Detection and Analysis of RF Data from Hypervelocity Impacts

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Ground based tests were performed at the Max-Planck-Institute für Kernphysik Van de Graaff accelerator in Heidelberg, Germany to explore radiofrequency (RF) emission associated with hypervelocity particle impact induced plasma. Meteoroids and dust traveling between 11 and 72.8 km/s are constantly bombarding spacecraft while on orbit. These hypervelocity particles may cause electrical anomalies in satellites through electromagnetic pulse (EMP) or electrostatic discharge (ESD). Ground tests were conducted by firing iron dust particles at speeds in excess of 11 km/s at target materials situated in a 1m diameter vacuum chamber. A set of broadband log-periodic dipole antenna, VLF loops, and a point electric field sensor are used to detect emission. The signal is dissected in order to corroborate the model of RF emission due to coherent plasma oscillation.

I. Introduction

Experiments dedicated to detecting radiofrequency (RF) emissions in hypervelocity particle impacts have been conducted by Bianchi (1983), Takano (2002) and Starks (2006). Bianchi detected 100kHz-200kHz RF signals from the acceleration of ~1g aluminum particles 10 km/s into hard materials in a vacuum chamber. Takano detected microwave signals at 22 GHz using a heterodyne receiver and acceleration of iron particles into a vacuum chamber at 2, 4 and 6.7 km/s. Eichhorn also detected magnetic field fluctuation during hypervelocity dust particle impact tests. Further, in-situ measurements have documented RF emission on board Cassini (Kelley 2010). Our experiment represents the first ground-based campaign dedicated to detection of RF emission due to hypervelocity dust particle impact at impact speeds attained during meteor showers. In this experiment, we aim to detect the broadband emission characteristics of impact-generated plasma. The theory behind plasma RF emission we seek to validate is derived elsewhere (Close, et al. 2010). The hypervelocity impact at speeds above 11 km/s has enough energy to ionize the incoming particle and a portion of the impacted surface. The resulting plasma charge separates by one Debye length due to the higher electron mobility and the electrons are subsequently recovered by the background ions. This process initiates oscillations at the characteristic plasma frequency. The plasma cloud continues to diffuse into the vacuum, lowering the plasma density, resulting in a down-chirping plasma frequency. Due to the ballistic expansion of the plasma, a sheath of electrons may oscillate coherently at this frequency, resulting in dipole emission. The emission ceases once the conditions for plasma are no longer met (Chen 1983). This process produces the down-chirping radio emission electromagnetic pulse (EMP) we aim to detect. In addition, we estimate the extent to which impact charge

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production may result in electrostatic discharge (ESD) on-board a satellite. An incoming charged particle may cause the charged satellite surface to discharge by acting as a conductor away from the satellite.

**Figure 1** Hypervelocity particle impact, charge production and ballistic free expansion model (Close, et al. 2010)

The motivations for studying hypervelocity impact-generated plasma emission properties are unexplained satellite anomalies attributed to electrical and space environment effects. When no momentum transfer or mechanical damage is detected, failures, upsets and anomalies may be attributed to electromagnetic effects. Documented instances of in-flight upsets due to electromagnetic interference (EMI) include the 1999 instance of phantom commands experienced by weather satellites NOAA-11 and NOAA-12 as they flew through a uniquely noisy VHF environment (Leach 1995). Additionally, the Tethered Satellite System (TSS-1R) failed in 1996. One possible failure scenario was degradation due to electrical discharge or electrical arcing (Vaughn 1997). These examples are illustrative of the types of failures that may be caused or exacerbated by the presence of a radiating and dense, impact-generated plasma.

EMI occurs when radiated energy from one source interferes with the operation of another. When a high power RF transmitter illuminates a piece of electronics, sufficient energy may be coupled into the victim to interfere with its operation (Clark 1995). In the case of impact-generated plasma EMP, radiated susceptibility in the satellite may occur when the RF power transmitted by the plasma is intercepted by wiring in the satellite victim. Predicting the radiated susceptibility of a piece of equipment begins with understanding potential exposure hazards (Clark 1995). As such, understanding the electromagnetic radiation properties of impact-generated plasma in the space environment should be of great importance to satellite designers.

In addition to radiated emission, arcing and discharging may occur due to a local plasma cloud with a density much greater than the background plasma density. The theory that impacts due to meteoroids could initiate an arc due to the coupling provided by the dense, impact-generated plasma cloud was proven experimentally by accelerating 75-micron particles into an anodized aluminum plate in the presence of simulated ionospheric plasma. The Marshall Space Flight Center team observed arc voltages as low as 55 V (Carruth 2001).

### II. Ground Based Impact Tests

While both RF emission and plasma production from hypervelocity particle impact are relatively well documented, the relationship between these two effects remains unclear. Further, the differences among the frequency spectra of measured emission among ground-based tests and in-situ measurements should be resolved. The theory proposed by (Close, et al. 2010) would explain the mechanism for plasma RF emission, and is in strong agreement with the broadband frequency spectra measured elsewhere. Detection of highly time-resolved, broadband RF emissions during hypervelocity dust particle impacts was a primary experimental objective of the December 2010 tests at the Max-Planck-Institute Van de Graaff accelerator in Heidelberg, Germany. An experiment to detect RF was instrumented with three types of antennas and sensors: (1) a high frequency (> 2 GHz) E-field sensor, (2) a UHF/VLF log-periodic array antenna, and (3) a tri-axial VLF loop antenna.
Additionally, a Low Noise Amplifier (LNA), and a gain stage to deliver useful signal levels for capture with a high-speed scope were used. The E-field sensors are of very low gain, typically -20 dB, but have very uniform frequency response, from near DC to 10 GHz. The LPA is included to provide frequency coverage from the E-field sensors’ low end and below to the VLF with close to unity gain, thereby bridging the gap in frequency coverage with nominal gain of the order of unity. The LNA is a 28 dB gain, broadband amplifier (50 MHz to 4 GHz), with a noise figure of ~1.5 dB. The LNA’s output is connected to two more identical amplifiers via 3 dB pads to produce 78 dB of total gain with a pre-LNA noise floor of ~1 µV, over the 4 GHz bandwidth. This noise level will be ~100 mV, and thus will attractively dominate the 1 mV noise floor of the high-speed oscilloscopes that are appropriate and necessary to capture the RF waveform produced by the impact generated plasmas. The coupling pads between the amplifier stages have adjustable attenuation allowing the RF system to support a dynamic range near 80 dB, and thereby
provide the means to capture RF waveforms with amplitudes from ~ µV to ~Volts. Finally, analyzing the results requires pico-second to nano-second scale signal processing.

![Figure 6 Gain stages and data acquisition for E-field sensor, LPAs and VLF Loop antenna](image)

**III. Radiofrequency (RF) Measurements**

Measurements from the E-field sensor are given additional weight. The E-field sensor was developed by Richard Adamo and his team at SRI, and is a capacitive coupled electric field stub attached to a ~1 cm diameter brass target. The target was aligned in the MPI dust accelerator close to the center of the beam line and hypervelocity dust impacts. The dust particles are charged in the process of acceleration in the MPI Van de Graff and that charge is deposited on the E-field sensor’s target during impact. Since the target’s capacitance is ~10 pF, and the particles are charged with ~10^3 to 10^4 electrons, the charge deposition on impact produces a voltage pulse of ~10 mV to 100 mV. Using a combination of a preamp in the sensor, and an additional LNA with 20 dB of gain outside the impact chamber, high SNR voltage pulses were recorded using a 5 GS/s sampling scope at MPI.

The interfaces between the E-field sensor, the LNAs and the high-speed oscilloscope possessed impedance mismatches that caused ringing in the recorded E-field response. Using a prototype response recorded using a calibration pulsar the impedance mismatch distortion of the voltage pulse was removed. Deconvolution was accomplished using frequency domain compensation for one E-field voltage pulse from a hypervelocity dust impact. A frequency domain process is illustrated where both the prototype impulse response, obtained using a pico-second pulser, and the E-field response are Fourier transformed. The product of the inverse pulser response, adjusted to attenuate influence of high frequencies, with the forward transform of the E-field response is formed. The inverse transform of the product yields the deconvolved response.
Figure 7 Impact 00355 (a) E-field sensor response upon impact; (b) MPI facility generated charge detector response; (c) E-field sensor response magnified

Figure 8 E-field sensor response to pico-second pulse
The deconvolved E-field response was searched for an RF signal with the signature of an expanding plasma cloud. The RF model for this signature is a rapidly down-sweeping ‘chirp’, an RF waveform resulting from charge separation on the cloud’s surface and a harmonic oscillation that decreases in frequency as the cloud expands and the surface charge density decreases. A matched filter was formed using the model of a plasma expansion chirp waveform.

Prior to the matched filter application, the E-field’s deconvolved response was modeled to remove the target’s response to charge deposition, plasma production and charge ‘blow-off’ using a multi-Gaussian model. An example of the multi-Gaussian modeling is illustrated in Figure 10, where four Gaussians are used to excise the principal features leaving a smooth, noisy residual. Even though Gaussian decomposition is not unique, the model is well matched to the E-field response. It is this residual that is used in the matched filter process.

Many of the deconvolved E-field responses exhibit pronounced features that are evident in Figure 10. The E-field responses typically possess a strong, prompt pulse, likely due to the deposition of the dust.
particle’s charge on the E-field’s disc. Following the prompt pulse is a slower, broader pulse, often enhanced in its center that may be due to the production of plasma and its expansion away from the sensor.

IV. Future Work

Future work will be undertaken in Summer 2011 to further mitigate noise in the resonant cavity chamber environment and capture both electrostatic and electromagnetic field measurements correlated with impact plasma production. Limitations of the setup in the MPI chamber excluded obtaining signal from both the plasma sensors and the E-field sensor, and thus the needed confirmation of plasma detection in the RPAs was not obtained simultaneously with the E-field measurements. This deficiency will be corrected in the next round of experiments at MPI. In the future, we will explore the existence of this RF emission mechanism between other mass and velocity regimes at other facilities.

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