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XXI Century Tower: Laser Orbital Debris Removal and Collision Avoidance

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Abstract

A tall “tower” may have many useful applications in scientific domain: energy production, telecommunications, entertainment.

Sometimes space towers are proposed for an easier access to space such as the TOTH project culminating to an altitude of more than 20km

Nevertheless, access to space is not the most promising use of a high-altitude tower, among them is the orbital debris removal, major point to keep a safe access to space.

Ground based laser has been studied several times, laser on-board of a satellite also (chaser), but never a laser at the top of a tower.

Such a solution may combine the advantages of the ground based system (i.e. maintenance, power supply, vast number of debris apparitions, versatility) and of the space based system.

Nevertheless, building a tall tower is a huge investment and must be profitable, but multiple applications of this tower may be envisaged such to have a good return of investment and so, the others potential utilisation may generate a bulk of revenues). As a driver, this tower supporting a powerful laser can be assimilated to a weapon and so kept under international control on the European territory.

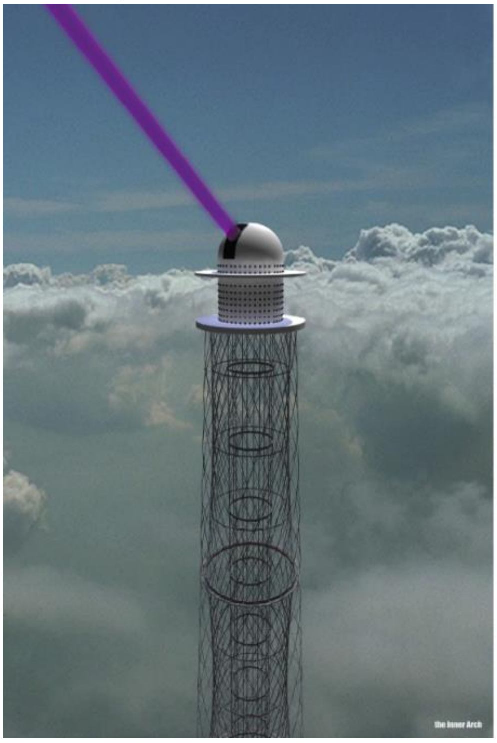
1. Introduction

A tall “tower” may have many useful applications in:

- The scientific domain
- The Energy production
- The telecommunications (Internet, connected objects…)
- Entertainment

Sometimes space towers are proposed for an easier access to space such as the last on -TOTH project-culminating to an altitude of more than 20km (9)

Nevertheless, these kinds of project are technically difficult to realise and access to space is not the most promising use of a high-altitude tower, among them is the orbital debris removal, major point to keep a safe access to space.



Ground bases laser has been studied several times, laser on-board of a satellite also (chaser), but never a laser at the top of a tower

Such a solution may combine the advantages of the ground based system (i.e. maintenance, power supply, great number of debris apparitions) and of the space (no clouds nor dust to cross over/ great availability, UV laser)

Nevertheless, building a tall tower is a huge investment and has to be profitable, but multiple applications of this tower may be envisaged such to have a good return of investment

Delivering fast and reliable Internet access to people, whose physical isolation precludes connectivity by wires and other traditional means, is challenging. Key players are racing to take on this challenge for creating a more accessible global Internet; some space applications may take the opportunity of a commonality of means that exists with the Internet access

Satellites can deliver Internet access to sparsely populated areas with little or no infrastructure, but the cost of satellite connections is a strong handicap and from a technical point of view the latency time constrain some applications; also, to offer a cost effective alternative other means are under study such as High-Altitude Platforms (HAP) like stationary balloons, Unmanned Aircraft Systems (UAS), net of free flying balloons

A tower culminating at 8km of altitude could be a realistic

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competitor on the future of Internet (coverage of desert countries with a radius of more than 300km in direct view …) and so may be funded for these applications (among others, market of connected objects expects a dramatic increase in the next decade generating a bulk of revenues)

This paper will be focused on collision avoidance and space debris removal by laser beam; a first analysis of advantage and draw back versus a ground version (old ORION project) and a satellite version conclude that it is the best compromise

If this kind of tower may be funded and realized, it would be a unique opportunity to have a revival of the ORION project taking also into account the huge progress made by the laser industry for twenty years in the field of military laser and laser fusion.

The expected recurring cost is very low [23]) make of the project an attractive and only solution to clean the low orbit of small debris. Very little target mass is ablated per pulse so the potential to create additional hazardous orbiting debris is minimal.

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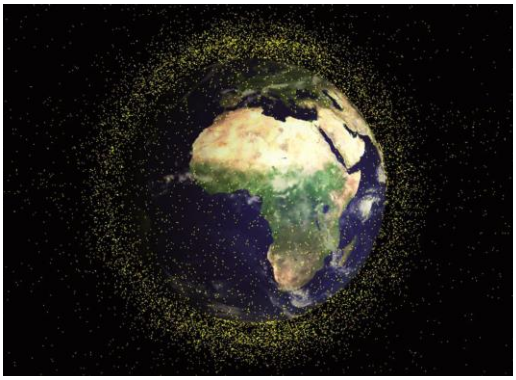

Fig. 2 *Population of objects larger than 10 cm in 2009 according to DAMAGE (University of Southampton)*
10 cm>22000 objects **tracked** from the Earth
1-10 cm > 500000 objects **big** enough to destroy a satellite
1 mm-1 cm > millions of objects too **small** to be detected can cause **anomalies** in spacecraft

2. Design of the tower

The design of this tower is conceived to have its major elements working in traction with a central tubular part containing an elevator (tight tube, gas pressure operated) , electric power lines and laser fiber transfer lines (if a Yb Fiber laser is selected, the laser itself remains close to the ground level). If its basis will be made of concrete and its lower part with steel its upper part could be realized with high stiffness special composite material.

Because of its open-lattice design, dramatic wind drag reduction is expected (30 percent?), as compared to a traditional “closed” tower. This means that it is much less susceptible to breaking or falling when subjected to high winds.

The mass and dimensions of the equipment of the summit of the tower are important parameters for its dimensioning but debris removal doesn’t need to have a top desk of important dimensions nor to sustain very heavy equipment; The envisaged surface ratio from the top to the basis will be less than 100

Geoffrey Landis [13] in several communications mentioned computation results for **a fifteen** kilometer tower size to support a launch vehicle (“fractal” truss design) if the structural material is graphite epoxy the tower mass would be 280 tons (!), using steel: the tower mass would be 5300 tons (!) (taper ratio 2.6) .The results of a NASA MFSC study of 2002 seems pessimistic but more credible for an all steel version (mass around one millions of tons) [14] (70 to 100 000 tons for 8Km height ??)

2.1 Choice of the altitude of the summit of the tower

Point of view of LODR: Why 8km?

- The quality of the atmosphere at 8km of altitude (high level of availability)
- Smaller air traffic exclusion zone
- Better deorbit efficiency thanks to low beam elevation
- Increase of the effective laser illumination duration
- Lesser perturbations of the laser beam (energy absorption, beam divergence and scattering)

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- Compromise cost efficiency, implemented at an altitude of 2000m on a mountain the height of the Tower can be limited to 6km and the tower remain under an altitude range of high velocity winds

For orbital Debris Removal, the two leading parameters linked to the altitude are:

- The quality of the atmosphere at 8km of altitude: 64% of the air is under the Laser Platform and only 36% above. Some Designers of HAP consider that the condition is very close to the outer space by a clear sky (Raleigh scattering mainly, no more aerosol or dust) These facts may simplify the choices related to laser and its wave length and reduce the optic size. At 8 km of altitude, nevertheless turbulence generated by high velocity winds cannot be totally neglected for the design of the adaptive optics ([12] page 265)
- Above this altitude remain only Cirrus and Cumulonimbus. GLAS / HIRS measurements show that for the zone between the 20° and 60° of North latitude over the land the average altitude of clouds is around 5.5km with a top at 7.3 km (Table 2 from [2]) the cloud coverage by high altitude clouds decrease strongly with the latitude. The figure 2 shows that CALIOP measurements confirm the data of the table 1 : over an altitude of 6km there are no clouds over the latitude of 30 degrees north : a multi-site in the southern Europe or a clear sky site (desert) –often politically sensitive- don't need to be selected anymore. A unique tower build in northern Europe may fulfil the requirements. This tower supporting a powerful laser can be assimilated to a weapon and so kept under international control

These points are leading to an infrastructure with a very high level of availability: it can be used for:

- A tracking and acquisition system of small space debris that reduces the position uncertainty (cf DLR web site or [18]). This one will include an active optical telescope associated with a laser that at the same time deliberately irradiated the target with laser pulses for example, it allows also a fast retargeting.
- A laser system to avoid a collision between debris (big or small),
- but also to the removal of the classes of debris that ORION project wanted to cover. The performance of the system is assessed in the altitude area 300-800 km on the debris population of small size (surface area less than 10 cm) for which we can consider a deorbit

TABLE 1. Comparison of the average cloud heights in km (over the land).

		Top	Base	Average
20°–60°N	**GLAS**	**7.3**	**4.4**	**5.9**
	HIRS			**5.4**
20°S–20°N	**GLAS**	**12.3**	**7.9**	**10.1**
	HIRS			**7.7**
20°–60°S	**GLAS**	**7.7**	**5.4**	**6.7**
	HIRS			**5.3**

Fig.3 **Cloud coverage at ground level**

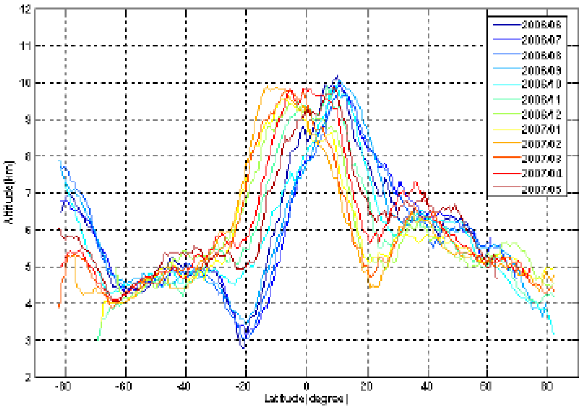

Fig.4 from [10] **Monthly average of the mean cloud top height against latitude (CALIOP measurements)**

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Point of view of the tower: Why 8km?

A NASA study of 2002 shows that the mass of the tower grows exponentially with its height (NASA MFSC Preliminary design, feasibility and cost evaluation of 1 to 15-kilometer height steel towers), there is a ratio of roughly 16 between a height of 8 km and 15 km (70 to 100 000 tons for 8Km height ?? according to [14])

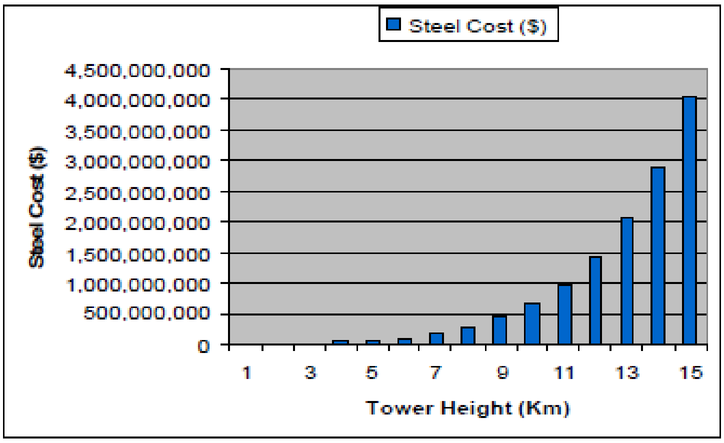

Fig.5 Steel cost vs tower height

3. Laser wave length and technological choices

The laser beam generation and its cooling system, the associated optic (telescope) will be located on the pinnacle platform over the clouds; the platform can receive its electrical power from the ground. A short-wave length should be used in the UV band and can be selected from an optimal point of view of the ablation of the materials of the target and of the optic size.

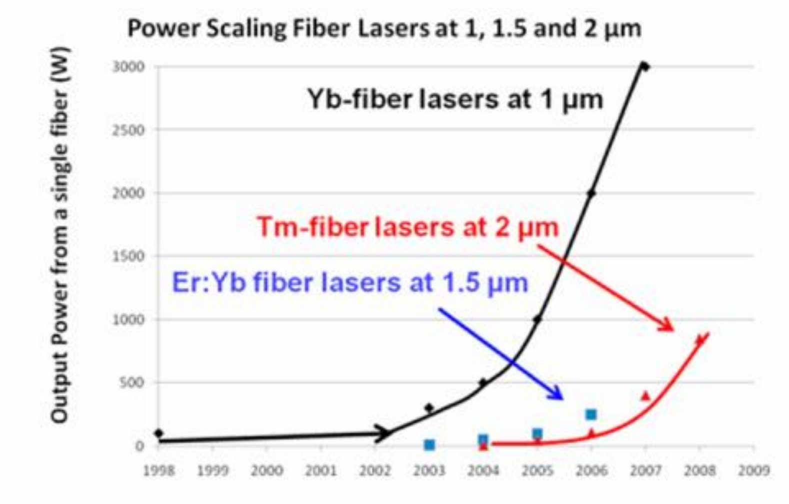

Fig. 6 Power Scaling (Institut d'optique P.George seminar 2010)

Today some military mobile lasers are tested in operation in the USA (such LaWS) and lasers under study or development are in the range of 30-150kW.

So, for orbit laser Removal **to be comparative** the hypothesis considered are those of [7] and [8] In this set of hypotheses, the Nd:YAG laser is functioning at wave length of 355nm (harmonic). The ORION project selected a wavelength near 1.06 µm (much less favourable but with a higher TRL) and either a pulsed solid-state laser or a CW gas laser (this project was cancelled after 10 years of work; the level of atmospheric losses was one of the blocking points).

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4. Main formulas and parameters values used for the computations

Laser spot diameter at target $d_s = a M^2 \lambda\, z / D_{eff}$

Laser peak pulse energy $W = S_s\, \Phi / T$

Optimal ablation criteria $\left(\frac{\Phi\lambda}{\sqrt{\tau}}\right)$ $, C_m \approx 100\, N/MW$ => $210^2 \leq \left(\frac{\Phi\lambda}{\sqrt{\tau}}\right) \leq 10^4$ (see [7] and [8])

Velocity impulse at each pulse $\Delta V = \eta\, S_S\, e\, \rho V_e / M_S$

or : $\Delta V = \eta\, C_m\, \Phi / \mu$ (see [7] and [8])

Where:
a : Spot dispersion parameter at target (practical value = **1.7** (hyper Gaussian distribution))
M^2 : Beam quality (usual value = **2** for ground based lasers), This pessimistic hypothesis for our case was kept; in the outer space this parameter is taken =1
λ : Wave length (choice **355nm**, UV laser 3rd harmonic of Nd:YAG)
z : Distance to target
D*eff* : Effective mirror diameter
D : Mirror diameter
S_s : Laser spot surface on target
Φ : Fluence on target (J/m^2)
τ : Pulse duration (value considered: **100** ps)
T : Product of all transmission losses (value considered: T = **0.7**)
η : Efficiency factor to take into account improper effects (target shape, tumbling, etc..)
e : Thickness of the material ejected during the pulse (m)
ρ : Density of the ejected material (kg/m^3)
V_e : Velocity of the material ejected during the pulse (m/s)
M_S : Satellite mass (kg)
C_m : Coupling coefficient between fluence and velocity impulse (N s/J or sometimes N/W)
μ : Target areal mass density (kg/m^2)

With a=1.7 (spot dispersion parameter), M^2=2 (beam quality), λ wave length, z distance, D mirror diameter, S_s spot surface, T=0.7 product of all transmission losses (apodization, physical obscuration, atmospheric transmission)

The quantity M^2 (=1 in vacuum) includes atmospheric phase distortions corrections by adaptive optics and a guide star system. As atmospheric turbulence is working like a distorted lens, its effects can be compensated with another optical element. The corrective element must be adaptive as the turbulence effects vary in time. A laser system for debris removal with corrected beam quality M^2= 2.0 gives Deff/D = 0.9 and a = 1.7 (hypergaussian beam after optic corrections ref [2])

For λ=355 nm, a pulse duration τ=100ps, the ablation criteria $\Phi\lambda/\sqrt{\tau} = 310^2$, the optimal fluence is Φ=8633 J/m^2

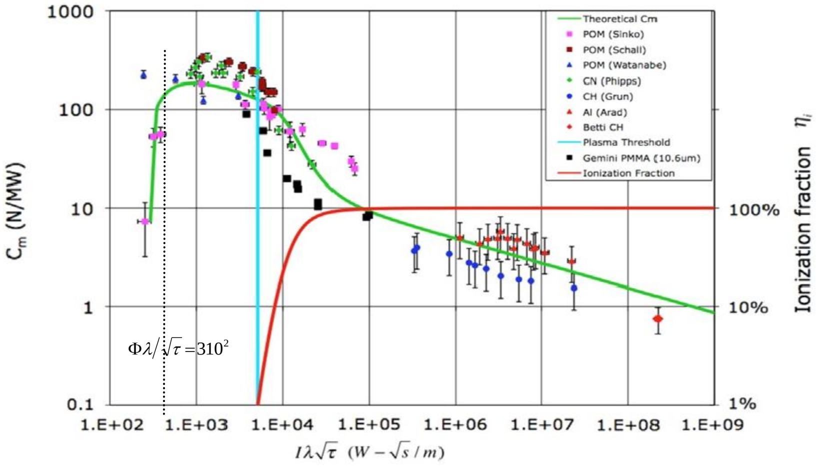

Fig.7 Example of results of models that allow to predict Cm for many likely plastics and metals. (ref [7])

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4.1 Debris removal

Considering this optimal fluence value, a pulse of 3.2kJ associated to an active optic of 4.2 meter in diameter, the requirement of a maximum range z=2000 km is satisfied with a spot diameter of 57 centimeters.
Considering a distance of 1000 km and keeping the size of the mirror (4. 2 m), the energy of the pulse is then 800 J

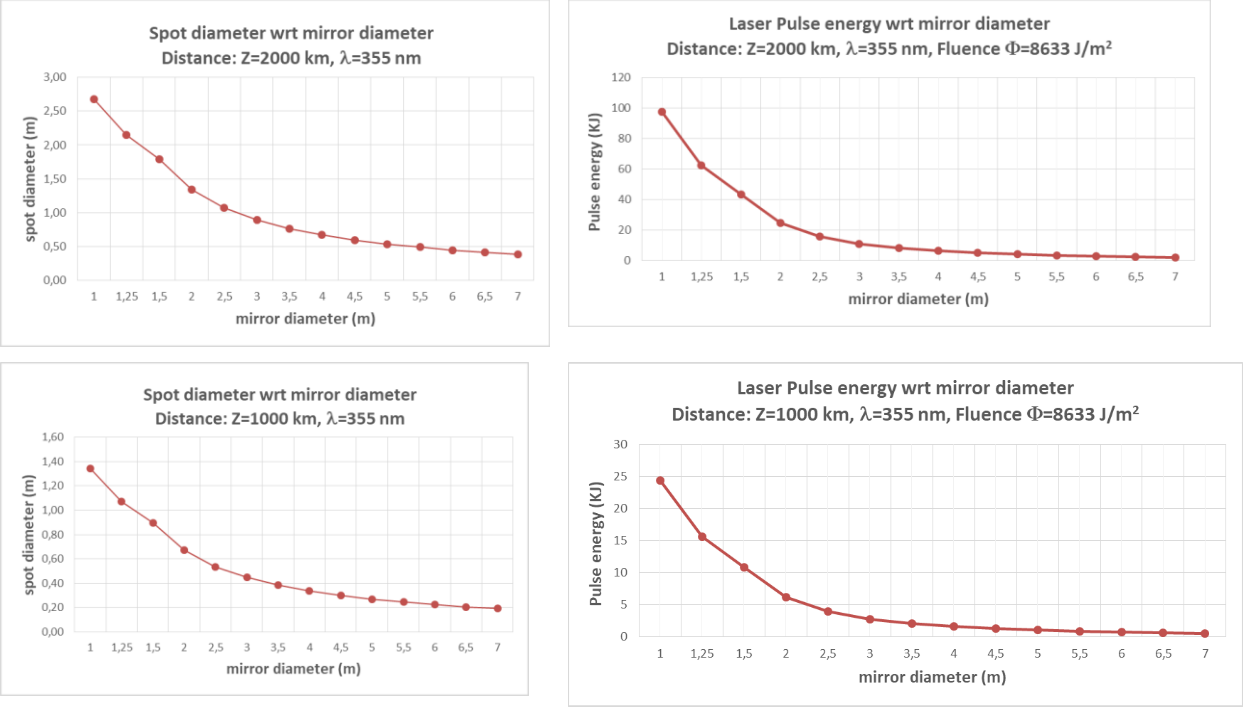

Fig: 8 Spot Diameter and laser pulse energy vs mirror diameter

For easiness of operations, it may be perhaps useful to select greater optic diameter and pulse energy than strictly necessary and play on defocusing the optic to obtain the optimum fluence.
Nevertheless, the main conclusion is that the laser debris removal system is not a dimensioning case for the tower in the panel of the potential utilization.

Laser sizing (Table 2)

Mirror Diameter (m)	Pulse energy (J)	Distance to target (km)	Laser spot Diameter (m)	Fluence (J/m^2)	Optimum ablation criteria ($\Phi \lambda/\sqrt{\tau}$)	Coupling Factor Cm (N/MW)
4.2	3200	2000	0.57	8633	3.06 10^2	110
8.4	1120	2000	0.28	8633	3.06 10^2	110
4.2	800	1000	0.285	8633	3.06 10^2	110
8.4	280	1000	0.14	8633	3.06 10^2	110

For the same fluence value (considering the ablation criteria) and at a given distance of the target, the laser design depends on the choice of three linked parameters: the mirror diameter, the laser spot diameter on the target, the laser energy.

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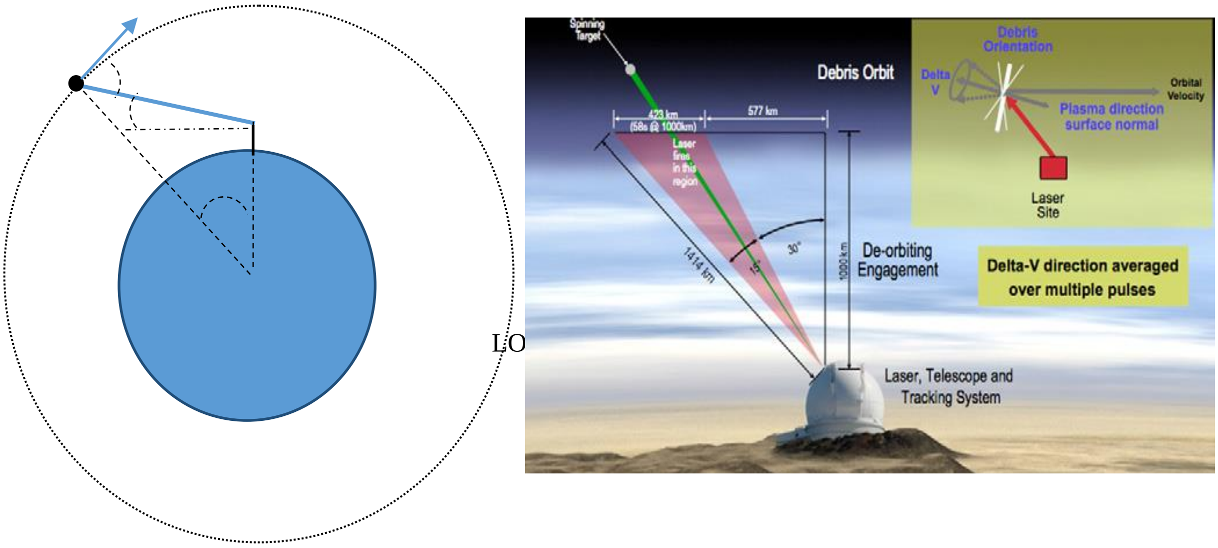

Fig 9 Geometric configuration of the laser operation

Geometric configuration of the laser operation

β: geocentric angle between the laser position and the satellite (debris)
θ: Laser beam elevation angle
ψ: angle between the laser beam and the satellite velocity (V)

The laser must operate as close as possible in the orbital plane of the target, in first approximation we can consider that the geometric configuration is planar.
To have a weak angle between the laser beam and the velocity (to optimize the satellite deorbit the ΔV produced by laser ablation must be in the opposite direction of the target velocity) and to increase the duration of the effective laser illumination, the laser must aim the target at low elevation, this condition is obtained if the intercept distance (z) is large enough.
Since the laser is located high enough, the energy loss is limited (64% of the atmosphere is below the laser altitude (8 km)) and we can consider a low value of the initial elevation angle of the laser beam. However we will consider losses in energy transmission of 30%, particularly those due to the atmospheric absorption (as considered in [8] but for a ground based laser).

Exclusion zone (Table 3)

The exclusion zone during the laser operation concerns primarily the air traffic. This zone is a cone until a predefined altitude, the table below shows the radius of the excluded zone around the laser position with respect to the minimal elevation of the laser beam and the exclusion altitude. Even for high exclusion altitudes (until 20 km) and low laser beam elevation angles, the exclusion zone is not widespread, in addition it decreases rapidly after the start of the laser operation.

Exclusion altitude km)	Minimal laser beam elevation	Excluded zone around the laser position (radius) (km)	Excluded zone around the laser position (radius) after 100 s (km)
12	9°	25	10.4
15		44	18
20		76	31
12	15°	15	6.4
15		26	11
20		45	19

Influence of the distance of the target acquisition (Table4)

Satellite orbit: circular orbit, altitude 600 km			
Distance laser – satellite at the first interception (km)	Minimal laser beam elevation angle Θ(d°)	Minimal angle between the laser beam and the satellite velocity ψ (d°)	Effective laser illumination duration (*) (s)
2000	8.8	25.3	217
1500	17.2	29	143
1000	32.7	39.7	63

(*) the laser illumination is considered as effective if the component of the ΔV produced by laser ablation along the opposite of the satellite velocity direction is more than 0.5 ΔV.

The table above shows that the duration of the laser illumination depends strongly on the acceptable maximum distance for the laser operation.

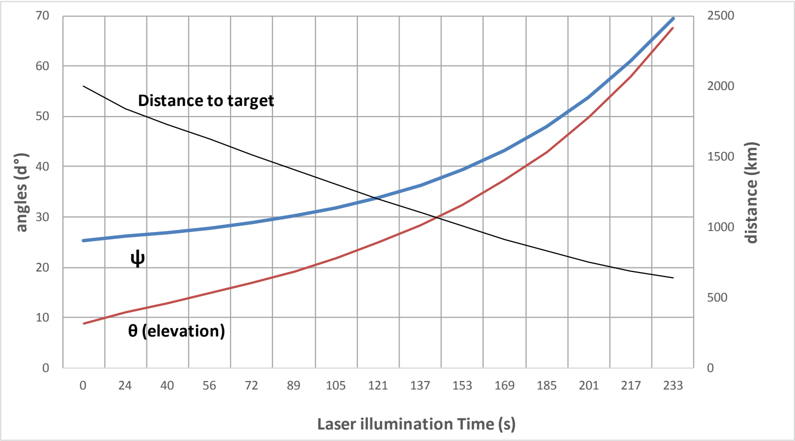

Fig:10: Laser illumination vs angle and distance

Choice of the latitude of the laser site

The latitude of the laser affects essentially the characteristics of the orbits attainable by the laser, and possibly on the frequency of review of the satellite to treat. Particularly the satellites with orbit inclination is lower than the latitude of the laser position cannot be reached effectively by the laser. The frequency of seeing again the satellite to treat does not depend of the laser latitude, except for the satellite with an orbit inclination near 90° (SSO satellites) for which a high laser latitude increases the frequency to see again the satellite to operate.
The space debris in low orbit are grouped in majority on orbits inclined between 60 and 105 degrees. A laser can be an interesting mean to avoid collisions between debris and the ISS whose orbit is inclined at 51. 6 d°. In addition, in average the mean cloud top height is minimal for latitudes between 40 and 60 d°, therefore a laser located in this latitude interval allows processing a maximum of debris in LEO orbit while maximizing the laser operational duration. For this choice, the duration of the debris revisit (passage of the satellite on the position of the laser to more or less 2 degrees) is 4 to 5 days.

Applications

1. Debris de-orbit

The figure below shows the deorbit of a debris of 5kg, the cumulated impulse velocity in the opposite direction of the satellite velocity allows to transfer the debris from a 600 km circular orbit to a (H apogee= 605km x H perigee = 154 km) orbit after one pass allowing a quick debris re-entry.

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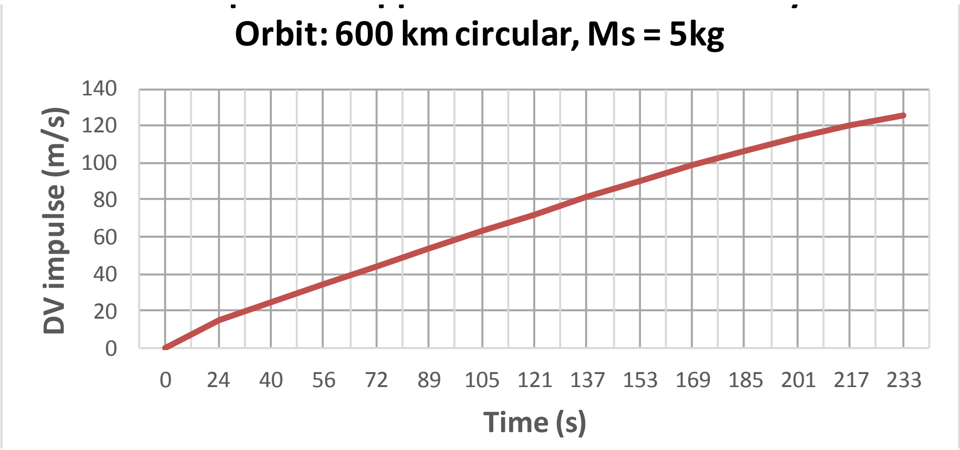

Fig11: Opposite δV to the satellite velocity vs time

Hypothesis: D = 4.2 m, Pulse laser energy W = 3.2 KJ, λ=355nm, η= 0.3, material: Al, pulse repetition frequency = 50 Hz, e=20nm, V_e=13.4 km/s, ρ=2700 kg/m^3, laser thrust direction: opposite to laser beam direction.
The hypothesis made above to compute the impulse velocity are equivalent to consider a coupling coefficient C_m = 110 μN. s / J and a target areal mass density μ=21 kg/m^2 for a fluence Φ=8633 J.
We suppose also that the target surface is as big as the beam focus in such way that the illuminated surface does not overflow the target object.

For these hypothesis, the spot diameter at Z=2000 km is ds =0.57 m, the theoretical effective velocity impulse delivered during 1 s is 0.68 m/s.

2. Massive small debris de-orbit consideration

Assuming an operational Laser occupancy rate of 50% (the rest of the time being devoted to the laser retargeting, the waiting for the next debris, maintenance, etc.) and an average laser processing time for a debris deorbit of 230 s (conservative assumption for a debris mass of 5 kg), the laser can deorbit about 68500 small debris by year, figure to compare to the 700 000-estimated debris number whose size goes from 1 cm to 10 cm and 22000 whose size is greater than 10 cm.

3. Large satellite avoidance

The collisions between debris are especially critical for low orbit (LEO) and inclined orbits between 50 and 110 °. The main concern is the collisions avoidance between medium-sized debris or large objects which can generate a multitude of debris (such as the collision between the Iridium-33 and Cosmos-2251 satellites in 2009). Another need is also to protect operational satellites against of all kinds of collision threats (against large and small debris).

The figure below shows that the debris environment is dominated by rocket bodies (R/Bs) and spacecrafts (S/Cs).

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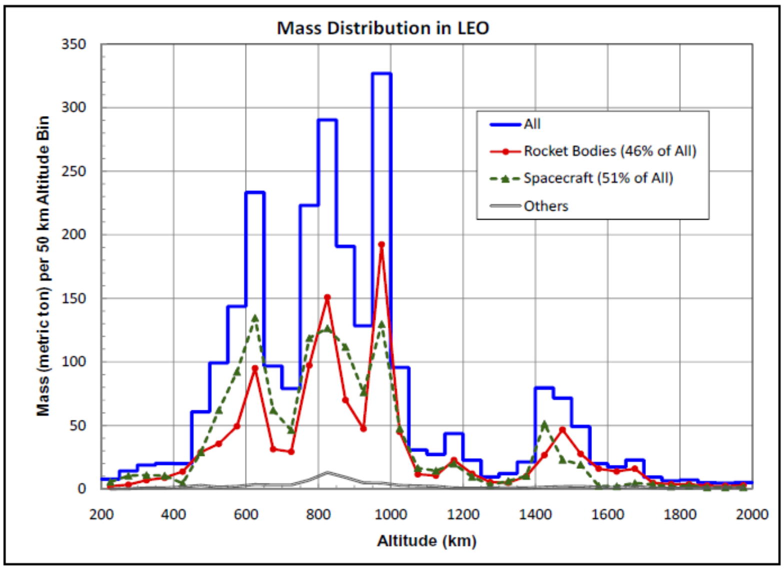

Figure 12: Mass distribution in LEO. (ref 19)

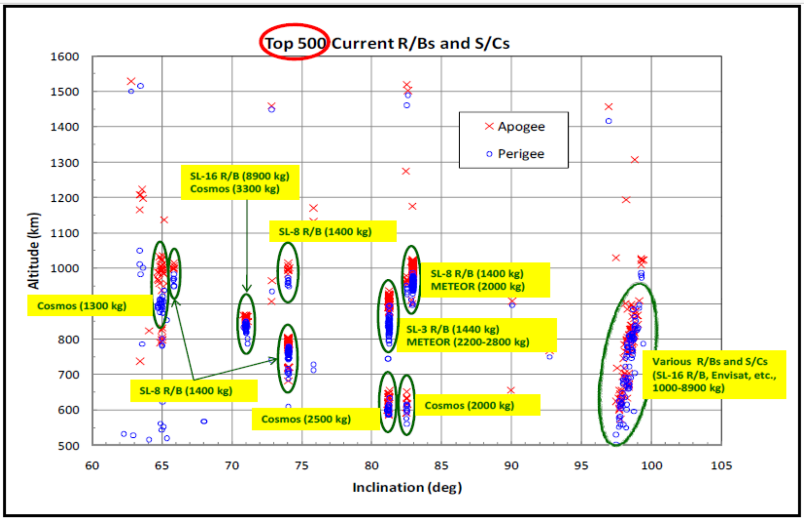

Figure 12: Objects with the highest [mass × collision probability] in the LEO environment (ref 19)

If the objective is to stabilize the debris environment, an effective approach is to avoid collision between objects that have the greatest potential of generating the highest number of fragments in the future. These are objects with the highest mass and collision probability products [3]. Figure 1 shows the mass distribution in LEO. It is obvious that the major mass reservoirs are located around 600, 800, and 1000 km altitudes. The 600 km region is dominated by spacecraft (S/Cs) while the other two regions are dominated by spent rocket bodies (R/Bs). Since the 800 to 1000 km region also has the highest spatial density in LEO, it is expected that many of the possible collisions will be caused by the R/Bs in that region. The mass of objects with a high probability of collision is around 2 ton.

If we consider a satellite on an 800-km circular orbit and an initial mass of 2000 kg with the same hypothesis than above but with η= 0. 5 (low satellite tumbling, larger surfaces, lower risk of beam spot overspreading on the target), the velocity impulse opposite to the satellite velocity reaches 0.44 m/s during one pass. This value is large enough to keep the satellite at several dozen kilometers from its initial position and avoid a possible collision. This mean is largely oversized, ΔV of 1 cm/ s or even less is sufficient: Mason from NASA Ames [6] suggests that a near-polar facility with a 5kW laser directed through a 1.5m fast slewing telescope with adaptive optics can provide sufficient photon pressure on many low-Earth sun-synchronous debris fragments to substantially perturb their orbits over a few days.

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1) ΔV Impulse for a distance to target < 2000 km

The assumptions are those considered previously, the target is illuminated when the laser-target distance is less than 2000 km
Pulse energy W = 3.2 KJ, mirror diameter D = 4.2 m, pulse repetition frequency = 50Hz

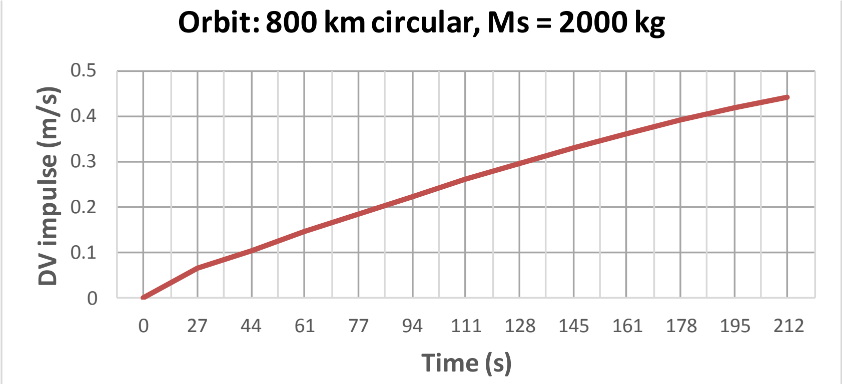

Figure 14: Opposite δV to the satellite velocity vs time

The ΔV provided to the target and opposite to the velocity is 0.44 m/s

2) ΔV Impulse for a distance to target < 1000 km

A pulse energy of 800J is then sufficient to obtain the critical value of the fluence (Φ=8633 J) to induce ablation. The beam spot diameter is then ds=0.285 m at 1000 km.
For a circular orbit at 800 km, the target can be reached at a distance of less than 1000 km only if the elevation of the laser beam is greater than 45°. This significantly reduces the illumination time of the target at 101 s, and therefore the ΔV supplied to the target is lower.

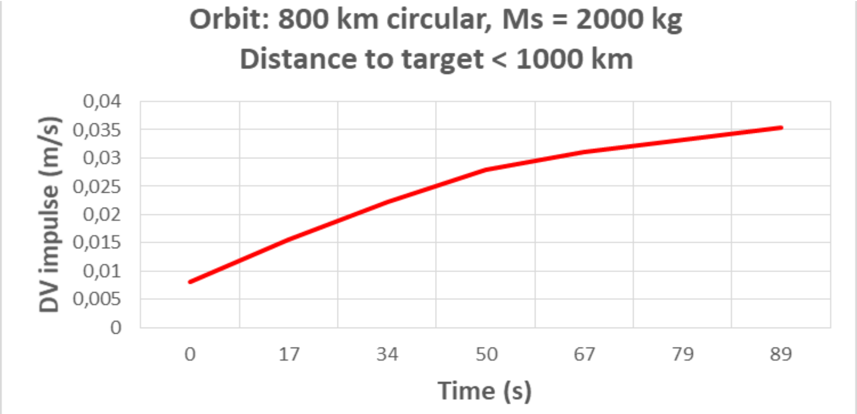

Figure 15: Opposite δV to the satellite velocity vs time

For this case the ΔV provided to the target and opposite to the velocity is 0.035 m/s

Distance drift estimation

A ΔV provided opposite to the velocity induces a semi-latus and period modifications.

Starting from the Gauss equation for the perturbed motion, we have:

$\frac{da}{dt} = \frac{2Va^2}{\mu}\Gamma_t$ where Γ_t is the perturbation acceleration along the orbit tangent

Then, as the semi-latus (a) and velocity (V) are few modified, the semi-latus modification can be approximated by:

$da = \frac{2Va^2}{\mu}\int \Gamma_t \, dt = \frac{2Va^2}{\mu}\Delta V = \frac{T}{\pi}\Delta V$ (for a circular orbit) where T is the orbit period.

Knowing that: $T = 2\pi\sqrt{\frac{a^3}{\mu}}$ and $V = \sqrt{\frac{\mu}{a}}$

$$\frac{dT}{da} = \frac{3}{2}\frac{T}{a}$$

The distance drift after one orbit is: $\Delta d = \frac{dT}{da} da \cdot V = 3T\,\Delta V$ (drift distance along the orbit tangent)

For an 800-km circular orbit T=6046 s, 14.3 orbits per day.

Table 5 Target mass 2000 kg / circular orbit at 800 km / η=0.5 / λ=355nm / τ=100ps

Maximal interception distance (km)	Pulse energy (J)	Pulse frequency repetition (Hz)	Mirror diameter (m)	Duration of the target illumination (s)	Longitudinal ΔV provided to the target during one interception (cm/s)	Normal ΔV provided to the target during one interception (cm/s)	Drift distance after laser interception and one orbit (km)	Drift distance after laser interception and one day (km)
2000	3200	50	4.2	212 s	44	51	8	114
1000	800	50	4.2	101 s	3.5	13	0.63	9
1000	280	50	8.4	101 s	0.85	1.5	0.15	2.2

Note: At the distance due to drift (in the direction tangential to the orbit), we should add the variation in distance in the normal direction to the velocity induced by the ΔV applied normally to the velocity (with a mainly effect on the orbit eccentricity and perigee argument), the difficulty is that this distance variation is oscillating and therefore its effect is more difficult to quantify in the general collision problem.

The drift distance must be compared with the trajectory uncertainties that we can have on the target. At the altitude considered (800 km), the disturbances of the orbit are well known (earth potential, moon and solar perturbations, aerodynamic disturbances are negligible). Furthermore, the tracking of the target (by laser or radar) during the laser operations can achieve a metric accuracy, so the trajectory can be predicted with accurate tools after one orbit certainly to a few dozen meters.

These results show that even for a moderate power laser (for instance: pulse energy 280 J and mirror diameter 8.4 m), its use is effective even for high mass objects (2t). The object distancing after an orbit appears sufficient and significant with respect to the trajectory inaccuracies in order to control the collision avoidance.

4. Large satellite de-orbit

To deorbit a satellite from a 800 km circular orbit to an (H apogee=800 km, H perigee= 150 km) orbit, an impulse velocity delivered at the apogee of 179 m/s is required. In practice 407 laser illumination passes allow to obtain this impulse velocity. The satellite passes over the laser position (with a 2 d° margin) on average every 4.3 days, therefore approximately five years are required to transfer the satellite on an orbit allowing a rapid re-entry of the

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satellite, however this value is low compared to the lifetime of a satellite on an 800 km circular orbit (between 150 and 400 years depending on the satellite characteristics and the atmospheric conditions).

3. Conclusion

The use of a Tower located between the 40° and 60° north is an interesting compromise between a laser on board of a satellite and a ground based laser (with the technical hypothesis taken in [7] and [8]) for the space debris removal; so, if there are no limitations on the detection and tracking of small debris, only one laser will be able to clean the space of small debris in a decade (and the orbit of the space station), the laser could be used also to avoid collisions between large satellites and to de-orbit some of them.
The technological choices made for the laser are challenging (pulse duration100ps, wave length 355nm, high power) but emerging technologies could create a path to enable deployment in a short-term future ([20], ([21], ([22]). Nonetheless more mature laser technology (e.g.wave length 533nm) could be equally effective for light debris removal or collision avoidance.

A tall tower has potentially several profitable utilizations and can be amortized on an extended period. A joint venture with an internet operator could be a solution to fund the study and the building of such a tower

	Ground	**Altitude (Tower)**	**Satellite**
Life Time	50 years or more	50 years or more	years
Potential target	>100k	>100k	Few number
System availability (%)	Depend on the site	High/independent of the site	
Air Traffic Interference	Important forbidden zone	Small forbidden zone	None
Maintenance	Easy	Easy	Not possible
Power supply	Connected to ground net	Connected to ground net	Batteries to re-load
Diffraction	2000km range	2000km range	Short distance shot
Beam attenuation	High but depends on the site	Very low	None
Scattering	High	Low	Very Low

REFERENCES

[1] Wavelength Selection Criteria and Link Availability due to Cloud Coverage Statistics and Attenuation affecting Satellite, Aerial, and Downlink Scenarios Florian Moll, Markus Knapeka
German Aerospace Center (DLR), ICN 2007 SPIE Free-Space Laser

[2] Cloud and aerosol measurements from GLAS: Overview and initial results James D. Spinhirne et al , Geophysical Research Letters, VOL. 32, 2005

[3] A Comparison of Cloud Cover Statistics from the GLAS Lidar with HIRS Donald Wylie et al
Space Science and Engineering Center, University of Wisconsin—Madison, James D. Spinhirne et al, NASA GSFC Journal of Climate vol.30

[4] Space Race 2.0 Expanding Global Internet Accessibility DATA ANALYTICS 2015 Bob Griffin IBM

[5] Review of New Concepts, Ideas and Innovations in Space Towers Acta Astronautica M. Krinker
City College of Technology, CUNY, New York

[6] Orbital Debris-Debris Collision Avoidance James Mason et al_NASA Ames RC 2001 Advances in Space Research

[7] A Space-borne, pulsed UV laser system for re-entering or nudging LEO debris, and re-orbiting GEO debris Claude R. Phipps and Chr. Bonnal - Acta Astronautica 118(2016)224–236

[8] Advances in Space Research 49 (2012) Removing orbital debris with lasers Claude R. Phipps et al

[9] CBC News TOTH Tower

[10] Comparison of cloud statistics from space borne lidar systems- Atmos. Chem. Phys., 8, 6965–6977, 2008 S ; Berthier et al

DOI: 10.13009/EUCASS2017-102

[11) An Intelligent HAP for Broadband Wireless Communications: Developments, QoS and Applications *EEE Vol Journal. 3, No. 2, April, 2015* Saeed H. Alsamhi et al

[12] NASA TM108522 Project ORION: Orbital Debris Removal Using Ground-Based Sensors and Lasers J.W.Campbell MFSC

[13] Towers for Earth Launch Geoffrey A. Landis NASA John Glenn Research Center

[14] Preliminary design, feasibility and cost evaluation of 1 to 15-kilometer height steel towers Ajay Shanker 2002 MFSC

[15] Remediation of space debris by laser nudging technology Toshikazu Ebisuzaki (RIKEN) et al 4th International workshop on Space Debris Modelling and Remediation, 6-8 June 2016, Paris.

[16] Lasers solides de puissance : Etat de l'art et applications Patrick Georges, Institut d'optique ,Lyon Séminaire 2010

[17] Optical-Turbulence and Wind Profiles at San Pedro Martir with G-Scidar, ,et al, Instituto di Astronomia 2007

[18] Laser Tracking of Space Debris, Ben Greene Electro Optic Systems Limited

[19] Orbital Debris Quarterly News Volume 15, Issue 2, April 2011

[20] R. Yamamoto, et. al., "Evolution of a Solid State Laser," SPIE **6551**: 55205 (2007).

[21] J. Caird, et. al., "Nd:glass laser design for laser ICF fission energy (LIFE)," Fusion Science and Technology, **56**, 607 (2009).

[22] High Energy Laser for Space Debris Removal C.P.J. Barty, et al October 31, 2009

[23] High Energy Laser for Space Debris Removal C.P.J. Barty et all- Lawrence Livermore National Lab 2009