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ELECTRICAL EFFECTS OF HYPERVELOCITY IMPACTS

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Abstract: While a large fraction of the space community is cognizant of the mechanical damage that can be caused by hypervelocity impacts, very few take into consideration the electrical pathway that can lead to satellite anomalies and failures. In this paper, we briefly describe the characteristics of the plasma that is generated when a satellite is struck by a meteoroid or a piece of orbital debris. We discuss the design of sensors for measuring the properties of the plasma and the accompanying electromagnetic pulse. Unlike the mechanical effects which are localized, the expanding plasma and the electromagnetic radiation associated with it allow for the detection and characterization of hypervelocity impacts over larger distances.

We present a brief summary of recent results from the ground-based hyper-velocity impact tests carried out by our research group at the Van de Graaff dust accelerator facility in the Max Planck Institute for Nuclear Physics, Heidelberg, Germany. Retarding potential analyzers, a photomultiplier tube, patch antennas, wide-band log-periodic arrays, VLF loops and E-field sensors were deployed and data were collected for projectile velocities ranging from 1-60 km/s. Tungsten, thick aluminum, thin aluminum foil, solar cells, solar panel substrate, optical solar reflectors (standard and conductive) and a brass knob on the E-field sensor were used as targets. Clear signatures of an expanding plasma and optical flash were observed.

We discuss how the information gained from these experiments helps us in the design of a compact sensor module which when aboard a satellite, can detect and characterize the hypervelocity impacts that it experiences. Coupled with radiation dosimeters and space charge monitors, such a module can serve as a black-box for satellites. The data from these experiments also enables us to design appropriate shielding mechanisms to mitigate the effects of hypervelocity impacts.

Introduction: Meteoroid hits have been known to occur on satellites and space systems on the basis of several experiments conducted in the past. Pegasus was a series of three satellites that measured the frequency of meteoroid impacts on its lofty panels[1]. Analysis of the structure of the space shuttle and other vehicles that have returned to the earth also reveals that objects in space are impacted by meteoroids at regular intervals. With the rapid burgeoning of the orbital debris population in low earth orbit (LEO), we now face a combined threat from the meteoroids and orbital debris (MMOD).

A recent NRC study highlights the increasing relevance of this threat, stating that "The long-lived problem of growth in the orbital debris population as a result of debris self-collision and propagation requires that NASA take a long-term perspective to safeguard the space environment for future generations." [2]

The mechanical damage caused by such hypervelocity impacts has been studied by many, leading to the design of the Whipple Shield by Fred Whipple which was used extensively on the space shuttle with similar designs being used in many other space missions [3]. However, not much attention has been given to the electrical effects of MMOD impacts on the functioning of satellites and space systems.

Depending on the radius of the orbit, chunks of orbital debris move at an approximate speed of 7km/s while the velocity of the meteoroids lies in the range of 11-72.8 km/s. The flux of these particles and the likelihood of their impact on a spacecraft increases significantly as their size decreases. When impacts occur on satellites at such high speeds, the projectile and some of the material in the impact zone of the satellite vaporize, leading to the formation of an expanding plasma bubble [4] (Fig. 1). This plasma and electromagnetic radiation that it is capable of generating can interfere with the functioning of various electrical sub-systems on the satellite.

According to the IEC 1000-4-3 EMI immunity standards, electronic components are often designed to withstand 10V/m of electric field across the frequency range of 80MHz to 1GHz. Estimates of electric field generated during hypervelocity impacts from theoretical modeling and results in literature suggest that the electric fields might be stronger than what the satellites are capable of dealing with [5]. While the semi-Faraday cage nature of satellite sub-systems helps tackling some of these issues, the exact nature by which the sub-systems might be affected is unclear as of now and there can be leaky pathways for the charged particles and radiation to influence the electrical sub-systems on the satellite.

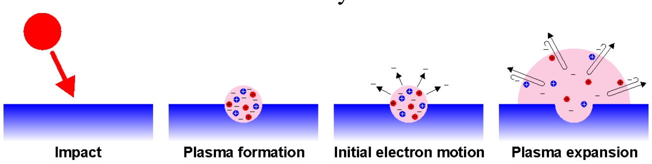

Figure 1 An illustration of the plasma generation and expansion process following a hypervelocity impact

There have been several instances of meteoroid impact related failures of satellites and space systems in the past. In 1993, the Olympus satellite experienced an anomaly in their gyro leading to a loss of attitude control[6]. The maneuvers required to de-spin and re-orient the satellite led to significant fuel depletion and the satellite had to be taken out of service. In 2009, Landsat 5 experienced a similar gyro-instability during the peak of the Perseid meteor shower[7]. Fortunately, in this case, the attitude control of the satellite was restored. On 16th March 2002, the satellite Jason-1 was hit by a meteoroid or orbital debris which led to a large spike in its power distribution system lasting 5 hours. A change in the semi-major axis of the satellite confirmed the occurrence of an impact. What is interesting to note about the above examples is the fact that the systems experiencing the anomaly were able to recover from the impact. It is hence highly unlikely that the cause of the anomaly was mechanical in nature. The evidence hints at there being an electrical pathway through which, hypervelocity impacts can disrupt the functioning of satellite sub-systems.

We are currently in the process of carrying out an analysis of data from Jason-1. We are also in the process of carrying out a comprehensive analysis of satellite and space system failures that have occurred in the past to come up with statistics of satellite failures that can be attributed to hypervelocity impact events.

We shall now describe some of the ground-based hypervelocity impact tests that our research group has been carrying out over the past one year and discuss the implications of the results that we have obtained. We then talk about the need for the design of a black-box for satellites and outline its salient features.

Ground-based Hypervelocity Impact Tests: For the past year, our research group has been involved in carrying out ground-based hypervelocity impact tests at the Van de Graaff dust accelerator facility in the Max Planck Institute for Nuclear Physics (MPIK), Heidelberg, Germany. The first set of tests was conducted in December 2010 and a more comprehensive set of tests was later conducted in August 2011.

At this facility, the projectile shot is closely linked to the mass of the projectiles. Spherical iron projectiles in the mass range of 1e-11 to 1e-15 g were shot at speeds ranging from 1km/s to 60km/s. Fig. 2 shows the mass-velocity distribution of the projectiles fired at our targets in December 2010.

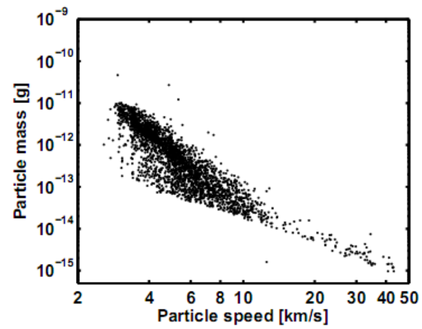

Figure 2 Distribution of projectile masses and speeds during first round of testing at MPIK in December 2010

During the course of the two tests, particles were shot at multiple targets at various bias voltages ranging from -1kV to 1kV. The various targets used are listed below

1) Tungsten
2) Aluminum
3) Copper
4) Brass
5) Solar cell with cover glass (bare)
6) Solar cell with cover glass (conductive)
7) Solar panel substrate (honeycomb composite)
8) Optical Surface Reflector (standard)
9) Optical Surface Reflector (conductive)

Targets 5-9 were donated by the Lockheed Martin division in Pennsylvania to analyze the behavior of the plasma generated by various components that are likely to be hit by meteoroids and orbital debris in space.

In order to study the characteristics of the impact plasma and the electromagnetic radiation it emits, a large number of sensors were deployed under different configurations. Fig. 3 shows some of the configurations used during the tests. The following is the list of sensors used during the tests

1) Retarding Potential Analyzers (RPA)

2) Patch antennas
3) E-field sensors
4) Photomultiplier Tube (PMT)
5) Faraday Plate Arrays (FPA)
6) Log-Periodic Arrays (LPA)
7) VLF antenna loops
8) Magnetometer

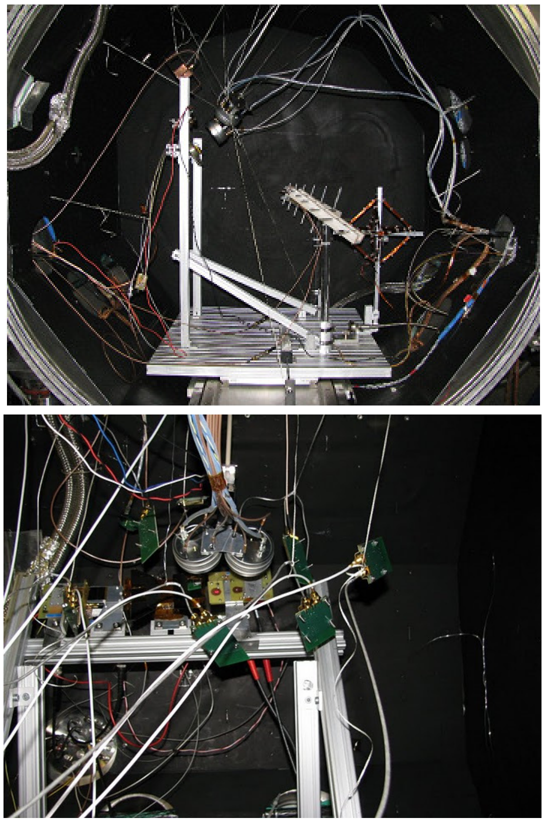

Figure 3 Snapshots of the experimental configuration at MPIK in December 2010 (top panel) and August 2011 (bottom panel)

The Retarding Potential Analyzers (Fig. 4) were the primary sensors used for plasma diagnostics. A retarding potential analyzer basically measures the flux of charge particles on a collector plate and the net current generated is then amplified by a high-bandwidth transimpedance amplifier. The presence of various grids in front of the collector plate allows one to select the species of the particle, threshold its energy and suppress the backscattering and secondary emission phenomena.

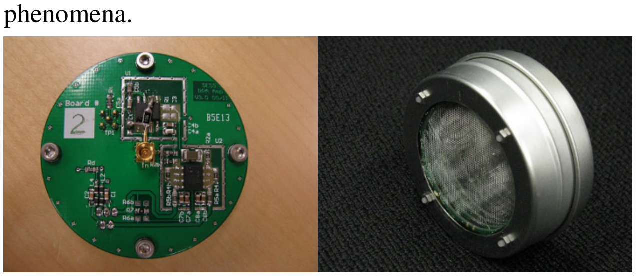

Figure 4 Images of the Retarding Potential Analyzer. The transimpedance amplifier board is on the left and the fully-assembled sensor is on the right

The patch antennas, used as an array, served as narrow-band RF sensors while the log-periodic arrays served as wideband antennas. The Faraday plate arrays were arrays containing stripped-down versions of the RPAs, without the grids. They were used to measure the geometry of the expanding plasma plume and also to measure the plasma expansion speed.

At the facility, particles that have been correctly steered in the direction of the target are sensed by a series of inductive loops. More than 6000 of these particles were sensed by the inductive loops closest to the impact chamber indicating a very high probability of having hit the target. We are still in the process of analyzing the data from all these impacts and we shall now present some of the results that were obtained during the tests conducted in December 2010.

Results: Evidence of plasma generation from the impact was detected in the Retarding Potential Analyzers[8]. In the December configuration, one of the RPAs (referred to as RPA-A) was closer to the target at a distance of 75mm, placed at an angle of 15˚ from the target normal while another identical RPA (referred to as RPA-B) was placed at an angle of 30˚ from the target normal at a distance of 150mm. Fig 5 shows some of the signals recorded at RPA-A.

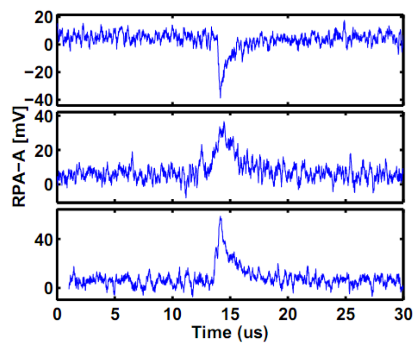

Figure 5 Signals from impacts on negatively charged (top panel), uncharged (middle panel) and positively charged (bottom panel) Tungsten target. The projectile speeds for these impacts were 4.7km/s, 3.0km/s and 3.1km/s and projectile masses were 2.2pg, 7.2pg and 8.9pg respectively.

Using the difference in the time of incidence of signal in the two RPAs and knowing their distances from the target, we arrived at a mean estimate of the plasma expansion speed to be 20.8km/s with a standard deviation of 3.5km/s.

During the tests conducted in August 2011, a photomultiplier tube was also used to measure the optical flash generated from an impact. The important parameters of the Hamamatsu H10721-110 module used are listed below in Table 1.

Parameter	Value
Active Diameter	8 mm
Responsivity	220 A/lm
Id	1 nA
Rise Time	0.57 ns

Table 1 Parameters of the photomultiplier tube used during the ground-based tests in August 2011

Optical flashes were observed on a regular basis during the impact tests. A typical response of the PMT to an impact flash can be seen in Fig 6. Further analysis of the data is currently being carried out.

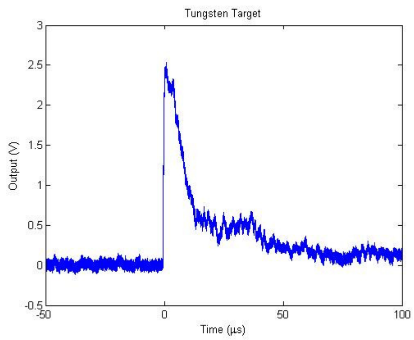

Figure 6 Typical response of the photomultiplier tube to the flash from a hypervelocity impact observed during ground based testing in August 2011

Discussion: Deleterious effects of space weather interactions with spacecraft include geomagnetic activity that can interfere with satellite-ground and satellite-satellite-communications, high energy particles that can cause single-event upsets in onboard logic systems, and the ambient plasma that can lead to electrostatic charging, resulting in electrostatic discharges (ESDs). Our ground-based experiments have confirmed that hypervelocity impacts also have the potential to influence the behavior of electrical systems on a satellite.

It is known that anomalies occur in space systems on a regular basis. While efforts are made to diagnose the cause of these anomalies, many of them go unaccounted for. The limited health monitoring data collected is often not sufficient enough to nail down the cause of the failure. Also, the mechanism by which the space weather phenomena influence the behavior of satellite and space systems is not well understood. We hence strongly believe in the need for a satellite black-box.

The development of this black-box technology can help diagnose the numerous electrical anomalies occurring due to space weather phenomena. Understanding the cause of these anomalies can lead to formulation of space system design practices and methodologies that increase the reliability of space systems. The large number of risk assessment studies, redundancy and safeguarding measures used to protect against space weather phenomena often leads to an increase in mass, size, cost and complexity of the spacecraft, eventually leading to long and delayed mission development cycles. Development of the black-box technology can help solve many of these issues crippling space system architectures. We envisage such a black-box being an integral part of all spacecraft in the near future.

Unlike black-boxes used on aircrafts, which primarily act as data recorders, a satellite black-box would contain a suite of sensors monitoring various space weather phenomena that can lead to satellite failures. The black-box would be a small, light-weight module (less than 1kg consuming less than 3W of power) that can be incorporated on any spacecraft. The black-box would contain

1) Semiconductor based sensors for measuring electron and proton fluxes
2) Discharge monitors for monitoring the ESD
3) Plasma/RF sensors for detecting hypervelocity particle impacts
4) Plasma sensors for detecting the density of ionospheric plasma (for a LEO orbit)
5) Optical sensors to further diagnose the source of failure
6) Magnetometer to sense changes in the background magnetic field

Silicon-based sensors for measuring radiation in space have already been developed for space applications. Space charge monitors have also been developed to provide advance warning of possible electrical discharge. A mechanical hypervelocity impact detector has been built and demonstrated by scientists at NASA Ames [7]. However, the mechanical effects of hypervelocity impacts are localized, while the electrical effects can be sensed at larger distances from the point of impact. Hence using plasma/RF sensors allows us to better diagnose both electrical and mechanical anomalies caused by hypervelocity impacts.

We intend to use the results from the ground based hypervelocity impact tests in the design of the black box. The hypervelocity impact tests can serve as a test bed for figuring out the optimum suite of sensors for measuring the parameters associated with an impact. The primary factors relevant to the impact phenomena are the mass and speed of the projectile. In1976, Eichhorn[9] found that the rise time of the integrated signal is related to the velocity of the projectile (Fig. 7) and also independent of the mass of the incoming projectile. Hence, the velocity of meteoroids and orbital debris hitting the satellites in space can be independently estimated using optical measurements with simple, fast photodiodes. We are currently in the process of carrying out a similar analysis with the optical data that we have collected in Germany.

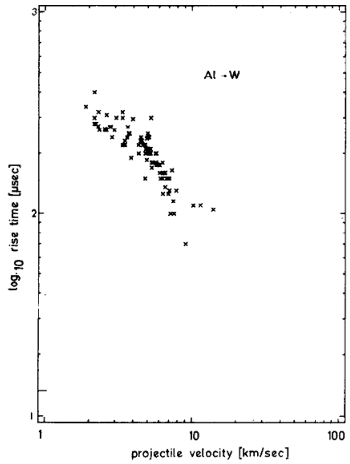

Figure 7 Variation of rise time of integrated signal with projectile velocity [9]

Having estimated the velocity, the mass of the projectile can be estimated from an empirical equation relating the strength *(P)* of the observed optical signal with the mass*(m)* and velocity*(v)* of the projectile[9]. This equation is of the form

$$P = Cmv^{\beta}$$

where the value of β has been found to lie between 3.8 and 4.6 for different target-projectile combinations. The value of the proportionality constant *'C'* depends on the geometry of the sensor configuration, target material, projectile material etc. Hence this method is bound to leave us with uncertainty in our estimate of the mass of the projectile. Further, it requires us to know the material of the target and the meteoroid. This is a hard problem to solve since the composition of meteoroids and orbital debris is highly uncertain.

The amount of plasma generated from an impact is also related to the mass and velocity of the projectile according relationship very similar to the relationship for the strength of an optical signal. Future research in this direction would look at the possibility of combining the optical and plasma sensor data to come up with a more credible estimate of projectile mass and velocity.

Other issues that need to be dealt with in the future include questions about the positioning of the black box on a spacecraft. Satellites in earth orbits are hit by meteoroids and orbital debris primarily in the same way in which bugs hit the windshield of a car. Hence the hypervelocity impact sensors in the black-box should be placed on the face of the satellite whose outward normal is along the direction of earth's velocity vector.

The placement of the surface charge monitor is trickier since the phenomena responsible for surface charging are different for low earth orbit (LEO) and geosynchronous earth orbit (GEO). In LEO, the difference in the mobilities of ions and electrons leads to differential charging across the leading (face with outward normal along the satellite velocity vector) and lagging sides (face with outward normal opposite to the satellite velocity vector). On the other hand, differential charging occurs across the sun and anti-sun sides in GEO with photoelectric emission being the dominant cause.

The semiconductor based sensors can be placed on the sun-side to monitor the flux of incoming radiation. In the past, UV-erasable EPROM modules have been used to monitor space radiation. X-ray CCDs (Charge Coupled Detectors) have also been known to serve as sensors for galactic cosmic rays and solar radiation.

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