# End-of-Life Deorbit Service with a Pulsed Laser Onboard a Small Satellite


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## ABSTRACT

To improve the post mission disposal (PMD) rate of the satellites and provide future active debris removal (ADR), SKY Perfect JSAT Corporation has begun designing a brand-new end-of-life (EOL) deorbit service satellite to remove nonfunctional satellite targets from orbit. The Corporation aims to launch a demonstration satellite in 2024 and begin service in 2026, in collaboration with RIKEN and other partners. A service satellite with a laser system (less than 50 W of output power) emits a focused laser beam to the target to cause laser ablation. The orbit and attitude (including rotational status) of the target can be changed sufficiently by the reaction force of the plasma/gas ejected from the target surface. In this paper, the results of a conceptual study and several advantages of the laser ablation method over conventional active methods for the removal of nonfunctional satellites are described.


## 1 Introduction

SKY Perfect JSAT Corporation has begun designing a new end-of-life (EOL) deorbit service satellite, as shown in Figure 1, to remove nonfunctional satellite targets from orbit using a pulse laser. In this method, the target is irradiated with a laser beam from a satellite in space, and the resulting laser ablation generates a thrust on the target to stop the rotation of the target and move it. In this paper, we describe the reason behind and the advantage of using this laser method, the outline of the feasibility of the EOL service mission on the basis of the experimental results, and the satellite system that is to be used to achieve it.

*Figure 1 Artistic illustration of EOL deorbit operation with a pulsed laser beam*

## 2 Background

Since Sputnik 1 was launched in 1957, more than 10,000 satellites have been launched into outer space [1] and about 4,000 of them are operational at present. On the other hand, there are also numerous nonfunctional objects remaining in orbit, such as nonoperational satellites and rocket upper stages or fragments generated by on-orbit collision or breakup. Such defunct objects are called space debris, and according to ESA's summary [2], there are about 28,000 pieces of orbital debris listed in their catalogue. In addition, besides the catalogued objects, it is estimated that there are a huge number of tiny objects orbiting the Earth that cannot be tracked by ground observatories. For example, ESA statistics models indicate that there are 900,000 objects with sizes from greater than 1cm to 10cm, and 128 million objects with sizes from greater than 1mm to 1cm [2]

The major source of space debris is an on-orbit breakup event such as collision or explosion. Even a single breakup can cause a marked impact on the neighbouring orbital environment. In 2007, China conducted an antisatellite test using their Fengyun-1C satellite, and it is estimated that its fragmentation increased the trackable space object population by 25 percent [3] and 50 percent of its fragments will stay in orbit for at least 20 years [4]. Two years later, the U.S. Iridium-33 and Russian Cosmos-2251 satellites accidentally collided into each other and added further fragments to the orbital population. Liou asserts that fragments from these two events account for 50 percent of the catalogued objects in orbits below an altitude of 1,000km [5].

If the spatial density of orbital objects at a given altitude reaches a certain value, the number of pieces of space


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debris starts to increase exponentially through mutual collisions. This chain reaction is called the Kessler Syndrome and the U.S. National Research Council reports that the current situation has already reached its critical point [6]. NASA estimates that even if there are no future launches, the number of collision fragments will continue to increase over the next 200 years [7].

In recent years, there have been many plans to build satellite constellations in low Earth orbit (LEO), and some private companies have already launched hundreds of satellites into such an orbit. Given that thousands of constellation satellites are to be launched in the coming years, constellations will soon outnumber the conventional population in LEO. This rapid rise in LEO population is posing a serious threat on operational satellites, including the constellation satellites themselves. AGI estimates that about 57,000 are planned to be launched in the next ten years, and the collision rates for those constellations against objects larger than 2 cm will exceed 10 times/year in the region from 475km to 600km in altitude [8]. Therefore, lively discussions on controlling the number of pieces of space debris are taking place in order to protect sustainable space utilization. As one of the measures, post-mission-disposal (PMD) is highly recommended.

Improving the success rate of PMD is an urgent task. IADC and COPUOS mention in their guidelines that every satellite or rocket body should perform the PMD maneuver correctly once their mission ends, and furthermore, ISO-24113 states that the PMD success rate should be 90 percent at least. However, according to ESA's report, the yearly PMD success rate is only about 60 percent at best [9]. In addition, NASA's study on constellation assessment suggests that even a 90 percent PMD success rate is insufficient for some types of constellation [10]. Since the reliability of PMD functions installed on satellites will be limited to a certain extent, some active debris removal (ADR) systems are under development as one of the most promising options in achieving higher PMD success rates.

## 3 Method of Laser ADR

In this section, the thrust generation mechanism and the advantages of the laser method are described.

### 3.1 Thrust Generation Mechanism

In this section, the mechanism by which lasers generate thrust by a phenomenon known as laser ablation will be explained. Laser ablation is the process of removing a material in the vaporized or ionized state from a solid surface by irradiation with a high-intensity laser beam. The thrust is generated by the reaction force of the plasma/gas ejected from the target surface. Figure 2 shows a photograph of a laser ablation experiment. In this figure, the area surrounded by the white dash circle is the jet of plasma generated by ablation and emitted from the surface of the ablator.

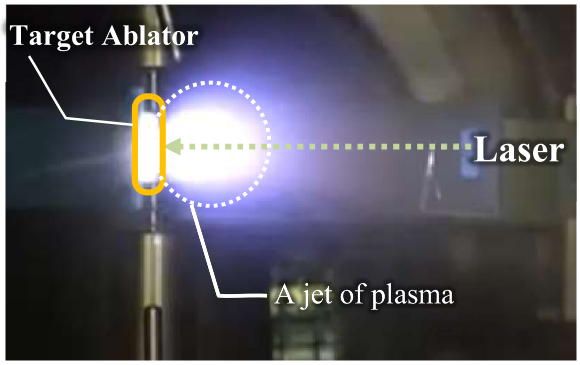


*Figure 2 Photograph of laser ablation experiment*

Here, the thrust due to laser ablation is not produced by photon pressure. The magnitude of the thrust produced by ablation is about four orders of magnitude greater than the photon pressure; therefore, the reaction force on the laser satellite when it emits the laser is negligible.

### 3.2 Advantages of Laser Ablation in EOL/ADR Service

There are three major advantages of using laser ablation when providing the EOL/ADR Service.

#### 3.2.1 High Safety

The laser satellite can provide thrust to the target from a distance. This study shows that thrust can be generated even at a distance of 50-200 m between the laser satellite and the target satellite. Most of the other EOL/ADR methods being studied and demonstrated worldwide require contact or a very close approach. Therefore, being able to provide thrust from a distance of 50-200 m is clearly safer than other methods.

#### 3.2.2 Adaptability to Tumbling Objects

Typically, many of the potential ADR targets have tumble rates above 1 rpm [11]. Therefore, in order to contact with a rotating object, it is necessary to achieve a state of relative stability with the tumbling object. However, if the amount of rotation exceeds a certain level, it would not be feasible to achieve safe contact. In the case of laser ablation, on the other hand, torque in the direction of detumbling can be created by determining the rotation state and irradiating the laser at the proper timing. The feasibility study on target detumbling is described in sect. 4.1.

#### 3.2.3 High Economy

We can show the high economy from two aspects.

(1) No need for the laser satellite to carry fuel to perform the target's deorbit

In the case of laser ablation, the material itself, such as the structure frame of the target, is turned into plasma by ablation and generates thrust. Therefore, the laser satellite does not need to carry fuel to move the target, and the laser satellite can be made lighter.

(2) No need for design changes of the target

The EOL/ADR Service by the laser ablation method does not require any design changes of the target satellite. Even if an attachment to the target is required, the actual frequency of use of such an attachment might be a few percent, given that the failure occurs in orbit. However, an attachment for PMD will be required for all satellites, which is an additional cost. The fact that there is no need for such an addition also makes the laser ablation method highly economical.

### 3.3 Thrust/Impulse of Laser Ablation

In this section, the impulse/thrust of laser ablation, as revealed in previous studies [12], is explained. Figure 3 shows the results of ablation impulse measurement by irradiating an aluminium material with a laser of 1064 nm wavelength and 10 ns and 20 ns pulse widths, plotted as the relationship between laser fluence and coupling factor.

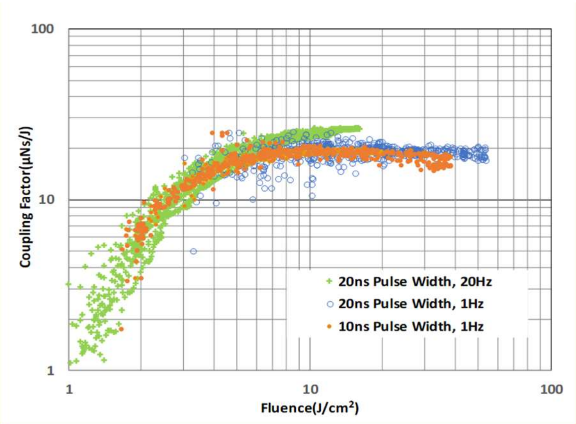


*Figure 3 Example of ablation impulse per irradiation energy (coupling factor) of aluminium*

Fluence, which is an index of energy divided by the irradiation area, shows the laser energy density. Coupling factor is an index of impulse divided by energy. In the case of aluminium, coupling factor is almost flat being approx. 20μNs/J with a fluence of more than 5 J/cm$^2$, that is, for energies above 5 J/cm$^2$, the impulse is proportional to the energy input. Therefore, even if the fluence is increased from the point where the fluence at the target irradiation position is 5 J/cm$^2$, the efficiency of the generated impulse against the input energy remains constant, and the fluence can be set to be 5 J/cm$^2$, which is the target index of the design. Also, since the coupling factor is 20μNs/J, a power of 1J and a 40Hz laser will result in a thrust of 0.8mN.

### 3.4 Laser Irradiation Range

In this section, examples of the laser irradiation range are discussed. When the laser beam is a Gaussian beam and focused, the spot area $A$ is expressed as

$$A = \pi\left(\frac{2M^2\lambda f}{\pi D}\right)^2,$$

where M$^2$ is the beam quality, $\lambda$ is the wavelength, $f$ is the focal length, and D is the diameter of the laser beam at the focusing lens. We fixed the pulse energy of 1 J and the wavelength of 1064 nm as the upper limit of the laser that can be developed. To achieve the fluence of 5 J/cm$^2$ at which a stable and efficient impulse is generated as discussed in sect. 3.3, $f$(focal length of irradiation) was calculated with variation of M$^2$ and D. The focal length of irradiation at which a fluence of 5 J/cm$^2$ is achieved is shown in Figure 4.

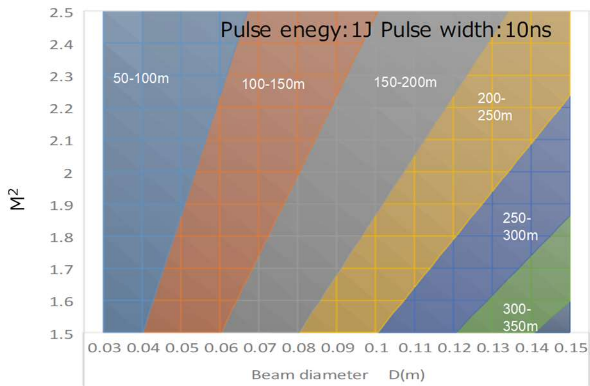


*Figure 4 Focal position to achieve fluence of 5J/cm$^2$ with the laser of wavelength λ=1064nm, pulse energy 1J, and pulse width 10ns*

For example, if the beam diameter is 10 cm and the beam quality is 2, a fluence of 5 J/cm$^2$ can be achieved at a distance of 200 m. This means that an ablation impulse of 20μN/J can be generated at a distance of 200m. This also means that at all distances closer than 200 meters, ablation is possible. The result is that thrust to the target can be provided from a sufficiently safe distance. Also, if the beam diameter is 10 cm, the lens would be small enough to be mounted on a small satellite.

## 4 Mission Scenario

In this section, the feasibility of the mission will be described. First, as described in sect. 3.3 and 3.4 , the laser irradiation range is 200 meters, and the thrust of a laser that can be mounted on a small satellite is less than 1 mN. Therefore, it is necessary to operate in a rendezvous state where the distance between the target and the laser satellite is kept within the laser irradiation range. In this section, rendezvous is not discussed because there are already several examples of rendezvous for space applications. The feasibly of detumbling and deorbit of the target satellite as subsequent operations is discussed. We need to discuss whether we need to stop the rotation of the target because of the following two ideas; (1) stop the rotation of the target object and then generate delta V to it or (2) merely generate delta V to the target object without stopping the rotation.

Since the direction of thrust due to laser ablation is perpendicular to the irradiation plane, it is preferable to generate delta V after stopping the rotation in order to efficiently generate delta V direction parallel to the orbit plane. Therefore, the first phase of the laser irradiation operation is to stop the rotation of the target object. This is called the detumbling phase.

## 4.1 Detumbling

In this section, an example analysis of the time required to stop the rotation using impulses generated by a laser is given. We calculated and analysed whether rotation control by the impulse generated by the desired laser is possible. This analytical model is simplified as much as possible because the purpose is to elucidate the order of the period required to stop the rotation. Specifically, the target object is assumed to be a cube, and the average mass distribution is assumed. The target is also assumed to be rotating on a single axis.

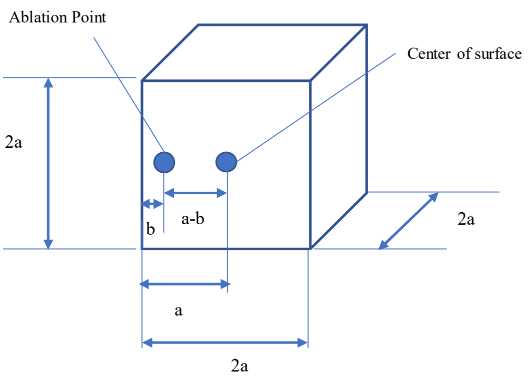


*Figure 5 Target figure and ablation point*

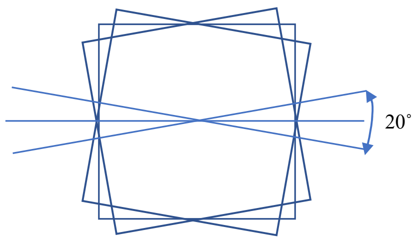


*Figure 6 Irradiation timing*

As shown in Figure 5 Target figure and ablation point, the laser irradiation position (ablation point) is defined as the length b [m] from the edge of the cube at the same height as the center of gravity. In this analysis, we assumed that irradiation occurs only when the incident angle is less than 10 degrees from the surface normal. In other words, only 80 degrees out of 360 degrees rotation can be used for the actual irradiation operation, as shown in Figure 6.

*Table 1 Results of detumbling analysis*

| Item | Small object | Large object |
|---|---|---|
| Target mass, M (kg) | 150 | 8200 |
| Length of a side, 2a (m) | 1 | 4.5 |
| Ablation point from edge, b (m) | 0.1 | |
| Laser ablation thrust, F (N) | 0.0008 | |
| Efficiency of irradiation timing | 20/90 | |
| Operation period for detumbling 1 rpm | 0.4days | 3 months |

Under the above assumptions, the mission operation period required for detumbling was calculated.

As a result of the analysis, it was found that the number of operation days required to stop the rotation of a small object at 1 rpm was 0.4 days, which means that the rotation of small objects can be stopped in a short time. The results of the detumbling analysis for a large object with ENVISAT-class size and weight are also shown in Table 1. It was shown to be possible to quickly stop the rotation of lightweight objects and that a mission to stop the rotation of an eight-ton-class object is fully feasible.

## 4.2 Deorbit

In this section, the mission period required for a deorbit is calculated and verified to be in a feasible range. As a prerequisite, the thrust of 0.8 mN and the target weight of 150 kg, which are the same as those in section 4.1, are used, An operation for 24 hours a day, 365 days a year is assumed. The delta V required for deorbit is calculated using the Hohmann orbit formula and shown in Table 2 as a matrix of initial orbit altitude/mission-end orbit altitude.

*Table 2 Delta V required for deorbit from initial orbit altitude to mission-end orbit altitude*

| | | Initial Orbit Altitude, km | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 600 | 700 | 800 | 900 | 1000 | 1100 | 1200 | |
| Mission-end Orbit Altitude, km | 500 | 55 | 108 | 161 | 212 | 262 | 312 | 360 | Required Delta V, m/s |
| | 600 | | 54 | 106 | 157 | 208 | 257 | 305 | |
| | 700 | | | 52 | 104 | 154 | 203 | 252 | |
| | 800 | | | | 51 | 102 | 151 | 199 | |
| | 900 | | | | | 50 | 100 | 148 | |
| | 1000 | | | | | | 49 | 98 | |
| | 1100 | | | | | | | 48 | |
| | 1190 | | | | | | | 5 | |

In the same way, the mission period required to achieve each delta velocity in operation for 24 hours a day, 365 days a year is calculated and shown in Table 3.

*Table 3 Operation days to deorbit from initial orbit altitude to mission-end orbit altitude*

| | | Initial Orbit Altitude, km | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 600 | 700 | 800 | 900 | 1000 | 1100 | 1200 | |
| Mission-end Orbit Altitude, km | 500 | 118 | 233 | 346 | 455 | 561 | 665 | 767 | Operation days, days |
| | 600 | | 115 | 228 | 339 | 445 | 550 | 652 | |
| | 700 | | | 113 | 224 | 332 | 437 | 539 | |
| | 800 | | | | 111 | 218 | 325 | 428 | |
| | 900 | | | | | 108 | 214 | 318 | |
| | 1000 | | | | | | 106 | 210 | |
| | 1100 | | | | | | | 104 | |
| | 1190 | | | | | | | 10 | |

For example, to deorbit a 150 kg satellite in a 1200 km orbit to a 600 km orbit, it takes approximately 652 days, indicating that a deorbit mission of less than two years is possible. Here, an altitude of 600 km is assumed as an orbit that meets the IADC guidelines. On the other hand, it takes about 10 days to deorbit from 1200 km to 1190 km, which indicates that it is possible for constellation operators who place many satellites at a particular altitude to conduct small deorbit missions quickly to avoid collisions with other satellites at the same altitude.

## 5 Mission System

The mission system consists of a mission control subsystem (MCS), laser ablation subsystem (LAS) and object detection subsystem (ODS). All subsystems are closely consolidated with each other in terms of function and performance. The mission system has an interface with the satellite bus. Figure 7 shows a subsystem-level block diagram of the laser satellite. We estimate the payload mass and power consumption to be approximately 50kg and 200W respectively, so that the entire system can be realized with a 200kg-class satellite.

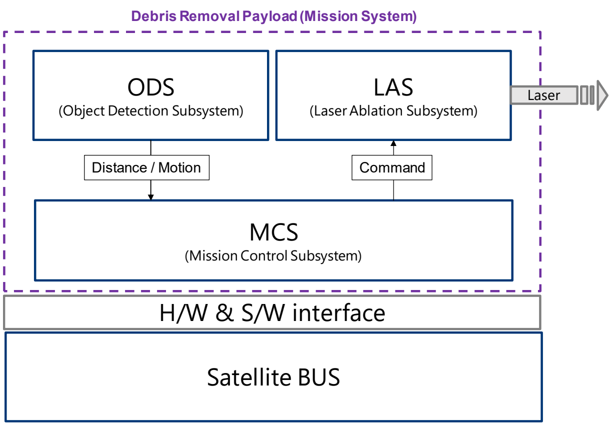


*Figure 7 Subsystem-level block diagram of laser satellite*

### 5.1 MCS (Mission Control Subsystem)

MCS controls some functions of the satellite bus and LAS to realize the mission scenario in accordance with the information provided by ODS. The function of MCS is divided into “mission control” and “target control”, as explained below.

The mission control function controls the entire mission sequence for performing the laser irradiation. This includes (1) the approach of the target object within the laser irradiation range, (2) the estimation of the target object’s orbit using the position information provided by ODS, (3) the reception of the motion information of a target object from ODS, (4) and the control of the orbit and attitude of the laser satellite by issuing the necessary commands to the bus system.

The target control function controls the motion of the target object. This unique function plans and performs the laser irradiation to stop the rotation of the target object or to accomplish its deorbit.

### 5.2 ODS (Object Detection Subsystem)

With onboard sensors within ODS, ODS estimates (detects or identifies) the relative distance, direction, rotation axis/rate of the target object as well as the target side of the object where the laser should be irradiated. This information is provided to MCS. In addition, ODS detects the laser irradiation point on the target object and provide it to MCS.

### 5.3 LAS (Laser Ablation Subsystem)

LAS adjusts the focal point of the telescope to tune the spot size on the target surface and irradiates the pulsed laser to the target object in accordance with the command from MCS. To control/adjust the laser irradiation direction, 2 methods are considered; (1) install a steering unit on LAS and (2) control the satellite bus attitude via MCS command.

## 6 Conclusions

For target objects in the 150 kg class, a laser of the specifications discussed in this paper was shown to be capable of accomplishing the detumbling of a satellite and deorbit from a high LEO altitude. It was shown to be possible to stop the rotation of large objects with this small laser payload. To remove a large target from orbit, since the method that requires physical contact can be used after this laser method is used to stop the rotation, it can be concluded that the removal of large debris is possible by combining the two methods.

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