Understanding Spacecraft Failures by Characterizing Hypervelocity Impact Plasmas

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Impact-Related Anomalies

- Olympus 1993
- Landsat 5 2009
- ADEOS II 2003
- ALOS 2011
- JASON-1 2005

- Numerous others with unexplained ESD-related failures: Galaxy 15, Fengyun-1, AusSat-A3, Intelsat 511, Telecom 1B, Intelsat 510, Arabsat 1-A, Anik-D2...

- NRC report (2011) recommends studying “...effects of plasma during impacts, including impacts of very small but high-velocity particles.”
The phenomenon of electrical damage from hypervelocity impact (of meteoroids or orbital debris) on spacecraft is not well-understood.

Impact energies are great enough to produce a plasma:

\[ Q = 0.1m_p \left( \frac{m_p}{10^{-11}} \right)^{0.02} \left( \frac{v_p}{5} \right)^{3.48} \]

**Meteoroids:**
- Smaller than 0.3 m diameter (including dust)
- Shower (associated with parent body) and sporadic (background) sources
- Parents are cometary (icy, 50–70 km/s) or asteroidal (rocky, 20–30 km/s)

**Orbital debris:**
- Human-made objects primarily in Low Earth Orbit (LEO)
- Range from paint chips to rocket bodies
- Slower than meteoroids (7–11 km/s) but comparable momentum
Research Areas

- **Ground-based observations** (radar, optical)
  - Meteoroid flux, mass, density
- **Space-based observations** (RF, plasma, optical, surface cratering)
  - Meteoroid and orbital debris flux, composition
- **Ground-based impact testing**
  - Mechanical and electrical impact effects

Research question:

*How can hypervelocity impacts of meteoroid and debris cause electrical anomalies in spacecraft systems?*
Possible Mechanisms

- **Electrostatic discharge (ESD)**
  Sudden liberation of electrons from the target surface

- **Arcing**
  Current flow through a conductive channel caused by vaporization and ionization of the target

- **Electromagnetic pulse (EMP)**
  Propagating wave packet of electromagnetic energy radiated from the impact point

- **Current pulse**
  Broadband spectrum from impulsive movement of charge

- **Electron oscillation**
  Decaying radio frequency chirp
Undertook ground-based hypervelocity impact tests to show electrical effects are feasible

- Determined that plasma is produced from grounded targets
- Characterized effect of target charge on plasma behavior
- Showed that impact plasma is a possible source of both EMP and ESD effects
Outline

- Overview of ground-based experiment
  - Accelerator technology and facility
  - Projectiles, sensors, targets
- Theory and results of plasma measurements
- Future work
• **Targets:** bare metal, spacecraft surfaces, and active sensors

• **Plasma sensors:**
  • Retarding Potential Analyzers (RPAs)
  • Faraday Plate Arrays (FPAs)

• **RF sensors:**
  • E-field sensors (SRI)
  • Patch antenna (PA) arrays (315 MHz and 916 MHz)

• **Optical:** photomultiplier tube (PMT)
Electrostatic Dust Acceleration

- Iron dust particles accelerated to 1–60 km/s through 2 MV potential
- Van de Graaff particles much smaller than representative meteoroid and debris populations
Experimental Configuration

- 1.4 m diameter vacuum chamber
- Operating pressure between $10^{-6}$ mbar and $10^{-5}$ mbar
Plasma Sensors

- Plasma particles impinge on metal collecting surface generating net current
- Current converted into voltage signal
- Two RPAs at similar distance and angle on opposite sides of beamline
Run 00920: $v_p = 39.4 \text{ km/s}$; $m_p = 1.45 \text{ fg}$; Target = SRI-T - W; Bias = $+1000 \text{ V}$
Plasma measurements show very different behavior with target bias.

- $+1000 \text{ V}$
- $0 \text{ V}$
- $-1000 \text{ V}$
• Overview of ground-based experiment

• **Theory and results of plasma measurements**
  • Positive target bias
  • Low target bias
  • Negative target bias

• Future work
Multiple positive peaks

Run 01101: \( v_p = 36.3 \text{ km/s}; \ m_p = 3.19 \text{ fg}; \) Target = SRI-T - W; Bias = +1000 V
Plasma speed distribution (half-Maxwellian):

\[ f_q(v) = \eta_j Q \sqrt{\frac{2m_j}{\pi k_B T_j}} \exp \left( -\frac{m_j v^2}{2k_B T_j} \right) \]

where

\[ \int_0^v f_q(u) du = \eta_j Q \text{erf} \left( \sqrt{\frac{m_j}{2k_B T_j}} v \right) \]
Equation of motion with high target bias:

\[
\vec{F}_j = q_j \left( \vec{E}_{\text{bias}} + \vec{E}_{\text{ambi}} + \vec{v} \times \vec{B}_{\text{geo}} \right) = m_j \ddot{x}_j
\]

\[
\ddot{x}_j = \frac{q_j E_{\text{bias}}}{m_j} = \frac{q_j V_{\text{bias}}}{m_j d_{\text{RPA}}}
\]

Initial speed required to reach RPA in time \(t_{\text{TOF}}\):

\[
v_0(t_{\text{TOF}}) = \frac{d_{\text{RPA}}}{t_{\text{TOF}}} - \frac{q_j V_{\text{bias}}}{m_j d_{\text{RPA}}} \frac{t_{\text{TOF}}}{2}
\]

Plasma current deposited on the RPA:

\[
I(t) \approx \sum_j \frac{\eta_j Q}{\delta t} \left[ \text{erf} \left( \sqrt{\frac{m_j}{2k_B T_j}} v_0(t) \right) - \text{erf} \left( \sqrt{\frac{m_j}{2k_B T_j}} v_0(t + \delta t) \right) \right]
\]
• 10 eV-based distribution had best fit based on shape of peaks
• Ion species: 25% hydrogen, 17% carbon, 7% aluminum, 31% iron, and 20% tungsten
• More balanced response in both RPAs
• Prompt positive signal

Run 01695: $v_p = 44.4$ km/s; $m_p = 2.48$ fg; Target = TGT-W; Bias = 0 V
Indications of Quasineutral Plasma

![Graphs showing RPA output and model comparison]

Run 01402: $v_p = 40.8 \text{ km/s}; m_p = 1.52 \text{ fg}; \text{ Target} = \text{TGT-W}; \text{ Bias} = +20 \text{ V}$

- Assumed same ion population as in positively-biased case
- Initial slope of modeled signal matches measurement
- Remainder of measurement masked by electrons
Negative Target Bias

- Fast bipolar response
- Sometimes a second peak microseconds later

Run 01129: \( v_p = 13.5 \text{ km/s}; \ m_p = 26.5 \text{ fg}; \) Target = TGT-W; Bias = −1000 V
Secondary Electron Emission

- High-energy electrons impinging on metal surface can bounce off and/or knock off another electron

- Secondary electron emission yield \( \delta \equiv \frac{I_{\text{out}}}{I_{\text{in}}} \)

Using data from Dekker (1958) for SEE from electron bombardment on tin:

![Graph showing the relationship between primary electron energy and secondary electron yield](image)
Positive Signal Explained

Run 01152: $v_p = 36.4$ km/s; $m_p = 3.61$ fg; Target = TGT-W; Bias = $-1000$ V

- Positive pulse from secondary electron emission
- Negative pulse from reabsorption of emitted electrons
- Subsequent peaks from additional electron emission due to secondary impacts
Summary of RPA Results

Positive bias separates ion species, causing multiple positive current pulses.

Impact at low bias results in quasineutral plasma with potential for electron oscillation.

Negative bias causes possibly multiple distinct negative current pulses.
Outline

- Overview of ground-based experiment
- Theory and results of plasma measurements
- **Future work**
  - Further analysis on existing data
  - In situ impact studies on orbit
Future Work

- Modeling and interpretation of impacts on other targets and measurements with other sensors
- 3D modeling of electrical environment
- Comparison of plasma results with optical and RF results
- Assessment of impact on spacecraft electronic systems
Future Work: In Situ Measurements

MEDUSSA:
Meteoroid, Energetics, and Debris Understanding for Space Situational Awareness

- 3U CubeSat mission
- Goal: study electrical effects of impacts in space
- RF, plasma, optical sensors
- Deployable 1 m × 1 m MMOD impact screen
- Expected detection rate of 1 impact per day from ng particle
Conclusions

- The plasma behavior observed in the ground-based impact tests was consistent with both ESD and EMP phenomena.

- The variation in plasma expansion behavior due to the bias of the impacted surface is significant in understanding impact events in space and mitigating their effect.

- Deleterious electrical effects of hypervelocity impacts can be mitigated through consideration of the spacecraft geometry and its interaction with the space environment.
References (I)


1993: Olympus

- Communications satellite in GEO
- Failed during Perseid meteoroid shower
- Experienced gyro shutdown
- Loss of mission due to fuel shortage
2009: Landsat 5

- Observation satellite in LEO
- Failed during Perseid meteoroid shower
- Experienced extreme gyro rates
- Resumed operation after recovery ops
• Japanese Advanced Earth Observing Satellite-II

• Failed during Orionid meteoroid shower

• Short-circuit between power cables on solar array boom

• Power decreased from 6 kW to 1 kW in 3 minutes
2011: ALOS

- Japanese Advanced Land Observing Satellite
- Failed during Lyrid meteoroid shower
- Switched to low power
- Experienced rapidly deteriorating power generation
2002: Jason-1

- Observation satellite at 1336 km altitude
- Detected impact event during Gamma Normid meteoroid shower
- Orbit semimajor axis changed by 30 cm
- Experienced power spike for 5 hours