THE IMPACT IMPERATIVE:
A SPACE INFRASTRUCTURE ENABLING A MULTI-TIERED EARTH DEFENSE

Jonathan W. Campbell*, Claude Phipps**, Larry Smalley***,
James Reilly****, and Dona Boccio*****
(and TBD Alabama A&M Colleagues)

**Advanced Projects/FD02, National Space Science and Technology Center, NASA/MSFC, Huntsville, Alabama, 35812*
***Photonics Associates 200A Ojo de la Vaca Road Santa Fe, NM 87505*
****Department of Physics, University of Alabama, Huntsville*
***** Northeast Science and Technology, East Sandwich, MA*
******Queensborough Community College of the City, University of New York, New York*

ABSTRACT

Impacting at hypervelocity, an asteroid struck the Earth approximately 65 million years ago in the Yucatan Peninsula area. This triggered the extinction of almost 70% of the species of life on Earth including the dinosaurs. Other impacts prior to this one have caused even greater extinctions.

Preventing collisions with the Earth by hypervelocity asteroids, meteoroids, and comets is the most important immediate space challenge facing human civilization. This is the **Impact Imperative**.

We now believe that while there are about 2000 earth orbit crossing rocks greater than 1 kilometer in diameter, there may be as many as 200,000 or more objects in the 100 m size range. Can anything be done about this fundamental existence question facing our civilization? The answer is a resounding **yes**!

By using an intelligent combination of Earth and space based sensors coupled with an infra-structure of high-energy laser stations and other secondary mitigation options, we can deflect inbound asteroids, meteoroids, and comets and prevent them from striking the Earth.

This can be accomplished by irradiating the surface of an inbound rock with sufficiently intense pulses so that ablation occurs. This ablation acts as a small rocket incrementally changing the shape of the rock's orbit around the Sun. One-kilometer

size rocks can be moved sufficiently in about a month while smaller rocks may be moved in a shorter time span.

We recommend that space objectives be immediately reprioritized to start us moving quickly towards an infrastructure that will support a multiple option defense capability. Planning and development for a lunar laser facility should be initiated immediately in parallel with other options. All mitigation options are greatly enhanced by robust early warning, detection, and tracking resources to find objects sufficiently prior to Earth orbit passage in time to allow significant intervention.

Infrastructure options should include ground, LEO, GEO, Lunar, and libration point laser and sensor stations for providing early warning, tracking, and deflection. Other options should include space interceptors that will carry both laser and nuclear ablators for close range work. Response options must be developed to deal with the consequences of an impact should we move too slowly.

INTRODUCTION

Astronomical telescopes and deep space radar systems have verified the existence of a large number of near-Earth objects (NEOs), such as asteroids, meteoroids, and comets that potentially could destroy most life on Earth. An asteroid with a diameter of 1-10 km would strike the Earth with a power rivaling the strength of a multiple warhead attack with the most powerful hydrogen bombs known to man. Computational fluid dynamics studies have indicated that an ocean strike by an asteroid this size would create a gigantic tsunami that would flood and obliterate coastal regions. More significantly perhaps, this strike would eject a massive dust cloud rivaling the most powerful volcanic explosion, which could seriously affect climate on the scale of two to three years. It could alter our biosphere to the point that life as we know it would cease to exist.

As recent as five years ago, it was thought by the astronomical and astrophysics community that most of the known NEOs do not pose a near term threat, and therefore that these objects do not present any danger to the Earth and its biosphere. However, the relatively recent collision of the comet Shoemaker-Levy 9 with Jupiter and continuing discoveries of uncatalogued asteroids passing near Earth without any advanced warning have increased concerns. It is worthwhile to note that one striking feature of practically every celestial body in our solar system is the abundance of impact craters. [See *The Threat of Large Earth-Orbit Crossing Asteroids*, 103rd Congress, First Session, Hearing House Committee on Science, Space and Technology, Subcommittee on Space (Washington, DC: March 24, 1993), which discusses NASA and international research on detecting and deflecting asteroids before these hit the earth.]

Figure 1: (Photo courtesy of the Smithsonian Institute) On June 30, 1908, at 7:40 AM, a cosmic projectile exploded in the sky over Siberia. It flattened 2,000 square kilometers of forest in the Tunguska region. If a similar event were to occur over an urban area today such as Washington or Moscow, hundreds of thousands of people would be killed, and damage would be measured in the hundreds of billion of dollars.

Since collisions with asteroids, meteoroids, and/or comets have caused major havoc to the Earth's biosphere on several occasions in the geological past, one reality of our civilization's continued existence is that the Earth will experience another impact in the future. The idea presented here is to use lasers to defend against Earth impacting asteroids and comets.

BACKGROUND

Impacts from Near-Earth Objects (NEO's) are not "academic" problems. Direct impact by a NEO approximately 10 km in diameter will annihilate most biota because of the resulting firestorm and nuclear winter. Such objects have a kinetic energy release of order 30TT (teratons), create tidal waves [Hills, 1992] and earthquakes. The last such epoch-ending event occurred 65M years ago at the so-called "K/T boundary". The location of the impact is now known to be the Chicxulub site off the coast Yucatan [see Sharpton 1993].

A multiple body impactor of greater energies (Comet Shoemaker-Levy) struck Jupiter in 1994. Each body left a mark the size of Earth in its upper atmosphere. A more recent (and more likely) example is the Tunguska event of June 30, 1908 (Figure 1), in which an object probably 110 m in diameter impacted with 10MT explosive equivalent, clear cutting 2150 km^2 of forest. It was probably a "snowball" NEO [BBC 2001]. NEO's include Earth-crossing Asteroids (ECA's), meteoroids and comets.

Table 1. NEO damage mechanisms

* Crater formation
* Sun-obscuring dust and clouds

  (Similar to nuclear winter)
* Blast overpressure

  (Destruction of manmade structures)
* Thermal burn from ablation plume

  (40-m-dia. NEO entering at 30 km/s and 10 km altitude will ignite pine forest [Hills 1992])
* Earthquakes

  (A 30km/s, 80-m-dia. iron NEO will cause a Richter 7 quake [Hills 1992])
* Ram-up of deep water tsunami

  (Tsunami from a 30km/s, 80-m-dia. Iron NEO will cause a 40-m-high tidal wave onshore)

Impacting NEO's cause damage via 6 mechanisms, whose relative importance depends on site, energy, diameter and path. Only three of these require the NEO to strike land [Table 1].

For the 10-km-size "doomsday asteroids," Earth impact frequency is about one per

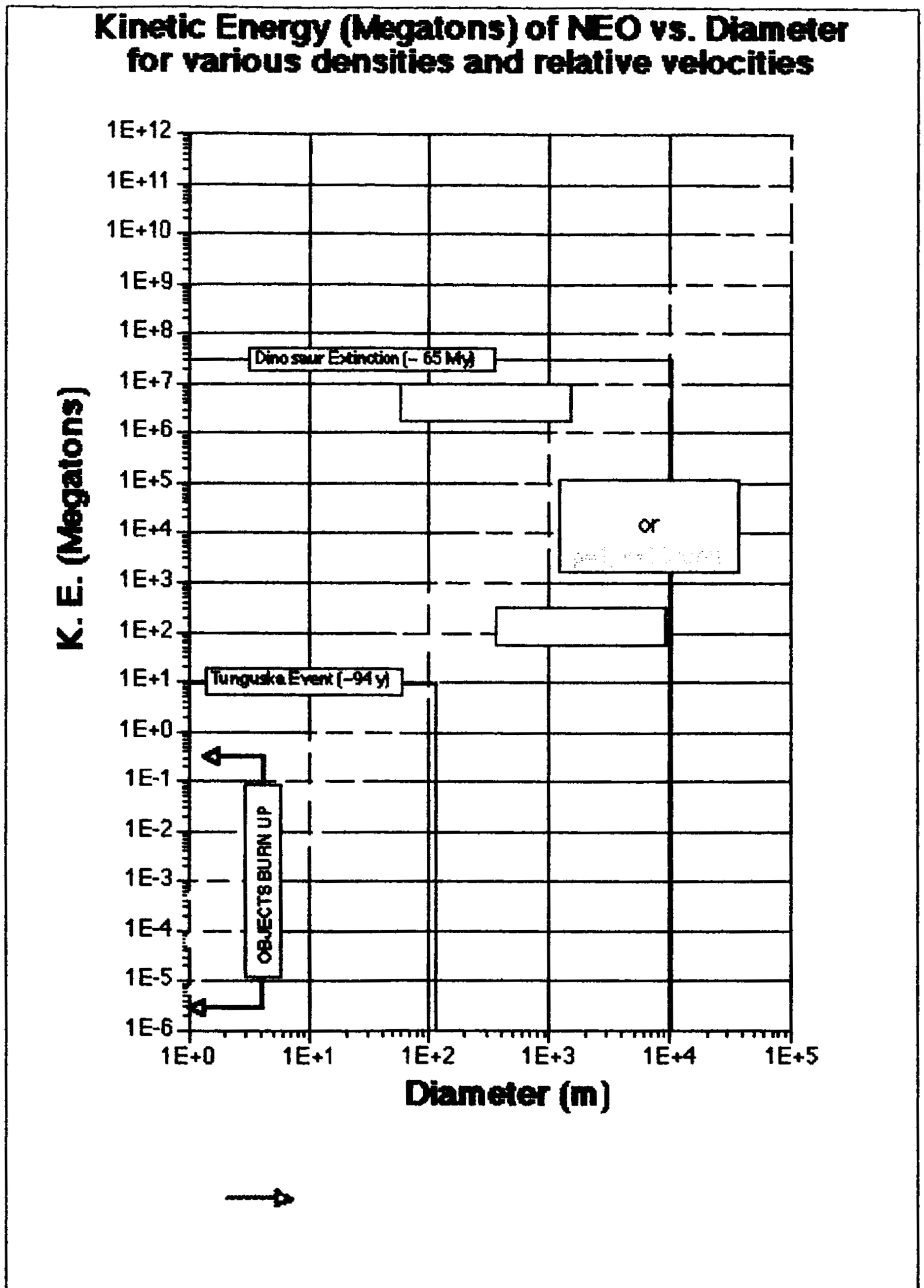

Figure 2. Kinetic energy (MT) vs diameter of Earth-crossing asteroids (NEO's) with velocity 10 to 30km/s and density ρ = 1000-9000 kg/m^3. Below the chart, total number of NEO's and probability of Earth impact are shown.

100My. However, impact probability is a strong function of asteroid diameter d, so that NEO impacts of the size that initiated the Tunguska event happen every few centuries. Where diameter d is in meters, NEO impact frequency (per year) is given by [see Shoemaker 1995 and Figure 2]

$$N(d) = 80/d^{x} \text{ where } 2.5<x<3 \qquad (1)$$

Each month, about 30 of these small (40-80m) diameter objects pass through the Moon's orbit, offering excellent opportunities for diagnostics and experiments. Epoch-ending NEO's have also passed within fractions of an AU in the past decade. Small NEO's are the most likely threat in our lifetime [see Eq. 1]. However, small NEO's are extremely difficult to detect in time to take action. For example, assuming detection at visual magnitude m_V=23, an 80-m-diameter, 30 km/s "dirty snowball" NEO with albedo 0.025 will be 200 light-seconds distant (0.4AU) on detection and just 23 days from Earth impact.

Nuclear deflection has been suggested [Solem 1993]. In this approach, a multi-MT weapon is detonated in the vicinity of, but not adjacent to, the NEO. Orbit modification occurs through rapid ablation of the object as opposed to gradual ablation from the laser approach. Considering the additional time required to verify orbit, 23 days leaves inadequate time for launching any kind of nuclear-tipped conventional interceptor, transporting the payload to the NEO, and matching its speed (in the reverse direction) and detonating optimally.

In contrast, laser deflection offers instant response, agility, and low cost compared to the nuclear alternative. Lasers do not have to be transported to the target. Laser deflection is also attractive relative to putting nuclear weapons in orbit, a suggestion that may not be embraced by the general public. Laser deflection uses the thrust produced by a jet produced on the surface of the NEO by laser ablation [Phipps 1992-5, 1997-8].

Because of the NEO's speed, deflection is only possible if this energy is delivered starting at a great distance. There is a *quadratic* effect here: the velocity change required to miss the Earth increases with decreasing time to collision, and decreasing time to act requires proportionally more power to achieve the same velocity change. Consequently, even if the laser spot diameter is never larger than the NEO, required laser power increases quadratically with decreasing range at detection:

LASER NONCOOPERATIVE PROPULSION

In essence, the intensity of the laser must be sufficiently great to cause the material on the surface of the object to ablate. As the resulting hot vaporized material expands, a reactive force (or thrust) is imparted to the object. For a given material and duration of a laser pulse there is an optimum intensity for coupling of laser energy into the material. Higher intensity's are no help because the resulting ionization of the vapor from the material effectively absorbs the additional energy.

Coupling is considered strong when the intensity reaches at least one tenth of the optimum intensity. The optimum intensity scales roughly as the square root of the pulse duration. Pulses with a modest energy and average power may have a high intensity if the pulse duration is short.

The Orion study considered laboratory experiments that were conducted with representative materials, and found useful models of the coupling of metals and nonmetals. An example is shown in Figure 3.

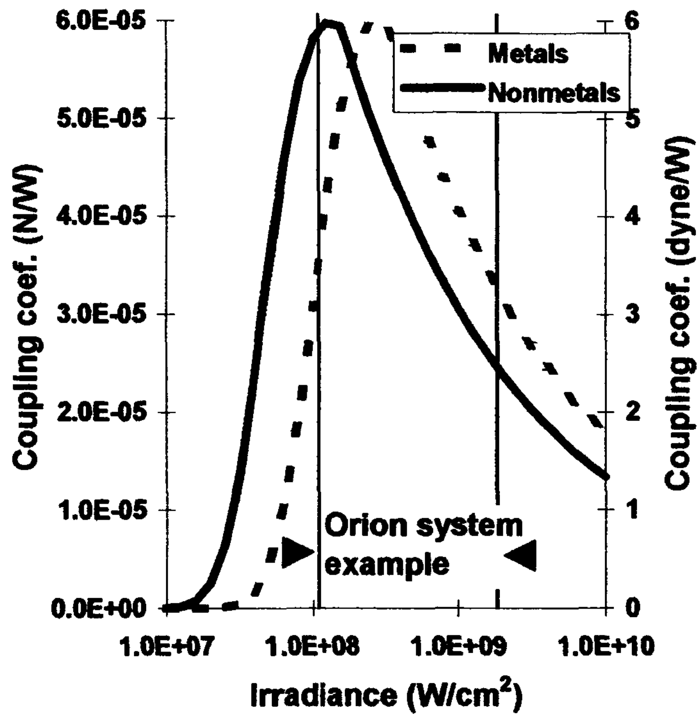

FIGURE 3. Laser coupling for 5 ns pulse duration.

The optimum intensity is higher for metals than for nonmetals, since energy tends to be conducted to the interior of the metal. However, at higher intensities, the coupling is higher for metals than for nonmetals. This is because the onset of plasma formation above the optimum intensity for nonmetals occurs at lower intensities. The peaks of the curves of Figure 3 are at the optimum intensities for 5 ns pulses, and the optima are at higher intensities for longer pulses. For example, the vertical marks in the figure are the range of intensities calculated for a system with only a 20 kJ, 5 ns pulsed laser at 1.06 μ directed by a 3.5 m aperture onto a target in a 500 km circular orbit as the zenith angle varies from 0 to 60°.

ATMOSPHERIC CONCERNS

For laser stations on the Earth's surface, adaptive optics would be required to operate through the atmosphere.

For example, we know from the Orion study that useful laser deflection results from placing instantaneous intensities on the order of 10^8 (W/cm^2) on the target. With a high pulse energy of 20 kJ, short pulse duration of 5 ns, and range of 1600 km, the angular diameter required is 1.4 μrad. Without adaptive optics, small-scale turbulence in the atmosphere spreads the beam to an angular diameter on the order of 10 μrad. Also, turbulence on larger scales tends to tilt the wavefront and displace the emerging beam from its intended path.

High-order correction for atmospheric turbulence has been demonstrated with laser guide stars and active optical correction. At the USAF Phillips Laboratory Starfire Optical Range (SOR), for example, resolution better than 1 μrad has been obtained at 0.85 μm with a 1.5 m aperture (Starfire Optical Range 1997).

The image shift due to large-scale turbulence can be measured by the shift in the apparent position of a star from its expected position. It is impractical, however, to use stars for a ground based, asteroid deflection system, since there is not enough integration time available for faint stars, especially during daytime with competition from scattered sunlight. The light from a laser guide star traverses the same path as the original laser, and hence is not useful for determining the wavefront tilt. At the Steward Observatory, for example, tilt correction was accomplished for the Multiple-Mirror Telescope (MMT) with a field star 200 μrad from the laser guide star (Center for Astronomical Adaptive Optics 1997).

Two key points relative to the adaptive optics remain to be investigated. First, since it is desirable to operate a future laser station at all times of the day, the requirements for adaptive correction during the daytime must be investigated. During the daytime, atmospheric turbulence increases and makes the adaptive optics more difficult.

A laser technology demonstration will be needed to determine to what extent the Fried scale of the turbulence decreases, and whether multiple guide stars will be needed for daytime operation. The second point to be investigated is how large the zenith angle can be while still maintaining good compensation. As we discuss below, it is desirable to reach 60 degrees from the zenith. The smaller apparent angular speed of the target at larger zenith angles will work to an advantage.

LASER EARTH DEFENSE CONCEPT

Many schemes have been discussed for dealing with NEOs on collision courses with the earth. These include the use of nuclear weapons to fragment the NEO, or landing on them using various methods (propulsive, explosive, etc.) to steer the asteroid into a passing orbit.

Fragmentation may not be a viable solution because the center of mass of the cloud would continue on the original collision trajectory as the parent mass. This would result in multiple impact events similar to the Shoemaker-Levy 9 collision with Jupiter. Also, fragmentation may make subsequent orbit shaping more difficult.

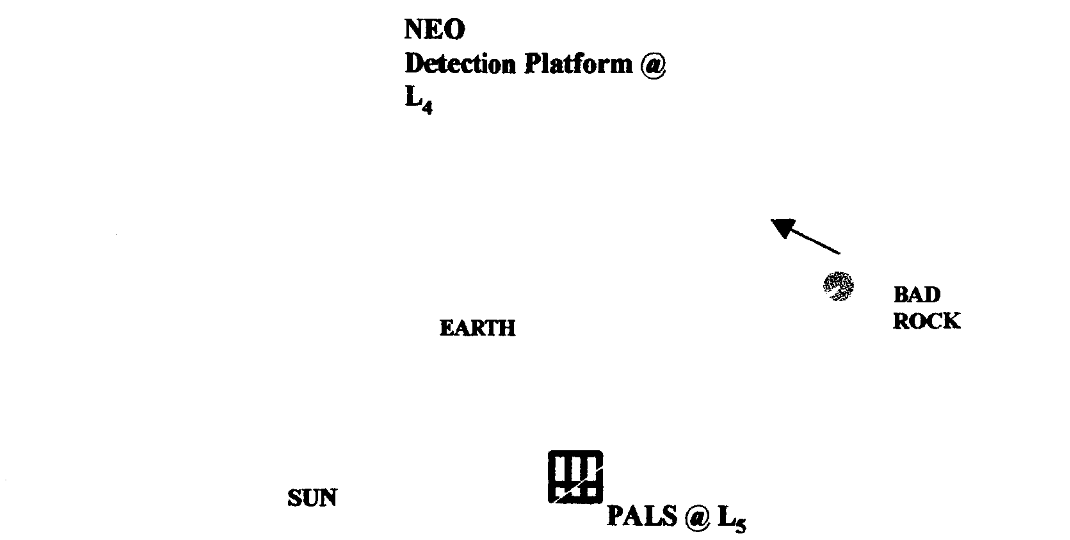

Figure 4. The Lagrange points are shown as L_n. PALS is placed at L_5 and a detection platform is placed at L_4. Note that nothing is to scale.

Many issues and engineering solutions need to be addressed in order to land on a NEO and place nuclear devices or other trajectory altering systems there. Although the cost of any NEO protection system will likely be significant, any system requiring a deep-space rendezvous would also require sufficient warning of an impact to be implemented. Additionally, a failure of such a defense system may not allow for a second mitigation effort to be attempted before the object impacts the Earth.

A better system would be one that is "on station" and could be used routinely to shape asteroid orbits over long periods of time so that they do not pose a potential threat. The system should also be able to handle the wide range of materials and sizes that constitute the NEO population (current or yet to be discovered). Phased Array Laser Systems (PALS) could be developed and placed in space, either orbiting or lunar based. Space-based laser constellations (SBL) are presently under development and will be flown during the next decade. The feasibility for a PALS based system is discussed below.

Laboratory experiments using a 20 kW pulsed laser have shown that the impulse imparted to aluminum targets due to the ejected plasma cloud gives an average surface pressure $p = 6.5 \times 10^{-4}$ N/cm^2, or equivalently, an acceleration $\mathbf{a} = 1.25 \times 10^{-6}$ m/s^2.

Thus, with present technology, an array of laser beam directors can be aimed at an asteroid, meteoroid, or a comet, providing sufficient power to ablate its surface. It is simply a matter of putting in place a sufficient number of lasers to accomplish the mission.

To generate ablation thrust, the main requirement is that the minimum laser intensity

$$I_{min} = 24/\tau^{0.55} \text{kW/cm}^2 \quad (2)$$

be delivered the NEO surface, either during a pulse or continuously. A laser momentum-coupling coefficient (thrust to optical power ratio)

$$C_m = F/P = 50 \text{ N/MW} \quad (3)$$

can be assumed [Phipps 1997].

Deflecting a 1 km diameter iron asteroid, as we will see in the simulation results that follow will require a peak laser power of approximately 200 GW. Several alternate potential approaches are available to power the array including nuclear or electric generation and solar power arrays.

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

$$R_e \cong R_E \left[1 + 2g \left(\frac{R_E}{v_0^2} \right) \right]^{\frac{1}{2}} \quad (4)$$

where R_E is the radius of the Earth, and g is the gravitation acceleration at the surface of the Earth. Clearly, for the large anticipated values of v_0, the Earth's gravitational pull will be insignificant in the encounter. There are two cases of interest:

- "Head-on" collision:
  $v_o = 40$ km/s ⟶ R_e=1.04 R_E

- "Catch-up" collision:
  $v_o = 5$ km/s ⟶ R_e=1.1 R_E

Hence, we may define a threshold for success for the two possible encounter scenarios. Table 2 provides the results of a two dimensional orbital mechanics simulation looking at an encounter with a 1 km spherical iron asteroid and gives the final displacement at the Earth as a function of the amount of time the laser works on the object.

Table 2 shows that a minimum of 38.8 days of illuminating the target is necessary for the case of a head-on collision, and in most cases would take much less illumination time. The warning time of impending impact is of critical significance, which highlights the importance of deep space surveillance of NEOs in addition to long-term monitoring and orbital calculations.

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

Table 2. Lateral displacement and final velocity of asteroid from original orbit per 2-D orbital mechanics simulation using expected coupling coefficients and state of the art laser intensities. The final velocity is a linear change, but the displacement is quadratic. Note the change of units in the second and third columns.

Early orbit shaping should be extraordinarily effective using a PALS. Also it is important that PALS be deployed at positions that are allow sufficient target illumination time to properly alter the trajectory of a confirmed impactor.

Clear seeing by space-based optical telescopes (i.e., the surveillance of small, dark objects such as asteroids) is greatly improved by the absence of stray light such as that reflected from the Earth or Moon. This fact would make it desirable to place a detection system far from these disturbances.

However, it is also advantageous for the PALS to be located sufficiently near the Earth that it is designed to protect. One candidate is one of the Sun-Earth Lagrange Points at which a spacecraft will maintain a fixed position with respect to the Earth. Another candidate location would be the lunar far side or the lunar poles that offers excellent seeing for astronomical observations and close proximity to the Earth for the PALS.

In Figure 4, we pictorially described an asteroid encounter with the Earth and a Lagrange Point based PALS. This orbit lay between the orbits of Mars and Venus, and is consistent with the recent news that an asteroid passed between the Earth and the Sun. Better data significantly altered the prediction of closest point of approach to 1,000,000 km with no significant threat in the foreseeable future. Nevertheless, the orbital period of an asteroid lying between Mars and Venus is roughly 0.9 yr.

If the collision scenario depicted in Figure 4 was encountered. The PALS firing with a good aspect from L_5 and sufficient lead time (as shown in the figure,) would have 2-3 months to move the asteroid away from a collision path with the Earth. Only with a sufficiently capable detection system would there be adequate time in advance, as shown in Table 2,. for the PALS to deflect the asteroid away from the Earth. This fact stresses the need for coupling with PALS an early warning system using optical and/or radar imaging techniques.

In another simulated scenario, the undetected asteroid could be chaotically ejected from the asteroid belt. In this case it is possible to describe similar results as depicted in Figure 5. In this case, the calculation is simplified by assuming that the entire impulse to the asteroid is given in one instant.

The ΔV of 5 km/s (see Table 2) is an obvious example of an impulse that yields a "miss distance." In this case, the simulation yields that the asteroid passes in front of the Earth by 1.25 Earth diameters.

An approach requiring significantly less power for PALS would be a gradual shift in the orbit by a long duration, low intensity impulse. This lower energy impulse would reshape the orbit over a long time period, perhaps several orbits. Ideally, for the asteroidal orbit shown in Figure 5, it might conceivable to move the asteroid into an

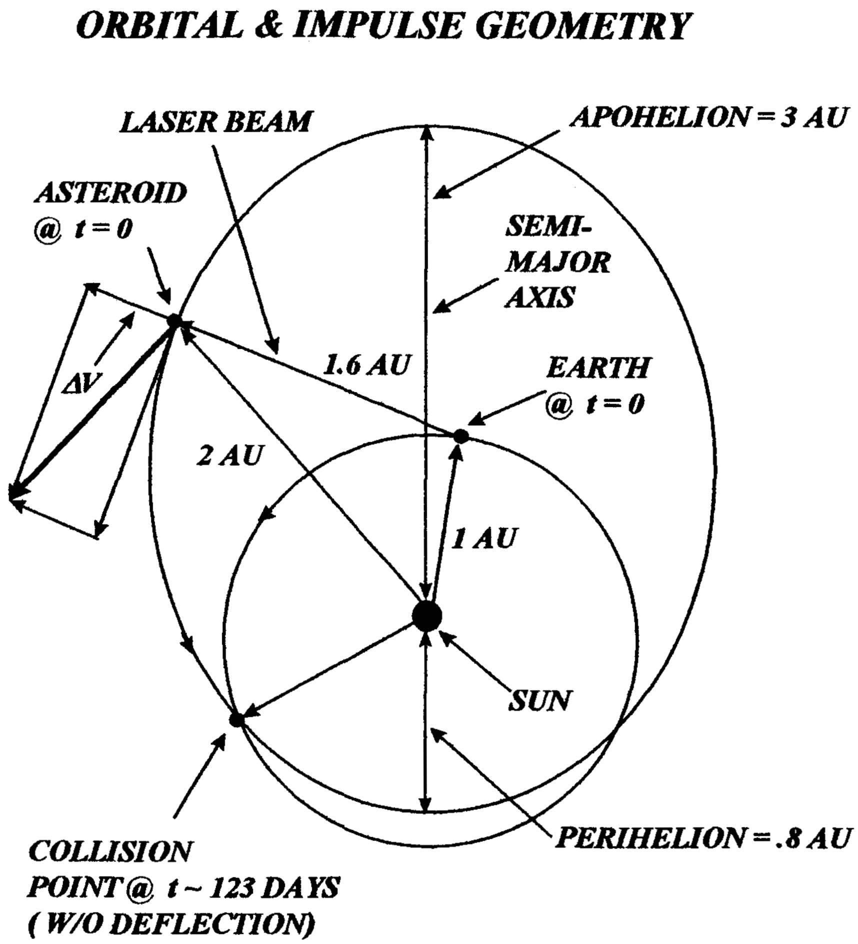

Figure 5. The ΔV is imparted to the asteroid in such a way as to reduce the period. As a result the asteroid will cross in front of the Earth.

orbit that removes any potential threat to the Earth.

From a non-defensive standpoint, it is interesting to contemplate asteroid orbit modification for the purpose of scientific exploration and/or commercial exploitation (i.e., asteroid mining). This application of a PALS may be particularly feasible for small asteroids (less than 100 m) in orbits that are "easily" modified to a desired rendezvous location for processing.

Additional considerations are illustrated in the two cases illustrated in Figure 6, the NEO is approaching Earth at 30km/s, and has been discovered at a range of 1000 Lt-s (1 A.U.), giving about 120 days for response. Two positions of Earth (E_1 and E_2) and of the NEO [(1) and (2)] are shown at times 48 hours apart. In the case II scenario, observers using telescopes on opposite sides of Earth make simultaneous measurements of the NEO angular position with a precision ±0.2 arc seconds, and determine range as 1000 ±23 Lt-s. This error, which is about equal to the 17 Lt-s relative motion of the NEO during 48 hours, gives about 1 radian uncertainty of the NEO's vector direction during the first 48 hours after discovery. To refine this measurement down to the level needed to predict whether the NEO will miss the Earth will take an additional month.

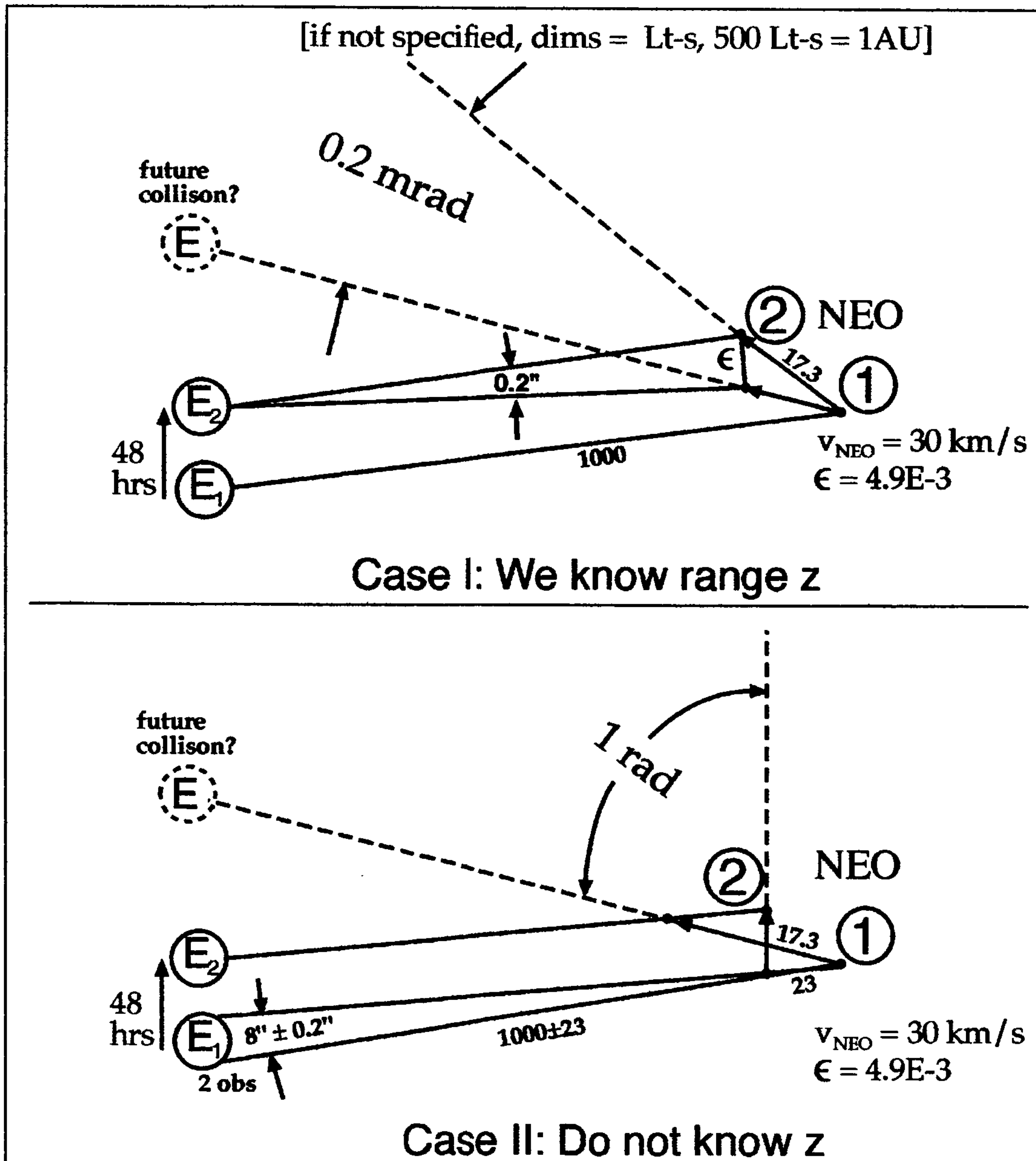

Figure 6. Illustrating benefit when independent range information is combined with conventional angular tracking

In the case I scenario, the same observations occur with the addition of tightly constrained range due to the laser or radar range measurement. With this constraint, the NEO's vector direction uncertainty is reduced to 200μrad. At a range of 1000 Lt-s, the future location of the NEO at closest approach has now been refined to about 5 Earth diameters during 48 hours of observation.

APERTURE REQUIREMENTS

In previous studies, the conceptual difficulty has been that making a laser spot as

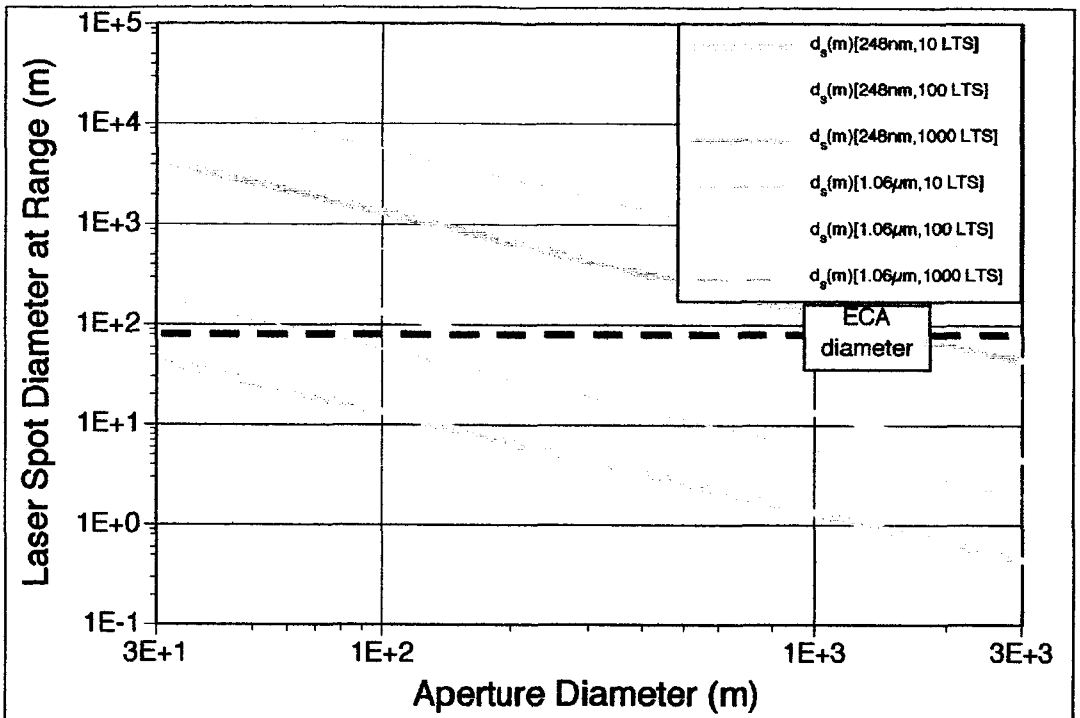

Figure 7. Laser spot diameter vs. aperture diameter (λ=248 nm and 1.06μm) for range 10, 100 and 1000 Lt-s

small as
the NEO at this distance requires a mirror of order 3km in diameter [Figure 7 & Phipps 1996].

With smaller mirrors than this, the spot spills over the NEO, wasting most of the laser power over exactly that portion of the NEO's travel in which thrust should be applied, and further failing to deliver the intensity required by equation [2] unless pulse width is drastically shortened. The spot size is inversely proportional to wavelength, making very short wavelengths, e.g., KrF at 248 nm, highly desirable.

A sparse phased array of lasers is analogous to the Very Large Array (VLA) in New Mexico. Several widely spaced laser apertures are phased together so that their wavefronts emerge in perfect mutual phase. In the "far field", i.e., a distance much larger than the laser separation, the result is a diffraction pattern in which the central spot retains a useful fraction of the total beam energy in a spot diameter which is nearly the same as that which would come from a single mirror with diameter equal to the array diameter.

CURRENT LASER TECHNOLOGIES

The US Air Force Airborne Laser (ABL) is a major weapon system development by the United States Air Force to provide an airborne, multi-megawatt laser system with a state-of-the-art atmospheric compensation system to destroy enemy theater ballistic missiles at long ranges [Lamberson 2002].

The Space Based Laser (SBL) program will use a high-energy laser to destroy boosting missiles in flight. The principal kill mechanism is to cause mechanical weakening of the booster skin, so that internal pressures will cause the missile to explode while it is still boosting [Riker 2002].

Both are examples of very high power lasers which are available now, and which could be deployed for preliminary asteroid thruster tests without much further development.

CURRENT SENSOR TECHNOLOGIES

In general, acquisition of remote objects for observation and tracking is accomplished by the observation of either self-emitted or reflected optical energy, RF energy, acoustic energy or other quanta in comparison to some background level. In particular, only optical and radar sensors are usable to acquire targets at long range. The three approaches below are ones that currently appear to even have a chance; given the ranges, object sizes and sensor characteristics involved.
The first is microwave radar with characteristics similar to the MIT/LL HAYSTACK, DoD PAVE PAWS or DEW Line radars, but with a very-much-higher-power electronically scanned beam (repeated linear two-dimensional scan or other acquisition strategy) for wide-angle search at long range.

The second is a passive optical system - an astronomical-class telescope perhaps with an angle-scanning capability along the lines suggested by MIT/LL in the NASA ORION study for a modified HAYSTACK-type, DoD PAVE PAWS type or DEW Line type radar. The illumination of the objects would be by sunlight. The size of the instantaneous Field of View of the system fixes the instantaneous spot size being viewed, while the angle-scanning capability determines the search Field of Regard. Ecliptic Plane as well as out-of-plane threat asteroid objects must be considered.

The third is an active illuminator laser-radar (LADAR) ranging system. Economy dictates that if this option were chosen, the transmitter would use the pusher laser as the energy source, but would use a de-focused beam to interrogate a large spot in space for the detection function. The beam would be then be narrowed to perform the ranging and tracking functions.

In the sections below, we sketch the driving parameters for each of the above approaches, and suggest approaches to acquire and track the target astronomical objects that will be examined in the proposed study.

ALL-RADAR ACQUISITION

The all-radar approach was extensively analyzed during the course of the first phase of NASA's ORION program. In that study, a radar system with beam parameters similar to those existing at the MIT/LL HAYSTACK facility was required for detection, acquisition, identification, track and handover of 2 mm-2 cm diameter near-earth orbital debris objects to the "pusher" laser system.

The ORION study [Campbell, 1996] recommended that another approach to the use of a radar be considered to dramatically increase the orbital debris detection rate: that of a static "picket fence" or a dynamic-motion "bow-tie" sky-scan pattern rather than a stationary staring beam be used, along with a longer pulse, to increase the measurement area from a single-beam 1 km x 100 km area to one with 10 km (or more) x 100 km area. Since threat objects could approach Earth in both the Ecliptic plane as well as out-of-plane, the search for such threat asteroid objects must be considered as a 3-D problem.

PASSIVE OPTICAL/LADAR/RADAR ACQUISITION

An effective approach to detecting the NEO uses a CCD-equipped, very-large-aperture, wide field of view (FOV) telescope and solar illumination, augmented by a "laser searchlight" or high-peak-power radar system.

The wide FOV unit enables detection in a time short compared to the time to act. In the ORION study [Campbell, 1996] it was realized early that "the sky is big". That is, although the signal-to-noise ratio of a searchlight beam is very high, the probability of finding a small-cross-section object at all is very low. This discrepancy increases as the cross-section of the target object decreases. A searchlight beam cannot scan the whole sky with any chance of accidentally discovering the NEO before it is upon us. In order to scan the ecliptic +/-20° for objects with 100Lt-s range in 2 months at a laser repetition rate of 1Hz, we need a spot size at range of order 100,000 km and, for a 80-m-diameter NEO with 16% reflectivity, using a 10-m-diameter transmitting/receiving aperture, we will need 1 PJ laser pulses at 530 nm to receive one returned photon. The radar case is much better in this regard, because there are more photons per joule, but still requires 50GJ pulses for a single returned photon.

The searchlight's ideal function is to be used as a searchlight. The passive optical system (POS) locates the object using reflected sunlight and then the searchlight beam, narrowed down to the position uncertainty of the POS, provides range. Used together, the two systems combine the best features of each. As indicated earlier, the searchlight beam and the pusher laser beam should be one and the same.

ALL-ELECTRIC SEALED-OFF GAS LASERS

The use of medium-power industrial and medical lasers (100-1000 watts average power) and much higher power (the Airborne Laser -ABL- and the Mobile Tactical High Energy Laser-MTHEL) Defense Dept laser systems have become accepted over the past few years. While industrial laser-base material processing is dominated by 10-micron CO_2 gas lasers and 1.06 and 0.67 micron solid-state lasers, there is growing interest in the dual use of ultra-compact rugged high-efficiency lasers for commercial (medicine, wavelength-specific photochemistry) and for Defense (ship self-defense) applications in other wavelength regions. Recent advances in wave-guide array laser technology promise efficient production of high power laser emission at the wavelengths necessary for these uses, making complete fielded laser packages small, rugged, practical and economical.

In addition, electrically powering the laser's ultra-compact gain medium allows active real-time control of the output waveform from CW, to short-pulse/high rep-rate to long-pulse/low rep-rate operation, and even intra-pulse output power temporal profiling.

A new high-power laser technology, sealed-off cooled no-flow rare gas lasers, show promise of providing line-selected operation in the 0.5-to-2.0 micron wavelength region with a single near-diffraction-limited output beam (using a phase-coupled folded array of waveguide gain media) and with selectable rep-pulse and CW waveforms (determined purely by the power input electrical waveforms).

Waveguide-array technology offers a novel approach to combining a sealed-off long-life gaseous electrical discharge gain medium, a laser resonator and an optimum thermal management system to create a sealed-off, compact, rugged and lightweight, maintenance-free high-power laser system.

NST, the USAF / AFRL and its industrial team members are currently engaged in a full exploitation of waveguide laser technology, for both DoD and commercial applications at wavelengths from 0.5 through 10.6 microns, and is in a unique position to evaluate this new all-electric sealed-off laser technology for NASA initiatives such as the asteroid deflection application.

AN APPROACH FOR GETTING STARTED

This approach should be a three-phase program (study, test, demonstration) and consist of the following elements:

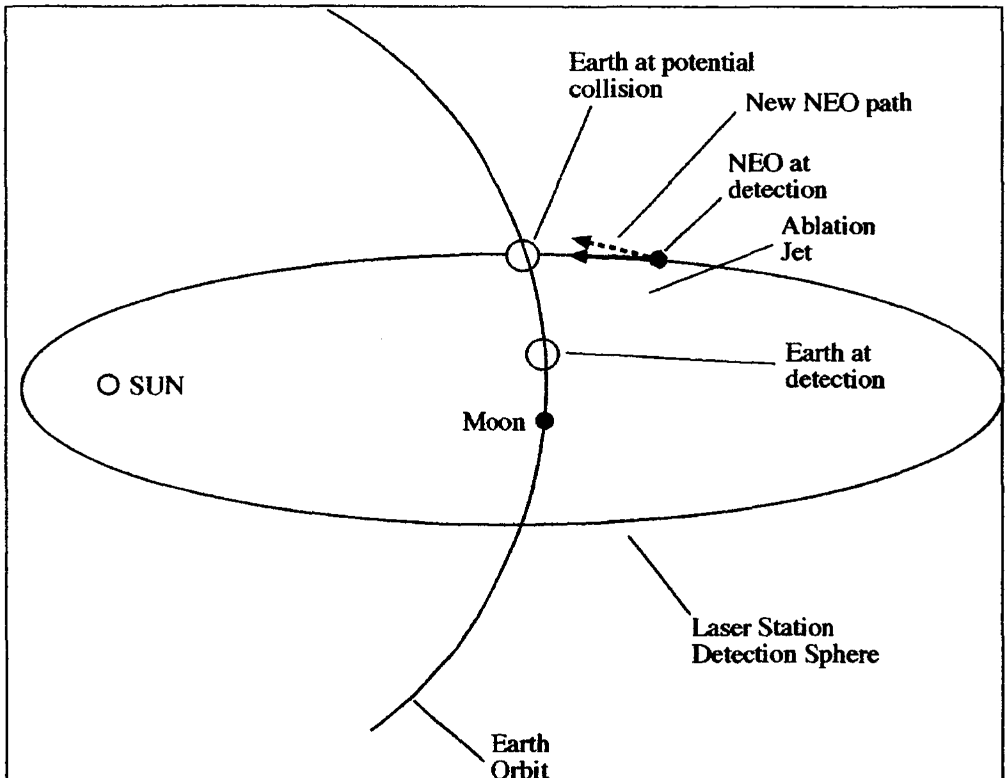

Figure 8. Cross-section in the ecliptic plane (not to scale) showing laser station. At least 5 stations on the Moon provide omnidirectional coverage. The NEO is handed off from one to the other during the interaction. Detection at 0.2AU (100Lt-s) gives at least 20 days action time. Electrical power for the lasers is beamed up from Earth.

a) Operational option comparisons -

b) Laser technology options comparison;

c) and sensor technology options comparison.

Table 3. Possible laser and interaction parameters
NEO diameter - 80m
NEO composition - Iron (ρ=9000 kg/m^3)
NEO average velocity - 30 km/s
NEO mass - 2.41E9 kg
Interaction time at detection - 20 days
Laser wavelength - 500 nm
Laser power to deflect (no beam spill) - 56 MW
Laser pulse duration - 10 ps
Laser pulse energy - 14 MJ
Laser pulse repetition rate - 4 Hz

TECHNICAL OBJECTIVES

The broadly stated technical objectives of the study proposed in Phase I should be:

Define the laser and pointer-tracker (PT) system's characteristics including capabilities of the laser and PT system that a potential Phase II test planning might require for thrust and impulse-production applications. This definition must be the first objective accomplished, since it sets the technical environment for the tasks in the rest of the program.

Complete the conceptual design for a rare-gas laser system (0.3-1 micron wavelength) and solid-state system (0.3-1 micron wavelength) that satisfies the requirements of the potential application as defined above.
Identify, characterize, prioritize and select laser parameters including wavelengths in repped-pulse operation, specific wavelengths, and range of gain medium options proven reliable, as obtained from ongoing test programs and analyses.

Adapt laser designs including solid-state and sealed-off gas laser designs to be compatible with the empirically determined laser operation envelope into a preliminary design of the solid-state cooled laser and the sealed-off cooled rare-gas laser.

With the concept for a solid-state and a sealed-off waveguide-array rare gas laser in place at the end of Phase I, the logical continuation into Phase II would be first the testing of the chosen waveforms and wavelengths on appropriate materials and objects to validate impulse and thrust production. Those options that survive Phase I scrutiny will then be tested in Phase II, optimized to satisfy the requirements of the Phase II and Phase III demonstrations.

Compare sensor technology options. Geometry and sensor technology will be studied in combination to determine the best approach. Areas of investigation will include back-illuminated CCD's, crossed photon-counting delay lines and other novel options.

Compare location options.

Moon - The Moon has strong advantages: providing a reaction mass for the station is critical. Disadvantages include wide temperature extremes.

Libration Points – These offer advantages and should be considered as well.

Earth – The most convenient location and least expensive superficially. Must overcome problems working through the atmosphere.

Mars - Mars is interesting as an early-warning outpost.

Rendezvous - Taking a smaller pusher laser to the target may be another option.

Examine Energy-gain Options. Study creative options for providing substantial energy gain in the laser-NEO interaction. Two of these are: a) the billiard-ball option, in which a small NEO is deflected into the path of the larger one at distance sufficient for most of the resulting fragments to clear Earth and b) the scattering option, in which the orbit of a NEO which is substantially similar to Earth's orbit is modified using Earth's gravitational field.

The impact of cost sharing should be considered. Other applications can support the cost of a NEO-deflection laser system. These include capturing small asteroids and mining their rich rare-metal deposits [Blacic 1993] and deflecting Earth-orbiting space junk so that it burns up in the atmosphere [ORION concept: Phipps, et al. 1996; Campbell 1996].

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

An elegant, cost effective, feasible laser technology approach has been identified - a global solution to solve a global problem. This solution is truly international in scope in that it solves the problem for everyone.

If a high energy, laser pulse of sufficient intensity strikes an asteroid, meteoroid, or comet in space; a micro-thin layer of material is ablated from its surface. This super hot vapor rapidly expands outward imparting a tiny amount of force to the object. Since current laser technology produces 10 to 100 pulses per second, the ablation interaction is rapidly repeated over and over again. This cumulative thrust acting on the object if applied at the appropriate point in the object's orbit is sufficient to deflect it from impacting the Earth.

In addition, the additional promise of orbit shaping capability for asteroids, meteoroids, and comets is that the orbit may be modified sufficiently to make it convenient for utilization such as mining or in situ materials utilization. One final note on statistics in an investment context: the probability of the Earth being struck by a hazardous asteroid in the near future is approximately a thousand times more likely than winning a recent Florida lottery.

We recommend a two-year program that will take these concepts to laboratory demonstration level as regards laser performance, laser-target interaction, detection and a lab-scale test of phased array performance.

We further recommend a follow-on program that will consist of an experimental program to prove the concepts at significant range, including detection of remote objects and pushing surrogate targets released by the Shuttle. This program will include a test in which an existing very high power laser (e.g., HELSTF, ABL,) is employed to illuminate and measurably push one of the 30 or so 40-m-size NEO's that pass through the Moon's orbit each month.

In general, we recommend that the World's space objectives be immediately reprioritized to start us moving quickly towards a multiple option defense capability – an integrated ground and space infrastructure. While lasers should be the primary approach, all mitigation options depend on robust early warning, detection, and tracking resources to find objects sufficiently prior to Earth orbit passage in time to allow mitigation.

Infrastructure options should include ground, LEO, GEO, Lunar, and libration point laser and sensor stations for providing early warning, tracking, and deflection. Other options should include space interceptors that will carry both laser and nuclear ablators for close range work. Response options must be developed to deal with the consequences of an impact should we move too slowly.

Preventing collisions with the Earth by hypervelocity asteroids, meteoroids, and comets is the most important immediate problem facing human civilization. This is the **Impact Imperative**.

REFERENCES

1. BBC News Online, 30 October 2001
2. Center for Astronomical Adaptive Optics (1997)
3. Starfire Optical Range (1997)
4. Cleghorn, George et al (1995) *Orbital Debris: A Technical Assessment*, National Academy Press, Washington, DC,
5. Blacic, J., "Mining Near-Earth Objects for Resources to Benefit Earth", Los Alamos National Laboratory internal white paper (1993)
6. Campbell, J.W., *Project ORION: Orbital Debris Removal Using Ground-Based Sensors and Lasers*, NASA Marshall Spaceflight Center Technical Memorandum 108522(1996)

7. Hills, J. G., "Fragmentation of Small Asteroids in the Atmosphere", Los Alamos National Laboratory report LA-UR-92-2321 (1992)

8. Kantrowitz, A. (1972) *Aeronaut. Astronaut.* **10**, 74

9. Lamberson, S., "The Airborne Laser", *Proc. SPIE High Power Laser Ablation IV* (2002) to appear

10. Phipps, C.R., "Dynamics of NEO Interception," *Report of the NASA Near-Earth-Object Interception Workshop,* John D. G. Rather, Chair, Report LA-12476-C, Los Alamos National Laboratory, Los Alamos NM (1992)

11. Phipps, C.R., "Astrodynamics of Interception," in *Report of the NASA Near-Earth-Object Interception Workshop,* John D. G. Rather, Chair (workshop summary), Report LA-12476-C, Los Alamos National Laboratory, Los Alamos, NM (1992)

12. Phipps, C.R., "Laser Deflection of NEO's," *Report of the NASA Near-Earth-Object Interception Workshop,* John D. G. Rather, Chair, Report LA-12476-C, Los Alamos National Laboratory, Los Alamos, NM (1992)

13. Phipps, C.R., "A laser concept for clearing space junk," in *AIP Conference Proceedings* **318**, Laser Interaction and Related Plasma Phenomena, 11th International Workshop, Monterey, CA October, 1993, George Miley, ed. American Institute of Physics, New York (1994) pp. 466-8

14. Phipps, C.R., "Lasers can play a rôle in planetary defense" in *Proc. Planetary Defense Workshop,* Report CONF-9505266, Lawrence Livermore National Laboratory, Livermore CA (1995)

15. Phipps, C.R., and Michaelis, M.M, "NEO-LISP: deflecting near-earth objects using high average power, repetitively pulsed lasers", *Inst. Phys. Conf. Ser. 140 section 9,* pp. 383-7, ICP Publishing, Bristol (1995)

16. Phipps, C.R., Friedman, H., Gavel, D., Murray, J., Albrecht, G., George, E.V., Ho, C., Priedhorsky, W., Michaelis M.M., and Reilly, J.P., "ORION: Clearing near-Earth space debris using a 20-kW, 530-nm, Earth-based, repetitively pulsed laser", *Laser and Particle Beams,* **14** (1996) pp. 1-44

17. Phipps, C.R., "Laser Deflection of Near-Earth Asteroids and Comet Nuclei", *Proc. International Conference on Lasers 96,* STS Press, McLean, VA (1997) pp. 580-7

18. Phipps, C.R., "Requirements for Laser Acquisition of NEO's", *Proc. International Conference on Lasers 97,* STS Press, McLean, VA (1998) pp. 928-34

19. Phipps, C.R., "Review of Direct-Drive Laser Space Propulsion Concepts", *AIP Conference Proceedings* **420**, Space Technology and Applications International Forum 1998, M. El-Genk, ed., American Institute of Physics, Woodbury, NY (1998) pp. 1073-80

20. Phipps, C.R., Reilly, J.P., and Campbell, J.W.,"Optimum Parameters for Laser-launching Objects into Low Earth Orbit", J. Laser and Particle Beams, **18** no. 4 pp. 661-695 (2000)

21. Phipps, C.R. and Luke, J.R., "Diode Laser-driven Microthrusters: A New Departure for Micropropulsion", *AIAA Journal*, 40, no. 1, pp. 1-9 (2002)

22. Reilly, J.P., Phipps, C.R., and Campbell, J.W., "Comparison of Repetitive-pulse laser Approaches for Boosting Small Payloads into LEO," Proc. Santa Fe High Power Laser Ablation Conference III, SPIE **4065** (2000) pp. 946

23. Riker, J., "Space Based Laser Overview and Target Interactions," *Proc. SPIE High Power Laser Ablation IV* (2002) to appear

24. Sharpton, V.L., Nature, October 29, 1993; *Sky and Telescope*, July 1991, page 38; *Sky and Telescope*, January 1993, page 12.

25. Shoemaker, E. M. "The NEO Flux, Present and Past", *Proc. Lawrence Livermore National Laboratory Planetary Defense Workshop,* Report CONF-9505266, Lawrence Livermore National Laboratory, Livermore CA (1995)

26. Solem, J. C. "Nuclear Explosive Propelled Interceptor for Deflecting Comets and Asteroids on a Potentially Catastrophic Collision Course with Earth", *Report of the NASA Near-Earth-Object*

Interception Workshop, January 14-16, 1992, Los Alamos, NM, John D. G. Rather, Chair, Los Alamos National Laboratory Report LA-12476-C (1993