CHANGES OF SPACE DEBRIS ORBITS 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 part contains exemplary results of the objects orbit changes due to the Laser Debris Removal (LDR) operation for different locations of the LDR station and different parameters of the laser energy and telescope diameter. The future orbit and re-entry parameters are estimated taking into account the influence of all important perturbation factors on the space debris orbital motion after the LDR action.

Key words: Laser Debris Removal, space debris orbital dynamics, re-entry of space debris.

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.

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 $\vec{v}$. The future orbit and re-entry parameters of the space debris after the LDR engagement can be calculated if the resulting $\vec{\Delta v}$ vector is known with the sufficient accuracy. The value of the $\vec{\Delta v}$ 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 $\vec{v}$ 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. 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.

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).

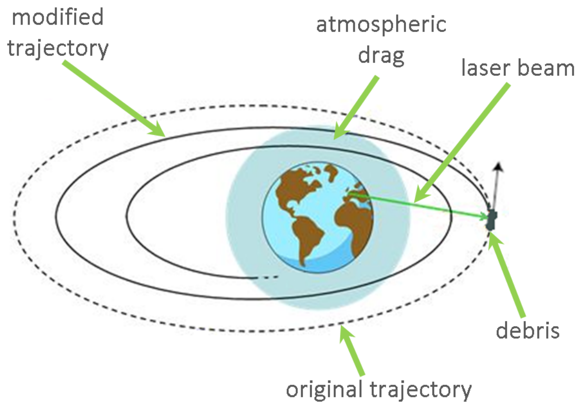


Figure 1. Trajectory lowering by the LDR operation.

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 2.

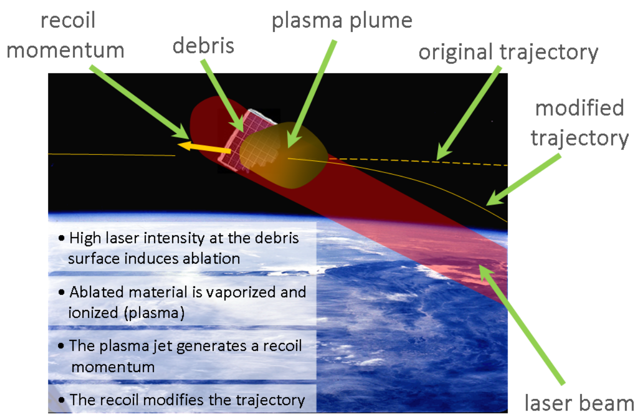


Figure 2. The LDR concept.

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. 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 use 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:	100-600 s
Intensity at the target:	0.1 - 0.8 GW/cm2 at the surface of the debris

A modelling 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. MODELLING OF THE DEORBITATION PROCESS

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

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

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:

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

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.

C_{mp} is given by [3]:

$$C_{mp} = 5.83\psi \left(I\lambda\sqrt{\tau}\right)^{1/4}, \tag{3}$$

where: C_{mp} is the laser/matter coupling coefficient [*dyne* s/J],
I is the laser intensity [W/m^2],
τ is the pulse duration [s],
λ is the wavelength of the laser [m],
ψ depends on the material:

$$\psi = \left[\frac{A}{2}\left(Z^2(Z+1)^{-1/3}\right)\right]^{9/16} A^{-1/8},$$

with Z the average state of the laser-produced plasma, and
A the atomic mass of the target.

C_{mv} is given by:

$$C_{mv} = \sqrt{\frac{2\rho C^2}{\alpha\Phi_0}\frac{\xi - 1}{\xi^2}\ln\xi}, \tag{4}$$

where: $\xi = C\,\Phi/\Phi_0$,
Φ_0 is the critical threshold fluence for vaporization of the target [J/m^2],
Φ is the fluence [J/m^2],
C is a parameter indicating multiplicative energy losses (reflectivity, divergence effects, etc),
ρ is the density of the target [kg/m^3],
α is the absorption coefficient.

Aluminium has been considered in this study, because this material is representative of the composition of 80% of the space debris population [4]. In addition, the vaporization threshold of Aluminum is quite high (0.2 GW/cm^2), so this material can be considered as a dimensioning case.

The variation of the coupling coefficient as a function of the intensity is shown on Figure 3. The model correctly fits the experimental measurements for intensities lower than 3 GW/cm^2. We can note that the optimal power density is between 0.5 and 0.8 GW/cm^2 at 1.06 μm.

3.2. Power density at the debris

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

$$W = \int\int_{\text{Surface Debris}} I_{\text{FarField}}\,(x, y)dxdy, \tag{5}$$

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:

$$I(x, y, R) = \frac{2I_0 T_{Atm}(\psi_Z)}{\pi\omega R^2} \exp\left[-2\frac{x^2 + y^2}{\omega R^2}\right], \tag{6}$$

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 ψ_Z, is estimated by using the Rozenberg model, which takes into account the mass of air X crossed by the laser beam:

$$T_{Atm} = (1 - A_{Atm})^X\,, \tag{7}$$

with

$$\begin{aligned} A_{Atm} &= 0.18\,\text{at}\,1.06\mu m,\;\; \text{for standard visibilities conditions}\,, \\ X &= \frac{1}{\cos\psi_Z + 0.025\exp\left(-11\cos\psi_Z\right)}, \\ \psi_Z &\;\; \text{the elevation angle.} \end{aligned}$$

$\omega(R)$ 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:

$$\omega(R)^2 \approx (2M_q^2 D(R/k))^2 + (D/2)^2(1 - R/f)^2 + \langle\rho_{\text{Turbulences}}\rangle^2 + \langle\rho_{\text{Tracking}}\rangle^2, \tag{8}$$

with

M_q the quality factor of the laser beam,
D the diameter of the emitting telescope,
f the focal of the emitting telescope,
k the wavenumber of the laser beam,
$\rho_{\text{Turbulences}}$ the mean broadening of the laser spot due to the atmospheric fluctuations, partly corrected by the adaptive optics system, and
ρ_{Tracking} the mean broadening of the laser spot due to the tracking error of the system.

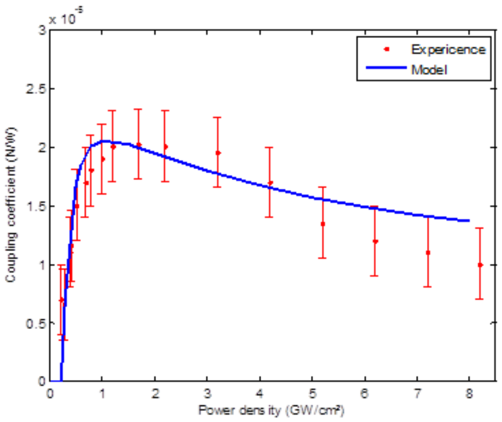


Figure 3. Coupling coefficient of aluminium object, for a laser pulse width of 27 ns at 1.06 m experimentally measured at EADS and modelled according to equation (2)

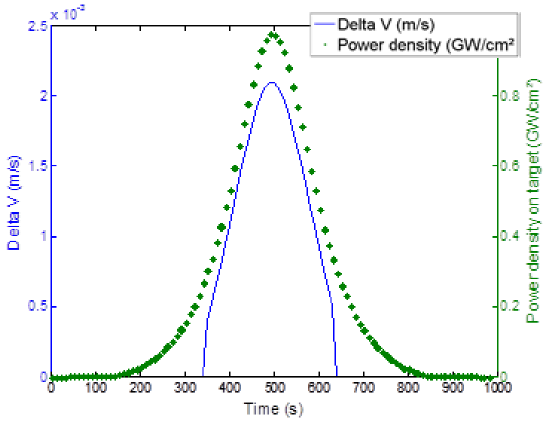


Figure 4. Modelling of the Δv per pulse and of the power density on target as a function of time, for a 10 cm aluminium object at 800 km

3.3. Estimated formulas for Δv

The specific impulse Δv is calculated by implementing a condition on the value of the power density on target, in order to model the vaporization threshold of the material P_0. For Aluminum, P_0 is equal to $2.10^{12} W/cm^2$.

If $W_{Deb} < P_0$ then $\Delta v = 0$,

if $W_{Deb} > P_0$ then

$$\Delta v = \left[\frac{E_0 T_{Tel} T_{atm}}{\pi \omega(R)^2} \right] \frac{S}{M} C_m, \tag{9}$$

with $-E_0$ the energy per pulse delivered by the laser source,
$-T_{Tel}$ the transmission of the emitting telescope,
$-\omega(R)$ the width of the laser beam, given by the equation (8),
$-R$ the range, deduced from the orbital parameters of the space debris, the location of the LDR station and the epoch time,
$-T_{atm}$ the atmospheric transmission as a function of the elevation angle,
$-S/M$ the area to mass ratio of the considered debris,
$-C_m$ the coupling coefficient, given by the equations (2), (3) and (4).

An example is shown on figure 4, for a 10 cm aluminium object at 800 km and for the laser parameters defined in 2.3. 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 the LDR action during a given pass over a given laser station is determined by modelling 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 and a series of passes of an exemplary space debris objects and different the LDR station location (Table 1 and Table 2).

Table 1. LDR stations

	λ [deg.]	ϕ [deg.]	H [m]
Grasse	6.92	43.75	1314
KLMS	-2.27	74.23	498
Kourou	-52.64	5.99	0

Table 2. Orbital parameters of exemplary debris objects

NORAD Number	a [km]	e	I[deg.]	S/M
4877	7055	0.0036	99.7	0.279
27137	6952	0.0024	97.6	0.107
35017	7013	0.0162	73.9	0.202

The values of the area to mass S/M parameter for the objects were 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 equations (1) and (9) determine 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 $\vec{R}$ (Fig.5):

$$\Delta \vec{v}^H = \frac{\vec{R}}{R} \Delta v. \tag{10}$$

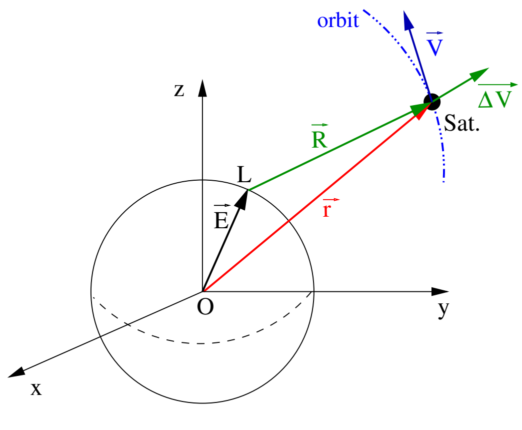
The resulting velocity vector $\vec{v_a}$ of the space debris object after single laser beam action is:

$$\vec{v_a} = \vec{v_b} + \Delta \vec{v}^H, \tag{11}$$

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

Table 3. The adopted LDR station parameters

No.	Laser energy [kJ]	Laser repetition rate [Hz]	Telescope diameter [m]
1	10	10	4
2	10	10	6
3	10	10	8
4	25	10	4
5	25	10	6
6	25	10	8



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

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

$$\Delta\vec{v}^H \rightarrow \Delta\vec{v}^G \tag{12}$$

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 values of the coupling coefficient and figure 7 presents changes of the $|\vec{\Delta} v^G|$ during one pass of the object No. 27137 above the LDR station located in Kourou for different parameters of the LDR (Table 3): the transmitting telescope diameter D (4 and 8 meters), the laser energy E_0 (10 and 25 kJ) and the laser repetition rate R 10 Hz. It is clearly seen that the value of Δv^G strongly depends on the laser and emitting telescope parameters.

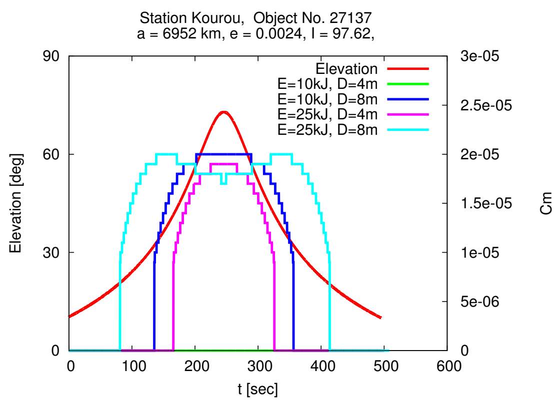


Figure 6. Values of coupling coefficient C_m for different LDR station parameters

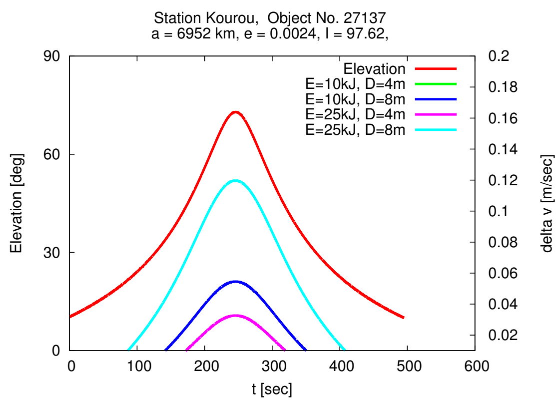


Figure 7. The Δv per pulse for different parameters of LDR station parameters

4.2. Orbit change

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

$$\vec{v_a} = \vec{v_b} + \Delta\vec{v}^G, \tag{13}$$

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

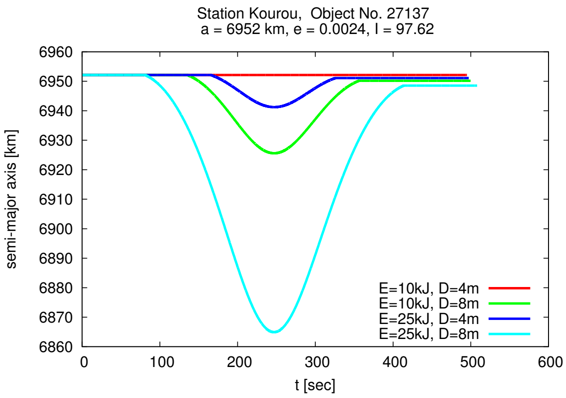


Figure 8. Changes of the semi-major axis after the LDR action for one pass and for different LDR station parameters

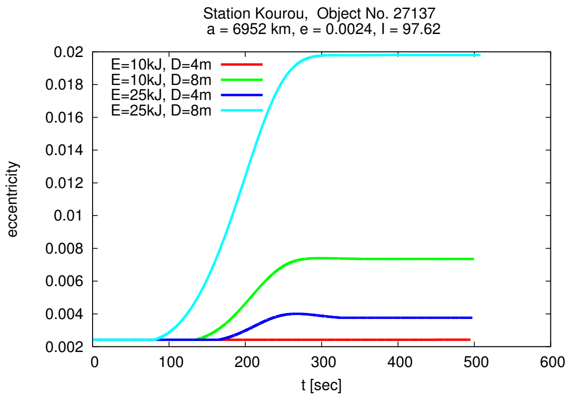


Figure 9. Changes of the eccentricity after the LDR action for one pass and for different LDR station parameters

$$(\vec{r}, \vec{v_a}) \rightarrow (a, e, I, \omega, \Omega, M_0)^{osc}. \tag{14}$$

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 8 and 9 show changes of the semi-major axis and the eccentricity respectively for the exemplary 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:

$$\begin{aligned} pq &= a(1-e) - a_e, \\ aq &= a(1+e) - a_e, \end{aligned} \tag{15}$$

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 a given debris object ("one pass LDR option") and for a series of passes ("multi pass LDR option").

4.3.1. One pass LDR option

The strategy of the "one pass LDR option" assumes the LDR engagement only during one pass for a given debris object. As the result the object's trajectory is changes, the perigee altitude may be lowered and the object's lifetime may be reduced.

Here we present results of our calculations for one pass of the object No. 4877 for the Grasse station. Figure 10 shows changes of the object's elevation and the perigee altitude for different parameters of the laser and the emitting telescope. For this pass, generally, the perigee altitude decreases 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 depends 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

Table 4. Perigee lowering and lifetime change due to LDR: object No. 4877, station Grasse

	dpq[km]	lifetime [days]	dt [days]
NORAD		2954	
Poznan prop.		2954	
D4 E10 R10	0	2954	0
D4 E25 R10	- 11	2792	- 162
D6 E10 R10	- 4	2860	- 96
D6 E25 R10	- 154	810	- 2144
D8 E10 R10	- 81	2410	- 544
D8 E25 R10	-379	15	- 2939

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.

Presented results of calculations show consequences of LDR engagement. Even after LDR operation during one pass (in practice a part of one pass), the object's trajectory may be changed significantly. The perigee lowering may reach a level of 100-200 km or even more, and the lifetime of the object may be reduced by several hundreds of days. The effectiveness of this process significantly depends on the LDR system parameters and on the object parameters, in particular on area to mass ratio.

Figure 11 presents the evolution of the perigee altitude of the object 4877 from the epoch just after the LDR action up to the re-entry in the atmosphere in comparison with the values of the perigee altitude in the case of no LDR as well as the values taken form the Satellite Catalogue. The initial epoch and values of initial orbital elements are taken for the time epoch of maximum perigee lowering, that means we assumed that the LDR action has been stopped when the perigee started increase.

Table 4 contains values of perigee altitude lowering (dpq), the lifetime and changes in the lifetime (dt) due to LDR for the object 4877 and different parameters of the LDR system.

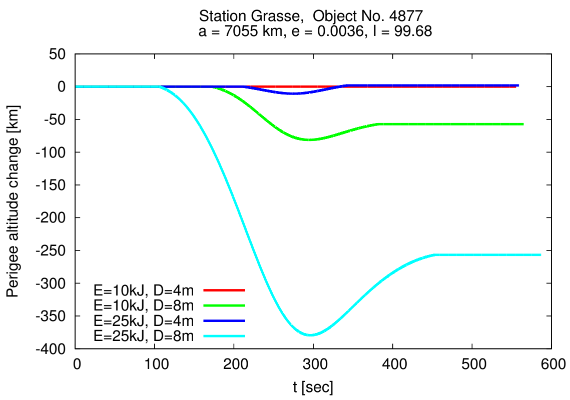


Figure 10. Perigee altitude changes during one pass for different LDR station parameters. The LDR engagement during the whole pass.

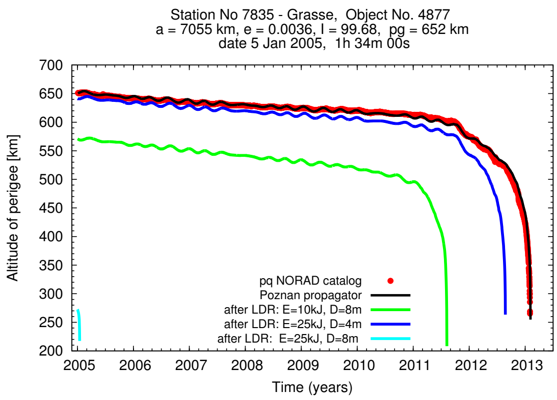


Figure 11. Evolution of the perigee altitude after LDR operation in comparison with the perigee altitude evolution without LDR and with Satellite Catalog data.

4.3.2. Multi pass LDR option

The strategy of the LDR operations in the case of "multi pass LDR option" assumes the LDR engagement for a given debris object during a series of passes from the same LDR station.The LDR operations are continued up to re-entry of the object into atmosphere. In our simulations of this process we stopped when the perigee altitude reaches 150 km. Figures

14-17 and tables 5 and 6 present results of multi pass LDR strategy for two exemplary debris objects, different locations of the LDR stations and different parameters taking into account both day and night passes. These results show that the LDR technique may be effective for removing of a number of small debris from the LEO orbits. The efficiency of this technique strongly depends on LDR station location, possibility of night and day (all day) operations, the laser energy and the emitting telescope diameter. The most efficient is the LDR station with the larger telescope and higher energy laser: variant 6 (25 kJ and 8m). The variant 3: smaller laser energy (10 kJ) and larger telescope (8m) is much more efficient than the variant 4 larger laser energy (25 kJ) and smaller telescope (4m). The first variant (10kJ and 4m) is completely not efficient.

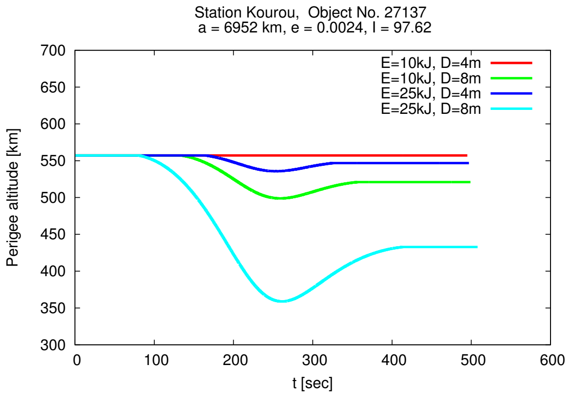


Figure 12. Perigee altitude changes during one pass for different LDR station parameters. The LDR engagement during the whole pass.

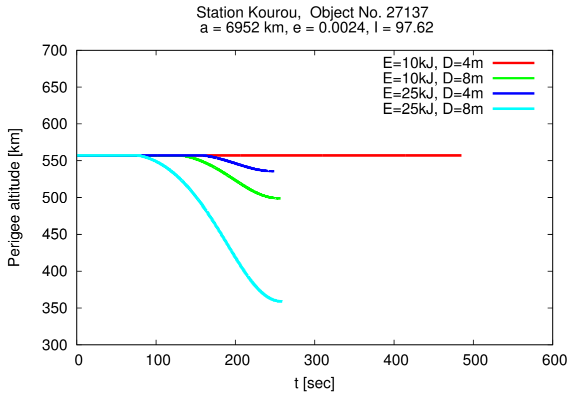


Figure 13. Perigee altitude changes during one pass for different LDR station parameters. The LDR engagement stopped at the perigee altitude minimum.

Table 5. Number of laser pulses needed for object's orbit lowering to 150 altitude - object No. 27137

Station	$10kJ, 8m$	$25kJ, 4m$	$25kJ, 8m$
Grasse	10 752	17 574	4 616
Kourou	10 482	22 170	7337
KLMS	11 509	18 202	5782

Table 6. Number of laser pulses needed for object's orbit lowering to 150 altitude - object No. 35017

Station	$10kJ, 8m$	$25kJ, 4m$	$25kJ, 8m$
Grasse	7 959	11 571	2 908
Kourou	7 559	11 871	3 127
KLMS	6 602	10 159	3 780

In the case of all day LDR operations (possibility of both night and day laser engagement) the efficiency of the perigee lowering is comparable for different station locations. However, for the night only option the efficiency significantly changes for different stations and strongly depends on the seasonal changes of the night duration.

Figures 16 and 17 show that LDR operation is efective only for some passes over a given station. In the case of the first example: laser energy - 10 kJ, telescope - 8 m (figure 16) the time span of multi pass LDR operation up to the object re-entry is 14 days. During this period the total number of passes of the object over the Kourou station was 25. However, only during 9 passes the LDR was efective in the perigee lowering. For the second example: laser energy - 25 kJ, telescope - 4 m (figure 17) the time span is 19 days and the total number of passes over the Grasse station was 32 but only during 13 of them the LDR was efective. For the rest of the passes, due to vaporization threshold defined in 3.3 and adverse geometirical condition between the laser beam and the object's velocity, the perigee altitude is not changed.

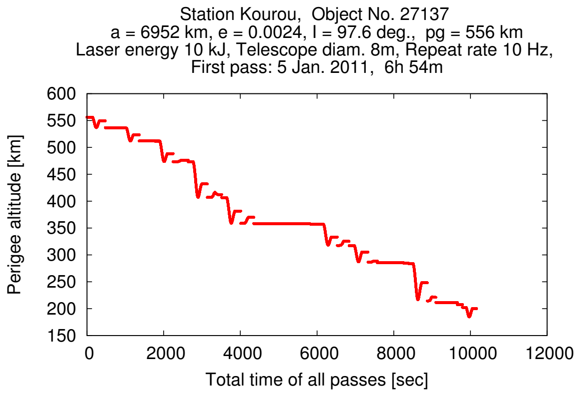


Figure 14. Perigee altitude changes during a series of passes. The LDR engagement during the whole pass.

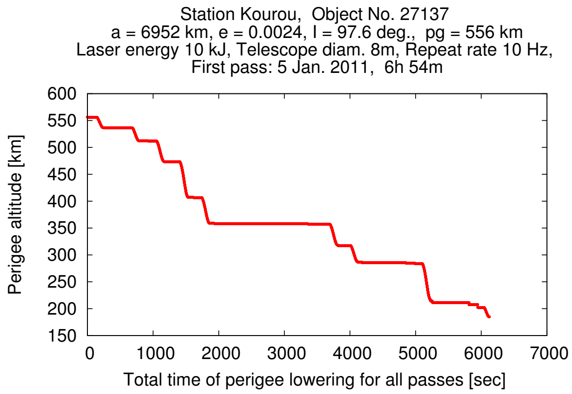


Figure 15. Perigee altitude lowering during a series of passes. The LDR engagement stopped at time of perigee altitude minimum for successive passes.

5. ORBIT AFTER LDR OPERATION

The orbital elements after LDR operation may by only estimated on the basis of the predicted $\Delta\vec{v}$ 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.

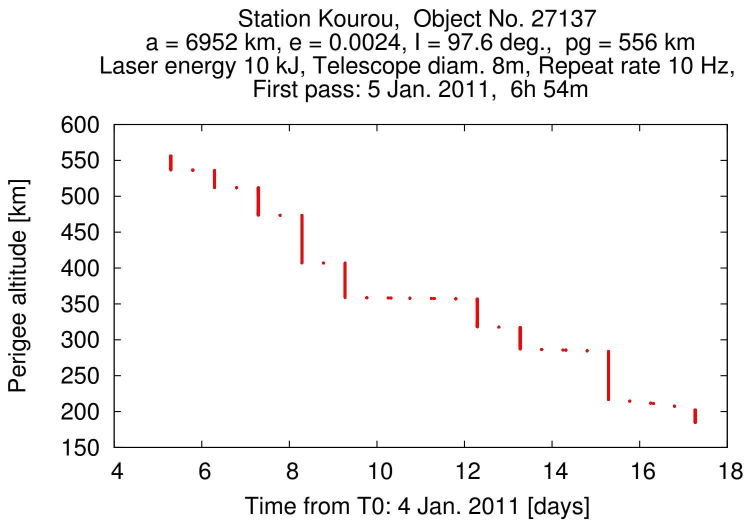


Figure 16. Perigee altitude lowering during a series of passes. The LDR engagement stopped at time of perigee altitude minimum for successive passes.

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 paper were obtained with the prediction tool developed in the Poznan Astronomical Observatory [5, 6, 7, 8, 9, 10] . 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.

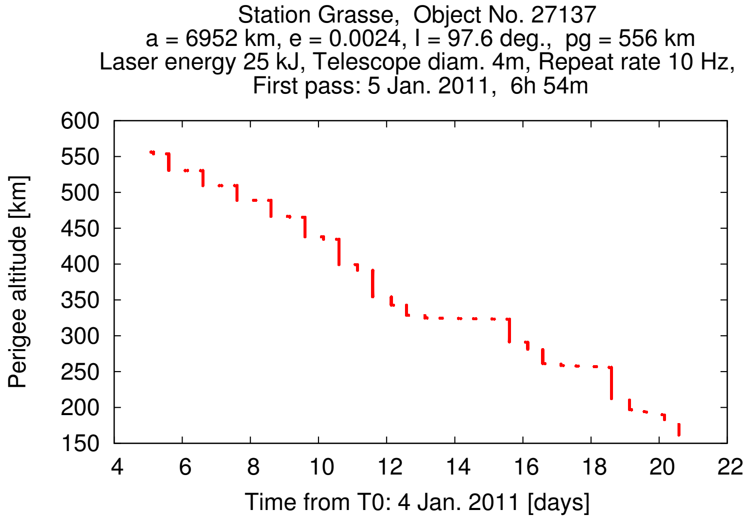


Figure 17. Perigee altitude lowering during a series of passes. The LDR engagement stopped at time of perigee altitude minimum for successive passes.

6. CONCLUSIONS

The 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 exemplary debris objects and different combinations of LDR characteristics. The perigee lowering after one pass and a series of passes of exemplary objects above different LDR station locations is estimated and analysed.

In the case of ”One pass LDR option” even after LDR operation during one pass, the object’s trajectory may be changed significantly. The perigee lowering may reach a level of 100-200 km or even more, and the lifetime of the object may be reduced by several hundreds or even thousands of days.

The ”Multi pass LDR option” enables the perigee lowering of a debris object during a series of passes from the same LDR station. The number of passes and the number of laser pulse needed for completely removing the debris from the orbit depends of different orbital and LDR station parameters.

The presented results show that the LDR technique may be effective for removing of a number of small debris from the LEO orbits. The efficiency of this technique strongly depends on LDR station location, possibility of night and day (all day) operations, the laser energy and the emitting telescope diameter.

All calculations performed with software developed by the Astronomical Observatory of the A.Mickiewicz University, Poznan show the potential interest of this challenging concept.

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REFERENCES

1. C. Phipps (2002). Laser applications overview: The state of the art and the future trend in the United States. *RIKEN Review* No. 50 (January, 2003): Focused on Laser Precision Microfabrication (LPM 2002)
2. Brian C. D'Souza et al. (2005). Direct Impulse Measurements of Ablation Processes from Laser-Surface Interactions. *AIAA 2005-5172 - 36th AIAA Plasmadynamics and Lasers Conference* - 6-9 June 2005, Toronto, Ontario Canada
3. C. Phipps, J. Luke (2002). Diode Laser-driven microthrusters : a new departure for micropopulsion. *AIAA Journal* bf 40 (2), 310-318 (2002)
4. J. N. Opiela (2009), A study of the material density distribution of space debris, *Advances in Space Research* **43** (2009), pp. 1058- 1064
5. Wnuk,E.,(1988). Tesseral Harmonic Perturbations for High Order and Degree Harmonics, Celestial Mechanics and Dynamical Astronomy 44., pp.179-193 (1988).
6. Wnuk,E., (1988). The Inclination Function for the High Value of Indices, Acta Astronomica, vol.38,No.2, pp.127-140.
7. Wnuk,E., (1990). Tesseral Harmonic Perturbations in the Keplerian Orbital Elements, Acta Astronomica, vol.40, No.1,.
8. Wnuk,E., (1995). Second Order Perturbations due to the Gravity potential of a Planet, in A.E.Roy and B.A.Steves (eds.) From Newton to Chaos, NATO ASI, Plenum Publ. Corp., New York, London, Washington, Boston, 259-267.
9. Wnuk,E., Szplit,D., (1995). Gravitational Perturbations of Highly Eccentric Orbits, in J.P.Carrou(ed.) Spaceflight Dynamics, pp. 225-232, Cepadues- Editions, Touluose .
10. Wnuk,E., (1997). Space Debris - The Short Term Evolution in the Earth Gravity Field, Celestial Mechanics and Dynamical Astronomy Vol. 66, pp 71-78.