

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

Demonstration designs for the remediation of space debris from the International Space Station

This is a pre print version of the following article:

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1578984> since 2016-06-30T17:13:49Z

Published version:

DOI:10.1016/j.actaastro.2015.03.004

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)

Remediation of cm-size debris from the International Space Station (ver20TE6)

Toshikazu Ebisuzaki¹, Mark N. Quinn², Satoshi Wada¹, Lech Wiktor Piotrowski¹, Yoshiyuki Takizawa¹, Marco Casolino^{1,3}, and Mario Bertaina⁴, Philippe Gorodetzky⁵, Etienne Parizot⁵, Toshiki Tajima^{2,6}, Remi Soulard² and Gérard Mourou²

¹RIKEN, 2-1, Hirosawa Wako, 351-0198, Japan

²IZEST, Ecole Polytechnique, 91128, Palaiseau, France

³INFN

⁴University of Torino

⁵APC-CNRS/Paris7 University, 1à rue A. Domonet L. Duquet, 75013 Paris, France

⁶Dept. of Physics and Astron. University of California at Irvine, Irvine, CA 92697

Abstract

We present here a design for an orbiting debris remediation system comprised of a super-wide field-of-view telescope and a novel laser system operating from the International Space Station (ISS). The telescope, EUSO (Extreme Universe Space Observatory), has been designed for operation onboard the ISS for the detection of ultra-high energy cosmic rays. Equipped with 2.5 m optics and a field of view of ± 30 degrees, the EUSO module can also be utilized for the detection of high velocity fragmentation debris in orbit near the ISS. Once detected, the CAN laser system will deliver a sequence of pulses to the debris surface inducing ablation and hence momentum impulse to reduce its velocity. The range of the detection/removal operation can be as large as 100 km. We will use a step by step approach employing the ISS :1) Proof of principle demonstration of the detection (and if possible laser impulse technology) with ISS based prototype, 2) Technical demonstrator debris-removal that consists of the EUSO telescope for the detection and a 1.5 m Cassegrain telescope with a space CAN laser for tracking and impulse delivery for debris re-entry, and 3) A free-flyer mission dedicated to debris remediation in a polar orbit with the altitude ~ 800 km.

Keywords: space debris, laser ablation, International Space Station

Corresponding Author:

Toshikazu Ebisuzaki

TEL: +81-48-467-9414

E-mail: ebisu@postman.riken.jp

Address: 2-1 Hirosawa Wako Saitama Japan, 351-0198

1. Introduction

In more than fifty years of spaceflight, over 30,000 tons of satellites and rockets have been sent to orbit. It is estimated that near 3,000 tons[1] of non-functioning space debris remain in Low Earth Orbit (LEO) in various forms ranging from fragments to spent rocket bodies and fully intact multi ton satellites. Since their orbital velocities are very high, of the order of 10 km/s as shown in Fig. 1(a), even the fragments with >MJ kinetic energies may cause severe or catastrophic damage to functioning satellites such as the International Space Station (ISS). In fact, in 1993, the Inter-Agency Space Debris Coordination Committee was established and the discussions concerning control of space debris among space agencies have started.

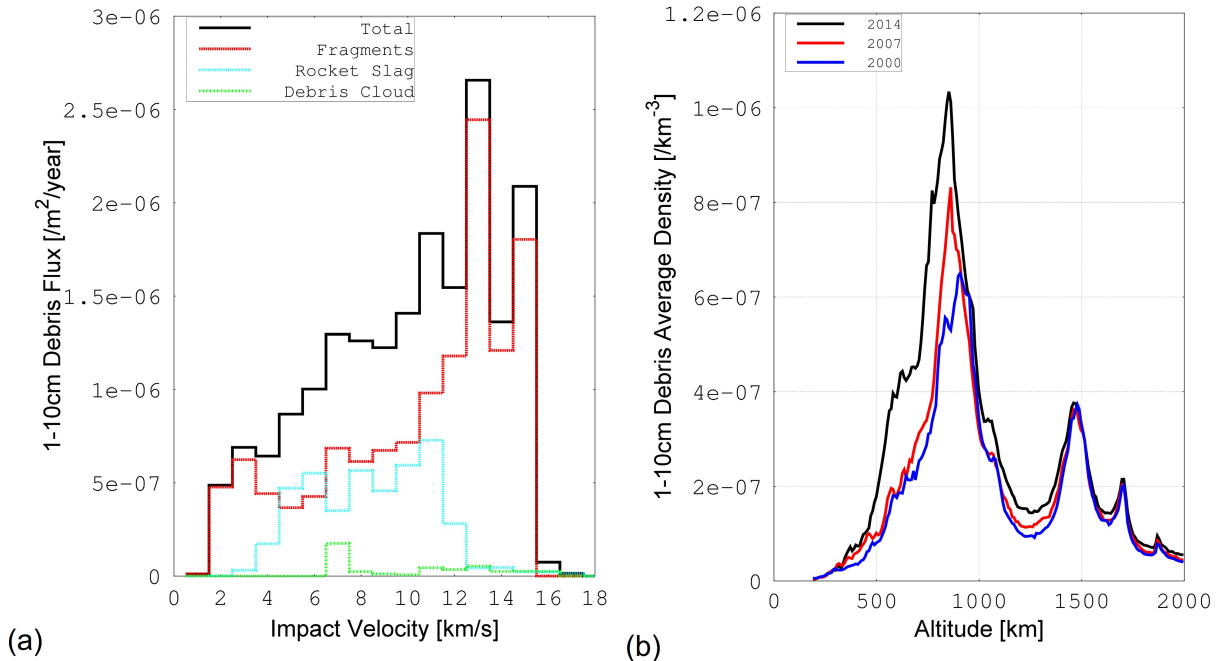


Figure 1. Results of simulations for 1-10cm size debris, performed with the MASTER 2009 code [2]: (a) The impact velocity and flux for 1-10cm debris components calculated for the ISS orbit for 2008, here fragments (red-line) include debris from satellite explosions or collisions (b) Recent evolution of 1-10cm debris in low-earth-orbit altitudes.

From a combination of techniques including ground-based radar, surface-impact measurements and statistical modelling the number of debris above 1 cm in size is estimated to $> 6 \times 10^6$. For most spacecraft, including the ISS, debris smaller than 1cm can be mediated by adequate shielding. Objects larger than 10 cm can be mitigated using collision avoidance manoeuvres if such debris are first identified and tracked. However the great majority are not, especially debris with sizes <10cm, and hence these hyper-velocity projectiles pose an increasing risk to spacecraft as their population builds. This issue is mounting since the triggered destruction of a number of satellites in LEO over the last decade including Iridium 33, Cosmos 2251 and Fengyun-1C. Such large objects are the main source of new debris when hit by the much more numerous smaller fragments in LEO. The small cm-size debris are thus the main threat to impacting the functioning and derelict payloads. The evolution of this population is shown in Fig. 1(b). Much of the increase after 2000 is attributed to the breakup of the fore mentioned satellites with significant increases seen for the sun-synchronous polar orbit near 800 km altitude.

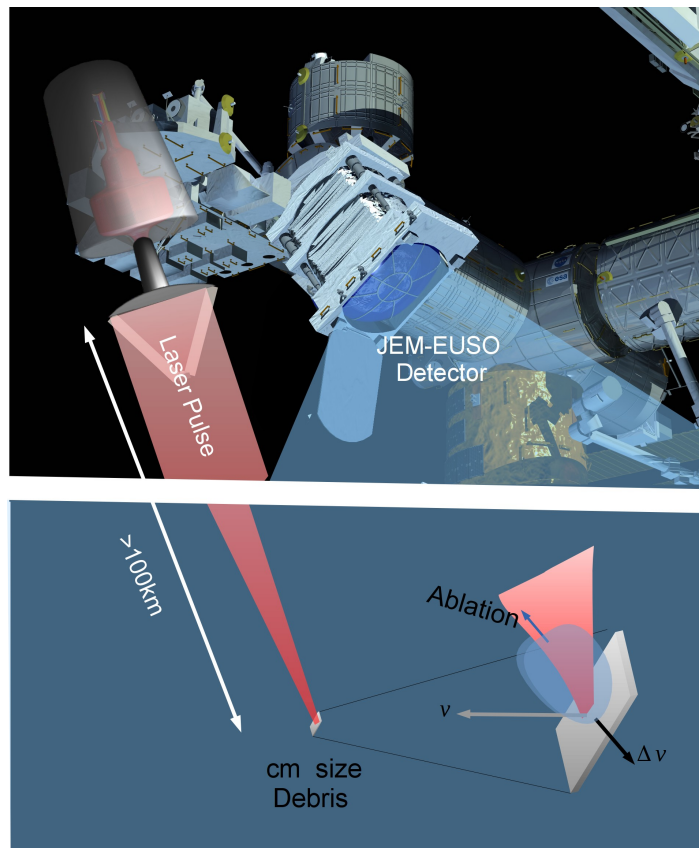


Figure 2: Concept of a technical demonstrator of the laser removal of debris onboard International Space Station. It consists of the JEM-EUSO telescope for acquisition and a CAN laser system for de-orbiting the cm size debris.

Due to their small size and high velocity (up to 10 times that of a bullet) there are few viable solutions to remove these projectiles before they collide with larger satellites. Laser impulse control is such a candidate for remediation. Here pulsed ablation of the debris surface leads to a momentum transfer via the rocket effect. With impulses $\ll 1N$ a rapid train of pulses are required to deliver a total Δv is pulses to impart impulses potential laser pulses are considered to be a leading Remediation solutions for these small hypervelocity debris have yet to be tested or implemented in orbit. Metzger et al. [4] proposed a nuclear-powered debris-sweeper with a 10 kJ, 1 Hz krypton fluoride laser (λ of 248 nm) powered by onboard a spacecraft. They evaluated the particle and laser beams for the debris removal, and found that neutral particle beams require 10 times as much energy as laser beams and significantly greater energy storage. A laser system had been estimated as total mass of 6300 kg and a cost of about 125M\$ to place on station. It was about twice the estimate for the cost of all ground-based system. Furthermore, the necessities of very fine tuning of the optical alignment and the frequent maintenance prevented such a concept. On the other hand, Phipps and Friedman [3] proposed to use a laser facility on ground to shoot the debris for deceleration by ablation. According to their recent paper [4], a 10 m size big telescope and a 100 kW-class laser is required to deliver enough power onto the 1-10 cm target with the distance of ~ 1000 km, even in the case of a diffraction limited spot. If the image distortion due to the atmospheric disturbance is taken into account, more powerful systems would be necessary. Recently, Phipps [13] has proposed L'ADROIT system to be launched consisting of of a super-wide-field debris detector with a powerful laser system with pulse energy of ~ 380 J or more, which is prohibitably powerful in space for another decade even with the advanced laser technology.

In this present paper, we propose to operate a large FOV detector in tandem with a short pulsed laser onboard the International Space Station (ISS) as depicted in Fig. 2. Here at an altitude near 400km the technology can be tested and improved before future design and deployment of freely orbiting systems at higher altitudes such as near 800km where the debris population in LEO peaks.

Precision determination of debris position and trajectories is a necessity both in the case of avoidance maneuvers and for attempts at remediation. Here we propose to apply the technology developed for the JEM-EUSO (Extreme Universe Space Observatory onboard Japanese Experiment Module) module designed for the ISS. The JEM-EUSO mission is to detect UV light emitted from the extensive air-showers produced by the ultra-high energy cosmic rays entering the atmosphere at night [6,7]. This detector has a super wide-field of view (FoV) as large as ± 30 degrees and a short time resolution down to a few μs . During daylight operation, this same detector can provide a unique technological solution for the detection and position determination of the non-catalogued debris from orbit.

The pulsed laser technology has rapidly advanced in the last two decades and it allows us now to consider a space-borne pulsed-laser system. In fact, Soulard et al. [8] proposed to use a space-based laser system applying their Coherent Amplifying Network (CAN) fiber-based technology,. A CAN laser is comprised of an array of fibers, each producing a laser beam of ~ 1 mJ, which is phase combined into a beam of total energy of a 1-100 J. Excellent electrical efficiency approaching 30% and a repetition rate higher than 10 kHz are possible which is an ideal solution methods for tracking, and impulses to the high velocity

This paper is organized as follows. In section 2, we describe the method of the detection, tracking, and laser impulse control of small debris. In section 3, a proof-of-principle prototype is described utilizing the mini-EUSO telescope which will be installed on the ISS. In section 4, we present a full scale system designed to effectively de-orbit small space debris. In section 5, a free-flyer mission, dedicated to debris remediation in a polar orbit with the altitude ~ 800 km and evaluate its performance.

2. Space-based debris remediation

The operation of the space-borne debris remediation system is divided into three stages:1) detection with a super-wide FOV camera, 2) tracking by a narrow FOV telescope and 3) velocity modification by laser ablation.

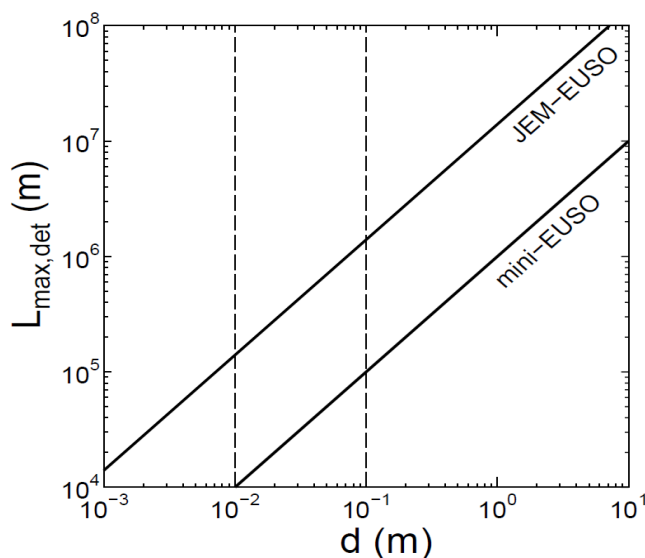


Figure 3. The actual maximum operation distance $L_{max,det}$ is plotted against the debris size d for EUSO ($D_E=2.5m, \Delta=0.08^\circ, \tau_d=1s$) and mini-EUSO ($D_E=0.25m, \Delta=0.6^\circ, \tau_d=0.1s$) parameters, where τ_d is the time window necessary to find the debris trajectory.

1.1.

Debris Detection

Passive detection of cm-size debris is possible via reflected sunlight in the twilight part of the orbit, where the Earth is in local night and the satellite and the debris is sunlit. In the case of ISS, this corresponds to once about 5 minutes at every orbit of 90 minutes. This detection of reflected solar light can be restricted to the U-band (300-400 nm) to avoid the contamination from terrestrial city lights. The flux of photons F_{sun} in the U-band is estimated as $10^{20} \text{ photons } m^{-2} s^{-1}$ [10]. The photon flux reflected by the debris is calculated as:

$$N_{debris} = \pi d^2 F_{sun} \xi_E = 3.1 \times 10^{15} \left(\frac{F_{sun}}{10^{20} \text{ photons } m^{-2} s^{-1}} \right) \left(\frac{\xi_E}{0.1} \right) \left(\frac{d}{0.01 m} \right)^2 \text{ photons } s^{-1}, \quad (1)$$

Where ξ_E is the reflection coefficient, and d the radius of debris, assuming a spherical shape. A super wide field-of-view telescope can be used for the detection of the debris by the application of the technology developed for the EUSO mission to detect photons coming from the air-shower produced by ultra-high energy cosmic rays.

The EUSO telescope provides a FoV of ± 30 degree, an angular resolution of 0.08 degree, and a time resolution of $2.5 \mu s$ [9]. The number of photons detected by the telescope is calculated as:

$$n_{debris} = \frac{\zeta D_E^2 N_{debris}}{16 L^2} = \frac{\pi \zeta \xi_E D_E^2 d^2 F_{sun}}{16 L^2} = 1.2 \times 10^4 \left(\frac{F_{sun}}{10^{20} \text{ photons } m^{-2} s^{-1}} \right) \left(\frac{\xi_E}{0.1} \right) \left(\frac{\zeta}{0.1} \right) \left(\frac{d}{0.01 m} \right)^2 \left(\frac{L}{100 km} \right)^{-2} \left(\frac{D_E}{2.5 m} \right)^2, \quad (2)$$

where L is the distance to the debris, D_E is the diameter of the optics of the EUSO telescope, and ζ is the efficiency of the telescope. A Linear Track Trigger algorithm can be employed for detection of small high velocity debris objects. This algorithm tracks the movement of the debris over a predefined time window to distinguish the unique pattern of the track of debris from the background [9]

We set the detection criteria of debris as:

$$SNR = \frac{n_{debris} \sqrt{\tau_d}}{\sqrt{B}} = \frac{\pi \zeta \xi_E D_E^2 d^2 F_{sun} \tau_d^{1/2}}{16 L^2 B^{1/2}} = 1.8 \times 10^1 \left(\frac{F_{sun}}{10^{20} \text{ photons } m^{-2} s^{-1}} \right) \left(\frac{\xi_E}{0.1} \right) \left(\frac{\zeta}{0.1} \right)^{1/2} \left(\frac{\Delta}{0.08 deg} \right)^{-1} \left(\frac{D_E}{2.5 m} \right) \left(\frac{\tau_d}{1 s} \right)^{1/2}, \quad (3)$$

where, τ_d is the integration time along the track in the Linear Track Trigger algorithm, and B is the number of background photons [9]:

$$B = 4.4 \times 10^5 \left(\frac{\Delta}{0.08 deg} \right)^2 \left(\frac{\zeta}{0.1} \right) \left(\frac{D_E}{2.5 m} \right)^2 \text{ photons } s^{-1} \text{ pixel}^{-1}, \quad (4)$$

where Δ is the angular resolution of the EUSO telescope. Here, we note that τ_d must be considerably shorter than the encounter time, which is about 10 seconds for the typical case of $L=100 km$ and $v=10 km s^{-1}$. In other words, the minimum detectable debris size at 100 km as shown in Fig.3 is:

$$d_{min} = 7.4 \times 10^{-3} \left(\frac{F_{sun}}{10^{20} \text{ photons } m^{-2} s^{-1}} \right)^{-1/2} \left(\frac{\xi_E}{0.1} \right)^{-1/2} \left(\frac{\zeta}{0.1} \right)^{-1/4} \left(\frac{\Delta}{0.08 deg} \right)^{1/2} \left(\frac{D_E}{2.5 m} \right)^{-1/2} \left(\frac{L}{100 km} \right) \left(\frac{\tau_d}{1 s} \right)^{-1/4} m, \quad (5)$$

or equivalently the maximum detection distance, $L_{max, det}$ for 0.01 m debris :

$$L_{max, det} = 1.4 \times 10^5 \left(\frac{F_{sun}}{10^{20} \text{ photons } m^{-2} s^{-1}} \right)^{1/2} \left(\frac{\xi_E}{0.1} \right)^{1/2} \left(\frac{\zeta}{0.1} \right)^{1/4} \left(\frac{\Delta}{0.08 deg} \right)^{-1/2} \left(\frac{D_E}{2.5 m} \right)^{1/2} \left(\frac{\tau_d}{1 s} \right)^{1/4} \left(\frac{d}{0.01 m} \right) m, \quad (6)$$

The angular velocity of the debris is also obtained as well. Based on this information, the debris tracking system is evoked, as discussed in the next subsection.

1.2.

Debris Tracking

The path of the debris has been defined by JEM-EUSO with an accuracy of 0.08° linked to the pixel size. Now, we must track the debris within this 0.08° cone, with an accuracy of the debris size. We call that active debris tracking, which is proposed employing a combined pulsed laser and telescope with a FOV consistent with the determination accuracy of the debris detection, which is about the angular resolution of the detection telescope. Thus a series of laser pulses is sent to the debris object where the beam angle is expanded by the telescope to the accuracy of the position determination, described above. The number of laser photons reflected by the debris from N pulses and detected by the telescope can be estimated as:

$$n_{laser} = \frac{\xi_T \zeta E_p N a^2 D^2}{(hc/\lambda)\theta^2 L^4} = 7.8 \times 10^4 \left(\frac{\xi_T}{0.1}\right) \left(\frac{\zeta}{0.1}\right) \left(\frac{N}{10^4}\right) \left(\frac{E_p}{10J}\right) \left(\frac{d}{0.01m}\right)^2 \left(\frac{D_T}{1.5m}\right)^2 \left(\frac{L}{100km}\right)^{-4} \left(\frac{\lambda}{0.35\mu m}\right) \left(\frac{\Delta}{0.08\text{deg}}\right) \quad (7)$$

where E_p is the energy of a pulse and D_T is the diameter of the tracking optics. The diffraction limited image and the arrival time of the signal enable the three dimensional position of the debris (two position angles and the distance) to be determined.

1.3.

Laser ablation of debris

debris

When an intense laser beam is focused on a small area of the debris, its material is ejected as ablation plasma, if the laser intensity is higher than the ablation threshold. Figure 5 shows the concept of the laser ablation propulsion. For a given energy deposit E , the resultant reaction impact E/v_a is much larger than that of radiation pressure E/c of the laser beam, since the velocity v_a of ablated material is much slower than the light velocity c .

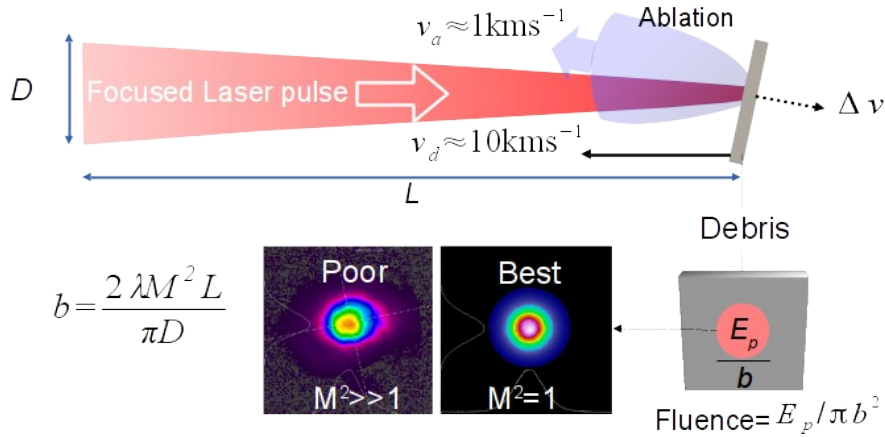


Figure 4: Concept of the propulsion by laser ablation. Ablated material is ejected as ablation plasma by the velocity of v_a .

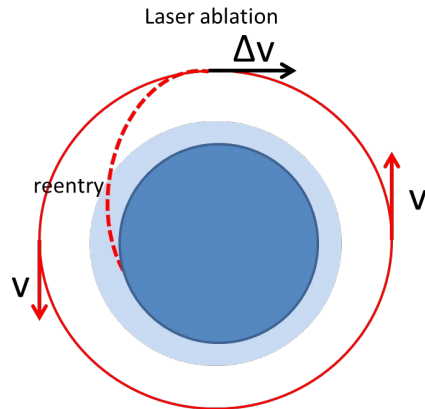


Figure 5. The concept of the removal of debris by laser ablation. Reducing the speed of debris by Δv via laser-ablation impulses

Space debris, smaller than 10 cm, can be sufficiently decelerated by laser impulses resulting in its re-entry to the Earth's atmosphere, as shown in Fig. 6. Here the debris of mass m is transferred to a lower orbit via a deceleration of Δv . The total laser energy required can be estimated as, $E_L \approx m C_m \Delta v$ where C_m is the efficiency of coupling to debris. For a given laser pulse duration and debris material, the optimal C_m requires a specific fluence to be delivered onto debris surface (Figure 4). Figure 6 shows the scheme of the shooting operation. Here EUSO telescope and the tracking optics are tilted backward 25° from the nadir, where the relative velocities of the debris are as low as 2 km s^{-1} (see figure 8).

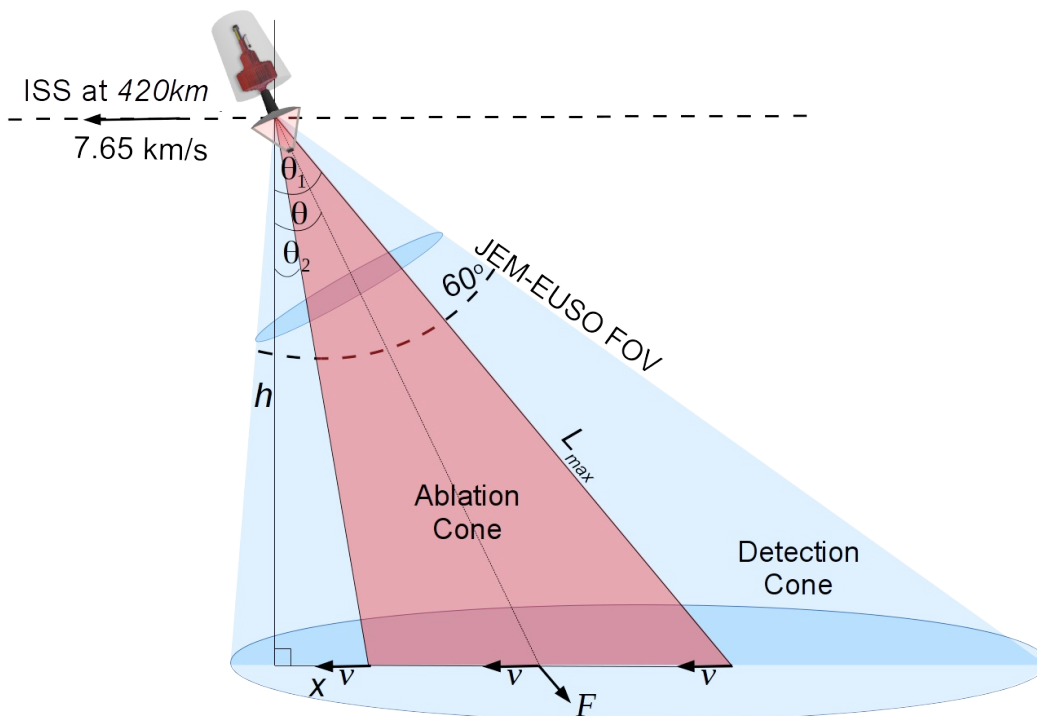


Figure 6. The scheme of the shooting operation from ISS. The detection telescope and tracking optics are co aligned and tiled backward by 25° degrees from the nadir. The shooting takes place from $\theta_1 40^\circ$ to $\theta_2 10^\circ$

Focusing of the pulse energy to the necessary fluence at large distances is limited by diffraction to:

$$b = \frac{aM^2\lambda L}{D} = 3.0 \times 10^{-2} \left(\frac{a}{1.27} \right) \left(\frac{\lambda}{0.35 \mu m} \right) \left(\frac{M^2}{1.0} \right) \left(\frac{D}{1.5 m} \right)^{-1} \left(\frac{L}{100 km} \right) \text{ m}, \quad (8)$$

which is dependent on the quality of the laser beam (M^2) with aperture D , wavelength λ and the L . According to Phipps et al. [11], the coupling coefficient C_m takes around 10^{-4} N/W for in the pulse duration τ_p shorter than 1 ns, if $F = 10^4 \text{ W m}^{-2}$ [11]. Assuming the ablation threshold to be

$F_{th} = 10^4 \text{ W m}^{-2}$ for $\tau_p < 1 \text{ ns}$, the maximum ablation distance $L_{max,ab}$ is determined by the ablation threshold:

$$L_{max,ab} = \frac{2}{aM^2\lambda} \left(\frac{DE_p}{\pi F_{th}} \right)^{1/2} = 9.8 \times 10^4 \left(\frac{a}{1.27} \right)^{-1} \left(\frac{M^2}{1.0} \right)^{-1} \left(\frac{\lambda}{0.35 \mu m} \right)^{-1} \left(\frac{D}{1.5 m} \right)^{1/2} \left(\frac{E_p}{10 J} \right)^{1/2} \left(\frac{F_{th}}{10^4 \text{ W m}^{-2}} \right)^{-1/2} \text{ m}. \quad (9)$$

The laser energy deposited E_d on to the spherical debris with radius d by one pulse is calculated as

$$E_d = 1.0 \times 10^1 \left(\frac{E_p}{10 J} \right) \min \left(1, \left(\frac{d}{b} \right)^2 \right) \text{ J}. \quad (10)$$

The average laser reaction force f_L exerted on the debris is calculated as:

$$f_L = C_m E_d R = 1.0 \times 10^1 \left(\frac{C_m}{10^{-4} \text{ N/W}} \right) \left(\frac{E_d}{10 J} \right) \left(\frac{R}{10^4 \text{ Hz}} \right) \text{ N}, \quad (11)$$

The time integrated force (impact) I by a laser operation along the direction of the motion of the debris:

$$I = \frac{-h}{v} \int_{\theta_1}^{\theta_2} \frac{f_L d\theta}{\cos \theta} = \alpha I_0, \quad (12)$$

where $I_0 = \frac{C_m E_d R h}{2v}$,

and θ is the angle between the directions of force and the debris motion, h the impact parameter of the debris and α the parameter of the order of unity for most of cases and represented by.

$$\alpha = \int_{\theta_1}^{\theta_2} \frac{\min \left(1, \left(\frac{d}{b} \right)^2 \right) d\theta}{\cos \theta} = \left(\frac{Dd}{aM^2\lambda h} \right)^2 (\sin \theta_2 - \sin \theta_1) \text{ for } d < \frac{aM^2\lambda h}{D \cos \theta_2}$$

$$\dot{\alpha} \ln \frac{1 + \sin \theta_0}{1 - \sin \theta_0} - \ln \frac{1 + \sin \theta_2}{1 - \sin \theta_2} + \left(\frac{Dd}{aM^2\lambda h} \right)^2 (\sin \theta_1 - \sin \theta_0) \text{ for } \frac{aM^2\lambda h}{D \cos \theta_2} < d < \frac{aM^2\lambda h}{D \cos \theta_1}$$

$$\dot{\alpha} \ln \frac{1 + \sin \theta_1}{1 - \sin \theta_1} - \ln \frac{1 + \sin \theta_2}{1 - \sin \theta_2} \text{ for } d > \frac{aM^2\lambda h}{D \cos \theta_1}, \quad (13)$$

Where the orbit of a debris is assumed by a horizontal straight line,

$$\theta_0 = \cos^{-1} \left(\frac{aM^2\lambda h}{Dd} \right) \text{ and } \theta_1 \text{ and } \theta_2 \text{ the angles that the shooting starts and ends,}$$

respectively. The velocity change Δv by an impact I :

$$\Delta v = 3.0 \times 10^1 \left(\frac{\alpha}{1.0} \right) \left(\frac{C_m}{10^{-4} \text{ N W}^{-1}} \right) \left(\frac{E_p}{10 J} \right) \left(\frac{R}{10^4 \text{ Hz}} \right) \left(\frac{h}{100 \text{ km}} \right) \left(\frac{v}{2 \text{ km s}^{-1}} \right)^{-1} \left(\frac{\rho}{2 \times 10^3 \text{ kg m}^{-3}} \right)^{-1} \left(\frac{d}{0.1 \text{ m}} \right)^{-3} \text{ m s}^{-1}, \quad (14)$$

for the case of debris in the LEO. The reduction Δr in the orbital radius of debris by an instantaneous change in the orbital velocity is given by [5]:

$$\Delta r = 1.0 \times 10^2 \left(\frac{\Delta v}{30 \text{ m s}^{-1}} \right) \text{ km}$$

$$\approx 1.0 \times 10^2 \left(\frac{\alpha}{1.0} \right) \left(\frac{C_m}{10^{-4} \text{ N/W}} \right) \left(\frac{E_p}{10 \text{ J}} \right) \left(\frac{R}{10^4 \text{ Hz}} \right) \left(\frac{h}{100 \text{ km}} \right) \left(\frac{v}{2 \text{ km s}^{-1}} \right)^{-1} \left(\frac{\rho}{2 \times 10^3 \text{ kg m}^{-3}} \right)^{-1} \left(\frac{d}{0.1 \text{ m}} \right)^{-3}$$

(15)

km.

The minimum operation distance L_{min} is determined by the maximum speed of the tracking system, which is likely to be less than $10 \text{ degrees s}^{-1}$, so that:

$$L_{min} = 1.1 \times 10^1 \left(\frac{v}{2 \text{ km s}^{-1}} \right) \left(\frac{\omega}{10 \text{ degrees s}^{-1}} \right)^{-1} \text{ km} ,$$

(16)

where ω is the angular velocity of the debris. The cross section A_{sh} of the shooting area is estimated as:

$$A_{sh} h^2 \tan \varphi_1 = L_{max}^2 \cos^2 \theta_1 \tan \varphi_1 = 1.6 \times 10^9 \left(\frac{L_{max}}{100 \text{ km}} \right)^2 \text{ m}^2$$

(17)

for $\theta_1 = 40^\circ$ and $\varphi_1 = 15^\circ$.

1.4. The CAN laser system

In choosing a laser system for active tracking and de-orbiting of small debris, there are a number of design factors which should be considered for operation onboard the ISS. Primarily the limited provision of solar power necessitates a laser system with high electrical efficiency. Likewise, with very high relative velocities $>10 \text{ km/s}$ between laser and debris, interaction times are short ($\sim 1\text{s}$), and hence a fast response and good average power are demanded. Heat dissipation, compactness and robustness are also key factors for operation in space. Many of these factors are absent with traditional gas or crystal-based laser technology which are limited by poor wall-plug efficiency $< 0.1\%$ and poor heat dissipation limiting the repetition to a few Hz and hence providing very low average power ($\sim 10\text{W}$). However, with the rapid development of fiber-based diode-pumped laser science, embodied by the CAN concept, these design factors can be realized.

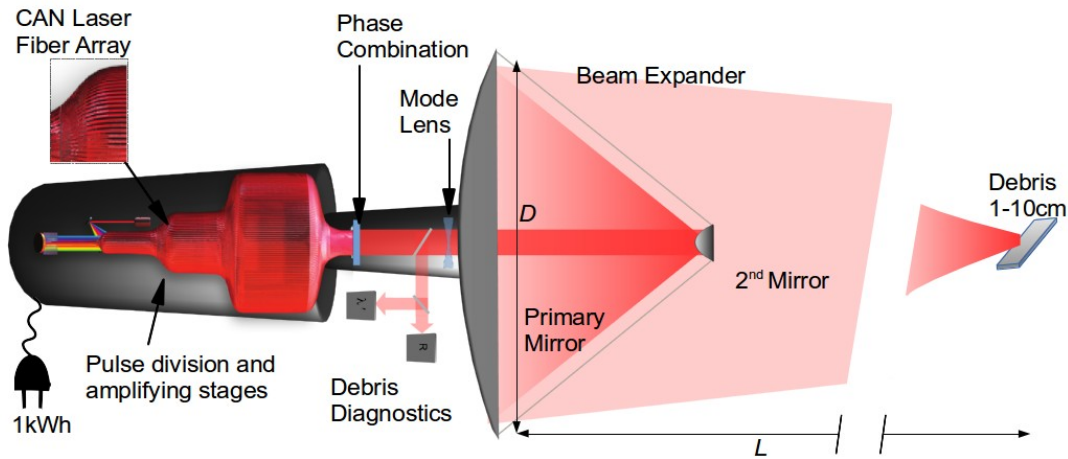


Figure 7: The CAN concept for the debris removal module. Powered by stored solar energy from the parent satellite, the amplified beam from the combined array of fibers is expanded via the telescope to aperture D which enables focusing to large distances, $L \sim 100\text{km}$, while the phase array controls wavefront and hence the focal distance of the beam.

The principle CAN design by Mourou et al. [12] involves propagating a seed laser pulse through an optical fiber network comprised of dividing and diode-pumped amplification stages. At the end of the network, there are $N \gg 10^3$ pulses which are then coherently combined both in time and phase to produce an overall array of laser pixels. Each channel in the array provides 1 mJ of laser energy with total energy of $N \times 1 \text{ mJ}$ per pulse, $1 \mu\text{m}$ wavelength and pulse duration of $\sim 100\text{ps}$. With

individual phase control of each pixel, the resulting beam is of excellent spatial quality. A very high degree of beam control is possible providing diffraction limited focusing and beam shaping with the potential for adapting heuristically to target surface interaction.

By virtue of their intrinsic geometry, the surface area of optical fibers enable more effective dissipation of heat than traditional media providing access to kHz repetition rates in pulsed-mode. Similarly, the orders of magnitude improvement in electrical efficiency of diode pumping over traditional lasing-media is well known (>30%) as is their high average power (>10 kW). Transport within single mode fibers provides increased robustness of the system which is critical for stability of optical systems in orbit.

A conceptual design for the CAN debris interaction module is shown in Fig. 8. Here, stored solar energy from the ISS provides the power required for the multi-channel fiber laser. In order to deliver pulses over ~ 100 km, the beam would be expanded to meter scales via multiple optics such as a simple telescope design. Here primary and secondary mirrors provide mechanical motion to steer and focus the beam with coarse precision over a FoV of 10 degrees. Fine precision is enabled through the individual phase control of the fibers. We expect that phase control enables a steering precision of $0.01 \mu\text{rad}$ over a range of 0.05 mrad . Similarly, focusing is finely controlled from a broad beam to a diffraction limited spot on the target when sufficient fluence is required to induce ablation and recoil impulses. Since phase adjustment can occur at rates of $\sim 10^3 \text{ Hz}$, debris surface condition scan be evaluated with trains of pulses and to tailor the beam profile for an optimal interaction. Such a heuristic approach could rapidly scan and optimize the coupling in terms of recoil thrust or reflectivity with debris of distinct orientation, rotation and surface type.

As reported in Soulard et al. (2014), a configuration of 10^4 fibers results in a pulse energy of 10J, an ablation range with best focus of 20-60km for $D_T=1.5 \text{ m}$ beam aperture. We can evaluate the performance of this system if it is employed in a nadir configuration onboard the ISS with the EUSO instrument. If operating at high rep-rate (10kHz) the laser could deliver very high average powers $\sim 100\text{kW}$. Since rates of debris of $\ll 1/\text{hr}$ are expected, a MJ of laser energy for debris ablation could be stored as 0.3kWh which, including efficiency losses, would be $\sim 1\text{kWh}$ equivalent to 8kg of Li-ion batteries, assuming a power density of 130Wh/kg. A key challenge here is the rapid beam pointing required when engaging debris, since the angular velocity of a debris is as high as 0.1 radian per second for the typical case of 10 km s^{-1} relative velocity and 100 km distance. Such a high speed requires special consideration in the mechanical design of the expanding optics. If necessary, we can only engage debris with the relative velocity less than 10 km s^{-1} , and may remove them in further encounters with more favourable conditions.

2. Proof of principle and prototype systems onboard the ISS

In utilizing the combined technology for the EUSO and CAN systems we propose a development in two steps

1. Scaled down proof of principle design operating from the ISS
2. Technical demonstrator capable of debris remediation operating from the ISS
3. Free orbiting system to remove most of LEO debris near 800km

A summary of the specification of these systems is shown in Table 1.

Table 1 Design parameters for debris removal systems

| | Prototype | Demonstrator at ISS orbit (400km) | Dedicated system near 800 km |
|---------------------------------|---------------------------------------|-----------------------------------|---|
| Debris size (cm) | >1 | $10 > a > 0.5$ | $10 > a > 0.5$ |
| Debris distance (km) | ~10-100 | ~100 | ~100 |
| Detector Aperture | 0.25 m | 2.5 m | 2.5 m |
| Photon detector | MAPMT | MAPMT | MAPMT |
| Wavelength (nm) | 350-400 | 350-400 | 350-400 |
| Angular resolution | 0.6 | 0.08 | 0.08 |
| Time resolution (μ s) | 2.5 | 2.5 | 2.5 |
| Field of View | $\pm 14^\circ$ | $\pm 30^\circ$ | $\pm 30^\circ$ |
| n_{sun} (photons/ms) | 1,0000 | 1,100 | 1,100 |
| Background (photons/ms) | 300 | 300 | 300 |
| Pixel crossing time (ms) | 10 | 1.2 | 1.2 |
| S/\sqrt{N} ratio | 600 | 60 | 60 |
| Tracking optics | 0.25 m | 1.5m | 1.5m |
| Wavelength (nm) | 335 | 355 | 355 |
| Photon detector | SiPM | SiPM | SiPM |
| Field of view (degree) | 1.2 | 0.6 | 0.6 |
| Spatial resolution (μ rad) | 10 | 0.3 | 0.3 |
| Number of pixels | 200x200 | 1600x1600 | 1600x1600 |
| Response time (s) | 0.01 | 3 | 3 |
| Time resolution (ns) | 1 | 1 | 1 |
| Pulse energy (J) | 0.1 | 1 | 1 |
| Laser system | solid state | 10^4 Fibers | 10^4 Fibers |
| Pulse energy (J) | 0.1 | 10 | 10 |
| Pulse duration (ns) | 1 | 0.1 | 0.1 |
| Repetition rate (Hz) | 10^2 | 10^4 | 5×10^4 |
| Laser average power (W) | 1 | 10^5 | 5×10^5 |
| Events per year | 20-30 (detection) 2-3 irradiation) | 10 (backward) 300 (forward) | 1.6×10^5 (forward) 1.6×10^3 (backward) |

2.1.

Proof of

principle system with Mini-EUSO

The prototype system will be installed onboard the ISS to demonstrate the technical feasibility of our concept in an LEO environment. Here the detection of debris can be performed by the Mini-EUSO system which is the prototype of the EUSO instrument. Its primary mission to observe the atmospheric cosmic ray events will be restricted to dark sky conditions resulting in a $\approx 20\%$ duty cycle. Some 20% of the remaining mission time is suitable for debris detection during which the ISS is in twilight while the debris are in sunlight. The Italian space Agency has approved to launch in the framework of the VUS-2 (Human Space Flight 2) call, with the flight scheduled tentatively in 2016.

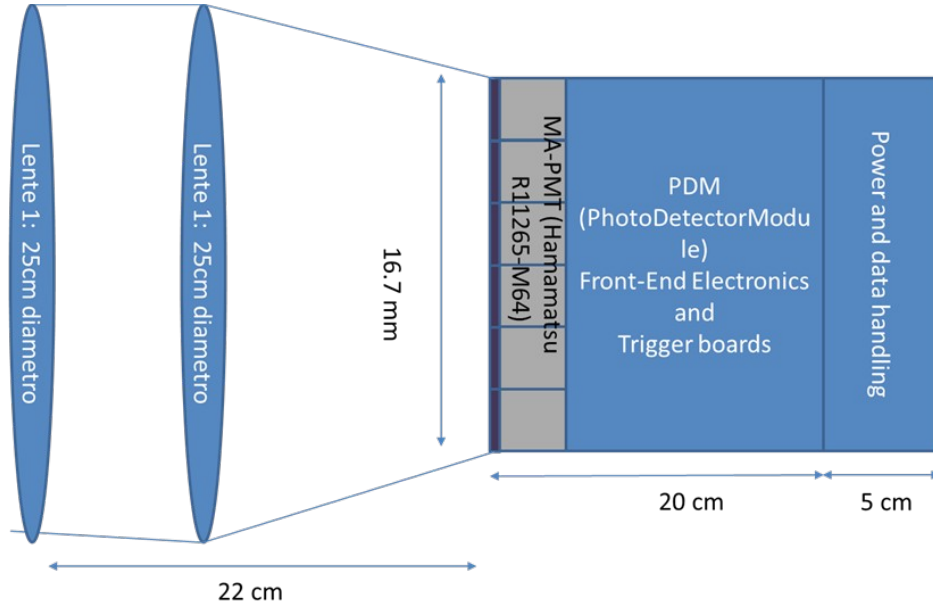


Figure 8. The concept of Mini-EUSO: Super wide field camera with two Fresnel lens and PMT array as the focal surface detector. [Is there a 2nd image of the real device?]

As shown in Fig. 8, the diameter of the Mini-EUSO optics is 0.25 m, the angular resolution is 0.8 degree (0.014 radian), Field of View of $\pm 18^\circ$ and a time resolution of $2.5 \mu m$. This signal is one order of magnitude higher than background photons, which is as low as one photon per GTU ($2.5 \mu s$). The integration time of 1 ms is more than enough collect photons to calculate position and the orbit of the debris. Since the angular velocity of a debris fragment at the distance of 1km is typically 1 degree per ms, Mini-EUSO can track the debris with a large margin.

The maximum detection distance of mini-EUSO is about 100 km for debris size of 0.1 m (see Fig. 3), the cross section of the detection area is estimated as

$L_{max}^2 \sin \phi_1 = 3.1 \times 10^9 m^2$ for $L_{max} = 10^5 m$, $\phi_1 = 18^\circ$, and $d > 0.1 m$. As the debris flux is about $1 \times 10^{-7} m^{-2} yr^{-1}$ for $> 0.1 cm$, approximately 310 debris should pass the ISS within a distance of 100 km. It is therefore expected to detect 15-30 debris per year assuming that the mini-EUSO is restricted to ISS twilights, which takes place 5 minutes every 90 minutes.

After the detection, we will conduct the experiment to irradiate the detected debris using a low power ICAN laser system comprised of 100 fibers. The successful irradiation can be confirmed by the brightening of the debris by the reflected laser photons. The number of laser photons of the wavelength of 350 nm reflected by debris is estimated as:

$$n_{laser} = \frac{\xi \zeta E_p N a^2 D^2}{(hc/\lambda) \theta^2 L^4} = 1.0 \times 10^1 \left(\frac{\xi}{0.1} \right) \left(\frac{\zeta}{0.1} \right) \left(\frac{N}{10^2} \right) \left(\frac{E_p}{0.1 J} \right) \left(\frac{\lambda}{0.35 \mu m} \right) \left(\frac{a}{0.03 m} \right)^2 \left(\frac{\theta}{0.01 rad} \right)^{-2} \left(\frac{L}{10 km} \right)^{-4} \left(\frac{D}{0.25 m} \right)^2, \quad (18)$$

where θ is the opening angle of the beam.

By this experiment with prototype EUSO and ICAN systems, we establish the technology to irradiate the debris by a laser beam immediately after the detection by a large angle detector. In the next step, we increase the diameter, field of view of the detector and laser power, where the steering accuracy of the latter is sufficient for debris de-orbiting, as we will discuss in the next subsection.

demonstrator of Laser Removal with JEM-EUSO

A technical demonstrator of a debris removal system is composed of a 2.5 m JEM-EUSO telescope for the detection and a scaled up CAN laser with a larger mirror. Continuing from the prototype experiment, this combined system will be housed on the International Space Station. The goal now will be to demonstrate detection, tracking and complete removal of 5mm-10cm debris fragments from this orbit.

As with its prototype, mini-EUSO, the JEM-EUSO telescope has been designed for cosmic ray observation on board the ISS (Takahashi et al. 2008; Casolino et al. 2011). This module can operate in the nadir direction (planned for the first two years) or in a tilted configuration up to an angle of 30° relative to nadir (for the rest of its mission) during the night., In terms of debris detection, it can be operated during the period of astronomical twilight or day time. Twilight operation is the best opportunity to detect debris since the sun still illuminates the objects in the ISS orbit in contrast to the dark background, where the sunlight cannot illuminate. The JEM-EUSO telescope can also detect debris in day time if it is directed above the horizon where the background photons flux is expected to be much lower than the surface of the Earth. The operation of the JEM-EUSO mission must be carefully redesigned to include the debris removal operation to compromise different tasks.

The CAN laser module will include a 1.5 m Cassegrain telescope. This will entail a dual function: as a beam expander to enable longer focal distances and as a collector of reflected photons which will be imaged to provide diagnostical data on the debris. The detector here will comprise SiPM technology with 4800×4800 pixels of 1 mm size with a time resolution of 1 ns. The number of background photons in 1 ns is negligible compared with the number of signal photons reflected by the laser as estimated in equation 24. As for the laser system, a 10000 fiber system will be capable of producing an average power of 100 kW (Table 1), as described in Soulard et al. (2014).

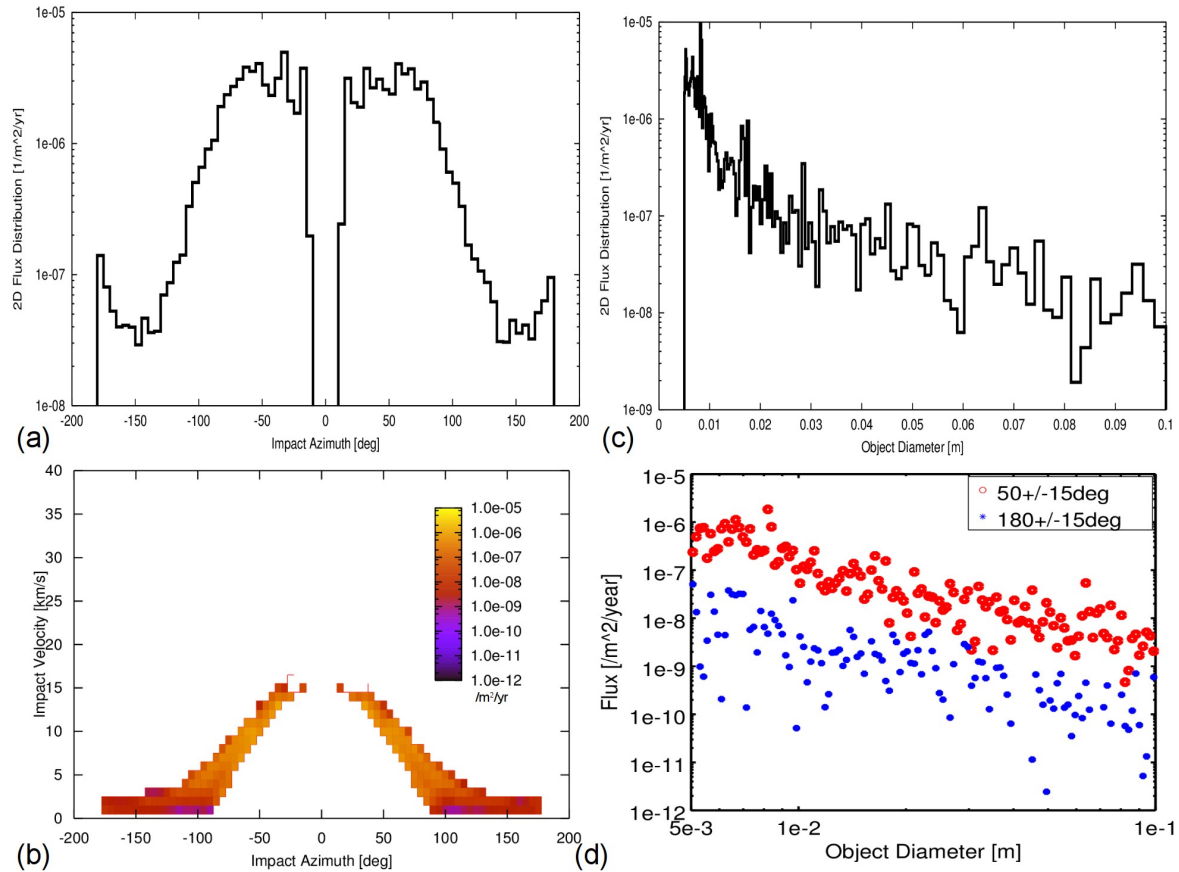


Figure 10. (a) Distribution of debris in azimuth-velocity diagram at the ISS orbit. The flux for forward direction (azimuth 0°) is higher because of the larger relative velocity than that of the backward direction (azimuth 180°). (b) The relative velocity of debris from the backward direction (azimuth $\sim 100-180^\circ$) is plotted against the azimuth angle from the direction of motion. It is as low as 2 km s^{-1} from the backward direction. Colours represent the 2D flux of the debris with the size of 0.5 cm to 10 cm. (c) The size distribution of debris in ISS orbit. (d) Debris distribution at the ISS orbit from backward ($180 \pm 15^\circ$) and forward ($50 \pm 15^\circ$) direction.

In order to estimate the effectiveness of this combined system for debris remediation we can calculate the expected debris flux for 5mm-10cm fragments. Results obtained with MASTER-2009 are shown in Fig. 10. Here the orbit is that of the ISS and debris distributions are of 2014 including data rocket motor slag with explosive and collision fragments. It is apparent that there is a strong directional component to the flux in terms the impact azimuth distribution (Fig. 10(a)) and also the impact velocity (Fig. 10(b)). The majority of impacts are due to the significant debris present on sun-synchronise orbits at inclination near 90° . The ISS which orbits at 52° is impacted by this flux at most angles except in the forward direction at 0° . Both the impact flux and debris velocity peak near $\pm 50^\circ$ **and diminish at large angles towards the backward directions.**

We can consider the two types of operational modes, those are backward and forward modes. As can be seen in figure 10(b), the velocities of the debris relative to ISS are as low as, or less than 2 km s^{-1} in the backward direction ($180^\circ \pm 15^\circ$). In this case, there are less demands for rapid tracking and beam steering, and thus complete removal of all the debris in the range is possible by an operation with one encounter (equation 15 and figure 9). On the other hand, just a dozen operations are

expected in one year (Table 1), since the flux from backward is as low as $10^{-7} \text{ m}^{-2} \text{ yr}^{-1}$.

The situation is different in the case near the forward direction ($50^\circ \pm 15^\circ$ for example). The relative velocity from the forward direction is higher ($\sim 10 \text{ km s}^{-1}$) so that the complete removal of the debris smaller than 6cm is possible (equation 15 and figure 9). Here, the flux from the forward direction is also increased to $2 \times 10^{-6} \text{ m}^{-2} \text{ yr}^{-1}$ and more than 200 debris will be detected and treated. Compared to the total flux distribution, Fig. 10(c), there two directional components

Using the pointing configuration shown in Fig. 6 we can calculate the amount of orbit reduction (Δr) possible for different debris sizes from 5mm-10cm. As shown in Fig. 9. and using Equations ?? the Here two orbits are considered, that of the ISS and that near 800km for a dedicated system which will be discussed in next section.

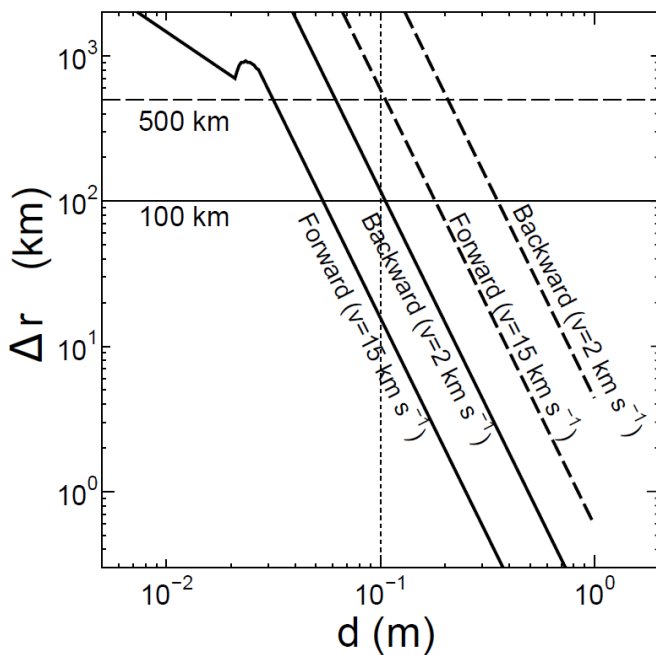


Figure 11. Reduction in orbital radius are plotted against the debris size d by the technical demonstrator onboard ISS (Solid lines; $\theta_1=40^\circ$ and $\theta_2=10^\circ$, and $R=10^4$) for the cases of backward ($v=2 \text{ km s}^{-1}$) and forward ($v=15 \text{ km s}^{-1}$). Those by a laser operation of the dedicated laser removal system located at the latitude of 800-900 km (Dashed lines; $\theta_1=40^\circ$ and $\theta_2=10^\circ$, $R=5 \times 10^4$), described in section 2.3. [800km ORBIT: IN TILT MODE TOO!]

2.3 Free orbiting system

If such a remediation solution from the environs of the ISS is successfully demonstrated, one should think of a

mission fully dedicated to the debris removal at critical orbits near 800 km altitude where there are many more satellites and indeed greater abundance of debris (flux x10) as shown in Fig. 1(b). The strategy of the removal operation must be carefully built-up based on the debris distribution in the position-velocity phase space. Such a system would be the ultimate goal after the proof of concept demonstration on the ISS.

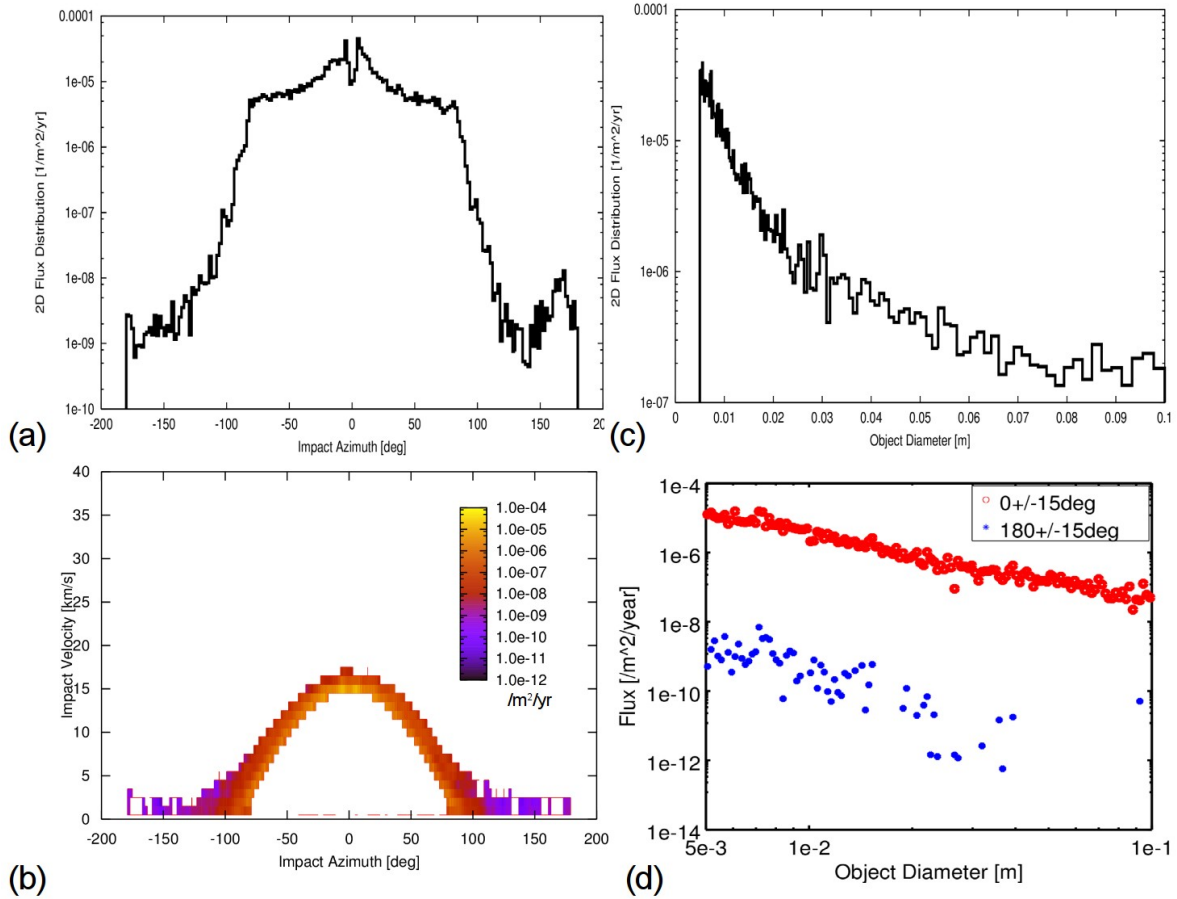


Figure 12.(a) 2D flux of debris is plotted against the azimuthal angle from the motion of the direction at the polar orbit at the altitude of 800 km.(b) The relative velocity of debris from the backward direction (azimuth~100-180°) is plotted against the azimuth angle from the direction of motion. Colors represent the 2-D flux of the debris with the size of 0.5 cm to 10 cm.(c)The size distribution of the debris at 800 km altitude..(c) The size distribution of debris in ISS orbit. (d) Debris distribution at the ISS orbit from backward (180±15°) and forward (0±15°) direction.

A useful comparison here is with L'ADROIT system proposed by Phipps [13]. Here a novel double mirror catadioptric system, developed by Köse and Perline [14], is implemented to provide the super-wide angle ($\pm 30^\circ$) passive detector. Active tracking and impulse control is provided by a 1.5m cassegrain system coupled to a powerful laser system producing 100ps pulses of UV energy (>188 J) at <20 Hz repetition. Phipps also specifies an elliptical polar orbit ranging from 560km perigee to 960km apogee.

Analysis of this orbit for 5mm-10cm debris is shown in Fig. 12, The global flux here is $9 \times 10^{-3} / \text{m}^2 / \text{yr}$ which is a factor of 10 greater than the ISS orbit. Impact angle is peaked in the forward direction (Fig. 12(a)) and therefore impulse interaction with these debris will involve relative velocities of 15km/s as shown in Fig. 12(b). This forward flux is increased by an order of magnitude compared to the ISS orbit while the backwards direction is relatively unchanged as shown in Fig. 12(d).

Operating a free orbiting system to remediate this debris, we propose a functionally similar system to that of Phipps but much more feasible from the technical point of view. As summarized in table 1, our system consists of an EUSO telescope with a diameter of 2.5 m for debris detection and an 1.5 m Cassegrain optics connecting to highly parallel ($\sim 10^4$) CAN laser system for debris manoeuvre. Both of them have

certain technical basis ready to use in ground. Only thing that we have to do is the increase in repetition rate up to five times than the technical demonstrator on board ISS. It has an ability to reduce altitudes of the most of debris less than 0.1m by 500 km by one encounter with the relative velocity of 2-17 km s⁻¹ at the altitude near 800 km (figure 12).

Since the debris flux is as high as $\sim 10^{-4} \text{ m}^{-2} \text{ yr}^{-1}$ (figure 11) and the cross section of the operation area is $1.6 \times 10^9 \text{ m}^2$ (equation 17), the system can operate against 1.0×10^5 debris per year (one per five minutes): the dedicated system is oriented above the horizon to be functional in whole the daytime. Since the polar orbit crosses all the possible orbits at the same altitude, the sweep-up time for a target zone of thickness $\Delta h = 70 \text{ km}$ around the system is estimated by [13]:

$$\tau_{sw} = \frac{4\pi r^2 \Delta h}{v \Omega A_{sh}} = 2.0 \times 10^6 \left(\frac{r}{7200 \text{ km}} \right)^2 \left(\frac{\Delta h}{70 \text{ km}} \right) \left(\frac{v}{17 \text{ km s}^{-1}} \right)^{-1} \left(\frac{\Omega}{0.82 \text{ str}} \right)^{-1} \left(\frac{A_{sh}}{1.6 \times 10^9 \text{ m}^2} \right)^{-1} \text{ s}, \quad (19)$$

The system may start from the orbit of an altitude of 1000 km and gradually reduce its orbit in the rate of 10 km per month. After 50 months (~ 4 years), it reaches 500 km removing most of the cm size debris between from 1000 km to 500 km.

3. Discussions and Conclusions

Increasing numbers of debris at higher orbits are elevating the risk of future collisions to both functional and derelict satellites. Remediation of cm-size debris which poses the main threat would require directed impulse control to promote atmospheric re-entry. Development of an orbiting debris sweeper, such as that described in recent articles, should be presided by a staged implementation of the novel technologies. We believe that the ISS can provide such an environment enabling scaling and rigorous testing of individual subsystems such as power, detection and laser impulse delivery.

Utilization of the JEM-EUSO telescope onboard the ISS can be accomplished without significant changes to the existing design as a proof of principle wide angle detector of debris. Original configured for nadir operation with provision to tilt astern to the direction of the motion by $\gtrsim 25^\circ$, this system would provide passive detection of cm scale debris at ranges $\gtrsim 100 \text{ km}$, from the ISS orbit. Measured population data for such small debris would greatly compliment the computation models used to predict risks to orbital payloads. No major obstacles are foreseen in implementing a debris detection mode to the operation of this orbiting air-shower telescope. In orbit, a robust, electrically efficient laser system such as that built on the CAN architecture would be required. Attributes of stability and good beam quality would enable precise taking and impulse delivery from distances $\gtrsim 100 \text{ km}$

Laser impulse control can be also be used to modify the rotation rate of large debris objects such as derelict satellites or spent rockets. Prior to their capture by dedicated removal spacecraft it is necessary to stop their rotation. The moment of impact necessary to stop the rotation is in the order of 10^2 N s m for the case of a typical satellite with the mass of 1000 kg the size of 1 m, and angular velocity of 0.1 Hz. It takes only several minutes to give this amount of impulse using a 1kW laser system. Also the precise orbital injection of a satellite can be done remotely with 10kW-class space laser system without additional propellant in the satellite. It may give us a significant freedom for the operation of the orbital bodies.

In conclusion, we have proposed a staged approach to the development of a space based system for the remediation of orbital debris fragments 5mm-10cm in size.

Beginning with demonstration missions on the International Space Station incorporating the JEM-EUSO module as a detector, we have shown that there are sufficient debris numbers to validate proof-of-principle operation of both tracking and remediation capability with the efficient fiber-based CAN laser system. This would lay the ground-work for a freely orbiting system to carry our remediation at higher altitudes where debris risks are increasing for highly populated polar orbits where $>10^4$ debris fragments would be removed per year.

Acknowledgement

This work was partially supported by JSPS KAKENHI Numbers 23340081, 24244042, and RIKEN Strategic Research Programs for R&D in Japan, the 'Commissariat à l'Energie Atomique et aux Energies Alternatives', l'Ecole Polytechnique and Thales in France.

References

- [1] Liou, J.-C., & Krisko, P., N UPDATE ON THE EFFECTIVENESS OF POSTMISSION DISPOSAL IN LEO. 64th International Astronautical Congress, Beijing, China, (IAC-13-A6.4.2), 2013
- [2] Flegel, S. et al., MASTER2009 Final Report, Institute of Aerospace Systems, June, 2011
- [3] Phipps, C. H. Friedman, et al., ORION: Clearing near-Earth space debris using a 20-kW, 530-nm Earth-based, repetitively pulsed laser, *Laser Particle Beams* 14, pp. 1-44, 1996.
- [4] Metzger, J. D., et al., 1989 *J. Propulsion & Power* 5 pp. 582-90
- [5] Liedahl, D. A.; Rubenchik, A.; Libby, S. B.; et al., 2013, Pulsed laser interactions with space debris: Target shape effects, *ADVANCES IN SPACE RESEARCH*, 52, 5, 895-915 DOI: 10.1016/j.asr.2013.05.019
- [6] Takahashi, Y. et al. 2008, The JEM-EUSO Mission, *New J. of Phys.*, 11, 065009.
- [7] M. Casolino, J. H. Adams, M. E. Bertaina, et al. Detecting ultra-high energy cosmic rays from space with unprecedented acceptance: objectives and design of the JEM-EUSO mission, *Astrophysics and Space Sciences Transactions* 2011, 7, 477.
- [8] Soulard, R. et al. 2014, A novel laser architecture for space debris removal, *Acta Astronautica*, 105. 192-200.
- [9] Adams Jr., J.H., 2013, An evaluation of the exposure in nadir observation of the JEM-EUSO mission, *Astroparticle Physics*, 44, 76-90.
- [10] Allen, C.W. 1973, *Astrophysical Quantities*, Third Edition, University of London, Athlone Press.
- [11] Phipps, C. 2006, Laser impulse coupling at 130fs, *Applied Surface Science*, 252, 4838-4844.
- [12] Mourou G. et al. 2013, The future of fibre accelerators, *Nature Photonics*, 7, 258-261.
- [13] Phipps, C.R. 2014, L'ANDROIT - A spaceborne ultraviolet laser system for space debris clearing, *Acta Astronautica*, 104, 243-255.
- [14] Emek Köse and Ron K. Perline, "Double-mirror catadioptric sensors with ultrawide field of view and no distortion," *Appl. Opt.* 53, 528-536 (2014)