## **ORION**:

Clearing near-Earth space debris using a 20-kW, 530-nm, Earth-based, repetitively pulsed laser

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#### Abstract

When a large piece of space debris forced a change of flight plan for a recent US Space Shuttle mission, the concept that we are trashing space as well as Earth finally attained broad public awareness. Almost a million pieces of debris have been generated by 35 years of spaceflight, and now threaten long-term space missions. The most economical solution to this problem is to cause space debris items to re-enter and burn up in the atmosphere. For safe handling of large objects, it is desired to do this on a pre-computed trajectory. Due to the number, speed and spacial distribution of the objects, a highly agile source of mechanical impulse, as well as a quantum leap in detection capability are required. For reasons we will discuss, we believe that the best means of accomplishing these goals is the system we propose here, which uses a ground-based laser system and active beam phase error correcting beam director to provide the impulse, together with a new, computer-intensive, very-high-resolution optical detection system to locate objects as small as 1 cm at 500km range. Illumination of the objects by the repetitively-pulsed laser

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produces a laser-ablation jet which gives the impulse to de-orbit the object. A laser of just 20 kW average power and state-of-the-art detection capabilities could clear near-Earth space below 1000 km altitude of all space debris larger than 1 cm but less massive than 100 kg in about 4 years, and all debris in the threatening 1 – 20-cm size range in about 2 years of continuous operation. The ORION laser would be sited near the Equator at a high altitude location [e.g., the Uhuru site on Kilimanjaro], minimizing turbulence correction, conversion by stimulated Raman scattering, and absorption of the 530-nm wavelength laser beam. ORION is a special case of Laser Impulse Space Propulsion (LISP), studied extensively by Los Alamos and others over the past four years.

## 1. Introduction

Satellite dishes have become common sights in the developed world, but the importance of satellite reliability and operating cost has not really reached public awareness because these systems are taken for granted. It is hardly realized that low-Earth-orbit installations will soon be seriously threatened by the legacy of the past. In fact, each new satellite runs an increasing risk of collision with the growing detritus of 35 years of space launching activity, in which upper rocket stages have often been deliberately detonated when their usefulness is finished. The same spirit fills arroyos in New Mexico with old washing machines and derelict automobiles.

In the first part of this article, we quantify the risk to space assets, and mention the alarming possibility of a "spacial chain reaction" in which mutual collisions of larger space objects produce a cloud of smaller debris which could threaten any long term LEO mission.

We then show that an affordable laser and detection system can eliminate this unacceptable threat in less than half a decade. The proposed process is but one example of a range of Laser Impulse Space Propulsion (LISP) applications, which we will briefly review.

The scientific basis of laser propulsion can be said to have started with studies for both the laser fusion and magnetic fusion programs. In laser fusion research, thin foils are routinely accelerated up to speeds of order 0.001c [Bolotin *et al.* 1992]. In magnetic fusion research, somewhat heavier targets (milligrams) are propelled to orbital velocities as part of the Tokamak refueling program [Burgess, *et al.* 1978]. Laser energy in all these experiments is in the range 10J<W<1kJ. The main difference between the lasers used in these experiments and that required for ORION is the repetition rate. An ORION 20-kJ frequency-doubled neodymium laser would need to be fired once or twice a second. We will describe such a system.

## 2. Debris Threat

One result of 35 years of space activity is that there are now several hundred thousand pieces of space debris larger than 1cm in near-Earth orbit. This environment includes 1.5 -10-cm size objects which are now sufficiently numerous to pose a significant threat to the International Space Station Alpha, to a few quite large items. For the Space Station, the impact velocity spectrum of these objects peaks at about 12.5 km/s [Cramer and Bogert 1993].

The cumulative flux distribution of near-Earth debris (flux of impacts caused by objects of size  $\ge$  d)

$$N(d) \approx \Lambda/d^{q}, \qquad m^{-2}yr^{-1} \qquad [1]$$

where  $\Lambda \approx 2.3 \times 10^{-5}$ ,  $q \approx 2.6$  for d<2 cm (a characteristic of interstellar debris) and  $\Lambda \approx 6.4 \times 10^{-5}$ ,  $q \approx 1.3$  for larger sizes [see Figure 1, based on Flury and McKnight 1993].

Figure 2, based on Figure 1, is a conservative estimate of the cumulative distribution of total number of objects in LEO. A most pernicious aspect of the space debris problem is that, with a doubling of current number density, some analyses show the onset of a runaway conversion of the few large objects to millions more small objects due to self-collision and pulverization [Flury and McKnight 1993 and Loftus and Reynolds 1993].

Note that debris number in the very important 1 - 10-cm size range has not been catalogued because they cannot be "seen" by current radar systems devoted to that purpose, and so <u>must</u> be estimated. In LEO, such systems can see objects 10 - 50 cm in size, but in the vicinity of h = 1,000 km where maximum debris density occurs, only objects one meter or larger have been catalogued. The fact that only 8,000 objects have been catalogued [Flury & McKnight 1993], and that they favor the midrange of the 10-100 cm interval in Figure 2, suggests that Figures 1 and 2 may underestimate the number of objects in the 1 - 10 cm range. However, until state-of-the-art detection systems such as the one we propose are built, the true number cannot be known.

In the very important range  $1.5 \le d \le 10$  cm, neither International Space Station Alpha's current mechanical shielding design nor easily imagined augmentations are able to prevent a catastrophic result from impact [Cramer and Bogert 1992] for the smaller sizes, and detection limitations make steering avoidance difficult or impossible for the larger debris pieces.

The conclusion from published data is that, in this size range, the probability of catastrophe may range from 1.5% to as much as 10% over Alpha's 10-year life, well beyond the  $4.5 \times 10^{-3}$  design failure probability.

Today, space debris in low-Earth orbit (LEO) threatens any mission in the h = 1000 km vicinity which has a product of exposed area and on-station lifetime of the order of

10<sup>4</sup> m<sup>2</sup> – years. This same product is as readily achieved by a project which requires many modest-size satellites to be reliably on staton as by one featuring a single large space station. Current projects in this category are the plans of Motorola, Inc. to launch a 77-LEO-satellite worldwide voice communication network, those of the Teledesic consortium to launch an even larger network of datacomm satellites, and the recent launch by Orbital Sciences Corporation of the first of a 26-satellite constellation.

Figure 3 shows the lifetime of objects in circular orbit vs. altitude and size, assuming average mass density of  $0.2 \text{ g/cm}^3$ , chosen to be representative of debris objects. Large satellites have even smaller average mass density, on the order of 0.03 g/cm<sup>3</sup> [Loftus and Reynolds 1993]. Below about 300km, 1-cm size objects will rapidly re-enter by themselves while large objects have lifetimes of a few months. For altitudes h>900 km, debris objects are permanent, in a practical sense, and 10-cm objects are of concern down to 400km.

## 3. Previous Mitigation Work

Previously, mitigation of space debris has been discussed by a number of authors, notably Metzger, et al. 1989, Loftus and Reynolds 1993, Monroe 1994, and various discussions of the present concept [Phipps 1993, Phipps and Michaelis 1994 and Phipps and Michaelis 1995].

The approach of Metzger, et al. is space-based, featuring a nuclear-powered spaceborne debris sweeper powering a neutral particle beam or a 10-kJ, 1-Hz krypton fluoride laser ( $\lambda = 248$  nm). The advantage of this concept is that, in principle, the source can get closer to the debris object than a fixed base system, and that, assuming as we will that the object is spinning, the laser propagation vector can be directed precisely opposite to the momentum of the object for maximum effect. The disadvantages are several. In the first place, mass costs 10 - 20/g to put in low Earth orbit, an added cost that must be well justified compared to the 1/g typical cost of high-tech equipment on Earth. More important than launch cost are the added problems posed by alignment, operation, maintenance and refueling in space. We note that a multi-billion-dollar effort equivalent to placing the Hubble Telescope in orbit is needed to match the quality of optics already installed on Earth which have been augmented by adaptive optics systems. The latter are able to compensate optical distortion due to atmospheric turbulence using, e.g., a sodium "guide-star", as will be described in Section 10 of this paper. Also, because of the 1000-km depth of the space debris band, an orbiting debris sweeper needs a range of action which turns out to be not dramatically different from that of its ground-based counterpart to be effective in a reasonable time. As regards debris detection, a space-based system discards a "free" advantage of the ground-based system in that, from the ground, interesting objects are all moving against a fixed

background, which makes detection simple. In space, velocity discrimination must be used, leading to complicated schemes, e.g., involving 4-wave mixing. For debris mitigation, neutral particle beams were found by Metzger, *et al.* to require 10 times as much energy as laser beams and significantly greater energy storage. The authors do not list their assumptions about beam divergence, but the fact that they consider a maximum range of 10km is indicative of these assumptions. With a total mass of 6300 kg, the system of Metzger, et al. would cost about \$125M just to place on station, a cost about twice what we estimate for the total installed cost of the ground-based system we propose.

Monroe 1994 proposes a ground-based system featuring a 10-m-diameter beam director with adaptive optics correction and a 5MW reactor-pumped 1.73- $\mu$ m wavelength laser. The momentum coupling coefficient in this work is assumed to be  $C_m = 1 \text{ dyne}/W$ , which is probably appropriate for continuous-wave (CW) lasers.

Loftus and Reynolds 1993 catalog forces available for removing objects from orbit, including direct propulsion, enhanced aerodynamic drag, solar sails, electromagnetic drag, and solar/lunar orbit perturbations.

In this paper, we wish to introduce one more force: that of the ablation jet produced when a pulsed laser strikes a debris object.

## 4. LISP Concept Overview

Laser Impulse Space Propulsion (LISP) [Phipps and Michaelis 1994] is hardly the first proposal of photon propulsion [see Sänger 1956, Marx 1966, Möckel 1972a, b and 1975, Kantrowitz 1972]. The Sänger reference actually predates lasers by five years. The novel contributions of our work have been to show how modern laser and optical technology makes possible a number of useful applications which were not viable in earlier times, to emphasize the importance of using pulsed rather than cw lasers for most applications, and to renew interest in the subject. Among these applications are keeping geosynchronous satellites on station, repeatedly reboosting low-orbit "cheap-sats" and LEO to geosynchronous (GEO) transfer [see Table 1, from Phipps 1995].

In the LISP concept, a repetitvely-pulsed laser transmits a high-quality beam to the propelled object's surface. The object then propels itself by the reaction force produced by the laser-driven ablation jet. The repetitive pulse format is crucial to permit using optimized laser-plasma interaction parameters, since laser target irradiation parameters I,  $\tau$  and  $\lambda$  remain free for each problem. In contrast, a major problem with impulse production with CW lasers is that they melt through the target before the generate much (or any) net impulse, and might detonate a debris object, dividing it into many smaller objects which are much harder to detect and track. The mass ablated from the object plays the rôle of mission fuel. The correct laser parameters to heat the ablation jet

to the required temperature for the desired  $I_{sp}$  in each application can be calculated [Phipps and Michaelis 1994; Appendix I]. Given a criterion such as minimum cost per kg for a specified velocity increment, optimum values of  $C_m$ , Q<sup>\*</sup> and  $I_{sp}$  result for each problem. Given other parameters such as laser range *z*, an optimum set (I,  $\lambda$ ,  $\tau$ ) also results. This feature explains our choice of repetitively-pulsed lasers, since cw lasers do not offer the peak target power we require at reasonable values of average beam power.

The tradeoff between per-pulse energy and laser repetition rate is decided by laser and optics technology as well as by the requirements for stable atmospheric beam propagation. For most applications, a ground-based laser station is used. This is because it can cost as much as 20/g to put objects (such as laser systems) into low-Earth orbit. Detection from ground base is advantageous because this perspective offers targets moving against a fixed background.

LISP variant	Definition	Laser Power	Optimum λ	Governs λ	Laser Location
NEO-LISP	Near-Earth-Object deflection	6 GW	4 <i>µ</i> m	Range, energy cost and SRS	Earth surface
LEO-LISP and SOLLISP	Direct launch, to LEO	2 GW	4 µm	Energy cost & atmospheric transmission	Earth surface
LO-LISP	LEO re-boost	100 kW	4 μm	Energy cost & atmospheric transmission	Earth surface
ORION	Clearing Space Debris	20 kW	530 nm	Range, object size	Earth surface
LEGO- LISP	LEO to GEO orbit transfers	10 kW	800 nm	Laser diode parameters and fiber loss	On board
LISK	GEO Station- keeping	100 W	530 nm	Range & atmospheric transmission	Earth surface

Table 1: No one type of laser is best for all scenarios

## 5. ORION System Roadmap

## 5.1 General

The target irradiation geometry is illustrated in Figure 4, and a conceptual layout for the laser system and its adaptive beam director is presented in Figure 5. We have concluded that a ground-based system consisting of a moderate-average-power, repetitively-pulsed laser, an astronomical observatory-style beam director and an acquisition and tracking system make sense for mitigation of the space debris problem. Mitigation occurs by causing an ablation jet to form on the Earth-facing side of the debris object, producing enough impulse to drop its perigee sufficiently to cause reentry. More conceptual details for this beam director, laser and tracking system will be shown later [Figure 20]. We chose a ground base for the system because the high cost of putting hardware in low-Earth orbit is not balanced by an equivalent increase in capability. Multiple laser pulses are required to impart adequate impulse to even the smallest objects. Such thrust as is produced will be perpendicular to each exposed surface element of the object.

## 5.2 Spinning

Spinning is expected for many of the objects due to the fact that they were created by detonation of upper stages of launch vehicles. The decay time for such spinning will be years for most of the objects with which we are concerned at altitudes above 600 km. For a spinning object, the thrust developed on each surface element will go to zero as the angle with the laser k vector goes to  $\pi/2$  incidence and, of course, no thrust is developed on a surface element whose surface normal lies not far from the laser propagation vector. As a result, for a general 3-component spin vector, and an irregularly-shaped object, a significant component of the time- and surface-averaged impulse vector must always be directed outward, away from the Earth, in the direction defined by the laser beam. In analysis for this paper, we take this to be the typical case.

## 5.3 Laser Wavelength

Laser wavelength was chosen to be 530 nm (frequency-doubled Nd:YAG) because a) ability to deliver intensity to the target at range is a critical cost factor, and this intensity varies inversely with the square of the wavelength in the limit of perfect atmospheric turbulence compensation, b) atmospheric transmission is still reasonably good for green light (but not, e.g., for uv excimer wavelengths), and c) the overall efficiency and state of development of Nd laser technology is such that system cost will be much less than for other acceptable alternatives (including excimers) [see § 6 and §9].

#### 5.4 Laser Pulse Duration

The requirement for producing impulse on the target is that a certain amount of laser energy  $W = I\tau$  be delivered to the target at the intensity for optimum momentum generation [see Appendix II]. Laser pulse duration is limited on the short side by unacceptable gain for conversion of the laser beam to undesired propagation vectors due to Stimulated Raman Scattering of the laser beam (SRS) in the atmosphere. This is intensity-dependent, SRS gain being fairly constant vs. altitude when expressed as cm/MW up to about 40 km. Reaching the SRS conversion limit forces us to choose longer pulse durations (and lower peak intensity) for the same laser pulse energy and nearly identical delivered mechanical impulse. On the long side, laser pulse duration is limited by unacceptable gain for unstable growth of transverse laser beam intensity variations due to refractive index gradients produced by beam-induced thermal inhomogeneities in the atmosphere [see Appendix II].

#### 5.5 Laser Spot Size at Range

We take 40 cm to be the laser spot size at maximum range, 1400 km, corresponding to 45-degree zenith angle at 1000 km target altitude, reasonable assumptions about laser beam quality transmitted through the atmosphere, and a 6-m-diameter beam launch optic [see §9-10]

The spot size d<sub>s</sub> at the target is related to beam launch optic diameter D, beam quality, range and wavelength by:

$$\frac{1}{d_s^2} = \left(\frac{\pi D}{4Nz\lambda}\right)^2 + \frac{1}{D^2}$$
 [2].

With N = 2.5 times diffraction-limited delivered beam quality, D=600 cm and  $\lambda$  = 532 nm are consistent with d<sub>s</sub> = 40 cm.

#### 5.6 Laser Pulse Energy

Laser pulse energy W is set by the requirement that the intensity on target be that for maximum mechanical coupling coefficient  $C_m$  [see Eq. A8, Appendix II]. This condition gives the laser pulse energy as a function of  $d_s$  and  $\tau$  [see Eq. A9]. We consider a few combinations of W and  $\tau$ , and make the final selection (W = 20kJ) based on least capital cost consistent with getting the debris clearing job done in an acceptable time.

#### 5.7 Laser Average Power

The final major laser parameter is mainly determined by urgency for clearing near Earth space of debris. In the concluding section of this paper, we select P = 20kW, for which a clearing time of about 4 years results, provided no new debris objects are added. This choice is tantamount to choosing laser repetition rate f = 1Hz. There is nothing critical about this choice: selecting f = 2 Hz or f = 1/2 Hz would not change the capital cost per laser watt very much. Larger changes would begin affecting other

tradeoffs in atmospheric propagation, component peak or average power capacity, and so on.

#### 5.8 Orbit Mechanics and Laser Pulse Number per Target

We have done orbit calculations to prove this laser intervention concept works [Appendix III].

For objects in circular orbit at altitude h<1000km,  $|\Delta v| \le 235$  m/s is sufficient to cause re-entry and burnup with comfortable safety factor and, for the case of a 1000km x 500 km orbit,  $|\Delta v| = 113$  m/s is sufficient [see Appendix III]. Considering the number of objects, the only realistic way to apply this  $\Delta v$  is with a laser, taking advantage of rapid retargeting. We further believe the laser should be a ground-based laser, in view of the present \$20k/kg cost of placing objects in LEO.

In vacuum, most opaque materials are "surface absorbers" (see Phipps, *et al.*, 1988), for which there exists an optimum laser pulse intensity  $I_{opt}$  near the threshold for plasma formation at which  $C_m$  is maximum. The reason for this behavior is that, below  $I_{opt}$ , more and more of the laser energy is invested in heating and melting rather than in ablation, while above  $I_{opt}$  the behavior  $C_m \propto 1/\langle v \rangle \propto 1/(I\lambda\sqrt{\tau})^{1/4}$  [Phipps *et al.* 1988] dominates.

We use laser momentum coupling parameters appropriate for a "non-cooperative" target,  $C_m = 10$  dyne-s/J, which is achieved by a variety of materials at green to UV wavelengths (see Figure A1 and Phipps, *et al.*, 1988).

We illuminate each debris object during the access time  $t_{acc} \le 58s$  while it is ascending between 45° and 30° zenith angle. We employ an efficiency  $\eta = 25\%$  to account for the combined effects of inefficient thrust generation ( $\langle \cos\beta \rangle \ne 1$  [see Figure 4]) and to take account of the effects of transmission loss in the optical system and in the atmosphere. An added safety factor accrues from the fact that laser spot size on the debris object is always assumed to be  $d_s = 40$  cm, whereas smaller spot sizes are possible for shorter ranges than 1400 km.

Including the factor  $1/\eta$ , a total energy W = 9.4 kJ/g is required to be supplied by n laser pulses to provide the maximum necessary  $\Delta v$  to the debris object. When, as in this case, only a small part of the debris object mass  $M_0$  is ablated, the energy required for an individual laser pulse can be expressed as

$$W = \frac{u M_o}{n \eta C_m} |\Delta v|$$
[3]

where

$$u = (d_s/d)^2 \qquad d_s > d,$$
  
=1  $d_s \le d$  [4]

is a step function accounting for the situation in which the beam is larger than the debris object. Combining Eq. [3] with Eq. [A9], we get an expression for the total number of laser pulses required to provide  $\Delta v$ :

$$n = 5.0 \times 10^{-5} \frac{u M_o |\Delta v|}{C_m A_s \sqrt{\tau}}$$
 [5]

#### 6. Detection and Tracking Roadmap

It is straightforward to show that a pulsed laser can cause objects in LEO to reenter in an energetically efficient manner. A more difficult problem is to acquire and track objects as small as 1cm at ranges as large as 1400 km.

The concept of Ho, Priedhorsky and Baron (1993) [see §7] plays a crucial rôle in our proposal, for high-efficiency target detection without an active source other than natural sunlight. With their existing design, it is possible to detect and track an individual 1-cm object with 0.08 albedo at 500 km range in sunlight with a 20-cm-aperture telescope having a 1-square-degree field of view. This is equivalent to recently demonstrated results from the MIT Haystack radar site which is, however, much more expensive and has a much narrower field of view. It is likely that the opto-electronic part of the Ho, Priedhorsky and Baron detector can be replicated in large numbers for \$200k or less. It would be a simple matter to increase the collection aperture for this detector to 50 cm to permit detection of 1-cm objects at 1400 km, as required for ORION.

The deficiencies of this concept for debris acquisition are that it can be used effectively only during 3 – 4 hours per day, on objects that are between 500 and 1000 km altitude and illuminated by the sun against the early dawn or late twilight sky background, and that it does not give range information. The first deficiency only applies to a single site, however. These detectors can be located at several sites distributed along the Equator so that at least two sites always have good observing conditions. To provide 2-D tracking information for a debris object, many arrangements are possible.

For example, detectors at each site can be arranged to form a "fence", viewing a 20° x 1° solid angle oriented along the Equator [Figure 5]. Armed with information from the detector fence, a small pulsed lidar at each site can then easily obtain range while tracking the object. With a 1-m mirror, a relatively simple dual wavelength, single-pulse Nd:YAG site-based tracking laser would suffice.

The tracking laser has 10-ns pulsewidth to provide 3-m range resolution, and a "coarse" and "fine" footprint of 20x20m and 2x2m, respectively, at a range of 1000 km (20 and  $2\mu$ rad). Output in coarse mode is 1.06 $\mu$ m, 500J and 530nm, 400J in fine mode.

In the "coarse" mode, target intensity is  $I=16 \text{ kW/cm}^2$  (>  $10^5 \text{ suns}$ ), giving 33 photons into the 100-cm-aperture tracking mirror at 1000 km range from a 1-cm-diameter, 0.2 albedo object. The 1-cm micro-channel intensified CCD detector array is gated on for 2ms to limit background to 20 photons for a 16th magnitude star. The CCD provides tracking error information to the tracking telescope drive on each tracking laser shot, so long as the illumination footprint embraces the object. To give this kind of performance, adaptive optics are necessary. Computer software subtracts most of the star background from each stored scene. The tracking telescope slews with the object being tracked. Note that this scheme could not work without the input provided by the fence of 20 detectors. In the "fine" tracking mode, 1660 photons per shot are received from the target, adequate for rapid tracking.

Once a preliminary track is formed and refined by 2 or 3 reacquisitions by other tracking stations and accurate ephemerides computed, an object's future position will lie within a 2x2x3-m pillbox, and the object can be handed off to the ORION station. There it can be acquired by a similar tracking laser using the station's full 6-m aperture, the pointing correction for the main beam determined, and the high-power target irradiation sequence carried out with guidance from tracking laser shots.

This will be possible even if the target is not illuminated by the sun at the ORION site, and operation in the dark is required if one ORION station is to 24 hours a day, as we assume. The ORION tracking laser is identical to that at the distributed sites, except that it has access to the full 6-m aperture of the ORION beam director, providing a finer maximum spacial resolution of 40 cm.

A word should be said about the expected data rate vs. the functionally necessary processing rate. On the average, there should be about 0.5 events per "fence" detector per second. However, as we shall see, we have 4 years to deal with the approximately 300k space debris objects, which means that we can pick and choose, as well as taking enough time to do the tracking right. It is sufficient to deal with 1 track each 2 minutes for one of the target acquisition sites somewhere on Earth, meaning that ephemeris data for debris objects should come in more rapidly than it is needed by the single target deceleration laser site.

## 7. High Efficiency Optical Detection System

#### 7.1 Concept

No matter how effective the means of sweeping debris, it will be useless unless the debris can be found and tracked. In the optical band, active laser techniques for sweeping the sky cannot compete with natural sunlight illumination. This is because of the enormous power in sunlight. For example, a 5km x 5km piece of sky (subtending 0.3

square degrees at a range of 500 km) receives 30 GW of continuous sunlight. It would be difficult to build a laser that could do better.

Sunlit debris is not particularly faint, as astronomical objects go. For example, a sunlit spherical object of 1.3 cm diameter and typical albedo at 400 km range has an apparent magnitude of 16. During dawn and dusk, this would stand out against the dark sky. A small telescope can easily detect a 16th magnitude star in seconds. The problem is the rapid motion of the object through the field of view. Imaging photon-counting detectors can make such detection possible [see Ho, et al. 1993].

The orbiting object moves at a high velocity relative to a fixed background of stars and diffuse light. This signature is unique to fast-moving foreground objects, and can be exploited to detect and track space debris. It is, however, difficult to detect small objects with an imaging detector collecting two-dimensional (2-D) data: the signal from the small debris, which is a faint track with length proportional to the image integration time, will be overwhelmed by the background. With the advance of fast imaging photon-counting detectors, the data can be collected in a three-dimensional (3D) format, i.e., (x,y,t) of individual photons. This additional dimensionality greatly enhances the statistical significance of linear features in the data. Figure 6 shows a schematic comparison of the significance of 2D and 3D data sets.

#### 7.2 Statistical Advantage of 3D (x,y,t) Data

For background photons randomly distributed in a volume V with density  $\rho_{hv}$  the mean number of photons contained in a line of length L is

 $\langle p \rangle = \rho_{hv} V_1$  [6]  $V_1 = LS$ 

where

is the "volume" of the line, and S its "cross-section". Then, with  $N_L(V_1)$  denoting the number of lines with volume  $V_1$  in V, the number of lines of length L consisting of  $\mu$  photons is

$$N_{L,\mu} = \frac{N_L(V_1)}{\mu!} ^{\mu} \exp(-)$$
[7]

The cross-section S of the line can be larger than one square pixel in digitized data, depending on the operational definition of the line.

For example, suppose there are B photons randomly distributed in a grid of  $\boldsymbol{D} \times \boldsymbol{D}$  pixels. Then, taking  $L = \boldsymbol{D}$ , S = 1 and  $N_L = \boldsymbol{D}^4$ , the expected number of lines which could consist of  $\mu$  photons due to random chance is

Digitized 3D data set: N 
$$\mathbf{D}_{\mu} \approx \frac{\mathbf{D}^4}{\mu!} \left(\frac{B}{\mathbf{D}^2}\right)^{\mu} \exp\left(-\frac{B}{\mathbf{D}^2}\right)$$
. [8]

Taking B =  $10^6$  and **D** = 2048, we get N<sub>**D**,  $\mu \le 10^{-10}$  for  $\mu = 16$ , showing that the detection of a 16-photon line against a background of  $10^6$  photons is highly significant in the 3D case.</sub>

In comparison, if the data is in 2D instead of 3D, the expected number of lines consisting of  $\mu$  photons due to random chance is

Digitized 2D data set: 
$$N \mathbf{p}_{,\mu} \approx \frac{\mathbf{D}^2}{\mu!} \left(\frac{B}{\mathbf{D}}\right)^{\mu} \exp\left(-\frac{B}{\mathbf{D}}\right)$$
 . [9]

With the same parameters, at the same level of significance  $(10^{-10})$ , we can only hope to find lines consisting of more than about  $\mu = 680$  photons. Of these, we expect about 500 photons to come from the background and about 180 from the source. A 16-photon excess would be utterly lost against the background.

In summary, we see a great advantage in going to a 3D data format. To realize this detection scheme, we need a) an imaging photon-counting system with high count rate, and b) a viable data analysis scheme to search for the line.

#### 7.3 Baseline Detection System

Our baseline detection system stares at a 1° circular field and detects debris objects transiting this field in any direction at any speed. Ho, Priedhorsky and Baron (1993) have developed a fast imaging photon-counting detector with a 2048 x 2048 format and 10<sup>6</sup>/s maximum count rate. This detector is based on microchannel plate intensification and crossed delay-line readout. Its time resolution is  $<1\mu$ s, even though we only need a resolution of ~ 1 ms for debris tracking. Choosing the largest possible telescope that does not saturate the detector dictates a 16-cm aperture, for which the night sky would vield a count rate of  $10^6/s$  in a 1° circular field of view, assuming typical quantum efficiency for an unfiltered S-20 detector. This count rate corresponds to the moonless sky brightness at zenith for mean galactic latitude, which is  $22.5 \text{ mag arcsec}^{-2}$ . Of the count rate, roughly 25% would be from stars brighter than 16th magnitude, and the rest would be airglow, zodiacal light, faint stars and diffuse galactic light. The stellar contribution would be removed in preprocessing, leaving a diffuse background count rate of ~  $7.5 \times 10^5$ /s to be processed for moving objects. A debris object of visual magnitude ~ 16 at 400 km will yield 16 counts in the 1 second that it is in the field of view. These are enough counts to be significant against the sky background. This magnitude corresponds to a 1.3-cm-diameter sphere at 400 km altitude, behaving as a Lambertian scatterer viewed at phase angle 90° with geometric albedo 0.08. An object with the same visual magnitude at 1000 km altitude would be 3.3 cm in diameter.

The detector will detect each photon at its location (x,y). With the detector electronics providing the approximate time tag t, each photon is represented by a point in a 3D digitized (x,y,t) space. A data set taken in one second consists of  $10^6$  photon

records in the  $(2048 \text{ pixel})^3$  volume. The reflected sunlight photons form a straight line in this volume. In comparison, a stationary object such as a star yields a concentration of photons in certain (x,y) locations independent of t, and the diffuse background yields randomly distributed photons. The data processing task can be reduced to the mathematical problem of finding a statistically significant line at an oblique angle in this volume.

One of the key challenges for debris detection is the large volume of data and processing needed to extract the useful information. A crude estimate of the number of independent lines passing through the box is  $(2048)^4 > 10^{13}$ . Examination of all possible lines is a formidable task, requiring very long processing time or massive parallelism. Ho, Priedhorsky and Baron (1993) have developed and simulated an algorithm to tackle this problem. Their "hierarchical pair and stretch" scheme dramatically reduces the processing problem, while providing a high probability of object detection.

We therefore anticipate that a small telescope with an imaging, photon-counting detector can detect cm-scale debris objects at useful range in LEO, then hand them over to an active tracking sytem for precise trajectory determination.

It is expected that the entire detection system, including telescope, mounts, detectors, electronics and digital acquisition system will cost less than \$200k when replicated in the quantities anticipated here.

## 8. Laser System Concept

Section 5 above shows that the most cost-effective laser system for this application is a pulsed, frequency-doubled neodymimum glass laser delivering roughly 20kJ/40 ns pulses of green light at a pulse rate of 1 Hz, with a beam that is better than about twice the diffraction limit (Strehl ratio >0.25). Strehl ratio is the ratio of the intensity of a beam in the center of the far-field divided by the intensity produced there by a perfect optical system. We show in this section that advanced glass laser technology has already demonstrated performance approaching this value in single pulses, and that there are technological development paths available to increase the pulse rate of these systems to the desired value.

## 8.1 "Beamlet" Demonstration Project

The Beamlet Demonstration project at the Lawrence Livermore National Laboratory (USA), shown in Figure 7, is a prototype for future large Nd:glass laser systems for inertial confinement fusion research [LLNL report 1994]. These fusion lasers would combine many such beamlets to achieve frequency-converted single-pulse energy greater than 1MJ in a few-ns pulse at a rate of perhaps once every few hours. The single prototype beamlet now operating has demonstrated performance close to the single-pulse requirements of the ORION laser, including fundamental energy (prior to frequency conversion) of 15.5 kJ in 8-ns pulses, 80% efficiency in conversion to the second and third harmonic, and a Strehl ratio of 0.4 in a high-energy beam [van Wonterghem, *et al.* 1995]. Frequency conversion tests have concentrated on the shorter pulses appropriate for fusion, so these have not been conducted at 40ns. However, the physics of frequency conversion is well-understood, and the converters should perform equally well with 40-ns pulses when these are re-optimized for the lower intensity.

Beamlet is a flashlamp-pumped, Nd:glass laser which uses 16 rectangular amplifier slabs with a 39-cm clear aperture tilted at Brewster's angle to the beam. It differs from previous large glass lasers in that it uses multiple passes through a single large amplifier stage, rather than using numerous intermediate amplifiers of increasing size, to go from an injected energy of about 1J to an output of about 10kJ. The advantage of this multi-pass arrangement is a dramatic reduction in component number and system cost.

To minimize system cost, it is important to operate a large laser system at the highest acceptable average fluence  $\Phi$ , since this quantity determines the area of the beam. Fluence in the system is limited by optical damage to small defects in the optical components in the regions of peak fluence, so we must minimize the ratio of peak to average fluence in the beam. Beamlet minimizes this ratio by using relay telescopes to reimage a very flat input intensity profile at several planes through the laser chain. The effective optical propagation distance from the original flat profile is reset to zero at each image, so diffractive noise growth is minimized by this strategy. High-spatial-frequency noise, which can see exponential growth at very high intensities, is also reset to zero by blocking at the position where the beam comes to a focus in the relay telescope. Because this focal fluence is very large, such telescopes are evacuated.

Figure 8 shows a diagram of the arrangement of the laser hardware in the system. An input pulse of about 1J from a preamplifier strikes a deformable mirror (DM), used to correct for optical aberrations, and enters the laser output stage by reflecting from a small mirror near the focal plane of a relay telescope formed by lenses  $L_1$  and  $L_2$  in the Figure. The pulse comes to a focus and reexpands to fill the amplifier aperture. Next, it passes through a long amplifier composed of 11 slabs, reflects from mirror  $M_1$ , and makes a second pass through the amplifier, emerging with about 100J energy.

At the other end of the laser cavity is an optical switch consisting of a plasmaelectrode Pockels cell (PEPC) and a thin-film polarizer. As the pulse is injected for its first two passes, the PEPC fires to rotate the polarization so that the pulse passes through the polarizer, strikes mirror  $M_2$ , and returns to the amplifier for a third and fourth pass, finally emerging with an energy of about 6kJ. By switching the PEPC off when the pulse returns to the Pockels cell, the pulse is now made to reflect from the polarizer and make a single pass through a second, five-slab amplifier. A transport spatial filter relays the pulse to the frequency converter, where the energy is 12 - 15 kJ. Figure 9 summarizes energy transfer in the Beamlet final amplifier stage. Output rises to 15.5 kJ for 1-J injected energy, with a zero-intensity beam size of 34x34 cm. During these tests, beam size was limited by the size of the Pockels cell crystal installed. Whole-beam conversion efficiency to the second and third harmonic excees 80% for intensities of  $3 - 4 \text{ GW}/\text{cm}^2$  using a frequency converter optimized for Inertial Confinement Fusion (ICF) pulses at the third harmonic. Second harmonic performance could be better with a converter designed to optimize performance at 530 nm.

Figure 10 shows the output beam intensity profile measured at the fundamental and third harmonic, and Figure 11 shows an intensity scan taken through the center of the third harmonic beam. Peak-to-average intensity noise is about 1.3:1 for both profiles. This ratio is somewhat lower for longer pulses, since the amplifiers will be highly saturated. The effective beam area, allowing for the gradual intensity decrease at the beam edges, is 970 cm<sup>2</sup>.

An output sensor samples the wavefront of the output beam from Beamlet and calculates a correction to be applied to the 39-actuator DM located between the preamplifier and final output stages. This system correctes for optical aberrations in the laser components, long-term thermal aberrations in the system, and the repeatable prompt thermal aberrations caused by the flashlamp pulse. Recent tests show that this system can correct the output beam to a Strehl ratio of 0.4, as shown in Figure 12. The measured far-field spot is shown in Figure 13.

#### 8.2 Scaling from Beamlet to the ORION laser

Similarly to fusion lasers, the ORION laser will operate at high fluence to minimize size and cost of laser optics. The limit to the output fluence from a Nd:glass laser is set by optical damage thresholds, which are reviewed in Table 2 [see Campbell, *et al.* 1990]. Single-pulse optical damage thresholds at 530 nm have not been studied extensively, but should be closer to the safe fluences for 1060 nm than for the third harmonic at 350 nm.

#### Table 2

<u>Sale peak working fluence <math>\Psi</math> for high-quality optical component</u>	Safe peak	working	fluence <b>Φ</b>	<u>for hi</u>	gh-c	quality	0	ptical	com	ponent
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	$\Phi$ variation with $\tau$ (1-10ns) (J/cm <sup>2</sup> )	Inferred $\Phi$ at $\tau$ =40 ns (J/cm <sup>2</sup> )
1060 nm		
Antireflection coating	$25  \tau^{0.40}$	110
KDP crystal, bulk damage	$24 \tau^{0.50}$	150
High-reflection coating	$18  \tau^{0.30}$	54
Polarizer, in reflection	$12  \tau^{0.35}$	44
350 nm		
Antireflection coating	$11  \tau^{0.40}$	48
KDP crystal, bulk damage	$7   au^{0.50}$	44

The laser output would be expected to have peak-to-average fluence modulations less than 1.4:1, so an oaverage output fluence of  $30 \text{ J/cm}^2$  in 40-ns pulses (peak of 42  $\text{J/cm}^2$ ) is very safe at 1060 nm, if we use care in positioning polarizers. At that fluence, a beam effective area of 1000 cm<sup>2</sup>, similar to Beamlet values, allows a single pulse energy of 30kJ at 1060 nm, ocnverting to about 24 kJ at 530 nm. This would probably be a round beam with 38-cm zero-intensity diameter. It might be necessary to expand the beam slightly to handle the 530-nm fluence on beam director mirrors.

The 16 Beamlet slabs are extracted to the maximum practical level at  $\Phi = 16 - 20$  J/cm<sup>2</sup>, depending on cavity losses, so the number of slabs in the system would rise to provide the extra fluence. Since the energy stored per slab is 1.6 J/cm<sup>2</sup>, the total number of slabs should be 22–24 for the ORION laser.

#### 8.3 Average power issues

LLNL conducted studies of technology for large gas-flow-cooled, Brewster's-angle slab amplifiers in the late 1980's which showed that such systems would operate continuously at pulse rates of one to a few Hz.

The amplifiers would use Nd:glass slabs surface cooled by gaseous helium [see Sutton and Albrecht 1991]. Figure 14 shows the amplifer and flow channel geometry. The Nd-doped center slab and two undoped glass windows define the flow channels. Helium gas flows through these channels at a velocity of about Mach 0.1 at a pressure of 2.5 atmospheres. Extensive analysis [Robey, *et al.*, 1991, Erlandson, *et al.* 1992] and experiments [Albrecht, *et al.* 1990] on heated glass slabs show that it is quite practical to remove a heat load of several W/cm<sup>3</sup> from the slabs with associated optical losses less than 1%. The amplifier would also require cooling of flashlamps and slab-edge claddings. Since these are not in the optical path, conventional liquid cooling techniques may be used. Some ICF amplifiers already use water-cooled flashlamps [Shoup, *et al.* 1992].

#### 8.4 Repetitive Pockels cell operation

The PEPC on Beamlet routinely operates at 1/4-Hz pulse rate for long periods. There would be no electrical or electrothermal issues for operation at 1Hz. The Pockels crystal should be deuterated to reduce 1060 nm absorption.

## 8.5 Frequency converter

Absorptive losses in the converter are small, so high-average power operation is not difficult, with deuterated crystals. LLNL has operated  $10\text{-cm}^2$ -area high-average-power doublers at up to 82% efficiency with 12-ns pulses and  $0.1 - 0.3 \text{ GW/cm}^2$  [Dane, *et al.* 1995]. The ORION drive intensity is  $0.7 \text{ GW/cm}^2$ , an operating point which lies between that for this doubler and the Beamlet converters discussed above. The average beam power in this doubler was  $\leq 15 \text{ W/cm}^2$ , a level comparable to the ORION system's  $30 \text{W/cm}^2$  average beam power ( $30 \text{ J/cm}^2$  at 1 Hz).

## 9. Limitations due to Atmospheric Transmission

In this section, the effects of various atmospheric processes, including those induced by the laser beam, will be discussed, and mapped together to graphically select the range of those parameters which are best for the ORION concept. Table 3 shows the effects we consider mapped against the parameters of the laser beam and of the atmospheric propagation path. Inspection shows that laser-induced thermal distortion (thermal blooming) is affected by the largest number of laser parameters, followed by air breakdown, beam spreading due to atmospheric turbulence, stimulated Raman scattering (SRS) and, finally, diffraction and atmospheric absorption.

The effects of these processes on delivered laser beam quality can be mitigated by adjusting laser device parameters, and by properly choosing the transmitter basing site and the propagation time-window to minimze beam degradation.

## 9.1 Atmospheric Turbulence

Diffraction and atmospheric turbulence combine to spread the beam relative to the path predicted by geometric optics. Turbulence can also re-point the beam [see §10]. The effective beam divergence angle controls the target spot size  $d_s$ . since these two effects are not correlated, they can be combined according to the relationship:

$$\theta_{\rm eff}^{2} = \left(1.22 \ \frac{\lambda}{D}\right)^{2} + \left(\Delta \theta_{\rm turb}^{\rm ref}\right)^{2} \left(\frac{\lambda^{\rm ref}}{\lambda}\right)^{0.4} \qquad (10)$$

In Eq. (10), with  $\lambda^{\text{ref}} = 1 \ \mu\text{m}$ ,  $\Delta \theta_{\text{turb}}^{\text{ref}} = 2.0 \ \mu\text{rad}$  for propagation from h = 6km to space, and 9.0  $\mu$ rad for propagation from sea level to space in conditions of heavy lower atmosphere turbulence.

Figure 15 compares the effective beam divergence angle given by Eqn. 10 for various laser wavelengths, initial beam diameters and path-integrated turbulence strength to that for diffraction-limited propagation. As is illustrated in the Figure, minimum  $d_s$  is not necessarily achieved by the shortest-wavelength laser, but rather depends on atmospheric turbulence. If adaptive optics are used to remove a large part of the turbulent beam spread [see §10], then the smallest focal points are made by the shortest wavelengths. Adaptive optics are crucial to the success of our approach.

The highest mass density portions of the atmospheric beam propagation path are in the near field of the transmitted beam. The ratio of target intensity limited by both diffraction and turbulence to that limited only by diffraction is given to first order by

$$\frac{I_{eff}}{I_d} = \frac{\theta_d^2}{\theta_{eff}^2} \qquad (11)$$

This ratio can be much less than 1 (low Strehl ratio) when reasonable size (1 - 10 meter) diameter) optics are employed in a ground-based beam director without adaptive optics. This relationship is plotted in Figure 16 for  $\lambda = 530 \text{ nm}$  and 1060 nm. The Figure makes it clear why it is important to launch the beam from an elevated site.

## 9.2 Other Effects

Extinction (absorption and scattering) of the beam has been studied extensively as a function of wavelength in the linear absorption regime, where neither the molecular or aerosol components respond to the radiation in any other way than passively absorbing energy. At high intensities, absorption can heat the propagation medium and cause enhanced scattering from aerosols and raypath bending (leading to thermal blooming). At very high intensities, intensity-dependent refractive index effects and air breakdown can occur [see §9.4], as well as plasma ignition. For the pulse durations we use, the latter two will dominate propagation at intensities well below those required for the former. Another effect occurring at high intensity is stimulated Raman scattering (SRS), the effect of which is to cause the nitrogen in the atmosphere to lase at a different wavelength, and with much worse divergence than that of the primary beam. The nonlinear effects of thermal blooming, SRS and air breakdown depend in a complicated manner on local beam intensity, laser wavelength and pulse duration. Scaling laws have been developed from the sparse experimental database and from the sparse selection of credible numerical simulations performed over the last 10-15 years. We have used these scaling laws to produce a map of the atmospheric propagation limits relevant to our problem so as to allow their comparison with beam parameters as dicatated by impulse production at the target. The cross-comparison allows us to recommend the range of laser wavelength, pulse duration, pulse repetition rate, beam diameter and intensity which satisfy all imposed conditions. The scaling laws are plotted in Figures 17 and 18. For air breakdown, see Lencioni and Kleinman 1975, Reilly 1976 and Hoffland 1986. For SRS scaling laws, see Ullrich 1984, Kurnit and Ackerhalt 1984 and Bischel and Heustis 1984. For more information on whole-beam thermal blooming, see Morris and Fleck 1977, Gebhardt 1976, Zeiders 1974 and Barnard 1989.

The fact that we are comparing ground-base sites at sea level and on a mountain peak determines the altitudes chosen for Figures 17 and 18. The wavelength region chosen for the Figures was 0.5 to  $1\mu$ m due to availability of laser device hardware, because this range is well-characterized for thermal blooming, SRS and air breakdown, and because adaptive optics technology has been demonstrated in this region.

#### 9.3 Stimulated Raman Scattering

A word should be said about the assumptions behind the SRS limit at  $\lambda = 530$  nm. The SRS gain  $g_R$  for a vertical path through the atmosphere from the 5.9-km-altitude of the Uhuru site on Kilimanjaro [see §11] at 530 nm is about  $5.5 \times 10^{-6}$  cm/MW [Kurnit 1994], the effective path length for zenith angles  $\leq 45$  degrees is L $\leq 35$ km, and I = 1.7 MW/cm<sup>2</sup>, so G = Ig<sub>R</sub>x<sub>atm</sub>  $\leq 35$  nepers. Based on our analysis, we believe SRS conversion should just be acceptable. That is, we have picked  $\tau = 40$  ns deliberately, in order to have a minimum pulse duration just on the edge of unacceptable SRS conversion [see Figure 17] in order to simplify certain laser design issues. A more detailed analysis might push the design toward somewhat longer pulse duration without difficulty from thermal propagation instabilities.

#### 9.4 Thermal Beam Propagation Instabilities

Pulsed laser beam propagation is subject to deleterious effects from the development of thermal propagation instabilities at micro as well as macro scales [Barnard 1989]. These are summarized in Appendix II. In the atmosphere, the laser beam parameters we have chosen give maximum fluence  $\Phi_{\text{beam}} = 70 \text{ mJ/cm}^2$ , insufficient to produce thermal propagation instabilities. This would not be true for a long-pulse or cw laser.

## 10. Adaptive Optics Correction

The need for an adaptive optics system is evident from the observation that the turbulence correlation scale, the so called Fried parameter [Fried 1965],  $r_{o'}$  is much smaller than the (beam director) mirror diameter, D = 6 m. This relation is true even for sites atop high mountains such as the Uhuru site at 5.9 km or the best astronomical sites such as Mauna Kea in Hawaii at 4.2 km.

Propagation through turbulent atmospheres distorts the beam quality of a laser in two ways: first the small scale turbulence increases the beam divergence to a value equal to  $\lambda/r_0$  so that for mirrors D >>  $r_{0'}$  the ratio of the beam divergence to the diffraction limit of the telescope is  $\approx D/r_0$ . For the ORION application where  $r_0(\lambda = 530 \text{ nm}) \approx 20 \text{ cm}$ , the increase in beam divergence and therefore in spot diameter at the target, is  $\approx 25$  times the diffraction limit (even for a high quality beam) or about 3.5 m. A spot this size would require enormous energy to ablate a jet from the debris.

The second effect is that the large scale turbulence results in a pointing error which may cause the laser to completely miss the target even though the effects of small scale turbulence may have been corrected. For D >>  $r_{o'}$  the ratio of the average tilt of the wavefront to the diffraction limited pointing angle is  $\approx 0.6(D/r_o)^{5/6} = 8.8$  for the same values of D and  $r_{o}$ . Thus even if the laser beam divergence has been corrected to the diffraction limit and the spot diameter is likewise diffraction limited, it will still miss the target most of the time unless the pointing error is corrected as well.

The adaptive optics technique is simple in concept. It involves sensing wavefront distortion from either the target, if it is sufficiently bright and moving slowly enough, or a nearby beacon which in the case of space debris must be generated artificially. The wavefront distortion is then removed by changing a computer controlled deformable mirror in the optical path of the laser. The sampling (spatial) frequency for the wavefront sensor is of the order of  $r_0^{-1}$  while the sampling bandwidth is of the order of  $v_w/r_0$  where  $v_w$  is the effective wind velocity. Therefore the number of photons needed to correct the laser beam scales as  $r_0^{-3}$  which is why astronomers and the high power laser community seek sites with the largest value of  $r_0$ . For high slew rates *apropos* of low earth orbit space debris, the effective wind is increased and results in a higher system bandwidth for good correction. Furthermore, since the turbulence correlation scales with wavelength according to  $r_0 \propto \lambda^{6/5}$ , laser wavelength must be traded off against other variables such as target interaction, Raman processes, thermal blooming instabilities, etc. in order to optimize the entire system.

While it is true that, all other things being equal, the value of  $r_0$  increases with altitude, there are variations with geographic location which can increase the value of  $r_0$  even at moderate altitudes. For example, the value of  $r_0$  estimated at the Uhuru site at 5.9 km is approximately 23 cm at 500 nm. Extensive data compiled at the excellent

astronomical site at Mauna Kea at 4.2 km indicates that the atmospheric coherence length  $r_0$  is not much different from that at the higher-altitude Uhuru site. The case of Mauna Kea is special in that the presence of such a high mountain in the middle of the vast Pacific Ocean creates the conditions for low turbulence at a relatively low altitude site. Furthermore, data collected at that site questions the assumption of Kolmogorovlike turbulence which is the basis of most analytical theories of adaptive optics corrections systems. The logistics of building and maintaining a major high power laser facility such as this are made more difficult by high altitude, and pressurized working spaces may be needed.

The usual figure of merit for laser propagation with adaptive optics systems is the Strehl ratio, which we introduced in §8. In the analytical formulation, the (rms) wavefront distortion,  $\sigma_{rms'}$  is calculated as a function of the various system parameters and the Strehl ratio is estimated using the Marechal approximation:

Strehl ratio 
$$\approx \exp(-\sigma_{\rm rms}^2)$$
 [12]

The Strehl ratio, however, is only one parameter characterizing a complex beam propagation process and it does not fully describe the entire phenomenon. For debris clearing, a more important parameter is the encircled energy as well as on axis intensity.

Adaptive optics systems designed for astronomical applications often result in far field distributions which resemble a diffraction limited core superimposed upon a low level, wide angle energy distribution. The Strehl ratio is reduced to reflect the energy lost in the tail of the distribution. For astronomy, this wide angle energy spread can often be compensated by setting detector thresholds and diffraction limited images can be reconstructed even for modest Strehl ratios of a few tenths or more. Adaptive optics designed for high power laser propagation must be designed for higher Strehl ratios and high values of encircled energy. The shape of the laser energy distribution in the far field, a quantity analogous to the "point spread function" in astronomy is the desired quantity to be maximized. This quantity is not amenable to analytic description and is often modeled by computer simulations of turbulent atmospheres and wave propagation codes. Final system optimization must involve modeling calculations to verify analytical estimates.

#### 10.1 Adaptive Optics Configurations

The basic optical configuration of a "conventional" AO system is shown in Figure 19. An optical element images the pupil of the telescope onto a Deformable Mirror (DM) which does the correction for the system. A dichroic element after the DM directs the beacon light onto a wavefront sensor followed by a controller which derives a set of control signal for the DM. The controller imposes the conjugate wavefront distortion in the DM thereby undoing the turbulent processes. The closed loop servo bandwidth of the control system must be high enough to keep up with atmospheric changes in the

presence of the effective wind caused by slewing. In most servo systems, the sample rate for the wavefront sensor must be 10-20 times the servo bandwidth and hence the need for bright beacon sources, fast cameras and high speed computer systems.

The configuration shown in Figure 19 is not the only one possible. The DM can be incorporated with either the primary or secondary mirrors of the beam projecting telescope. Designs for a large, segmented primary mirror may reduce the cost of the primary as well as correct high power laser beams. A modification of a "chopping secondary" mirror usually designed for sky background subtraction in IR astronomy would put actuators behind the mirror to combine high order adaptive optics correction with tilt correction. Such a scheme is planned for the new 6.5 m upgrade to the Multiple Mirror Telescope in Arizona. These alternative configurations certainly reduce the optics complexity of adaptive optics schemes but at the present time, it is not clear that these designs are technically feasible.

#### 10.2 Bandwidths of the Adaptive Optics System

The adaptive optics system naturally splits up into tilt and wavefront corrections with the former having low and the latter high spatial and temporal bandwidths. For the tilt correction, the entire telescope aperture can be used corresponding to the lowest spatial frequency and the temporal bandwidth can be several times slower than the characteristic frequency,  $v_w/r_o$  where  $v_w$  is the effective wind velocity. In this case of low earth orbit debris where the orbital velocity at 1000 km is  $\approx$  7 km/s, the effective wind for the turbulence at  $\approx$  10 km is  $\approx$  70 m/s. This value is roughly 10 times the normal wind and gives a characteristic frequency of 400 Hz.

The higher order wavefront correction must be sampled on a scale over which the wavefront is still flat, albeit tilted. This scale is precisely the value  $r_0$  and indeed this is sometimes used as the definition of  $r_0$ . Thus the subaperture area is  $r_0^2$  and the actuator spacing on the deformable mirror is  $r_0/M$  where M is the demagnification of the telescope, i.e. the ratio of telescope to deformable mirror diameter. The servo bandwidth of the actuators is then roughly 400 Hz corresponding to a wavefront sampling rate of approximately 4000 Hz. These spatial and temporal bandwidths set the requirements of the illumination sources used for both the tilt and wavefront corrections.

#### 10.3 Tilt Correction System

The lowest order wavefront distortion for a laser beam propagating through turbulence is an average tilt which results in a pointing error. The easiest way to sense and correct this tilt error is to view the debris using either reflected sunlight, where possible, or by actively illuminating the debris with a laser source. The tilt in the wavefront is measured simply by focusing the light from the debris as collected by the entire telescope aperture onto a quad cell and measuring the displacement of the focal spot. The focal displacement is proportional to the tilt with the constant of proportionality being simply the focal length of the lens system. This wavefront tilt must be compared with the tracking information obtained from the high resolution detection system in order to extract the turbulent contribution.

Reflected light from the debris is not precisely at the correct place due to the lead angle, 2v/c, where v is the orbital speed of the debris and c is the speed of light. The lead angle corresponds to the distance the debris travels in the time it takes light from the debris to reach the ground and the laser light to reach back to the debris. For low earth orbit space debris, the lead angle is  $\approx 50$  mrad or  $\approx 10$  arcsec. The relation for the tilt error as a function of the lead angle is:

$$\sigma_{\text{tilt}} \approx 0.6h_t \lambda_0 \Delta \sec \theta_z / \{ D^{7/6} [r_0(\lambda_0)]^{5/6} \}$$
[13]

Assuming a turbulence layer at 5 km, a lead angle  $\Delta$  of 50 mrad, a telescope diameter of 6 m and a value of  $r_0 = 20$  cm, the tilt angle is 75 nrads. The diffraction angle, assuming perfect higher order correction is  $\lambda/D \approx 80$  nrads. Thus the tilt angle is less than the diffraction angle and the loss factor is given by:

Loss factor 
$$\approx (\lambda/D)^2 / [(\lambda/D)^2 + \sigma_{\text{tilt}}^2]$$
 [14]  
= 53%

This loss factor can be interpreted as a 100 nrad spot jittering pulse to pulse by an amount of 50 nrad. Thus, 53 % of the time, the laser spot hits the target if the angular spread of the beam were truly diffraction limited. In this systems analysis, the angular spread of the beam is allowed to be as high as 0.4m/1400 km  $\approx 300$  nrad and hence the effect of tilt anisoplanatism is negligible.

The source of illumination for the tilt reference can be either sunlight, or a dedicated laser if the logistics of natural illumination are too constraining. To calculate the average power of the illumination laser, it is assumed that this laser beam in not compensated for atmospheric turbulence so that its divergence in the uplink propagation path is simply  $\lambda/r_0$ . It is further assumed that the laser loses a factor of two in a combination of optics and atmospheric absorption, the albedo of the debris is 0.5 and that 100 photons per millisecond are required for a modest signal to noise in the detector. The laser power for a 100 cm<sup>2</sup> debris is then about 70 W, certainly a modest

laser, but for  $1 \text{ cm}^2$  debris, the laser power jumps to 7 kW. The required laser power drops by a factor of about 25 to 280W if the laser beam director diameter is one meter and a separate adaptive optics correction system is used. Sunlight, on the other hand is sufficient to illuminate even a  $1 \text{ cm}^2$  debris sufficiently.

#### 10.4 Higher Order Correction System

For the higher order corrections, the debris cannot be used as a beacon. This fact is clear from the observation that the isoplanatic angle is roughly given by  $r_0/h_t$  where  $h_t$  is the effective height of the turbulence layer. Assuming a turbulence layer at 5 km, the isoplanatic angle is about 40 mrad which is smaller than the point ahead angle of 50 mrad. Hence a separate beacon created by a laser source which leads the debris is needed.

The power required by the beacon laser depends upon the mechanism for laser backscatter and the height of the beacon spot. Low altitude beacons formed by Rayleigh backscatter from the top of the troposphere at  $\approx$ 10km are not appropriate for large telescopes, due to the large subtended angle. A better beacon mechanism is resonance backscatter from mesospheric sodium atoms at  $\approx$ 100 km because of the higher altitude and high atomic resonance cross-section.

The basic equation for the return signal for a sodium-layer laser beacon is the following:

$$n_{hv} = (P/hv)N_{Na}\sigma_{Na}x_{Na}/(4\pi h_{Na}^2)$$
 [15]

In Eq. 15,  $n_{h\varpi}$  is the photon flux incident on the telescope pupil. Taking  $hv = 3.75 \times 10^{-19} J$  at 530 nm wavelength,  $N_{Na} = 5 \times 10^3 cm^{-3}$ ,  $h_{Na} = 90 km$ ,  $x_{Na} = 10 km$ ,  $\sigma_{Na} = 5 \times 10^{-12} cm^2$  (spectral average), the return signal expected at the telescope aperture is about 70 photons  $cm^{-2} s^{-1}$ . There are some other correction factors, namely the transmission of the laser beam director and the absorption of the atmosphere which together conservatively cut the return signal by half. Finally, the above equation applies when the peak power at the sodium layer is low so that saturation does not occur. It is difficult to build high average power CW lasers in the visible and even long pulse lengths are problematic because of chirp in the wavelength. Hence, most laser systems operate repetitively pulsed and near saturation further reducing the return signal by another factor of two. The final figure for the return signal is thus:

$$n_{hv} = 20 \text{ photons } \text{cm}^{-2} \text{ s}^{-1} \text{W}^{-1}$$
 [16]

In the ORION case with  $r_0 = 20$  cm, the return signal in a subaperture of  $r_0^2$  is  $\approx 8 \times 10^3$  photons s<sup>-1</sup>W<sup>-1</sup>. The wavefront sampling rate is 4 KHz, giving a return signal

of about 2 photons/W of laser power. In order to collect 100 photons in a subaperture for a modest signal-to-noise ratio, 50 W of laser power are needed for each beacon spot.

A single beacon spot, however, cannot provide enough information to correct a large telescope. The angle subtended by a point beacon at 100 km from a 5 m telescope is 50 mrad and the isoplanatic angle is only 40 mrad. More beacons are needed to provide correction to a Strehl of >50%. While these heuristic arguments must be further quantified by detailed modeling calculations, it is clear that at least 4 beacons would be needed for correction raising the beacon laser power to 200 W.

The pulse format for the beacon laser must be chosen to avoid saturation of the sodium layer. High peak powers will pump the sodium atoms causing the reradiation to follow the laser propagation direction away from the earth and away from the wavefront detector. Therefore it is necessary to keep the peak power below the saturation flux which is given by:

$$I_{sat} = h\nu / \sigma_{Na} \tau_u$$
[17]

In Eq. 17,  $hv = 3.37 \times 10^{-19} J$  at 589 nm, and  $\tau_u = 16$  ns, so  $I_{sat} \approx 5W/cm^2$ . Dye lasers of a suitable pulse format have been built for Laser Isotope Separation up to power levels of a few kW. For example, a 50 W laser beam at 10 KHz repetition rate and pulse duration of 150 ns will deliver a 5 W/cm<sup>2</sup> peak power to a spot 1m in diameter which is appropriate for a beacon spot under these atmospheric conditions. An all-solid-state laser configuration has also been developed which meets the necessary criteria but this system has not yet been scaled to the necessary average powers.

The remainder of the adaptive optics system consists of the deformable mirror, wavefront sensor, and controller.

#### 10.4.1. Deformable Mirror

The deformable mirror is usually a thin facesheet backed by piezoelectric actuators with the appropriate spacing. The residual wavefront error resulting from finite actuator spacing is given by:

$$\sigma^2 = 0.3 \, (s/r_0)^{5/3}$$
 [18]

where d is the actuator spacing. For  $s = r_{o'}$  the fitting error, according to the Marechal approximation, gives a Strehl of 75% which is acceptable for a system such as this. The total number of actuators is  $(\pi/4)(D/r_o)^2 \approx 500$  which is within present state-of-the-art.

## 10.4.2. Wavefront Sensor

The standard configuration for the wavefront sensor is the Shack-Hartmann concept whereby the wavefront is sampled by a lenslet array with lens spacing also equal to  $r_0$  (scaled by the appropriate magnification). The lenslets are focused onto a CCD array and the transverse motion of the Hartmann spots measured to give the local

wavefront tilts. Low noise, high speed CCD chips have been developed by MIT/Lincoln Labs and a new version with 128 x 128 pixels, adequate for this application, should be available within a year.

#### 10.4.3 Wavefront Controller

The wavefront controller converts the Hartmann spot information into a set of drive signals for the deformable mirror. Several computer configurations are being developed including highly parallel digital signal processor (DSP) boards and single boards containing many general purpose microprocessors. Both have advantages in computing speed and flexibility and detailed tradeoffs would be made in a full system analysis.

Figure 20 is a picture of the LLNL sodium beacon laser in operation.

It appears that the adaptive optics system necessary for correcting both tracking errors (tilt) and wavefront errors (beam divergence) can be constructed with present or very near term technologies.

## 11. Candidate Sites for ORION Laser Base

An equatorial location for the ORION station has the advantage that it would be able to address all orbits, although those with far North or South apogees could not be addressed with optimum efficiency.

For reasons discussed in the present paper (see Figures 17 and A2) and in Phipps and Michaelis 1994, the ideal site would be a very high, flat-topped equatorial mountain. Table 4 [Times Atlas of the World 1992, Encyclopaedia Britannica 1992] reviews the properties of some candidates. The ultimate choice will not simply depend on altitude. Other important considerations are geoligical stability (Chimborazo, e.g., lies in a belt of high seismic activity), political stability, local infrastructure, and environmental impact of a ORION system.

Among very high altitude sites, we favor "Uhuru", the summit of Mt. Kilimanjaro in Tanzania, for the following reasons. The extinct volcano has a flat top (unlike neighboring Mt. Kenya), and is so vast (200k hectares) that the laser system would have minimum environmental impact. Outside the rainy season (April – May), the sky is clear, especially at night when the –30°C African starlight is proverbial [Nnko 1994]. Other positive points are that Moshi International Airport lies at the foot of the mountain, and that it is not too far from the ports of Mombasa (300 km) and Dar-es-Salaam (500 km). The negative aspects are bad roads, unreliable infrastructure and very difficult altitude for performance of humans, as well as of electrical equipment. This last disadvantage could be compensated by pressurization of habitation and offices during construction and operation. The Mauna Kea site, upon which the Keck telescope is already installed, deserves consideration because of its considerable existing infrastructure. Considering turbulence, Mauna Kea's lower altitude (4.3km) is offset by geography: as we said earlier, the fact that the mountain is an isolated prominence in a laminar flow gives seeing conditions which we believe to be equivalent to those at 6 km altitude elsewhere. Its disadvantage is its northerly latitude from the point of view of debris access, but, since almost all the objects have been injected at higher latitudes, this may not be a serious difficulty, depending on the significance of mutual debris collisions by the time the station is built.

#### 12. ORION System Performance, Summary and Conclusions

Pulse number is plotted vs. object size in Figure 21. The break in the plot of n vs. d occurs at the assumed laser spot size on target. The reduced slope of this plot below 40 cm object diameter is somewhat counterintuitive, but results from the fact that progressively more laser energy is wasted for the smaller objects.

In the Figure, three laser sizes are shown. One shot from the 2-MW unit will deorbit 1-cm size objects. A single 1-m size object would require only 9 minutes total access, spread over about 9 days, to de-orbit with this laser.

Choosing the least costly laser option [ $\tau$ =40ns, W=20kJ, f = 1Hz and P=20 kW], one access time per object per day (90% clear weather) and assuming an average density 0.2 g/cm<sup>3</sup> for the debris objects, our system will cause a 1-cm object to re-enter in less than one access time.

While awaiting reappearance of a particular object, the laser station will address other objects, weather permitting. A maximum of about 12 minutes (available during 12 days, given our assumptions) is required for 10-cm objects, and 13 hours (2.2 years) for 1-m objects.

With rapid retargeting, and based on the estimated number shown in Figure 2, all objects  $1 \text{cm} \le d \le 1 \text{m}$  presently known to be in near Earth space (h $\le 1000 \text{ km}$ ) can be cleared in 4 years of continuous operation of the 20-kW laser. We estimate total system capital cost at \$50M, assuming the ORION laser can cooperatively use an existing 5-m-aperture observatory, and that the optoelectronic components of the crossed delay-line acquisition detectors can be replicated in large numbers at a per-unit cost of \$10k.

We believe that the best system tradeoff of those considered is the 20-kW ORION system. We summarize its features in Table 5.

# **Table 3:** Laser and atmospheric path parameters that influence laser beam propagation to space



	<u>Table 4</u>	
Particulars of some	of the highest equatori	<u>al mountains</u>

Name	<u>Height (km)</u>	<u>Location</u>	<u>Country</u>	<u>Remarks</u>
Antisana	5.70	0° 30′ S 78° 9′ W	Ecuador	snow-capped
Cayambe	5.84	0° 2′ N 77° 9′ W	Ecuador	volcano
Chimborazo	6.31	1° 29′ S 78° 52′ W	Ecuador	extinct volcano
Cotopaxi	5.90	0° 40′ S 78° 52′ W	Ecuador	active volcano
Elgon	4.32	1° 7′ N 34° 35′ E	Uganda	extinct volcano 8km dia. crater gentle slopes
Huascaran	6.77	9° 8′ S 77° 36′ W	Peru	snow-capped major earth- quake 1970
Ilniza	5.30	0° 40′ S 78° 45′ W	Ecuador	snow-capped
Jaya	5.03	4° 5′ S 137° 9′ E	Indonesia	13-km-long glacier-capped ridge
Karisimbi	4.50	1° 31′S 29° 25′ E	Rwanda	volcanic core
Mt. Kenya	5.20	0° 10′ S 37° 19′ E	Kenya	volcano, ridges radiate from central peak
Mt. Stanley	5.12	0° 23′ N 29° 54′ E	Uganda	extensive glaciers
Kilimanjaro	5.90	3° 2′ S 37° 20′ E	Tanzania	flat-topped extinct volcano highest point in Africa
Mauna Kea	4.2	20° N 157° W	U.S. (Hawaii)	excellent infrastructure – site of 10-m Keck telescope

Table 5				
ORION System Summary				
Interception Laser Parameters:	Quantity:			
Average power	20 kW			
Wavelength	530 nm			
Pulse energy	20 kJ			
Pulse repetition rate	1 Hz			
Pulse duration	40 ns			
Laser type	Flash-pumped Nd, frequency-doubled			
Interception Telescope Parameters				
Corrected Turbulent Strehl Ratio	50%			
Primary diameter	6m			
Slew rate	1 deg/s			
DM actuator number	500			
Tilt Correction Laser average power	280W			
Beacon Laser Parameters				
Total average power	200W			
Wavelength	589 nm			
Pulse duration	150 ns			
Pulse repetition rate	10 kHz			
Beacon laser number	4			
Acquisition System Parameters				
Field of view	20° x 1°			
Telescope aperture	20 cm			
Resolution	20x20m at 1000 km			
Detection limit	1cm object at 500 km			
Tracking System Parameters				
Laser average power	1.5 kW			
Laser pulse energy	500J			
Beam director aperture	1 m			
Maximum resolution	2x2x3m at 1000 km			
System Performance Parameters				
$ \Delta \mathbf{v} $	235 m/s			
Beam delivery efficiency	25%			
Time to clear objects 1cm <d<100cm< td=""><td>4 years</td></d<100cm<>	4 years			

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## ORION page 31 February 23, 2007 edition

## Symbols

- $A_s$  object irradiation area (cm<sup>2</sup>)
- $\alpha$  absorption coefficient at  $\lambda$  (cm<sup>-1</sup>)
- B total photon number
- C energy cost per unit mass delivered (J/g)
- $C_m$  impulse coupling coeff.= j/ $\Phi$  (dyne-s/J)
- $c_s$  sound velocity (cm/s)
- D laser beam diameter at launch (cm)
- $D_{th}$  thermal diffusivity (cm<sup>2</sup>/s)
- **D** pixel number
- d<sub>s</sub> laser beam diameter at target (cm)
- d object diameter (cm)
- $\Delta$  lead angle
- e orbit eccentricity =  $(r_a r_p)/(r_a + r_p)$
- E orbital kinetic energy (ergs)
- η thrust efficiency

 $\eta_{AB}$  ablation efficiency =  $(1/2)mv_E^2/10^7\Phi$ 

- f laser repetition rate (s<sup>-1</sup>)
- $\Phi$  target-incident laser fluence (J/cm<sup>2</sup>)
- g standard gravity (980 cm/s<sup>2</sup>)
- g<sub>R</sub> SRS gain (cm/MW)
- G universal gravitational constant
- h<sub>a</sub> apogee altitude (cm)
- h<sub>p</sub> perigee altitude (cm)
- h<sub>t</sub> turbulence layer height
- h<sub>Na</sub> sodium layer height
- hv photon energy
- H total orbital energy
- I laser intensity on target = $\Phi/\tau$  (W/cm<sup>2</sup>)
- I<sub>sat</sub> sodium layer saturation intensity
- $I_{sp}$  specific impulse =  $v_E/g$  (s)
- J mechanical impulse =  $\int j dA_s (dyne-s)$
- j momentum fluence =  $m v_F (dyne-s/cm^2)$
- k  $2\pi/\lambda$  = optical wavenumber
- k<sub>1</sub> transverse spacial frequency (cm<sup>-1</sup>)

- $\lambda$  laser wavelength (cm)
- $\lambda_0$  500 nm reference wavelength
- L line length
- $\Lambda$  constant in object number density equation
- m target ablated mass fluence (g/cm<sup>2</sup>)
- M<sub>A</sub> atomic mass number of ablation plasma
- M mass of the Earth (g)
- M<sub>o</sub> initial mass of the object (g)
- M magnification in an optical system
- $\mu$  photon number
- n total number of laser pulses
- $n_{hv}$  photon flux (number cm<sup>-2</sup>s<sup>-1</sup>)
- $\boldsymbol{n}$  atmospheric refractive index
- N laser beam quality factor
- N<sub>D</sub> Barnard distortion number
- $N_{L,\mu}$  number of lines L with  $\mu$  photons
- $N_{Na}$  sodium atom density (cm<sup>-3</sup>)
- mean photon number on line L
- P laser average power =  $W/\Delta t$
- q exponent in number density equation
- $Q^*$  specific ablation energy =  $\Phi/\delta m$
- r object radius (cm)
- r<sub>o</sub> atmospheric coherence length
- $r_0(\lambda_0)$  atmospheric coherence length at  $\lambda_0$
- R Earth-centric object orbit radius (cm)
- R<sub>a</sub> Apogee radius (cm)
- R<sub>p</sub> Perigee radius (cm)
- $\rho$  mass density (g/cm<sup>3</sup>)
- $\rho_{hv}$  photon density (pixel <sup>-2</sup>)
- s deformable mirror actuator spacing
- S line cross-section in xyt space  $(cm^2s)$
- $\sigma_{rms}$  rms wavefront distortion (wavelengths)
- $\sigma_{Na}$  sodium resonance cross-section (cm<sup>2</sup>)
- $\sigma_{tilt}$  wavefront tilt angle (radians)
- $\Delta t$  mission time
- $t_{Na}$  mesospheric sodium layer thickness

## ORION page 32 February 23, 2007 edition

 $\tau$  laser pulse duration

 $\tau_{diff}$  thermal diffusion time

- $\tau_{u}$  upper state lifetime
- $\theta_d$  beam divergence angle due to diffraction
- $\theta_{eff}$  effective beam divergence angle
- $\theta_{z}$  object azimuth angle
- u step function in Eqs. 3 & 4
- $\Delta v$  object velocity increment (cm/s)
- v object velocity
- v<sub>a</sub> apogee velocity (cm/s)

- v<sub>E</sub> effective exhaust velocity (cm/s)
- $v_w$  effective transverse wind velocity
- v<sub>p</sub> perigee velocity (cm/s)
- V orbital potential energy (ergs)
- W laser pulse energy =  $\int \Phi dA_s (J)$
- x object thickness (cm)
- $x_{Na}$  sodium layer thickness
- W laser energy per unit payload mass (J/g)
- z object to target (cm)
- Z ionization state of ablation plasma

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**Figure 1:** Cumulative flux of orbital debris and meteoroids vs. size, with data sources, based on Flury and McKnight 1993, with additions: Haystack '91 (based on results with the MIT Lincoln Laboratory Haystack radar) and PL '93: (see Maethner, *et al.* 1995). LDEF refers to the NASA Long Duration Exposure Facility. GEODSS is the US Air Force Ground-based Electro-optical Deep Space Surveillance system. STS window impacts are impacts on the Space Shuttle window. SpaceCom is the U.S. Space Command. In the Figure, the two ordinates are quantitatively equivalent.



Figure 2: Cumulative number density distribution for space debris vs. diameter, estimated from Figure 1.



**Figure 3:** Lifetime of a spherical satellite with mass density 0.2 g/cm<sup>3</sup> versus altitude and size, based on the U.S. standard atmosphere.



Figure 4: Geometry for satellite debris irradiation.



Figure 5: Layout of a typical target acquisition and tracking site, showing the array of Ho and Priedhorsky detectors, and the high resolution tracking laser.



**Figure 6:** Schematics of linear features in a 3D data set. In 3D, the line consisting of filled circles is significant against the background represented by the open circles. The line is not significant in 2D.



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Figure 7: The Beamlet Demonstration project at LLNL (artist's conception). The laser cavity is 36 meters long.



**Figure 8:** Schematic diagram of the Beamlet laser. The input pulse enters the multipass cavity by reflecting from the small mirror near the focal plane of the vacuum spacial filter. After two round trips through the cavity amplifier, it is reflected out of the cavity by a thin-film polarizer, passes through a booster amplifier, and continues on to the frequency converter.



Figure 9: Output energy at 1.06  $\mu$ m as a function of input energy for Beamlet.



Figure 10: Beam profiles of Beamlet at the fundamental (1060 nm) and third harmonic (350 nm)

5.0 kJ at 3 $\omega$  (351 nm), 3 ns, 6.7 J/cm<sup>2</sup>



Figure 11: Vertical and horizontal intensity scans through the center of a high-energy third-harmonic beam show intensity modulation of about 1.35:1.



**Figure 12:** Wavefront of Beamlet output. The rms wavefront error in the corrected beam is less than 0.2 wave, which gives a Strehl ratio of 0.4 in the far field.



**Figure 13:** Far-field image of the fully-corrected Beamlet output. The profile is consistent with the wavefront shown in Figure 12.



Figure 14: Cross-section of an amplifier-slab, gas channels, and channel-forming windows in a gascooled Brewster's-angle slab amplifier.



Figure 15: Comparing effects of diffraction and atmospheric turbulence on laser beam divergence for two laser wavelengths and two beam launch altitudes, vs. beam director mirror diameter.



Figure 16: Laser intensity expected on the debris target with atmospheric turbulence normalized to that limited by diffraction alone, for two laser wavelengths and 6km.



**Figure 17:** Chart for selecting near-field beam intensity and pulse duration, showing effects of optically induced air breakdown, whole beam thermal blooming, fine-scale thermal blooming instability, stimulated Raman scattering (SRS), and the approximate requirement  $I\sqrt{\tau}$  = constant, which comes from optimizing target effects, for sea-level laser station altitude. The target effects line is calculated for a 6-m (8.5-m) diameter mirror at 532 nm (1.06  $\mu$ m) and 1400-km range.



**Figure 18:** Chart for selecting near-field beam intensity and pulse duration, showing effects of optically induced air breakdown, whole beam thermal blooming, fine-scale thermal blooming instability, stimulated Raman scattering (SRS), and the approximate requirement  $I\sqrt{\tau}$  = constant, which comes from optimizing target effects. The target effects line is calculated for a 6-m (8.5-m) diameter mirror at 532 nm (1.06  $\mu$ m) and 1400-km range. This chart is for 6-km laser station altitude and, by comparison with figure 16, shows some considerations that make 6km preferable.



Figure 19: Conceptual details for beam director, laser and tracking system coupled with a "conventional" adaptive optics (AO) system.



**Figure 20:** LLNL's 1200-W Sodium Beacon laser created a fifth-magnitude star in the Earth's sodium layer overhead, actually visible to the unaided eye.



**Figure 21:** Pulse number required to cause re-entry of an object with a circular, 1000-km altitude orbit for lasers with three different pulse energies and pulse durations, vs. the object's diameter (lower axis) or mass (upper axis). Time shown on the right-hand vertical scale is estimated "real time" for re-entry execution, given 90% clear weather and estimated availability of the object within a 2,000-km diameter overhead circle. The efficiency with which laser energy is delivered through the atmosphere is assumed to be  $\eta = 25\%$ . The laser spot diameter in the vicinity of the object is 40 cm. For this reason, the plot has a "knee" at d = 40cm, and a different trend for small objects which is caused by the fact that progressively more energy is wasted as the objects become smaller.

## Appendix I. Momentum Coupling and Specific Impulse

## Momentum Coupling Theory

The laser momentum coupling coefficient  $C_m$  is defined (by custom, in mixed units) as the ratio of momentum flux delivered to a target system to the incident laser pulse fluence. Momentum transferred is mainly due to formation of an ablation jet on the surface of the target, and only very slightly due to light pressure.

$$C_m = j/\Phi$$
 dyne-s/J [A1]

Where laser pulse fluence is constant over the target surface,

$$C_m = J/W$$
 dyne-s/J [A1a]

For opaque materials in vacuum irradiated by pulsed lasers at or above plasma threshold intensity [see Phipps, *et al.* 1988],  $C_m$  is given within a factor of 2 by [see Figure A1]

$$C_{\rm m} = 3.95 \, M_{\rm A}^{0.44} / [Z^{0.38} (Z+1)^{0.19} (I \lambda \sqrt{\tau})^{0.25}]$$
 dyne-s/J. [A2]

while

and

$$C_m Q^* = v_E = g I_{sp} \qquad cm/s \qquad [A3]$$

$$gC_m I_{sp} = C_m^2 Q^* = 2.10^7 \eta_{AB}$$
 [A4]

by inspection. The two elements of the pairs ( $C_m$ ,  $Q^*$ ) and ( $C_m$ ,  $I_{sp}$ ) are not independent, but increasing one decreases the other. For orbit transfers, the laser energy cost C per unit mass delivered is

$$C = Q^* \left\{ \frac{1 - \exp\left(-|\Delta \mathbf{v}|/v_E\right)}{\exp\left(-|\Delta \mathbf{v}|/v_E\right)} \right\} \qquad J/g \qquad [A5]$$

Minimizing C gives the solution

 $C_{m} = 3.18 \cdot 10^{7} \eta_{AB} / |\Delta v| \qquad dyne-s/J. \qquad [A6]$ and this, combined with Eq. [5], can be shown to be equivalent to  $v_{E} / |\Delta v| = 0.628 \qquad [A7]$ 

a result derived earlier by Möckel [1975]. The practical implication of Eq. [A5] is that very high  $C_m$  (low Q\*) values are appropriate for very small velocity changes, for minimum energy cost. In a specific case, choices for  $C_m$  different from that given by Eq. [A6] may govern, as for example, in LISK, where the consideration of maximum satellite lifetime outweighs that of energy cost, driving the designer toward low mass loss, high Q\* and thus low  $C_m$ . In other cases such as NEO-LISP, the target is "uncooperative", i.e.,  $C_m$  is not a free parameter.

Optimum laser intensity on target during each pulse is [see Phipps & Dreyfus 1993]

$$I = 4 \cdot 10^4 / \sqrt{\tau}$$
 W/cm<sup>2</sup>, [A8]

ORION page 36 February 23, 2007 edition and we allow  $W = 8 \cdot 10^4 A_s \sqrt{\tau}$  J [A9] during each laser pulse to be sure of ignition. We note that Eqs. [A2] and [A8] have been verified experimentally for 1MW/cm<sup>2</sup><I<1GW/cm<sup>2</sup>, and laser pulse durations ranging from about 1ms to about 10ns, in vacuum. On the short-pulse extreme, this simplified coupling theory probably breaks down around 20 ps for normal conditions. The limit for pulses of longer duration, for the purpose of the ORION analysis, is provided by deterioration of the opical path due to thermal propagation instabilities long before the coupling analysis breaks down, and by the onset of rear-surface thrust. The first effect arises is because the distortion number of Barnard (1989) [see Appendix II] increases with pulse duration according to

$$N_{\rm D} = 2.0 \times 10^5 (n - 1) \alpha k z \sqrt{\tau}$$
 [A10]

when Eq. [A8] is incorporated. The second is discussed in the next subsection.

Figure [A1] shows the good agreement obtained between experimental data and our theory for a wide range of laser parameters which includes the ones we propose using in this paper. The example shown is for metal targets, although agreement is equally good for nonmetals.

## Long Pulse Duration Applicability Limit

From the above, we have seen that the laser intensity delivered to the target debris front surface and the irradiation time in a given pulse must be played off against each other in such a way as to maximize the efficiency of producing impulse on the target surface.

In addition, the duration of a given pulse must not be so long that the impulse being generated on the front surface of the debris object is negated by pressures being generated on its rear surface. Below the plasma threshold, such pressures will be generated by heat conduction through the thickness of the target material, as well as by gasdynamic expansion of debris vapor around the object itself. In the plasma regime which we use here, only the gasdynamic expansion around the debris object must be considered. This limits the time for efficient impulse generation to approximately 1-10  $\mu$ s for hot 1mm spherical or disc-shaped debris, to 10-100  $\mu$ s for hot 1-cm-size debris particles. The approximate scaling law for this pulse duration limit,  $\tau_{max}$  is given by:

$$\tau_{\text{max}} = r_{\text{particle}} / c_{\text{s vapor}} \qquad [A11]$$

Beyond this limit, rear-face counter-thrust will begin to develop. Thermal conduction through 1-mm-thick aluminum platelets occurs in approximately 6 ms, and in 600 ms for 10-mm thickness, or in general:

$$\tau_{\rm diff} = x^2 / (\pi D_{\rm th}) \qquad . \qquad [A12]$$

Clearly, the gasdynamic timescale is shorter than that for thermal conduction, and dominates the question of long-pulse applicability limit for this theory.

These are both soft limits in the sense that at the end of these timescales, the efficiency of impulse production begins to decrease, not in the sense that impulse production ceases.

#### Appendix II: Gain for thermal blooming beam propagation instabilities

It is a been well-known problem in gas laser design as well as beam propagation that small ripples in local beam intensity produce ripples in local refractive index due to heating of the gas in the beam propagation path, and that these can cause intensity ripples to propagate with gain. The variables which determine whether this gain is significant for a given  $k_{\perp}$  are the refractive index, sound speed, laser absorption coefficient and thermal diffusivity of the medium, and the laser intensity, wavelength and pulse duration. A comprehensive theory exists [Barnard, 1989] which relates these quantities to the gain G for sinusoidal transverse intensity disturbances with a given  $k_{\perp}$ . In the Barnard model, different gain expressions apply depending on the sixe of  $k_{\perp}$ . The five regions of  $k_{\perp}$  space which are relevant to our problem and their corresponding gain expressions are shown in Table A1.

A central feature of Barnard's linear stability theory is the distortion number,

$$N_{\rm D} = 2.53 \, (n - 1) \, \alpha \, \Phi \, kz$$
 [A18]

which depends linearly on the energy density abstracted from the laser beam  $\alpha \Phi$  (J/cm<sup>3</sup>), path length z and wavenumber k.

Note that the gain expression given in Eq. A13 of Table A1 is numerically identical to a result derived by Prokhorov [see Hongwoo 1987]:

$$G = 0.37 (\alpha c_s^2 z^2 I_0 \tau^3 k_{\perp}^4)^{1/5},$$
 [A19]

for whole beam self-phase modulation in gases, with an appropriate value for (n-1). The Barnard formalism applies to whole beam effects to the extent that it is valid to describe the laser beam's transverse intensity distribution as a sinusoid.

Because our pulse duration is short, phase mixing (in the context of Barnard's analysis) due to wind shear and turbulence can be ignored.

We did Barnard-type calculations based on the laser beam propagation parameters relevant to this paper, and these are shown in Figure A2. For our beam intensity I = 1.7 MW/cm<sup>2</sup>, maximum gain for thermal blooming instabilities is about 2.7 nepers, and peaks at a perturbation wavelength around  $2\mu$ m.

There is no significant threat to beam quality from this source.

## **Appendix III: Orbital Mechanics**

In the process of simulating Keplerian orbits, it is rapidly noted that the best effect (in terms of lowering a part of the orbit most energy-efficiently) is obtained by applying a negative velocity decrement at the apogee, and that the result of this is an orbit with the same apogee and a lower perigee.

To obtain the relationship between velocity decrement and change of perigee for a general elliptical Earth orbit, we note:

$$\frac{1}{R_a} = \frac{1}{GM} \left( \frac{v_a^2}{2} - \frac{H}{M_o} \right)$$
 [A20]

and

 $\frac{1}{R_p} = \frac{1}{GM} \left( \frac{v_p^2}{2} - \frac{H}{M_o} \right)$  [A21]

where

H = (E + V) < 0 [A22]

is total energy in orbit. Using

$$H = -\frac{GMM_{o}(1+e)}{2R_{a}}$$
 [A23]

we find

 $R_a v_a^2 = GM (1 - e)$  . [A24]

Since if  $R_a$  is to remain constant subsequent to a change  $\Delta(v_a^2)$ , a corresponding change  $\Delta e$  must occur, and this can be related to  $\Delta R_p$ . Since

$$e = \left(\frac{R_a - R_p}{R_a + R_p}\right)$$
[A25]

we find 
$$\Delta(v_a^2) = \left\{ \frac{2GM}{(R_a + R_p)^2 \left[ 1 + \Delta R_p / (R_a + R_p) \right]} \right\} \Delta R_p$$
 [A26]

Eqn. [A26] is exact. This relationship together with

$$v_a^2 = \frac{2GMR_p}{R_a (R_a + R_p)}$$
[A27]

for the old apogee velocity permits us to calculate the desired quantity

$$\Delta v_a = v_a - \sqrt{v_a^2 - \Delta(v_a^2)} \quad . \tag{A28}$$

If, for example, it is desired to drop the perigee of an orbit which with initial altitude 1000km x 500 km by  $\Delta R_p = -400$  km to produce re-entry, a velocity decrement of only  $\Delta v_a = -113$  m/s will give the desired result. We have verified this value in simulations.

Figure A3 uses Eqs. [A26 and A28] to determine the required apogee velocity decrement to cause re-entry for orbits with various values of  $h_a$  and  $h_p$ . Re-entry is

assumed to be inevitable and the calculation is terminated when  $h_p = 100$ km is first achieved.

Figure A4 shows a computer simulation of re-entry achieved for a 5-cm-diameter, 10-gram object with just 75 shots of the 20-kJ laser applied between zenith angles of 44° and 22°, just before the object reached apogee in a 1000x500-km orbit. Our simulation code accurately computed a new orbital trajectory for a target object after each laser shot. The debris object was assumed to be spherical, so that the ablation jet was always counterparallel to the laser beam. Note that part of the  $\eta = 25\%$  "beam delivery efficiency factor" quoted in Figure 21 accounts for the fact that  $\Delta v$  is not applied counterparallel to the debris velocity vector, but at a typical angle of 60° to it as the object rises over the ground-based laser station. Actual results obtained in the simulation are somewhat better than might be expected by considering the 50% reduction of effective thrust due to this effect.

This is because the above analysis ignores the smaller (but helpful) effects of radial  $\Delta v$  at apogee in lowering perigee, which is accurately represented in the simulation. While an analytical description of this effect is beyond the present scope, it is qualitatively described as a dip in the perigee which follows "pop-up" of the apogee. This is not a major effect: our simulations have shown that a joule of laser energy is about 4 times less efficiently expended at a zenith angle of zero degrees than over the 44° to 22° interval which we found to be approximately optimum for this case, given the laser's range limitation.

Figure 21 predicts about 300 pulses (rather than 75) required for this case. This discrepancy is partly due to the "apogee pop-up" effect, and partly is because the  $|\Delta v|$  of 235 m/s assumed in Figure 21 is for the case of a 1000-km circular orbit with 25% beam delivery efficiency, whereas, in the more typical 1000x500-km case simulated, the  $|\Delta v|$  required is only 113 m/s.

# Table A1: Gain Regions in the Barnard Model

<u>k</u> _	Condition	<u>Gain G (nepers) for k<sub>l</sub></u>	<u>Physics</u>	
1.k」 and	$k_{\perp} << 1.96 \left[ (\boldsymbol{n} - 1) \alpha  \mathrm{I}  \mathrm{c}_{\mathrm{s}}^{4}  \mathrm{k}^{5} \right]^{1/6} \sqrt{\frac{\tau}{z}}$ $k_{\perp} << 1.27  \frac{(\boldsymbol{n} - 1) \alpha  \mathrm{I}  \mathrm{z}^{2}}{\alpha^{3}  \mathrm{z}^{2}}$	G = 1.88 [( $n$ –1) $\alpha c_s^2 z^2 I \tau^3 k_{\perp}^4$ ] <sup>1/5</sup>	acoustic effects	[A13]
2.	$c_{s}^{2} \tau^{2}$ $k_{\perp} \gg 1.96 \left[ (n-1) \alpha I c_{s}^{4} k^{5} \right]^{1/6} \sqrt{\frac{\tau}{z}}$ $k_{\perp} \ll 1.50 \sqrt{(n-1) \alpha I kz}$	G = 2.02 [( $n$ –1) $\alpha c_s^2 kz I \tau^3 k_{\perp}^2$ ] <sup>1/4</sup>	acoustic & diffractive effects	[A14]
3. <sup>k</sup>	$K_{\perp} \ll 1.59 \sqrt{\frac{c_s^2 \tau}{c_s^2 \tau}}$ $\Rightarrow > 1.78 \left[ \frac{(n-1) \alpha  \mathrm{I} \tau  \mathrm{k}^3}{z} \right]^{1/4}$	G = 2.22 [( $n - 1$ ) $\alpha$ I $\tau$ kz] <sup>1/2</sup>	isobaric growth with diffractive effects	[A15]
and 4.	$k_{\perp} \gg 1.59 \sqrt{\frac{C}{c_s^2 \tau}}$ $k_{\perp} \gg \sqrt{\frac{G}{\tau \chi}}$	$G << \frac{\tau}{\tau_{diff}}$	grating washout by thermal diffusion	[A16]
5.	$k_{\perp} \ll 1.78 \left[ \frac{(\boldsymbol{n}-1) \alpha  \mathrm{I}  \tau  \mathrm{k}^3}{z} \right]^{1/4}$	$G = 1.30 [\alpha I \tau z^2 k_{\perp}^2]^{1/3}$	isobaric growth	[A17]
but	$k_{\perp} >> 1.96 \left[ (\boldsymbol{n} - 1) \alpha I c_s^4 k^5 \right]^{1/6} \sqrt{\frac{\tau}{z}}$			



**Figure A1:** Compilation of experimental data for impulse coupling coefficient on C-H materials vs. the parameter  $(I\lambda\sqrt{\tau})$ , based on Phipps, *et al.* 1989. It is seen that the assumption  $C_m = 10$  is not unreasonable . While the exponent for the solid trendline shown summarizing many different experiments is 0.30, theory for a particular material when Z is fixed yields a 0.25 exponent. References refer to that paper: (a): Afanas'ev, et al., ref. 26, 1.5 ms, 1.06  $\mu$ m on ebonite rubber. (b): Afanas'ev, et al., ref. 26, 1.5 ms, 1.06  $\mu$ m on carbon. (c): Phipps, et al., ref. 25, Sprite, 37 ns, 248 nm, on silica phenolic. (d): Phipps, et al., ref. 25, Sprite, 37 ns, 248 nm, on vamac rubber. (e): Turner, et al., ref. 6, 22 ns, 248 nm, on buna-n rubber. (f): Phipps, et al., ref. 25, Gemini, 1.7  $\mu$ s, 10.6  $\mu$ m on carbon. (j): Phipps, et al., ref 25, Sprite, 36, 1.7  $\mu$ s, 10.6  $\mu$ m on carbon. (j): Phipps, et al., ref 25, Sprite, 36, 1.7  $\mu$ s, 10.6  $\mu$ m on carbon. (j): Phipps, et al., ref 25, Sprite, 36, 1.7  $\mu$ s, 10.6  $\mu$ m on carbon. (j): Phipps, et al., ref 25, Sprite, 36, 1.7  $\mu$ s, 10.6  $\mu$ m on carbon. (j): Phipps, et al., ref 25, Sprite, 36, 1.7  $\mu$ s, 10.6  $\mu$ m on carbon. (j): Phipps, et al., ref 25, Sprite, 37 ns, 248 nm on carbon. (j): Phipps, et al., ref 25, Sprite, 37 ns, 248 nm on carbon phenolic. (k): Phipps, et al., ref. 25, Gemini, 1.7  $\mu$ s, 10.6  $\mu$ m on graphite epoxy. (l): Phipps, et al., ref 25, Sprite, 37 ns, 248 nm on carbon phenolic. (m): Grun, et al., ref. 39, 4 ns, 1.05  $\mu$ m, on C-H foils.



**Figure A2:** Calculated gain (following Barnard, 1989) for our beam propagating through the atmosphere. The graph shows that the growth rate for transverse beam intensity ripples is maximum for  $2 - 30 \ \mu m$  ripples, but that the gain is at most 2.5 nepers, not large enough to be of concern.



**Figure A3:** Calculated re-entry produced by irradiation of a 5-cm, 10-g space debris object in an initial 1000 km x 500 km orbit with 75 pulses from the ground-based laser station.



**Figure A4:** Calculated apogee velocity decrement required to produce re-entry, for various initial perigee and apogee altitudes.