Feasibility Study of Spaceborne Pulsed Laser System Removing Small Debris Objects in Near-Earth Orbits

Shigeaki Uchida
Henan University of Science and Technology, School of Materials Science and Engineering, Luoyang, China
and
Coherent Systems Inc., Moriya, Ibaraki, Japan
Kazunori Shibata
Institute for Laser Engineering, Osaka University, Osaka, Japan
Kotomi Kawakami
Kitasato University, Sagamihara, Kanagawa, Japan
Hideki Okamura
International Christian University, Mitaka, Tokyo, Japan
Nakai Mitsuo,
Fukui University of Technology, 6-1, Gakuen 3chome, Fukui, Fukui, Japan
Xiao Xiao, Yin Danqing , Keke Zhang
Henan University of Science and Technology, School of Materials Science and Engineering, Luoyang, China
Zhonghao Heng
Qinghai University, School of Mechanical Engineering, Xining, Qinghai, China

Abstract

This paper describes the technical specifications necessary to implement a scheme of removing lethal non-trackable (LNT) debris objects using a space borne pulsed laser.
The main issues that need to be dealt with are how large the laser pulse energies should be, how big the debris can be tackled, and whether LNT can ever be an attackable target for laser pulses. We will discuss laser pulse characteristics to obtain a better laser-to-momentum coupling coefficient, C_m, Two problems on debris object tracking are clarified; a fundamental difficulty for determining orbital debris trajectory with down to mm accuracy, and compare the tolerable errors with that the current state-of-the-art technologies can offer..

1. INTRODUCTION

Among debris problems, small debris, known as LNTs (Lethal nontrackable)[1], can cause very serious problems, yet no effective countermeasures have been developed. The degree of the problem can be measured in terms of its damage scale and probability of occurrence. The relative velocity of collision between objects in the low earth orbits exceeds 10 km/s, well beyond the sound velocity of solid materials. This means that energy deposition at the collision takes place without the elastic waves dissipation and energy density builds up very intensively, leading a high-power explosion. The explosive power is so strong that a small debris destroys a target with mass a thousand larger than itself[2]. Even a one gram of LNT destroys one-kg of working part on a satellite, the reason why they are called “lethal”. As to the collision probability, several debris flux models show the probability of debris collision as a function of its mass as shown in Fig. 1[3], [4]. These models are “calibrated” by the on-orbit witnesses. The most recent example is from SpaceX Dragon starship. During its recent half-year mission to the ISS was inspected after returning to the earth[5]. It found 14 craters on the surface of the ship with the size corresponding to micrometer class collisions implying that the micrometer collisions are taking place every week basis. If the frequency is translated into the mm to cm range, the lethal collision could happen once every few hundred weeks or every few years. Furthermore, the flux distribution is continuously rising and the frequency is reasonably expected to increase in near future. Immediate attention needs to be paid to the category.

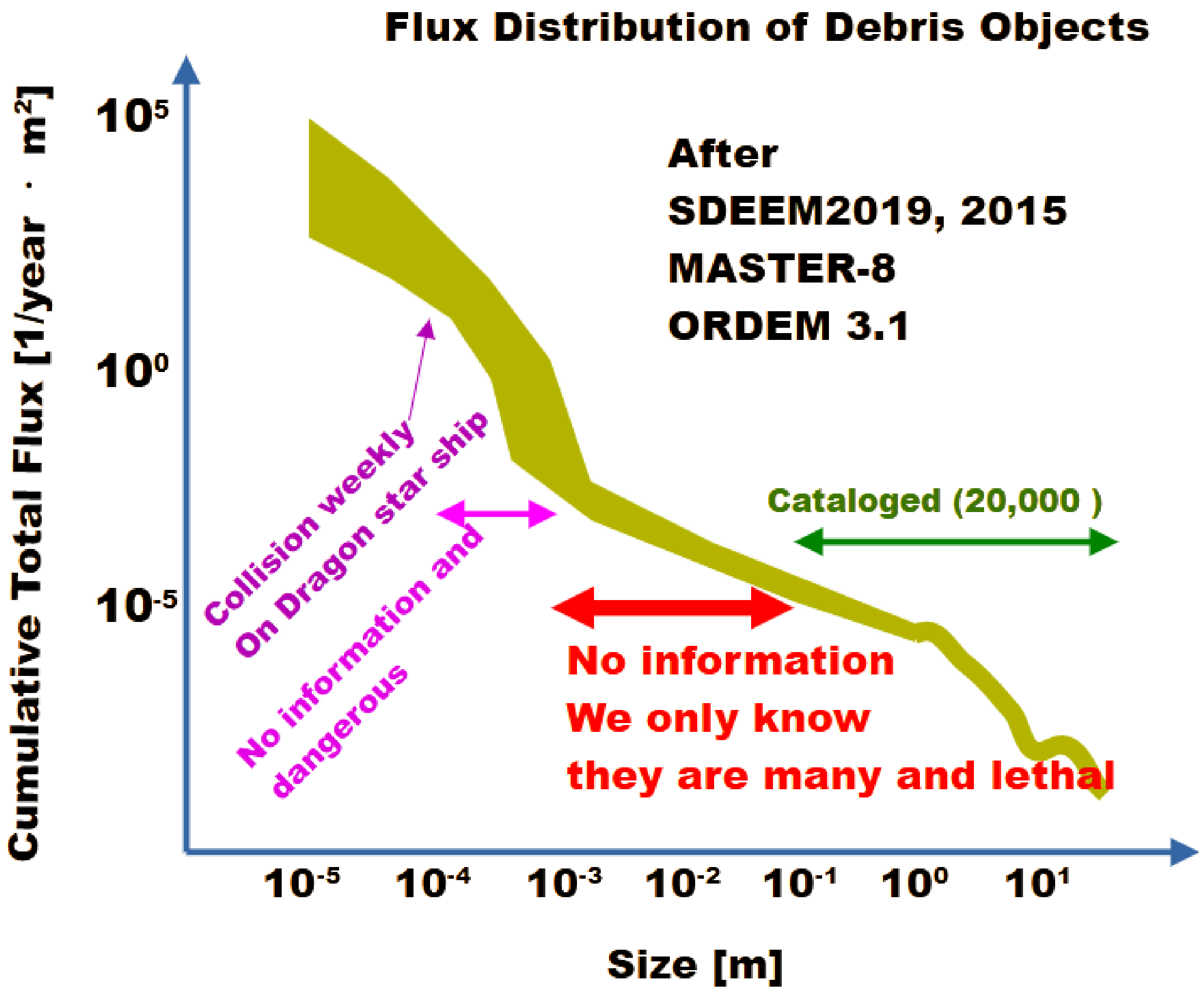

Fig. 1. Flux distribution of orbital debris in the low earth orbit

The difficulty of tackling LNT comes from the fact that they are not only cooperative but even no prior information about them is available, they are very small, and their number is tremendous. Laser ADR (Active Debris Removal) seems a possible solution, however, little research has been conducted to investigate the feasibility of the scheme to some detail. To conduct a feasibility study of the technique, the outline of the scheme is set;

(1) Targeted debris size: 1 mm to 10 cm
(2) Working orbits attitude: from 400 km to 1000km
(3) Mechanism of removal from orbits: generate ΔV so that the object is transferred to the very low orbit of 200 km altitude
(4) Impulse delivery: Single shot
(5) Energy driver: Pulsed laser and ablation thrust on target
(6) Focusing condition: Overlap focusing (all the laser power hits the target)
(7) Target spotting: Probing pulsed laser
(8) Platform: Space-borne laser
(9) Laser pulse steering and focusing: Optical wavefront controlling technologies such as synthetic aperture telescope and digital holography

The main concerns of the study are energy supply, very small target spotting, and focusing. Since the scheme uses the space-borne laser system, the scale of energy or power supply determines almost everything on the system, especially the size of debris the system can handle and the rate of the removal operation, for instance, the number of debris removed/per day. Therefore, laser pulse conditions to maximize energy efficiency for debris removal were studied from the principle of laser propulsion. The size of the LNT requires very careful consideration on

The microscopic nature of LNTs requires very sensitive considerations in laser ADR. This is because of the instability of their orbits and the need for laser irradiation to meet diffraction-limit conditions. In addition, the large relative velocity to the debris also increases the distance scale of the removal operation, so the system design must take into account the finiteness of the velocity, even at the speed of light. The orbit prediction error between the debris and the laser satellite, which becomes significant at this time, must also be investigated in detail to confirm whether a solution exists as an extension of current technology.

2. FINDING AND ACQUIRING DEBRIS TRAJECTORY

Since no prior information about the targets is available, debris objects need to be located before laser shot. A LADAR(Laser Detection and Ranging) method is employed for locating them. The locating function consists of three consecutive operations, “acquisition”, “probing”, and “tracking” as shown in Fig.2. Acquisition starts from accidentally finding the object. The difficulty to the operation comes from lack of prior knowledge about the incoming direction and high velocity (order of 10 km/s) of the object. Because of the object velocity, the time period the object is within the field of view is very short and probe beam scanning is not suitable for the case. To accomplish this operation, a film of laser light pulse is emitted from the laser system. The transmitting optics is designed so that the reflected laser beam is emitted into 4π or any desired solid angles. The thickness of the film corresponds to the pulse width. The probing light film looks like a shell of soap bubble from a distance. Depending on the intensity of the light film, the reflecting signal from the object could be very faint but strong enough to acquire the approaching object.

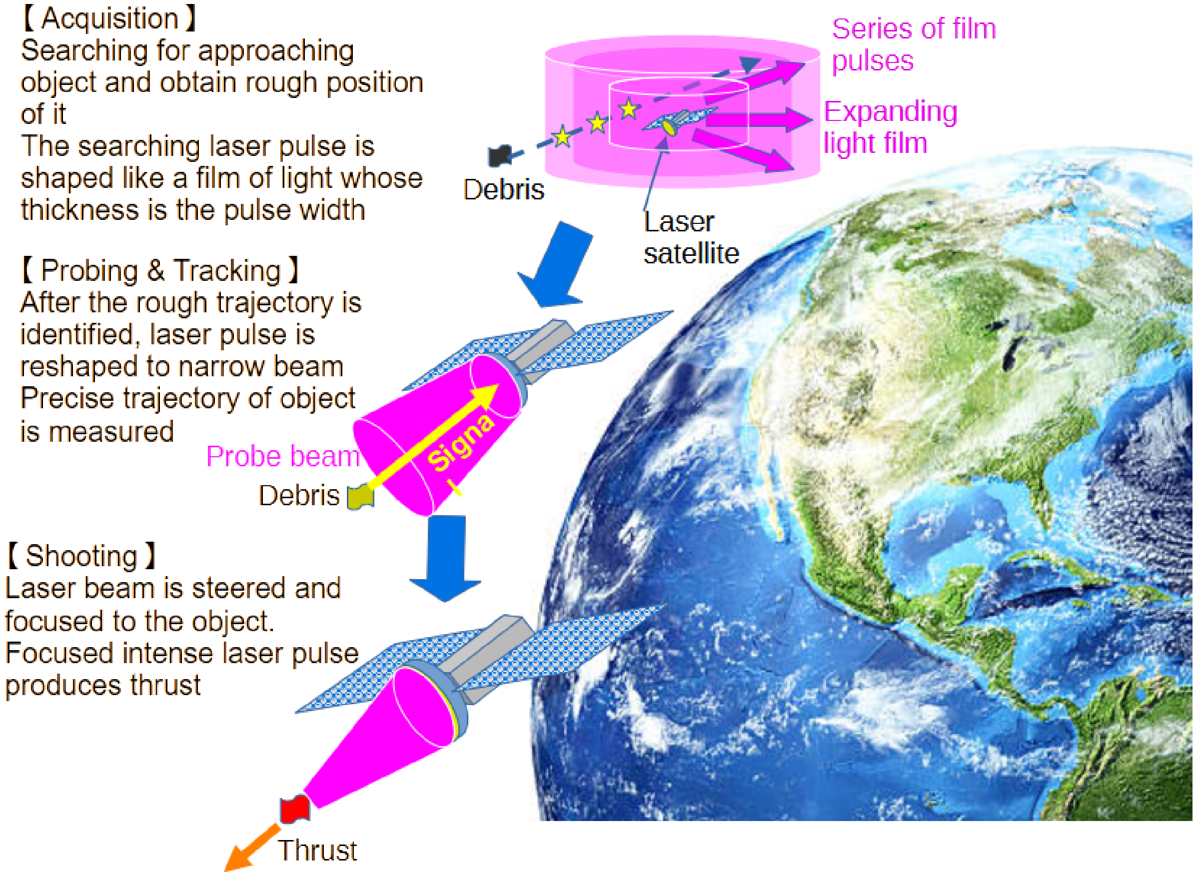

Fig. 2. Operation sequence of laser ADR for LNT objects

After acquiring the object, narrowed probe beam is directed to the vicinity of the object to obtain stronger reflected signals. The repetitive frequency of the laser pulse is set to high enough that the number of detection of the reflecting light from the object during its passage through the vicinity is suitable for probing and tracking. In probing, precise location and velocity are obtained and beam will be further narrower to get stronger signal for each pulse. During this operation, probing beam spot is as large as the shift of the object during the pulse interval so that the probe won’t miss the target and small enough to obtain strong enough reflecting signal for precise locating.

In tracking operation, beam spot is further narrowed and the reflecting signals become strong enough for generating hologram at the laser site. This hologram is used to control the wave front of the focusing laser pulse later to precisely steer it to the debris object[6]. During this operation, most precise location and velocity of the object are obtained as well as the hologram. Based on these data, the expected object location and modified hologram is calculated. Here “expecting” and “modifying” take into account the position shift of object during the light round trip between object and laser site. The direction and focusing of the transmitted laser pulse, shooting the object for ablation are controlled by the digitally generated hologram and no mechanical “tweaking” of optical components is involved.

3. ENERGY EFFICIENCY OF DEBRIS REMOVAL

As to thrust generation, the technique of laser propulsion exhibits very unique characteristics, that is, it can control the usage balance of two factors generating thrust, mass and energy. In the case of chemical propellants, specific energy, energy per unit mass, or specific impulse I_{sp} is roughly limited by the chemical potential of the propellant with a range of variation no more than twofold. In the case of electrical propulsion such as ion thrusters, on the other hand, thrust is characterized by its high energy, and thus high-speed propellant ejection

For laser propulsion, very short pulses such as in nano, pico and even femto second regions are used as an energy carrier leading generation of high-temperature plasmas. They are usually associated with the energy transfer to ionization of material and intense emission of thermal radiation, none of them do not only contribute to the kinetic motion of propellant but also result in losses through radiation. For the sake of thrust generation with a limited amount of energy available, hot plasma as a thruster is not the choice. Actually, for debris acceleration, debris itself can be used as the propellant.

Laser ADR uses the principle of laser propulsion for ΔV generation. Thrust is generated using both energy (represented by exhaust gas velocity) and mass of propellant. In general, the balancing between the two factors is the most important design consideration under the specific condition of application. The most prominent characteristic of laser propulsion is the capability of generating very high-temperature propellant exhaust that is not limited by the chemical potential of conventional propulsion systems. However, this condition is valid only when an arbitrary amount of energy is available for propulsion and is not the case for debris acceleration in orbits. The most use of propellant mass and to save energy is the design strategy.

The conventional laser propulsion studies have mainly focused on using very short pulses such as in nano, pico and even femto second regions as an energy carrier leading the generation of high-temperature plasmas. They are usually associated with the energy transfer to ionization of material and intense emission of thermal radiation, which not only does not contribute to the propellant motion but also results in losses due to radiation. For the sake of thrust generation with a limited amount of energy available, hot plasma as a thruster is not the choice. Actually, for debris acceleration, debris itself can be used as the propellant.

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This leads to the use of laser pulse conditions that keep the focused intensity just above the vapor generation threshold of the target. In the case of plasma generation on metal surfaces, the threshold intensity is in the order of 10^8 W/cm^2[7]. The intensity for vapor generation I_{th} on the other hand is much lower like 10^4 W/cm^2 [8]. I_{th} gives the minimum intensity on the target. The focused laser intensity is determined by laser pulse energy E_{laser}, duration t_{laser}, and focused spot size d_{spot}. The general principle of design is to give the maximum pulse energy within the overlapping spot size on the debris while laser intensity on the target is kept at or close to I_{th}.

ΔV determines the pulse energy E_{laser} through the momentum coupling coefficient C_m [9] and given the debris size d_{spot}, the pulse duration τ_{laser} can be determined. By using,

$C_m \equiv \frac{m\Delta V}{E_{laser}}$ and

$I_{th} < \frac{4E_{laser}}{\tau_{laser}\pi d_{spot}^2}$,

$\tau_{laser} < 800$ µs is determined, where $C_m = 10^{-5}$ Ns/J, ΔV=200 m/s, I_{th}=10^8 W/cm^2, d_{spot} = 1 cm, and aluminum as the debris material are assumed. Note that the it is assumed that the ΔV is generated in the direction of antiparallel to the laser incidence. This assumption is the most favorable one and, in general, ΔV is larger and so are E_{laser} and τ_{laser}. In any case, the shooting laser pulse length for higher C_m could be much longer than one used in most of the previous works of momentum generation, and requires verifications.

4. ACCURACY OF DEBRIS TRAJECTORY PREDICTION

Since the distance between the laser system and the object is 10 km and the relative velocity is 10 km/s, laser pointing and focusing controls are done by the predicted debris trajectory with extreme precisions. The errors associated with the prediction need to be less than the size of debris itself or within micro radian. Even if the measurements have been done with the high accuracy, there would be a lag time between the detection and laser shot. The pointing of laser pulse needs to calculated to include the position shift during the light pulse round trip between target and laser system. For example, debris object 5 km away means that there will be a 30-cm position shift at the object before a shooting pulse arrival at the target. The laser light definitely misses the target without compensating the position shift. Trajectory deviation during the lag could be significant and larger than the debris object itself.

There are two categories of errors; one caused by the debris trajectory deviation due to various unpredictable perturbing phenomena such as gravity deviation from earth, sun, moon, atmospheric drag, radiation pressures from earth and sun. They are “intrinsic errors”, and generally very tiny but fluctuate unpredictably. Their magnitudes could affect the trajectory prediction with certain degree. The other one comes from the measuring errors caused by device performance and system design as well as any unpredictable perturbations or noises affecting the signal acquisition. They are “technical errors”. Precision needs to be smaller than the debris size, about 1cm to a few cm.

We estimated the magnitude of the intrinsic errors. It has been found that the upper limit of positioning error is within the size of the objects, that is in the order of millimeters[10]. It should be noted that the limit is only relevant to the time duration of tens of seconds, and not to mention that the measurement accuracy needs to be less than the target size. Now we can concentrate on the technical errors!

To achieve the accuracy on both observation and shooting, diffraction-limited qualities are needed on the transmitted wavefront shape and receiving optics. However conventional methods for obtaining those qualities such as using very large apertured optics or adaptive optics are not suitable for the present application. Considering the strong requirements on both system size and weight, the option, in this case, would be using a synthetic aperture LADAR, SAL system that does not require a single gigantic and heavy optics. The required envelope aperture size of SAL, D_{SAL} is given by $\frac{L_{deb}\lambda}{d_{deb}}$, where λ, L_{deb}, d_{deb}, are the distance between the laser system and debris object, laser wavelength and the representative dimension of the debris object. As an example, D_{SAL} is calculated to be 10 m to satisfy a mm resolution at 10 km distance.

Now, specifications of diagnostics to satisfy the accuracy of debris position and velocity are evaluated. Doppler shift, time of flight, and incoming direction of the reflected light from the debris object are to be measured. For the analysis of these measurement errors, coordinate systems for data acquisition are defined.

The schematic diagram of the acquiring operation is depicted in Fig. 3. It shows the time lapse of both debris object and laser satellite motion. There are two coordinate systems; one is the coordinate system of laser satellite (fixed on the image sensor) and the other is defined on the debris object. The main coordinate system, the laser coordinate, is the rest frame of the center of the image sensor. The x, y, z axes in the frame are in the direction of satellite motion, northward direction perpendicular to the orbital plane, and outward perpendicular to both. Individual laser coordinates are defined for each corresponding laser shot instant.-There are virtual object planes consisting of the transmitting laser pulse “film” irradiating in the vicinity of the object. The pulse width and beam divergence determine the thickness and area of the light film. The coordinate system is the rest frame of the intersection of the laser beam axis and the light film itself. The coordinate axes x’, y’, lay in the film surface, while z’ is perpendicular to the film and oriented in the direction of laser incidence. Since the position of the debris is measured at each pulse, only a series of discrete pairs of coordinate systems corresponding to the laser pulses is relevant for the debris trajectory analysis.

Using the above coordinate systems, debris trajectory, and associated errors are evaluated. The calculated errors are then checked if they are within the error tolerance. For simplicity, a case where both debris and laser satellite velocity vectors are in the same plane is considered.

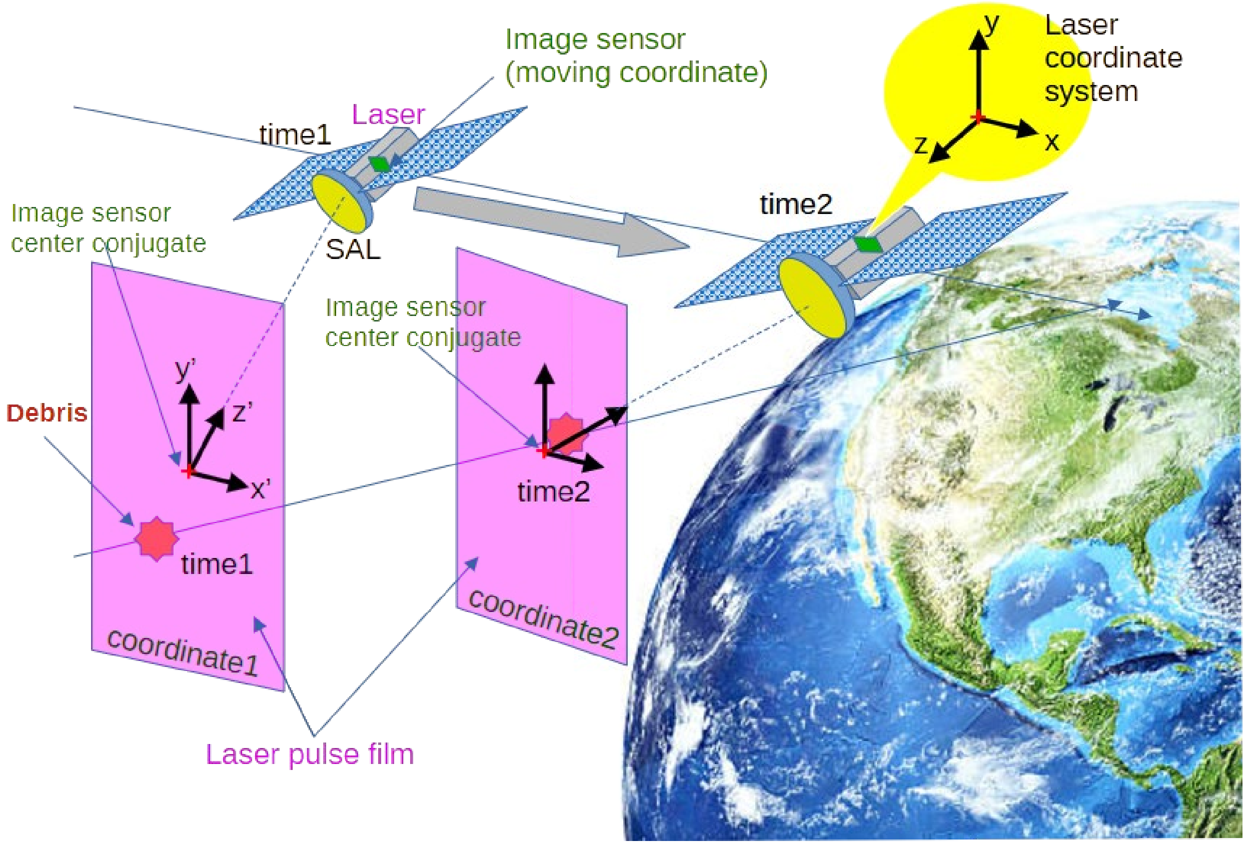

Fig. 3 Moving coordinate systems for tracking debris object

Debris positions based on these coordinate systems are measured using the image on the sensor (the position of the debris object is converted to angles seen from the sensor) and time of flight (ToF) as well as the Doppler shift of the reflecting light. Taking the diffraction-limited imaging into granted, the image sensor should provide enough resolution (number of pixels) at the image plane. The accuracy of the longitudinal position in the z’-axis direction is determined by the accuracy of pulse width, $\tau_{pulse,}$ and timing jitter of the pulse repetition, t_{rep}. The pulse width accuracy is determined by a “no blurry condition”, that the distance traveled by the object during $\tau_{pulse,}$ is smaller than tolerated error, ε_{tol}. $v_l \times \tau_{pulse} < \varepsilon_{tol}$, where v_l is the longitudinal velocity component of debris seen by the laser satellite. Taking v_l =10 km/s and ε_{tol}.=1 mm gives $\tau_{pulse,}$<100 ns.

Using the time intervals between the probe pulses, t_{rep}, the average velocity of the object is calculated. Requiring the same order of accuracy on the velocity, an order of or less than 100 ns precision is required on t_{rep} as well. Assuming the pulse repetition rate is 10 to 100 Hz, an accuracy of four to five digits is required on the repetition interval timing setting, t_{rep}.

For v_l measurement, the Doppler shift of the reflected light can be used. Taking the order of 10 km/s with five-digit precision on the velocity, similar five-digit precision in the order of 10^{-5}th frequency sensitivity to the probing light frequency is required. This spectroscopic accuracy is within the reach of the current technologies.

In addition to these sensing capabilities, attitude monitoring of the imaging sensor is needed which is the base of the coordinate systems. Ordinary fiber optic gyroscope technology has achieved 10^{-10} rad/s sensitivity and is well capable of compensating the attitude perturbation of the laser and sensor system.

5. SUMMARY AND PROSPECTS

It is shown that LNT can be removed by laser ADR method, which is the only solution for LNT that cannot be solved by other methods at present. The error evaluation of orbit prediction and the necessary observation accuracy were clarified, and the possibility of orbit prediction necessary for laser aiming at debris, which is the most difficult task, was shown. The laser technology itself is an extension of current technology. On the other hand, some of the elemental technologies for optical wavefront control necessary for debris observation and irradiation exist in ground-based applications and at the laboratory level, but the development of technologies that can be applied on an on-orbit scale is a future challenge. Once this system is operational, it is estimated that small debris in LEO can be removed in a period of about seven years.

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