Space mini-vehicle with the laser propulsion system
Space Laser Cleaner

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Abstract

In the paper, the space mini-vehicle with a laser propulsion system, called like a Space Laser Cleaner (SLC), is considered. The vehicle is assumed to be used to remove space debris off geostationary orbit, to monitor a large-size space station during its inter-orbital missions, to monitor near-Earth space, and so on. In all cases, there is a necessity of using a small mobile spacecraft without the fuel and power great consumption. SLC system is specially designed to meet complex space manoeuvre and to save propellant consumption. SLC thrust system is also based on a new technique of laser propulsion production in a supersonic mode.

1. Introduction

One of the challenging problems of modern astronautics is a mitigation of space debris surrounding the Earth [1]. The space debris consists of spent space vehicles, third rocket stages as well as small fragments of satellites produced due to their mutual collisions, and so on. All of these objects are safety hazards to new space missions and for man-tended mission especially.

A number of various projects on de-orbiting the debris objects off near-Earth space are under the development at present time [2]. These projects are usually based on application of passive or active de-orbiting techniques. As the examples of the passive one, the use of electrodynamics tethers with a length of a few hundreds meters interacting with the Earth electric field or solar sails unfolded in a space are considered [3]. But, uncontrolled and long term period of debris de-orbiting are main disadvantages of the passive technique.

The use of space trash-collectors picking up large-size debris and transferring it into the storage or submerge orbits is an example of active de-orbiting technique [3]. Trash-collector is usually considered as a part of a common space transportation system in geostationary orbit (GEO). It is estimated the use of trash-collector will allow removing about 750 of GEO spent vehicles during 10 years of an exploration [3]. Taking into account the fact that there are about 1500 of the vehicles in GEO, one can conclude that about 20 years will past to make the GEO free against the objects.

The trash-collector concept has a great appeal, but it demands more detailed elaboration of technical requirements to the collector design and composition. For the example, to perform the mission on removal of spent vehicle arranged in GEO, the trash-collector has to rendezvous to every vehicle at a short distance, to pick up it including also such maneuvers as approaching, acquisition, and de-orbiting. Every rendezvous takes large fuel consumption, while number of the trash maneuvers is limited because of that. To solve the fuel problem, MDA Canadian Company develops Space Infrastructure Servicing station arranged in GEO that will allow to fuel trash-collector when the necessity arises. Another way of solving the problem is a development of space mini-vehicle pre-arranged on a trash-collector board and being used to transfer spent vehicles onto the collector board [3].

There are also a few projects on the development of space tugs based on laser propulsion for space missions [4, 5]. Laser Orbital Transfer Vehicle (LOTV) is considered in [5] and other publications [6] as an example of the tug. We also analyzed the LOTV approach as applied to space debris mitigation by the use of airborne high-power lasers to produce a thrust [4]. Multiple experimental and theoretical investigations on laser propulsion have been done during past decades in such countries as Russia, USA, Germany, China, Japan, Brazil (see Proceedings of International Symposium on Beamed Energy Propulsion [6]). The investigations resulted in the use of high-power lasers (a 500 kW power and more) for the LOTV missions even then a precise delivery of the laser power to the vehicle through space distances is provided.

In the paper, we propose a space mini-vehicle with a laser propulsion system for consideration, called like a Space Laser Cleaner (SLC). The vehicle is assumed to be used to remove space debris objects off GEO, to monitor a large-size space station during its inter-orbit missions, to monitor a near-Earth space, and so on. In listed cases, there is a

necessity of using a small mobile spacecraft being capable of a complicated orbital manoeuvre without a great propellant consumption at average laser power.
Space Laser Cleaner differs from LOTV by relatively small outside base, requires less laser power, and provides mitigation of GEO spent satellites at a joint operation with a trash collector.

2. Optic arrangement of the space laser cleaner

The SLC optical arrangement is designed by using the following basic points.
1. Independence of the SLC orbital manoeuvre on a mutual orientation of a remote laser and the vehicle. In this case, laser propulsion engine of a special design is developed [7].
2. Minimal energy losses are accepted to receive the laser power and to covert the power into a thrust. The losses are known to depend on matching of the transmitter and receiver laser telescopes apertures, laser radiation wavelength, and total efficiency of the laser power delivery to SLC receiver telescope.
3. Basic optical axis in the SLC optical scheme is assigned by such a way that both SLC spatial orientation system and receiver telescope axes are combined.
4. Laser propulsion engine provides a high production efficiency of laser propulsion (~ 70 % [8]), being no less than the efficiency of electric jet engines.
SLC optical arrangement is shown in Figure 1 conceptually. Here, X is a basic optical axis. Laser propulsion engines are arranged at Y and Z axes. The SLC receiver optical system includes itself two telescopes with optical turrets, related by X axis. Every turret turns around X axis up to 170^0 in the X-Y plane. To change a plane of coverage space, turret turns around X-axis at a plane angle of 120^0. Every telescope provides receiving laser power, and combined optical switch transmits the power to every laser propulsion engine. The SLC spatial orientation system is assumed to be based on stray trackers providing a space orientation angular accuracy of 10^{-3} radn.

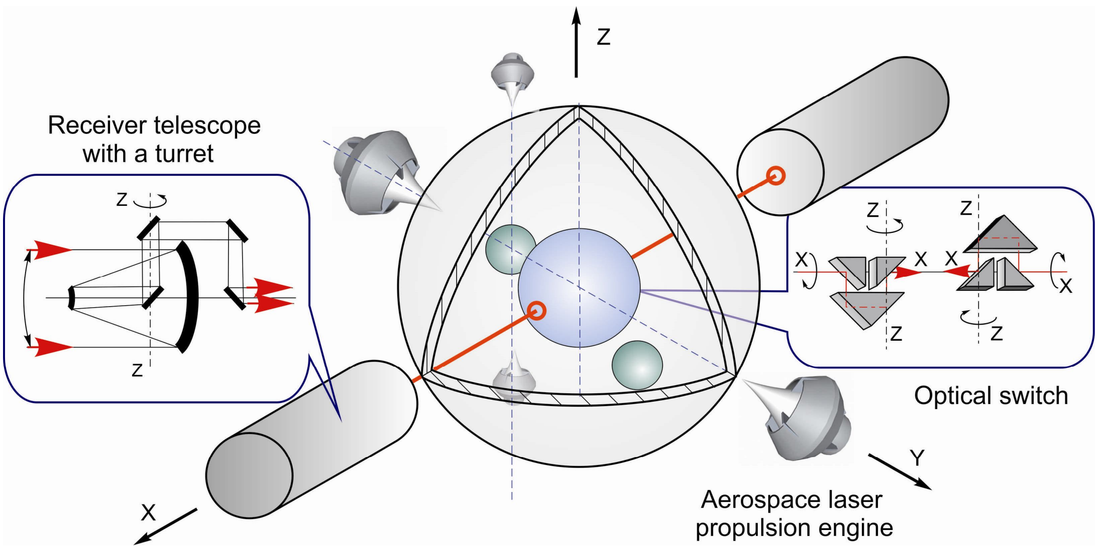


Figure 1. SLC optical arrangement.

SLC laser propulsion system involves three modules of laser propulsion engines as a minimum to provide a complete SLC space maneuver. At that, every thrust vector of the engines crosses a center of the SLC inertia.
The receiver telescopes are designed by the use of a conventional two-mirror system constructed by off-axis scheme [9] to exclude laser power losses because of laser beam screening by a secondary mirror. The optical circuit of one of the telescopes is shown in Figure 2. Here, M1-M4 are mirrors of optical turret directing a laser beam to the SLC basic optical axis, and M5 and M6 are the off-axis telescope mirrors. The turret provides keeping the beam direction inside the SLC independently on a direction of incoming beam.
In the figure 2, the turret rotation axes are identified by chain lines. Horizontal one indicates a basic optical axis of the receiver telescopes. M4, M5, and M6 are the mirrors rotating around a vertical axis and providing coverage space in a plane being perpendicular to the figure plane. Mirror M2 is designed as a low-transparent mirror to supply an equipment to detect the laser beam characteristics (laser power, radiation intensity, and so on).

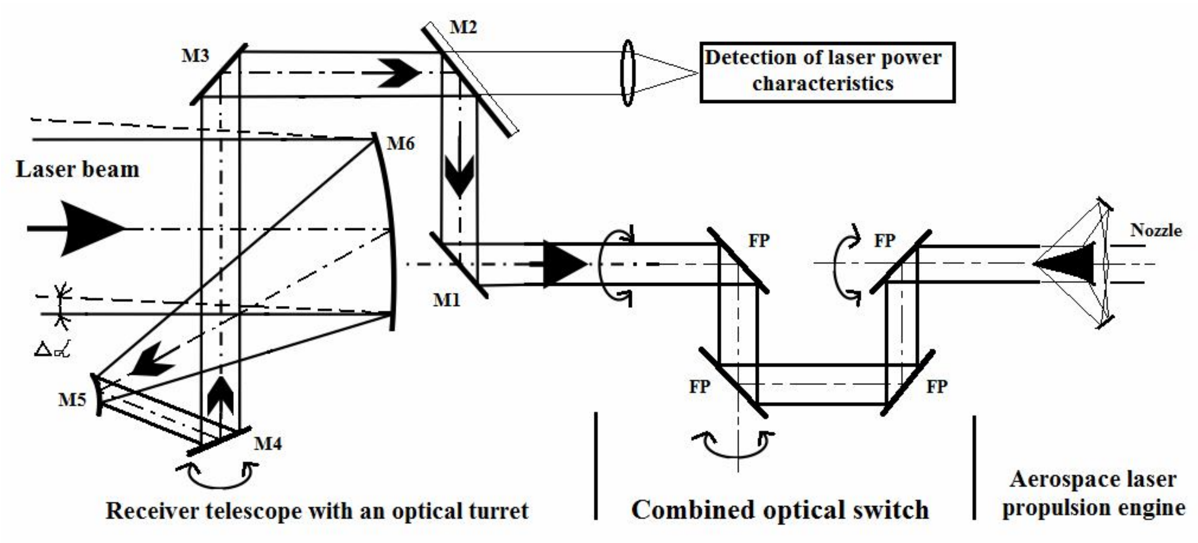


Figure 2. SLC optical circuit including airspace laser propulsion engine.

Here, FP is flat mirrors, Δα denotes an input angle of incoming laser beam in respect to a basis optical axis of SLC. Expected parameters of the telescope mirrors are listed in Table 1 at the assumption the distance between laser and SLC is 100 km (see below).

Table 1.

mirror	diameter, m	thickness, m	mass, kg (min/max)
M1, M2, M3, M4	0.16	0.025	1.11 / 4.47
M5	0.12	0.02	0.46 / 1.85
M6	0.35	0.05	10.6 / 42.8

Combined optical switch (see Figure 3) is one of the main units of the SLC optic arrangement, which is specially designed to distribute a laser power between laser engines operating at the moment. Various optical deflectors are assumed to be used as an actuator mechanism of the switch [11].

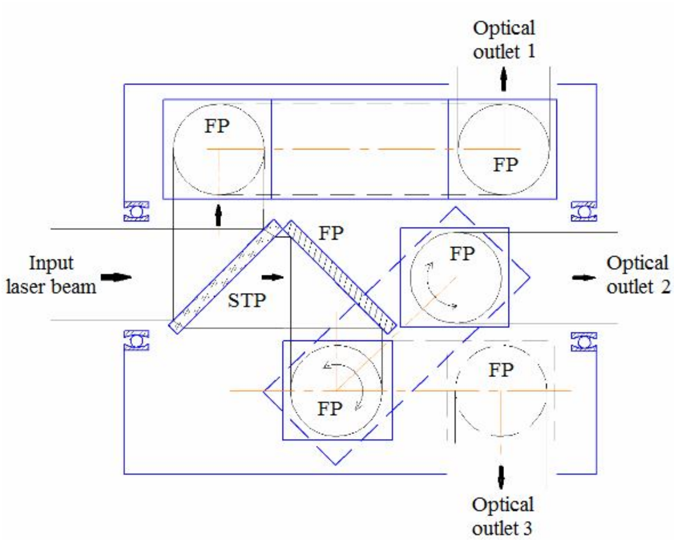
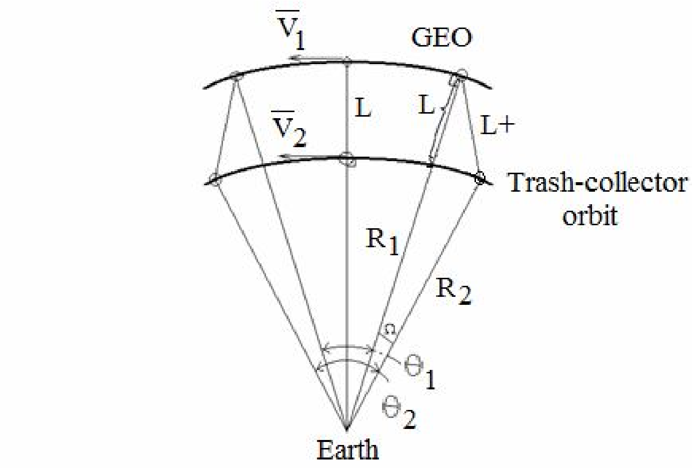


Figure 3. Combined optical switch scheme

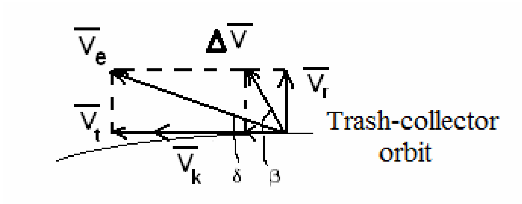
The switch operates as follows. Laser beam comes into the switcher on the left input. Then, the beam passes to a semi-transparent plate (STP). A part of the beam reflected from the plate comes to a fixed optical element and then to optical output 1. A part of the beam that came through a semi-transparent plate is reflected by a flat plat (FP) into conventional optical switch unit, which distributes laser power between two optical outlets, 2 and 3. Then the laser beam is directed to one of laser engine modules to produce a thrust.
Some auxiliary requirements to the SLC optical arrangement units are considered more detailed below at developing the SLC maneuver scenario.

3. SLC maneuver scenario to remove GEO debris

To define technical requirements to the SLC optical units and to onboard laser propulsion, we suggest the following scenario of SLC maneuver from a trash-collector board to GEO satellite and to back way. At a moment of time when a trash collector approaches the satellite at a distance of L~ 100-200 km in the orbit being lower than GEO, SLC module detaches from the collector and moves to the satellite by a controlled trajectory. At that, one of the SLC receiver telescopes tracks continuously a laser arranged on a board of the trash collector to catch the laser beam. Another SLC telescope follows up the satellite orbital position to control the SLC maneuver. When SLC comes closely to the satellite at a distance of a few hundred meters, the SLC laser propulsion module equalizes orbital speeds of the SLC and satellite. After capturing the satellite as an additional load, SLC moves back to a trash-collector. If it is necessary, the SLC operational maneuver is resumed to capture another object.
SLC maneuver control is assumed to be realized by the following two ways. By the first one, laser propulsion modules control the SLC maneuver in whole, including equalization of the SLC and GEO satellite orbital speeds. By the second way, such operational procedures as the speeds equalization and capturing satellite are carried out by using electric jet engines, reducing SLC onboard propellant consumption. But in this case, lightweight devices of the electric engines has to be chosen because of limitations on the SLC load mass [12].
Let's consider the case when trash-collector moves along an orbit located lower than GEO at a distance of 100 km (see Figure 4). Satellite arranged in GEO has an orbiting period T of 23 hours 56 minutes and 4.09 s, which is equal to a sidereal day. It moves in a near-circular orbit with a zero orbit inclination in respect to the Earth equatorial plane.



a)



b)

Figure 4. SLC inter-orbit transfer diagram and velocity vectors

Initial distance (L+Δ) (Figure 4a) between the trash-collector and satellite specifies a time interval t that is required SLC to approach the satellite, capture it, and carry the satellite onto the collector board. Here, L is a radius difference of both orbits and Δ is auxiliary increment of the distance difference. The time interval is the SLC operation period. In accordance with the orbits geometry, we can define the period as:

$$t(\Delta) = 2 \cdot acos\left(\frac{R_{ц}{}^{2}+R_{н}^{2}-(L+\Delta)^{2}}{2\cdot R_{ц}\cdot R_{н}}\right) \Big/ \left|\frac{V_{н}}{R_{н}} - \frac{V_{ц}}{R_{ц}}\right|, \quad (1)$$

Here, $R_{н}$ and $R_{ц}$, are the Earth orbits radius of SLC and satellites, $V_{н}$ and $V_{ц}$ are the trash collector and satellite orbital velocities, consequently. The results of calculation of the SLC operation period are listed in Table 2.

Table 2. SLC operation period for various distance increments, Δ.

Δ, km	1	2	3	4	5	10	14	16	20	100
t, hours	0.72	1.02	1.25	1.45	1.63	2.33	2.78	2.99	3.37	8.78

Let's estimate an extra velocity that has to be imparted to SLC and a propellant consumption for that the SLC module comes to the satellite. It is assumed also the trash-collector, SLC module, and satellite are coplanar ones to simplify the task. The moment of time when SLC module detaches from the collector is considered as a reference time point.

To analyze numerically the SLC orbital maneuver, the geocentric coordinate system is chosen [13]. At that, an origin point of the system is located in the Earth center (see figure 4a). And X axis is directed into first point of Aries, Z axis is directed into the North Pole in the line of an angular velocity vector of the Earth proper rotation, and Y axis forms a right-handed coordinate system jointly with other axes. The equatorial and GEO planes coincide with the OXY plane in the co-ordinate system.

As is known, the rendezvous-compatible orbital trip can be realized by a few ways [13], namely:

1) double-pulse maneuver along an intermediate orbit that is called as a Hohmann orbital transfer;
2) orbital maneuver from a circular orbit into an intermediate elliptical orbit crossing the satellite orbit in a specified point K;
3) orbital maneuver along a spiral trajectory at a low thrust operational mode.

Hohman ellipse transfer and spiral orbital trips under a low thrust are not suitable ones for the SLC maneuver because both of a long transfer time to be realized. Therefore, we consider a SLC elliptical trajectory crossing both the trash-collector and satellite orbits as a most probable transfer trajectory. It is known the elliptical trajectory is not an optimal one as regarding a propellant consumption for the maneuver [14]. But, estimations show a minimal transfer time is achieved in the case if both orbits, between which SLC moves at a moderate propellant consumption, are coplanar ones.

To change SLC orbit into a specified elliptical transfer orbit, the SLC vehicle has to be accelerated up to V_e velocity, vector of which crosses the circular orbit at a δ angle in a specified point of the transfer orbit (see Figure 4b). We consider also the case when SLC initially moves on a circular orbit with a V_k velocity jointly with a trash-collector.

As one can see from the figure, velocity increment vector (ΔV) crossing the SLC initial orbit at an angle of β can be expressed as a vector sum of radial V_r and tangential V_t velocity components. The increment vector value is determined from the following equation [14]:

$$Ve = \Delta V \Big/ ln\left(\frac{m}{m-{F_t}/{(I_{sp}\cdot g)}\cdot t_d}\right) \quad (2)$$

Here, $V_e = I_{sp} g$, I_{sp} is a specific impulse of laser propulsion and $g = \mu/R_n^2$ is a gravitational acceleration at the trash-collector orbit (m/s^2), μ is a gravitational parameter.

Table 3 summarizes the results of numerical calculations of the SLC maneuver parameters at various values of ΔV. In the table, SLC vehicle mass is assumed to be m = 50 kg. And the following thrust characteristics of laser propulsion are taken for the SLC orbital maneuver, namely: thrust F_t = 1.5 N, specific impulse I_{sp} = 2367 s, momentum coupling coefficient C_m = 150 dyne/W, which corresponds the engine operation efficiency of 40 %.

In the table, t_d is laser propulsion engine operation time; t_{flight} is a transfer time period of LSC from start point to satellite orbit; Σ $t_{LPE}/t_{LPE\ op}$ are total periods of the jet engine operation without/with speed losses caused by gravitational forces, Σ ΔV is a total characteristic velocity of the LSC maneuver; ΔV_g and ΔV_u are velocity losses caused by the gravitational forces and flight control; $\pi/2-\delta_к$ is a crossing angle of the SLC elliptical orbit with a satellite orbit; Σ $M_{P.B.}$ and Σ $M_{P.B.p}$ are total propellant mass consumption without and with subject of the velocity losses.

Table 3.

β, °	ΔV_1, m/s	t_{flight}, s	Σ t_{LPE}/ $t_{LPE\ op}$, s		ΔV_2, m/s	$\Delta V_g + \Delta V_u$, m/s	Σ ΔV, m/s	Σ ΔV_{op}, m/s	π/2-$\delta_к$, °	Σ $M_{P.B.}$, kg	Σ $M_{P.B.p}$, kg
0		34818	159	197	2.79	1.146	4.79	5.94	0.042	0.45	0.56
10	2	34243	155	191	2.67	1.027	4.67	5.69	0.039	0.44	0.53
20		35341	142	163	2.27	0.626	4.27	4.89	0.026	0.40	0.46
0		12060	868	1610	16.7	23.14	26.7	49.84	0.287	2.44	4.53
60	10	8923	751	1395	13.0	19.73	23.0	42.74	0.241	2.11	3.92
90		11211	582	1057	7.75	14.462	17.7	32.2	0.127	1.64	2.97
0	50	5242	3303	6232	59.6	101.54	109.6	211.17	0.691	9.29	17.53

The SLC velocity losses caused by the gravitational forces and velocity control are taken into account in the calculations, which growth at increasing an angle between the thrust and vehicle velocity vectors. The velocity losses decrease at shortening the operation period of laser propulsion engine and at optimal control of laser propulsion. All these procedures result in an optimization of the SLC orbital maneuver parameters.

One can see from the table, the larger SLC maneuver velocity increment the less total SLC transfer period. But at that, the operation period of laser propulsion engine increases and it results in increasing of an onboard propellant consumption herewith. For the example, the propellant consumption reaches 17-18 kg if ΔV = 50 m/s (see low rod in the Table 3). And the consumption constructs 1 kg at minimal velocity increment of 2 m/s. The later case requires so long trip period as 10 hours SLC to reach GEO satellite. There is also an optimal scenario of the SLC rendezvous with the GEO satellite, which parameters are functions of the initial velocity increment imparted to SLC, as follows from the table. These parameters include an optimal angle between local horizontal line and thrust vector as well, when the minimal transfer period is achieved. We chose the following parameters of the SLC orbital transfer to refine requirements to laser propulsion characteristics, namely: ΔV = 10 m/s, $\beta = 60^0$, and Σ $M_{P.B.p}$, ~ 4 kg as a perspective one for removing space debris objects occupying GEO.

As is following from the table 3, a minimal period of the SLC transfer to GEO satellite is achieved if the velocity increment of ΔV = 10 m/s is imparted to the vehicle at β = 60°. And the total transfer interval t_1 is equal to 8923 s or 2.48 hours. At the end of the transfer period, SLC captures the satellite by using of one of the developed techniques such as special meshes and so on [1,2]. The capture flight period will take a t_2 long period. After that, SLC comes into operation of back way transfer to a trash-collector with an auxiliary onboard load. In accordance with a classification of geosynchronous objects [2], satellites with a middle mass of 1 000 kg and heavy-mass satellites of 6500 kg are arranged in GEO. But main part of them has a mass of 1000-3000 kg.

To estimate a reliability of the SLC back way to a trash collector, we have also to take into account the trash orbital movements during the SLC transfer missions. Angular orbital velocity of the collector is determined like $\omega_н = V_н/R_н$ or $\omega_н = 7.318\times10^{-5}$ radn/s. The difference in angular velocities of the collector and satellite is $\Delta\omega = 2.602\times10^{-7}$ radn/s. The velocity difference imposes a limit on total time interval that is required SLC to capture the satellite and to come back to the collector board. SLC back transfer to the collector has also 3 stages including acceleration, passive orbiting, and equalization of the SLC and collector velocities, total time of which is t_3. To fulfill the total SLC orbital maneuver, we have to satisfy the condition of alignment of vehicles angular position, namely:

$$\omega_н\times(t_1 + t_2 + t_3) = \theta, \qquad (3)$$

where θ is angular orbital position of SLC at the end of maneuver.

The results of calculation of main parameters of the SLC transfer maneuver are tabulated in Table 4 for spent satellite with 1000, 2000, and 3000 kg masses.

As can see from the table, it is feasible to transfer GEO spent satellites onto a board of a trash-collector by using SLC with laser propulsion produced under the laser power of 1-10 kW. Total transfer time takes of 12 hours if spent satellite has a mass of 3 tons. And total propellant mass consumption will amount to 15.5 kg if a momentum coupling coefficient of laser propulsion is C_m = 150 dyne/W.

Table 4.

a) Maneuver parameters of transferring SLC to satellite and capturing it	
laser propulsion engine operation time , s	777.4
total velocity increment ΔV, m/s	6.56
laser power, kW	1
propellant mass consumption, kg	2.2
inactive orbital flight period, s	841
capture interval t_2, s	600

b) Maneuver parameters of back transferring SLC to trash-collector			
laser power, кВт		10	
satellite mass, kg	3000	2000	1000
laser propulsion engine operation time , s	1567	1252	1028
total velocity increment ΔV, m/s	5.61	4.9	4.1
propellant mass consumption, kg	13.5	12.1	10.8
inactive orbital flight period, s	32855	32875	32890

4. Supersonic laser propulsion as applied to the SLC inter-orbit maneuver

One of special features of the SLC application in a space is a high-efficient production of laser propulsion at a supersonic mode [15]. The supersonic mode means that the interaction processes of laser radiation with a propellant runs in a supersonic gas flow originated in jet engine nozzle [16]. The laser propulsion efficiency is usually estimated by two parameters, namely: momentum coupling coefficient C_m and propulsive efficiency [15]. The coupling coefficient C_m is specified as a ratio of thrust produced to incoming laser power and it defines a laser power per unit thrust. Increasing of total efficiency of laser propulsion engine allows saving onboard propellant and increasing quantity of active transfer made by SLC. The following characteristics of laser propulsion are assumed to be obtained for the SLC mission, namely: 1.5-10.0 thrust, $C_m = 10^{-2}$ N/W at a laser power of 1 – 10 kW, and SLC vehicle mass of 50 kg. It should be noted, the momentum coupling coefficient is high enough as compared to data on C_m obtained earlier by others researchers [16].

One of the first works on laser propulsion at space conditions was published by Pirri A.N. in 1977 [17]. In the paper, the laser propulsion phenomena in a parabolic nozzle at a repetitively pulsed mode of laser operation are analyzed. The parabolic nozzle works also as a beam concentrator producing laser breakdown of a gas propellant in a focus of the nozzle. Basing on a gas-dynamic model of the interaction of induced shock waves with a nozzle wall, self-similar solution of the thrust production in a supersonic gas flow is obtained. It is shown the thrust depends on pulse repetition rate, average laser power, and such geometric parameters of nozzle as the nozzle throat diameter and total length. Moreover the pulse repetition rate is determined by a time period needed to recover the gas flow characteristics after flow choking the nozzle throat by every shock wave.

Technical feasibility of this type of laser propulsion production is limited by strong load impacts on the nozzle walls caused by strong shock waves as well as mechanical resonance, arising at high pulse laser energy and loading the walls. Similar problems of choking jet engine nozzle by shock waves are observed also in the investigations on supersonic laser propulsion made by using supersonic shock tubes and high-power lasers [18-20].

To produce laser propulsion at space conditions, one assumes also using such effect as a laser ablation of solid propellants under a laser power, including [21]:

- direct laser ablation of solid propellant when the propulsion is produced due to the pressure of evaporated material (evaporation mechanism of propulsion production);
- combined ablation when auxiliary shock wave arising with the laser breakdown of evaporated material near its surface is used to produce thrust;
- laser ablation in structured materials.

Characteristic variable ($I\lambda\tau^{1/2}$) appears in the theory of laser ablation [21] as a parameter similarity, being used to describe an interaction of a laser pulse with solid materials. In the theory, it is assumed (i) the material strongly absorbs laser radiation and the absorption depth exceeds value $1/\mu_\lambda$, where μ_λ is the absorption coefficient at a specified radiation wavelength λ, and (ii) the radiation intensity on a solid surface corresponds to the conditions of production of maximal specific recoil impulse in a vacuum if the radiation is not screened by originated plasma. It is also assumed that the laser-induced plasma absorbs the radiation via the inverse Bremsstrahlung effect.

C_m obtained experimentally under the direct laser ablation for many metals and nature materials does not exceed tens of dynes per Watt (10^{-5}N/W). One of the possible ways of increasing C_m is producing of additional thrust by shock waves, generated under a laser breakdown of evaporated materials close to the solid surface. At that, the laser plasma extension is accompanied by strong shock waves increasing the gas pressure behind its up to 10^3-10^6 atm and plasma temperature up to tens or hundreds of electron-Volts. In a vacuum, the effect results in increase of C_m by 1-2 orders as compared with the direct laser ablation.

But in common case, various processes of laser-induced gas discharge interaction with a supersonic gas flow is distinguished by instability and complexity of the gas dynamic phenomena [22]. The effects following the laser breakdown of gas flows and arising in the interaction region depend on the laser characteristics (radiation intensity, pulse duration, and so on) and gas flow parameters (density, pressure, velocity). They include themselves laser-supported detonation waves, radiative waves, and fast ionization waves [23]. Moreover, powerful local flows are produced in the breakdown region, which are directed outside the region. Both supersonic and subsonic flow regions are observed behind a shock wave in dependence of the laser input power [24]. All these phenomena decrease the thrust production efficiency at a supersonic mode. Moreover to stabilize the process of laser power input into a gas-discharge supported by a laser power, hard balance conditions between the laser pulse characteristics and gas-flow parameters have to be fulfilled [25].

That is why to produce a thrust by SLC laser propulsion module and to exclude undesirable effects, we suggest using the response of a supersonic flow on a laser ablation jet induced by a laser beam focused closely by laser propulsion engine nozzle wall [26]. The suggestion is based on the results of theoretical and experimental investigations of gas jet effects, blowing through a wall hole into a supersonic stream [27]. The purpose of our study is to determine parameters of the ablation jet which affect the laser propulsion production efficiency at a supersonic gas flow in propulsion engine nozzle.

In accordance with a general theory of laser ablation [21], momentum coupling coefficient C_m produced by a jet is determined as a ratio of jet momentum density $\dot{m}v_E$ to laser power density P. In the assumption of quasi-continuous evaporation of a wall material, mass rate in the jet can be considered as:

$$\dot{m} = \rho_a \times c_a \ [\mathrm{kg/(m^2 s)}], \qquad (4)$$

where ρ_a is a vapor jet density, c_a is an adiabatic speed of sound in the vapor. And the vapor pressure closely by a wall is determined as:

$$p_a = [(1 + \gamma M^2)]\, \rho_a \times c_a^2 = [(1 + \gamma M^2)] \times \dot{m} \times c_a = [(1 + \gamma M^2)] \times \dot{m} \times V/M, \quad (5)$$

where M is Mach number of vapor flow, γ is adiabatic constant ($\gamma = 1.1$ at a plasma temperature of $T_0 \sim 10^4$ K), V is a vapour flow speed.

One can assume the temperature of plasma induced closely by a nozzle wall is a constant one and does not depend on the laser power because of plasma screening effects limiting the laser power absorption by the plasma [23].

As the examples for numerical calculations of laser propulsion production at a supersonic mode, we chose two devices of a laser propulsion nozzle. First device is a parabolic nozzle with a reflecting internal surface, which can be used both as a jet nozzle and laser beam concentrator [17]. Second one is the jet nozzle consists both off-axis paraboloid and circular shroud, which has been developed for Lighcraft technology [18,19].

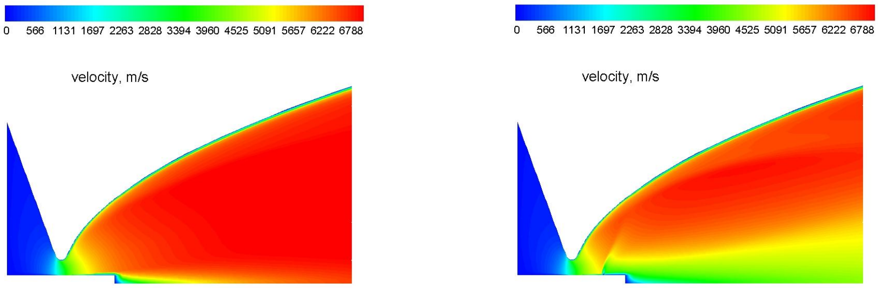
Thus, the input data on the laser ablation jet and gas propellant parameters are listed in Table 5.

Table 5.

$\dot{m}_i$	T_i	V_i	M	p_a	m_0	p_0
kg/m^{2}s	K	m/s	-	Pa	kg/s	Pa
$31.4\cdot10^4$	$1\cdot10^4$	3800	2,33	$3.5\cdot10^6$	0.25	$2\cdot10^3$

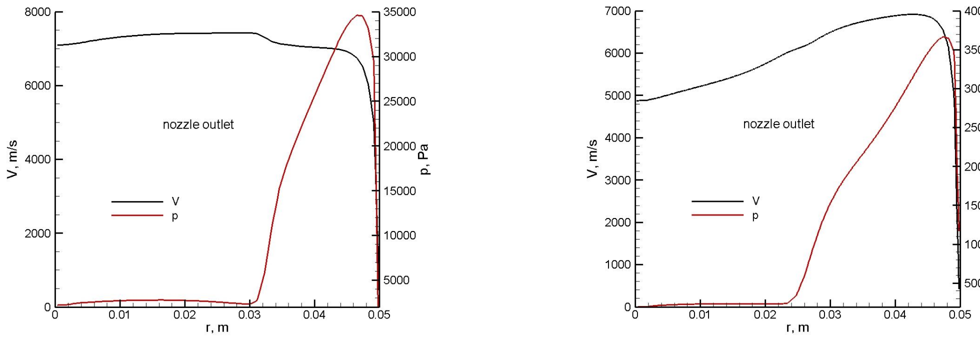
Here, m_0 and p_0 are the gas flow rate and gas pressure close by an ablation region on the nozzle wall.

The results of numerical simulation of the laser ablation jet interaction with supersonic flow in the parabolic nozzle are shown in Figure 5 and Figure 6. The results are presented as profiles of flow velocity across an axial section (Figure 5) and as the velocity and pressure radial profiles in outlet cross-section (Figure 6) of the nozzle. It is assumed the outlet cross section has a 10 cm diameter. In the figure 5b, one can see stationary shock waves generated inside the nozzle, which change a gas-dynamic structure of an initial supersonic flow by such a way that a stable jet with an average velocity of 6 km/s is formed in the nozzle outlet. Simultaneously, gas pressure distribution in the nozzle is transformed so that the pressure maximum is shifted to the nozzle wall (Figure 6b).



(a) (b)

Figure 5. Velocity profiles in a cross-section of parabolic nozzle: (a) initial supersonic flow and (b) at steady- state mode of laser ablation jet interaction with the supersonic flow.



(a) (b)

Figure 6. Velocity and pressure radial distributions in an outlet section of parabolic nozzle: (a) initial supersonic flow and (b) at steady- state mode of laser ablation jet interaction with the supersonic flow.

The integration of gas pressure surface distributions in the nozzle in both cases shows the thrust produced in case (b) (T= 1404 N) is larger than the thrust produced in case (a) (T= 1103 N) by a value exceeding a power of ablation jet ($F_i = V_i \cdot \dot{m}_i = 292.6$ N). The derived power difference is assumed to be a result of a reconfiguration of the supersonic flow in the nozzle caused by the laser ablation jet.
To estimate the efficiency of laser propulsion production in the discussed case, we have to include the laser power providing specific characteristics of laser ablation jet into the consideration. The power depends on both thermophysical properties of ablated material and laser radiation characteristics. Nevertheless, sufficiently general parameter of the ablation jet is a performance of recoil momentum generation that is imparted to the ablated target. The efficiency is equal to $C_m I_{sp} g/2$ where g is an acceleration of gravity [15]. Usually, it does not exceed ~ 0.4 for an ablation of a strongly absorbing material. In accordance with the initial parameters listed in Table 5, specified specific impulse of the jet is chosen to be $I_{sp} = 380$ s, then $C_{m\ abl} = 2.1 \cdot 10^{-4}$ N/W. In this case, momentum coupling coefficient of laser propulsion as a whole is $C_m = 2.93 \times 10^{-3}$ N/W. The derived value of C_m is sufficiently large and it exceeds similar data obtained for laser ablation propulsion [21].
Similar numerical results are obtained at simulating the laser ablation jet in off-axis parabolic nozzle [24]. Moreover, the calculations demonstrate stability of the laser propulsion production in a supersonic flow against invariability of laser power. That is why we suggest using this type of laser propulsion for SLC space missions considered.

5. Conclusion

It is clear some period is required to make the SLC reliable for space exploration and to solve some technical and technological problems such as development of the vehicle control system, equipment for capturing various types of spent satellites and so on. All the problems associate with specified conditions of the SLC exploration. In our opinion, the developed design of SLC has a right to exist on the strength both of urgency of space debris problem and confirmed capability of creating the SLC design components. Design experience accumulated in our institutes at creating of lasers, laser propulsion engines, space optics, and laser beam control systems is assumed to be used at development of the SLC space mini-vehicle.

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