Detecting the Undetected Satellite Killer: Meteoroids

PNT SYMPOSIUM 2016

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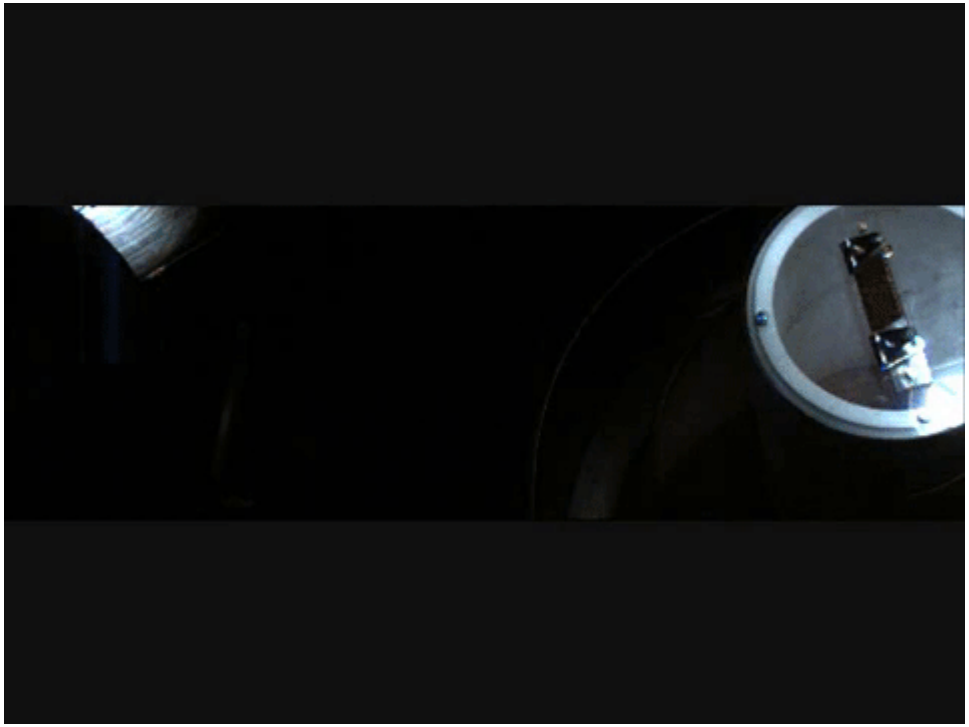
Space Environment

Effects on spacecraft can stem from:

- Space Debris
- Radiation
- Spacecraft Charging
- Drag
- **Meteoroids**
  - **Primary concern from more massive meteoroids is mechanical damage.**
  - **Primary concern from less massive meteoroids is electrical damage.**

Impact Plasma Generation



Research Goal

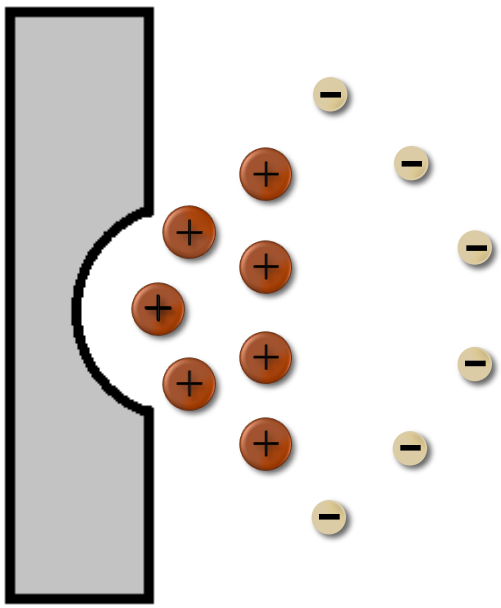
- Spacecraft are routinely impacted by hypervelocity particles with possibility of damage
  - Mechanical: "well-known", larger, rare
  - Electrical: "unknown", smaller, more numerous
    - Electrostatic Discharge (ESD)
    - Electromagnetic Pulse (EMP)
      - **EMP from impacts on negatively charged spacecraft**
      - **…**
- Goal: *characterize plasma and potential radio frequency (RF) emission from hypervelocity impacts to assess possibility of spacecraft damage*

Research Outline

1. Hypothesis EMP emission mechanism
2. Understand frequency/relevancy of emission mechanism occurrence
3. Perform experiments to investigate into EMP production
4. Perform signal processing to isolate and aggregate RF impact observations
5. Develop model of EMP production based upon impactor mass and velocity

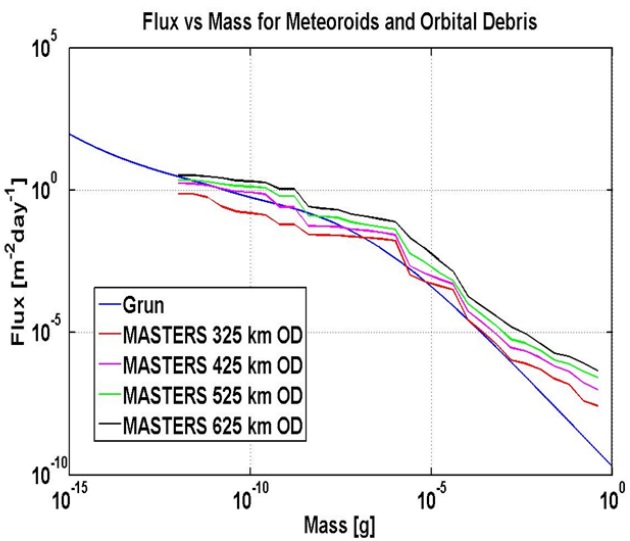
RF Emission Mechanism

Biased Target



- EM emission power scales according to Larmor formula for bulk electron acceleration.
- Negatively biased targets accelerate liberated electrons in impact plasma.
- RF emissions scale with the amount of impact plasma and target bias.

Meteoroid Populations

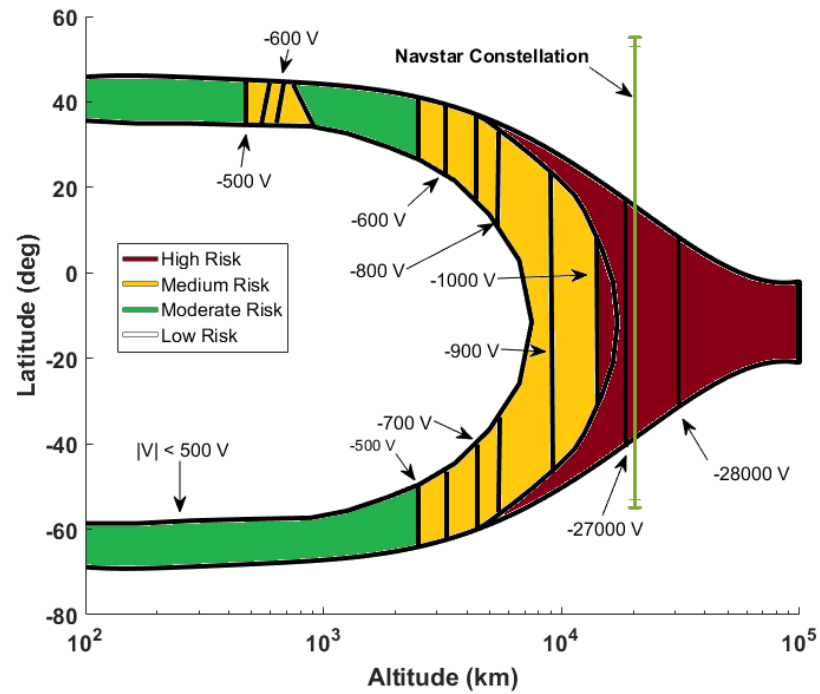


Gurnett, D. and Team, C. 2004. Initial results from the Cassini radio and plasma wave science investigation at Saturn. 35 p. 1895.

- Meteoroid flux is a combination of sporadics and showers.
- Sporadic flux dominates at lower masses, and shower flux dominates at higher masses.
- Meteoroid showers shift the velocity and mass distribution of the background meteoroid population.

Spacecraft Charging

- Satellites orbiting Earth are immersed in its magnetosphere.
- Fluctuations in solar activity can adjust size and shape of the plasmasphere.
- Geomagnetic storms and substorms can inject energetic particles into satellite orbits/

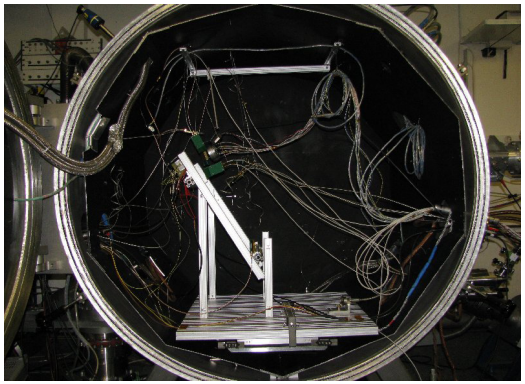


Whittlesey, A., H. Garrett, and P. Robinson. "The satellite space charging phenomenon, and design and test considerations." *IEEE INTERNATIONAL SYMPOSIUM ON ELECTROMAGNETIC COMPATIBILITY*. INSTITUTE OF ELECTRICAL ENGINEERS INC (IEEE), 1992.

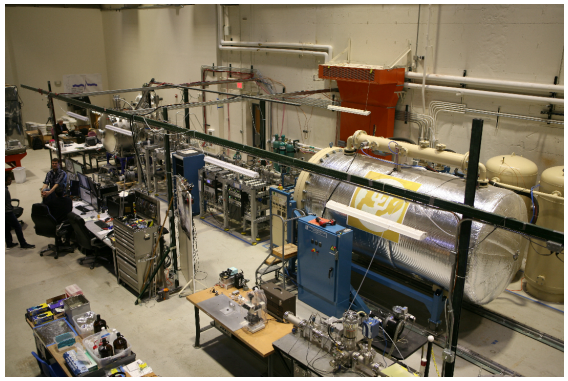
Ground Based Testing

To better understand the impact event series of ground based tests were conducted.

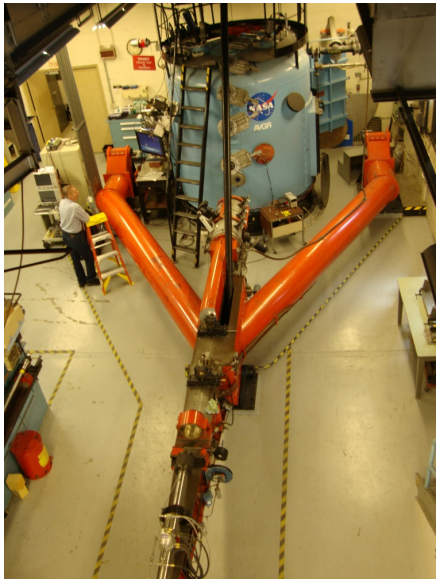
Max Planck Institute



IMPACT



Ames Vertical Gun Range

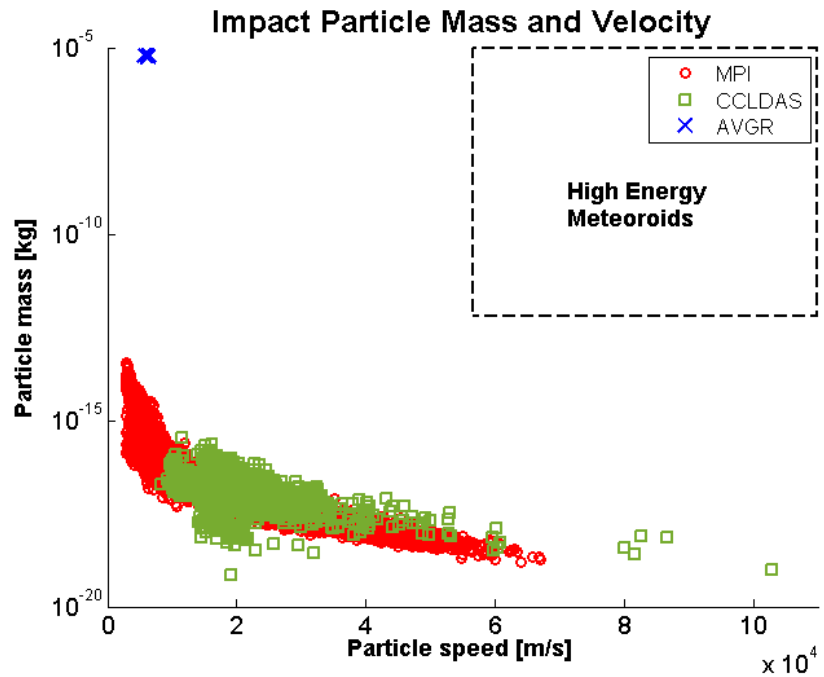


Impactor Configuration and Scaling

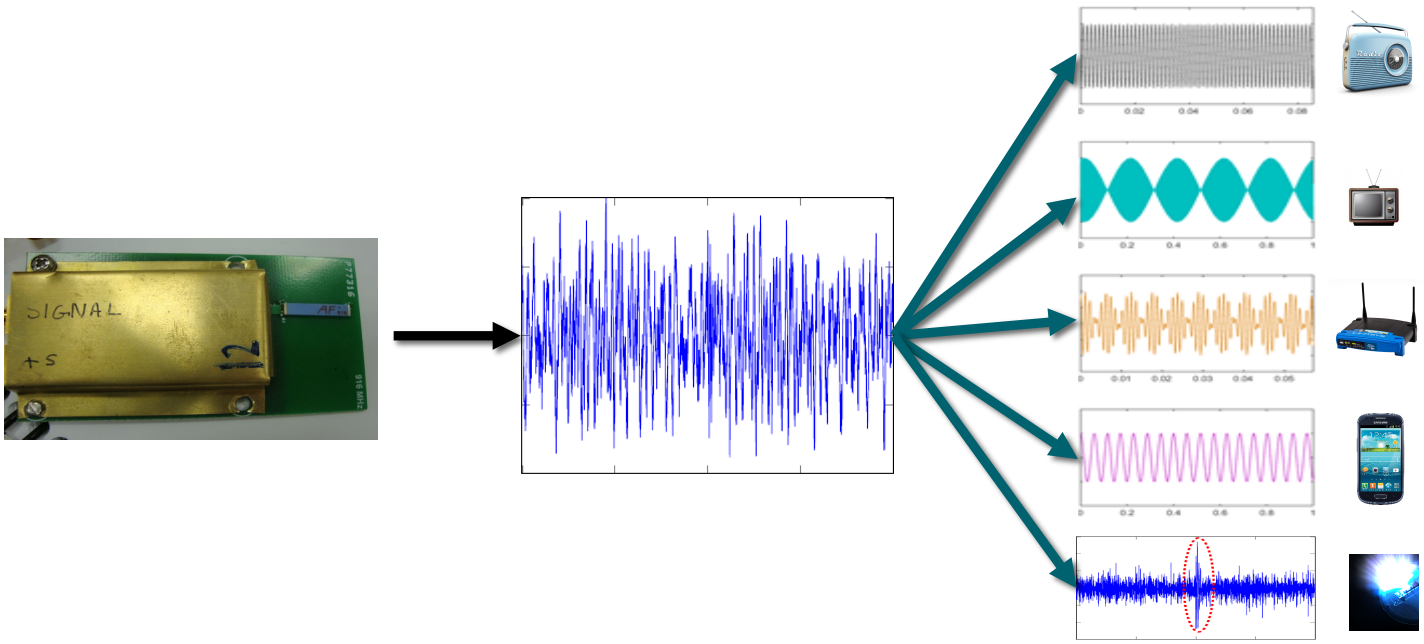
Meteoroids can achieve a wide range of masses and velocities

<u>Available Ground Based Tests</u>

- Electrostatic – MPI/CCLDAS
  - Mass: ~ 10^{-16} - 10^{-20} kg
  - Velocity: 5 – 100 km/s
- Light Gas Gun – AVGR
  - Mass: ~milligram
  - Velocity: ~5 km/s



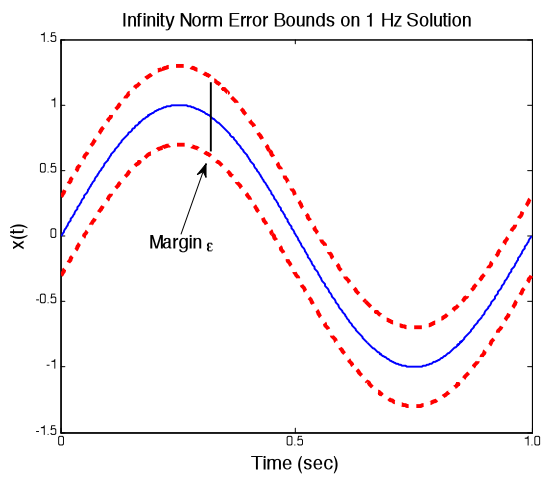
Single Channel Source Separation



A Constrained Bayesian Approach to BSS

A Bayesian approach estimates the most probable model of the system. Goal becomes to maximize

$$P(model \mid observation)P(model \mid observation) \propto P(Y|A,X)P(A)P(X)$$



$$\textbf{\textit{maximize}}: \quad P(Y|A,X)P(A)P(X)$$

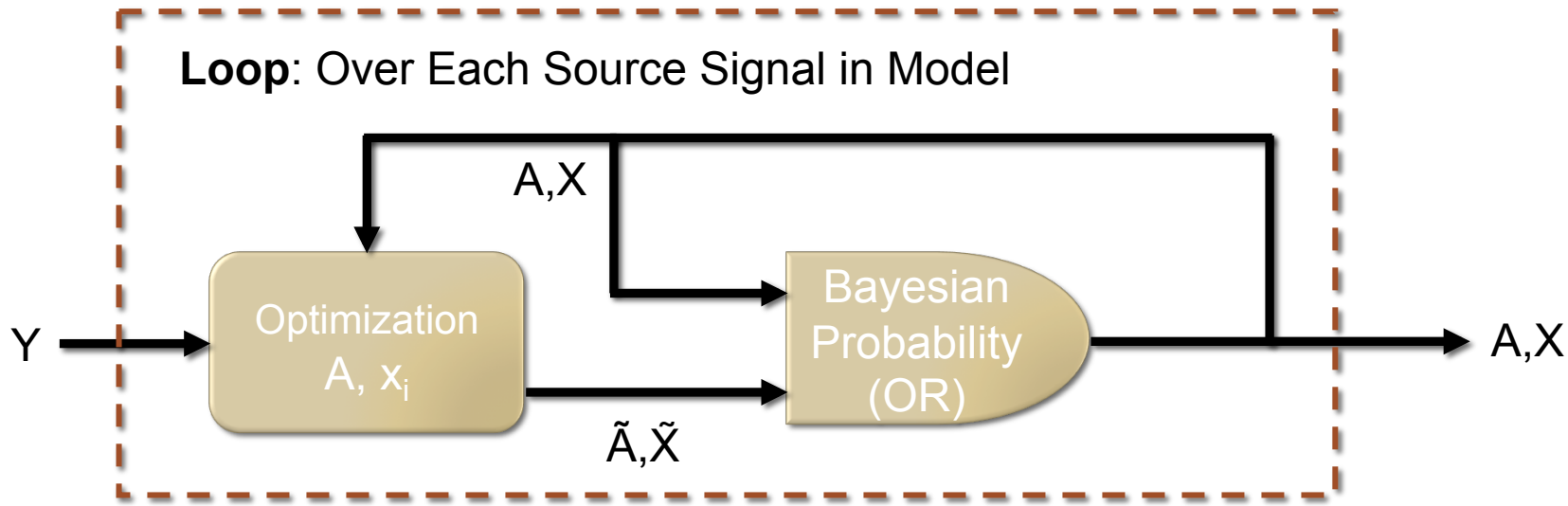
$$\textbf{\textit{subject to}}: \quad f(A,X) \leq 0$$

$$h(A,X) = 0$$

$$A \geq 0$$

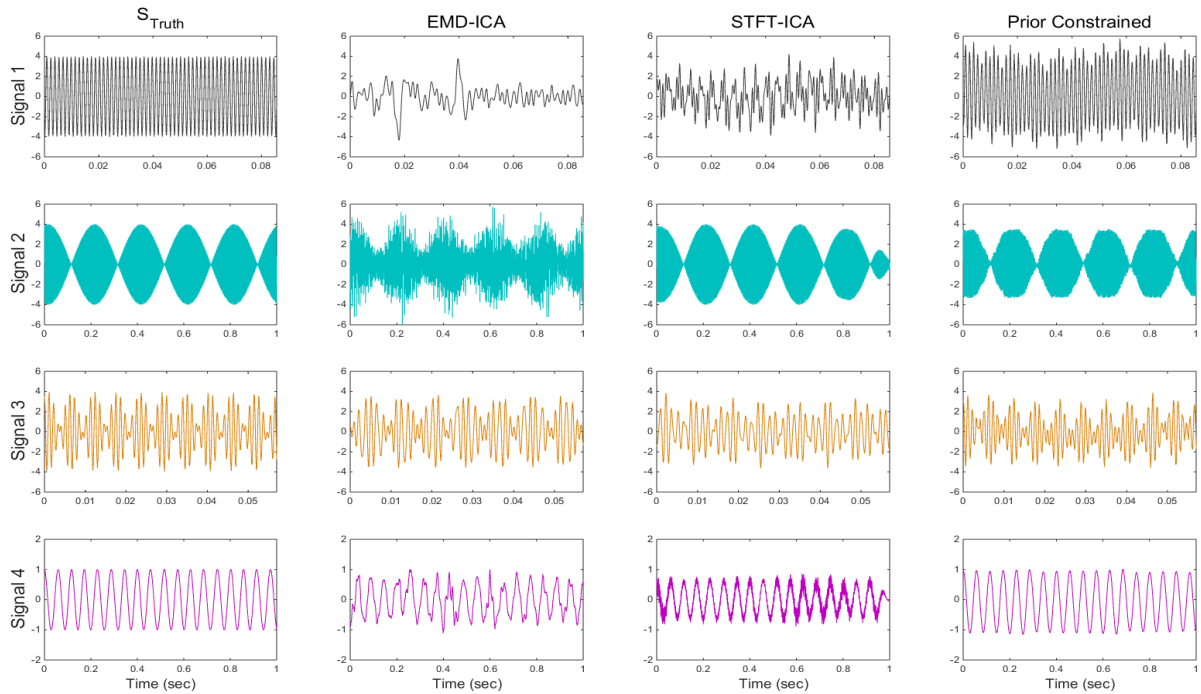
Prior Constrained

Repeat Until Convergence

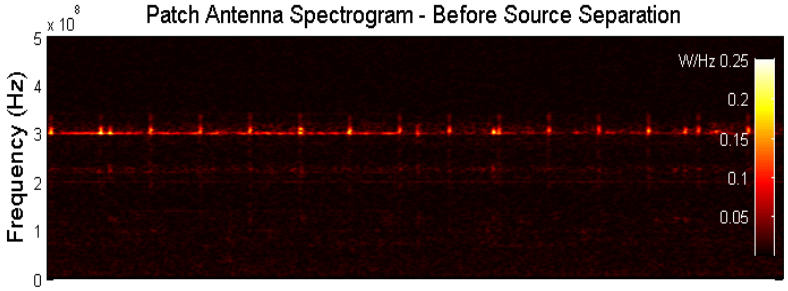


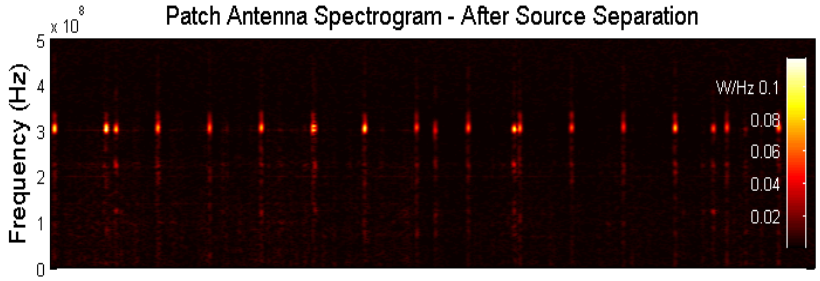
A,X: Most Probable Model **Ã,X̃**: Current Guess of Model

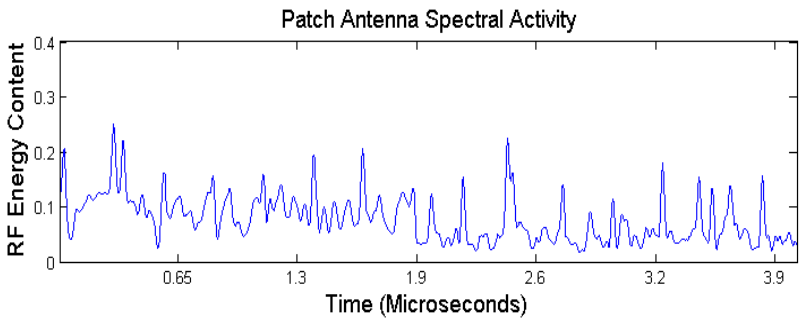
Results Synthetic

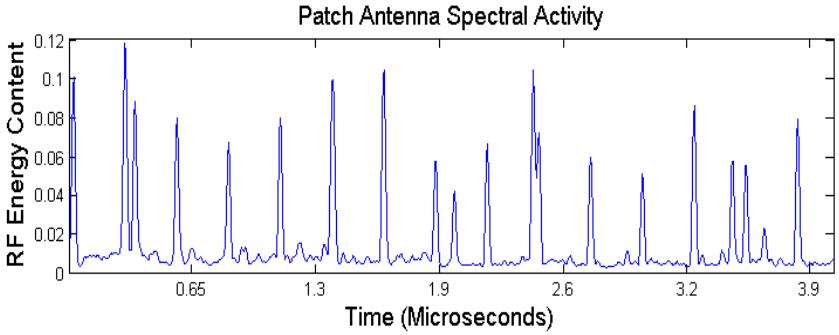


Results RF


Patch Antenna Spectrogram - Before Source Separation
x 10^8
Frequency (Hz)
W/Hz 0.25
0.2
0.15
0.1
0.05


Patch Antenna Spectrogram - After Source Separation
x 10^8
Frequency (Hz)
W/Hz 0.1
0.08
0.06
0.04
0.02


Patch Antenna Spectral Activity
RF Energy Content
Time (Microseconds)


Patch Antenna Spectral Activity
RF Energy Content
Time (Microseconds)

Impact Data Aggregation

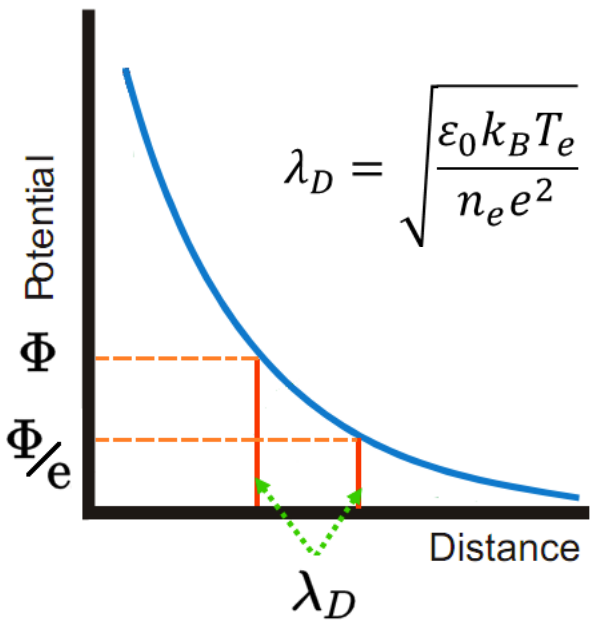
A linear time dilation is applied to each impact for all times after the time of impact. The dilation is performed to create a consistent time of Debye length proportionality to plasma dimensions.

Linear time dilation

$$T_i = \frac{\bar{\tau}}{\tau_i}$$

$$\tau_i = \left(\frac{Qe}{{}^{2}/_{3}\, \epsilon_0 k_B T_e \pi} - r_{0,i} \right) \frac{1}{C_s}$$

Debye Length

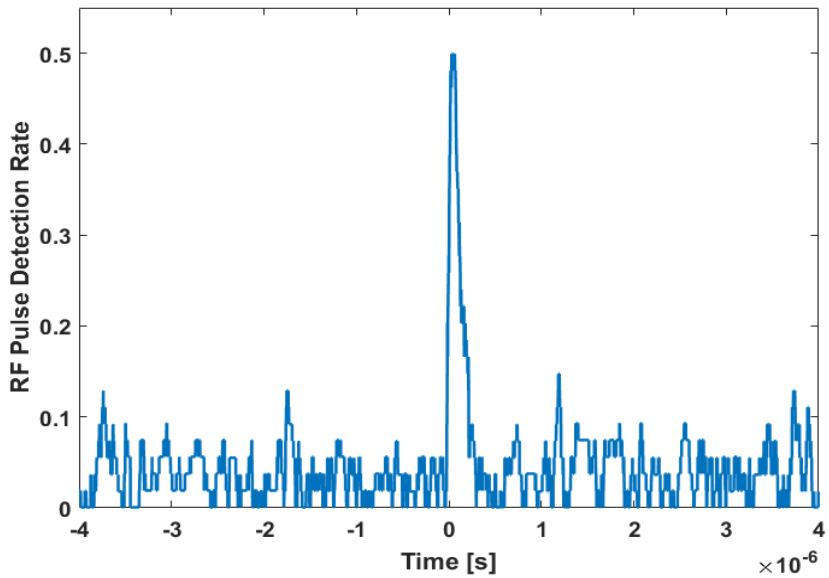


$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}$$

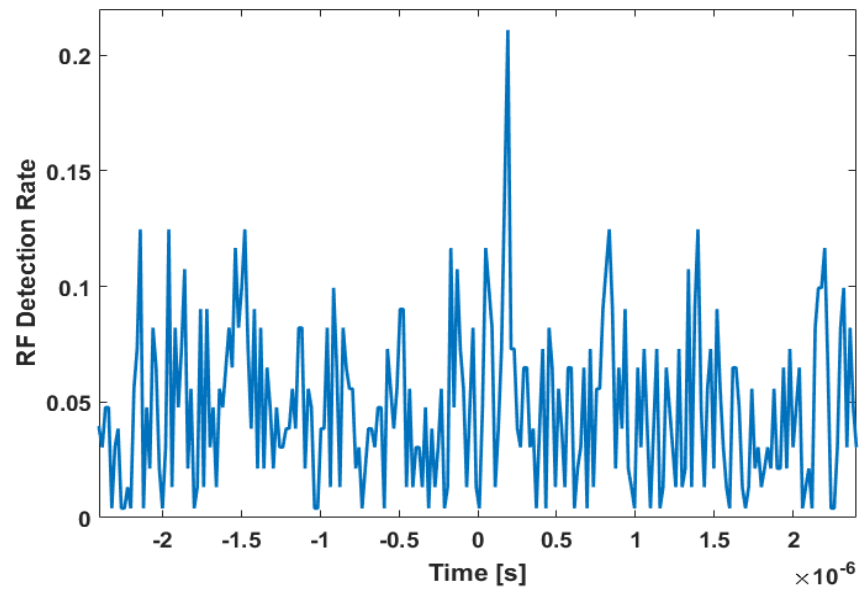
EMP Detection Rates

$$D_{t,i} = P_{t,i} \geq a\bar{P}_i$$

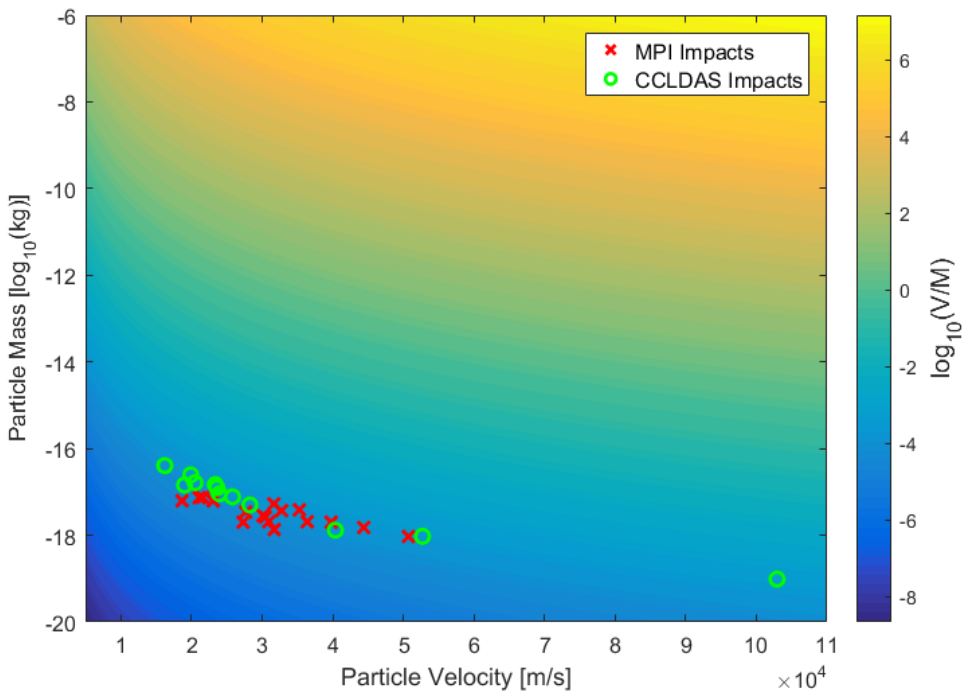
MPI: -1000V Target



MPI: -500V Target



-1000V EMP Emission Scaling



Scaling Analysis was conducted and error bounds were generated using a Monte Carlo simulation

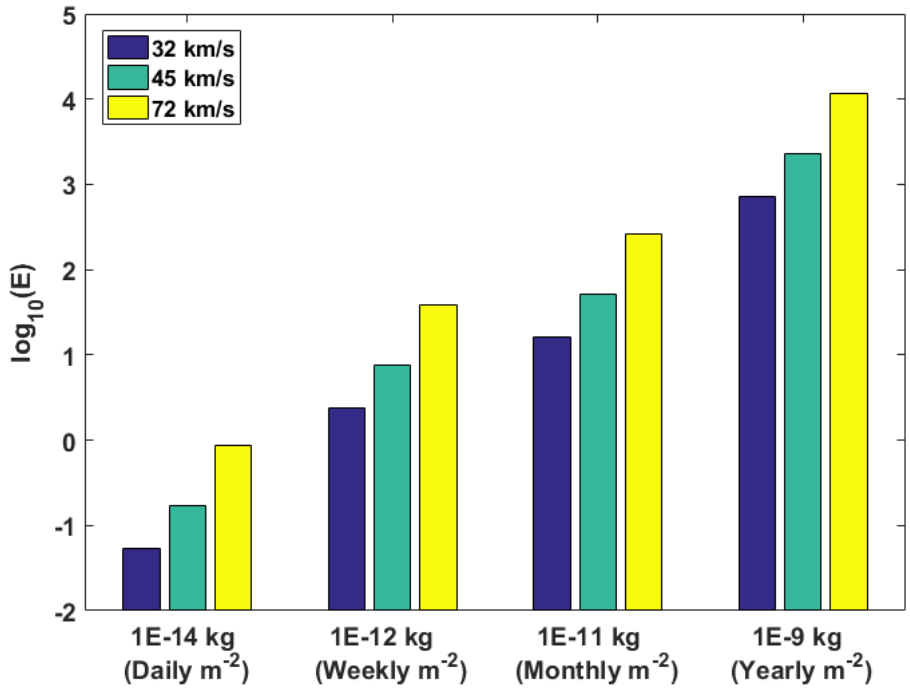
Nominal:

$$E = 6.13 \times 10^{-6} m^{0.82} v^{3.45}$$

Error:

$$E = A m^{0.83 \pm 0.29} v^{3.45 \pm 0.81}$$

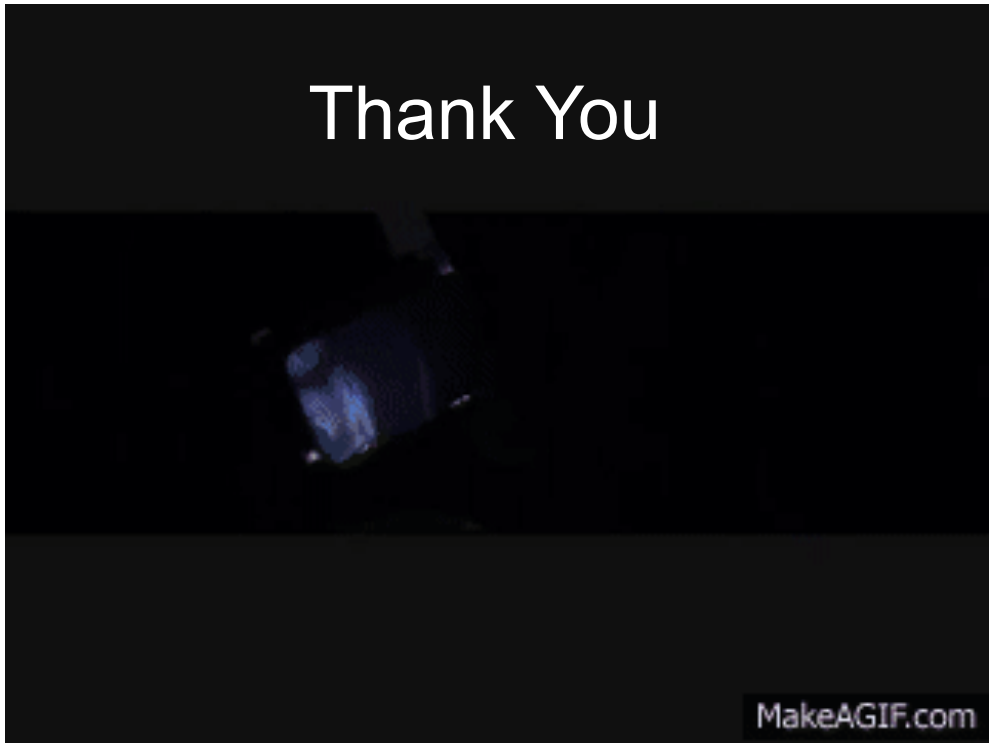
-1000V EMP Emission Scaling



Conclusions

- Dust-sized meteoroids can impact satellites on a routine basis.
- Spacecraft charging state sets the boundary conditions for hypervelocity impact plasma.
- Experiments were conducted a both light gas gun and electrostatic accelerator facilities.
- RF emissions were observed with the potential to scale to disruptive levels.

Questions



Results Comparison

- Error metric defined using time domain subtraction.
- Prior constrained methodology able to outperform other methods by factor of 2.5-3.5.

$$N_e = \frac{\|S - S_{truth}\|_2}{\|S_{truth}\|_2}$$