Research & Reviews: Journal of Pure and Applied Physics

Elimination of Space Debris and Objects of Natural Origin by Laser Radiation

Apollonov VV*
Prokhorov GPI RAS, Vavilov str.38, Moscow, 119991, Russia.

Review Article

Received date: 26/05/2015
Accepted date: 28/01/2016
Published date: 30/03/2016

***For Correspondence**

Victor V Apollonov, Prokhorov GPI RAS, Vavilov str.38, Moscow, 119991, Russia, Tel: +385 (51) 770 447

E-mail: vapollo@kapella.gpi.ru

Keywords: Anti-satellite, Collision, High-frequency, Laser radiation, Space debris.

ABSTRACT

Studies show that the number of debris in Low Earth Orbit is exponentially growing despite future debris release mitigation measures considered. Especially, the already existing population of small and medium debris is today a concrete threat to operational satellites. Ground based DF-laser solution which can remove at low expense and in a non-destructive way hazardous debris around selected space assets appears as one highly promising answer. SSL with LD pumping based on space vehicle as an additional solution is under consideration in the paper.

INTRODUCTION

Space debris is a collection of man-made objects and their fragments in space, which no longer function and serve any useful purpose. Besides, space debris includes objects of natural origin, such as meteorites, asteroids, etc. Thus, we can single out several categories of space debris:

(i) Spent upper rocket stages and detached stages;

(ii) Old satellites;

(iii) Products of anti-satellite tests and debris formed due to collisions of satellites;

(iv) Objects of natural origin.

DANGEROUS STRANGERS

Most space debris includes small fragments less than 10 cm in diameter. The most significant contribution to the 'littering' of the near-Earth orbits have been made by anti-satellite missiles used to destroy worn-out satellites, which led to the formation of new fragments measuring from centimeters to several meters in size. Explosions and unintended collisions in space are the most dangerous sources of space debris [1-4].

One of the first victims of the space debris was the crew of the shuttle Challenger in 1983, when the spacecraft collided with a small-size particle (less than 1 mm in diameter); as a result, there appeared a crack in the porthole. Later, the experts concluded that it was a microscopic particle of paint detached from some spacecraft. The Soviet space station ‘Salyut-7’, which was also hit by microscopic particles, continues the list of victims of space debris. The Russian space station Mir whose solar battery was punched in the 1990s by a piece of space debris, which resulted in a ‘hole’ of more than 10 cm in diameter, was no exception.

Now the International Space Station (ISS) can maneuver to avoid possible collisions with space debris (this year it has been already done seven times), but the safety of the station is still the main concern to the experts. Thus, in 1999 the ISS nearly collided with a fragment of the upper stage of the rocket, long wandering in space. In 2001 the station had a chance to be hit by a 7-kg instrument lost by U.S. astronauts during a space mission. Based on this experience, the station orbit correction and its maneuvers are carried out regularly.

Besides, space debris is also unsafe for the inhabitants of the Earth, because it can fall down on heads in the literal sense of the word. Suffice it to recall the fall of the Skylab satellite in Australia. Fortunately, no one was killed except a cow in this accident. In 1991 the Soviet station 'Salyut-7', which had already experienced much during its operation life, got broken up into fragments over Argentina. Of particular concern is the space debris, which contains radioactive materials. Thus, the Cosmos 954 satellite powered by a nuclear reactor fell from orbit in 1978 in Northern Canada to the "delight" of local authorities and ecologists.

In addition, there were cases when fragments of space debris, which did not burn up during the atmosphere re-entry, injured people. For example, in 1997 a fragment of the second stage of the Delta launch vehicle injured a woman's shoulder.

It becomes apparent that what in the near future the problem of collisions with space debris will have to be taken into account when calculating the ballistic trajectories of any space mission (at the moment it is done only for orbital stations and large satellites). The trend of miniaturization of spacecraft and use of groups of small spacecrafts instead of a large one only exacerbates the problem, increasing the total number of objects in the near-Earth space.

Virtually the entire man-made space debris is metal fragments of the former spacecrafts (made of steel, titanium and other metals) moving in elliptical orbits around the Earth. By their size they are divided into four categories: small (from 1 to 10 mm), medium (from 1 to 10 cm), big (larger than 10 cm for LEO and larger than 1 m for geostationary orbits) and microfragments (less than 1 mm). The distributions of space debris in size and damage as well as the ways of struggling with it are presented in **Table 1.**

Table 1. The distributions of space debris in size and damage.

Size	>10 cm, LEO >1 m, geostationary orbit	Medium, 1 – 10 cm	Small, 0.1 – 1 cm	Microfragments, <0.1 cm
Number	14 thousands (under observation)	300 thousands	70 – 80 millions	10 – 100 trillions
Effect	Loss of a spacecraft	Serious damage	Significant damage	Surface erosion
Solution	Mechanical removal, maneuvering, laser removal	Laser with a power up to 500 kW	Architectural protection, hardening	Not necessary

Large SD fragments can be observed by ground-based tracking systems. Many of them are tracked and catalogued. Due to the presence of different space debris categories and methods of debris removal by different laser systems, one can single out the following independent tasks which differ in formulation, criteria for space debris irradiation and, correspondingly, in the average power and the output repetitively pulsed radiation parameters:

1. Avoidance of collisions between controlled space debris and spacecraft.

2. Spacecraft protection from collisions with approaching space debris.

3. Removal of space debris from LEO and GEO.

The first two problems are directly related to the protection of a particular spacecraft from space debris, whereas the third one refers to the task of global LEO and GEO cleanup.

As an effective means of addressing these problems, it is proposed to use high-frequency, high-power repetitively pulsed laser systems. The principle of debris removal is very simple: Radiation of a laser system rapidly heats the debris surface and removes part of the material owing to evaporation. Depending on the absorbed energy and the exposure time, the space debris can break down into smaller fragments which do not threaten the spacecraft, or can change the flight trajectory due to a recoil momentum, and prevent a collision with the spacecraft. Complete evaporation of small fragments of space debris is also possible.

The most powerful at the moment are DF chemical lasers [5]. Their use is preferable when the laser beam passes through the atmosphere. When use is made of a space-borne laser setup, advantage can be taken of a solid-state diode-pumped laser. To remove efficiently the space debris, it is proposed to use a DF chemical laser and a solid-state laser in the *Q*-switched or the gain medium modulation regime, i.e., in the repetitively pulsed regime. In this case, the peak values of the intensity of the radiation incident on the space debris increase by orders of magnitude compared to the cw regime. Experiments performed at the A.M. Prokhorov General Physics Institute of the Russian Academy of Sciences showed that the optimal (in terms of the maximum energy output) modulation frequency of a DF laser is ~150 kHz, and the excess of the peak power over the average output power is 2-3 orders of magnitude. In the case of a solid-state laser the optimal frequency is about 100 kHz, the pulse duration lying in the range ~10^{-7}-10^{-8} s.

To solve the above-mentioned problems, use can be made of various laser systems, both with a ground-based and a space-based power plant:

-A stationary ground-based laser system (GBLS) ensuring beam focusing and pointing on a space debris fragment;

-A standalone space-based laser system (SBLS) also ensuring beam focusing and pointing on a space debris fragment.

This paper presents the results of preliminary calculations, which allow one to address the above-mentioned problems relying on the use of different laser systems. To determine the ratio of the chemical laser power in the cw and repetitively pulsed regimes, use was made of the models based on the Navier–Stokes equations, with all the essential chemical and vibrational kinetics processes taken into account. Radiation on various vibrational–rotational transitions in the repetitively pulsed regime was calculated using the equations for a free-running and *Q*-switched laser resonator. At small pulse durations (<100 ns) non-equilibrium distribution of emitting molecules in the rotational levels of the generation process was taken into account.

LARGE TARGETS

A considerable part of space debris fragments is controlled by means of tracking, their trajectories are known, and the largest space debris fragments are catalogued. The space debris fragments that represent a threat to the spacecraft and the time of a possible future collision are well known. Due to collision threat warning technology, there is an opportunity to remove a fragment in advance **(Figure 1).**

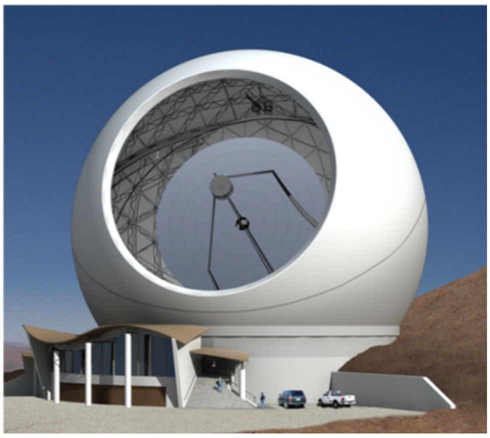

Figure 1. Larger mirror of a ground-based laser.

This problem can be solved by using a ground-based DF laser, which directly shots the fragment from the Earth (from a mountain of height 2.5–3.5 km). More preferable are mobile airborne laser systems (ABLSs), which allow their transport at the right moment. The most preferred mobile system is an ABLS at a height of ~20 km, which allows one not to distort radiation during its passage in the upper atmosphere and to transport the installation to any part of the Earth. The advantage of mobile systems in case of low repetition rate lasers is the fact that in case of failure when the fragment is not destroyed by a train of pulses or in the case of the system failure, the possibility of rapid transport of the system to the nearest point of the space debris fragment passage allows the laser firing to be repeated after a short period of time (less than one day).

A stationary GBLS is used to destroy space debris fragments moving at a low orbit over the laser. The beam impact is effective in the sector with a full opening angle of ~30° with respect to the vertical, and the region of interaction at a height of 300 km is a circle with a diameter of ~160 km. When flying over the Earth the space debris leaves a spiral ‘footprint’ with a width of 160 km, making 16 orbits a day, which are spaced at a distance of about 2.5 thousand km from each other. Thus, ~5200 km of the circumference of the Earth is covered each day, the circumference being covered in 8 days on average. Therefore, stationary lasers can be used only when the global early warning system tracks a fragment and the laser itself is mounted in the right place. However, with a significant increase in the laser pulse repetition rate (high-frequency repetitively pulsed regime), there can arise a situation when the space debris fragment is destroyed during its orbiting over the stationary laser system.

Consider the mechanism of irradiation of a metal space debris fragment. Metals are good absorbers of radiation in the mid-IR range. Part of the melt is removed in the form of droplets with a sharp increase in the interaction zone. In the absence of gravity, this effect is most pronounced because the melt cannot be kept on the surface. In weightlessness, liquid droplets are quickly destroyed by heating, because the internal pressure overcomes the surface tension before the process of evaporation **(Figure 2).**

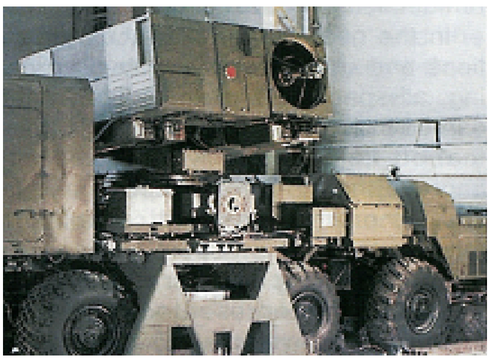

Figure 2. Mobile, ground-based laser.

Thus, the task is to ensure the conditions of intensive evaporation of the space debris material. In this case, we should 'pump' by a pulse train the required energy into a thin surface volume for the time when the material have no time for the heat spreading to occur throughout the entire volume, which ensures the destruction of the fragment surface and the creation of a mechanical recoil momentum.

We carried out assessments on the basis of a DF laser and an Nd: YAG laser. The estimates allow us to formulate fairly precisely the technical requirements to a laser system, whose parameters correspond to the achievement of a minimally sufficient pulse when laser radiation interacts with the surface of a refractory target. It is assumed that this is sufficient when the onset of irradiation is appropriately chosen in order to remove a space debris fragment from the interaction region of the spacecraft's and debris fragment's orbits. For more fusible materials requirements to the average laser power are lessened. It is clear that the increase in the average power of a laser source simplifies the solution to this problem, thereby making it possible to destroy or remove a space debris fragment by using fewer pulses.

SHORT-RANGE PROTECTION

The problem of protection of a spacecraft from collisions with space debris or objects of natural origin (when they approach the spacecraft) is solved by using an autonomous, solid-state, diode-pumped SBLS installed directly on the protected spacecraft, or running along the same orbit near the spacecraft. The laser must have sufficient electrical power to operate continuously in orbit.

To remove the threat of a collision requires endowing the space debris fragment with such an amount of energy that the fragment will start braking and lag behind the spacecraft or its trajectory will change so much that it will miss the spacecraft. It is clear that the net effect on the target, compared to the stationary problem, should be much more powerful. This is accompanied by intense evaporation of the space debris material; therefore, ionization of vaporized molecules and plasma formation are also possible. To evaluate the braking effect, there exists a semi-empirical formula, which shows that under the action of a laser pulse, the space debris fragment velocity Δv, associated with the absorbed pulse energy, changes due to the expansion of the plasma produced Δv=Cm $E[m$, where E is the absorbed energy; m is the target mass; and C_m is the coefficient determining the energy efficiency of the usage of laser radiation energy to implement evaporation and, to a large extent, depending on the type of target material, the radiation intensity I_{peak} and pulse duration.

The conditions being far from optimal, the laser pulse action decreases rapidly; therefore, we assume that the peak intensity is optimal. Note that the power density of ~10^8 W/cm^2 is widely used for laser drilling and cutting of materials under sublimation or ablation. This irradiation regime of space debris can be called 'hard.' In the interval between two successive pulses at a repetition rate of ~100 kHz the plasma expanding into vacuum has the time to travel a distance of about 1 to 2 cm, which is enough to get rid of the plasma screening effect on a target.

The average laser power is associated with a mirror diameter, distance to the target and beam divergence. Space-based, diffraction-limited, repetitively pulsed, solid-state, diode-pumped lasers with an output power of 100−1000 kW and a pulse duration of 10−100 ns will provide in the 'soft' regime the necessary impact on a space debris fragment at an aiming distance of 100 km. The light spot on the fragment at this distance will be within 8 cm.

This scenario of using a ground-based DF laser (both mobile and stationary) with a receiving glass mounted on the spacecraft is suitable only when the point of collision of a spacecraft with a space debris fragment lies in the region of the GBLS action, which is a highly unlikely event. However, we note that in this case the receiving glass mounted on the spacecraft needs to be large enough to intercept the entire radiation beam. Estimates show that the required diameter of the receiving mirror, depending on the beam divergence, must be several meters. The use of a fully terrestrial laser system for 'hard' irradiation of the space debris fragment by a DF laser directly from the Earth would require a laser system with high average powers.

LASER BRAKE

As was stated above, clearing near-Earth space debris is possible when use is made of a standalone space-based HF laser with a focusing and a beam pointing systems. To speed up the fall of a space debris fragment to the atmosphere requires the fragment braking and transfer to a lower altitude with a shorter 'lifetime.' It is known that the dwell time ('lifetime') of a space debris fragment in orbit is highly dependent on the height of the orbit. The lifetime of a fragment at an altitude of 1000 km is about 2000 years, at an altitude of 600 km− ~25−30 years, at an altitude of about 200 km−about a week. In the altitude range of 100−1000 km the dependence of the space debris fragment lifetime on the height above the Earth can be approximated as $T \sim H^7$. With such a strong height dependence, even a small deceleration and an orbit decrease lead to a significant reduction in lifetime. Thus, the lifetime decreases from 120 to 6 days with decreasing the orbit from 300 to 200 km.

The accurate estimates require special modeling and calculations for each particular orbit. Theoretically, in the entire range of laser irradiations (from 'soft' to 'hard'), the fall of space junk on the Earth is accelerated. As follows from the estimates, in the 'hard' regime a train of high-power laser pulses (when a fragment flies over the stationary laser) can decrease the orbit of a space debris fragment to the required level. If this fragment enters the upper atmosphere (H~100 km), it slows down and burns out during 1-2 orbits; thus, the problem is solved. However, this formulation seems excessive, because it is quite often sufficient to lower the fragment's orbit, so that its orbit is below that of the spacecraft.

Based on the available literature data, we can assert that the space-based laser power of about several tens of kilowatts is sufficient to significantly reduce the lifetime of a small fragment. Naturally, the further increase in the laser power further reduces the lifetime, i.e., increases the effectiveness of the fragment entry to the atmosphere; therefore, near-Earth space debris can be rather rapidly cleared using a standalone SBLS with an output power of several hundred kilowatts. The number of laser shots will be determined by the accuracy of direct hits and the time needed for a space-based laser to become operational again.

When use is made of a ground-based laser system with a receiver mirror installed on a spacecraft, the energy loss during the passage of radiation through the atmosphere and the mirror loss will require a much more powerful installation (apparently, the level of several MW). The number of laser shots is determined by the number of passes of the mirror over the ground-based laser (on average no more than once every 8 days) and the probability of the fragment location within the laser hitting range in these periods. In this case, less laser shots are needed compared to the case when use is made of a standalone SBLS. There exists a scenario of a simultaneous maintenance of many space debris objects, which will require their constant monitoring and cataloging.

Finally, we note that a more detailed study of the presented problem, in particular, of the effect of the pulse repetition rate and duration, relative velocities of the space junk, laser power, etc. on the space debris destruction should rely on a more accurate mathematical modeling of repetitively pulsed laser processes, radiation propagation, effectiveness of its action on the target, etc.

The laser systems considered in this paper can be applied not only to the problems related to the space debris, but also to other large projects. In particular, they can be used to design and build laser rocket engines, to perform wireless energy transmission over long distances, to clean the water surface from oil products, to clean lengthy and complex surfaces, to protect valuable and environmentally hazardous objects, etc.

POSSIBLE VARIANTS OF CREATION OF LASERS

The need for a repetitively pulsed chemical laser operating at a pulse repetition rate of ~10−100 kHz and duration of 10–100 ns leads to the fact that the laser system should rely on the use of an optical scheme with two small- and medium-scale active medium generators, an average output power level in the master oscillator not exceeding 5–10 kW. First of all, this will allow one, for the repetitively pulsed regime implementation, to use well-proven methods, based either on the electro-optic effect or on the method of a passively *Q*-switched optical resonator in the master oscillator. Secondly, it is well known that at a relatively low power level, near-diffraction divergence of radiation is easy to obtain.

A solid-state, diode-pumped laser should be compact and lightweight to transport in outer space. A prototype of such a laser with a power of over 100 kW has been recently designed in the USA. Soon, we can expect this laser to be scaled up to a level of 500–1000 kW. The repetitively pulsed regime in the case of this technological solution is also possible.

Fabrication of high-power, solid-state lasers with a large cross section of the output beam (wide-aperture lasers) is a complex scientific and technical problem of modern laser physics. One of the possible solutions is based on a multi-channel laser principle. In accordance with this principle, the laser represents an array of identical channels, each of which ensures lasing. Such an array of lasers forms an optical source with a composite aperture, whose output radiation is a collection of individual laser beams. The small cross section of the channels allows efficient and easy energy pumping into the active medium and the heat removal from its volume.

With large structural advantages of multibeam lasers, to obtain high directivity of their radiation is a challenging physical problem. In a multichannel laser each channel in the case of independent lasing emits a wave whose phase is not dependent on the phase of the waves of other channels. Fields of the channels are incoherent, and their intensities are summed.

In a multichannel laser beam in the case of in-phase regime of collective generation, the radiation phases of the individual channels coincide. The output beam is in this case formed by the interference of the waves whose phases on its axis are equal. The angular divergence in the axial region of the beam during the in-phase generation of channels is close to the divergence of a wide-aperture laser with an aperture diameter D. Therefore, a key challenge for multichannel lasers is to provide an in-phase regime of collective generation.

The system of detection, beam formation and pointing–the information-sighting system (ISS)–should be directly mounted on a spacecraft. The issues concerning the system elements' arrangement in the spacecraft modules (together with the elements of the system of radiation generation) are not discussed here. Note that the ISS makes use of two pointing channels (radar and high power). More complex ISS schemes relying on the use of two, three or more channels are also possible.

The ISS telescope, forming the output radiation, is placed on a rotating platform. The ISS must provide the following basic functions:

(i) To receive target designation from external (with respect to the laser) systems;

(ii) To point the shaping telescope axis in the direction of the target;

(iii) To determine the target angle;

(iv) To make the laser radiation power axis coincident with the target angle by controlling the angular position of one of the ISS mirrors;

(v) To carry out real-time tracking of the target with the required accuracy;

(vi) To provide automatic readjustment of the cavity mirrors and power channel as a whole; and

(vii) To record the radiation arrival at the target.

A wide range of functions performed by the ISS suggests a rather complex structure, which should be developed in line with the objectives imposed on a laser system. We only note that at an average power level of 500 kW the specific consumption of fuel components is estimated to be 3.5 kg per second. Despite the repetitively pulsed irradiation of a space debris fragment, working components should be supplied continuously. With the onset and termination of laser operation taken into account, the typical irradiation duration of a space debris target will take at least 2-3 s. It is clear that a sufficiently effective use of the laser implies that the fuel supply should be sufficient to destroy or remove quite a large number of targets (~100), which means that the desired amount of fuel before the next refueling should to be at least 600 kg.

As noted in the previous section, due to the significant absorption of radiation in the atmosphere, in the case of a GBLS use should be made of a DF chemical laser. This laser should be placed at a sufficient height above sea level (~2.5–3.5 km). Besides, the DF laser should operate in the repetitively pulsed regime with a repetition rate at 10–100 kHz, the optical quality of output radiation being better than three diffraction limits (the latter can be achieved, for example, by the method of adaptive optics). With a shaping telescope having a main mirror of diameter D = 30 m the DF-laser radiation is directly transmitted to a space debris fragment or a receiving mirror mounted on the spacecraft. Apart from a focusing telescope, the spacecraft should have the systems installed which allow detection, tracking and pointing of power radiation at a space debris fragment.

The estimates show that the current level of chemical laser technology in Russia [6] makes it possible to construct a stationary system for efficient removal of space debris fragments from orbits. International cooperation is possible and, which is more important, desirable in this field. Two last conferences in the area of high power lasers and applications confirming this. The space of the Universe is vast. However, here in our solar system, as at home, we need to put things in order, to throw away old and buy new stuff, and ensure that the ‘space casket’ is not overfilled one day. To date, the problem of space debris removal is one of the challenging and cannot be solved by any single country separately. However, both politicians and scientists in space industry are united in one thing: Space debris must be controlled to ensure space activity in the future. Members of all space-faring nations must sit down at a round table and discuss the implementation of the problem in practice rather than in theory.

REFERENCES

1. Phipps CR, et al. Proc. SPIE. 2004;5448.
2. Apollonov VV, Elimination of space debris and objects of natural origin by laser radiation. Quantum electronics. 2013;43:9.
3. Apollonov VV, Symposium ISBEP-7. 2012; Ludwigsburg. Germany.
4. Apollonov VV, Expertnyi Souyz No5, 2014.
5. Bashkin AS, et al. On the possibility of simultaneous emission of an autonomous cw HF-DF chemical laser in two spectral ranges. Quantum electronics. 2008;38.
6. Apollonov VV, High power P-P lasers, NOVA. 2014.