SPACE DEBRIS DEFLECTION BY SPACE BASED LASER STUDY

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ABSTRACT

Laser technology is a promising candidate for space debris remediation and removal. Pulsed lasers are currently used for tracking space objects from ground, and also considered for generation of small speed variation (Δv), on the order of a few mm/s on uncontrolled LEO targets on the range of 1cm to 10cm debris size. In order to reduce the collision risk a small Δv of mm/s is considered to be applied a few orbital revolutions before the event to increase the radial separation at the conjunction epoch.

The Space Debris Deflection by Space Based Laser study focuses on the use of Continuous Waves (CW) lasers on-board a spacecraft as an alternative to classical collision avoidance manoeuvers. This study was initiated by the European Space Agency at the beginning of 2020 and the research activities were carried out by a consortium led by Thales Alenia Space (TAS) with strong contribution from the Finnish Geospatial Research Institute (FGI).

To facilitate communication, acronym OLaMoT has been used for in Orbit Laser Momentum Transfer. OLaMoT study is referring to the study performed for Space Debris Deflection by Space Based Laser, whereas OLaMoT mission, system, satellites, payloads are referring to the envisaged mission and associated components.

1 INTRODUCTION

The space environment remediation issue is a growing topic for space mission actors. The amount of operational satellites but also debris is increasing with time. Leading to an increase of the risk of collision. Collision avoidance manoeuvres performed by satellites are very demanding and disturb the operation of the concerned satellites.
Multiple concepts for space environment remediation have been analysed and the Laser Momentum Transfer (LMT) solution is a promising one. This solution offers capability to deflect small space debris by using the radiation pressure of a light beam, allowing to perform small debris manoeuvres. One of the benefits of such mission is neither to have intrusive action (no ablation) nor emitted bodies, meaning that no additional debris are generated during the manoeuvre.
In order to perform the requested mission, i.e. to perform space debris deflection with a determined level of efficiency the architecture shall rely either on high platform manoeuvre capability or on a large set of assets.

2 DEBRIS POPULATION

The study focuses on the 1cm to 10cm size debris, to address a large population of potential dangerous bodies. This population has been analysed for properties and obits parameters.

ESA MASTER Database provides relevant information on debris population density depending of altitude. Major part of the target population is located within [750; 880]km altitude range (Fig.1).

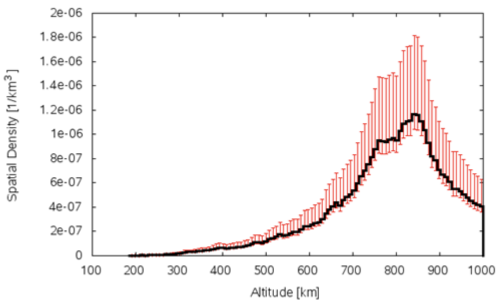

Figure 1. [1; 10]cm size debris spatial density depending of altitude (ESA MASTER Database)

The main population orbits are:

- Isotropic in right ascension,
- Highly inclined (70° to 110°) (Fig.2),
- Rather circular (eccentricity < 0.01).

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Ed. T. Flohrer, S. Lemmens & F. Schmitz, (http://conference.sdo.esoc.esa.int, May 2021)

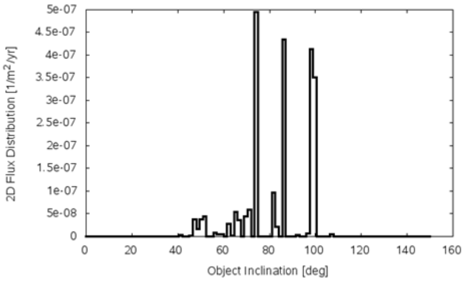

Figure 2. [1; 10]cm size debris inclination distribution (ESA MASTER Database)

Debris properties have a direct impact on the response to Laser Momentum Transfer efficiency. Therefore a review of these properties has been performed in the frame of the study.

Debris materials are dominantly plastics and aluminium, with small amounts of other materials including metals, glass, paints, and carbon. The shapes of debris particles vary in a wide range from compact spheres to nuggets, flakes, wires, curly plates, and messy aggregates of all of the above. Surfaces can be rather degraded. The particles presumably spin relatively fast with random speed and axis direction. The spin axis may prefer to orient along two stable inertial axes, and fast spinning objects may show asymmetry even after time averaging.

Main property to impact the LMT efficiency is area over mass ratio (A/m). A/m varies in large range between 0.01 and 100 m²/kg, the mean probably below 1 m²/kg.

3 LASER MOMENTUM TRANSFER

We focus here on photon pressure can with no ablation effect.

By definition the change of velocity (Δv) is expressed using additional forces (F) applied on a body:

$$\Delta v = \int_{t_0}^{t_0+\Delta t} \frac{F(t)}{m} dt \tag{1}$$

With:

- m the mass of the debris,
- Δt the time during the force is applied.

The light pressure force can be expressed as:

$$F = \sigma_{rp} \frac{I}{c} \tag{2}$$

With:

- σ_{rp} the light pressure cross-section,
- I the incident light irradiance,
- c the speed of light.

For Eq.1 and Eq.2, considering that in a first order, only the light pressure associated force is applied, the resultant velocity change can be expressed as:

$$\Delta v = \int_{t_0}^{t_0+\Delta t} \frac{A(t)I}{mc} dt \tag{3}$$

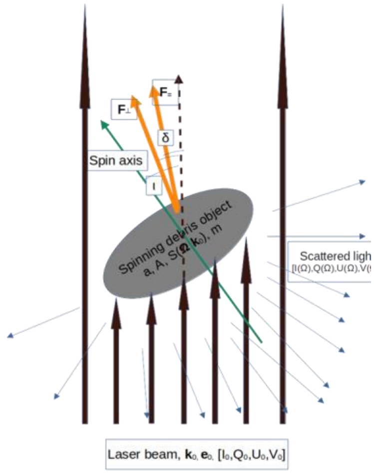

Figure 3. Illustration of the LMT geometry. Laser light comes from below. The particle is spinning around the green axis, inclined by an angle ι from the beam. The light scatters asymmetrically and thus also the radiation force deviates by an angle δ from the beam

By definition debris, are uncontrolled, various shape, size and material. Therefore scattering albedo can usually vary in almost the full range between 0 and 1 and the asymmetry factor also in principle can be anywhere $|g| \leq 1$ [1][2]

Leading to first order efficiency of:

$$\frac{AI\Delta t}{mc} \leq \Delta v \leq \frac{2AI\Delta t}{mc} \tag{4}$$

For mean A/m value, mm/s Δv request 3E5 W.s/m².

Therefore the following budget can be considered:

- 4kW optical power laser,
- 1m² spot size at debris surface,
- 75s illumination duration,
- mm/s induced Δv.

These parameters have been used as inputs for a space debris deflection by space based laser mission definition.

4 PAYLOADS DEFINITION

OLaMoT space segment will have to perform the following function to achieve mission objectives:

- Debris Detection,
- Debris Tracking,
- Line of Sight pointing towards debris,
- Laser Illumination,
- Monitoring of debris response to LMT.

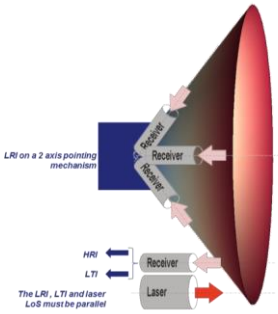

Figure 4. Accommodation of the optical functions

4.1 Debris Detection

Debris detection function is similar to other Space Situational Awareness (SSA) mission. The main challenge is the small size of the debris. The proposed concept is able to detect debris up to 18 visual magnitude (Mv). The solution relies on a Low Resolution Imager (LRI) based on 35cm optics TAS smart-telescope (Fig.4) [3].

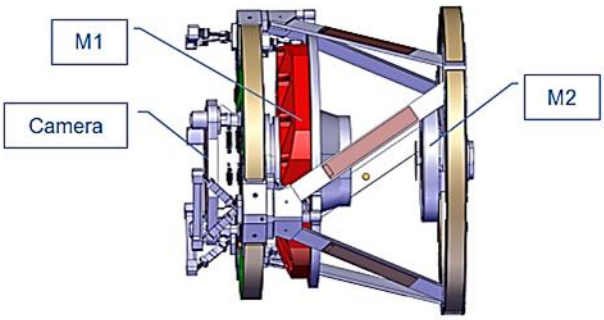

Figure 5. Thales Alenia Space smart-telescope solution.

This telescope will be mounted on a 2 axis mechanism in order to provide an enlarged Field of Regard (FoR). Large area matrix is implemented in order ensure a large Field of View (FoV), to ensure to have the debris within the FoV even with the foreseen uncertainties orbit propagation.

LRI will detect debris and define relative displacement propagation in order to guide the satellite line of sight towards the debris. LRI will perform coarse debris tracking.

4.2 Debris tracking

LRI large FoV is not compatible with debris direction angular accuracy requested to perform the illumination. As the LMT CW laser beam is foreseen to be around >100cm diameter on target, the position of debris has to be determined with few tens of cm at several hundred of km. Therefore an additional instrument is requested to provide the needed <1µrad angular resolution.

High Resolution Imager (HRI), is based on the same architecture that LRI. Smart-telescope solution is used but adapted to a reduced FoV and so enhanced angular resolution. HRI FoR is fixed and in the same direction than the Laser telescope. LRI will perform fine debris tracking.

To improve the tracking capabilities during illumination, it is proposed to implement a Laser Tracking Imager (LTI) function. Combined with the LRI instrument, an additional 4 quadrants detector is used to acquire the reflected CW laser flux on the debris and to determine any mis-alignment to correct the line of sight.

4.3 CW Laser Illumination

The core of OLaMoT mission is based on the illumination of debris using high power Continuous Wave (CW) laser. >63cm telescope optic is requested to limit the beam divergence and ensure a reduced spot size at debris surface. Such large telescope is not compatible with mounting on mechanisms, and it is then recommended to install this instrument in the centre of the satellite.

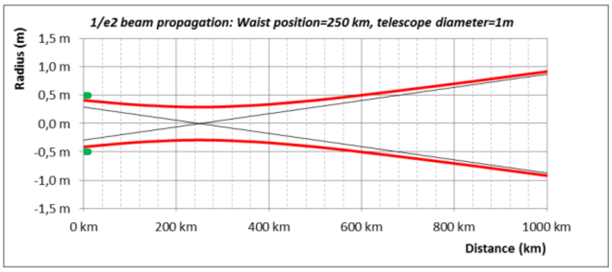

Figure 6. Laser Beam size evolution for 100cm telescope optic diameter and 250km Rayleigh distance

Compact 1024nm single-mode fiber lasers and amplifiers are considered for 4 kW output power with diffraction-limited beam quality and fulfil the applications requirements.

4.4 Monitoring debris response to illumination

To ensure the monitoring of the targeted debris to illumination, it is recommended to perform the measurement from the same satellite that has performed the illumination.

Laser ranging (LR) is a proven technique to measure the distance using Time of Flight (ToF) of a short laser pulse.

Time of Flight system measures a laser pulse travel time from laser to the debris and back; to achieve high distance accuracy, the time measurement resolution must be excellent.

In practical, a counter is started when a laser pulse is generated and stopped when the echo is received. Notice that for a space application the situation is simpler that for a ground application, where parasitic echo's due to parasitic objects or the atmosphere can create ambiguities.

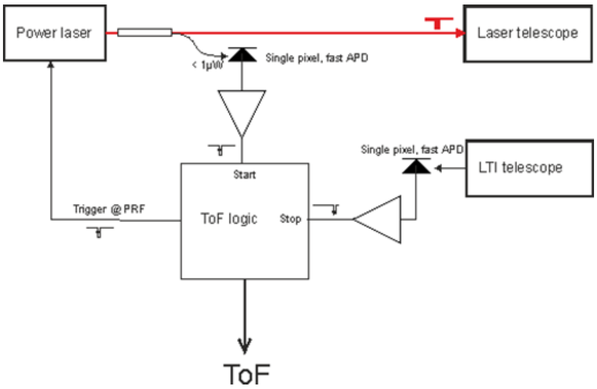

Figure 7. ToF measurement principle

The ranging laser wavelength must be different (1310nm) from main CW power laser to avoid perturbing the detection.

The ToF pulsed laser will be injected as the CW laser in the main telescope. The detection chain of the ToF function will be combined within the LRI instrument.

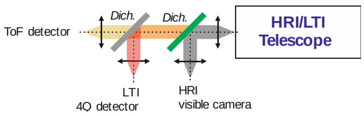

Figure 8. HRI-LTI-ToF configuration

5 SATELLITE DEFINITION

LMT efficiency is directly linked to the laser Irradiance (I) on debris surface. The relative large distance foreseen between debris and OLaMoT Satellite(s) then request large optics telescope for illumination. The envisaged satellite architecture is a hexagonal structure with the main telescope in the center (Fig.8). 3 Solar Array (SA) wings configuration is proposed, with the objective to minimize satellite inertia and improve agility.

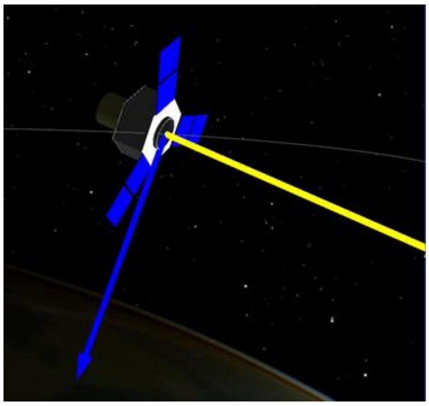

Figure 9. OLaMoT satellite concept. (Yellow line is sun vector, blue arrow is the nadir direction, main telescope line of sight is in anti-sun direction)

OLaMoT platform will face several challenges:

- Power management,
- Thermal management,
- Agility.

High power laser will request high power generation. 40% laser efficiency is foreseen, leading to 10kW need to perform illumination. This budget can be reduced thanks by reducing the laser duty cycle and using batteries.

Laser consumed power not emitted as light will be dissipated as thermal energy. Up to 6kW have to be managed to ensure the system thermal stability. Phase Change Materials (PCM, Fig.9) are foreseen to be used to collect this amount of energy and to diffuse it later.

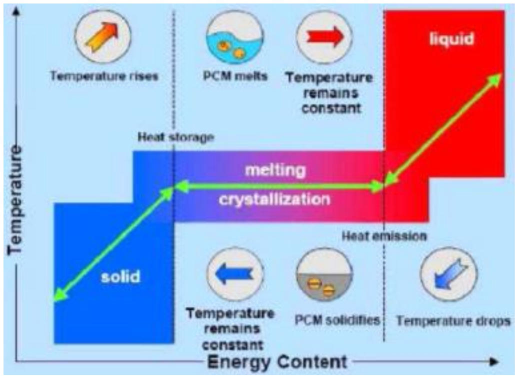

Figure 10. PCM thermal behaviour

Satellite will have to ensure the fine pointing of payloads Line of Sight toward the debris, using HRI and LRI-LTI information.

6 OLaMoT System

The selection of the orbit altitude has been determined taking into account the need to see as much as possible any debris of the targeted population. Lower and higher orbit than the debris population range will benefit of the respectively higher and lower satellite speed, ensuring a derive of the satellite relative anomaly wrt to debris. The altitude should not be too much far away of the [750km; 880]km range to limit the distance between satellite and debris, this to optimize the detection and illumination performance. Therefore two altitudes are proposed for the mission, around 650km and 950km, allowing to ensure a derive of half an orbit within two days between the satellite and any debris.

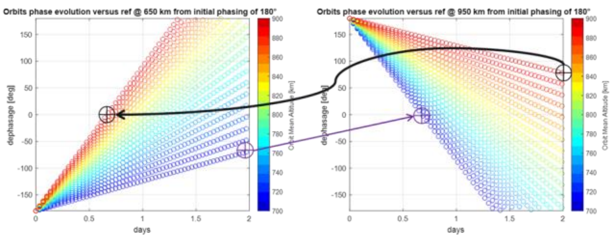

Figure 11. Debris to OLaMoT satellite(s) phase evolution depending of altitude with initial relative anomaly of 180°.

Combination of both altitudes has to be considered to ensure a better debris population visibility in a short time horizon.

A debris In-track laser illumination is providing the best response in term of velocity change impact on miss distance for a predicted risk of collision.

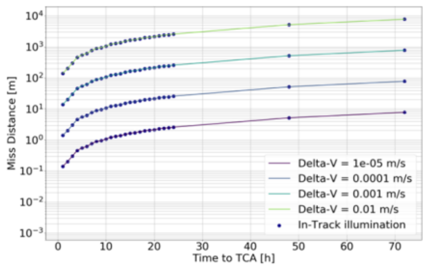

Figure 12. In-track illumination induced ΔV influence on the miss distance w.r.t instant of application before closest approach

Optimum performance is when the debris and the satellite speed directions are close to be collinear. Therefore we can split in two distinct parts the debris population with regards to a reference velocity vector (for instance that of the first chaser satellite), half in the same direction (+) the others in opposite direction (-).In order to optimize the debris visibility condition and duration, it is preferable to consider two opposite orbital planes.

Therefore the mission will rely on a constellation of satellites. In order to cover the full 360° of potential relative anomaly difference in less than two days, at least two satellites are needed. Two different altitudes are requested to cover the debris altitude range, leading to at least 4 satellites. Then considering the need to have opposite orbital planes to optimize the mission efficiency, double of satellites are requested leading to a constellation of 8 satellites.

The space segment architecture will be then based on a constellation of 8 identical satellites distributed on 4 orbital planes:

- 2 satellites 180° anomaly separation on 6h-18h SSO at 650km,
- 2 satellites 180° anomaly separation on 18h-6h SSO at 650km,
- 2 satellites 180° anomaly separation on 6h-18h SSO at 950km,
- 2 satellites 180° anomaly separation on 18h-6h SSO at 950km.

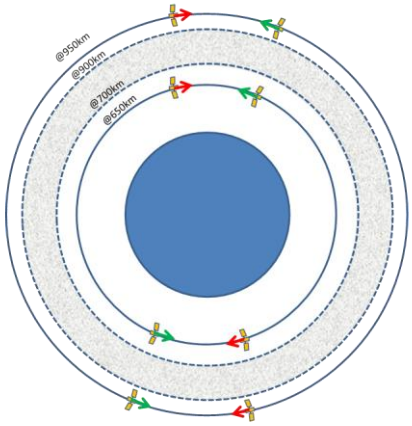

Figure 13. OLaMoT Space Segment configuration

7 CONCLUSION

OLaMoT study has demonstrated the feasibility of space debris deflection by space based laser mission. Few mm/s velocity change should be achieved with identified concept. Large optics telescope (>63cm diameter) is requested to optimise the incident irradiance on target an optimise the LMT efficiency. Main difficulties for such mission are the detection capacities, and the fine pointing toward very small debris (<10cm) at very long distance (>300km). Combination of several instruments is requested.

Further studies are now requested to refine the outcomes and the system definition.

8 Reference

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