**Introduction**

Re-entering vehicles, particularly those with a capsule-like geometry, are often engulfed in a plasma sheath due to shock and frictional heating of the surrounding air. For a certain duration of time during reentry, there is a complete blackout of all radio signals (communications, control, and telemetry) to and from the spacecraft. (Figure 1)

![Figure 1](image1.png)

We present the results of our theoretical analysis of the reentry plasma sheath and motivate electron bunching as a possible solution to the problem. We propose two different techniques to cause electron bunching and discuss the merits and demerits of both approaches.

**Motivation**

The duration of the blackout problem can vary from seconds to minutes, dependent upon the vehicle shape and atmospheric angle and density. Nevertheless, it is important to resolve this problem for the following reasons:

- A spacecraft encounters the most extreme temperatures and pressures during reentry. The absence of communications, control, or telemetry during these few critical minutes is highly undesirable.
- In the event of a failure during reentry, data collected during reentry will prove invaluable for diagnosing the cause of failure and improving flight safety in the future.
- The problem mainly plagues capsule-shaped reentry bodies. With the space shuttle fleet retired and missions to the Moon and Mars planned in the future, a return to the capsule geometry is imminent. (For example, the Orion or Dragon capsule)

**Design Philosophy**

When it comes to solving problems for spacecraft systems, simplicity is of the essence. While other methods for solving the reentry blackout problem have been proposed in the literature, their complexity necessitates invoking assumptions about the dynamics of the plasma layer that may not be valid. It is important for a practical method to not be severely constrained by the non-ideal behavior of the plasma sheath. Furthermore, a practical solution must consider weight and power constraints imposed by the reentry vehicle.

For this reason, magnetic fields will not be included as part of our solution. It has been found that magnetic fields are not effective in confining plasmas unless very strong magnets are used. The range of temperatures encountered when dealing with this problem are well above the Curie temperature of permanent magnets. Therefore, electromagnets must be utilized to produce the magnetic field; this adds a large weight penalty.

Our proposed solutions seek to manipulate the electrons in the reentry plasma layer through electric field alone. Since static electric fields create arcing hazards in plasmas through sheath formation, we propose to cycle the fields in a smart way in order to avoid these hazards.

**Flow Field Analysis**

Reentry vehicles often enter the Earth’s atmosphere at speeds greater than Mach 25 (depending on the origin of the vehicle). In order to slow down to landing speeds and to withstand extreme heating, blunt-body shapes are used for the leading surface of the vehicles. This creates a very strong bow shock in front of the vehicle. Hypersonic flows typically have a small shock standoff distance and a thick boundary layer. Usually, these two distinct aspects of the flow are merged together into a “shock layer”.

A pictographic description of the reentering Apollo Command Module is given in Figure 2 (Lehnert et al. 1965). As the flow moves through the strong bow shock, it experiences an almost discontinuous jump in temperature and pressure. The sudden addition of this energy into the flow causes rotational and vibrational modes of diatomic molecules to get activated. The heat energy is also enough to cause the chemical breakdown of air into its constituent molecules and also cause ionization. The area in the vicinity of the shock is also characterized by chemical and thermal non-equilibrium.

![Figure 2](image2.png)

**Bunching Using Two-Stream Instability**

Two opposing streams of electrons in a plasma resonantly exchange energy with each other based on a phase-matching condition, generating a two-stream instability. The dispersion relation in a cold one-dimensional plasma with a background of immobile ions is given by [3]:

\[ \omega^2 = \frac{1}{(\alpha - \tilde{\omega})^2} - \frac{1}{(\alpha + \tilde{\omega})^2} = 0 \]

When these two beams interact, they form electron bunches. These bunches are accompanied by regions in phase space and physical space, where the electron density is reduced. A 1-dimensional Particle-in-Cell simulation of this phenomenon is shown in Figure 3. This could, in principle be achieved by firing a phase-matched electron beam along the vehicle surface into the reentry plasma layer.

![Figure 3](image3.png)

**Bunching Using Electric Pulses**

Bunching using the two-stream instability seems to work in principle. However, there are some practical considerations that make it difficult to implement. First, the onset of the instability over the scale length of an antenna aperture is rather strongly dependent on the phase matching condition, which would be difficult to maintain throughout the blackout. The requirement that the injected electron beam be parallel to the vehicle surface creates spacecraft integration problems.

Another possible way to induce bunching is to use a set of electrodes; a schematic is shown in Figure 4. An identical set of such electrodes would be placed at the azimuthally opposite point on the vehicle. At any given instant, a high-voltage pulse of opposite polarities is applied to both sets of electrodes. This pulse has a short duration and creates a bunch which starts to smooth out as soon as the voltage is shut down. Figure 4b shows the presence of a potential trough between two negatively charged plates which traps electrons. The bunch needs to be sustained only for the period of time it takes for the mean flow to transport it over the antenna area, from where transmission or reception can take place. This system can be used in pulsed mode, at a set frequency, and a pre-determined time offset from required transmission times.

![Figure 4](image4.png)

**Conclusions**

Electron bunching by electrical manipulation suggests itself as a viable method for reentry blackout alleviation. It is inherently simple in concept and easier to analyze numerically than the instability method. Some possible challenges that need to be studied include faster-than-expected breakdown of the bunch and shorting between electrodes on opposite sides.

**Bibliography**


**Further Information**

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