Propagation of Surface-to-LEO Vortex Rings For Orbital Debris Management

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Nomenclature

CFD	Computational Fluid Dynamics
GITM	Global Ionosphere-Thermosphere Model
LEO	Low Earth Orbit
SpaDE	Space Debris Elimination

I. Purpose

Orbital debris has gradually accumulated at a wide range of LEO and geosynchronous altitudes. This debris usually forms from spent mission artifacts, explosions, and collisions of dead satellites and spent fuel stages, producing large quantities of small particulate matter including bits of metal and flecks of paint. These collision particles form the most severe and rapidly growing debris threat to modern hardware[1] (see Figure [1]).

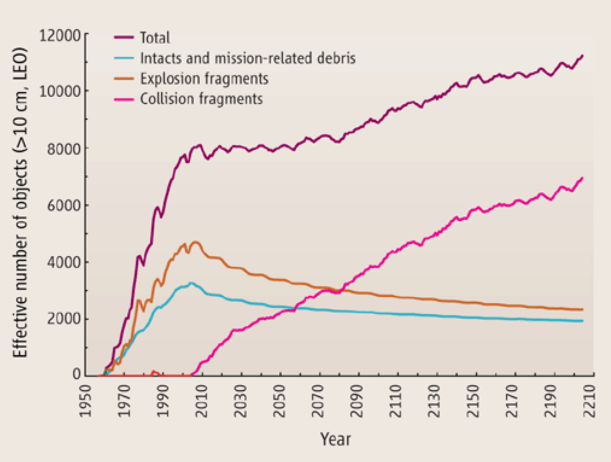

Figure 1. Projected debris growth over time.[1]

The number of tracked objects ranges in the tens of thousands. These objects persist in orbit for very long durations. Due to atmospheric forces in LEO, orbital debris at these altitudes will eventually reenter the

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atmosphere, although debris at higher altitudes have stable orbits lasting into millennia. While it is fairly easy to de-orbit large, intact objects, small particulate matter still poses a significant threat.

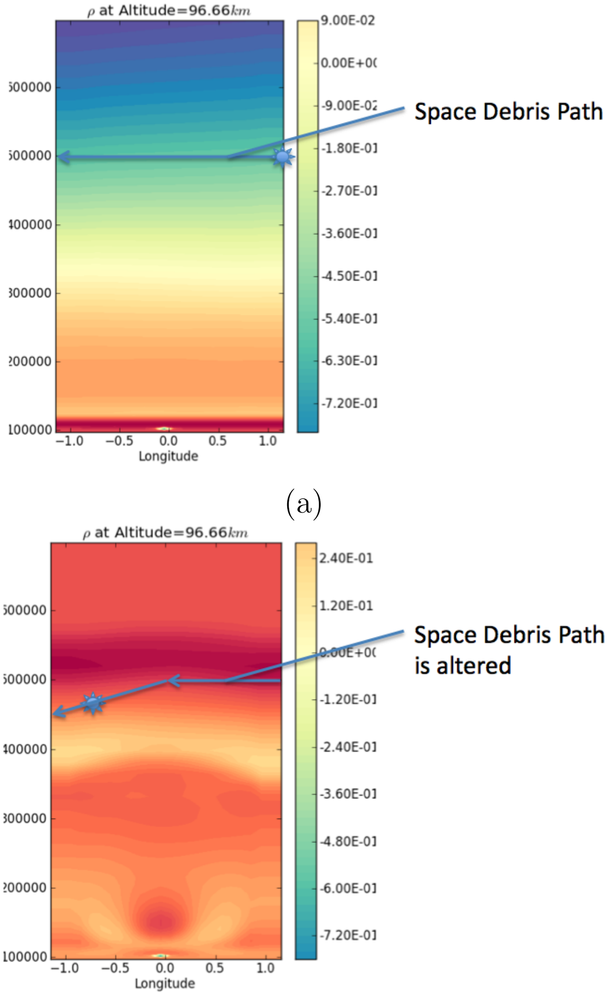
To remove small debris, some degree of force must be applied, though trajectory modification need only be enough to intersect the atmosphere. Due to the size and quantity of particulate matter, and risk of damage, this force ideally would occur without the direct contact of a cleanup vehicle.

II. Contribution to the State of the Art

This paper proposes the use of a ground station equipped with a high-energy air compressor, which will fire an air ring into the upper atmosphere to perturb the orbits of LEO debris. Drag forces will then continue the slowing and vaporization.

The cannon would likely need to be fired at or near zenith (to reduce energy requirements) and hence be located in a remote area near the equator. Propellant gas would not reach escape velocity, and would instead return to Earth. Such a system is fail-safe; anomalous operation will not produce more debris from the ring generator structure.

The use of vortex rings for debris management is an expansion upon research into the use of high-altitude airbursts. The NASA SpaDE[2] project documented explosions of weather balloons at altitudes higher than 30 km with atmospheric CFD using an in-house Global Ionosphere-Thermosphere Model. This model handles many challenges associated with atmospheric propagation, including variations in ionization, temperature, pressure and gravity, as well as motion of rigid-body satellites through the perturbed field.[3] Initial results suggest the concept is plausible (see Figure [2]), with air bursts successfully propagating several hundred kilometers to LEO altitudes in less than 1 minute of travel time with over 20% density change over the expansion period.



(a)

(b)

Figure 2. Air density (color not consistent) of GITM perturbation run (a) before air pulse and (b) after propagating up to LEO altitude and modifying debris trajectory.[2]

The SpaDE analysis demonstrates viability, but needs to be improved. Key factors include comparison of propagation method efficiency, energy pulse efficiency, and improving the realism of simulations below 30km. Weather balloon usage will be very costly per use; estimates by the author suggest costs as high as hundreds of thousands of dollars for the balloon material alone.

A surface-based air-compression system can mitigate some operating costs of high-altitude balloon bursts by reducing the costs of consumables, as well as improve control and spread of the propagating vortex. However, increased air density can complicate propagation.

III. Scope

The first portion of this paper shall focus on improved computational simulation of vortex ring propagation starting from sea level by expanding the GITM model. Improvements shall concern rapid propagation of highly turbulent vortex ring flow at altitudes of less than 30km, taking into account ozone absorption of solar energy, increased air density, flow polarization, and high shear stresses in jet stream currents. The expanded model also involves a more accurate debris model. Results from these simulations are run with multiple ring diameters and velocities to optimize energy losses and spread at high altitude.

The second portion shall focus on scale wind-tunnel testing of these variables. Tunnel tests include vortex ring propagation at various densities, pressure, and wind velocities. These tests will be compared with CFD analysis to provide a real-world analogue of this unique application.

IV. Methods and Key Results

A wealth of information in the literature supports current understanding of vortex ring propagation. Rapid pressure variation at low altitudes requires exploration of high Reynolds number turbulent ring stability at continuous density interfaces. While studies suggest non-dense vortex rings cannot penetrate dense fluids (particularly at thin interfaces), this barrier largely does not apply in this application. A dense vortex ring should not be as greatly hindered in transitioning to a low-density region, however accurate CFD and wind tunnel analysis is still required.[4]

Polarized flow can also affect ring dynamics. In the case of polarized flow, which is characteristic of an axisymmetric ring, a head (vortex ring) - tail (axial vortex) ring develops. Greater circulation loss occurs with a stronger tail, up to a point; finding ways to reduce polarization output by the ring generator can thus lead to longer-lasting, and more stable ring structures.[5]

High wind shear stresses are not a significant factor above 30 km, but are significant between 10-16 km in subtropical regions (areas a vortex ring generator is likely to be placed, due to orbital inclinations of most satellites). This requires more rigorous analysis of wind shear. These forces tend to align vortex rings perpendicular to the stress direction, which can significantly alter propagation direction and possibly ring stability. Based on estimates from the SpaDE project on propagation speed, the short timescale and altitude of effect of these wind currents is hypothesized to not be a significant issue for this application, although CFD and wind tunnel testing will be needed for verification[6] (see Figure [3]).

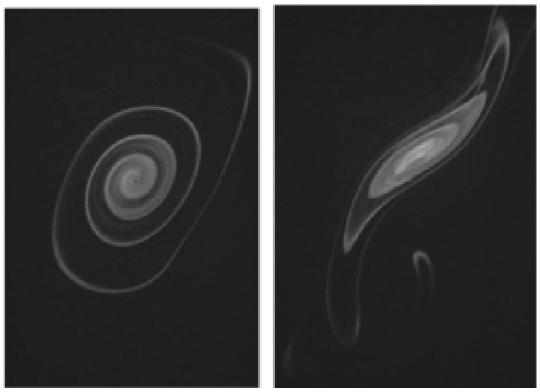

(a) (b)

Figure 3. Vortex deformation (i.e. vortex ring cross-section deformation) from a shear stress.[6]

Finally, a more accurate debris model is required to demonstrate vortex ring effectiveness. The first goal is to explore how a full satellite would react to sudden, increased drag. Specifically, whether the satellite will de-orbit as a single structure, fragment and de-orbit as debris, or fragment into debris and continue to orbit (a worse case scenario). The second goal is to determine whether the small surface area of micro-debris (paint chips, pieces of metal, fasteners, etc.) will create necessary drag forces. Should full satellites fragment and continue orbit, the vortex ring method may still be viable if multiple firings can effectively handle small objects.

V. Conclusion

In this paper, an expansion of research performed by the NASA SpaDE project will determine the effectiveness of using surface-based vortex ring cannons to deliver atmosphere to LEO altitudes, creating a drag force to remove debris in a fail-safe manner. This is to reduce logistical difficulties and operating costs from using expendable, high-altitude weather-balloon air bursts. The project focuses on the following key elements:

1. Expansion of the GITM atmospheric model to account for propagation below 30 km in higher densities, lower flow polarizations, high wind shear stress, and satellite structural integrity.
2. Scale wind-tunnel analysis of computational results of flow propagation.

References

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