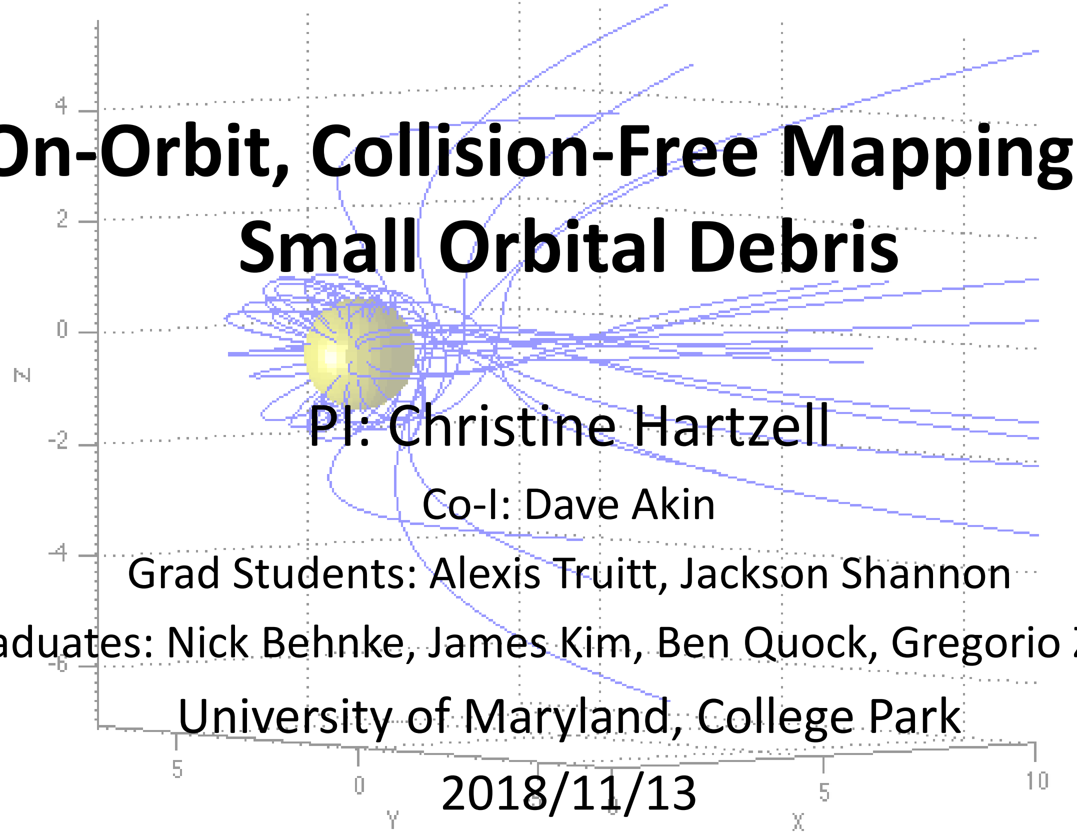
On-Orbit, Collision-Free Mapping of Small Orbital Debris



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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]

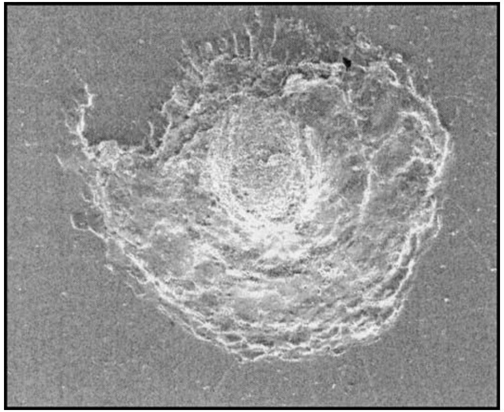


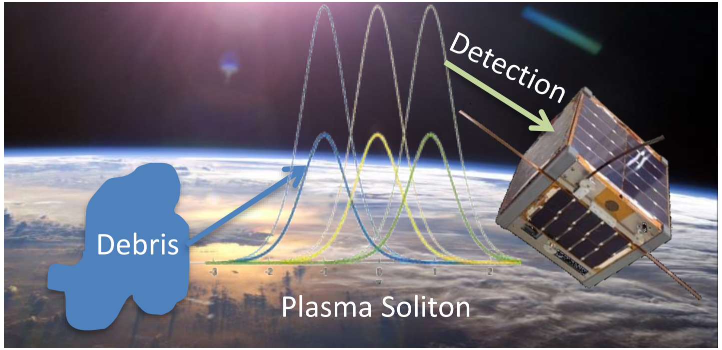
Fig. 2. STS-92 left-hand #2 window crater (10-mm diameter by 1.9-mm deep) caused by orbital debris (paint).

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)
- <u>NIAC Concept:</u> Use an equatorial constellation of cubesats to map small orbital debris by detecting plasma solitons produced by the debris.

Figure Source: Nature [3]



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

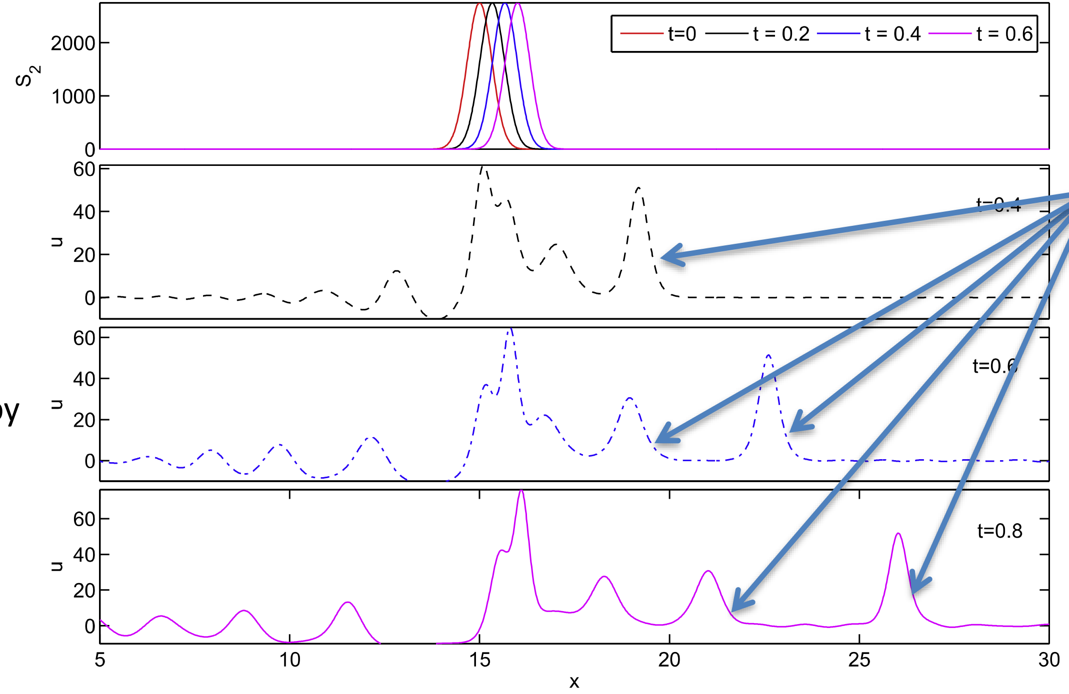
- Solitons have previously been observed in plasma around Earth by the Cluster spacecraft (ESA mission)
- Precursor solitons have been observed experimentally [6]
- Equations for time and spatially varying plasma density take the form of the **forced Korteweg-de Vries (fKdV)** equation
  - IF the system 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.



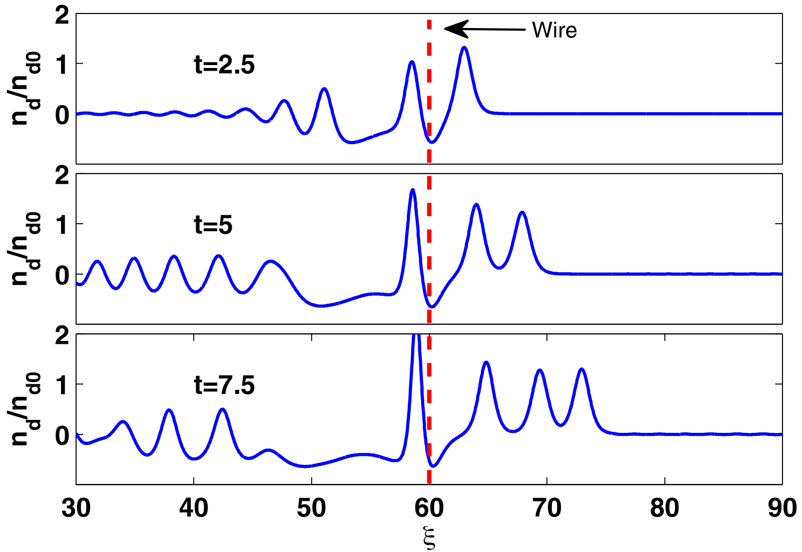
Precursor solitons, traveling ahead of and faster than the source

Position, nondimensionalized by Debye Length

Figure Source: Sen *et al*. [4]

Numerical Soliton Simulation

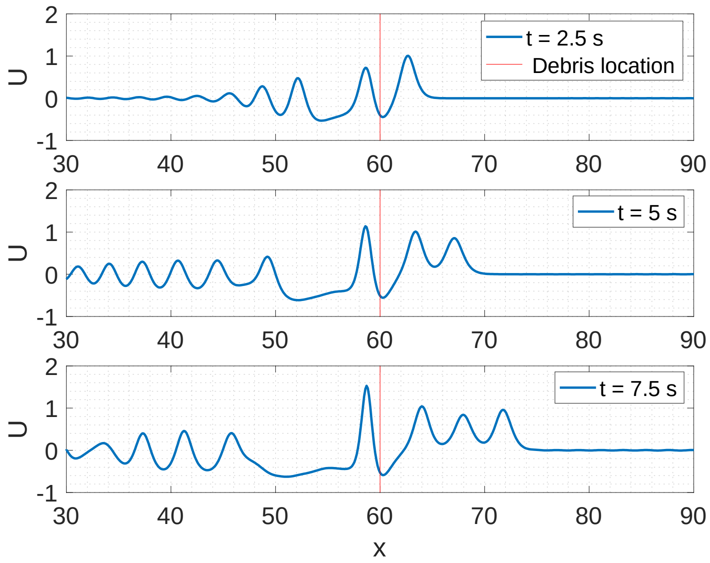
We have implemented and validated a spectral method to solve the fKdV



Sen *et al.* numerical simulation of precursor solitons

Note: Y axis is (n1 - n0)/n0

X axis normalized by Debye Length



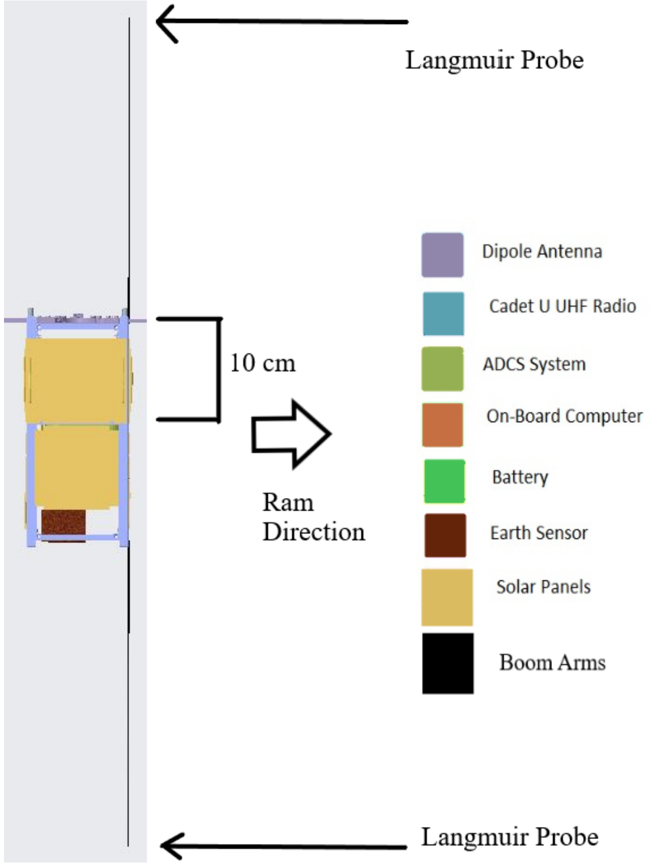
Our numerical solution

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

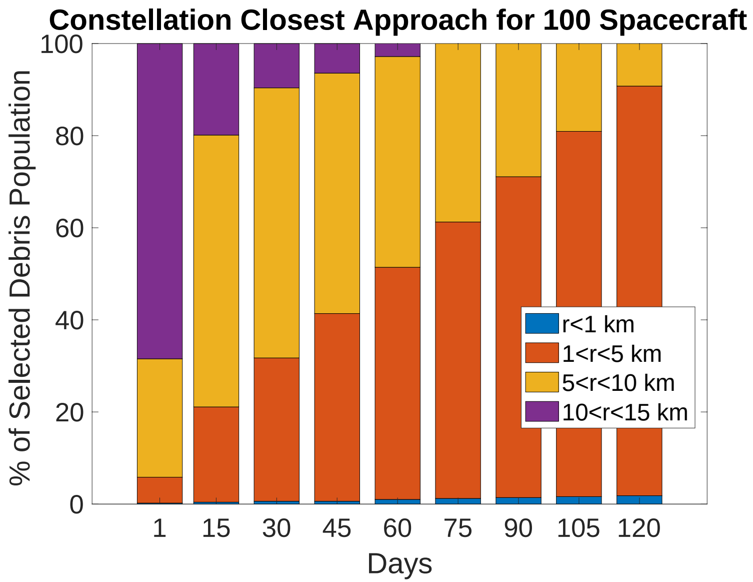
Langmuir Probe Design

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



Mapping Debris using a Cubesat Constellation

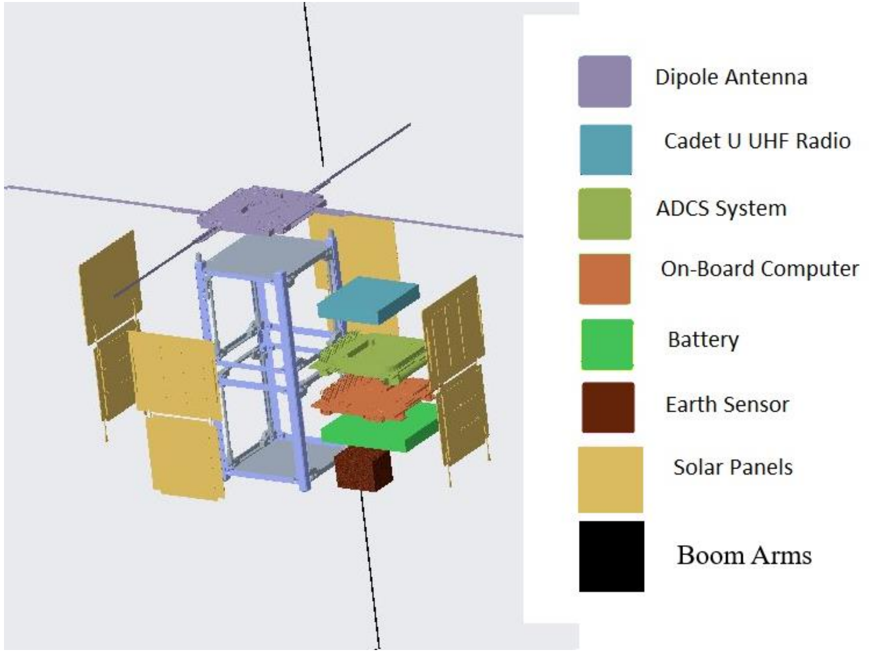
- Orbital debris will be mapped using a constellation of equatorial cubesats
  - all debris will cross the equatorial plane 2x/orbit
  - time required to map the debris will depend on "detection distance"
- In proposal, we estimated the required mapping time by considering the debris as a static background 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: 760cm^3 (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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Backup

Outline

- 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]

Figure Source: Nature *[4]*

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 <u>pinned</u> solitons increases with:
  - increasing source amplitude (i.e. more charge=larger physical object)
  - increasing source velocity
- [6] also shows that <u>pinned</u> solitons can be produced with a subsonic (compared to the ion acoustic velocity) source
- [7] experimentally observes that the shape and velocity of <u>precursor</u> solitons is <u>not</u> dependent on source velocity

Experimental Investigation

- Jaiswal *et al* 2016 [6] experimentally observed precursor solitons in a dusty plasma
- 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.

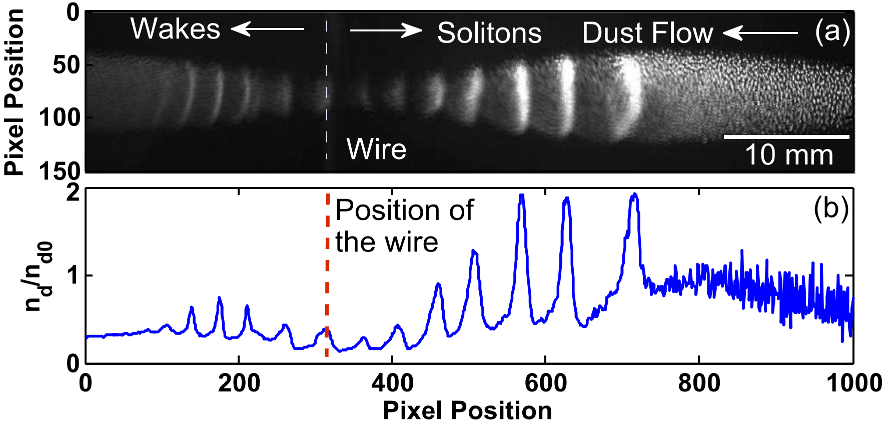


Figure Source: Jaiswal *et al*. [6]

Dust Acoustic Wave Speed:
- 2.4cm/s

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

Soliton velocity:
- 4.15cm/s=M1.7

Alexis Slide

- 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

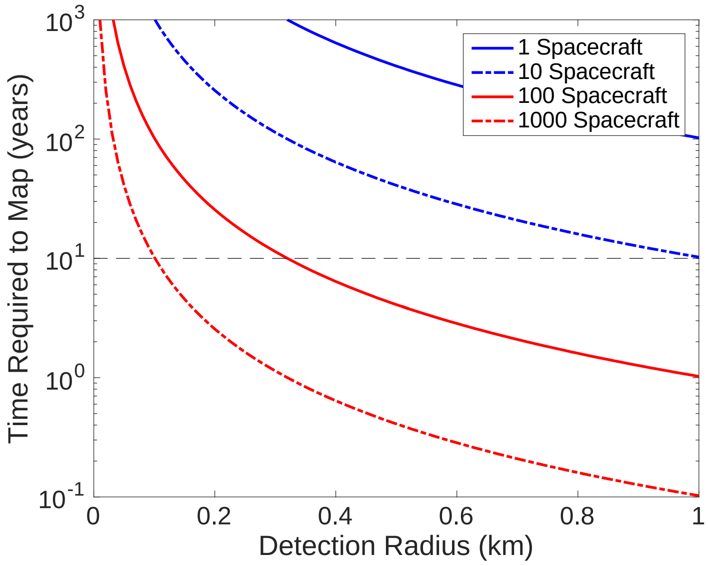
- Electrically Charged:
  - Yes, plasma currents and photoemission
  - Charging can be modeled
- Velocity:
  - [6,7] observed that precursor solitons are produced when the velocity of the source is greater than 1.1-1.5*the ion or dust acoustic velocity
  - Ion acoustic wave speed in ionosphere ≈1 km/s
  - 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?
4. Specific predictions: debris size X, altitude Y, produces a precursor soliton (amplitude Z, velocity W).

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

Component	Mass (g)
Langmuir Probe	4
Dipole Antenna	100
UHF Radio	200
Earth Sensor	33
Magnetorquer Board	196
On-Board Computer	94
Power System Electronics	140
Solar Panels	400
2U Chassis	206
Mass Margin	20%
Total	1648

Volume Budget

Component	Dimensions (cm)	Volume (cm^3)
Dipole Antenna (Stowed)	9.8 x 9.8 x 0.7	67.22
UHF Radio	6.9 x 7.4 x 1.6	81.7
Earth Sensor	4.33 x 3.18 x 3.18	43.8
Magnetorquer Board	9.6 x 9.0 x 1.7	146.9
On-Board Computer	9.6 x 9.0 x 3.6	311.1
Battery	9.6 x 9.0 1.3	112.3
2U Chassis External Dimensions	10 x 10 x 22.7	2270
2U Chassis Internal Dimensions	9.84 x 9.84 x 19.7	1905.6
Total Utilized Internal Volume	-	763
Remaining Internal Volume	-	1142.6

Link Budget

Data Type	Data Amount (bits/sec)	Time (mins)
Langmuir Probe Data	11600	-
Floating Potential Probe Data	11600	-
On-Board Computer/GPS Data	50	-
Error Margin	20%	-
Total	23250	-
Up-Link Data Rate	9600	-
Down-Link Data Rate	3e6	-
Time Required to Down-Link 24 Hours of Data	-	13.39

Power Budget

Component	Power (W)	Duty Cycle (%)	Power Required Per Orbit (W)
Science Board	0.5	100	0.5
Dipole Antenna	0.04	100	0.04
UHF Radio	12	10	1.2
Earth Sensor	0.132	100	0.132
Magnetorquer Board	1.2	100	1.2
On-Board Computer	0.55	100	0.55
Power System Electronics	0.015	100	0.015
		Power Margin	20%
		Total	4.36

Table 2: Power Budget