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Eric D. Gillman and John E. Foster
University of Michigan, Ann Arbor, Michigan

Isaiah M. Blankson
Glenn Research Center, Cleveland, Ohio

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Eric D. Gillman and John E. Foster
University of Michigan
Ann Arbor, Michigan 48109

Isaiah M. Blankson
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

Vehicles flying at hypersonic velocities within the atmosphere become enveloped in a "plasma sheath" that prevents radio communication, telemetry, and most importantly, GPS signal reception for navigation. This radio "blackout" period has been a problem since the dawn of the manned space program and was an especially significant hindrance during the days of the Apollo missions. An appropriate mitigation method must allow for spacecraft to ground control and ground control to spacecraft communications through the reentry plasma sheath. Many mitigation techniques have been proposed, including but not limited to, aerodynamic shaping, magnetic windows, and liquid injection. The research performed on these mitigation techniques over the years will be reviewed and summarized, along with the advantages and obstacles that each technique will need to overcome to be practically implemented. A unique approach for mitigating the blackout communications problem is presented herein along with research results associated with this method. The novel method involves the injection of ceramic metal-oxide particulate into a simulated reentry plasma to quench the reentry plasma. Injection of the solid ceramic particulates is achieved by entrainment within induced, energetic cathode spot flows.

I. Introduction

Atmospheric gas flowing by a hypersonic vehicle will be heated by the supersonic shock in front of the vehicle and then frictionally as it flows around the vehicle. At velocities near or above Mach 10, this intense heating of the gas will result in the disassociation of molecules and atoms (Refs. 1 to 3). This transforms the gas flow into an ionized flow, or so-called "plasma sheath" that surrounds the vehicle. The plasma layer can reach densities exceeding $10^{13} cm^{-3}$ (Refs. 4 to 17). At such high densities the plasma frequency greatly exceeds the frequency range of conventional S, C, and X band communication signals that range from approximately 1 GHz to just over 10 GHz. Electromagnetic radiation under normal nonmagnetized conditions cannot penetrate thick plasma layers where the plasma frequency is greater than the electromagnetic wave frequency. The signal is instead reflected. Even at frequencies higher than the plasma frequency, collisional damping can severely attenuate the signal (Refs. 18 and 19). This layer of charged particles therefore prevents spacecraft reception of GPS signals and usually prevents and disrupts reception and transmission of communication signals between ground control and the spacecraft. These communication signals are often reflected altogether, or at least significantly attenuated. This period of flight is known as the "blackout" period and lasts between 4 and 10 min for Earth reentry (Refs. 17, 20 to 24). However, entering atmospheres of large planetary bodies such as Jupiter may take as long as 30 min (Ref. 17)! This problem currently persists for many vehicles including small, capsule-shaped manned spacecraft reentering Earth's atmosphere, ballistic missiles, robotic spacecraft entering

the atmospheres of other planetary bodies, and will plague future hypersonic cruise vehicles if progress is not made.

Ever since the inception of ballistic missiles and manned spaceflight, methods to mitigate the communications blackout period have been investigated, but no satisfactory or elegant solution has yet been established. The communications blackout problem was at the forefront of NASA's technological interests during the days of the Apollo lunar missions. The communications blackout period ultimately became an undesirable, yet tolerable obstacle. Space shuttle operations, which followed the Apollo program, were not appreciably hampered by the communication blackout problem which plagued the capsule-based reentry vehicles. The angle of attack of the reentering space shuttle is such that the blackout plasma forms predominantly over the broad underbelly of the shuttle, leaving the upper surfaces relatively plasma free. Communications between the reentering shuttle and ground stations could be carried out using transponders on the top surface which would uplink to an orbiting satellite that would relay this signal back to the ground station. In practice this was achieved using the NASA Tracking and Data Relay Satellite System (TDRSS) (Refs. 15, 17, and 20). In this regard, interest in the blackout mitigation problem dwindled somewhat during the shuttle era. However, blackout mitigation research has recently become a significant interest again for NASA with the space-capsule architecture of the Ares spacecraft, similar to the Apollo mission architecture, for the next lunar missions and possibly future Mars missions. The reception of GPS signals during blackout, critical for vehicle navigation, has been deemed the top priority in this field of research (Refs. 2, 3, and 17). Several useful and informative reviews and collections of the research in this field have been published throughout the years (Refs. 2, 19, and 21).

Current unmanned space missions as well as future manned missions to Mars and other planets with atmospheres would greatly benefit from a communications blackout solution (Refs. 20, 22, 25 to 29). Obviously, the TDRSS Earth satellite system will not be available to help with communications for spacecraft reentering the atmospheres of other planets. Communications with spacecraft is and will be just as critical, particularly when entering unfamiliar atmospheres (Refs. 15, 17, and 20). Furthermore, many missions to planetary bodies with atmospheres necessarily require the use of aero-braking. Aero-braking is a technique in which spacecraft "dip" into the atmosphere briefly to use atmospheric friction to slow themselves down without fully reentering the atmosphere. During this period, spacecraft experience the same communications blackout experienced by reentering spacecraft (Refs. 20 and 22).

In addition to mitigating the dangers that are faced by space missions during reentry blackout, mitigation technology can also be applied to ballistic missile systems (Ref. 30). Ballistic missiles face the same communications challenge that smaller capsule-type spacecraft encounter, and are currently not able to use a satellite system like TDRSS for communication (Refs. 15 and 17). Critical functions for weapons systems such as tracking and radar identification of missiles for more accurate targeting, missile electronic countermeasures like radar jamming, and mission abort functions are prevented by the communications blackout period (Refs. 19, 31 to 38). Furthermore, radar identification of objects for anti-ballistic missile defense programs may benefit from a blackout mitigation technique (Ref. 36).

Future hypersonic cruise vehicles would also suffer from blackout plasma related communication disruptions. In general, future hypersonic cruise vehicles will need to have constant radio contact with ground control for communication and navigation (Refs. 39 to 40). It stands to reason therefore that future hypersonic planes and cruisers will also require blackout mitigation technologies.

Clearly blackout mitigation is a key technological challenge that remains largely unresolved and that stands as an obstacle to hypersonic flight. In the sections that follow, an overview of important communications blackout flight experiments, hypersonic plasma sheath diagnostics, computer modeling approaches, testing facilities, and suggested mitigation methods will be presented. The measured and modeled parameters of a hypersonic reentry plasma sheath and the governing equations regarding radio communications attenuation, reflection, and propagation in the plasma sheath are also analyzed. A more thorough review of some of the leading mitigation methods currently being investigated today are also discussed, including the presentation of a relatively new and novel communications blackout mitigation method involving quenchant injection via applied plasma flows.

II. Brief History and Literature Review

A. Brief Research History

Some of the first research on blackout mitigation techniques began around 1960 at the NASA Langley Research Center (LaRC) with the radio attenuation measurements (RAM) program (Ref. 41). The purpose of this program was to develop diagnostics to measure various reentry plasma sheath parameters to enhance reentry plasma simulation (creating lab plasmas to simulate the reentry plasma for experimental testing and for computational models), as well as to begin in-flight testing of some of the mitigation methods. These flight tests and the collected data, which are still referred to in the literature and used as a standard today, led to countless publications that yielded invaluable information on the reentry plasma sheath parameters and the first glimpses at the effectiveness of some of the communications blackout mitigation methods (Refs. 8, 10, 12, 16, 17, 19, 21, 24, 34, 36, 37, 41 to 53). The RAM program flew seven successful flights, and the program lasted for about a decade, with the last flights occurring in 1970 (Ref. 36). Concurrent with the RAM program were several other flights and programs sponsored by NASA and the Air Force: Fireflight (NASA), Asset (USAF), Mercury MA-6 (NASA), Gemini 3 (NASA), and Trailblazer (USAF) (Refs. 37 and 54).

Diagnostics were required for the flight experiments to make accurate measurements in the reentry plasma sheath. Many diagnostics were developed or reformulated specifically for this application including electrostatic Langmuir probe rakes, electroacoustic resonance systems, conductivity probes, pressure transducer systems, microwave radiometry, and various types of antenna diagnostics (Refs. 1, 6 to 9, 11, 12, 17, 19, 23, 24, 37, 46 to 48, 51, 52, 55 to 62). Electrostatic probe rakes or arrays of electrostatic probes similar to that shown schematically in Figure 1 were flown on at least one flight in both the Trailblazer and RAM programs (Refs. 12, 36, 46 to 48, and 60). The probe rakes were used to make plasma density measurements at various distances from the spacecraft surface within the plasma sheath, but had to be retracted as the thermal loads increased due to an increase in air density as the spacecraft descended to lower altitudes. An electroacoustic diagnostic system flew on the Trailblazer vehicle taking measurements within the plasma sheath, similar to those made with the probe rake (Refs. 37 and 56). With multiple electroacoustic measurements, all taken from the surface of the spacecraft, this diagnostic system was able to deduce the plasma density at various distances from the spacecraft surface within the plasma sheath without placing a physical probe at that location, as with the probe rake. A conductivity probe was also proposed and flew on a Trailblazer vehicle to measure the conductivity of the plasma sheath and deduce the plasma density (Refs. 19 and 55). Also flown on a Trailblazer flight was a system used to make measurements of the thermal radiative pattern of the plasma sheath with a microwave radiometry system to deduce the plasma temperature (Refs. 19 and 37). Antennae mounted on the vehicles for communications were developed and used as a diagnostic tool on all documented test flights. Many methods were used to deduce plasma properties from the way the antennae behaved during blackout. Antenna impedance, signal attenuation, signal reflection, microwave interferometry, and microwave cutoff frequency measurements made with antennae at various frequencies
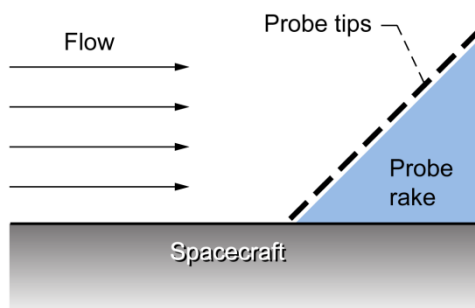

Figure 1.—Schematic showing a probe rake, a diagnostic used on many flight tests.

yielded useful insight into the properties of the plasma sheath (Refs. 7, 19, 23, 24, 36, 37, 51, 52,58, 59, 62, and 63). Even optical spectroscopy measurements of the reentry plasma sheath were proposed, even though no optical diagnostic system was ever flown (Ref. 37). The primary payload for these flights was the diagnostic and blackout alleviation apparatuses themselves. Since the test flights were relatively expensive, countless diagnostic systems, such as those discussed above, were used on each individual flight.

Not necessarily known at the time that the diagnostics were developed to be flown on the experimental flights was the role that computers and modeling would someday have in the simulation of the communications blackout problem. Many accurate and precise computer models and codes to simulate the plasma sheath exist today. These models are used to test many different mitigation techniques and to analyze their feasibility before expensive experiments are performed. These models were and are being developed, refined, and made more accurate through comparisons with experimental data collected many years ago (Refs. 4, 7, 9, 10, 13 to 15, 21, 22, 26, 34, 46, 50, 64 to 69). The Boundary Layer Integral Matrix Procedure (BLIMP) code was a 'workhorse' for many years in boundary layer calculations of the plasma sheath. The code was novel in that it accounted for ablation products and chemically reacting flows (Refs. 21 and 50). A more recently developed code, called HYGPSIM uses the REACH code to calculate the boundary layer plasma sheath and EMRUN to evaluate the antenna performance and attenuation. REACH can incorporate equilibrium or nonequilibirium flow as well as ablating or nonablating shields (Refs. 21, 50, and 66). PIRATE and PNS (HYCOM) are two other recently developed 'toolboxes' for making plasma sheath computations (Refs. 21, 50, and 69).

Experimental work, however, still provides valuable information to validate theoretical derivations and models. Experimental flights can be prohibitively expensive though, so considerable effort has been made to produce ground-based facilities that simulate the conditions of a reentry plasma sheath. Most facilities constructed primarily for reentry plasma simulations typically use a plasma generator combined with a sub-sonic, supersonic, or hypersonic wind tunnel (Refs. 30, 60, 70, and 71). The Atmospheric Reentry Materials and Structures Evaluation Facility (ARMSEF) was constructed at the NASA Johnson Space Center in 1968 and has been involved in the development of the Apollo reentry shields as well as the Space Shuttle thermal protection system (TPS) (Ref. 70). ARMSEF is a 10 MW facility that creates an arcjet plasma in a supersonic wind tunnel. NASA Ames also has the capability to create reentry like plasmas in hypersonic wind tunnels (Ref. 30). However, test facilities such as these are very expensive, so smaller, more inexpensive, albeit less accurate, alternatives for simulating the reentry sheath are attractive. Shock tubes and laboratory plasma sources such as helicon, arcjet, and MPD thruster sources have been used as less expensive alternatives (Refs. 16, 17, 63, 67, 72 to 74). Sources have even been developed to simulate particular regimes within the reentry trajectory (Ref. 72).

The total number of ideas that exist on ways to mitigate the communications blackout is incredibly vast. Though not meant to be comprehensive, the predominant approaches include: ion injection (Ref. 32), electromagnetic (ExB) drift collection (Refs. 6, 10, 13, 62, and 63), electrostatic collection (Refs. 65 and 75), antenna cooling (Ref. 2), optical communication (Refs. 2, 3, 19, 33, and 37), relay ejection (Refs. 2 and 3), trajectory modification (Ref. 2), antenna location (Refs. 2 and 43), MHD generators (Refs. 6, 60, and 76), electron beam modulation (Refs. 2, 3, 23, and 75), 3-wave/Raman scattering (Refs. 2, 3, 15, 21, 26, and 77), high-power transmission (Refs. 2, 3, 17, 19, 21, 46, and 68), low-frequency transmission (Refs. 2, 3, 17, 19, 20, and 75), whistler-mode antennae (Refs. 2, 3, 21, and 46), high-frequency transmission (Refs. 2, 3, 15, 17, 19 to 21, 36, 37, 46, and 75), aerodynamic shaping (Refs. 2, 3, 15, 17, 19, 21, 23, 25, 36, 37, 44, 46, 51, 75, 76, 78 to 80), magnetic windows (Refs. 2, 3, 13 to 15, 17, 19 to 21, 23, 26, 31, 36, 37, 46, 60, 65, 75, 76, and 81), and liquid injection (Refs. 2, 3, 5, 7 to 10, 12, 15, 17, 19 to 21, 23, 24, 27, 34, 36, 37, 42, 44 to 49, 52, 53, 60, 68, 75, 79, 82 to 86). Not all the methods listed above would be adequate to allow two-way communication (spacecraft to ground control and ground control to spacecraft). Three of the more important and most promising techniques will be reviewed in more detail in the subsequent sections (Refs. 2, 19, 21, and 37). These methods include aerodynamic shaping, the magnetic window, and liquid injection. The mitigation methods to be reviewed can potentially allow two-way communication and may provide an adequate solution to overcome the

communications blackout challenge with further advancements. The predominant approaches may also be used in combination to overcome this technical challenge (Ref. 2).

B. The Plasma Sheath

The reentry plasma sheath acts to reflect radiowaves in the frequency bands that are commonly used for spacecraft communication. The reflection is a consequence of free electrons synchronously responding to the incident wave. This response gives rise to radiation at the incident frequency but in the opposite direction, resulting in wave reflection (Refs. 18, 29, and 23). The very high frequency (VHF) band was often used for telemetry and voice communication (230.4 and 296.8 MHz, respectively) during the Mercury, Gemini, and Apollo missions. S-band is now more commonly used for communication (2.3 GHz) and C-band is often used for radar tracking (5.69 GHz). However, the GPS signal (1.176 GHz), vital for navigation, has been recognized by the technical community as the most important signal for reception during reentry (Refs. 2, 8, 17, 21, 24, 26, 27, 46, 87, and 88).

The density of the layer of plasma, specifically the density of electrons, that surrounds the hypersonic vehicle is the most important parameter in the plasma sheath (Refs. 10, 23, 46, 59, and 67). The density and temperature of the plasma sheath is strongly correlated to the spacecraft velocity, ranging from approximately 4.6 km/s (>Mach 13) for reentry from earth orbit to as high as 10.7 km/s (>Mach 32) for reentry from lunar missions (Refs. 1, 8, 12, 34, 36, 41, 42, 44, 45, 47, 48, 59, 84, and 89). The literature contains an extensive amount of data on the plasma sheath encountered by vehicles reentering the atmosphere. Complete density profiles as a function of several variables such as elapsed time, altitude, vehicle shape, vehicle velocity, and distance from the vehicle surface have been measured. The density of the plasma sheath cited in the literature ranges from 10^9 to 10^{15} cm^{-3} (Refs. 1, 2, 4 to 17, 24, 27, 30, 43, 47 to 49, 59, 78, 81, and 89). The altitude range, or range of flight over which this plasma sheath is present varies, but ranges from approximately 90 km down to 30 km, with the most intense plasma sheath occurring at lower altitudes, close to 30 km (Refs. 4, 7, 8, 12, 13, 21, 23 , 24, 46, 48, and 79). The atmospheric pressure during reentry blackout ranges from approximately 0.75 torr up to 75 torr (Refs. 11, 17, and 89).

C. Theory

Ions and electrons within the plasma, when displaced slightly, create a restoring force in the form of electric fields between each other. If we consider only one electron-ion pair, and we slightly displace the electron, then an electric field will form, causing the electron and ion to be attracted to each other. However, since the ion appears infinitely massive to the electron, we can safely assume that only the electron will move. As the electron moves towards the ion it gains momentum and then overshoots the equilibrium position. As it is travelling beyond the equilibrium position, an electric field is formed that begins to pull it back. In this way the electrons oscillate in a plasma, much like a mass on a spring, at the so-called "plasma frequency" (Ref. 18):

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \tag{1}$$

Where ω_p is the plasma frequency, n_e is the electron density, e is the electron charge, m_e is the mass of an electron, and ε_0 is the electric constant.

For a nonmagnetized, noncollisional plasma, the plasma frequency also happens to be the cutoff frequency (Refs. 18 and 90). That is, electromagnetic waves below the plasma frequency will not propagate through a thick layer of plasma. Note that the preceding statement is true only under the assumptions that the plasma is nonmagnetized, noncollisional, and relatively thick in the direction of wave propagation. For all practical purposes, the reentry plasma sheath generally fits this description.

Notice that for the plasma sheath density range cited above (10^9 to 10^{15} cm^{-3}), the plasma frequency range is approximately 285 MHz to 285 GHz. The radio frequencies used for spacecraft are well below 285 GHz. This suggests that operating at very high frequencies may be a potential solution; however, it is important to note that radio frequencies above 10 GHz are significantly attenuated by water vapor in the atmosphere (Ref. 17). Therefore, the spacecraft will experience radio blackout for a significant portion of the reentry period.

III. Leading Mitigation Methods

A. Aerodynamic Shaping

Electromagnetic waves with a wavelength much longer than the plasma sheath layer thickness near the antenna may be able to penetrate the plasma layer, regardless of the plasma frequency. Signals travelling from the spacecraft to ground control as well as from ground control to the spacecraft may be able to penetrate the plasma layer with sufficiently long wavelengths relative to the plasma sheath thickness. The so-called aerodynamic shaping mitigation method attempts to take advantage of this property.

The spacecraft capsule design in the Mercury, Gemini, and Apollo space programs, as well as that to be used in the Ares program, reenter the atmosphere with the blunt or flat side facing forward to slow down as quickly as possible. The blunt vehicle reentry, however, results in a bow shock that stands in front of the vehicle, resulting in a very thick plasma sheath. If the leading edge of the vehicle is very sharp, then an attached shock wave will form, producing a very thin plasma sheath region with relatively low ionization levels. Electromagnetic penetration of such thin, reduced density plasma layers becomes possible.

Several approaches to forming an attached bow shock have been investigated. The simplest approach simply uses a sharp-nosed body. Others have proposed placing a remote antenna assembly (RAA) in front of the blunt body bow shock, shown in Figure 2. Yet others have investigated injecting gas (also known as a gas spike, shown in Figure 3) at the stagnation point in front of a blunt vehicle to change the flow so as to simulate a sharp-nosed body (Refs. 2, 3, 15, 17, 19, 21, 23, 25, 36, 41, 44, 46, 51, 75, 76, 78, and 79).

The Trailblazer 4 and RAM A-1 flights were flown to test the aerodynamic shaping approach. The Trailblazer 4 flight test utilized the gas spike method and was ultimately unsuccessful. The helium gas spike was initiated at altitudes much too low so that the desired effect was not achieved. This test demonstrated that this approach is limited in its range of effectiveness, namely at low altitudes (Ref. 23). The RAM A-1 test simply used a sharp-nosed body, but performed measurements on the ascending
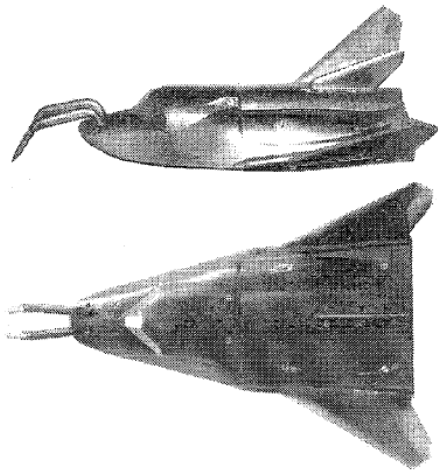

Figure 2.—Photograph from Belov et al. (2001) of a model with an RAA attached (Ref. 78).
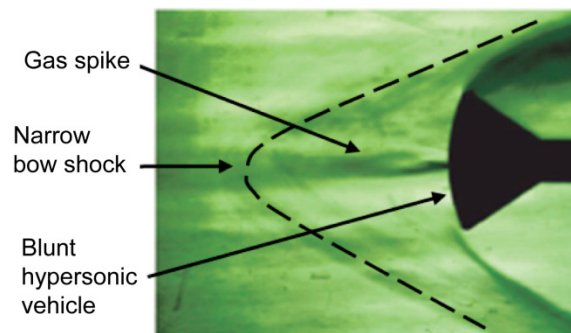

Gas spike

Narrow bow shock

Blunt hypersonic vehicle

Figure 3.—Schliren photograph image of a blunt body in a wind tunnel demonstrating a gas spike modifying the bow shock, from Daso et al. (2009).

portions of the flight test and flew at a maximum velocity of 5.4 km/s to minimize heating problems. The goal of this flight was achieved, showing only 'medium' VHF signal loss. The maximum attenuation was 25 decibels (dB) on the forward slot antenna and only 10 dB on the aft ring antenna (Ref. 51). It should be noted, however, that 25 dB attenuation is referred to as "substantial" and significant signal loss by others (Refs. 21 and 81).

Tests have also been performed in shock and wind tunnels without the huge expense of reentry flight experiments. Significant success at mitigating the blackout conditions have been observed using RAA's in hypersonic wind tunnels. An RAA is a small antenna assembly that will transmit and receive communications signals and sticks out in front of the bow shock of a blunt object so that an attached shock will forms on the small protrusion. However, in these tests the RAA's usually melted without the use of an active cooling system (Ref. 78). The approach of using a counterflowing gas spike has been shown to be able to affect the flow so as to weaken the bow shock in front of a blunt body. The gas spike approach has also shown potential as a thermal control system, demonstrating the possibility to reduce structural heating and plasma temperature (Refs. 25 and 76).

The aerospace shaping method of blackout mitigation has several advantages over many of the other proposed methods. Aerodynamic shaping manipulates the properties of gas flow around the vehicle and has the potential to be a passive system, requiring very little if any extra mass to be added to the vehicle. Mass considerations are extremely important in the field of aerospace and aeronautics, with every kilogram of material costing approximately $10,000 to be lifted into low earth orbit (Refs. 17 and 91).

Despite the advantages of aerodynamic shaping, there are also several disadvantages. To begin, no shaping solution has yet been able to mitigate the plasma sheath without requiring an active cooling system to provide thermal relief for the exposed surfaces. This cooling system may significantly increase vehicle mass and therefore increase cost, not to mention the increase in design complexity. Exposed surfaces will be subject to intense heating and corrosion, possibly resulting in the degradation of surfaces that may lead to disrupted flow before the end of flight. For reusable vehicles, leading edges may need to be refurbished and restored for each flight. Furthermore, the constraints that are placed on the system design for sharp-tipped bodies are significant and may limit the vehicle payload.

Aerodynamic shaping may not provide a complete solution to the blackout communications problem, but "may aid" in the ultimate solution if used in conjunction with another mitigation method (Ref. 2).

B. Magnetic Window

As mentioned above, electrons are able to react to the electric field of an incoming electromagnetic wave provided the wave's frequency is below the plasma frequency. The electrons act to cancel the electric field, thus reflecting the incident wave at the surface of the plasma. However, by constraining the motion of the electrons, new modes of propagation can be exploited, and waves below the plasma frequency can propagate through the plasma sheath. The magnetic window approach attempts to take advantage of changes in the dispersion relation made possible by the presence of the applied magnetic field, thereby enabling two-way communication between the spacecraft and ground control.

The RAM A-2 flight is one of very few known flights to have tested the magnetic window mitigation technique, and very little has been revealed regarding the results of the test (Ref. 41). The most likely cause for the limited number of test flights is the prohibitively large mass requirements for any magnetic system. Therefore, research on the magnetic window method has been carried out primarily via computational modeling. These modeling efforts have been largely successful, showing that based on reentry plasma sheath parameters, magnetic windows should work to mitigate the reentry blackout (Refs. 2, 3, 13, 14, 15, 17, 23, 26, 31, 36, 46, 60, 65, 76, and 81). Several calculations have determined the magnetic field strength required for propagation. Results show that right-handed polarized waves will propagate along magnetic field lines with a magnitude as low as 357 Gauss (G), through a plasma sheath with a density of 10^{12} cm^{-3}, with no attenuation at frequencies up to 1 GHz (Ref. 31). Other calculations indicated a 20 dB improvement in signal reception with a magnetic field of 750 G (Ref. 81). Preliminary results from calculations performed at the NASA Glenn Research Center show comparable results

(Ref. 92). Calculations indicate that variable magnetic fields may be required as the reentry sheath density varies throughout the reentry trajectory. A variable magnetic field would require electromagnets, with significant additional mass. However, other calculations have shown that exceedingly large magnetic fields up to 13 kG are required for S-band communication signals and electron gyrofrequencies near X-band (Ref. 23).

Recently, both modeling and experimental work has been done on a hybrid magnetic window and electrostatic collection type of mitigation system. The system takes advantage of ExB drifts experienced by both electrons and ions to collect charged particles and excite new propagation modes. Computer modeling results showed a significant decrease in electron density and a corresponding increase in transmission. Experimental results using a helicon plasma to simulate the reentry sheath indicated that the magnetic effect rather than the ExB drift charge collection was the predominant mechanism behind the density reduction (Refs. 14, 15, 17, 26, and 65).

The magnetic materials themselves may quite possibly be the largest potential barrier for the magnetic window approach. However, the development of advanced magnetic materials has emerged as a very important field for space applications, stressing the attributes of low mass and high reliability as a priority for the space community (Refs. 76 and 91). Advancements in carbon nanotube materials have shown potential for future use as lightweight magnets (Ref. 20).

The magnetic window has the advantage that the system could be a passive system if it were designed to use permanent magnets. However, the Curie temperature, or temperature at which a permanent magnet loses its magnetic properties, for present-day state of the art permanent magnets is well below the spacecraft surface temperature during reentry. Therefore, permanent magnets placed on or near the surface of the spacecraft would lose their magnetic properties. If a way to enact the use of permanent magnets while thermally isolating them from the reentry plasma was devised, the magnetic window approach may be realized as a solution to the communications blackout problem.

Electromagnets could potentially be used instead of permanent magnets. Electromagnets, however, carry along with them the disadvantages of complexity, mass, and power costs. The mass alone of an electromagnet system would be on the order of 50 kg, not including power supplies (Ref. 17). The added cost just for launching such an electromagnetic system, would be more than $500,000! (Refs. 17 and 91). In addition to the importance that is placed on mass in space systems, an almost equivalent importance is placed on electrical power for space systems. The power for the electromagnet system would need to be supplied by batteries with limited capability during reentry.

C. Liquid Quenchant Injection

It is clear that the plasma frequency is a critical value, above which electromagnetic waves propagate freely. Notice that the electron density is the only parameter in the expression for the plasma frequency that can be controlled. Reduction of the electron density will reduce the plasma frequency, allowing lower frequency radiowaves to propagate through the plasma sheath. Therefore, reduction of the electron density or "quenching" of the plasma by injecting liquids, has been one of the most important and successful methods of mitigating the plasma sheath. Quenching of the plasma can be achieved by injecting various liquids into the plasma flowing past the spacecraft. These liquids can have various effects on the plasma sheath and interact with the plasma flow in different ways. Water is usually used to cool the plasma, causing ions and electrons to recombine to form a neutral air atom or molecule. Other liquids are used for their chemical properties. Liquids that have an affinity for reacting with electrons, commonly referred to as electrophilic liquids, are often times used. When injected, these liquids will undergo chemical reactions that will bond with electrons, therefore reducing electron density. Effective penetration into the plasma sheath is required for transmission of signals both to and from the spacecraft.

Liquid quenchant injection has been the most commonly investigated blackout mitigation method and has probably had the largest amount of success over the years. Tests have been performed with many different liquids to determine the effectiveness of each fluid. Liquids like water, sulfur hexafluoride, carbon tetrachloride, tricholoroethylene, various types of Freon, and various fluorocarbons have all been

tested as quenchants (Refs. 3, 8, 10, 12, 19 to 21, 24, 42, 45 to 49, 52, 53, 79, 82, 84, 85, and 93). Flight tests of the liquid quenchant mitigation method began with the RAM B-2 flight and continued to dominate flight tests with 3 of the 7 successful RAM flight tests along with several Trailblazer flights investigating liquid injection (Refs. 8, 10, 24, 34, 36, 41, 42, 44, 48, 49, 52 and 53). Reports of varying success from little affect to almost complete elimination of blackout were reported. This led to a water injection experiment being flown on the Gemini 3 manned mission. Results from this experiment showed moderate success, with VHF and C-band signals being recovered in some respect for at least part of the reentry trajectory (Refs. 9, 19, 21, 24, 36, 38, 46, 53, and 85). To date this is the only manned mission that was successful in mitigating radio blackout and transmitting through the plasma sheath, directly to ground control.

In general, it has been shown through lab experiments and flight tests that many of the electrophilic chemicals are more effective than water at reducing the electron density that cause plasma blackout effects (Refs. 19, 20, 49, 52, and 82). However, it has been shown that water is actually more effective at penetrating and mixing further into the plasma layer. Water is also more effective in reducing thermal loads to spacecraft, although electrophilic chemicals have also been shown to be somewhat effective (Refs. 47, 53, and 85). Unfortunately, many of the electrophilic chemicals happen to be very toxic and "environmentally unfriendly". In fact, the more volatile chemicals react more readily with electrons and therefore are more environmentally harmful, but also more successful in mitigating the blackout plasma (Ref. 82).

Liquid injection is the only method to have successfully demonstrated its ability to reduce the communications blackout period on a manned spacecraft reentry (Refs. 9, 19, 21, 24, 36, 37, 46, 53, and 85). It has also seen wide-spread, sustained success in laboratory experiments and other unmanned test flights (Refs. 8, 10, 24, 34, 36, 41, 42, 44, 46, 48, 49, 52, and 53). Compared with gaseous and solid materials, liquids are relatively easy to feed and inject into a gaseous flow.

There are, however, a few disadvantages associated with liquid quenchants. A feed system with injectors, although fairly simple and straightforward, would increase overall design complexity and add mass to the spacecraft. Furthermore, the mass of water or other electrophilic liquid required would likely not be inconsequential. In fact, some even think that the mass of water required would make this method prohibitive. As mentioned previously, unnecessary mass should be avoided at all costs due to the substantial added launch price. However, short bursts of water to temporarily alleviate blackout communication may be more practical.

IV. Solid Quenchant Mitigation Method and Discussion

A. The Proposed Mitigation Method

Research on a method of injecting a quenchant material, similar in concept to injecting liquid quenchants, is under investigation for use in solving the reentry communications blackout problem. Like liquid quenchants, our method involves injecting material into the reentry plasma to reduce the electron density and therefore the plasma frequency. If the electron density and plasma frequency can be sufficiently lowered, then the transmission and reception of voice communication, telemetry, and most importantly, GPS radio waves through the plasma sheath will be possible.

However, our proposed method will use a solid metal-oxide powder as the quenchant material to be injected into the reentry plasma. Our method takes advantage of the natural electrical properties of a partially ionized plasma. If an electrically isolated particle is immersed in a plasma medium, the isolated particle will naturally collect both ions and electrons. However, the initial flux of ions and electrons to the particle surface will not be equal. Rather, the particle will collect more electrons than ions and 'float' to a negative potential, called the floating potential. The particle continues to gain a greater negative potential by collecting more electrons until the electron and ion fluxes become equal, according to the following equation (Ref. 94):

$$0.61 e n_e \sqrt{\frac{kT_e}{m_i}} = \frac{1}{4} e n_e \exp\left[\frac{e\left(V_f - V_p\right)}{kT_e}\right] \sqrt{\frac{8kT_e}{\pi m_e}} \qquad (2)$$

Where e is the elementary electron charge, n_e is the plasma density, k is Boltzmann's constant, T_e is the electron temperature, V_f is the floating potential (the particle potential with equal ion and electron flux), V_p is the plasma potential, and m_e and m_i are the electron and ion masses, respectively. With many of these metal oxide particles injected into the plasma and with each particle collecting numerous electrons, a very significant fraction of electrons will be collected. This will reduce the electron density, plasma frequency, and in turn, cutoff frequency, allowing lower frequency waves to propagate through the plasma sheath.

Previous studies have analyzed the collection of charge by electrically isolated particles in the presence of a plasma primarily for other applications. Theoretical calculations have been carried out with relatively conservative parameter estimates showing that 96 percent of all electrons may be absorbed (Ref. 74). An experimental study almost identical to our experimental setup showed that alumina particles can be accelerated by electrically biased targets, indicative of the charge collected by the particles (Ref. 94). Another author reports an experiment in which the electron density was lowered by a factor of three by the injection of metal-oxide particles (Ref. 63). A separate experiment investigated sublimating tungsten-oxide, a metal oxide powder similar to alumina, to quench the plasma (Ref. 86). Despite the use of a similar material, this experimental approach is more similar to the liquid quenchant approach because of the chemical reactivity of the quenchant material, which is in the gas phase when injected.

B. Practical Application

In practice it is relatively straightforward to inject liquid or gaseous materials into a gaseous or fluid medium such as the plasma sheath. However, metal-oxide particles have been demonstrated as an effective means of plasma depletion (Refs. 63, 74, and 86). Several viable solid particle material injection methods have been proposed for practical application. Many spacecraft are fit with an ablative heat shield to protect the spacecraft from the intense temperatures experienced during reentry. The heat shield is designed to slowly burn away as the spacecraft encounters the intense and hot reentry plasma. It has been shown, however, that some materials used to make heat shields, especially alkali metal impurities in heat shields, add significantly to the electron density of the reentry plasma sheath as they burn away into the plasma flow (Refs. 6, 8 to 10, 12, 19, 24, 34 to 35, 37, 45, 48, 60, 66, 84, and 95). It is possible to reduce alkali metal impurities and concurrently impregnate metal oxide particles such as alumina into the heat shield. In this case, heat shield ablation will naturally carry the alumina particles into the plasma sheath, thereby allowing depletion of the sheath plasma density via metal oxide particle charging. This ablative shield approach, in general is considered to be a very promising approach (Ref. 2). Locating the shield in the near vicinity of the antenna may maximize its effectiveness. However, a key aspect of this approach would be ensuring that the plasma flow would be intense enough to ablate the shield near the antenna without destroying the antenna itself. This arrangement may not be possible as the heat flux required to ablate the shield in the vicinity of the antenna would most likely destroy the antenna. A metal-oxide particle coating could even be applied to the antenna itself so that in the process of transmitting, metal-oxide particles are being injected to quench the plasma. Again, this approach is predicated on the assumption that the antenna could withstand the heating required for surface ablation. Any of these approaches would be a relatively passive solution to the communications blackout problem and presumably minimize the amount of added mass required.

C. Current Status of Solid Particle Injection Approach

The apparatus used for active injection of dielectric particles into a simulated reentry plasma sheath is shown in Figure 4. When the electrode containing a layer of particles is negatively biased in the presence of a background plasma, cathode spot formation at the surface of the electrode is initiated. Cathode spots are localized arcs that tend to form at small surface protrusions where high localized electric fields are possible. A combination of field emission and ion bombardment at these microprotrusions leads to localized heating and ultimately explosive electron emission. The localized discharge is intense, resulting in local vaporization of the electrode material (Ref. 96). This vaporized electrode material is emitted from the electrode surface in the form of a high pressure, high speed plasma plume, as shown in Figure 5. Cathode spots have very short lifetimes (~0.2 to 25 µs) (Refs. 96 to 98). The plasma plume emanating from the cathode spot rooted at the electrode surface, acts to push alumina powder up and into the overhead plasma, leaving behind an area of the electrode cleared of alumina powder. Through cathode spot formation, decay, and subsequent reformation, dielectric particles can be quasi-continuously injected into a surrounding background discharge.
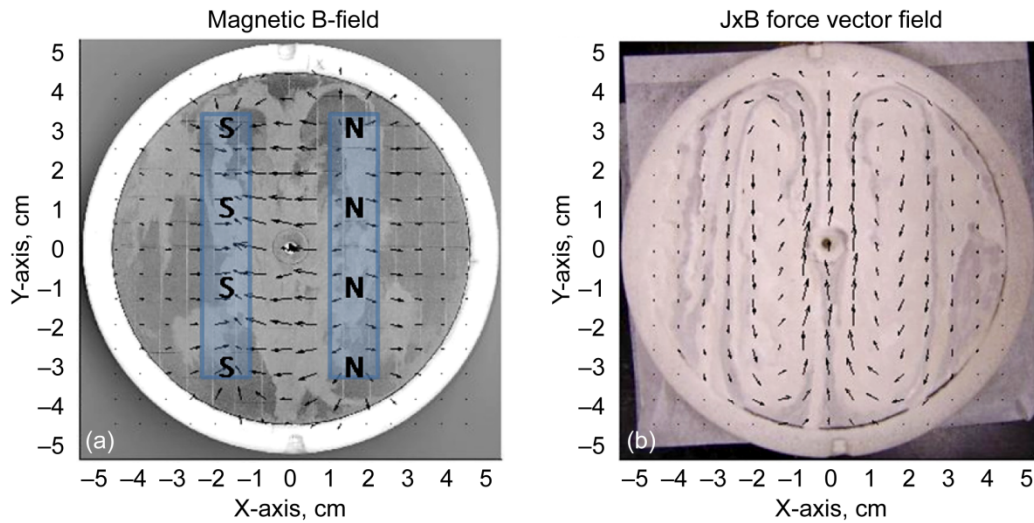

Figure 4.—Images depicting the fabricated electrode for alumina injection. (a) Two rows of permanent magnets are located under the electrode resulting in the magnetic field shown. (b) Removal of alumina powder from electrode surface is indicated by the grey areas expos--ing the steel electrode surface after a short experiment. Predicted cathode spot tracks are shown by the vector field with the cathode spot tracks following the vector field very closely.

Figure 5.—Image of a cathode spot plume emanating from the electrode surface captured with a fast frame rate camera. The cathode spot is located on the electrode surface, and the plume is vaporized steel.

Previous research has been focused on investigating the behavior of cathode spots in the presence of an applied magnetic field. Cathode spots preferentially form at locations nearby previously active cathode spot locations where the cathode spot has since decayed or become "extinct" (Refs. 96 and 97). This repetitive formation, decay, and reformation at nearby locations gives the impression that a cathode spot is continuously traversing the surface of the electrode, vaporizing small areas on the electrode, and clearing the electrode surface of dielectric powder. It was observed that in the presence of an applied magnetic field such as the one depicted in Figure 4, the cathode spot motion is constrained, giving rise to the formation of repeatable etch patterns in the dielectric powder. This constrained motion appears to be consistent with JxB motion also illustrated by the vector plot in Figure 4. Such patterns are in stark contrast to the investigated case in which no applied magnetic field was present, and seemingly random, nonrepeatable patterns resulted (Refs. 97 and 98).

The velocity and trajectory of ejected particles will be important for effective mitigation. The particles must be ejected with sufficient velocity to penetrate the flowing plasma sheath in order to provide a quenched passageway extending from the antenna region to regions beyond the sheath layer. Communication signals can then be sent and received through this depleted plasma "window" that acts as a waveguide extending from the spacecraft antenna to free space beyond the plasma sheath region. Recently, efforts have focused on obtaining particle trajectories and the ejected particle velocity distribution (Ref. 98). Laser scattering has been used to illuminate the particles, enabling recording of the trajectories of ejected particles with a high speed camera. These scattering experiments will enable the mapping of the velocity distribution. The experimental setup for these experiments is shown in Figure 6.
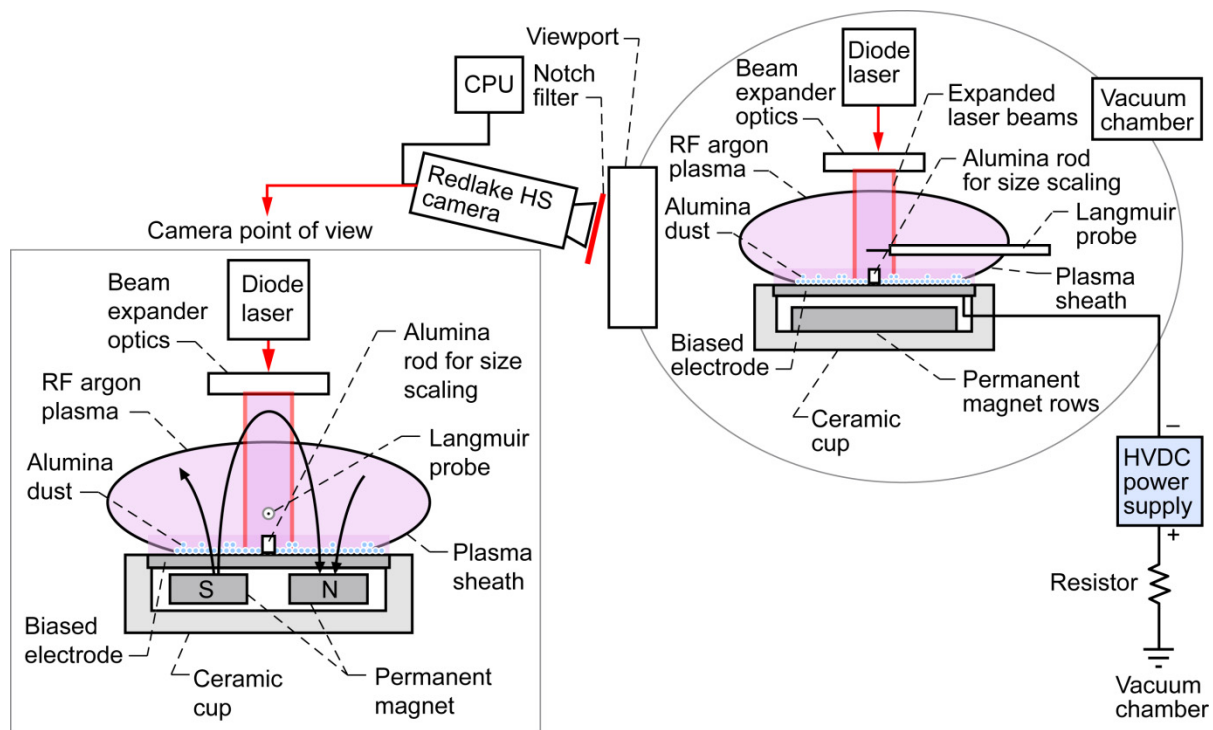

Figure 6.—Experimental setup for laser velocimetry measurements.

Conclusions and Future Work

With the renewed effort to return to the Moon and eventually Mars, the currently planned return vehicle architecture will consist of an Apollo-like capsule. Such vehicle design will be subject to communications blackout akin to that experienced by manned reentry capsules of the 60s and early 70s. A brief historical overview of the blackout problem and efforts to mitigate it has been presented. A more in-depth analysis of three of the leading mitigation methods including aerodynamic shaping, magnetic windows, and liquid quenchant injection are reviewed and discussed. These methods would be the most likely methods to fly today if a flight test research program to study reentry communications blackout were to be funded again. Advantages of each of these methods were discussed as well as the barriers that need to be overcome for the implementation of these methods.

A recently developed method of reentry blackout mitigation which features the injection of solid, chemically inert particles to quench the plasma was also presented. The collection of electrical charge by these particles, when injected into the plasma sheath, depletes the free electron density. Measurements to verify sufficient particle dispersion into the flowing plasma sheath is underway. Direct measurement of electron density via microwave interferometry or electrostatic probes will be required to verify plasma quenching. The simplicity of this plasma quenchant injection approach makes it an attractive candidate for future flight testing.

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14. ABSTRACT
Vehicles flying at hypersonic velocities within the atmosphere become enveloped in a "plasma sheath" that prevents radio communication, telemetry, and most importantly, GPS signal reception for navigation. This radio "blackout" period has been a problem since the dawn of the manned space program and was an especially significant hindrance during the days of the Apollo missions. An appropriate mitigation method must allow for spacecraft to ground control and ground control to spacecraft communications through the reentry plasma sheath. Many mitigation techniques have been proposed, including but not limited to, aerodynamic shaping, magnetic windows, and liquid injection. The research performed on these mitigation techniques over the years will be reviewed and summarized, along with the advantages and obstacles that each technique will need to overcome to be practically implemented. A unique approach for mitigating the blackout communications problem is presented herein along with research results associated with this method. The novel method involves the injection of ceramic metal-oxide particulate into a simulated reentry plasma to quench the reentry plasma. Injection of the solid ceramic particulates is achieved by entrainment within induced, energetic cathode spot flows.

15. SUBJECT TERMS
Reentry vehicles; Antenna breakdown; Blackout mitigation

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