FUTURE ORBITS OF SPACE DEBRIS AFTER LDR OPERATION

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ABSTRACT

The paper, in the first part, presents general information about the CLEANSPACE project including the main drivers and requirements. Overall CLEANSPACE objective is to define a global architecture (including surveillance, identification and tracking) for an innovative ground-based laser solution which can remove hazardous medium debris around selected space assets. The CLEANSPACE project is realized by an European consortium in the frame of the European Commission Seventh Framework Programme (FP7). The second contains estimations of velocity changes, perigee lowering and lifetime reducing for an exemplary objects for different parameters of the LDR system.

Key words: Laser Debris Removal, space debris orbital dynamics.

1. INTRODUCTION

A lot of technical studies are currently developing concepts of active removal of space debris to protect space assets from on orbit collision. For small objects, such concepts include the use of ground-based lasers to remove or reduce the momentum of the objects thereby lowering their orbit in order to facilitate their decay by re-entry into the Earth's atmosphere. The concept of the Laser Debris Removal (LDR) system is the main subject of the CLEANSPACE project which is realized by a European consortium in the frame of the European Commission Seventh Framework Programme (FP7), Space topic.

The use of sequence of laser operations to remove space debris, needs very precise predictions of future space debris orbital positions. Orbit determination, tracking (radar, optical and laser) and orbit prediction have to be performed with accuracy much better than so far. For that, the applied prediction tools have to take into account all perturbation factors which influence object orbit.

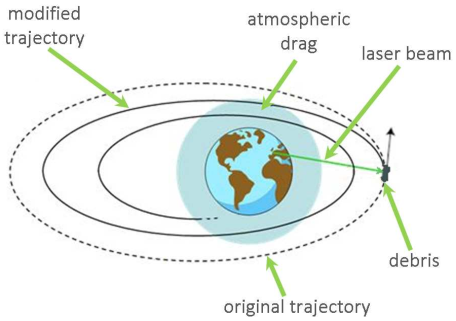

Figure 1. Trajectory lowering by the LDR operation.

The expected object's trajectory after the LDR operation is a lowering of its perigee as illustrated in the figure 1.

To prevent the debris with this new trajectory to collide with another object, a precise trajectory prediction after the LDR sequence is therefore the main task allowing also to estimate re-entry parameters.

The LDR laser pulses change the debris object velocity v. The future orbit and re-entry parameters of the space debris after the LDR engagement can be calculated if the resulting Δv vector is known with the sufficient accuracy. The value of the Δv may be estimated from the parameters of the LDR station and from the characteristics of the orbital debris. However, usually due to the poor knowledge of the debris object's size, mass, spin and chemical composition the value and the direction of the vector v cannot be estimated with the high accuracy. Therefore, a high precise tracking of the debris will be necessary immediately before the engagement of the LDR and also during this engagement. By extending this tracking and ranging for a few seconds after engagement, the necessary data to evaluate the orbital modification can be produced in the same way as it is done for the catalogue generation.

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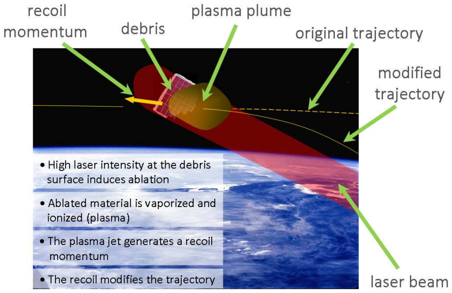

Figure 2. The LDR concept.

2. CLEANSPACE PROJECT

CLEANSPACE is a three year project which began on the 1st of June 2011 and its objectives are to define a global architecture for an innovative ground-based laser solution which can remove hazardous medium sized debris (from 1 cm to 10 cm). This approach is divided into four steps:

- to propose a global system architecture comprising survey, tracking, identification and debris treatment by the laser system in a way that is complement with the ESA Space Situational Awareness (SSA) program,
- to tackle safety regulation aspects, political implications and future collaborations,
- to develop affordable technological building blocks (with more effort on laser technology),
- to establish a roadmap for the development and the implementation of a fully functional laser debris removal system.

The CLEANSPACE concept will allow both for changing the orbit of a piece of debris, thereby avoiding a predicted collision with valuable space infrastructure, and ultimately the removal of the debris as its new course takes it on a trajectory to atmospheric re-entry. The LDR concept is based on the ablation process induced by a high laser intensity beam, creating a plasma plume which generates a recoil momentum that modifies the debris trajectory as illustrated in the figure below:

2.1. Global architecture

The first high level requirements for such laser-based space debris removal system have been deduced. These requirements are based on the current situation concerning space debris regulations, the actual and predicted debris population, the hazard potential of space debris and the actual monitoring techniques and networks. They are divided by the 3 phases:

- Space Situation Awareness, Space traffic management functions,
- Fine tracking functions and debris identification,
- Laser debris treatment function.

The operational concept of a de-orbitation sequence activated in the case of a collision risk has been presented. The different functions which have to be managed during the sequence and their relationships are resulting from this concept of operations. It will be developed in chapter 3. Global laser system architecture has been strengthened by defining the:

- necessary functions and associated components (hardware and software),
- engagement laser system to protect space assets through de-orbitation or modification of the debris orbit based on analysis of the laser debris removal operational sequence and modelling of the de-orbitation process.

2.2. Safety regulation

The recommendations and regulations of the International Civil Aviation Organization (ICAO), a sub-entity of the United Nations Organization, the United States of America, France and Germany have been investigated. The conclusions based on this analysis are the following:

- The usage of lasers in navigable airspace is possible, however, official permission and observations of that airspace is required due to air safety reasons. In Europe, the air traffic services have to be included in the observation process.
- Laser Debris Removal (LDR) stations have to be located far away from airports and air routes.
- The standards concerning laser used in public lightshows can serve as an orientation for Cleanspace. In this case, safety distances for the public have to be observed.

However, there is no uniform formal approval process, giving a laser operator the right to use lasers after certain legal requirements have been fulfilled. This causes the necessity to seek for a new and appropriate legislation for those countries in which LDR will most likely take place, which will give the operators the permission to operate the LDR lasers in navigable airspace once a set of clearly defined legal regulations have been fulfilled.

2.3. High energy laser technology

The main laser parameters required for the CLEANSPACE project are:

Energy per pulse:	$>$ 10 kJ
Repetition rate:	$>$ 10 Hz,
Pulse length	1 ns $< \tau <$ 50 ns
Beam quality:	M2 $<$ 2.5
Engagement time:	300-500 s
Intensity at the target:	0.1 0.8 GW/cm2 at the surface of the debris

A modeling and simulation phase on laser concepts has been addressed at the beginning of the “High energy laser technology” task. Two laser concepts have been initially proposed. After a risk analysis a third architecture based on actively coherently coupled laser amplifiers has been deduced as the reference laser configuration.

3. MODELING OF THE DESORBITATION PROCESS

The mechanical impulse generated by a laser pulse has many applications and has been widely studied. It is given by [1]:

$$\Delta v = W \cdot \frac{C_m}{M} \tag{1}$$

where W is the energy collected by the object [J],
C_m is the coupling coefficient [dyne.s/J],
M is the mass of the object [kg]

3.1. Coupling coefficient

The coupling coefficient describes the efficiency with which incident laser pulse energy is converted into kinetic energy. Rigorously, it is the ratio of the laser ablation impulse density to the incident laser pulse fluence. It is therefore dependant of the power density of the incident laser beam [2]. According to [3], two different regimes can be identified, corresponding to the vapour and the plasma phase. Therefore, both processes have to be taken into account in order to model the coupling coefficient, which can be expressed as:

$$C_m = \eta_i \cdot C_{mp} + (1 - \eta_i) \cdot C_{m\nu} \tag{2}$$

where:

η_i is the ionization fraction;
C_{mp} is the coupling coefficient for the plasma regime;
$C_{m\nu}$ is the coupling coefficient for the vapour regime.

In this study, the coupling coefficient is modelled as a function of the laser parameters (defined in 2) and the material properties (density, absorption coefficient and atomic number). Aluminium and graphite have been considered, because those materials are supposed to be representative case of the envelope of the possibilities for the majority of the space debris population. For Aluminium, the optimal power density is between 0.5 and 0.8 GW/cm^2 at 1.06 μm. For Graphite, the optimal power density is between 0.1 and 0.2 GW/cm^2 at 1.06μm.

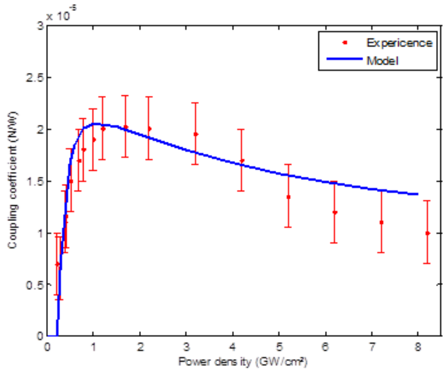

Figure 3. Coupling coefficient of aluminium object, for a laser pulse width of 27 ns at 1.06 m experimentally measured at EADS and modelled according to equation (2)

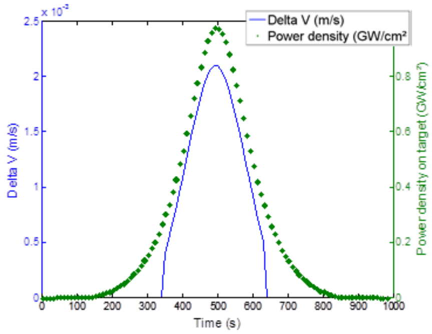

Figure 4. Modelling of the Δv per pulse and of the power density on target as a function of time, for a 10 cm aluminium object at 800 km

3.2. Power density at the debris

The power density at the debris W can be written as:

$$W = \int\int_{\text{Surface Debris}} I_{\text{FarField}}(x, y) dxdy \tag{3}$$

where $I_{\text{FarField}}(x, y, z)$ is the intensity distribution of the laser spot at the level of the debris.

We assume that the propagation of the laser beam is described by the Gaussian beam theory, which is a good approximation at far field for most of the cavity modes. The general expression of a Gaussian beam is:

$$I(x, y, R) = \frac{2I_0 \cdot T_{Atm}(\Theta_Z)\cdot}{\pi\omega(R)^2} \cdot \exp\left[-2\frac{x^2 + y^2}{\omega(R)^2}\right] \tag{4}$$

where:

I_0 is the total energy per pulse at the exit of the telescope

T_{Atm} is the atmospheric transmission.Its variation as a function of the elevation angle;

Θ_Z is estimated by using Fascode software for standard atmospheric conditions.

$\omega(R)$ is the width of the laser beam at $1/e^2$, as a function of the range R. It is estimated by taking into account the influence of the atmosphere, the divergence of the laser beam, the tracking error of the telescope and the performances of the adaptive optics system.

Finally, the expression of the specific impulse Δv as a function of the station parameters is modelled by using equations (1) to (4). An example is shown on figure 4, for a 10 cm aluminium object at 800 km and for the laser parameters defined in 2.2. The effect of the vaporization threshold on the Δv is clearly identifiable.

4. ORBIT CHANGE DUE TO LDR OPERATION

The result of the velocity change due to laser beam is the change of debris object's orbit. If the vector $\vec{\Delta v}$ is known, the new orbital elements may by calculated. Therefore the orbit evolution of the object in the time span of LDR action during a given pass over a given laser station is determined by modeling calculations.

In the next sections we present results of calculations of orbit changes during the LDR operation and the object's orbit evolution after the LDR for one pass of an exemplary space debris objects:

Satellite Catalog number:	4877, 1970-025FC Thorad Agenda D deb
Epoch of elements:	JD 2453373.3733 (2 Jan. 2005)
Orbital elements:	
a	7055 km
e	0.0036
I	99.68°
pq (perigee altitude)	652km
Area to mass for the object:	$S/m = 0.28$
Laser station No.	7835 (Grasse, France)
Date of pass:	5 Jan. 2005 1h 34m

The adopted LDR parameters:

The laser energy	$E_0 = 10kJ$ and $E_0 = 25kJ$
The laser repetition rate	$R = 5Hz$ and $R = 10Hz$
Transmiting telescope diameter:	$D = 4m$ and $D = 8m$

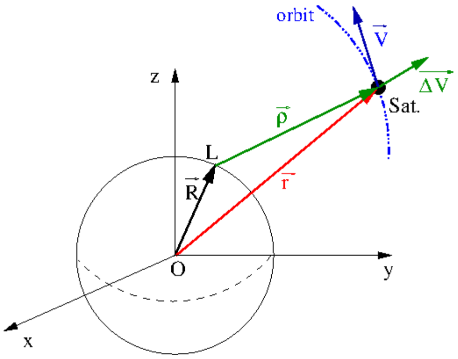

Figure 5. Laser beam, $\vec{\Delta v}$ vector and orbital velocity $\vec{v}$ geometry

The value of the area to mass parameter ($S/m = 0.28$) for the object was estimated on the basis of historical orbital data taken from the NORAD Satellite Catalog.

All calculations were performed with the use of the orbital software developed in the Astronomical Observatory of the A.Mickiewicz University, Poznan, Poland.

4.1. Velocity vector change

The equation (1) determines only the value of the vector $\vec{\Delta v}$ after single laser beam operation: $\Delta v = |\vec{\Delta v}|$. The direction of this vector depends of many factors, including shape and composition of the space debris object. In our estimations presented in this paper we assumed the $\vec{\Delta v}$ direction along the laser beam, i.e. in the direction of the vector $\vec{\rho}$ (Fig.5):

$$\vec{\Delta v}^H = \frac{\vec{\rho}}{\rho}\Delta v. \qquad (5)$$

The resulting velocity vector $\vec{v_a}$ of the space debris object after single laser beam action is:

$$\vec{v_a} = \vec{v_b} + \vec{\Delta v}^H, \qquad (6)$$

where $\vec{v_b}$ is the velocity before the laser action. The object's velocity $\vec{v}$ is given in the same frame in which the object's orbit is determined, i.e. in the inertial geocentric reference frame (IGF) with the Earth's equator as the fundamental plane and the vernal equinox as the principal direction. On the other hand the vector$\vec{\Delta v}$ is given in the local horizontal frame (LHF) rotating with the Earth

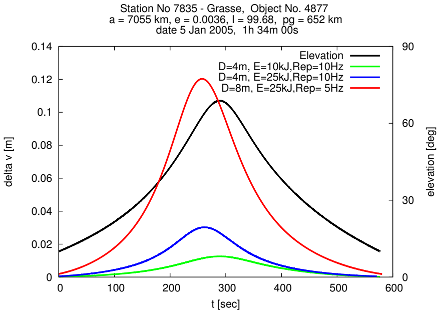

Figure 6. The Δv per pulse for different parameters of LDR

in the IGF. Therefore, the $\Delta\vec{v}^H$ vector has to be transformed to the IGF:

$$\Delta\vec{v}^H \rightarrow \Delta\vec{v}^G \tag{7}$$

by appling two rotations: by $(\varphi - \frac{\pi}{2})$ about the y axis and by $(\Theta + \lambda)$ about the z axis, where φ and λ are geodetic coordinates of the laser station and Θ is the sidereal time.

Figure 6 presents changes of the $|\vec{\Delta} v^G|$ during one pass of the object No. 4877 above the laser station Grasse for different parameters of the LDR: the transmiting telescope diameter D (4 and 8 meters), the laser energy E_0 (10 and 25 kJ) and the laser repetition rate$R$ (5 and 10 Hz). It is clearly seen that the value of Δv^G strongly depends on the laser and transmiting telescope parameters.

4.2. Orbit change

After each laser beam operation, the new velocity vector $\vec{v_a}$ is determined:

$$\vec{v_a} = \vec{v_b} + \Delta\vec{v}^G, \tag{8}$$

and next the osculating orbital elements are calculated from the the vectors $\vec{r}$ and $\vec{v_a}$:

$$(\vec{r}, \vec{v_a}) \rightarrow (a, e, I, \omega, \Omega, M_0)^{osc}. \tag{9}$$

The position vector $\vec{r}$ and the velocity vector $\vec{v}_b$ for the time of the laser beam operation (in fact for the time just before the operation) are known from precise orbit prediction.

Figures 7 and 8 show changes of the semi-major axis and the eccentricity respectively for the exemplary pass.

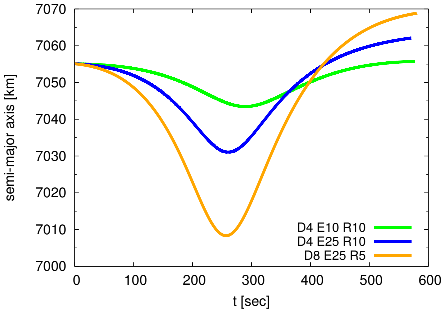

Figure 7. Changes of the object's semi-major axis during one pass

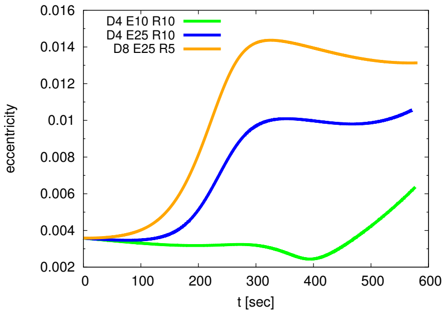

Figure 8. Changes of the object's eccentricity during one pass

4.3. Perigee lowering

Each laser beam acting on the space debris object changes the object's orbit,i.e. all six orbital elements. Since the aim of our project is the lowering of the space debris object orbit, we are mostly interested in lowering of the perigee altitude and apogee altitude:

$$\begin{aligned} pq &= a(1-e) - a_e, \\ aq &= a(1+e) - a_e, \end{aligned} \tag{10}$$

where a_e is the Earth's radius.

We calculated changes of perigee after LDR actions for different space debris objects taking into account different parameters of the LDR operations. Here we present results of our calculations for one pass of the object No.

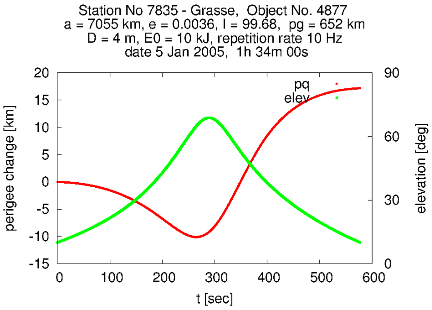

Figure 9. Changes of the object's elevation and perigee altitude during one pass

4877 for the Grasse station. Figures 9 - 11 show changes of the object's elevation and the perigee altitude for different parameters of the laser and the transmiting telescope. For this pass, generally, the perigee altitude decreasec as the elevation increases and the perigee altitude increases as the elevation decreases, but it is not a rule. For other passes of this object and the same laser station the situation may be quite different. The perigee altitude lowering strongly depend on the laser energy, the telescope diameter and the pulse repetition rate. The result of LDR action also strongly depends on the area to mass ratio S/m of the object. For the object 4877 we adopted the value of this parameter equal to 0.28. Our calculations show that for $S/m = 0.028$ the perigee altitude lowering is about 10 times smaller for the same LDR parameters.

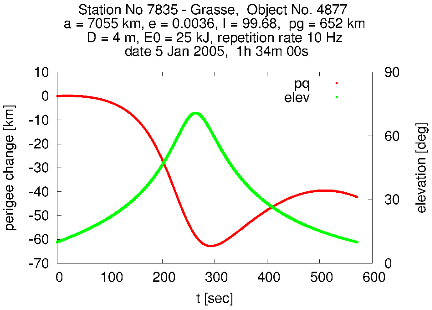

Figure 10. Changes of the object's elevation and perigee altitude during one pass

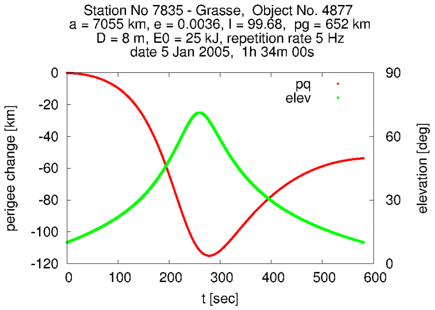

Figure 11. Changes of the object's elevation and perigee altitude during one pass

5. ORBIT AFTER LDR OPERATION

The orbital elements after LDR operation may by only estimated on the basis of the predicted $\vec{\Delta v}$ vector. Precise determination of the object's orbit require continuous tracking during and after the LDR operations. Taking into account new tracking data, the new osculating orbital elements have to be determined.

5.1. Orbit modeling after LDR

If the new osculating elements are known for a new epoch, it is possible to predict the future orbit. The precise prediction of the object's trajectory is very important for prediction of close approaches of the object and potential a space assets. It is also important for prediction of the re-entry time of the object into the low atmosphere. The precise trajectory prediction needs the software prediction tool that takes into account the perturbing force model on a very high level of accuracy.

The results presented in this section were obtained with the prediction tool developed in the Poznan Astronomical Observatory [4, 5, 6, 7, 8, 9] . This tool includes the following force model: geopotential up to the arbitrary high order and degree, luni-solar perturbations with the Sun and the Moon positions form JPL ephemeris, solar radiation pressure and atmospheric drag with best possible dynamical atmospheric model.

Figure 12 presents the evolution of the semi-major axis of the object 4877 from the epoch just after the LDR action up to the reentry in the atmosphere in comparison with the values of the semi-major axis in the case of no LDR as well as the values of the semi-major axis taken form the Satellite Catalog. The initial epoch and values of initial orbital elements are taken for the time of maximum

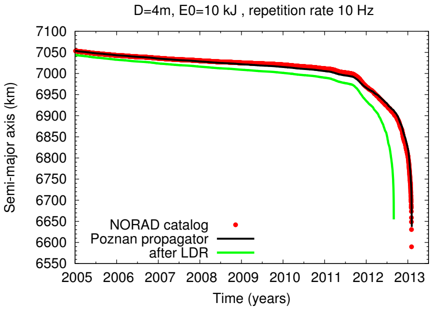

Figure 12. Semi-major axis evolution after LDR operation in comparison with the the evolution without the LDR.

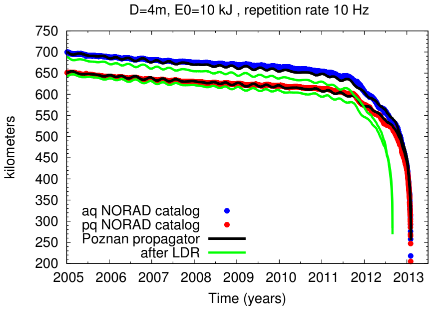

Figure 13. Perigee and apogee altitude evolution after LDR operation in comparison with the the evolution without the LDR.

perigee lowering, that means we assumed that the LDR action has been stoped when the perigee started increase.

Figure 13 shows the similar evolution for the perigee and the apogee altitudes.

The results presented on this figure has been obtained for the telescope diameter 4 meters, the laser energy 10kJ and the repetition rate 10 Hz.

The evolution af the semi-major axis for different combinations of the LDR system is given on the Fig 14. The similar evolution for the perigee altitudes are on the Fig. 15.

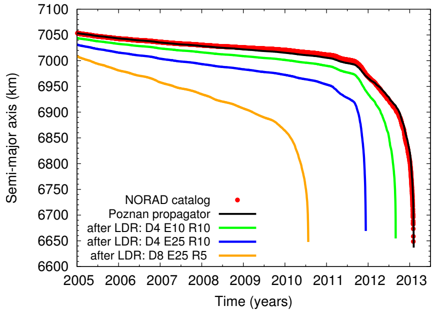

Figure 14. The evolution af the semi-major axis for different combinations of the LDR system.

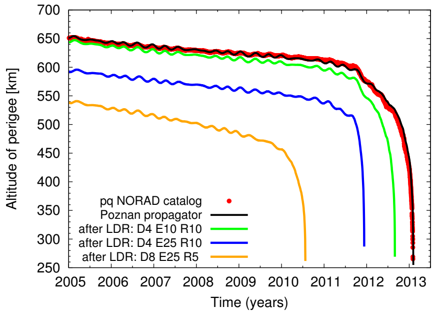

Figure 15. The evolution af the perigee altitudes for different combinations of the LDR system

5.2. Lifetime prediction

Results of calculations presented in the previous sections show consecquences of LDR engagement. Even after LDR operation during one pass (in practice a part of one pass) the object' trajectory may be changed significantly. The perigee lowering may reach a level of 100 km or even more, and the lifetime of the object may be reduced by several hundreds of days. The effectiveness of this proces significantly depends on the LDR system parameters and on the object parameters, in particular on area to mass ratio. Table 1 contains values of perigee altitude lowering (dpg), the lifetime and changes in the lifetime (dt) due to LDR for the object 4877 and different parameters of the LDR system.

Table 1. Perigee lowering and lifetime change due to LDR

	dpq[km]	lifetime [days]	dt [days]
NORAD		2954	
Poznan prop.		2954	
D4 E10 R10	- 11	2799	- 155
D4 E25 R10	- 58	2536	- 418
D8 E25 R5	- 112	2032	- 922

6. CONCLUSIONS

In the frame of CLEANSPACE project, the concept of protection of space assets against collision by small and medium size debris by a ground based laser system has been validated and a preliminary architecture has been proposed including crucial points like laser safety and the necessity to have international authority to ensure safe operations.

The second part of this paper demonstrates the interest of of ground based laser system to modify the LEO orbit of hazardous objects and then protect specific space assets and at long term to reduce the time life of the debris in orbit.

Orbit prediction results on the influence of the velocity change due to Laser Debris Removal engagement is performed for one debris and different combinations of LDR characteristics.

The perigee lowering is estimated and the associated lifetime reduction evaluated to a gain from half a year to 3 years. All these calculations performed with software developed by the Astronomical Observatory of the A.Mickiewicz University show the potential interest of this challenging concept. Some additional calculations should have to be performed about multiple pass effect (lifetime reduction as a function of number of engagement). The last year of the CLEANSPACE project will be devoted to roadmap elaboration for the future.

7. ACKNOWLEDGMENTS

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- Universit Claude Bernard Lyon 1 (UCBL), VILLEURBANNE, France,
- Institute of Low Temperature and Structure Research (ILT and SR), Wroclaw, Poland,
- Adam Mickiewicz University, Astronomical Observatory (AMU), Poznan, Poland,
- Astri-Polska Sp. z.o.o.(ASTRIPL), Warszawa, Poland,
- Universit de Limoges (UNILIM), Limoges, France.

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