates final orbital elements after a pass with continuous hits over the selected zenith angle range, but these numbers must be considered as estimates only. They don't take into account the changes in trajectory over the course of the bombardment.

RESULTS OF SPREADSHEET INVESTIGATIONS

Debris in circular orbits are considered first. A small target is one for which the laser always illuminates the entire target. A large target is one for which the laser only illuminates a portion of the target. A target which is entirely illuminated when near the laser and not entirely illuminated further from the laser is an intermediate case, acting as a large target at small zenith angles and as a small target at large zenith angles.

A single pulse is most effective in lowering the perigee of a small target when it is fired near a zenith angle of 30 degrees (altitude 60 degrees) as the target rises in the west. This is the angle at which the decrease in intensity with distance is balanced by the increase of the

effectiveness of the impulse as it is applied more nearly opposite the velocity vector. At the

LASER2D are shown in Table 2. The perigee is lowered below 400 km in 13 passes, so that the entire process could be accomplished in as little as about four days.

Table 1. Maximum diameter of Na sphere whose perigee can be lowered to 400 km in a single pass. The initial orbit is circular. Laser pulses of 1000 J are fired at 20 Hz over the zenith angle range from 60 degrees (rising) to -1 degrees (setting). The launch diameter of the beam is 5 m and the wavelength is 530 nm. The pulse duration is 1.43 ns. The maximum momentum coupling is at the zenith, where the range is least and the intensity greatest, but the effect of a pulse in lowering perigee is greatest near 30 degrees.

Initial altitude (km)	Max. diameter (cm)	Max. mass (g)	Max. Cm (dyne/W)
1500	0.40	0.032	5.6
1400	0.50	0.064	5.8
1300	0.62	0.121	6.1
1200	0.77	0.23	6.4
1100	0.99	0.49	6.7
1000	1.31	1.14	7.1
900	1.83	3.1	7.6
800	2.7	10.2	8.2
700	4.4	45	8.8
600	8.5	310	9.6
500	18.1	3000	10.8

Table 2. Orbital history for 100 cm, 10 kg object in an initially circular orbit of altitude 1500 km. The laser is fired over the zenith angle range of 75 degrees (rising) to -1 degree (setting). It is fired only on passes when the piece of debris is near apogee at transit. The laser energy per pulse is 1000 J and it is fired at 20 Hz. The wavelength is 530 nm and the pulse duration is 2.73 ns. Because the target is larger than the beam for most of the pass, it is advantageous to fire at high zenith angles (low altitudes). The perigee can be brought below 400 km in thirteen favorable passes.

Pass number	Perigee altitude (km)	Apogee altitude (km)
0	1500	1501
1	1411	1495
2	1319	1493
3	1227	1492
4	1135	1492
5	1044	1492
6	954	1493
7	865	1494
8	777	1495
9	690	1496
10	604	1497
11	519	1498
12	435	1499
13	352	1500

CONCLUSIONS

The spreadsheet is an important tool for relating the many variables in the laser strategy. It would be a fairly simple matter to generalize to the three dimensional case, in which the laser is located at any latitude and the orbit may have any inclination. This would make it possible to track changes in the inclination as well as the perigee. It would also be a simple matter to include extinction by the mechanism of Rayleigh scattering. If this were done, more realistic conclusions could be drawn about the best zenith angles at which to launch the laser pulses.

My studies indicate that several technical problems must be solved in order for the strategy to be feasible.

1. A detection scheme must be found which finds pieces of debris as they rise low above the horizon, and measures their ranges, radial velocities, and transverse velocities. These are to be used to calculate the orbital circumstances well enough to decide where in the pass it would be effective to hit the object with the laser. The system should operate day and night to be most effective. The system must be capable of recognizing targets such as working satellites which are not to be hit.

2. A large adaptive optics system must be built which compensates for the density fluctuations in the atmosphere, so that a near-diffraction limited beam can be concentrated on the target. This system should work at all zenith angles, day and night, and for a target which is moving rapidly with respect to the air mass.

3. A targeting system must be built with a pointing accuracy on the order of 0.1 μrad to place the beam on the target and keep it there. This must be done while the target is moving rapidly, and take into account that retardation causes the target to appear many beam widths behind its actual position at the time the pulse is to arrive. It must also be possible to follow the object as its path changes due to the cumulative effects of laser pulses.

REFERENCES

1. S.R. Maethner, A.E. Reinhardt, and L.O. Anderson, "Report on USAF space debris phase one study", Phillips Laboratory Technical Report, PL-TR--94-1042, June, 1994.

2. E.G. Stansbery, D.J. Kessler, and M.J. Matney, "Recent results of orbital debris measurements from the Haystack radar", AIAA 95-0664, AIAA 33rd Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 9-12, 1995.

3. D.S. McKnight and M.L. Fudge, "Space station Freedom vulnerability study", SPIE Vol. 1951, Space Debris Detection and Mitigation, pp. 98-105, 1993.

4. W. Flury and D. McKnight, "Space debris: an international policy issue", *Advances in Space Research*, Vol. 13, No. 8, pp. 299-309, 1993.

5. J.P. Loftus Jr. and R. Reynolds, "Orbital debris mitigation: issues and options", SPIE Vol. 1951, Space Debris Detection and Mitigation, pp. 144-153, 1993.

6. C.R. Phipps and M.M. Michaelis, "NEO-LISP: deflecting near-Earth objects using high average power, repetitively pulsed lasers", LA-UR--94-3124, 23rd European Conference on Laser Interaction with Matter, St. John's College, Oxford, England, Sep. 19-23, 1994.

7. M.A. Henesian, C.D. Swift, and J.R. Murray, "Stimulated rotational Raman scattering in nitrogen in long air paths", *Optics Letters*, Vol. 10, No. 11, pp. 565-567, Nov. 1985.

8. M.D. Skeldon and R. Bahr, "Stimulated rotational Raman scattering in air with a high-power broadband laser", *Optics Letters*, Vol. 16, No. 6, pp. 366-368, Mar. 15, 1991.