Using Lasers in Space

Laser Orbital Debris Removal and Asteroid Deflection

Jonathan W. Campbell, Colonel, USAFR

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Jonathan W. Campbell, a Colonel in the United States Air Force Reserve, is presently assigned as the Individual Mission Augmentee to the CADRE Commander at Air University. In civilian life, Dr. Campbell is a scientist and advanced projects manager in the Advanced Projects Office of the National Aeronautics and Space Administration (NASA) at the Marshall Space Flight Center in Alabama. In that capacity he has worked for over 20 years in the space program a number of advanced research projects. He served as the project manager on Project ORION, which was a NASA study published in 1997 that explored the feasibility of using lasers to remove orbital debris. He has published more than fifty scientific papers on various subjects, including laser orbital debris removal and laser asteroid, meteoroid, and comet deflection. He has a doctorate in astrophysics and space science from the University of' Alabama in Huntsville; masters degrees in theoretical physics from the University of Alabama in Huntsville, in engineering management from the University of Alabama in Huntsville, and in experimental plasma physics from Auburn University; and a bachelor's degree in aerospace engineering from Auburn University. He is also a graduate of the Army's Airborne School at Fort Benning, Georgia, the Air Command and Staff College and Air War College at Maxwell Air Force Base in Montgomery. Alabama.

Editor's Note

The Center is devoted to publishing studies that examine the relationship between technology and strategy and has been doing so since 1997. While most of the studies published by the Center place a significant emphasis on technological and policy problems, this study distinguishes itself because it places the emphasis on the scientific and technological challenges of using lasers to remove debris from earth orbit. This is an important idea that has gained prominence in recent years as a result of advances in directed energy, notably in the field of lasers. The second idea presented in this study is that defending the Earth against asteroids, as popularized in recent films, is an important, but admittedly far-reaching topic that the defense establishment must consider. The United States can proceed to tackle this latter issue on a more leisurely pace than the problem of man-made debris in earth orbit, which increasingly limits our ability to place satellites in orbit. The Center is pleased to publish this study in the hopes that it will stimulate further thought and discussion in the technological and policy communities as well as society at large about these problems.

Abstract

Orbital debris in tow-Earth orbit ranging in size from 1 to 10 centimeters (cm) in diameter, poses a significant problem for space vehicles.[1] While this debris can he detected, it cannot he tracked with sufficient reliability to permit spacecraft to avoid these objects. Such debris can cause catastrophic damage even to a shielded spacecraft. Given the technological advances associated with adaptive optics, a ground-based pulsed laser could ablate or vaporize the surface of orbital debris, thereby producing enough cumulative thrust to cause debris to reenter the atmosphere. One laser facility could remove all of the one-ten centimeter debris in three years or less. This study proposes that the United States develop a technology demonstration of this laser space propulsion in order to implement a system for removing debris from earth orbit. The cost of this proposed demonstration is favorable in comparison with the typical costs [or spacecraft operations.

Orbital debris is not the only form of “space junk” that is deleterious to the Earth.[2] Since collisions with asteroids have caused major havoc to the Earth’s biosphere on several occasions in the geological past, the reality is that the Earth will probably experience another impact in the future. For this reason, this study also considers the possibilities of scaling up a system for removing orbital debris to a system that could prevent these catastrophic collisions if we have sufficient warning.

I. Introduction

Functional satellites represent only a small fraction of the estimated 150,000 or more objects, which are larger than 1 centimeter in diameter, that are currently in low-Earth orbit (LEO) (Maethner 1994). Most of these objects are fragments of larger objects that have broken up in explosions and other events. Since the closing velocities of these objects are roughly 8 kilometers per second (km/s), a collision with any one of these objects is likely to cause catastrophic damage to a space vehicle or satellite, of which the Space Shuttle and International Space Stations (ISS) are noteworthy examples. As the number of pieces of debris in orbit continues to rise so does the likelihood of collision. Maneuvers for avoiding tracked debris have been undertaken by the Space Shuttle and are planned for the International Space Station as well. Furthermore, procedures for dealing with damage are being developed for the 155 in the event of a collision with orbital debris.

Claude Phipps suggested the use of laser propulsion with a ground-based pulsed laser as a solution to the orbital debris problem in 1994 (Phipps 1994). The Orion Project, which was a study conducted by NASA and the USAF in 1995-96, concluded that the concept of using ground-based lasers for removing orbital debris is feasible and cost effective relative to the cost of placing objects in orbit (Campbell 1996). This study presents an analysis of the debris removal concept, and a plan for developing the technology for removing orbital debris with near-Earth lasers. This study begins with an analysis of the cost of a laser orbital debris removal system as the first step toward establishing the cost-effectiveness of this concept. This study then investigates the requirements for using laser propulsion for the diverse ensemble of debris particles in orbit. The following section demonstrates that the adaptive optics requirement for debris removal is within technological reach. After demonstrating that laser systems can effectively remove debris from orbit with the proper engagement strategy, the study concludes with a proposal to develop the technology for debris removal and advance that technology for laser space propulsion.

II. Hazards from Orbital Debris

The USAF Space Command maintains a catalog of space objects. Depending on the altitude and radar cross-section of these objects, it can reliably track objects that are larger than 10-30 cm in diameter in low-earth orbit. That catalog contained roughly 8000 objects in 1997. While roughly six percent of the cataloged objects were active payloads, the remainder consisted of inactive payloads, rocket bodies, and smaller fragments, many of which were produced during more than 100 breakups of space systems in orbit. Most of these breakups were caused by explosions, but collisions with other objects cannot he ruled out. For example, the breakup on July 24, 1996 of the French Cerise satellite has been linked to a collision with a cataloged object.

Fragmentation generally produces large numbers of objects that are too small to he tracked reliably. High-velocity impact tests have shown that shields that are designed to protect satellites can he effective against objects that are less than about 1-2 cm in diameter. Such shielding is part of the design for the International Space Stat ion. Depending on environmental requirements, satellites and space vehicles may require shielding, or active protection from impacts with small particles, notably orbital debris and micrometeoroids. For particles that are larger than 2 cm, the cost of shielding a space vehicle is prohibitive.

There have been numerous surveys of debris in the 1-10 cm diameter range. Radar and optical surveys, when used in conjunction with computer models, reveal that there is roughly 150,000 objects in orbits below 1500 kilometers. The problem is that each of these objects is quite capable of causing catastrophic damage to shielded spacecraft, and yet are too small to he tracked reliably by avoidance sensors. The likely composition of the debris was considered by the Orion study. The debris was classified into five representative groups, with objects made of aluminum, steel, sodium/potassium metal, carbon phenolic, and multi- layer insulation (MLI). [1]

Based on the number of objects in low-earth orbit, and using the Iridium satellite system as an example, if we assume that the replacement cost of one of the 66 satellites in the $3.450 billion system is roughly $50 million, then the total cost to LEO satellites from orbital debris is estimated to be roughly $40 million per year. Debris-related expenses that are on the order of tens of millions of dollars per year should he compared with estimates from the Orion study for debris removal. It estimated that eliminating debris in orbits tip to 800 km in altitude within 3 years of operation would not exceed $200 million. It was for this reason that the study team has proposed a technology demonstration project as a next step, which is estimated to cost roughly $13-28 million.

Laser Propulsion of Uncooperative Debris. Laser propulsion is one technique for using radiant energy rather than fuel on space vehicles for the purpose of propulsion. In the case of removing orbital debris, the surface material of the debris becomes the propellant. In essence, the intensity of the laser must he sufficiently great to cause the material on the surface of the object to form a vapor, which as this hot vapor expands imparts a force or thrust to the object. For a given material and duration of a laser pulse there is an optimum intensity above which the ability to couple laser energy onto the material decreases.[2] This is because the resulting ionization of the vapor from the material effectively absorbs the energy of the laser: This means that a series of short pulses is the most effective way to generate propulsion for orbit debris.[3]

Since orbital debris consists of many materials, a debris removal system must be designed with this in mind. The Orion study considered laboratory experiments that were conducted with representative materials and found useful models for the coupling of metals and nonmetals, as shown in Figure 1. The optimum intensity is higher for metals than for nonmetals, since energy tends to he conducted to the interior of the metal. At higher intensities, however, the coupling is higher for metals than for nonmetals because the onset of plasma formation above the optimum intensity for nonmetals occurs at lower intensities.[4] This system would he effective against both metallic and nonmetallic targets in space, and could be effective against materials that arc at higher orbital altitudes.

Adaptive Optics for Debris Removal. We have seen that useful laser propulsion of orbital debris results from placing an intensity on the order of 10^8 W/cm^2 on the target. The angular beamwidth required to achieve this is given by

$$\alpha = \frac{1}{z}\sqrt{\frac{E}{\frac{\pi}{4}It}}\,, \tag{1}$$

where E is the pulse energy, I the required intensity. t the pulse duration, and z the target range. With a high pulse energy of 20 kJ, short pulse duration of 5 ns, and range of 1600 km for debris at an altitude of 800 km and zenith angle of 60^0, the angular diameter required is 1.4 μrad. Without adaptive optics, small-scale turbulence in the atmosphere spreads the beam to an angular diameter on the order of 10 μrad. Also, turbulence on larger scales tends to tilt the wavefront and displace the emerging beam from its intended path.

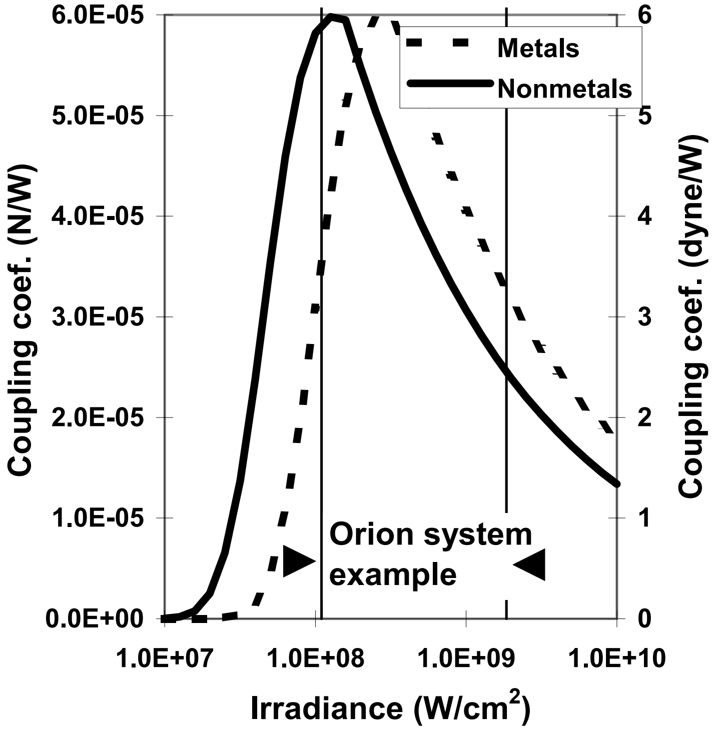


FIGURE 1. Laser Coupling For 5 ns Pulse Duration.

High-order correction for atmospheric turbulence has been demonstrated with laser guide stars and active optical correction. At the USAF Phillips Laboratory Starfire Optical Range (SOR) in Albuquerque, New Mexico, for example, resolution better than 1 μrad has been obtained at 0.85 μm with a 1.5 m aperture (Starfire Optical Range 1997). Sealing these results to 1.06 μm and a 3.5 m aperture would meet the requirements of a laser system for orbital debris removal with existing technology.

The image shift due to large-scale turbulence can be measured by the shift in the apparent position of a star from its expected position. It is impractical, however, to use stars for an orbital debris removal system, since there is not enough integration time available for faint stars, especially during daytime with competition from scattered sunlight. The light from a laser guide star traverses the same path as the original laser, and hence is not useful for determining the wavefront tilt. An alternative to the use of a field star to sense the wavefront tilt is to illuminate the debris particle, which should follow a predictable orbital path, and measure its apparent position (as affected by tilt) in the reflected light.

Initial analysis of the debris removal strategy raised concerns that reflected light from the moving target, which can be up to 50 grad from the intended laser impact position because of the finite light-travel time, would he too far removed for effective tilt sensing. Recent astronomical results, however, have reduced this concern. At the Steward Observatory, for example, tilt correction in the K band was accomplished for the Multiple-Mirror Telescope (MMT) with a field star 200 μrad from the laser guide star (Center for Astronomical Adaptive Optics 1997).

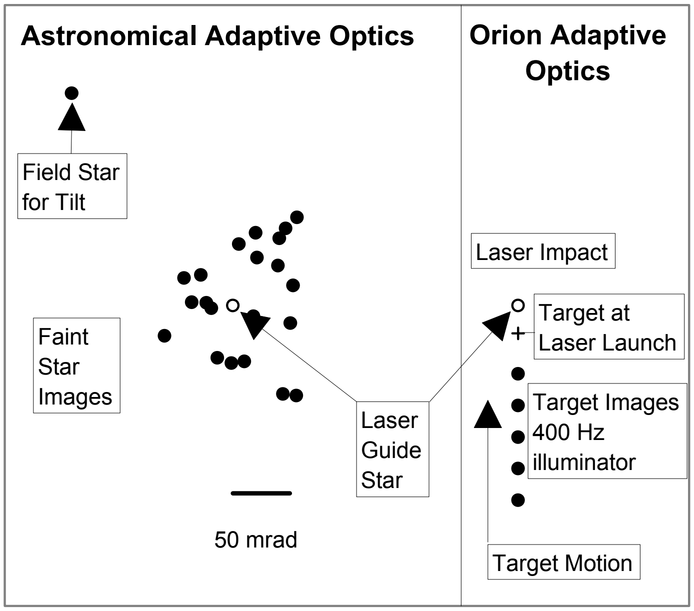


Figure 2. Comparison Of Adaptive Optics For Astronomical Imaging And Orbital Debris Removal shows Orion well within the envelope for correcting tilt errors.

Figure 2 is a comparison of adaptive for astronomical imaging and orbital debris removal. On the left, a field of dim stars is imaged with high-order correction calculated on the basis of a laser guide star created in the center of the field. A brighter field star to provide the tip/tilt correction is shown 200 µrad from the center. On the right, a series of solid circles shows the reflected signal from an object in a 500 km circular orbit at a zenith angle of about 45 degrees. We have assumed a 400 Hz illuminating signal. The solid circle nearest the laser impact is the last reflected signal, allowing 1 ms for data processing and moving the mirror actuators. The laser guide star must be created at the calculated position of the laser impact just before the pusher laser launch. The actual position of the target at the time of the pusher laser launch is shown as a cross. While the orbital debris removal scheme is shown as if it were imaged in a stationary telescope, however, in practice the debris will he tracked as it moves across the sky at up to 14 mrads/s.

The assumption of a 500 km circular orbit in Figure 2 is not critical. In a higher orbit the time delay between the launching of a light pulse and the return of its reflection is greater, but the apparent angular speed of the target is less, with the result that the picture is nearly the same. Images obtained at the Steward Observatory show that the field star may he as much as 200 µrad from the center and still he useful for correction •The orbital debris portion of the picture shows that reflection from the target in orbit provides wavefront tilt information quite close to the site of the pusher laser launch in comparison with the astronomical imaging scenario. Thus, the orbital debris removal by laser propulsion should he successful in terms of the adaptive optics requirements.

Two key points relative to the adaptive optics remain to be investigated. First, since it is desirable to operate a future orbital debris removal or ground-based laser propulsion station at all times of the day, the requirements for adaptive correction during the daytime must be investigated. During the daytime, atmospheric turbulence increases and makes the adaptive optics more difficult. A laser technology demonstration will be able to determine to what extent the Fried scale of the turbulence decreases, and whether multiple guide stars will he needed for daytime operation. The second point to be investigated is how large the zenith angle can be while still maintaining good compensation. Answer discuss below, it is desirable to reach 60 degrees from the zenith. The smaller apparent angular speed of the target at larger zenith angles will work to an advantage.

Debris Engagement Analysis. We have demonstrated in the laboratory that laser energy can he used for propulsion on a wide range of uncooperative debris surfaces, and that spreading of a laser related to turbulence in the atmosphere can he overcome by adaptive optics. In this section, we will examine strategies for removing orbital debris with an ground-based pulsed laser.

Let us assume a fairly difficult target, a 1-cm diameter Na/K sphere, of which there are believed to he tens of thousands from the leakage of a liquid metal reactor coolant in orbit. These targets are difficult because of their low area-to-mass ratios and the higher optimum intensity for a metal surface. The laser is taken to be a 1.06 µm, 20 kJ, 5 ns laser pulsed at 5

Hz. We assume the target is in a 500 km x 600 km elliptical orbit, and passes over the laser as it is between apogee and perigee. The effects of individual hits are shown in Figure 3 as a function of zenith angle. The single pulse effects on the perigee, apogee, and lifetime are small but significant. The effects are generally beneficial at positive zenith angles (target approaching the laser).

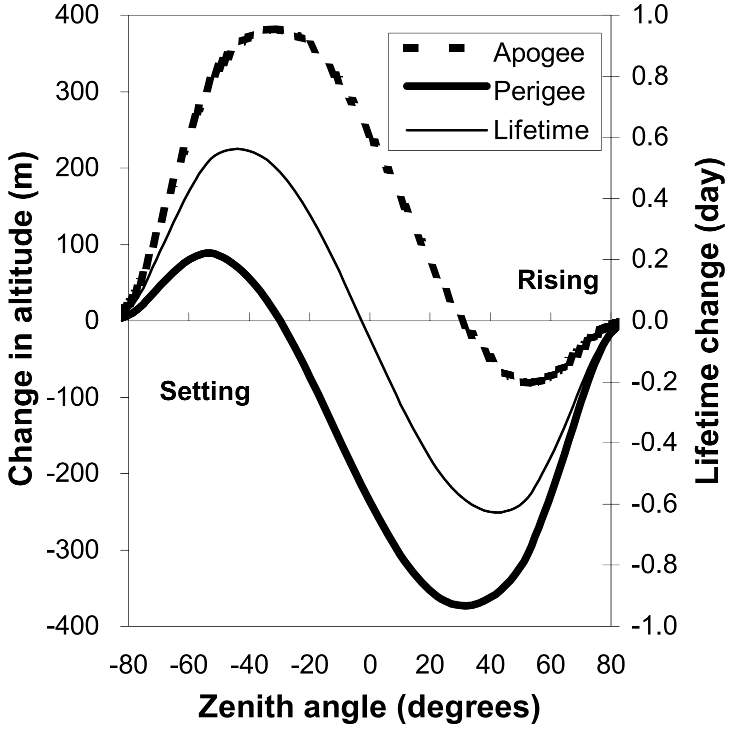


Figure 3. Effect Of Single Laser Pulse

In Figure 3 we exhibit the cumulative effect on the lifetime of engagements over zenith angle ranges. The final lifetime is plotted as a function of the starting zenith angle, assuming zero ending zenith angle. The initial lifetime of this target is about 171 days. An engagement that begins at 60 degrees reduces this to just 20 days and leaves the target in a 317 km by 595 km orbit. The figure shows the importance of firing at large zenith angles. At the larger angles, the apparent angular speed of the target is low, and there is time for more pulses than at smaller zenith angles. This and similar analyses show that all orbital debris in low earth orbit can he removed in one or more engagement.' consisting of pulses delivered by a single ground-based laser. The laser of this example is capable of removing debris up to 800 km in altitude in two or three years of operation.

Technology Demonstration. The serious international concern over the orbital debris problem, when coupled with the evident feasibility and cost-effectiveness of debris removal by ground-based pulsed laser propulsion, has led to planning for the next step toward debris removal. The Orion report contained a suggestion for a technology demonstration in which a 120-J pulsed laser would he joined with a 3.5 m aperture telescope with tracking capability, such as the USAF Advanced Electro-Optical System (AEOS) under construction in Hawaii or the Starfire Optical Range (SOR) in New Mexico. Specially constructed targets, which would he deployed from the space shuttle, would have corner-cube reflectors or a UPS unit to return a strong signal for calibration tests. This demonstration would have a number of goals.[5]

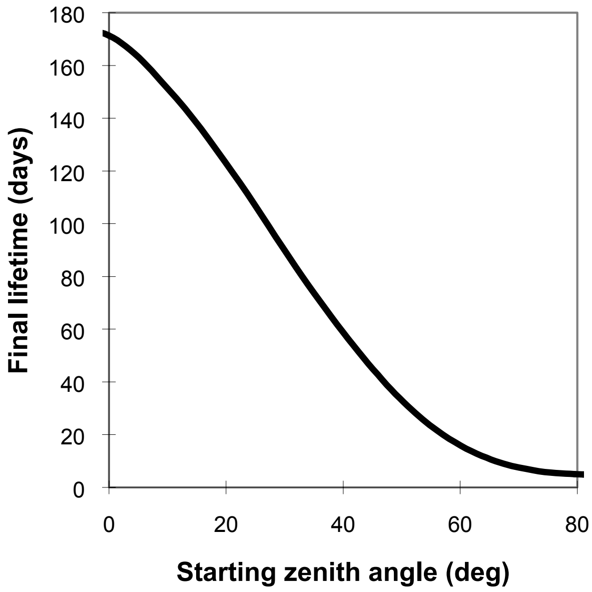


Figure 4. Post-Engagement Lifetime For an Orbital Debris Object With Zero Final Zenith Angle.

Cost estimates for the technology demonstration are in the range of $13-28 million, which is comparable with the cost of a single flight of the least expensive orbital launch vehicle (Pegasus). The potential benefits, if the demonstration leads to an operational system, are saving tens of millions of dollars per year in expenses (increased shielding, damage control systems, and satellite replacements) related to orbital debris, and the accelerated development of other applications of laser space propulsion and laser power beaming.

III. Near Earth Asteroid Avoidance System

Astronomical telescopes and deep space radar systems have observed the existence of at least 2000 Near Earth Objects (NEO), such as asteroids and comets, which potentially could destroy most life on Earth. An asteroid with a diameter of 0.2 km would strike the Earth with a power rivaling the strength of a multiple warhead attack with the most powerful hydrogen bombs. This strike would throw' up a cloud of dust rivaling the most powerful volcanic explosion, which would seriously affect climate on the scale of two to three years. A strike by a larger asteroid, say 1 km, (especially in the ocean) would create a gigantic tsunami that would flood and obliterate coastal regions. More significantly it would eject a massive dust cloud that would alter cur biosphere to the point that life as we know it would cease to exist with no chance of recovery within the near term.

The consensus in the astronomical and astrophysics community was that most of the known NEOs do not pose a near term threat, and therefore that these objects do not present any dancer to the Earth and its biosphere in the foreseeable future. However, the recent collision of a comet Iauki with Jupiter and the discovery of an uncatalogued asteroid, that passed near Earth without any advanced warning, have increased concerns.

Several schemes have since been discussed for dealing with NEO on collision courses with the earth. •These include blowing them up with nuclear weapons or landing on them and using small, shaped nuclear detonations to steer the asteroid into a passing orbit. However, fragmentation may not be a solution because the center of mass of the resulting cloud of debris would continue on the original collision trajectory. Also, we presently do not have the lift capability to land and place nuclear devices on asteroids without extremely long lead times. The research and development of a nuclear deflection system would cost billions and would still require sufficient warning of an impact to be implemented.

A better system would he one that is “on station” and could he used routinely to shape asteroid orbits over long periods of time so that they do not pose a potential threat. Phased Array Laser Systems (PALS) could he developed and orbited. Space-based laser constellations (SBL) are presently under development and will he flow-n during the next decade.

Coupling PALS with powerful telescopes, such as those being developed under the Next Generation Space Telescope (NGST) project, would provide long-term warning for implementation of an overall NEO avoidance system. The feasibility of this system is discussed below.

The lasers that would he used in Project Orion have demonstrated sufficient capability for orbital debris removal for objects in the size range from 1-10 cm diameter. Ground based experimental data, using a 20 kW pulsed laser, show that the impulse imparted to aluminum targets due to the ejected plasma cloud gives an average surface pressure $p = 6.5 \times 10^{-4}$ N/cm^2, or equivalently, an acceleration, $a = 1.25\times 10^{-6}$ m/s^2 With present technology, a laser phased array can be aimed at the asteroid with sufficient power to ablate its surface. Assuming that a laser array can be scaled up to operate on a 1 km diameter iron asteroid, this would require a 200 GW power grid. Several alternate potential power sources are available, including nuclear or electric generation and solar power arrays.

Let us assume that the asteroid is at infinity moving toward the Earth with a velocity v_0 and impact parameter R. The closest point of approach R_e is given by

$$R_e \cong R_E\left[1+2g\left(\frac{R_E}{v_0^2}\right)\right]^{\frac{1}{2}}$$

where RE is the radius of the Earth, and g is the gravitation acceleration at the surface of the Earth. There are two cases of interest:

- Head-on collision: $v_0 = 40$km/s, → R_e=1.04 R_E

- “Catch-up” collision: $v_0 = 5$km/s → R_e=1.1 R_E

The catch-up collision is the most dangerous. However, it is only necessary to move the asteroid laterally away from its original orbit by at most 1.1 R_E, which is the worse case scenario. Table 1 gives several relevant times for irradiation.

Time (in days)	Displacement ΔR	Final lateral velocity v_f
1.0 d	4.9 km	0.11 m/s
10.0	485.0 km	1.08 m/s
36.0	1.00 R_E	4.07 km/s
38.8	1.10 R_E	4.19 km/s
44.0	1.45 R_E	4.75 km/s
46.3	1.56 R_E	5.00 km/s

Table 1. Lateral displacement and final velocity of asteroid from original orbit for perpendicular illumination of target. The final velocity is a linear change, but the displacement is quadratic. Note the change of units in the second and third columns.

Table 1 shows that a minimum of 38.8 days of illuminating the target is necessary for the worse case of a head on collision, and in most cases would take much less time. The warning time of impending impact is of critical significance, which highlights the importance of deep space surveillance for NEOs, using the NGST for example, in addition to long-term monitoring and orbital calculations. Early orbit shaping would be extraordinarily effective. Also it is important that PALS be deployed at positions, which are free from occluding (obstructing) the beam by the Earth or the Moon. The ability to see clearly, i.e., surveillance of small, dark objects such as asteroids requires freedom from Earth-and Moon-shine, is essential for the NGST. However, it is obvious that the PALS must be located sufficiently near the Earth, which it is designed to protect. A primary candidate is one of the Sun-Earth Lagrange points at which a spacecraft will maintain a fixed position with respect to the Earth.[6]

Figure 5. The five Lagrange points are shown as L_n, n=l-5. PALS is placed at L_5 and NGST is placed at h. Note that nothing is to scale.

In Figure 5, we pictorially describe an asteroid encounter with the Earth.

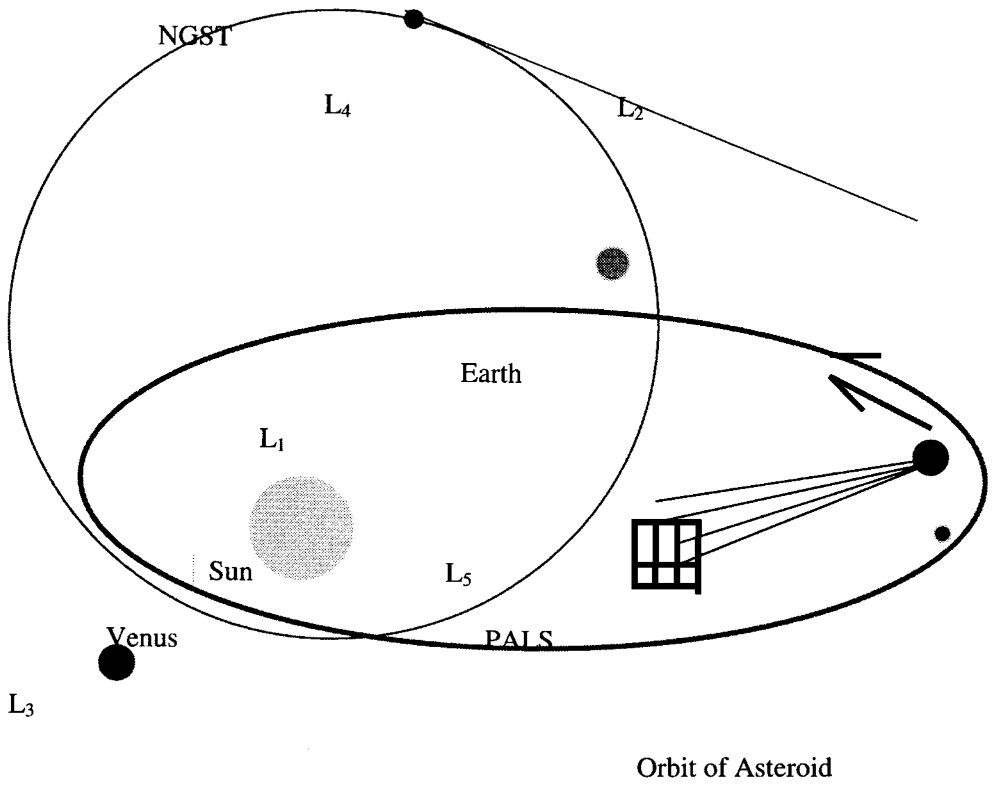


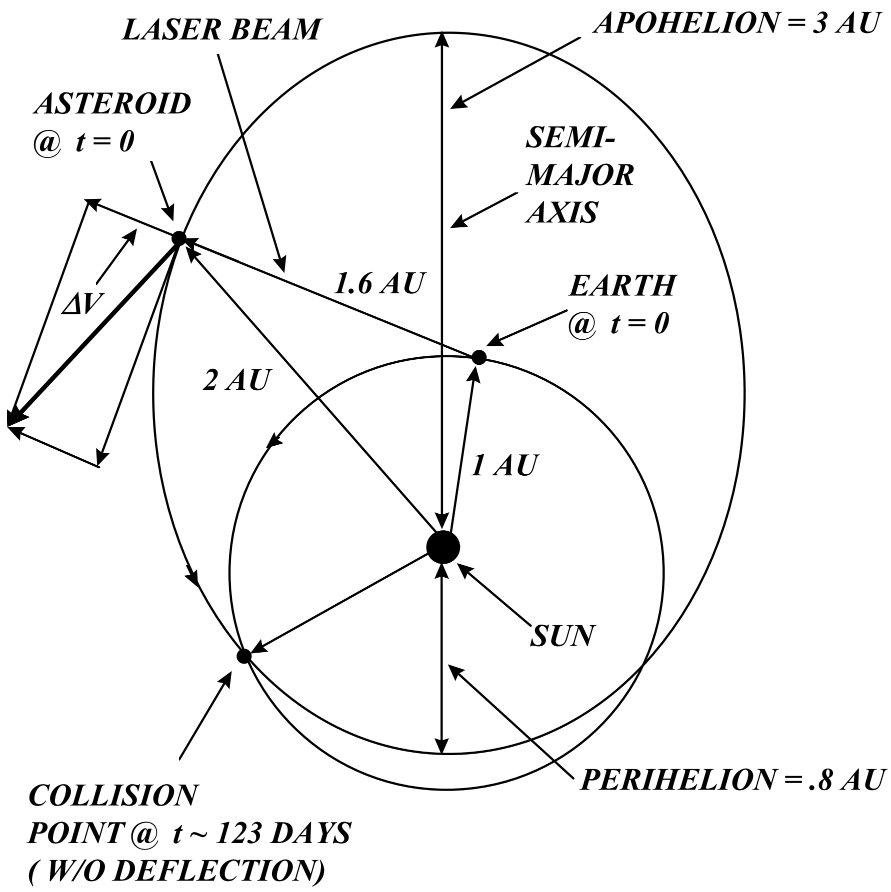
Figure 5. The five Lagrange points are shown as L_n , n=1-5. PALS is placed at L_5 and NGST is placed at L_4. Note that nothing is to scale.

This orbit, as depicted in Figure 5, lies between the orbits of Mars and Venus, and is consistent with the recent news false alarm that an asteroid would pass within 48.000 km of the Earth. Better data significantly altered the prediction of the closest point of approach to 1,000,000 km, and suggested that there is no significant threat in the foreseeable future. Nevertheless, the orbital period of an asteroid lying between Mars and Venus is roughly 0.9 yr. Thus, if the collision scenario depicted in Figure 5 was correct, then with sufficient lead-time, then PALS firing with a good aspect from L_5, as shown in the figure, would have had two-three months to move the asteroid away from a collision path with the Earth. Since, however, the original news report in this case, was very late, there probably would not have been sufficient time in advance, as shown in Table 1, for PALS to deflect the asteroid away from the Earth. This fact stresses the need for coupling with PALS an early warning system based on a technology similar to the NGST, in addition to deep space searches with radar.

In another scenario, the undetected asteroid could he chaotically ejected from the asteroid belt. In this case it is possible to describe similar results as depicted in Figure 5. In this case, the calculation is simplified by assuming that the entire impulse to the asteroid is given in one instant. It is necessary to set the stage for this event:

- **ASTEROID ORBIT=.8 X3AU, POSIGRADE**
- **COPLANAR WITH ECLIPTIC**
- **BEGIN LASER IMPULSE WHEN**
  - **ASTEROID IS 2 AU FROM SUN**
  - **ASTEROID DESCEADS TO LAST PERIHELION BEFORE COLLISION**
- **LASER IMPULSE DIRECTED THROUGH ASTEROID CG**
- **IMPUSIVE ΔV INCREMENT**

This particular event can he calculated from the data given in the following figure.



ORBITAL & IMPULSE GEOMETRY

Figure 6. The ΔV imparted to the asteroid causes the semi-major axis of the asteroid to rotate clockwise and thereby reduces the period. As a result the asteroid will cross in front of the Earth.

The ΔV of 5 m/s (as given in Table 1) is an obvious example of an impulse that yields a “miss distance,” In this case the asteroid passes in front of the Earth by 1.25 Earth diameters. The realistic case, however, would be a gradual shift in the orbit by a long duration, low intensity impulse that gradually reshapes the orbit over long time period, perhaps over several orbits. Ideally, for the asteroidal orbit between Mars and Venus, it might conceivable to move the asteroid into an orbit that removes the threat to the solar system, On the positive side, it is interesting to contemplate orbit shaping for the purpose of asteroid mining.

IV. Conclusions

For several years, the Air Force and NASA have worked to characterize the implications for orbital debris for the risk to spacecraft. While there is a continuing debate about the risk, there is agreement that some risk exists and that these risks will increase as the use of space expands. A related question concerns the threshold at which the risk become too high. While we cannot answer complex questions here, there are reasons for responding to this problem.

The use of space is vital for future economic and political power for many reasons. Since an impact from a meteorite, asteroid, or comet would he an unimaginable catastrophe, we have little choice but to deal with this threat. On a lesser scale, the threat of orbital debris to spacecraft raises important economic questions. While there are many risks with spaceflight, we must decide at what threshold the risks are too high and action s necessary. That threshold must balance the possible impact to the mission, resources available to accomplish that mission, and the technical arid cost feasibility of reducing that risk. In addition, that threshold must balance all of the risks that are associated with a mission. In other words, if there is a practical way to reduce risk, then it is probably prudent to do so. The purpose of this study is to describe one solution for reducing the risk posed by orbital debris.

Presently, there are significant quantities of orbit debris in all sizes, altitudes, and inclinations. However, the debris ranges in size from the microscopic to several meters, including worn out satellites arid upper stages of rockets, and fortunately there are many more small objects than large ones. The typical closing velocities for a collision with orbital debris are on the order of 20,000 mph, which means that a collision with a satellite would likely end its useful service life at costs that exceed one billion dollars.

With the technological state of the art in orbital debris protection, satellites can he effectively shielded against hypervelocity objects that are less than 1 cm in size. This shielding, however, is extremely expensive. For example, the cost of increasing the protection for critical modules on the Space Station from 1 cm to 2 cm has been calculated to be on the order of 100 million dollars for launch costs alone, not including research and development and manufacturing costs.

For objects that are greater than 10-30 cm in size, the Space Station will rely on the Space Command tracking network to provide early warning. If an object will come too close to the station, it will maneuver to avoid it. But the total costs of this maneuvering system are substantive, and we should note that it will not provide absolute protection, principally because the Space Command could have difficulties in continuously tracking objects that are less than 30 cm in size. In the event of a solar flare, the tracking system may lose objects for days at a time.

The reality is that there is no system in to protect against the approximately 150,000 objects that are in the range of 1-10 centimeters in size. Using the example of a ten n is ball that is approximately five centimeters; a hypervelocity collision between a tennis hall and a satellite will probably reduce that satellite into orbital debris. And it may have a cascading effect as many smaller objects produce orbital debris, which in turn increases the overall risk to objects in orbit.

While the probability of a collision with an individual satellite is quite low, the probability of a collision occurring with in the, entire population of space assets is not as remote. An analysis suggests that with the current level of orbital debris and the sizes of satellites, the probability is that there will be one collision per year. And that loss could amount to billions of dollars. This is a global problem and will involve an international effort that is coordinated by the United Nations. No one project cannot redress this problem. Nor is it economically practical to shield each spacecraft and give it maneuvering capabilities.

An elegant, cost effective, and feasible approach is to use laser technology to solve this problem. It is estimated that a single. Ground-based laser facility that costs about $100 million and that operated near the equator could remove all orbital debris up to an altitude of 800 km in two years Since satellites typically cost several hundred million and given the half billion price tags on shuttle and Titan launchers, this investment is relatively small given the potential losses of rockets. Furthermore, the development of this technology will stimulate other approaches, including laser power beaming, deflecting asteroids, meteoroids, and comets, and propulsion for interstellar missions. In closing, this study addressed a problem that the international community must resolve if we are to reduce the risk to spaceflight, and hence to economic progress, that is caused by orbital debris.

References

Maethner. SR., A.E. Reinhardt. and LU. Anderson (1994) Report on USAF Space Debris Phase One Study. Phillips Laboratory Technical Report PL-RT-94-1042.

Phipps. Claude R. and M. M. Michaelis (1994) "NEO-LISP: Deflecting Near-Earth Objects Using High Average Power, Repetitively Pulsed Lasers", 23rd European Conference on Laser Interaction with Matter, St. John's College, Oxford, England. September 19-23. 1994, LA-UR 94-3124.

Campbell, J.W. et al (1996) "Project ORION: Orbital Debris Removal Using Ground-Based Sensors and Laser", NASA Technical Memorandum 108522, http//infinity.msfc.nasa.gov/Public/orion/default.html.

Cleghorn. George et al (1995) Orbital Debris: A Technical Assessment, National Academy Press. Washington, DC, http://www.nas.edu/cets/aseb/debrisl html.

Starfire Optical Range (1997) http//wwwsor.plk.af.mil/.

Center for Astronomical Adaptive Optics (1997) http ://athene.as.arizona.edu:8000/caao/.

Notes

1. The 1994 USAE study (Maethner 1994) found a peak collision flux of about 0.0002 m^{-2} yr^{-1} for debris one cm or more in diameter at an altitude of 800 km and an inclination of 98^0. At an altitude of 500 km and an inclination of 28^0 the flux was estimated at 0.00001 m^{-2} yr^{-1}.·According to results cited in the 1995 National Research Council report on orbital debris (Cleghorn 1996)' there were then approximately 400 spacecraft in the altitude range from 700 km to 1000 km. If we estimate that half of these are functional, and allow a typical cross-section of 20 m^2 for each satellite, then there is a total functional satellite cross-section of about 4000 m^2 near 800 km. The expected rate of collisions with orbital debris one cut or more in diameter is thus about 0.8 yr^{-1}

2. Coupling is strong when the intensity readies at least one tenth of the optimum intensity. The optimum intensity scales roughly as the square root of the pulse duration.

3. The reason is that a pulse with a modest energy may have a high intensity' if its duration is short, and at the same time the optimum intensity is somewhat smaller for a short pulse.

4. The peaks of the curves in Figure 1 are at the optimum intensities for 5 ns pulses, and the optimum are at higher intensities for longer pulses. The vertical marks in the figure are the range of intensities calculated for a system with a 20 kJ, 5 ns pulsed laser at 1.06 µ directed by a 3.5 m aperture onto a target in a 500 km circular orbit as the zenith angle varies from 0-60^0.

5. These include the goals of accurately predicting the position of illuminated targets, correcting for wavefront tilt, performing high-order correction for turbulence, correcting for atmospheric turbulence at large zenith angles- operating during daylight, determining whether target response to laser impact is within predictions, and locating and tracking small targets (with or without handoff from remote tracking station) quickly and often enough to provide pusher laser targets.

6. Another advantage is that a slightly displaced spacecraft will orbit the Lagrange point.

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