Laser Ablation for Efficient Space Debris Removal

Jaden E. Dougal*, **Prasoon K. Diwakar**

Mechanical Engineering Department, South Dakota Mines, Rapid City, SD 57701, USA
*Jaden.Dougal@mines.sdsmt.edu

Abstract

Space debris poses an escalating threat to safe and sustainable use of space. To tackle this problem, several strategies are being explored, including spacecraft design enhancements, mission program revisions, space traffic management, and active space debris removal.

A promising approach for debris removal involves laser ablation, which employs laser-induced plasma techniques to adjust debris trajectories, facilitating safe re-entry into Earth's atmosphere for termination of debris or sending debris to graveyard orbits. This presentation will explore the use of nanosecond pulsed laser ablation (with fluence around 100 kJ/m^2 and a 6 ns pulse duration) to develop efficient methods for space debris removal.

Furthermore, femtosecond pulsed laser ablation (with a 100 fs pulse duration) will be investigated for its unique directional plasma plume, enhancing control in debris removal. This research will address key challenges, including real-time tracking and targeting, and showcase the potential of ground-based laser targeting in space for debris removal.

Laser Ablation

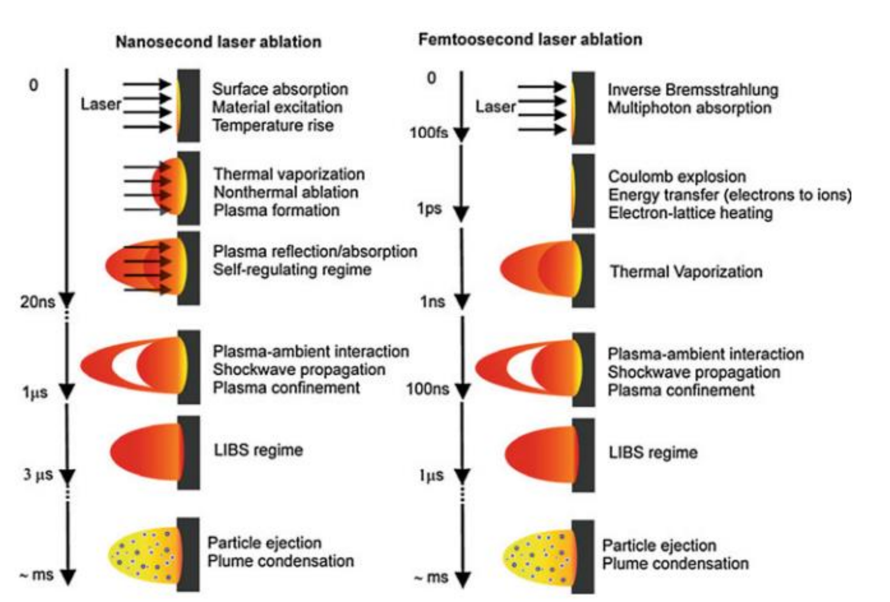

Fig. 1 Laser ablation process explained for nanosecond and femtosecond laser pulse, Harilal et. al. [1]

- Pulsed laser pulses provide unique opportunity for mass removal from materials including space debris
- Mass removal from laser ablation is highly dependent on laser pulse properties namely laser pulse duration and laser wavelength
- Typically, shorter wavelength and ultrafast femtosecond pulses lead to greater mass removal, which could be utilized for momentum change of space debris.

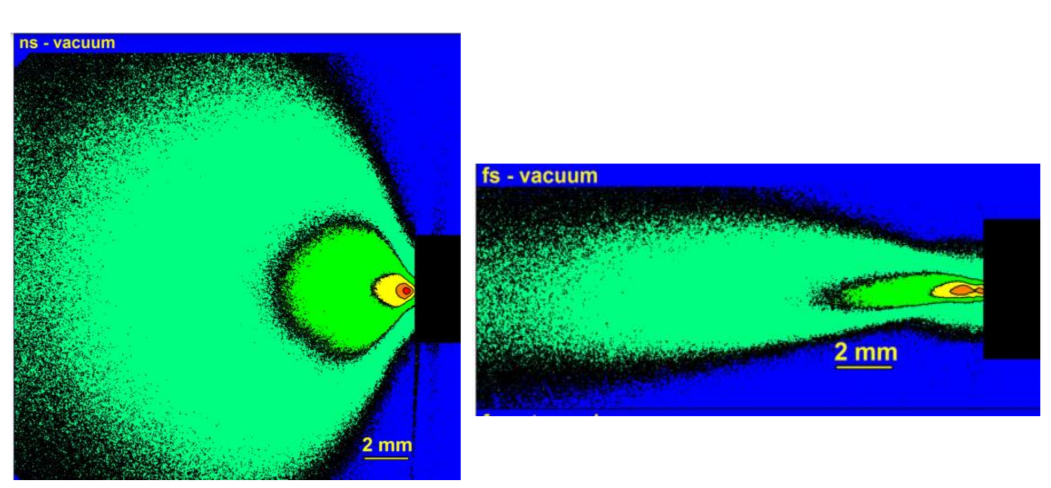

Fig. 2 and Fig. 3 ICCD time-integrated images of emission from ns and fs laser ablation in vacuum, displaying directionality of plasma for ultrafast laser pulses, Freeman et al.[2]

This provides further opportunity for momentum manipulation of space debris using laser ablation

Laser Ablation

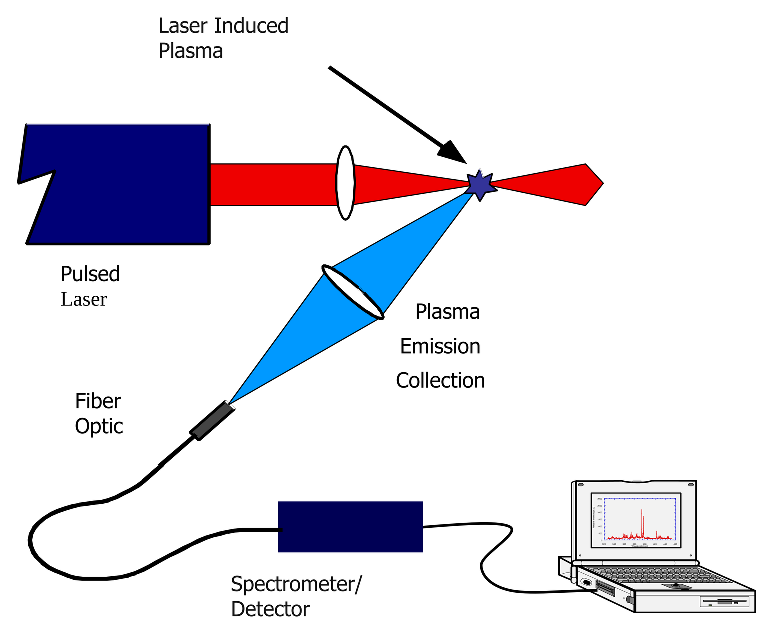

Fig. 4 Experimental setup for laser ablation studies in conjunction with plasma characterization studies

The image to the left shows the experimental set-up for conducting laser ablation studies. A pulsed laser (ns, fs) will be used for the ablation of surrogate space debris samples in a lab in a vacuum chamber. The plasma plume will be characterized using a spectrograph and ICCD detector.
The goal will be:

- To estimate momentum change achieved using ns and fs laser ablation
- Role of laser wavelength, pulse duration and pulse energy on momentum change
- Role space debris material on laser ablation process.

Overall, this momentum change will be utilized in the modeling of orbits.

Equations of Motion Modelling

In order to propagate and model orbits, MATLAB was used to solve the equations of motion for a two-body orbital dynamics problem[3]. The function solves the equations using a 6x1 state vector containing the x, y, and x position vector and the x, y, and z velocity vector. The function returns a 6x1 vector containing the x, y, and z velocity vector and the x, y, and z acceleration vector.

```
function udot = EqM(t, u)
rSatellite = u(1:3);
V = u(4:6);

% Initial Conditions
R = norm(rSatellite);

% Earth parameters
mu = 3.986E5; %km^3/s^2

a =((-mu)/R^2)*(rSatellite/R);

udot = [V; a];

end %ends sub function satellite
```

Fig. 5 MATLAB code for the equations of motion for a two-body system

The MATLAB function ode45 was used to solve the ordinary differential equations with high accuracy over a given time vector. For the example cases in this presentation, a time vector equal to one period of the specified objects orbit was used.

```
function [stateout,stateFinal] = orbit_propogation(t, u)

%get time vector for ODE
tODE = [0,t];

% integrate equations of motion
opts = odeset('reltol', 1e-6, 'abstol', 1e-6);
[tout, stateout] = ode45(@EqM, tODE, u, opts);



%%% Get final x, y, and z
xFinal = stateout(:,1);
yFinal = stateout(:,2);
zFinal = stateout (:,3);
```

Fig. 6 MATLAB code to solve the equations of motion

Orbit Propagations

For this presentation, the orbits of ENVISAT, SL-16R/B and METEOR 3M were propagated. These three pieces of debris were chosen as they are no longer in use and pose an increased threat in Low Earth Orbit for future space missions[4].

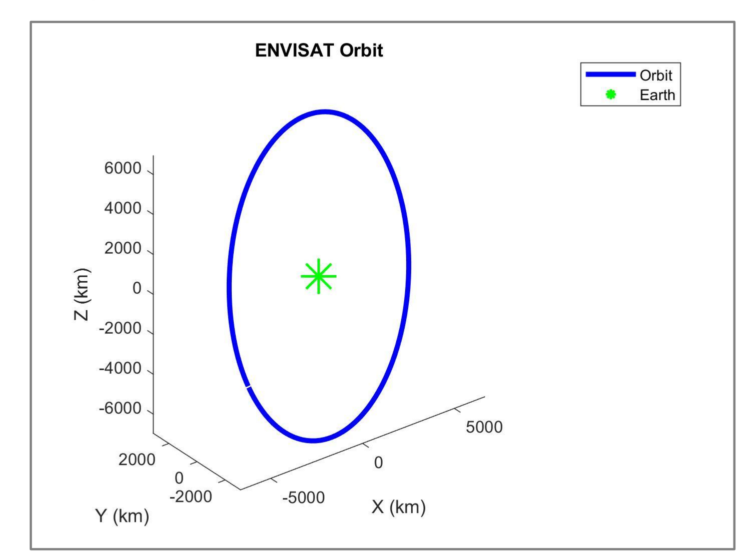

Fig. 7 ENVISAT Orbit for One Period (100 min)

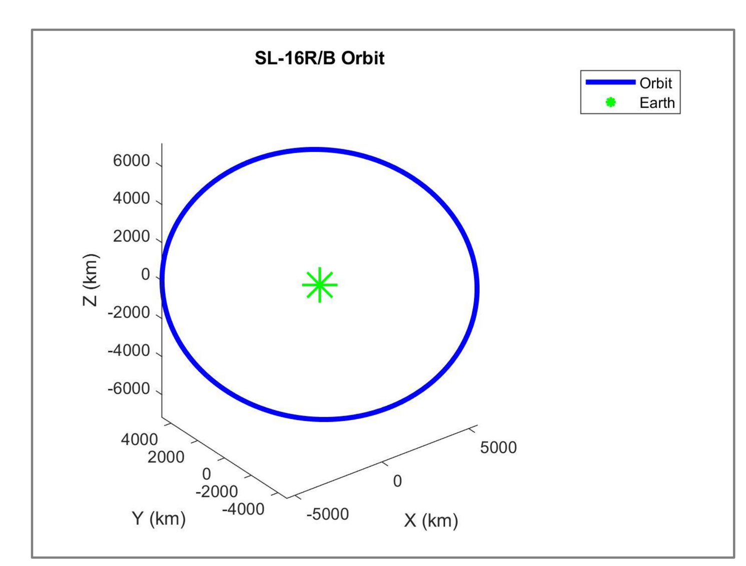

Fig. 8 SL-16R/B Orbit for One Period (102 min)

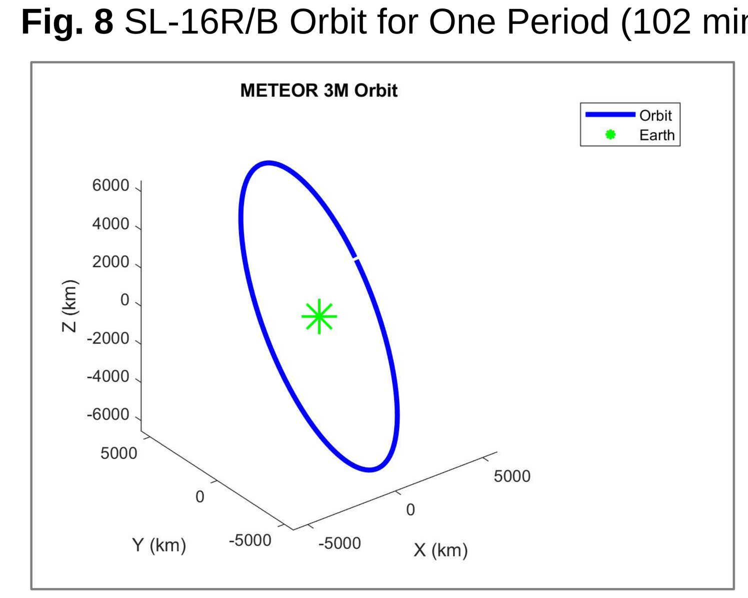

Fig. 9 METEOR 3M Orbit for One Period (105 min)

Change in Orbital Momentum

The change in momentum will facilitate whether the debris can be slowed down enough to fall into Earth's atmosphere or sped up enough to be pushed into a graveyard orbit.

In this example, ENVISAT's semi-major axis was reduced by 1000 km, scaled, and graphed against its original orbit which was also scaled. The Earth's atmosphere is also shown to see whether or not the new orbit will be pulled into the Earth's atmosphere.

The change in orbital angular momentum would come from a laser pulse and the energy released due to laser ablation. The pulse and subsequential ablation would affect the velocity of the satellite and thus, the momentum.

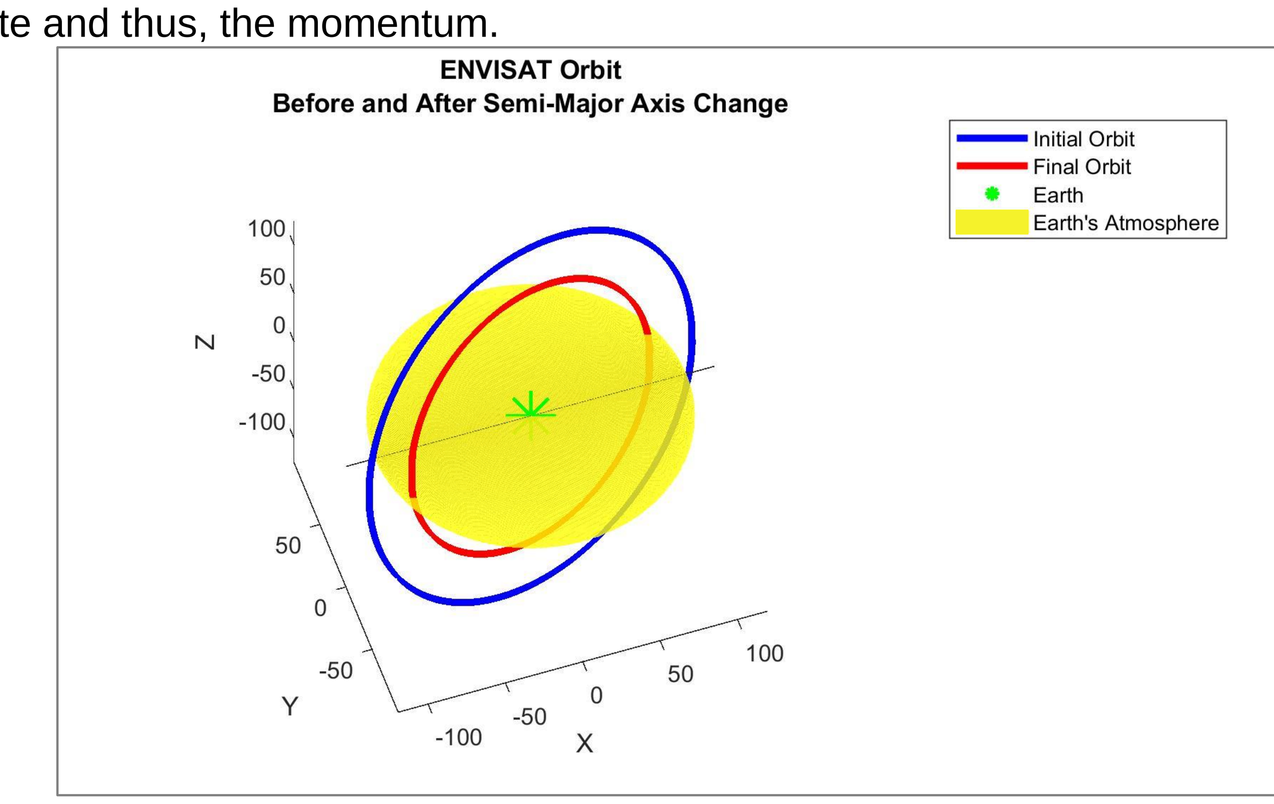

Fig. 10 ENVISAT Orbit for One Period (100 min) Before and After a Semi-Major Axis Deduction of 1000km Due to a Change in Orbital Angular Momentum

Discussion

- This study analyzes how a change in momentum due to laser ablation would affect a piece of space debris in Low Earth Orbit.
- Models of different orbits based of a state vector obtained via classical orbital elements or two-line elements will be utilized to illustrate the orbit of an object before and after the momentum change.
- Laser ablation will further be studied to observe how the pulse and strength of the laser affect both the mass removal and subsequent change in momentum and trajectory.

Citations

1. Harilal, Sivanandan S., Justin R. Freeman, Prasoon K. Diwakar, and Ahmed Hassanein. "Femtosecond laser ablation: Fundamentals and applications." *Laser-Induced Breakdown Spectroscopy: Theory and Applications* (2014): 143-166.
2. Freeman, J. R., S. S. Harilal, P. K. Diwakar, B. Verhoff, and A. Hassanein. "Comparison of optical emission from nanosecond and femtosecond laser produced plasma in atmosphere and vacuum conditions." *Spectrochimica Acta Part B: Atomic Spectroscopy* 87 (2013): 43-50.
3. Vallado, D. A. "Fundamentals of Astrodynamics and Applications." *Space Technology Library* (2001): 303-323
4. McKnight, Darren, Rachel Witner, Francesca Letizia, Stijn Lemmens, Luciano Anselmo, Carmen Pardini, Alessandro Rossi et al. "Identifying the 50 statistically-most-concerning derelict objects in LEO." *Acta Astronautica* 181 (2021): 282-291.

Acknowledgements

I would like to acknowledge the Mechanical Engineering Department at South Dakota School of Mines, The South Dakota Space Grant Consortium, the APS Braslau Travel Grant and Surabhi Bhadauria at Purdue University for their help and support throughout the research thus far via modelling, experiments, data sources, and modelling.