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Focused Solar Ablation: A Nanosat-Based Method for Active Removal of Space Debris

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A novel concept for the active removal of space debris using solar power is proposed. *Focused solar ablation* is an in-space propulsion concept based on using concentrator mirrors on nanosats and using the solar power to evaporate material from the debris to produce deceleration thrust thereby providing the ΔV necessary to deorbit. An energy balance is used along with free-molecular effusion theory to estimate the thrust produced by the concept and the corresponding deorbit times for an aluminum debris masses of 10 kg and 0.27 kg for various concentrator mirror areas and the diameter of the spot on which the solar power is concentrated. The analysis shows that the deorbit times of a few hours for both masses showing that the method is attractive for active space debris removal. Experiments performed using electron beams to evaporate aluminum in a vacuum chamber show that the method is also practically feasible to deorbit space debris using solar power available in low earth orbit (LEO).

I. Introduction

The population of space debris in some LEO altitudes has risen sharply in the last decade and, by some estimates, is projected to grow exponentially[1] even in the absence of new space launches. The largest source of new space debris is by orbital collisions between existing high-mass resident space objects. An example of such event is the 2009 collision between the operational Iridium-33 spacecraft and the defunct Kosmos-2251 that generated more than 2,000 trackable fragments. The collision fragments initially placed in highly elliptical orbits, with typical apogee and perigee of about 800 and 350 km, respectively, are now undergoing orbital decay passing through the orbital regime of the International Space Station (ISS).[2] The threat of collision with large resident space objects presents a significant challenge for the operation of ISS. For at least five times in the last two-and-a-half years the ISS had to execute a collision avoidance maneuver. In April of 2011, a close encounter with a 10-15 cm sized fragment of Iridium-Kosmos collision required the use of European Automated Transfer Vehicle 2 (ATV-2) to provide a $\Delta V = 0.5$ m/s for the ISS. It is projected that such encounters will become more frequent in the next few years due to solar activity increase. The significant long-term threat to the manned missions in LEO and to commercialization of space activities[3] calls for new technologies for orbital manipulation and active debris removal (ADR).

Even though a number of ADR concepts[4,5] have been proposed in the past, there is at present no proven technology for the active removal of space objects. This is mainly due to multiple challenges related to high thrust and precision maneuvering required for de-orbit. Many of the de-orbit technologies currently under consideration rely on the development of future in-space propulsion systems which can provide the necessary deceleration thrust to impart the change in velocity, ΔV required for an orbital perturbation or complete de-orbit. In this work we propose an alternative ablation concept based on solar thermal propulsion[6] that would require a much smaller on-board power and launch mass as compared to laser-ablation methods considered in the past.[7]

The active de-orbit concept proposed in this work is based on the use of a concentrator mirror to concentrate solar flux on the space debris object. Figure 1(a)-1(b) show a schematic of the concept. The technological components for implementing this concept include a relatively mature technology of space-deployable solar concentrators;[8,9] small satellites such as CubeSats and micropropulsion systems. The development of

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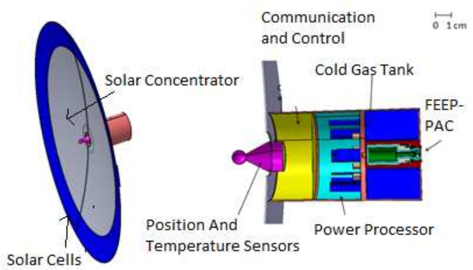
the solar concentrator-based space debris removal technology requires developing combined analysis for solar drag enhancement, metal ablation, and multi-body orbital dynamics of the debris object, ablator spacecraft taking into account their positions with respect to Sun and Earth. The present investigation focuses on the theoretical formulation and preliminary case studies of the propulsion aspects of the focused solar ablation.

Depending on the space debris object mass, its orbit and target timeline for the de-orbit maneuver, the solar concentrator mirror can be applied in two different modes. In the low-flux mode, suitable for objects with multilayer insulation such as defunct satellites, the solar concentrator in the proposed concept can be used for *enhancement of the solar drag* to decrease the orbital lifetime. In the high-flux mode, specifically applicable for objects with significant exposed metal surfaces such as spent upper stages and small metallic parts or objects in low Earth orbits requiring fast orbital changes, the solar concentrator can be used to create deceleration thrust by *focused solar ablation*. In both modes, the solar concentrator provides significant advantages over laser-powered debris removal concepts by avoiding the losses associated with conversion of solar to electrical power. The two modes of operation specified above can be briefly described as follows.

(a) Solar ablation concept for active removal of space debris.



(b) Schematic of nanosat with a solar concentrator and a micropropulsion system[10]

Figure 1. Nanosat based removal of space debris. The proposed electric/chemical micropropulsion system[10] is enabling nanosat maneuvering and precise stationkeeping

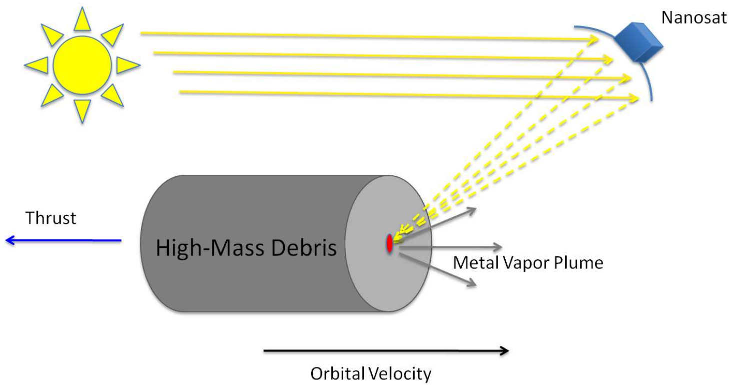


Figure 2. Schematic of the focused solar ablation process.

One of the options that has been proposed for deorbiting space debris is to increase the drag force on the debris by inflating or deploying large structures to increase the surface area thereby increasing the atmospheric drag. One such drag enhancement deorbit device is the GOLD concept[11] developed by Global Aerospace Corporation which uses a large balloon to increase the atmospheric drag. In the proposed concept, concentrator mirrors are used to increase the solar drag which is given by

$$D_{\text{solar}} = C_R \frac{I}{c} S \tag{1}$$

where I is the solar radiation intensity, c is the velocity of light, S is the cross-sectional area, and C_R is the solar radiation coefficient. The concept of solar drag enhancement is particularly useful for satellites in GEO where the solar drag produced due to the concentrator can be significant.

For de-orbit of satellites in the LEO, the proposed concept uses solar energy to vaporize metallic parts of the satellite to produce metal vapor which when expanded produces thrust that can be used to produce the ΔV required for de-orbit. The The flow rate of metal vapor that depends on the incident solar energy and the heat loss mechanisms in action. The main goal of this paper is to perform a theoretical feasibility study of the *focused solar ablation* concept by estimating critical parameters such as burn time required to de-orbit and also present results of the preliminary experiments for aluminum evaporation using an electron-beam in an ultra-high vacuum chamber that resembles the atmospheric conditions in LEO orbits.

II. Theory

As mentioned earlier, the *focused solar ablation* de-orbit concept that we propose is based on the use of a concentrator mirror that uses solar power to melt and subsequently vaporize a given mass of the space debris with the solar power providing the heat of vaporization. This section presents a theory to estimate the ideal thrust obtained by considering thermal radiation as the main source of energy loss. The metal vapor that is formed then effuses at the equilibrium temperature that is governed by an energy balance

$$q''_{\text{solar}} = \dot{m}_{\text{flux}}(T_{\text{eq}})\Delta h + \epsilon\sigma T_{\text{eq}}^4 \tag{2}$$

where q''_{solar} is the solar flux concentrated on the debris, Δh is the heat of vaporization per unit mass, ϵ is the emissivity, T_{eq} is the equilibrium temperature of the metal vapor, $\dot{m}_{\text{flux}}$ is the mass flux at the equilibrium temperature given by[12]

$$\dot{m}_{\text{flux}} = \frac{1}{4} n m \bar{c} \tag{3}$$

where m is the molecular mass, n is the saturation number density obtained using the Clausius-Clapeyron equation relating saturation vapor pressure and temperature along with the ideal gas equation and is given by

$$n = \frac{\exp\left(-\frac{\Delta H}{R_u}\left(\frac{1}{T_{\text{eq}}} - \frac{1}{T_{\text{p=1}}}\right)\right)}{kT_{\text{eq}}} \tag{4}$$

where ΔH is the heat of vaporization in J/mol, $T_{\text{p=1}}$ is the temperature corresponding to a saturation vapor pressure of 1 Pa, and R_u is the universal gas constant. $\bar{c}$ in Eq.(3)is the average thermal speed given by

$$\bar{c} = \sqrt{\frac{8kT_{\text{eq}}}{m\pi}} \tag{5}$$

It can be seen that both n and $\bar{c}$ depend on the T_{eq}. Referring to the temperature as an equilibrium temperature is valid because the burn times estimated later are significantly higher than the time during which transient processes will gain significance. Substituting from Eq.(4) and Eq.(5) in Eq.(2), we get an equation that can be solved numerically to get T_{eq} for a given value of the input solar flux. The T_{eq} computed using the energy balance is used to compute the specific impulse using the relation obtained using the free-molecular effusion assumption and is given by

$$I_{\text{sp}} = \frac{\sqrt{\pi R T_{\text{eq}}/2}}{g} \tag{6}$$

where R is the specific gas constant and g is the acceleration of gravity. The thrust is computed using Eq.(6) and the $\dot{m}$ corresponding to the equilibrium temperature T_{eq}

$$F = \dot{m} g Isp \tag{7}$$

It should be mentioned that the validity of the free-molecular effusion assumption becomes invalid at higher mass flow rates and collision effects will have to be considered for a more accurate model. However, for the purpose of initial analysis, the approximate theory can be used. Finally, the burn time to achieve a given ΔV to enable de-orbit is calculated as

$$t_{\text{burn}} = \frac{M\Delta V}{F + \dot{m}\Delta V} \tag{8}$$

III. Results & Discussion

In this section, we present preliminary results for the theoretical analysis performed for focused solar ablation of a debris mass which we assume predominantly consists of aluminum. The mass of the spacecraft was taken as 10 kg and a solar flux of 1 kW/m^2 was assumed to be incident on the mirrors with a mirror efficiency of 10 %.[8] Though the results obtained will depend on the exact mass of the debris and the solar power available for the mirror, these are typical values used for the purpose of preliminary analysis. The efficiency of the mirror is defined as the ratio of solar power it focuses on the debris to the solar power it receives. The ΔV required for de-orbit was taken as 300 m/s which is a reasonable value for LEO. For a given set of parameters, Eq.(2) is used to solve for the equilibrium temperature which determines the mass flux, the thrust produced due to the effusion of metal vapor and hence the burn time required for the given ΔV. We consider various solar concentrator mirror areas and also diameter of the spot size on which the solar power is concentrated. Tables 1 and 2 show the summary of all relevant parameters corresponding to mirror areas of 1 m^2 and 10 m^2 for three different values of the spot size on which the solar power is concentrated. Figure 4 compares the burn times as a function of spot diameter for 4 different values for concentrator mirror area.

For a given value of the spot diameter, the burn time increases with decreasing mirror area. On the other hand, for a given mirror area, the burn time increases with increasing spot diameter. The variation of burn time for mirror areas of 5 m^2 and 10 m^2 are qualitatively similar whereas the smaller mirror areas of 1 m^2 and 2 m^2 show a different trend with a larger rate of increase of burn times for the larger spot diameters. It is desirable to decrease the burn times and hence operating at larger spot diameters could be more disadvantageous for the lower concentrator mirror areas. For example, when the spot diameter is increased from 1.5 cm to 1.6 cm, the burn time for a concentrator mirror area of 1 m^2 increases from 395.51 hr to 518.38 h which corresponds to a percentage increase of 31 %. For a concentrator mirror area of 10 m^2, when the spot diameter is increased from 1.5 cm to 1.6 cm, the burn time increases from 8.54 hr to 8.76 hr which corresponds to a percentage increase of only 2.6 %. This trend shown for mirror areas of 1 m^2 and 2 m^2 can be explained by considering the energy required for vaporization and that lost due to radiation and comparing them to the total incident solar energy. Figure 3 shows how the total input solar flux is distributed between the radiation loss and the vaporization required for a given mass flux of the metal vapor for concentration mirror areas of 1 m^2 and 10 m^2. For the 1 m^2 concentration mirror and small spot diameters, the radiation loss is considerably less when compared to the vaporization energy and the entire solar energy incident on the debris is used in vaporizing the aluminum. However, as the spot diameter increases, the radiation loss becomes comparable to the vaporization component and for larger spot diameters dominates the vaporization component. This leads to the higher rate of increase of the burn time for spot diameters larger than a critical value. The spot diameter size for which the energy required for vaporization is same as the radiation loss is 0.98 cm for the 1 m^2 concentration mirror. It increases to 1.38 cm for the 2 m^2 concentration mirror. For the spot diameters considered in Figure 4, the vaporization component always dominates in the cases of concentration mirror areas $A_{\text{mir}} = 5\ m^2$ and $A_{\text{mir}} = 10\ m^2$. Figure 5 shows the variation of the limiting value of spot diameter for which the vaporization energy and the radiation loss are equal as a function of the concentration mirror area. For a given concentration mirror area, it is advantageous to operate at spot diameters less than the limiting value beyond which the deorbit time increases rapidly with increase in spot diameter.

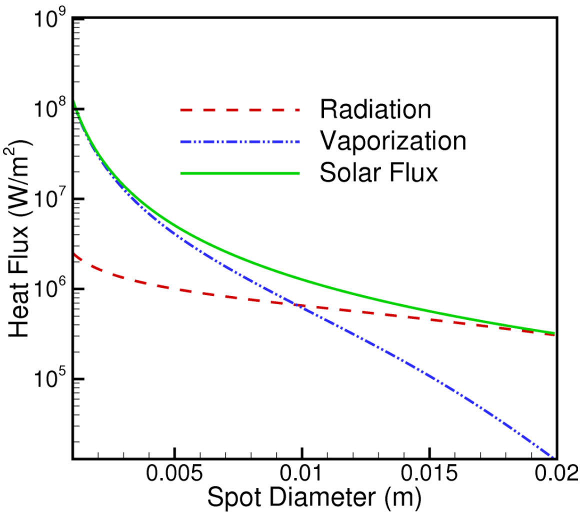
The dependence of the deorbit or burn times on the mass of the space debris was studied. A space debris of mass 0.27 kg was considered and the analysis for deorbit times was repeated with a $\Delta V = 100$ m/s. Figure 6 shows the burn time as a function of the spot size for 4 different concentrator mirror areas. While the general trend is similar the burn times are significantly smaller and the space debris is shown to acquire the ΔV required for deorbiting in a few hours even using the 1 m^2 concentrator mirror. It should be mentioned that apart from the burn times, the other parameters such as T_{eq}, F, etc do not depend on the mass of the space debris and will have identical values for the larger and smaller debris.

Table 1. Summary of various relevant parameters for a mirror area of 1 m^2 and spot sizes of d = 0.5 cm, 1 cm, and 2 cm.

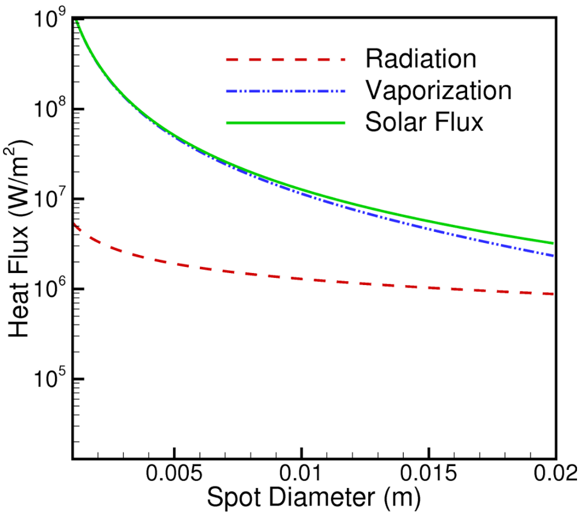
Spot Size	$d = 0.5\ cm$	$d = 1\ cm$	$d = 2\ cm$
$T_{\mathrm{eq}}\ (K)$	2051	1843	1524
$n\ (1/m^3)$	2.6434×10^{22}	4.2187×10^{21}	9.2058×10^{19}
$\bar{c}\ (m/s)$	1268	1202	1093
$\dot{m}\ (kg/s)$	7.38×10^{-6}	4.46×10^{-6}	3.54×10^{-7}
$F\ (mN)$	7.345	4.214	0.304
$t_{\mathrm{burn}}\ (h)$	87.2	150.1	2030.3

Table 2. Summary of various relevant parameters for a mirror area of 10 m^2 and spot sizes of d = 0.5 cm, 1 cm, and 2 cm for the 10 kg debris and ΔV = 300 m/s.

Spot Size	$d = 0.5\ cm$	$d = 1\ cm$	$d = 2\ cm$
$T_{\mathrm{eq}}\ (K)$	2409	2185	1983
$n\ (1/m^3)$	2.9231×10^{23}	7.1626×10^{22}	1.5159×10^{22}
$\bar{c}\ (m/s)$	1374	1308.8	1247
$\dot{m}\ (kg/s)$	8.84×10^{-5}	8.25×10^{-5}	6.65×10^{-7}
$F\ (mN)$	95.4	84.8	65.2
$t_{\mathrm{burn}}\ (h)$	6.84	7.6	9.8



(a) $A_{\mathrm{mir}} = 1\ m^2$



(b) $A_{\mathrm{mir}} = 10\ m^2$

Figure 3. Comparison of vaporization and radiation loss to the total solar flux as a function of the spot diameter for concentrator mirror area of $A_{\mathrm{mir}} = 1\ m^2$ and $A_{\mathrm{mir}} = 10\ m^2$ for the 10 kg debris and $\Delta V = 300\ m/s$

In order to study the feasibility of ablating aluminum using solar power, experiments were performed to evaporate aluminum using an electron beam. The whole experiment was performed under ultra-high-vacuum conditions to simulate the atmosphere in the LEO. The experiments were performed at the Birck Nanotechnology Center, Purdue University. Figure 7 shows the photographs taken during the experiments with the heated spot clearly seen. The experiments shown here were performed at two slightly different electron-beam powers of 2.91 kW and 3 kW. While the voltage and beam current for the 2.91 kW run were 6.35 kV and 459 mA respectively, the 3 kW run corresponds to a voltage of 6.49 kV and a beam current of 462 mA. Using the digital images obtained during the experiments and the known source diameter, the spot size was estimated for the two cases as 10.6 mm and 14 mm respectively. Though the experiments

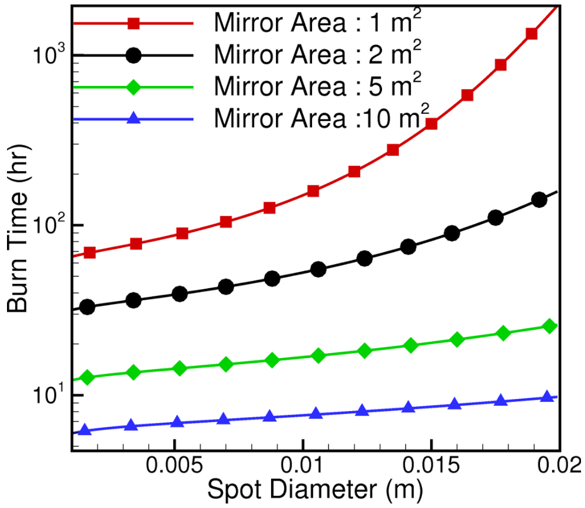


Figure 4. Comparison of burn time as a function of the spot diameter for various concentrator mirror areas for the 10 kg space debris and ΔV = 300 m/s

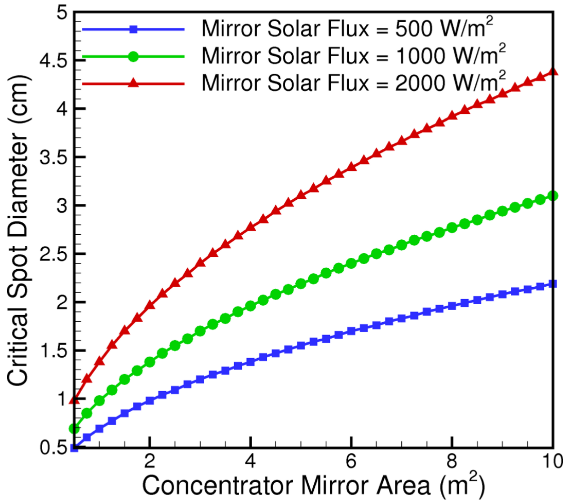


Figure 5. Variation of critical spot size as a function of concentration mirror area for various values of solar flux incident on the mirror for the 10 kg space debris and ΔV = 300 m/s

were performed using electron-beams instead of solar power that will be used in the actual de-orbiting, they demonstrate the feasibility of using solar power to ablate or evaporate aluminum by converting to vapor.

IV. Conclusions

A novel concept is proposed for the active removal of space debris using solar power. The concept uses concentrator mirrors installed on a nanosat to focus solar power on the debris thereby producing thrust by the evaporation of material from the debris. Free-molecular effusion theory was used to obtain estimates of time taken to perform the de-orbiting for various values of the spot size and concentrator mirror areas. The analysis shows that the deorbit times obtained makes focused solar ablation a feasible method for removal of space debris. While the deorbit times obtained for a 10 kg space debris using a 1 m^2 mirror area were $\sim$ 100 hr, the corresponding times decrease to $\sim$ 5 hr for a debris mass of 0.270 kg. The theoretical deorbit times decrease rapidly with increasing mirror area and decreasing spot size. Evaporation experiments were performed using high energy electron beam in a vacuum chamber for two different values of beam power leading to different mass flow rates of aluminium vapor showing that the proposed de-orbiting concept is

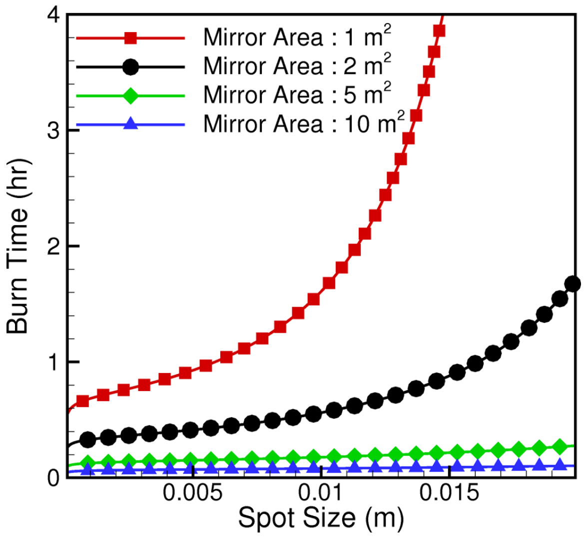


Figure 6. Comparison of burn time as a function of the spot diameter for various concentrator mirror areas for a debris mass of 0.27 kg and a ΔV = 100 m/s

Table 3. Comparison of burn times for various spot sizes and concentrator mirror areas for a 0.270 kg space debris and ΔV = 100 m/s

Spot Size	d = 0.5 cm	d = 1.0 cm	d = 2.0
$A_{\text{mir}} = 1\ m^2$	0.93 hr	1.61 hr	21.24 hr
$A_{\text{mir}} = 2\ m^2$	0.41 hr	0.56 hr	1.70 hr
$A_{\text{mir}} = 5\ m^2$	0.15 hr	0.18 hr	0.28 hr
$A_{\text{mir}} = 10\ m^2$	0.07 hr	0.08 hr	0.10 hr

(a) Power = 3 kW; Spot diameter = 14 mm

(b) Power = 2.91 kW; Spot diameter = 10.6 mm

Figure 7. Photographs showing the spot size during the electron-beam evaporation of Aluminum for two different beam powers.

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