Addressing Key Challenges to Mapping Sub-cm Orbital Debris in LEO via Plasma Soliton Detection

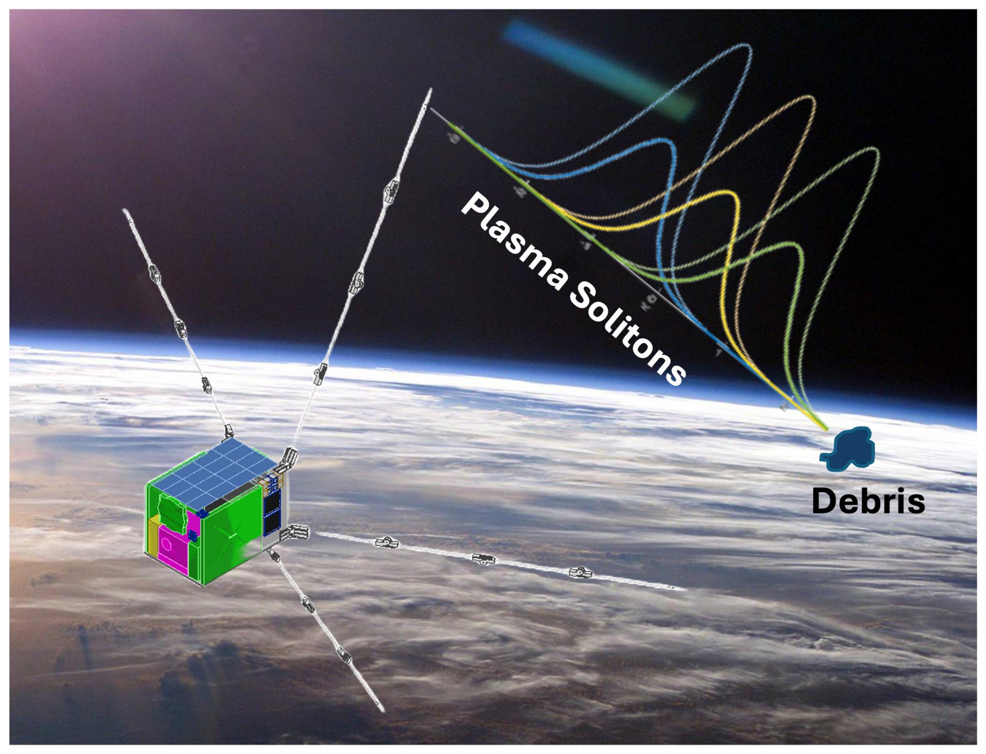
PI: Prof. Christine M. Hartzell*

Co-I: Prof John Martin, Postdoctoral Researcher: Adnan Mansour

*hartzell@umd.edu, 301-405-4647, Department of Aerospace Engineering, University of Maryland - College Park

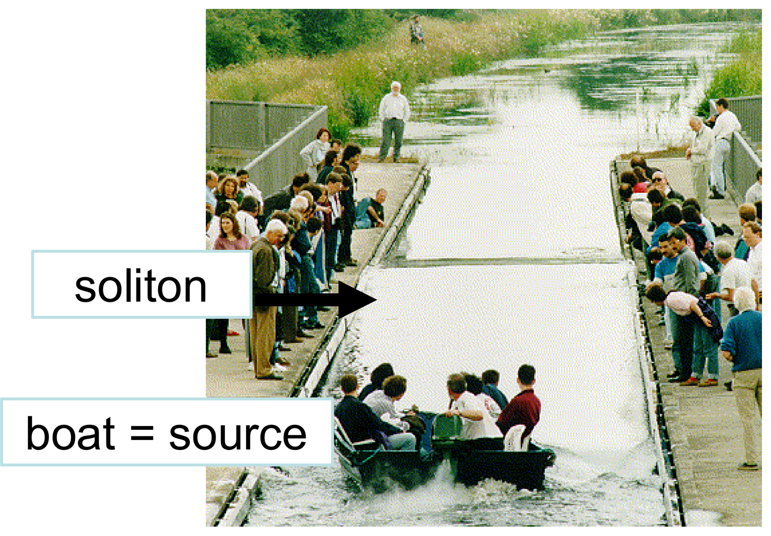
Concept Summary:

Map small (micron to sub-cm) orbital debris (that is currently untrackable) by detecting precursor plasma solitons with a fleet of Langmuir probe-carrying smallsats.

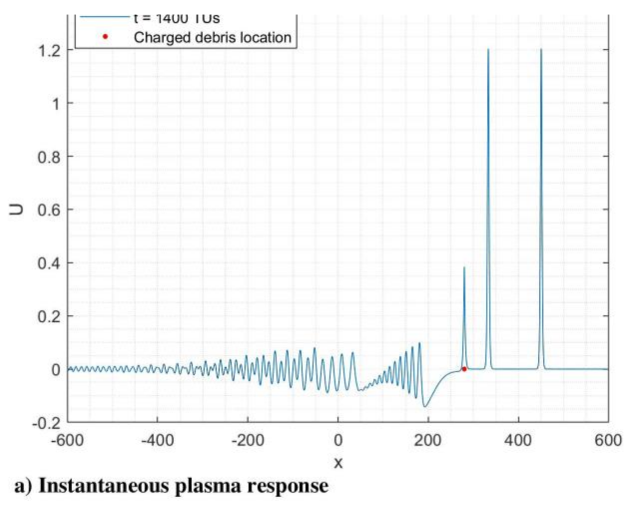


What is a Soliton?

- Solitons are a specific type of wave that does not dissipate as quickly as a classical wave.
- Exist in fluids, plasmas, light
- A wave in a plasma is a region of increased plasma density.
- Precursor solitons are similar to solitary standing waves and travel **ahead of** their source.
- Langmuir probes can be used to measure the density of a plasma and have considerable space flight heritage.



Re-creation of the first observed soliton
Source: Nature [1]



Precursor Soliton, 2.5mm debris, 1200km circular orbit
Source: Truitt and Hartzell, 2020, JSR.

Innovation and Impact:

- First method for detecting small (sub-cm) orbital debris prior to a collision.
- Detects hazardous and currently undetectable orbital debris.
- Knowledge of debris environment is useful to commercial and governmental spacecraft designers and operators (e.g., NASA, NRO, NOAA).
- Enables realtime evaluation of mitigation efforts.

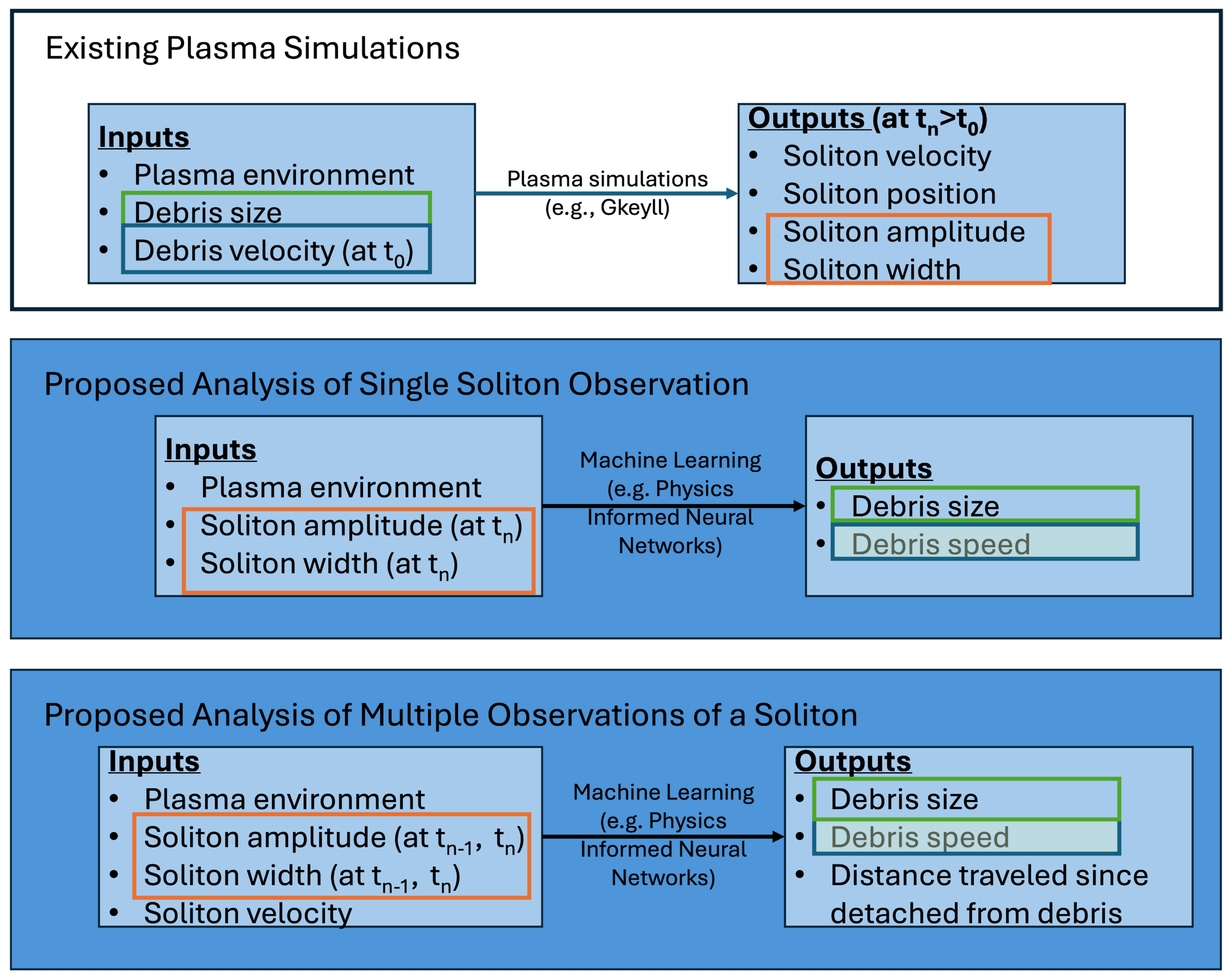
Current State of the Art in Debris-Generated Soliton Modeling:

- Sen and colleagues [2-4] have shown that precursor plasma solitons in plasmas can be described and predicted using the forced Korteweg-de Vries (fKdV) equation, which is known from the study of fluids.
- Truitt and Hartzell [5-7] characterized the solitons (amplitude, width, generation frequency) produced by cm and smaller debris at altitudes from 700-1200km. These investigations also demonstrated the effect of damping as well as 2D propagation.
- Desjardin and Hartzell [8] showed that the inverse scattering transform could be used to autonomously identify a soliton in a stream of data.
- Desjardin, Hartzell and Wrieden [9] refined the debris speeds that produce precursor solitons.
- Sam et al. [10] use a Particle-in-Cell code to more accurately predict soliton characteristics and dissipation.
- Sen et al. [11] and Ganguli et al. [12] describe the characteristics of electromagnetic solitons. Including an external magnetic field controls the transmission direction and reduces dissipation.

Major Outstanding Questions:

- Given an observation of a soliton, what information can we extract about the debris that created it?
  - Possible answers: debris size, shape, material, velocity, distance from spacecraft
- Can on-orbit soliton-based debris detection be used to predict the debris' orbit?
  - Requires estimate of debris position and velocity
  - Requires multiple detections of a single soliton

➔ Answering these questions is the goal of this NIAC

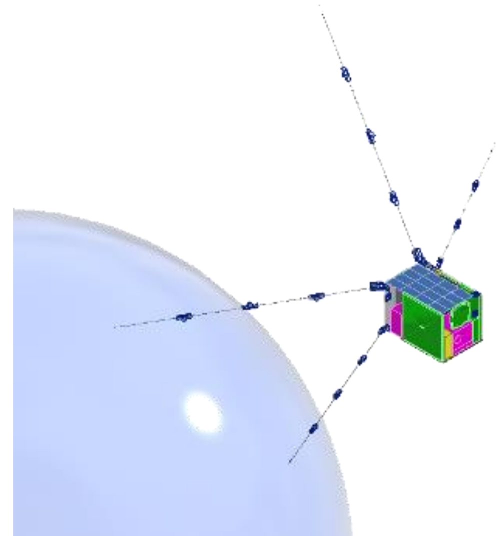


Even if the debris' orbit cannot be solved, this technique will provide a collision-free method to quantify the flux of debris that is currently undetectable.

- Laboratory-based experimental validation of modeled soliton characteristics (Funded through NASA Heliophysics)
- On-orbit demonstration of soliton generation and detection

Methods:

- Develop a Physics-Informed Neural Network to do the Inversion Problem
- Analyze architecture with one spacecraft and multiple probes
- Analyze architecture with spacecraft constellations, with each spacecraft hosting multiple probes
  - probes cannot operate in the wake behind another spacecraft



CAD by Wallops Mission Planning Lab, funding from NRO

NIAC Phase II Tasks:

1. Develop a ML algorithm to determine debris characteristics from a single, and then multiple, soliton observations.
2. Evaluate the feasibility of obtaining multiple soliton detections via multiple Langmuir probes on a single 12U smallsat.
3. Evaluation the feasibility of obtaining multiple soliton detection via a constellation of smallsats.
4. Trade compabilities and complexity of single and multiple spacecraft architectures.
5. Develop technology development roadmap considering hardware and software needed for operationalization.

References

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