Orbital Debris Mitigation Using In Situ Low Earth Orbit Plasma
Orbital Debris
- The collection of man-made objects in orbit around the Earth that no longer serve any purpose
- NASA estimates about 500,000 debris objects in orbit
  - This number does not account for debris having dimensions < 10 cm
- Objects are concentrated in Low-Earth Orbit (LEO) and Geosynchronous Orbit (GEO)
Background

• The orbital debris problem is a growing concern
• Created from:
  • Old inactive satellites
  • Collisions between existing debris particles
  • Rocket stages
  • Miscellaneous nuts and bolts from satellite deployments

• It is a serious threat to existing space infrastructure:
  • LEO satellites
  • Communication satellites
  • International Space Station
• Debris travel at orbital velocities (roughly 7 km/s)
  • Average impact velocity is roughly 11 km/s
• International Space Station conducts maneuvers
  • Encounters several debris scares per month
• Refuge taken by astronauts 5 times- Most recent is a remnant of rocket motor travelling at 19,800 mph
• Long Duration Exposure Facility (LDEF)
  • 20,000 documented impacts during 5.7 years of its space time
Big Problem
Debris Mitigation: Methods

- Current solution: maneuvering in orbit around debris in the presence of a threat
- Most solutions attempt to slow debris and have them de-orbit
- Previously proposed solutions for removal of debris:
  - Sail Sweep
  - Water Spray
  - Net Structures and
  - High Precision Lasers from ground/in-orbit satellite

- Disadvantages
  - Limited Impact area
  - Very large drag coefficient
  - Requires unreplenishable fuel
  - Limited orbital lifetime
  - Stringent pointing required
  - High energy consumption
Proposed Solution

- The Idea: Use plasma for debris mitigation
- Why?
  - Plasma is readily available in LEO
- What is plasma?
  - Plasma: Charged particles
    - Positive ions + negative electrons
- How?
  - Ions have a higher mass → generates form drag
By applying an electric field, plasma in the LEO environment can be concentrated into a higher density plasma field resulting in increased drag forces felt by traversing debris particles.
Model current environment
- Atmospheric model and plasma density model

Simulation
- Simulate plasma drag environment to characterize effectiveness
- Generate drag model

Ground testing
- Verify drag model with experiments
Plasma model: LEO

Relative Composition of the Constituent Ionospheric Gases vs. Altitude \[5\]
Electron Density vs. Altitude

Electron Density vs. Altitude$^5$
Combined Model

Plasma Density Model, derived from Electron Density curve and Ionospheric Constituent Gases

\[ \rho_{ion}(h) = C_1 h^6 + C_2 h^5 + C_3 h^4 + C_4 h^3 + C_5 h^2 + C_6 h + C_7 \]

Eq. 1: 6th-order approximation of ion density as a function of altitude

where:

\[ C_1 = -6.978441 \times 10^{-30} \]
\[ C_2 = 2.41493 \times 10^{-26} \]
\[ C_3 = -3.46545 \times 10^{-23} \]
\[ C_4 = 2.642054 \times 10^{-20} \]
\[ C_5 = -1.12625 \times 10^{-17} \]
\[ C_6 = 2.519352 \times 10^{-15} \]
\[ C_7 = -2.238598 \times 10^{-13} \]
Approach: Energy

\[ E = \frac{1}{2} m \cdot v^2 - \frac{\mu m}{R} \]  \hspace{2cm} (1)

Energy Equation: Mechanical Energy of an orbiting object

\[ \Delta \varepsilon = -2\pi \cdot R \cdot \frac{F_D}{m} \]  \hspace{2cm} (2)

Change In Specific Mechanical Energy due to drag forces

\[ F_D (R) = \frac{1}{2} \rho_{\text{air}} (R) \cdot v(R)^2 \cdot C_D \cdot A \]  \hspace{2cm} (3)

Drag Equation as a function of Radius of the orbit from the center of the earth
“Finite Difference” numerical approach of subsequent orbits

The code takes in several inputs of mass, starting radius, plasma density at starting orbit, drag co-efficient

Three energy components of debris: kinetic, potential and energy loss due to drag
Assumptions

- Circular orbit below 350 km altitude
- Atmosphere at LEO altitudes behaves as a fluid
- Atmosphere rotates with the earth at a particular angular velocity

\[ \omega_a (R) = \omega_{Earth} \cdot \frac{R_{Earth}}{R} \] (4)
Results

Altitude (km) vs. Lifetime (days) 1-80 x concentration of plasma
Results

Lifetime Decrease vs. Plasma Increase (up to 80x)
Decrease in orbital lifetime is proportional to the amount of plasma increase.

Assuming a roughly linear relationship, the slope of the curve is 0.16 % decrease in lifetime per fold increase in plasma.

- An 80-fold increase in plasma density → 12% reduction in orbital lifetimes.
From this data

- An experiment will be designed to determine whether such densities are achievable in orbit.
- Amount of plasma in orbit is limited → An upper limit to the amount of orbital decay exists.
- This will be determined by the limitations of the experimental payload.
Preliminary analysis Results

- Concept has merit
- Orbital lifetime is lowered by increasing the local density of plasma
  - Drag forces experienced by space debris can be increased
  - An energy approach taken and applied to a “finite difference” numerical method
Future Work

- To expand the simulation
- Fabrication of a test platform
  - Verification of simulation results
- Once verified, the experiment can be redesigned to be implemented onto a future small satellite mission
  - In orbit testing
  - Self Data Acquisition
Questions?