On-Orbit, Collision-Free Mapping of Small Orbital Debris

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Risk Due to Small Debris

• According to the 2015 NASA Technology roadmap: “debris as small as 0.2 millimeter poses a realistic threat to human spaceflight and robotic missions in the near-Earth environment” [1]

• First significant Space Shuttle small debris incident: a 3.8mm diameter pit on STS-7 [2]

• Haystack radar:
  – 1-30cm debris (below 2000km)
  – >5mm at ISS altitude [11]

• Long Duration Exposure Facility

• 2015 NASA Technology roadmap identifies “a critical data gap for debris between 0.5 and 3 millimeter in LEO” [1]

Fig. 2. STS-92 left-hand #2 window crater (10-mm diameter by 1.9-mm deep) caused by orbital debris (paint).

Figure Source: Christiansen et al. [2]
Detection via Precursor Solitons

• Prior computational and experimental work by Sen et al. [4-6] showed that precursor solitons can be produced in plasmas
  – Solitons are solitary waves, where the nonlinear and dispersive effects are balanced, meaning that the waves propagate without dissipating (assuming that the environment remains unchanged).

• Preliminary calculations predict that small orbital debris (≤cm-scale) may produce solitons

• Solitons may be detected using relatively simple instrumentation (i.e. Langmuir probe)

• NIAC Concept: Use an equatorial constellation of cubesats to map small orbital debris by detecting plasma solitons produced by the debris.
Significance

• Sub-centimeter orbital debris is currently undetectable

• Maps of this orbital debris would be of interest to NASA, DoD, and Commercial Spacecraft Operators

• Mapping capability could also be used to evaluate efficacy of orbital debris remediation

• Plasma solitons could potentially be used to identify meteoroids near other planetary bodies
Feasibility

• What are the characteristics of plasma solitons that would be produced by small orbital debris?
  – What are the amplitude and velocity of the solitons? How quickly do solitons dissipate due to variations in plasma environment? Does the signal contain information about the size or velocity of the debris?

• How long would it take to map the debris?
  – How many satellites are necessary? How close do the satellites need to come to the debris in order to detect a soliton?

• What are the size, weight and power requirements of a cubesat that hosts a Langmuir probe?

• Alternate architectures:
  – Are solitons detectable from the ground?
  – Could the Langmuir probe detector be a standard hosted payload?
Debris, Solitons and Plasma

- Solitons have previously been observed in plasma around Earth by the Cluster spacecraft (ESA mission)
- Precursor solitons have been observed experimentally [6]
- Equations for time and spatially varying plasma density take the form of the forced Korteweg-de Vries (fKdV) equation
  - IF the system is weakly nonlinear
  - the nonlinearity and dispersion coefficients will depend on the plasma environment
- Solutions to the fKdV take a variety of forms depending on the form and speed of the disturbance
  - [4-6] observed that precursor solitons are produced when the velocity of the source is 1-1.5*the ion acoustic velocity
- Sen et al. [4] predicts that cm-scale LEO debris would produce electric field perturbations of mV/cm
Solitons in Plasmas

Given an arbitrary source (Gaussian charge density), solve numerically for the resulting ion velocity profile.

Nondimensional source charge density

Plasma density, nondimensionalized by freestream density.

Precursor solitons, traveling ahead of and faster than the source.

Figure Source: Sen et al. [4]
Numerical Soliton Simulation

We have implemented and validated a spectral method to solve the fKdV

Sen et al. numerical simulation of precursor solitons
Note: Y axis is \((n_1 - n_0)/n_0\)
X axis normalized by Debye Length
Soliton Detection

• Soliton signal present in plasma density variations
• Langmuir probes are a standard method to measure plasma density
  – a wire in plasma, where the electric potential of the wire is swept through a range
  – electrical current (I) to wire observed as the electric potential (V) is varied
  – analysis of I-V curve generates plasma densities
• The DICE cubesat mission hosted 2 Langmuir probes in a 1.5U cubesat [8]
• The challenge of hosting Langmuir probes on cubesats is holding the electric potential of the cubesat constant
  – the current collected by the probe must be balanced, but the cubesat has a small surface area, making it difficult to collect ions (which are relatively heavy)
• Baselining a second probe required to measure the spacecraft floating potential, but more work required
Langmuir Probe Design

- Minimum anticipated Debye length in LEO is 0.24 cm
- Langmuir probe dimensions: radius 0.2 cm, length 5 cm
- Probe must be mounted on a boom to avoid contamination from the plasma sheath around the spacecraft
  - Boom length: 30 cm (2x maximum anticipated Debye length)
- Probe Sweep Limits [9,10]: -3V to +15V
Mapping Debris using a Cubesat Constellation

- Orbital debris will be mapped using a constellation of equatorial cubesats
  - all debris will cross the equatorial plane 2x/orbit
  - time required to map the debris will depend on “detection distance”

- In proposal, we estimated the required mapping time by considering the debris as a static background and assumed that spacecraft always sampled previously unmapped space (no overlap between orbits)
  - lower bound on mapping time

- For Phase I, we are updating this prediction to include the phasing of the debris and cubesats and include J2 effects.

Time required to map 498 pieces of orbital debris between 400 and 500km altitude. Data beyond 45 days is a linear extrapolation.
Cubesat Design

• Undergraduate students completed a preliminary design of a cubesat to host Langmuir probe payload
• Detection can be completed with a 2U cubesat
  – Mass: 1.6kg
  – Volume: 760cm³ (67% of allowed)
  – Power Required: 6.5 W hr/orbit
• With the exception of the payload, systems are available commercially
  – UHF radio with deployable antenna
  – Active magnetotorquers + Earth horizon sensors (need to know spacecraft attitude)
  – Standard chassis, body-mounted solar panels
Alternate Architectures

• A “black box” standard Langmuir probe that can be hosted by other LEO satellites
  — Probes and (30cm) boom: ~35g
  — Electronics: ~45g, ~400mW
  — Imposes attitude pointing requirements since probe cannot be in plasma wake
  — Larger satellites will have a more stable floating potential

• Ground-based detection of solitons
  — measurements of ionospheric plasma densities and temperatures are routinely conducted from the ground
  — Sen [4] suggests that solitons produced by debris are detectable, but additional analysis is required
Conclusions

• Orbital debris is likely to produce precursor solitons in the LEO environment
• Preliminary work indicates that detection should be possible using Langmuir probes aboard 2U cubesats
• Next Steps:
  – simulate precursor solitons produced by orbital debris in LEO
  – continue to refine mapping time requirements
  – continue to refine Langmuir probe design (as hosted on cubesat)
Questions?

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References


8. https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database, Swartwout, Saint Louis University


Backup
• Risks due to Small Orbital Debris
• Current Detection Techniques
• Concept Overview
• Intro to Solitons
• Solitons in Plasmas
• Solitons from Orbital Debris
• Key Feasibility Questions
Current Detection Techniques

• Current capabilities for tracking
  – larger than 10cm
• Smaller than 10cm: detection and statistical population modeling
• Goldstone:
  – >2-3mm at ISS altitude (400km, Matney)
• Haystack radar:
  – 1-30cm debris (below 2000km)
  – >5mm at ISS altitude (Matney)
• Long Duration Exposure Facility
• GEO:
  – MODEST optical telescope
  – MCAT: 10cm at GEO
What are Solitons?

- Solitons are solitary waves, where the nonlinear and dispersive effects are balanced, meaning that the waves propagate without dissipating (assuming that the environment remains unchanged).

- First discovered in 1834 by John Scott Russell, who observed a boat stopping in a channel. “The fluid surrounding the prow of the vessel... rolled forward with great velocity, assuming the form of a large solitary elevation, a rounded, smooth and well-defined heap of water, which continued its course along the channel apparently without change of form or diminution of speed.... at a rate of some eight or nine miles an hour, preserving its original figure. Its height gradually diminished, and after a chase of one or two miles I lost it in the windings of the channel.”[3]
Solitons in Plasmas

• Sen et al. 2015 [5] analyzed the dynamics of ion acoustic waves in 1D
• They considered a background plasma and a charged debris object with some velocity
  – the debris object will be charged because it’s exposed to the local plasma and may also photoemit
• The debris object acts as a source term (a disruption in the flow)
• The equations of motion are heavily manipulated and eventually take the form of a forced Korteweg-de Vries (fKdV) equation
Solitons in Plasmas (2)

- The fKdV equation is known in fluid mechanics
- Certain forms of this PDE are easier to solve than others
  - If the forcing term is set to zero, then exact, analytical solutions can be obtained
  - For certain forcing terms, analytical solutions (pinned solitons) can be described
  - These solitons travel at the same velocity as the source: there is a spike in the ion velocity/density (i.e. the wave) as compared to the baseline (assumed stationary).
Soliton Utility

• Tiwari and Sen 2016 [6] found that the amplitude of the pinned solitons increases with:
  – increasing source amplitude (i.e. more charge=larger physical object)
  – increasing source velocity
• [6] also shows that pinned solitons can be produced with a subsonic (compared to the ion acoustic velocity) source
• [7] experimentally observes that the shape and velocity of precursor solitons is not dependent on source velocity
Experimental Investigation

- Low frequency dust acoustic waves can be observed optically by imaging light scattered off of the dust.
- In this experiment, the plasma flows (right to left) over a stationary wire (which serves as a potential hill).
- The amplitude of the disturbance is controlled by varying the current draw from the stationary wire.

Dust Acoustic Wave Speed:
- 2.4 cm/s

Flow velocity:
- 2.65 cm/s = M1.1

Soliton velocity:
- 4.15 cm/s = M1.7
• Keep either Sen precursor or experiment slide (probably need to decrease total slide count)
• Sen et al. [4] predicts that cm-scale LEO debris would produce electric field perturbations of mV/cm
• Key points: We have implemented and validated a spectral method to solve the fKdV.
• Next steps: understand how the characteristics of the solitons (amplitude, velocity) vary on debris characteristics (size=charge, velocity)
Orbital Debris as a Source

• Electrically Charged:
  – Yes, plasma currents and photoemission
  – Charging can be modeled

• Velocity:
  – [6,7] observed that precursor solitons are produced when the velocity of the source is greater than 1.1-1.5*the ion or dust acoustic velocity
  – Ion acoustic wave speed in ionosphere ≈1 km/s
  – Orbital debris velocity at 400km ≈7.65km/s
  – At higher altitudes, “Mach” speed of debris will be lower, producing more frequent solitons [5]

• Derivation of fKdV equation makes no assumptions regarding the plasma temperature or density. Thus, the derivation can be applied to ionospheric plasma as well.

• Sen et al. [5] predicts that cm-scale LEO debris would produce electric field perturbations of mV/cm
Key Questions: Precursor Solitons

1. How does the soliton amplitude/velocity depend on the source charge? Source velocity?
2. Can characteristics of the debris (size, velocity) be derived from a soliton signal?
3. How quickly does the soliton dissipate with changing background plasma?
Use Cases

- Map debris environment using a fleet of cubesats
- Langmuir probes as a standard spacecraft payload
- Deploy cubesats to assess mitigation efforts

- Time required to map 400-1600km within ±5° of equatorial plane
- Function of detection radius
- Varying number of cubesats
- Approx. 120 cubesats launched in 2015 [9]
Key Questions: Detection

• What is the smallest signal that can be distinguished from noise?
  – Dependent on sensor characteristics
  – Translates into debris size and charge constraints

• What is the maximum distance between the sensor and the debris for detection?
  – Dependent on signal dissipation with varying plasma environment
  – Drives mission operations, viability of cubesat mapping
# Mass

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (g)</th>
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<tbody>
<tr>
<td>Langmuir Probe</td>
<td>4</td>
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<tr>
<td>Dipole Antenna</td>
<td>100</td>
</tr>
<tr>
<td>UHF Radio</td>
<td>200</td>
</tr>
<tr>
<td>Earth Sensor</td>
<td>33</td>
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<tr>
<td>Magnetorquer Board</td>
<td>196</td>
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<tr>
<td>On-Board Computer</td>
<td>94</td>
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<tr>
<td>Power System Electronics</td>
<td>140</td>
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<tr>
<td>Solar Panels</td>
<td>400</td>
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<tr>
<td>2U Chassis</td>
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<tr>
<td>Mass Margin</td>
<td>20%</td>
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<tr>
<td><strong>Total</strong></td>
<td>1648</td>
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## Volume Budget

<table>
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<tr>
<th>Component</th>
<th>Dimensions (cm)</th>
<th>Volume (cm³)</th>
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<tbody>
<tr>
<td>Dipole Antenna (Stowed)</td>
<td>9.8 x 9.8 x 0.7</td>
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<tr>
<td>UHF Radio</td>
<td>6.9 x 7.4 x 1.6</td>
<td>81.7</td>
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<tr>
<td>Earth Sensor</td>
<td>4.33 x 3.18 x 3.18</td>
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<tr>
<td>Magnetorquer Board</td>
<td>9.6 x 9.0 x 1.7</td>
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<tr>
<td>On-Board Computer</td>
<td>9.6 x 9.0 x 3.6</td>
<td>311.1</td>
</tr>
<tr>
<td>Battery</td>
<td>9.6 x 9.0 1.3</td>
<td>112.3</td>
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<tr>
<td>2U Chassis External Dimensions</td>
<td>10 x 10 x 22.7</td>
<td>2270</td>
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<tr>
<td>2U Chassis Internal Dimensions</td>
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<tr>
<td>Total Utilized Internal Volume</td>
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<tr>
<td>Remaining Internal Volume</td>
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## Link Budget

<table>
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<tr>
<th>Data Type</th>
<th>Data Amount (bits/sec)</th>
<th>Time (mins)</th>
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<tbody>
<tr>
<td>Langmuir Probe Data</td>
<td>11600</td>
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<tr>
<td>Floating Potential Probe Data</td>
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<td>-</td>
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<tr>
<td>On-Board Computer/GPS Data</td>
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<tr>
<td>Error Margin</td>
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<td><strong>Total</strong></td>
<td><strong>23250</strong></td>
<td>-</td>
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| Up-Link Data Rate                       | 9600                   | -           |
| Down-Link Data Rate                     | 3e6                    | -           |

**Time Required to Down-Link 24 Hours of Data**: 13.39
# Power Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (W)</th>
<th>Duty Cycle (%)</th>
<th>Power Required Per Orbit (W)</th>
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<tr>
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<td>Dipole Antenna</td>
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<tr>
<td>UHF Radio</td>
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<td>10</td>
<td>1.2</td>
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<tr>
<td>Earth Sensor</td>
<td>0.132</td>
<td>100</td>
<td>0.132</td>
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<tr>
<td>Magnetorquer Board</td>
<td>1.2</td>
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<td>1.2</td>
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<tr>
<td>On-Board Computer</td>
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<td>0.55</td>
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<tr>
<td>Power System Electronics</td>
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<tr>
<td><strong>Power Margin</strong></td>
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Table 2: Power Budget