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LASER DEBRIS SWEEPER FOR THE SPACE STATION FREEDOM

Thomas J. Settecerri
Jorge E. Beraun

LOCKHEED / NASA JSC, HOUSTON, TEXAS
PHILLIPS LABORATORY, KIRTLAND, AFB, NEW MEXICO

ABSTRACT

This paper presents a laser debris sweeper concept to actively move orbital space debris. Such a systems is capable of detecting, tracking, and moving orbital debris that could collide with the Space Station Freedom (SSF). Currently. shielding is being designed to protect the Station against debris particles smaller than 1 cm. Larger objects will be tracked and avoided by maneuvers. The potential number of orbit changes could lesson the success of the SSF's space experiments. Actively removing space debris by momentum transfer through laser-induced ablation is a viable concepts to reduce the altitude of the orbital debris. This paper assess the critical parameters of a laser debris sweeper system: target fluence, impulse coupling, momentum transfer, fluence, energy, beam size, pulse length pulse repetition frequency, detection and engagement range, and system optics and power.

1.0 INTRODUCTION

This paper is the summary of a feasibility design study for an orbital debris collision avoidance system. The laser debris sweeper concept described focuses on debris mitigation for the Space Station Freedom. An active laser system can transfer momentum, nearly instantaneously, to orbital space debris through laser-induced ablation. If space debris adsorbs sufficient laser energy, surface emission of particles occurs that imparts momentum to the debris changing its orbital parameters. This paper describes: the phenomenon of laser-induced ablation and impulse coupling, estimates of the velocity change that is imparted to a debris object due to momentum transfer, calculations of the impact of the velocity change on an object's altitude, and assessment of the effectiveness of various laser parameters to de-orbit or move space debris. The selection of laser characteristics is based on maximizing the momentum transferred to the orbital debris. The critical parameters of a laser system include: fluence on target, beam size, beam profile, pulse repetition frequency (PRF), pulse duration, system power, and optimum detection and engagement range for 1-10 cm diameter aluminum particles. The proposed space debris sweeper consists of a laser, an acquisition, tracking and pointing system, power supply, power storage system, and requires an accurate catalog of orbital space debris down to 1 cm. Currently, treaty prohibits such directed energy systems in space. The proposed laser debris sweeper does have ancillary capabilities that would have to be considered in a new treaty.

2.0 THE ENVIRONMENT

Since the launch of Sputnik 1 by the Soviet Union in 1957, there has been over 22,000 space launches. Today, there are an estimated 35 million orbiting objects, weighing 3 million kilograms (6.6 million pounds). Most of this mass consists of spent rocket stages, inactive satellites, and a few active satellites. In fact, only a small percent are functional satellites; the rest are considered orbital space debris. The space object catalog maintained by the United States Space Command (USSPACECOM) contains over 7000 objects. However, the catalog is limited to most objects larger than 20 cm, some objects greater than 10 cm, but none smaller than 10 cm. Recent studies verified by advanced radar and optical systems now lead NASA space debris experts to believe that better information is needed to quantify the debris environment down to 1 mm. However, even smaller objects still can do considerable damage to spacecraft. Such as the tiny 0.2 millimeter titanium oxide paint chip that collided with the Space Shuttle Challenger in 1983 and damaged a window.

The Space Science Branch at Johnson Space Center has been collecting orbital debris data since October 1990 using the Haystack radar in Massachusetts. To date over 1500 hours of data have been analyzed to assess the debris population at Space Station altitudes. Figure 1 shows the potential danger to the Space Station from analysis of the data collected.

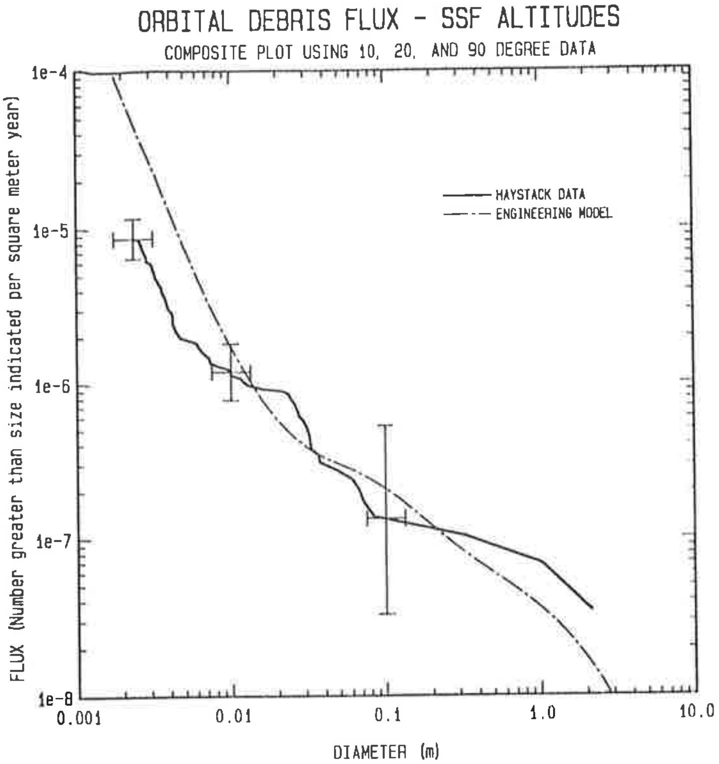

Figure 1 Orbital Debris Flux

The majority of orbital space debris originated from boosters or satellites breakups. Analysis of foreign and US satellites and rocket body designs indicates that the composition of the debris is primarily aluminum.

3.0 SPACE STATION FREEDOM

The Space Station FREEDOM (SSF) is scheduled to launch it first element in 1996, be man-tended by 1997, and be permanently manned by 1999. The planned orbit is between 300 and 500 kilometers at an inclination of 28.5 degrees. The Space Station's shielding is designed to protect against objects smaller than 1 cm and altitude changes are planned to avoid debris larger than 10 cm. However, that leaves the 1-10 cm range where the population is not totally known; nor are debris particles in that size range tracked. In order to fill this gap augmented capabilities are planned. This is notionally shown in Figure 2.

Based on the projected space debris environment, the SSF plans to change orbit 10 time per year to avoid debris; using four of these burns for required orbit keeping. However, NASA studies indicate that due to the inherent limitations of USSPACECOM's capabilities and the postulated increase of space debris by 2010 collision avoidance maneuvers may be needed every 1-2 weeks.

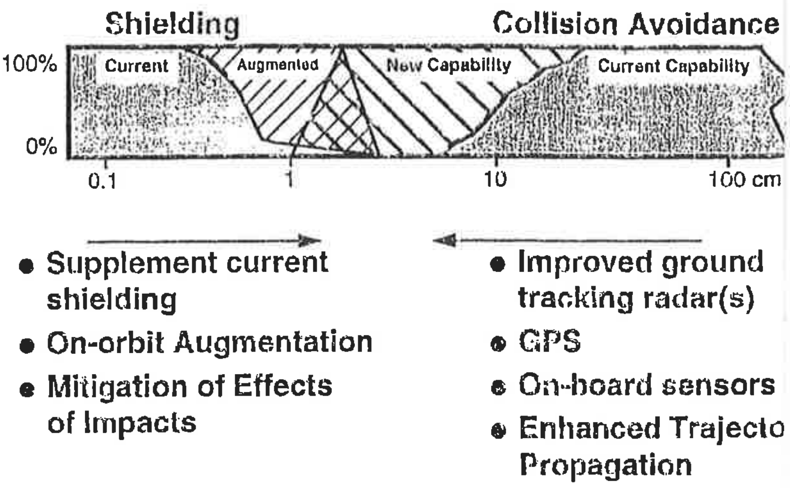

Figure 2 Conceptual Approach

The factors considered to direct a altitude change are ultimately determined from a conjunction. A conjunction exists when the uncertainty in the Space Station Freedom's position and the uncertainty in the position of an orbital debris particle are projected to overlap/intercept at a future time. Since, space debris is a critical factor in the Space Station Freedom's lifecycle, NASA plans to accurately track orbital debris to reduce its position uncertainty. Further analyses derived from the inclination distribution of the USSPACECOM catalog shows that the most likely direction of potential collisions is from 40-70 degrees on either side of the SSF's velocity vector (See Figure 3). This results from particles inclined at 80-100 degrees from the Space Station's inclination.

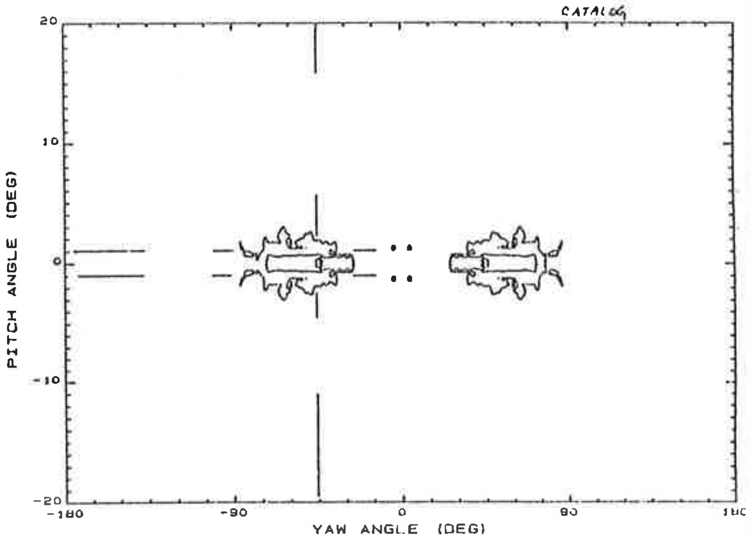

Figure 3 Collision Angles

An active system using a laser debris sweeper is another option to minimize the orbital space debris hazard. A laser system relies on the momentum transfer delivered to orbital debris through surface ablation. The momentum imparted alters the orbital debris' lifetime by lowering its orbit. Such a laser debris sweeper system would be capable of detecting, identifying, tracking, and moving orbital debris that could collide with the station. A long term stable platform is critical to unique SSF experiments such as microgravity crystal growth or protein production. Actively moving space debris would reduce the number of avoidance maneuvers.

4.0 DETECTION RANGE

In order to engage orbital debris with an active laser system the acquisition, tracking and pointing system requires sensors capable of detecting and tracking debris at extended ranges. We considered the state-of-the-art for such sensors and examined the detection range for infrared detectors as a function of size and temperature. The NASA Debris Collision Warning Sensor Study shown in tabular form below depicts these dependencies.

SIZE (cm)	TEMPERATURE (K)	DETECTION RANGE (km)
1	240	70
2	240	210
5	240	1000
10	240	2500
1	300	170
2	300	630
5	300	2150
10	300	5400

Table 1

We then considered the following scenario: two objects in 28-degree and 118-degree inclination orbits both at 400 km altitude. We started the two objects on a collision course 3000 km apart and determined their separation parameters using the SATRAK program. The results show that the average range rate is 10.5 km/sec, the maximum azimuth angle rate is .01 degrees/sec, and the maximum elevation angle rate .045 degrees/sec.

Considering a 1 cm object at 240 K, this closing rate yields a warning time of 7 seconds. Based on this short time it can be seen that an accurate catalog of space debris down to 1 cm is required so that a debris object can be quickly acquired and tracked in order to engage it with an active laser system. However, ongoing research in the area of optical phase conjugation and analog image processing reports that 1 cm sized objects can be imaged at 300 km.

5.0 LASER INDUCED ABLATION

The debris sweeper is based on the phenomenon that when a laser pulse is incident upon metal and composite materials, particles are ejected from the surface if the laser's fluence is sufficient to exceed the material's volumetric absorption threshold. The particles ejected from the surface produce a rocket-like effect that imparts a momentum to the target object. The mechanism that describes the transfer of pulsed laser energy into a target is called the impulse coupling coefficient. Impulse coupling coefficients have been determined experimentally at the Phillips Laboratory using pulsed lasers at various wavelengths, power levels, and pulse lengths. The coupling coefficient defined as the ratio of impulse to fluence (dyne-sec/joule) has been experimentally determined to be a strong function of the laser pulse length, the surface material, and to lesser degree wavelength. The impulse coupling coefficient exhibits a threshold, peak, and asymptotic region depending on fluence (see Figure 4).

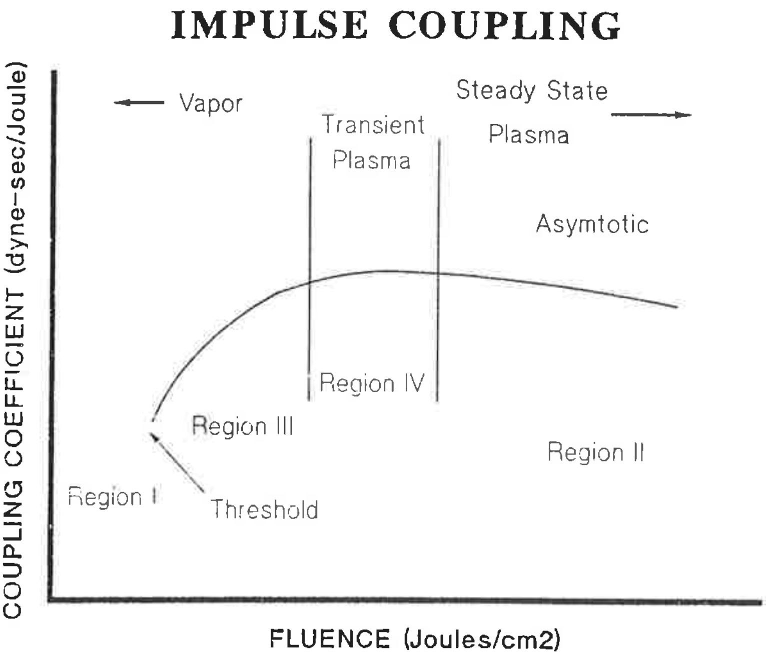

Figure 4 Impulse Coupling Conceptual

Impulse coupling occurs when there is volumetric absorption also referred to as in-depth absorption. Depending the material's surface and laser wavelength there is an absorption depth that ranges from a few nm to hundreds of μm. At low fluences (Region I), the majority of the energy is reflected from the surface. The small amount of energy that is absorbed is conducted into the target both radially and laterally and no impulse is generated. At the onset of in-depth absorption we reach a threshold. This results in the ejection of mass fragments and impulse to the object (Region III). The asymptotic regions is characterized by surface vaporization (Region II). A sustained plasma causes beam blockage which somewhat restricts in-depth absorption of the laser energy. At even higher fluence the impulse coupling coefficient is seen to roll off slightly. The maximum or peak impulse coupling results when the fluence is sufficient and the pulse length correspondingly short such that the energy is absorbed before beam blockage can occur (Region IV). Experimental results depicted in Figures 5 - 6 shows these regions.

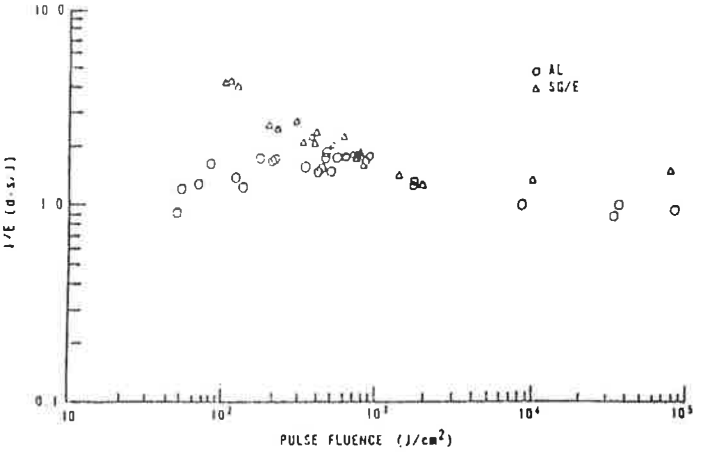

Figure 5 Impulse Coupling Experimental

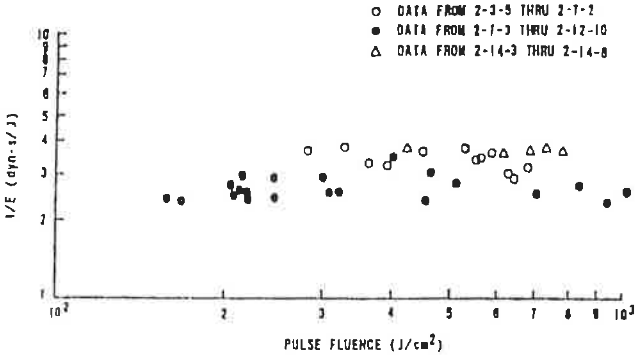

Figure 6 Impulse Coupling Experimental

Impulse couple data on 2024 aluminum (Figure 5) indicates a peak coupling coefficient of approximately 3 dyne-sec/joule at 100 J/cm². Figure 6 shows that aluminum coated with MLI remains a fairly constant impulse coupling over a fluence range from 100 to 1000 J/cm². The experimental results show that outside that range the coupling coefficient decreases. The data shown in both figures is from eximer laser tests with a 1.5 μsec pulse length. However, one means of maintaining high impulse coupling for higher or lower fluences is by changing the pulse length. Experimental data shows that the peak impulse coupling coefficient can be sustained by scaling the pulse length and fluence accordingly:

$$\frac{\sqrt{F_2}}{\sqrt{F_1}} = \frac{\sqrt{t_2}}{\sqrt{t_1}}$$

F_1 is the experimentally derived fluence at peak impulse coupling for pulse length t_1; t_2 is the required pulse length for peak coupling at fluence F_2. Figure 7 shows the results of calculations that scaled a 1 μsec laser pulse length to 500 nanoseconds. The solid line is experimental results and the dashed is calculated. Notice that by decreasing the pulse length results in a threshold fluence of 5 J/cm² and a peak of 8 J/cm².

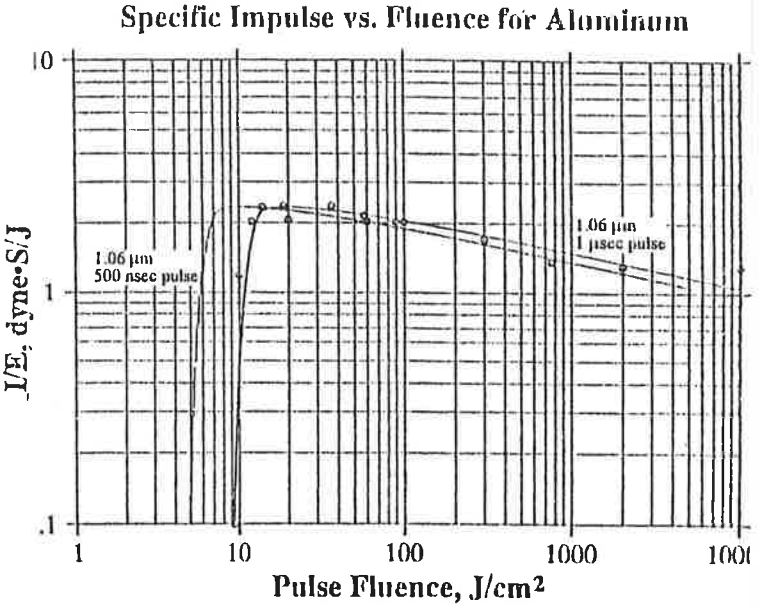

Figure 7 Impulse vs Fluence

6.0 MOMENTUM TRANSFER

To determine the feasibility of a laser to move space debris, the object's velocity change (ΔV) must be compared to the ΔV that is required to adequately alter the orbital parameters of the object. When negative ΔV is imparted to an object in a circular orbit its orbit is changed to an elliptical orbit with a perigee that is less than the altitude of the original circular orbit. To determine the effectiveness of a laser as a collision avoidance system, one needs to determine the ΔV required to achieve a certain miss distance. Assuming two objects are in the same circular orbit, this relationship is shown in Figure 8. This plot depicts the change in velocity required for two objects to miss each other by 100 and 500 meters depending on the two objects' separation when the change in velocity to one object occurs. Figure 8 was derived for objects between 300 and 500 km altitude.

Using the results shown in Table 1 the engagement range can be bounded between 170 and 5000 km for 300 K objects. At these extremes the required velocity changes for a 100 meter miss distance are 100 m/sec and 0.2 m/sec respectively. Similarly, the ΔV for a 500 meter miss distance is 1.0 m/sec at 5000 km and 70.0

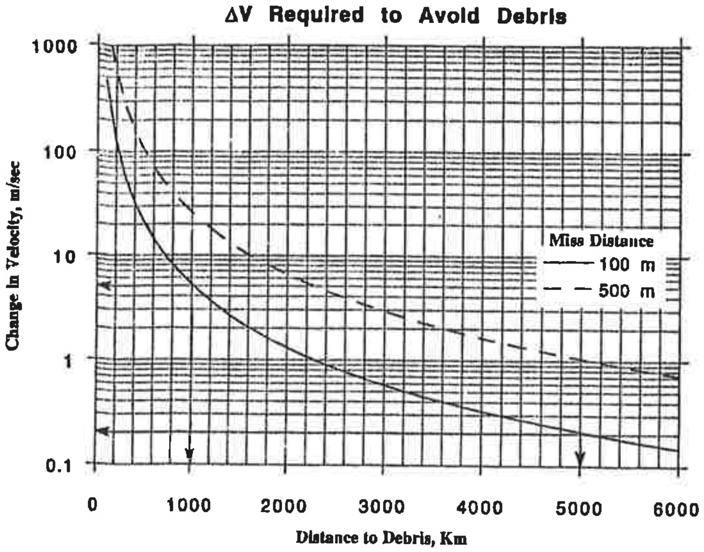

Figure 8 Velocity Change

m/sec at 500 km. Using these velocity changes Figure 9a & 9b can be used to determine the energy required for a laser system to alter the orbit of 1, 5, and 10 cm debris objects, at a specified engagement range. Figures 9 derived from NdYag laser-effects experiments, assume a maximum impulse coupling value of eight dyne-sec/joule taken from Figure 7.

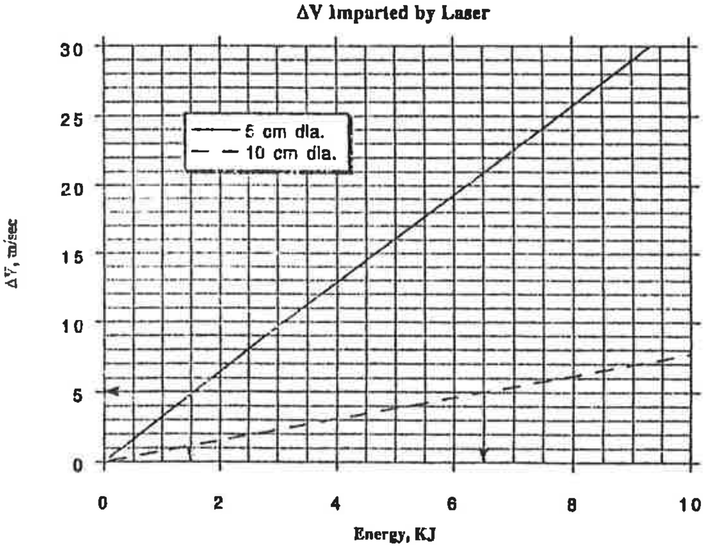

Figure 9a ΔV vs Energy

Using the above values Table 2 summarizes these examples.

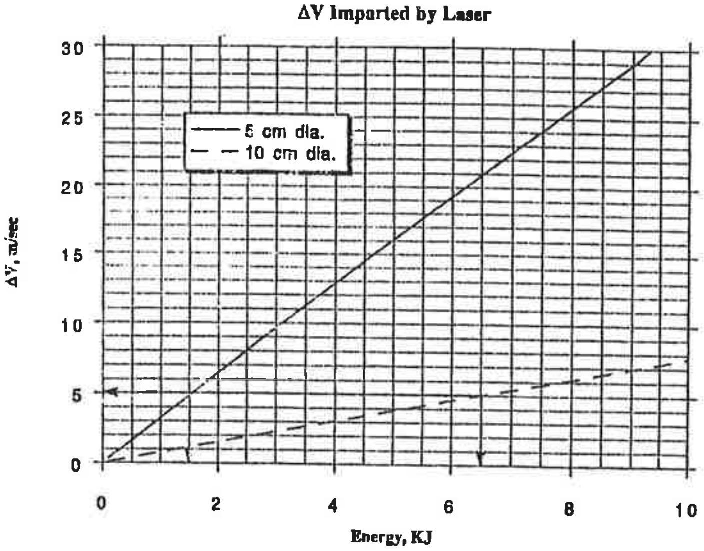

Figure 9b ΔV vs Energy

Example Laser Debris Sweeper
Fluence on Target

Range (km)	Miss Dist (m)	Δv Req (m/sec)	Tgt Size (cm)	Fluence (KJ)
170	100	100	1	1.3
170	100	100	5	---
170	100	100	10	---
5000	100	0.2	1	0.003
5000	100	0.2	5	0.06
5000	100	0.2	10	0.3
500	500	70	1	0.9
500	500	70	5	21
500	500	70	10	91
5000	500	1	1	0.1
5000	500	1	5	0.3
5000	500	1	10	1.3

Table 2

We note that larger objects must be engaged at longer ranges; however, they are easier to detect at longer ranges. Also small objects not detectable until shorter ranges, require a higher velocity change.

Ultimately the limiting factor is available fluence. We next calculated several engagement ranges as a function of miss distance for a fixed energy. Considering a single 2-KJ laser pulse against 1 - 10 cm space debris, we arrived at the following:

Minimum Engagement Range
Fixed Energy System

Fluence (KJ)	Target (cm)	Δv (m/sec)	Miss Dist(m)	Range (km)
2	1	155	100	200
2	5	6.5	100	900
2	10	1.5	100	2100
2	1	155	500	450
2	5	6.5	500	2000
2	10	1.5	500	4500

Table 3

From the above table we concluded that 2-KJ per pulse on target is a reasonable value to consider for a laser debris sweeper system. Again, we only assessed 1-10 cm debris objects against a single pulse laser engagement. Multiple pulses at even a modest repetition rate of 1 Hz are certainly possible since each pulse would impart a greater ΔV as the range decreases.

To examine this condition, we considered a worst case scenario: 1 cm debris, 70 km detection range. Assuming target acquisition in 2 seconds brings us to firing range of 50 km (10.5 m/sec closing rate). At this distance a ΔV of 700 m/sec is required for a 100 meter miss distance--this equates to a single 10-KJ pulse on target. But, keeping with the 2-KJ laser system and stepping through ΔV as a function of range for multiple pulses yields that five pulses at a 2 Hz PRF would achieve a 100 meter miss distance. Recall in Figure 7, it was shown that shorter pulse lengths can sustain the same peak impulse coupling at lower fluence. Hence, achieving a greater ΔV on a 1 cm debris with 2-KJ at the target plane target may be possible with a shorter pulse length, shorter wavelength laser system. Further investigation and testing of pulse length scaling is warranted. However, increasing the detection range of 1 cm debris object would also mitigate this problem.

7.0 LASER PARAMETERS

The laser that is selected for the debris sweeper will have to exceed the required energy at the target plane. The results from the examples above are only valid when the laser spot size completely illuminates the object. Yet, we need the smallest spot size possible to achieve sufficient fluence on target. To size the laser system, careful consideration is given to the selection of pulse length in order to achieve the maximum impulse with the minimum fluence. The NdYAG laser results in Figure 7 shows that peak impulse coupling occurs at a fluence of 11 J/cm^2 for a 1 μsec pulse. Through pulse length scaling we can achieve the same impulse coupling at 8 J/cm^2 for a 0.5 μsec pulse. Given the fluence and total energy we can determine the spot size required at the target plane; then, we can size the optics by factoring in engagement range, beam quality, and jitter. Using the 2-KJ fluence-on-target example and peak impulse coupling at 8 J/cm^2 equates to a maximum spot diameter of 17.8 cm.

Considering the state-of-the-art for today's laser-optics systems a 1.2x diffraction limited divergence with a pointing accuracy of 100 nano-radians is possible. With a 100 nrad pointing accuracy or jitter the maximum engagement range is approximately 1500 km. Using the Rayleigh range as a first-order approximation for 1.2x diffraction limited KrF laser (0.25 microns wavelength) system to achieve a 10 cm (radius) spot size at 1500 km requires 1.3 meter optics. Optics of this size are common in systems today. However, further analyses of the parameters we considered and decreasing engagement range would reduce the size of the system optics.

8.0 LASER SYSTEM POWER NEEDS

The laser debris sweeper's energy storage system must be able to retain its capacity over extend periods and not required constant recharging. Several options are possible, batteries are probably the best option. To size the power required we selected a 2-KJ per-pulse, 1 Hz repetition rate laser system with 10-percent efficiency. This equates to 20 KW/pulse regardless of the pulse length. The SSF solar cells will probably deliver about 30 KW net power. Recalling that a maximum of one maneuver per week was postulated to avoid debris there should be adequate time to maintain energy storage requirements and recharging can be accomplished during low energy consumption periods. However, scenarios may occur when power may have to dedicated to recharging the debris sweeper system when multiple pulses are required.

9.0 CONCLUSION

Key to an active system are the station's altitude, position accuracy, orbital debris population density, debris position accuracy, warning sensor capability, impulse coupling, detection range, laser beam profile, laser operating parameters, pointing accuracy, engagement range, and power available.

The debris object must be accurately tracked to determines its velocity vector relative to the SSF. Expanding the laser beam to illuminate cataloged objects will enhance detection. Also, tracking the debris with on-board sensors during a laser engagement becomes less difficult since the debris' brightness increases due to laser irradiation. Once a track file is established laser energy can be directed as required to continue decreasing the debris object's velocity until the debris object is below the Station. In some cases, depending the object's substance, the debris itself may be reduce to particles that are smaller than 1 cm. However, the real time assessment of size changes or the breakup of debris, via on-board sensors may not be practical.

The optimum range to engage orbital debris particles is between 600 to 1500 km, given a closing rate of 10.5 km/second. Target detection, acquisition, and tracking should be achieved in 1-3 seconds depending on the size and range. The laser's beam quality must be nearly diffraction limited so that sufficient intensity can be focused on the object to attain maximum energy transfer. Candidate laser systems that meet these requirements today include CO2, free electron, eximer, and NdYAG lasers.

An active system using a laser debris sweeper is an option to decrease the number of avoidance maneuvers. Reducing the velocity of space debris reduces its altitude and eliminates its potential threat to the Space Station.

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