Executive Summary Report

ESR

Space Debris Deflection by Space-Based Laser Study (OLaMoT)

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CHANGE RECORDS

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
1	19/04/2021	First Release	Study team
2	19/05/2021	Update Following ESA feedback	Study team
3	08/06/2021	Footer update	Study team

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1. INTRODUCTION

1.1 Scope and purpose

The aim of this document is to provide a summary description of all the work performed in the frame of the Space Debris Deflection by Space Based Laser study.

1.2 Applicable documents (ADs)

Contents of the documents listed below are applicable to this document :

Id	Reference	Issue	Title
AD01	19-D-T-OPS-01	1	Space Debris Deflection by Space-Based Lasers Statement of Work
AD02	0005-0011390255	1	Space Debris Deflection by Space-Based Lasers Thales Alenia Space Proposal

Table 1 : Applicable documents list

1.3 Reference documents (RDs)

Contents of the document listed below support this document understanding :

Id	Reference	Issue	Title
RD01	0005-0011584377	1	Space Debris Deflection by Space-Based Lasers Kick-Off Minutes of Meeting
RD02	0005-0011885150	1	Space Debris Deflection by Space Based Laser Study Phase 2 Kick-Off Meeting Minutes
RD03	0005-0011898896	5	Space Debris Deflection by Space Based Laser Study Debris properties effects in laser-induced Δv efficiency (D1)
RD04	0005-0012202112	5	Space Debris Deflection by Space Based Laser Study, Payload Concept Design Report (D2)
RD05	0005-0012202114	4	Space Debris Deflection by Space based Laser Study, Top-Level Payload Requirement Report (D3)
RD06	0005-0012203311	2	Space Debris Deflection by Space Based Laser Study, Detection of Debris response to laser Illumination (D4)
RD07	0005-0012203338	2	Space Debris Deflection by Space Based Laser Study, High level

			platform design and development Roadmap (D5)
RD08	0005-0012203343	2	Space Debris Deflection by Space Based Laser Study, Cost estimation, Technology and Regulatory gaps (D6)
RD09	0005-0011898904	7	Space Debris Deflection by Space Based Laser Study, Mission analysis Report (D7)
RD10	0005-0012769998	2	Space Debris Deflection by Space Based Laser Study, Mission Concept Architecture (D8)
RD11	0005-0012203369	1	Space Debris Deflection by Space Based Laser Study, Final Report (FR)
RD12		2	TAS Smart Telescope product

Table 2 : Reference documents list

1.4 Definition and Acronyms

Abbreviation	Meaning
A/M	Area over Mass ratio
CMG	Control Momentum Gyroscope
CW	Continuous Wave
FoR	Field of Regard
FoV	Field of View
HRI	High Resolution Imager
LMT	Laser Momentum Transfer
LRI	Low Resolution Imager
LTAN	Local Time of Ascending Node
LTI	Laser Tracking Imager
MCS	Mission Control Segment
OLaMoT	in Orbit Laser Momentum Transfer
PCM	Phase Change Materials
RAAN	Right Angle of Ascending Node
RW	Reaction Wheel
SA	Solar Array
SSO	Sun Synchronous Orbit
TAS	Thales Alenia Space
ToF	Time of Flight

Table 3 : Acronyms list

2. CONTEXT

The study takes place in the context of the space environment remediation. Space debris are becoming more and more critical and dangerous for the existing and future space missions, and solution have to be founded to ensure the space mission security and to clean space environement. Laser pressure solution are considered promising as only using momentum transfer to perform debris manoeuver to avoid collision. Therefore no additional debris is generated using this concept. The goal of the study has been to analyse the feasability of such Laser Momentum Transfer mission and to identify the associated performance and envisaged solution architecture.

3. ACTIVITIES

3.1 Laser Momentum Transfer Analysis

The goal of this task was to study laser-matter interaction and the resulting effects on the targeted debris attitude.
Literature review and physical analysis of the radiation pressure force have been done to identify the Laser Momentum Transfer (LMT) performance and the induced velocity change (Δv) on the targeted debris population.

3.1.1 Targeted Debris population

The first activity was to perform a review of the target debris population to highlight the main properties to be taken into account for the analyzed interaction.
The study was focused on 1cm to 10cm size debris as this corresponds to a large number of debris not easily monitored from ground due to the small size, but large enough to induce relevant damage to space mission in case of collision.
The following debris properties have been highlighted and taken into account as assumption for the LMT efficiency analyses :

- Material are mostly aluminum and plastics, but other metals, glass, carbon and painted surface have to be considered. Albedo values are then inhomogeneous from 0.1 up to 0.8.
- By definition, a debris is a or part of space mission and then could have a random shape and random attitude.
- Apparent Surface over Mass (A/m) ratio can vary in large range defined by the biggest surface of a thin plate of the lightest material and the smallest surface of a long bar of the weightiest material. This lead to consider a A/m ratio in the range 0.01-100m²/kg.

3.1.2 LMT

From debris population analysis presented above, it is very complex to defined precisely the impact of a laser illumination on all the potential debris. Therefore two proposed extreme cases have been identified in order to perform estimation of the LMT performance

- For darkest debris $\Delta v \approx A/m \times I \times \frac{\Delta t}{c}$;
- For brightest and reflective bodies $\Delta v \approx 2 \times A/m \times I \times \frac{\Delta t}{c}$;

With :

- Δv the induced velocity change;
- A the Apparent Surface of the Debris, as debris are not flat, and are mainly random shaped and have random attitude (constant but random), the apparent surface will change with the time and so an average over time of illumination have to be considered.
- m the debris mass;
- I the Laser Irradiance at debris position;
- Δt the laser illumination duration;
- c the speed of light;

The impact of the illumination will also depend of the relative direction with respect to the normal to the debris illuminated surface. Depending of the considered cases the resultant velocity change is oriented either in the same direction than the incident laser beam direction, or in the opposite direction to the normal to the surface.

Therefore the LMT efficiency can be evaluated as following, for an Irradiance of 1kW and an illumination duration of 10 seconds between $\Delta v \approx 3{,}3.10^{-7}$m/s and $\Delta v \approx 3{,}3.10^{-3}$m/s.
Which mean that with sufficient powerful illumination duration up to cm/s Δv should be achievable.

3.2 Mission Analysis

Purpose of this activity was to identify a destination orbit for a potential future mission to perform debris deflection by continuous wave (CW) laser illumination.

3.2.1 Debris population

As defined previously, the targeted debris population is 1cm to 10cm size range. 750-880km mean altitude range is presenting the highest debris density for this population.
Large part of these population present quasi circular orbit with very low eccentricity (near 0) and high inclination (70-110°). It is also important to highlight that the current analysis have not identified any specific distribution on RAAN of the analysed population. Therefore assumption has been made on an homogeneous distribution in RAAN.

3.2.2 Mission Orbit analysis

As the debris population is quite well distributed in term of inclination and RAAN, the foreseen mission, for debris deflection, orbit won’t be driven by this parameters. Therefore the orbit selection have been done considering the best condition to achieve the mission.
Two main aspects have been considered or the mission orbit determination :

- Power generation for optimizing mission duty cycle ;
- Debris detection capabilities.

3.2.2.1 Satellite Power generation

Satellite duty cycle is the percentage of time for which the satellite is able to perform space debris deflection (detection, tracking, illumination, monitoring). It mainly depends of the power generation capacity.
As presented before, in order to induce a relevant debris velocity change, the requested laser power shall be kW order of magnitude, considering a few tens of percentage for laser efficiency, it then requires satellite to be able to generate a few kW or tens of kW of electrical power. Orbit parameters shall be selected to ensure the best conditions to generate this amount of power. From this point the best configuration is to consider a 6h-18h Sun Synchronous Orbit (SSO) that will provide the highest satellite sun illumination all years during.

3.2.2.2 Debris Observation condition

Debris are non-collaborative object and so their attitude is not controlled. As orbited bodies, their orbit could be determined from observation and could be propagated with a limited accuracy. Therefore to target a debris it would have to be detected first. Active (light or radar) detection of debris will request a lot of resources due to the large distance and the small target size configurations. Therefore it is more realistic to consider passive detection as a first step.

This passive detection could only be performed if the debris emit or reflect some signal. As most of debris are passive ones, mainly for the targeted population, it is more sensitive to consider that the best way to detect a debris is to measure the sun light reflection on the debris.
Considering the previously defined 6h-18h SSO, it has been determined that the best debris observation conditions would be to have a relative Right Angle Ascending Node (RAAN), close to 0° ensuring the largest number of and longest observation opportunities.

3.2.3 Mission Orbit Definition

As debris are not all located on the same orbit, it implies that they will move with respect to others while time running. Therefore it is not relevant to consider a mission orbit adapted to one specific debris orbit. The envisaged induced Δv is limited and therefore the associated manoeuver is also limited. In order to envisage to perform the manoeuver with a collision avoidance objective, it shall be considered to be able to perform this manoeuver with sufficient time (at least a few days) prior the event. As collision risks are mainly raised around one week before the event, it means that the manoeuver shall be performed within 2 days following the alert to be efficient. To achieve this, the envisaged configuration is a 4 planes constellation of at least 2 satellites per plane, with two planes at 950 km altitude ensuring the high frequency revisit of below 800km altitude debris and the two other planes at 650km covering the orbits higher than 800km altitude. This configuration should limit the minimum distance between the satellites and any debris of the population, which allow to consider reasonable size for payload as it will be presented in section 3.3. The two orbital planes per altitude, de-phased by 180° in RAAN ensure an optimum conjunction with the debris to be seen in its own velocity vector direction, to optimize the LMT efficiency.

Therefore the foreseen configuration for the space segment for such debris deflection using continuous wave laser radiation pressure mission is summarized hereafter :

Number of satellites	**8 (2 per plane)**			
Altitudes	650km		950km	
Orbit	6-18h SSO	18-6h SSP	6-18h SSO	18-6hSSO

Table 4 : OLaMoT Mission orbits configuration

The 6-18h and 18-6h SSO configurations have been selected to optimise the power generation and the satellite-debris-sun angle, with the objective to enhance the mission efficiency.

3.3 Payload analysis

OLaMoT mission payload will have to ensure the 2 mains functions :

- Debris detection and tracking;
- Debris illumination ;

From the analysis performed in the frame ot eh OLaMoT study, it appears that these three functions can not be uncorellated and that function combination will have to be considered at instrument level.
The main challenge are the detection of such small debris population to be targeted.

3.3.1 Debris detection and Tracking

The first step for a LMT mission is to be able to detect the targeted population. The debris size ([1;10]cm) and properties (albedo, shape, material, spin) hardened the detection of the debris as the associated visual magnitude are be quite high ([14;18]M_v), requiring high sensitivity instrument. Medium class telescope (35cm main optic diameter) with high sensitivity detection area based on TAS smart-telescope [RD12]. The instrument will have to be mounted on 2 axis mechanisms to ensure agility without requiring platform pointing to scan space and to partially compensate debris speed for improving detection and tracking.

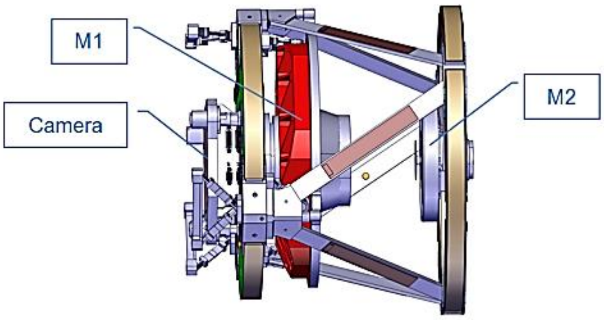


Figure 3-1 : TAS smart telescope fully adapted for such debris detection function, low resolution (LRI) and high resolution (HRI).

This first instrument (Low Resolution Imager, LRI), will ensure a detection of targeted debris with coarse accurracy. The main characteristics to be large FoV and agility for large FoR.

The fine direction determination will have to be ensured by a second instrument with reduced FoV, and higher sensitivity and higher frequency rate. This High Resolution Imager (HRI) is also based on a smart-telescope solution with high focal length and so reduced FoV. The HRI will be fine aligned with the main laser telescope to prepare the line of sight for to follow illumination. The HRI will be line of sight fixed and therefore will request satellite agility to reach the LRI determined debris direction.

3.3.2 Debris illumination

Once debris detected and tracked thanks to the combination of LRI, HRI and satellite agility, the main goal is to perfom laser illumination of the debris to induce a velocity change using the light radiation pressure and moment transfer.

The objective is then to be able to finely point the debris and to send as much as optical power on it. Therefore it is mandatory to avoid too large laser beam spot at debris position, which can be of hundreds of km. In order to achieve this, large optic telescope (>0,63m) is requested to limit the spot size and ensure the high Irradiance on targeted debris. Few kW of optical power are requested at instrument output to ensure a sensitive velocity change (few mm/s).

Fiber lasers technology is envisaged for this mission as well adapted for such application with high power .

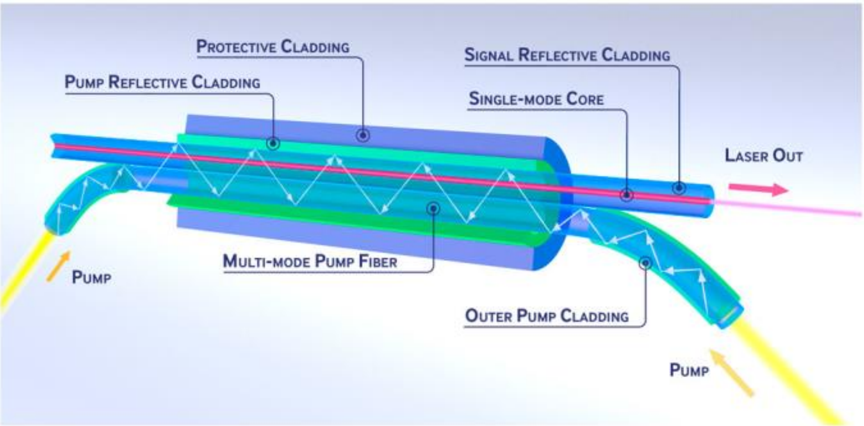


Figure 3-2 : Schematic of the multi-mode pumping of a fiber laser. The single-mode doped core is embedded in a multimode core for laser-diode pumping. The pump light partially overlaps with the signal core and is being absorbed

The laser telescope must be as simple as possible, the laser power is injected thanks to a fibre; the laser beam quality must be preserved do not impact the divergence. To ensure the high reflectivity and thermal resistance, Aluminium is foreseen for the mirrors materials. According to Thales experience, the telescope structure could be a combination of Carbon Fiber panels and Ceramic bars.

The pointing of the line of sight is performed using the HRI information with a limited accurracy. A finer pointing of the laser to enhance the debris illumination is performed using a piezo 2D-table to move the laser injection point to perform this high accurrate pointing.

3.4 Active Tracking

Once debris is illuminated by the CW laser, the retro-reflected light send back to the satellite will be collected by the HRI telescope and transmitted throught a dedicated optical path, using filter/dichroic, to a dedicated focal plane. A four quadrant high speed and high sensitivity detector is then used to detect any variation of the geometric distribution of the laser flux on the debris to correct the line of sight pointing. The Laser Tracking Imager (LTI) function goal is to ensure an optimum pointing towards the debris once illumination have started even in the case of loss of the passive detection (for instance due to increase of magnitude).

3.4.1 On-ground mechanisms.

Monitoring small speed variation of a debris from ground appears to be very challenging. First of all, the requested accurracy (few mm/s max) and the size of the debris will request high performance and by definition complex ground means (impacted by the atmospheric disturbance and large distance to cover). Furthermore the debris location during the LMT manoeuver can be positionned everywhere around the earth (within the targeted altitude range), and currently on-ground space environment surveillance means are not covering the entire space. Finally monitoring the debris later than the manoeuver will face two main issues, to clearly identify and monitor the targeted debris, and to discriminate the induced manoeuver from all other velocity change contributors. Indeed the atmospheric drag and sun radiation pressure, for instance, will modify the debris orbit and after a certain time it is not possible to predict precisely the impact. It has been preliminary conluded than on-ground mechanisms could be used as a support but not as the main means to perform the monitoring.

3.4.2 On-board mechanisms.

In space mechanisms will benefit for no atmospheric disturbance, and reduced distance from debris to be monitored.

Nevertheless external measurements will face the same issue than the on-ground mechanisms, which is the difficulty to detect and monitor the illuminated debris, mainly if the measurement is performed a time after the manoeuver.

Therefore the best considered approach is to be able to perform the monitoring from the same satellite that the one performing the LMT illumination.

This combination will ensure that the targeted debris is the one monitored. Furthermore several measurements will be performed prior during and after the illumination ensuring to discriminate the impact of the LMR with regards to the others velocity change contributors.

3.4.3 Monitoring payload

Most promising solution is to combine the moniroting function within (or next to) the main payload performing the detection, tracking, LMT illumination function.

Time of Flight (ToF) measurements between the emission of the signal by the satellite and the reception of the echo sent back by the debris is considered as the best concept to perform velocity change monitoring.

Principle is based on a high energy pulsed laser sent through the main CW laser telescope towards the target. The reflected light from the debris will be collected thanks to the HRI telescope, and using a different wavelength for the pulsed laser than for the continous one, can be extracted than to filtering and transmitted up to a Single photon Avanlanche Photo Diode (SPAD) to measure with the highest accarucy the time of reception of the echo.

3.5 Satellite analysis

The main challenge regarding the satellite architecture is to manage the demanding aspect of the payload :

- High power generation;
- High power dissipation;
- Agility and pointing accuracy;

The main payload will rely on a at least 4kW optical power laser. Considering the anticipated 40% efficiency, at least 10kW of electrical power will have to be generated and up to 6kW will have to be dissipated. Considering the envisaged reduced laser operating time due to collision avoidance manoeuver to be performed, we have estimated to less than 10% of time the satellite duty cycle. Indeed it has been analysed that considering the in orbit missions to be protected from debris collision, up to 24 manoeuvers per day and per chaser have to be performed with 8 satellites constellation. With up to 500 seconds of illumination, it would then lead to 10% of space debris deflection operations per day. Considering this duty cycle and the need for power generation coming from the plateform and other payload parts (HRI, LRI, Ranging), less than 2kW in average shall be generated, compatible with solar array are of 8m^2.

Heat rejection will be a big challenge as up to 6kW thermal power will be generated for a duration of a few hundreds of seconds. Such high power dissipation need would request only a limited radiator surface mainly due to the reduced duty cycle and so the reduced average value over time. Nevertheless Phase Change Materials (PCM) are considered to ensure to maintain an operational temperature of the payload as it would absorb energy dissipation peaks.

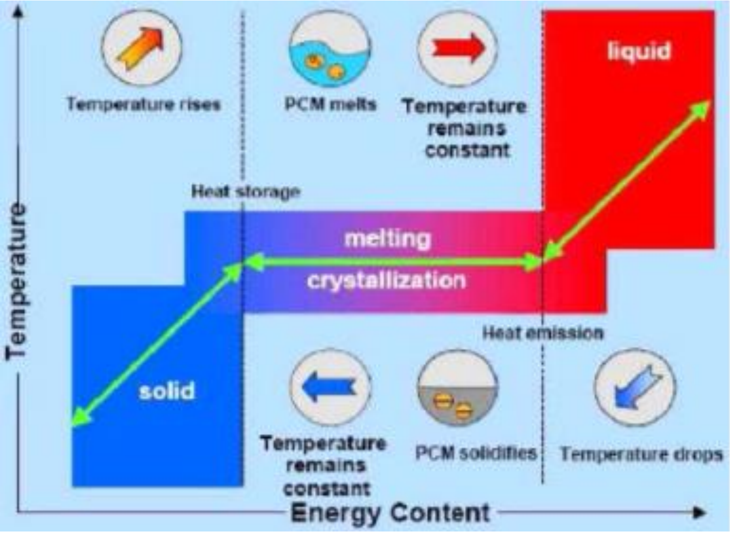


Figure 3-3 : PCM thermal behaviour

The platform will have to provide sufficient agility to ensure a coarse pointing towards and to follow the debris once coarse debris propagated orbit is determined by the LRI. Reaction Wheel (RW) or Control Momentum Gyroscope (CMG) are envisaged and will mainly depend of the demands of plateform agility, resulting of a refined mission analysis.

Due to size of the main telescope, it is preliminary relevant to consider that the satellite would be built around the main telescope . An envisaged configuration features 3 Solar Array (SA) wings with the objective to minimize satellite inertia and to improve agility. Preliminary mass budget lead to a satellite mass around 1.3T which may be compatible of a dual launch on VEGA-E.

3.6 Mission concept of operation

Two approches are considered for such debris deflection mission. Either the satellite is able to perform debris orbit propagation on-board and to estimate a risk of collision by it-self, or the risk of collision is determined by ground segment in a first step.
The final solution should be combination of both.
A chaser would have a determined instantaneous range of action, defined by the detection capability and the sizing of the illumination payload. Therefore a chaser would be able to interact with a limited number of debris in this action range. To enlarge this range, small manoeuver are envisaged, but it implies to have determined in advance the direction of the manoeuver.
Therefore the envisaged concept of operation would be to have a first detection of risk of collision from ground, with a debris orbit determination and propagation. This orbit propagation is then used to determined the best conjunction point between chaser and debris orbit to perform the debris deflection. If requested, limited manoeuvers are defined to optimise the conjunction. Once conjunction point is reached by the chaser, the satellite could perform passive observation with LRI to detect the debris and make an orbit verification to confirm the selection and tracking of the previously identified debris. Once confirmed the LMT manoeuver sequence and monitoring can be engaged. As the main goal of the mission is to avoid any

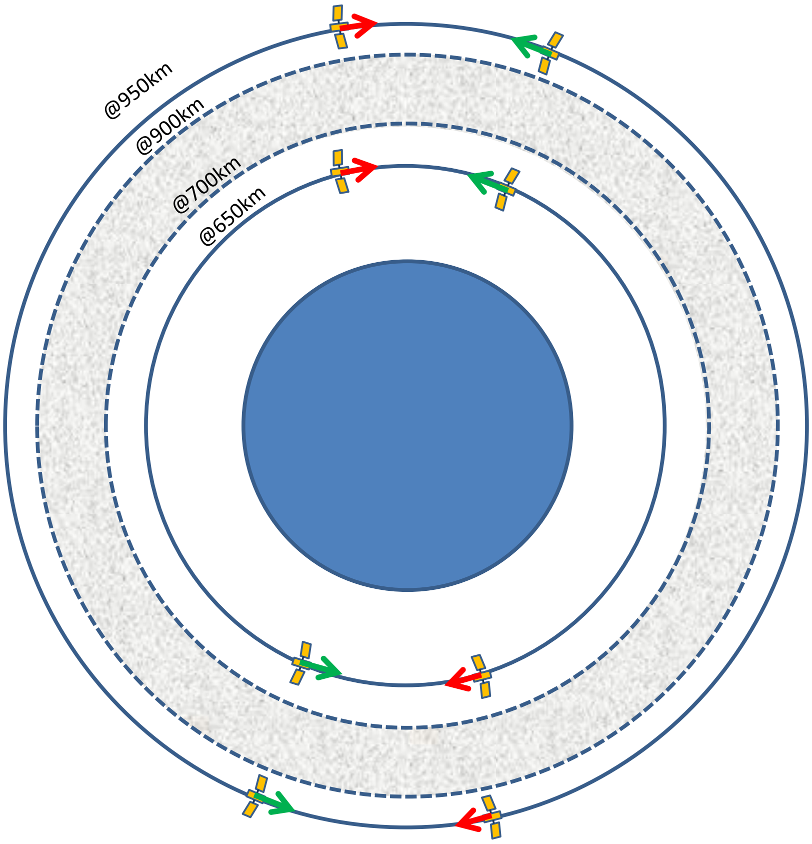
intrusive operation, there is no risk to damage any external mission in the case that the target is not the selected debris. With a certain level of coordination between space actors prior to the workplan defintion no further authorisation is needed for the satellite to operate. The satellite will perform debris position monitoring before during and after the illumination to detect debris response to illumination.

3.7 System Architecture

The previous section have presented the identified concept for a space debris deflection by space based laser mission.

Up to 8 satellites would be requested to ensure a high mission efficiency, which mean the capability to perform debris manoeuver whatever the initial debris and satellites configuration is. All the satellite will be based on the same architecture, build around a large telescope (>0,63m of diameter) used for Laser illumination. With the additionnal payloads for coarse debris detection and refined orbit detection, tracking and monitoring. These additionnal payloads will be based on small telescope (0,3m diameter) solution and high sensitivity detection chain.

The 8 satellites will be distributed on 4 SSO orbital planes, 6-18hour and 18-6hour and at aroudn 650km and aournd 950km altitude. Each orbital planes will have two satellites separated by 180° in mean anomaly.



4. WORKPLAN AND ROADMAPS

The study has identified some technological challenges to be managed to achieve the identified solution.
The core of the mission rely on a high power continous wave laser for space application. Fiber laser seems promising but further studies are requested to demonstrate the space environment compatibility for several kW optical output power laser with high efficiency.

Laser Momentum Transfer interaction have been preliminary analysed but additionnal study is requested to further determine the efficiency of such momentum transfer and to refine the need for ilumination power and duration.

Even if based on existing solution, the payload and satellite architecture would benefit of further analysis to enhance the mission performance and efficiency.
Detection, tracking and monitoring solution have to be further investigated and detailed architecture have to be analysed.
Power generation and thermal dissipation at platform level would request more detailled analysis to refine the solution.

Finaly, refined mission analysis with more detailled model would be the first step to assess the mission feasability and mission efficiency.

5. CONCLUSION

Space Debris Deflection by Space Based Laser (OLaMoT) study has allowed to demonstrate the feasability of such debris manoeuver mission using Laser Momentum transfer.

Few mm/s induced debris velocity change could be achieved thanks to high power (several kW) continuous wave laser, and would requested large class optics telescope for the illumination. Debris detection, tracking and monitoring of response to illumination, can be performed using concepts based on the TAS in-development Smart Telescope solution with adapted detection chains.

Futher analysis on technological solution and refined mission analysis are requested to assess the benefit of the mission and to trade-off the best configuration.

Demonstrator phase with reduced action range and efficiency would allow to consolidate the mission feasability and to refine the requirements.

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