Spacecraft Communication Through High Density Plasma in the D-Region of the Ionosphere during Reentry

Siddharth Krishnamoorthy and Sigrid Close

Department of Aeronautics and Astronautics, Stanford University

Introduction

Re-entering vehicles, particularly those with a capsule-like geometry, ionize the surrounding air due to shock and frictional heating, and form a plasma sheath that surrounds them. The plasma sheath contains a large number of highly mobile electrons, which damp out electromagnetic waves with frequency below the plasma frequency. As the spacecraft crosses the D-region of the ionosphere and the mesosphere (40-80 km), the plasma frequency becomes high enough to attenuate all the common spacecraft communication bands. As a result of this attenuation, there is a blackout of radio signals (communications, control and telemetry) to and from the spacecraft for up to 10 minutes during reentry. (Fig. 1)

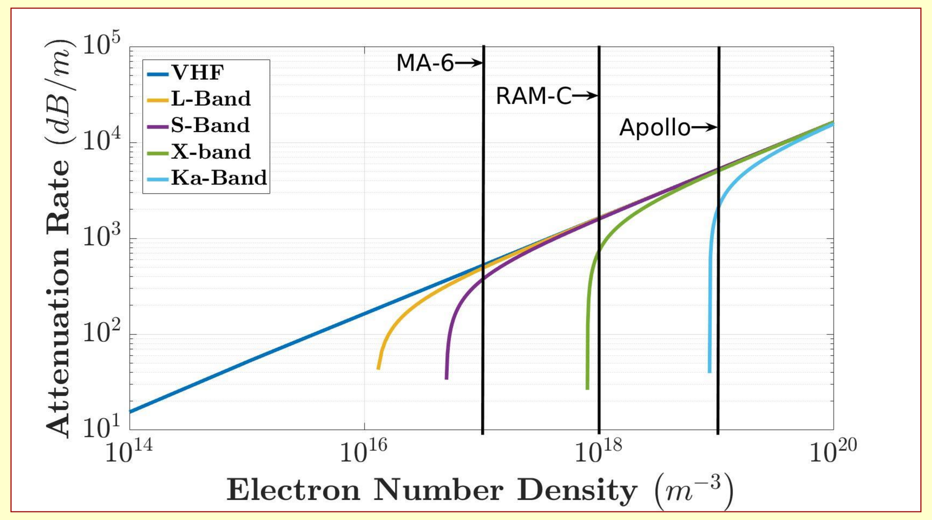

Figure 1: Attenuation of radio signals during reentry

The communications blackout presents a major obstacle to nominal spacecraft operations and a safety hazard for the payload. We propose a new method to alleviate this blackout through the application of strong electric fields, called Pulsed Electrostatic Manipulation (PEM). We present the results of a 2-D electrostatic Particle-In-Cell (PIC) simulations of the reentry plasma sheath and its interaction with strong voltage pulses applied from the surface of the reentry vehicle. The simulations have been performed using the PICARD environment developed at Stanford University.

Pulsed Electrostatic Manipulation

Pulsed Electrostatic Manipulation (PEM) seeks to alleviate reentry communications blackout by creating "windows" of lower electron density (thereby lowering the plasma frequency) at antenna locations on the reentry vehicle through the application of electronegative pulses. The electronegative pulses are applied using insulated electrodes arranged on the surface of the vehicle. When a negative pulse is applied to the reentry plasma sheath, the electrons evacuate the vicinity of the electrode, while ions in the plasma get attracted to the area of negative voltage. However, owing to the difference in their mobility, the electrons respond to the electric field up to 2-3 orders of magnitude faster than the ions, thereby providing a time window to communicate through the plasma (Fig. 2).

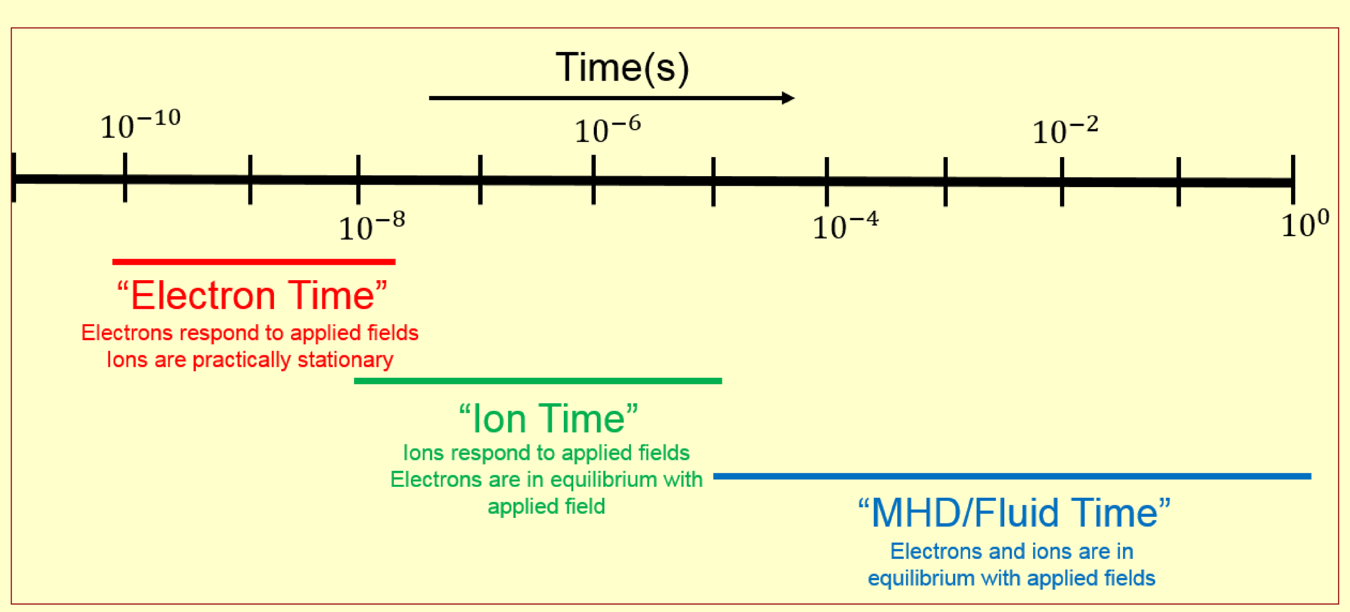

Figure 2: Description of time scales in an unmagnetized, full-ionized Argon plasma with electron density = 10^{17} el/m^3

The voltage pulse is turned off as the dielectric breakdown hazard rises due to the accumulation of ions in the electrode area. This cycle, when repeated periodically, can provide discrete broadcast time-windows for the spacecraft to send data to a ground station. A schematic diagram for PEM is shown in Fig.3.

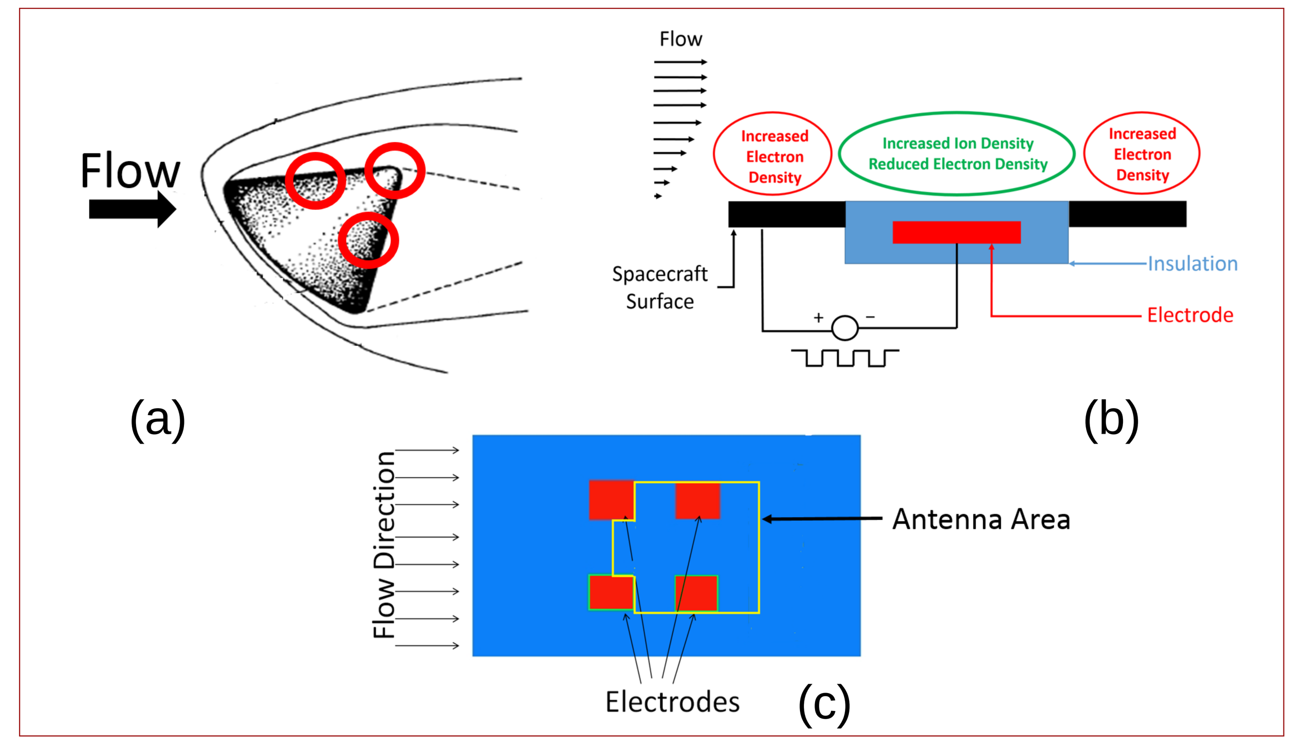

Figure 3: Description of Pulsed Electrostatic Manipulation.
(a) Candidate locations on spacecraft (b) Side view (c) Top view

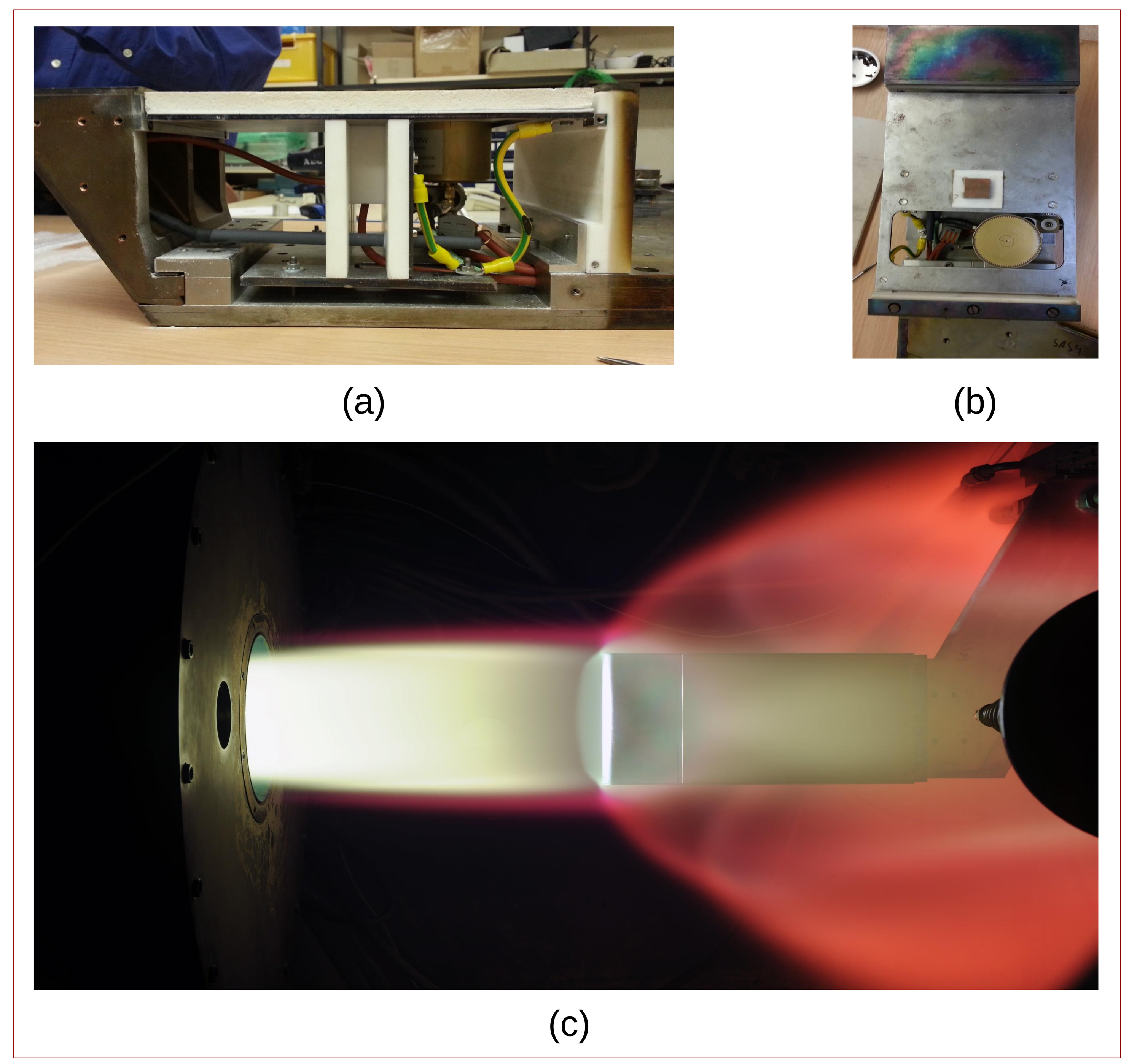

Figure 4: Images from the test campaign at DLR.
(a) Side view of the test stand (b) Top view of the test stand
(c) Full flow test (Image courtesy of DLR)

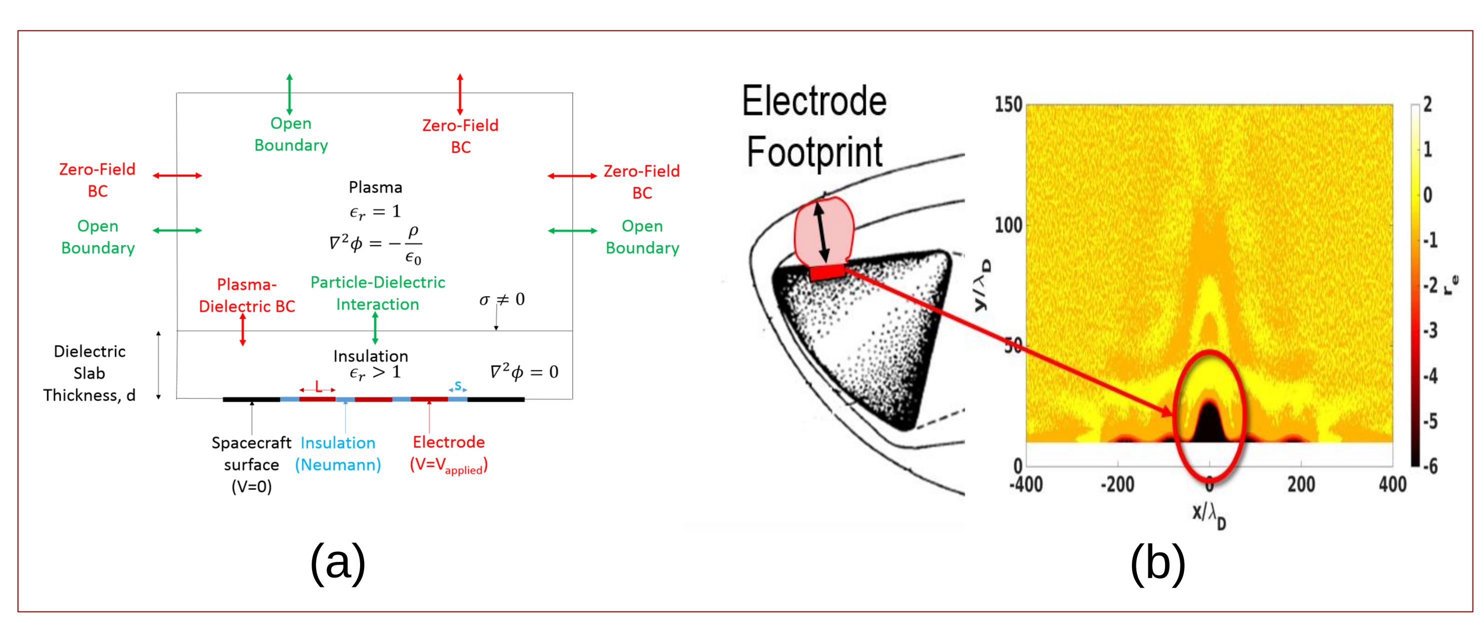

Figure 5: Setup of 2-D PIC simulation
(a) Simulation domain (b) Definition of electrode footprint

Simulation Results

The interaction of the reentry plasma layer with electronegative pulses was studied using the PIC algorithm. A two-dimensional simulation was performed using a simulation domain that may be thought of as a cross section of the experimental setup shown in Fig. 4. The computational setup is shown in Fig. 5. At the plasma-dielectric interface, the tangential electric field was held constant and the normal electric field was allowed to be discontinuous:

$$E_{t_{below}} = E_{t_{above}}$$

$$\epsilon_{r_{above}} E_{n_{above}} - \epsilon_{r_{below}} E_{n_{below}} = \frac{\sigma}{\epsilon_0}$$

Further, when ions and electrons impacted the surface, they were absorbed, reflected and allowed to eject secondary electrons probabilistically, thereby affecting σ, the charge absorbed on the surface. A range of voltages were applied, and the results from this computation are shown in Fig. 6.

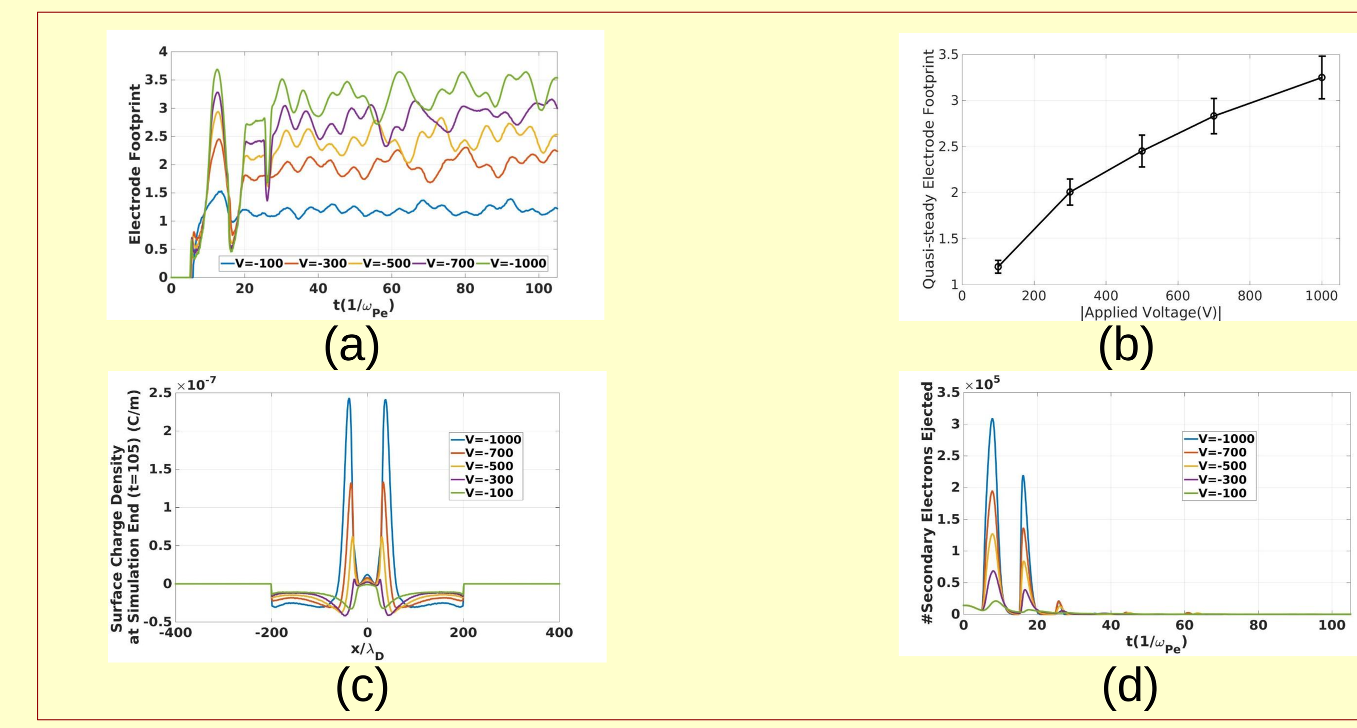

Figure 6: Results from 2-D PIC simulation
(a) Electrode footprint as a function of time (b) Mean footprint as a function of voltage
(c) Surface charge absorbed on the interface (d) Secondary electrons ejected by particle impact

In 2-D, with the application of fields of ~4MV/m, a single electrode is able to reduce the electron density by three orders of magnitude (required for GPS communication in an Apollo-class mission) over a length scale about three times its length (Fig. 6). As time progresses, the ions flow to the vicinity of the electrode and shield out the applied voltage and close the communication window. This process depends critically on how fast charge can be deposited on the dielectric surface. The footprint can also be increased by the use of multiple electrodes and different electrode shapes. This will be studied in the future.

Further Applications in Aeronomy

The analysis and tools presented here is also relevant to the study of the interaction of spacecraft with plasma in the lower ionosphere. These interactions include spacecraft charging, electrodynamic tethers and ElectroStatic Discharge (ESD) avoidance. Further, the PICARD tool is modular and extendable. Detailed models for solid-plasma interactions, charge-neutral collisions and free plasma dynamics have already been incorporated. These features also allow the code to be used for a wide variety of problems, such as the study of meteor ablation and dynamics of planetary plasmas. Addtionally, more features may be added with ease by interested researchers due to the modular nature of the tool.

Conclusions

PIC simulations for PEM show encouraging results. The experimental campaign conducted has also provided vital information about system performance, which will be utilized in the design of future experiments. Future simulation work will focus on constructing the full multi-dimensional design space in 2-D, and electrode shape studies in 3-D.

SESS Space Environment and Satellite Systems STANFORD UNIVERSITY

DLR

Stanford University

For more details,
Email: skrishnamoorthy@stanford.edu, sigridc@stanford.edu
Web: www.stanford.edu/~skmrthy