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A Study of Various Mitigation Strategies For RF Communications Blackout Phenomenon

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ABSTRACT

In any aerospace application, the vehicle travelling in space, upon re-entry is subjected to high temperatures and high pressures. The matter surrounding the re-entry vehicle due to high temperature and pressure gets converted into the plasma state and results in high attenuation of electromagnetic signals. This phenomenon is called a Radiofrequency (RF) blackout. Radiofrequency blackout has critical implications during the reentry phase of space vehicles or missiles. In this paper, the RF blackout phenomenon is discussed with an emphasis on mitigation techniques. Shapes of the re-entry vehicle, higher frequency communication, electrophiles, magnetic windowing, and metamaterials have been discussed and compared. The comparison is performed with respect to weight, complexity, cost, and attenuation performance. Metamaterial-based mitigation technique has low design complexity, weight, cost, and attenuation performance and can provide minimum RF blackout time.

Keywords: ICBM; Telemetry; Mach; Metamaterials; RF blackout; Plasma

NOMENCLATURE

N : Nitrogen
O : Oxygen
H : Magnetic field intensity
E : Electric field intensity
j : Imaginary part of a component
ω : Angular frequency
Hz : Hertz
μ : Magnetic permeability
ε : Electric permittivity

1. INTRODUCTION

Humans have been using reusable re-entry vehicles for aerospace missions since 1969. Ever since then, scientists have encountered and have been battling the RF blackout hurdle during the re-entry phase of the flight. Specifically, when a re-entry vehicle penetrates the earth's atmosphere with high speeds such as Mach 19, the atmosphere around it, especially in front of the vehicle experiences high pressures and gets highly compressed, forming a shock wave around it[1]. The highly compressed gas also experiences high temperatures resulting from the altitude of the atmosphere and friction against the re-entry vehicle. This results in the generation of high heat around the vehicle. The high heat and compression will ionize the gases in the atmosphere within the shock region eventually forming electron plasma as shown in Fig.1[2].

The electron plasma has a characteristic which is extremely disadvantageous to the re-entry vehicle. The electron plasma attenuates electromagnetic signals propagating through it[3]. These electromagnetic signals consisting of various radio frequencies which have the data of copious systems such as tracking, telemetry, voice communications, and Global Positioning Systems. The attenuation of the RF signals is directly proportional to the thickness of the plasma sheath. As the density increases, attenuation increases. An illustration is shown below which helps in understanding the gravity of the problem.

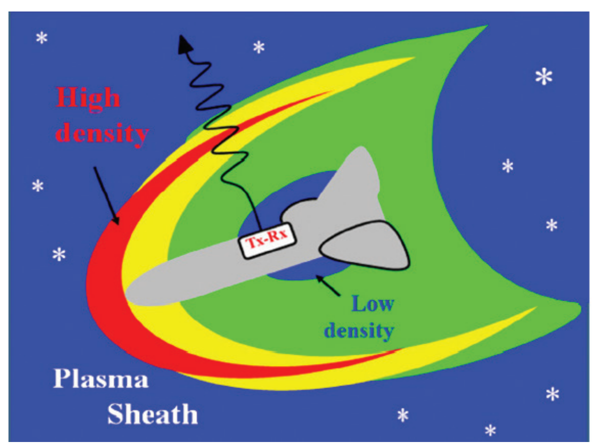

Figure 1. Plasma sheath during re-entry phase.

It can be observed that the density of the plasma sheath encompassed around the re-entry vehicle increases as the thickness increases. The electron plasma affects the RF signals in an adverse manner resulting in a complete loss of communication with the re-entry vehicle and even a loss of GPS acquisition.

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The RF blackout can last from 50 sec. to 12 min. depending upon the speed and flight trajectory of the re-entry vehicle[4]. Various approaches to reduce the RF blackout issue have been proposed resulting in varying magnitudes of success. Specifically, modifying or reshaping the nose of the re-entry vehicle to generate less friction while penetrating the atmosphere; switching to higher frequencies of operation which can perforate through the electron plasma; instead of directing the RF signals from the vehicle to the ground station, communication is established with re-entry vehicle using a satellite as an intermediary. Another approach is the use of coolants. Decreasing the outer layer temperature of the vehicle using coolants prevents the atmosphere in the shock wave region from undergoing high temperatures, eventually restraining the formation of plasma or ionization of gases into plasma[5].

The paper presents the plasma formation during re-entry phase of the vehicles, it also discusses various re-entry vehicles and their advantages and disadvantages, various mitigation techniques have been discussed. The mitigation techniques are based on shaping, using higher frequencies, electrophiles liquid quenchants, magnetic windows, and metamaterials. The paper compares the different mitigation techniques with respect to RF attenuation, RF blackout time, payload weight and complexity.

2. PLASMA SHEATH FORMATION ON THE RV

The re-entry phase of every flight trajectory is the most crucial and nail-biting phase. During this phase, the vehicle descending from space pierces through the atmosphere possessing high kinetic energy levels. This kinetic energy compels the re-entry vehicle to radiate heat energy in inordinate proportions. These high energy levels of enthalpy excite the air around the vehicle to ionize. Ionization converts air into plasma and forms a thick plasma sheath around the re-entry vehicle. This very plasma sheath attenuates the RF signals emerging out or entering the re-entry vehicle. Not only during the re-entry phase, but also during the entry (take off) and landing approach. The vehicle inevitably experiences an RF blackout phenomenon during re-entry, which leads to complete communications, telemetry and tracking, and GPS acquisition loss[6].

To overcome the RF blackout issue, the properties of the plasma must be comprehensively studied. At atmospheric pressure, the nitrogen and oxygen molecules start to dissociate at 4000K and 2000K respectively, and at temperatures 9000K and above, nitrogen and oxygen undergo the ionization effect. In between 4000 K, and 6000 K, the *NO* gets ionized to form NO^+. Such ionization of different atmosphere elements tends to form a plasma envelop around the re-entry vehicle. At higher altitudes, the atmospheric pressure drops, consequently, the temperatures of ionization and dissociation also decrease. The following reactions take place to ionize the atmospheric elements[7].

$$N_2 + M \rightleftharpoons N + N + M$$
$$N_2 + e^- \rightleftharpoons N + N + e^-$$
$$O_2 + M \rightleftharpoons O + O + M$$
$$NO + M \rightleftharpoons N + O + M$$
$$NO + O \rightleftharpoons N + O_2$$
$$N_2 + O \rightleftharpoons NO + N$$
$$N + N \rightleftharpoons N_2^+ + e^-$$
$$O + O \rightleftharpoons O_2^+ + e^-$$
$$N + O \rightleftharpoons NO^+ + e^-$$
$$N + e^- \rightleftharpoons N^+ + 2e^-$$
$$O + e^- \rightleftharpoons O^+ + 2e^-$$
$$NO^+ + O \rightleftharpoons N^+ + O_2$$
$$O_2^+ + N \rightleftharpoons N^+ + O_2$$
$$O^+ + NO \rightleftharpoons N^+ + O_2$$
$$O_2^+ + N_2 \rightleftharpoons N_2^+ + O_2^+ + N_2 \rightleftharpoons N_2^+ + O_2 O_2$$
$$O_2^+ + O \rightleftharpoons O^+ + O_2$$
$$NO^+ + N \rightleftharpoons O^+ + N_2$$
$$NO^+ + O_2 \rightleftharpoons O_2^+ + NO$$
$$NO^+ + O \rightleftharpoons O_2^+ + N$$
$$O^+ + N_2 \rightleftharpoons N_2^+ + O$$
$$NO^+ + N \rightleftharpoons N_2^+ + O$$
$$N_2 + N^+ \rightleftharpoons N_2^+ + N$$

$$M = N_2, O_2, NO, N_2^+, O_2^+, NO^+, N^+, O^+, N, O$$

As these reactions occur, the atmospheric air is converted into ion-dense plasma filled with N_2^+, O_2^+ ions. The concentration of these ions is very low, but the density of free electrons liberated due to the chemical reactions is sufficiently high enough to attenuate the incoming or outgoing RF communications signals. But contrary to popular belief, the blackout is not caused by the factor of high-density electron plasma; instead, it is caused by high frequency of oscillations of the electrons. This concept can be thoroughly understood by studying Maxwell's Eqn. describing the propagation of electromagnetic waves in free space and the interaction of an electromagnetic wave with plasma governed by Maxwell's Eqn.[8]:

$$\nabla \times \mathrm{H} = \mathrm{j}\omega\varepsilon_\mathrm{v}\mathrm{E} + \mathrm{Nev} \tag{1}$$
$$\nabla \times \mathrm{E} = -\mathrm{j}\omega\mu_\mathrm{v}\mathrm{H} \tag{2}$$
$$\nabla \cdot \mathrm{E} = \frac{\mathrm{ne}}{\varepsilon_\upsilon} \tag{3}$$
$$\nabla \cdot \mathrm{H} = 0 \tag{4}$$

After solving the above four Eqn., the following expression is obtained which represents plasma by a dielectric permittivity.

$$\varepsilon = \varepsilon_\upsilon\left(1 - \frac{\omega_P^2}{\omega^2}\right) \tag{5}$$

This Eqn. can also be written as:

$$\frac{\varepsilon}{\varepsilon_\upsilon} = \mathrm{K_o} = 1 - \mathrm{X}$$

where

$$7X = \frac{\omega_P^2}{\omega^2}$$

The above Eqn. demonstrate that, in a plasma, the wave propagation is similar to that in any ordinary dielectric medium, provided X is less than unity i.e., $\omega > \omega_p$. But if the X is more than unity i.e., $\omega < \omega_p$ then plasma offers attenuation to the electromagnetic signals.

However, the concepts of plasma sheath formation as a combination of chemical reactions and thermodynamic processes are still complex to understand. Furthermore, the rate at which these thermodynamic and chemical reactions take place changes abruptly in a continuous manner, making it very hard to find a pattern to study systematically. Therefore, a comprehensive study of plasma characteristics using analytical techniques is not possible. Hence, plasma parameters are evaluated experimentally using different sensors on board at the re-entry flights.

The plasma sheath enveloping a typical ICBM re-entry vehicle has four flow regions, as shown in Fig. 2[9]. The stagnation region is the first region where the impact from the angle of attack takes place. This region comprises high-temperature and high-pressure gases and is bounded by a thin boundary layer and shock region.

Consequently, extreme plasma conditions arise in this region. Therefore, antennas are usually not mounted near the stagnation region. Instead, they are placed in the aft body region, where the environmental conditions are comparatively tolerant.

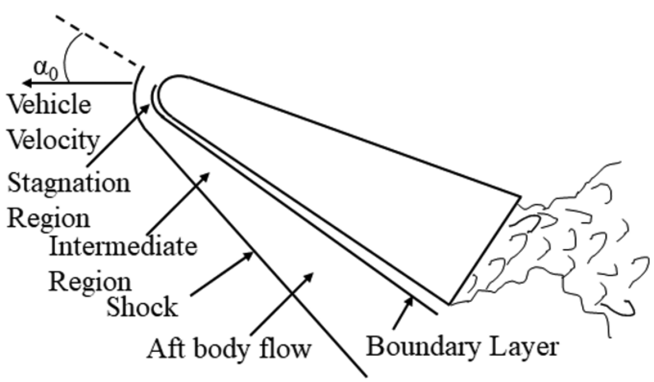


Figure 2. Flow regions of ICBM payload during re-entry phase.

The Intermediate region consists of gases in a non-equilibrium state. The plasma conditions in this region are not as strong as in the earlier region but dire enough to cause total RF blackout from the antennas situated on the aft body.

The aft body region consists of gases that get ionized by entering through the boundary of the shock region. Factors such as the shape of the re-entry vehicle and the angle of attack determine the electron density of the plasma. The conditions of plasma in the aft body region are not as extreme as in the region of the intermediate stage. The boundary layer is just below the aft body flow region. Generally, this layer is very important in terms of ionization. The typical plasma formation starts to take place along the surface of the re-entry vehicle i.e., along the boundary layer region. The ionization in this region begins to take place at the altitude of 80 km and starts to rapidly grow along the surface of the re-entry vehicle.

The region behind the re-entry vehicle is called the wake region, where a prominent rate of recombination of ions and electrons takes place. Generally, the region is not affected by plasma and does not experience RF communications blackouts.

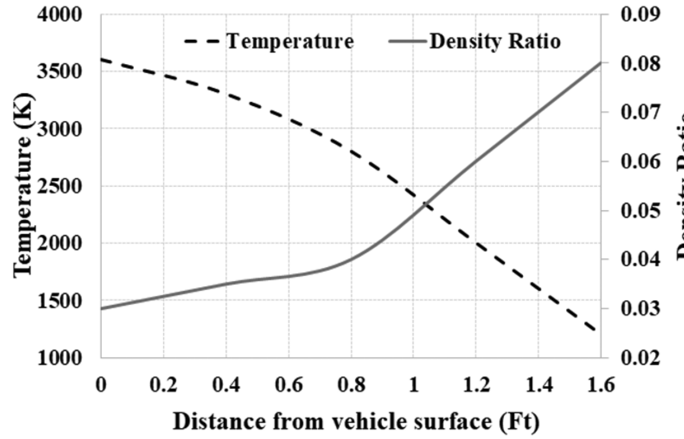


Figure 3. Variation of temperature and relative air density at antenna location.

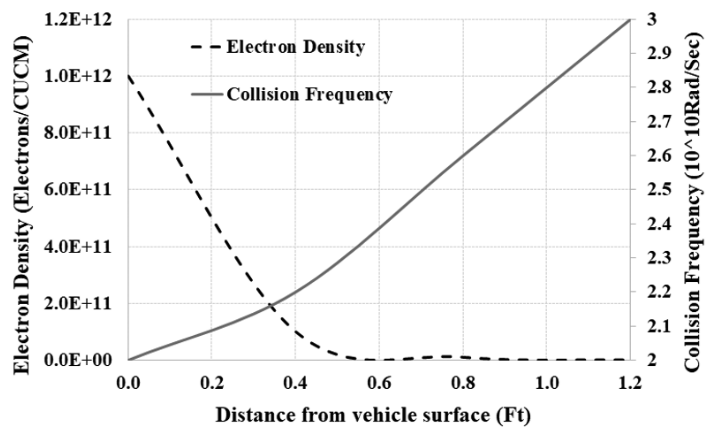


Figure 4. Variation of electron density and collision frequency at antenna location.

As the re-entry vehicle descends from outer space into the earth's atmosphere, the air surrounding the re-entry vehicle gradually turns into plasma as the re-entry vehicle pierces the atmosphere. The plasma attains the highest frequency of oscillation and density somewhere around the middle of the descent journey. Consequently, due to the decreasing velocity of the re-entry vehicle and the high electron densities at lower altitudes, the plasma again gradually gets converted back into air gradually. The conversion of plasma back to air occurs as the electrons of the plasma collide with neutral particles of air. A graphical representation of the changes in temperature during the descent phase and the relative air density at the antenna location forming radially outwards against the distance from the re-entry vehicle surface is shown in Fig. 3 while Fig. 4 shows the graphical representation of the changes in the electron density of the plasma and collision frequency rate of electrons with neutral particles against the distance from the re-entry vehicle surface[10].

3. TYPES OF RE-ENTRY VEHICLES

This section discusses different re-entry vehicles, which form a pre-requite for mitigation approaches.

3.1 Ballistic Re-entry Vehicles

The ballistic re-entry vehicle, as shown in Fig. 5[11], is

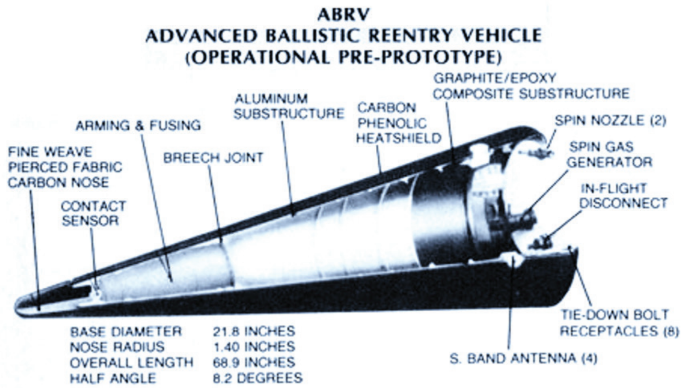


Figure 5. Typical re-entry vehicle.

Figure 6. NASA space shuttle orbiter re-entering Earth with a 40° angle of attack.

categorised into two types, i.e., Blunt nose and sharp nose, based on the physical appearance and the construction of the re-entry vehicle. A blunt nose re-entry vehicle is surrounded by a strong shock wave with a large circumference, which can convert large volumes of air flowing and present within the shock region into a large volume of plasma upon which the sheath properties are characterized. Whereas the sharp-nose re-entry vehicle is enveloped by a weak, thin shock wave which can convert the air into a plasma medium only along the boundary layer region by viscous dissipation of the atmosphere engulfed inside the shock wave, which determines the sheath properties.

Another fascinating characteristic of the blunt-nosed and sharp-nosed re-entry vehicles is that the blunt-nosed re-entry vehicle has the potential to produce high levels of electron densities and a large thickness of plasma sheath on the re-entry vehicle, whereas the sharp-nosed re-entry vehicle has a void between the shock wave region and boundary layer along the surface of the re-entry vehicle.

3.2 Blunt Re-entry Vehicles

This class of re-entry vehicles is studied by taking two subjects into consideration. The first subject is the NASA shuttle orbiter, as shown in Fig. 6[12]. The shuttle orbiter leaving the international space station, re-enters the atmosphere at very high altitudes with high angles of attack with an intent to decelerate and not get affected by the aerodynamic heating. A 40° angle of attack is maintained by the shuttle orbiter during the re-entry phase. After a calculated descent, the shuttle is levelled back into normal flight mode for landing operation

The second subject under study is RAM C – III, as shown in Fig. 7[13]. The RAM C – III vehicle is the payload of spacecraft Project RAM. A series of tests were conducted by NASA in 1972 using a RAM C – III vehicle to understand the RF blackout phenomenon. This re-entry vehicle recorded the beginning of the blackout phenomenon for the S-Band antenna at 77 km from the ground and recorded the dissipation of the phenomenon at 24 km from the earth's surface.

During this descent, the antenna was placed in the re-entry vehicle at 0.22 meters from the tip of the nose. Another test was carried out by varying the frequency bands of operation of the antenna in the re-entry vehicle[14].

S, X and K_a bands are subjected to the blackout phenomenon and are carefully studied. An antenna positioned

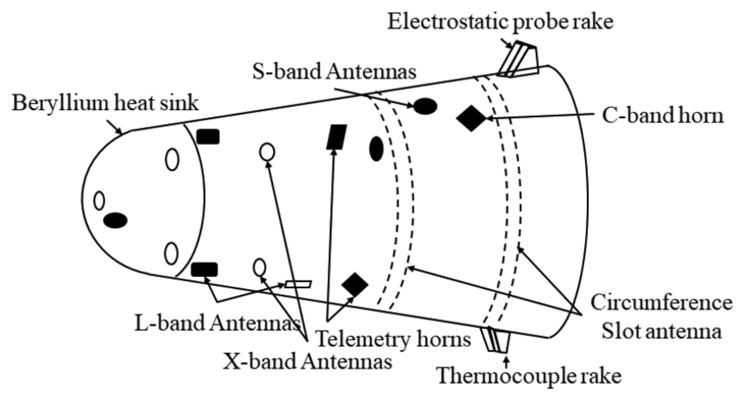


Figure 7. Various antennas on the surface of a re-entry vehicle.

at 0.22 mtr from the tip of the nose of the re-entry vehicle, experienced the onset of 20 % attenuation of the RF signals from 77 km to 69 km when X band frequency of operation is used. Whereas the K_a band frequency of operation realized the onset of 20 % attenuation at 38 km, thus, giving an advantage of 39 km difference when compared with S-Band This shifting of frequency from SS-band to K_a band reduced the duration of this phenomenon to only 4 sec. instead of 28 sec.[15].

3.3 Sharp–Tipped Slender Cones

In a sharp-nosed re-entry vehicle, as shown in Fig. 8[16], when descending from space, the air offers friction and heats up the re-entry vehicle, causing the heat shield to erode and introduce these impurities into the atmospheric flow. A weak, oblique shock wave is formed around the re-entry vehicle during the descent and the air engulfed in between the shock wave and the boundary layer doesn't get ionized due to insufficient temperatures[17]. A laminar flow is formed and maintained on the boundary layer at very high altitudes and is thin when compared with the RF wavelength which beneficially decreases the attenuation[18].

At 22 km altitude, a transition takes place from laminar flow to turbulent flow at the boundary layer, causing the air temperature to increase to its peak value and also extending the thickness of the boundary layer region by fourfold. This results in the rapid increase of the attenuation of RF communications to a maximum extent over the entire flight path[19].

3.4 Unpowered Lifting Glide Vehicle

To study this class of re-entry vehicles, an Apollo

Figure 8. Sharp tipped re-entry vehicle.

Figure 9. Re-entry of Apollo capsule.

Figure 10. X – 43 re-entry flight.

capsule as shown in Fig. 9[20], during descent phase is taken into consideration. After a series of flight tests, NASA arrived at the conclusion that, at an altitude of 80 km, the blackout phenomenon turned up and lasted to 49 km, resulting in 16 min. of total blackout. The capsule that re-entered with a 40-degree angle of attack and sustained blackout for S-band antennas that are mounted on the belly of the re-entry vehicle at high altitudes are subjected to strong degrees of ionization. A pragmatic solution to counter the blackout and keep the communications without any interruptions is by employing the antennas located above the crew compartment to transmit to the satellite constellations and relay back those signals to ground stations by means of Tracking & Data Relay Satellite System (TDRSS)[21]. After successive flight tests, NASA was able to decrease the blackout duration to 15 min. i.e., by 1 min. by decreasing the angle of attack from 40° to 20°[22].

3.5 Powered Air Breathing Lifting Vehicle

In 2004, NASA test launched an air breathing propulsion vehicle having capability of hypersonic cruising under X – 43 programs. The X – 43 as shown in Fig. 10[23], was launched prior to engine ignition at hypersonic speeds from the nose of the Pegasus rocket. The X – 43 A achieved speed of Mach 7 at 30 kms. The X – 43 had sharp edges and drifts with zero angle of attack, making it almost immune to the blackout problem. If the vehicle achieves higher Mach numbers, there is a possibility of the blackout problem[24].

3.6 Commercial Cargo "Slightly Lifting" Ballistic Re-entry Vehicle

An example of this class is K – 1 fully recoverable two stage vehicle is shown in Fig. 11[25]. Upon launch, after the first stage separation, the second stage enters the orbit, delivers the payload, re-enters the earth's atmosphere and is eventually recovered by employing parachutes at Mach 2.5. The re-entry vehicle is blunt nosed cylinder, terminated with a large flare. During re-entry, no flow fields were formed and detected, hence no studies have been made about the ionization distribution[26].

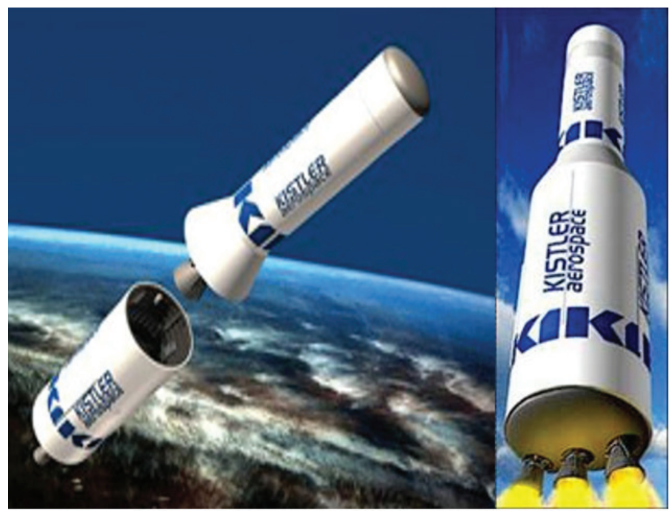
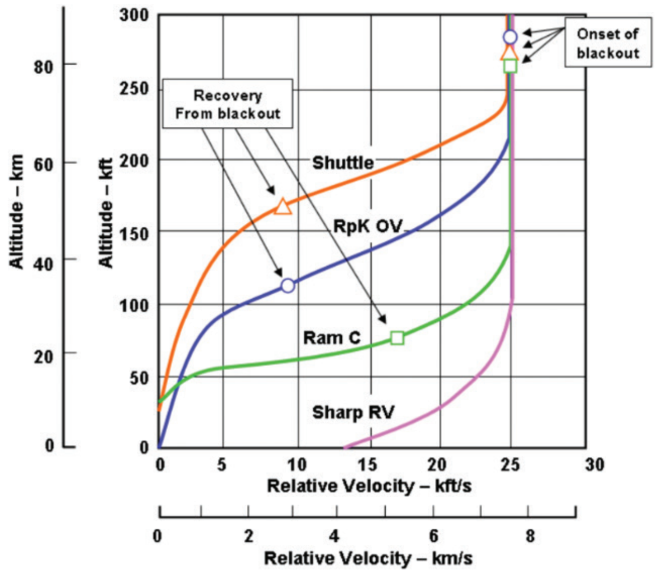


Figure 11. K–1 rocket booster lauch and seperation.

3.6.1 Comparison of Blackout Trajectories for Four Re-entry Vehicle Classes

Comparison of trajectories encompassing the blackout phase for four re-entry vehicle class is illustrated in Fig. 12[27]. They are space shuttle orbiter, RpK OV, RAM C and sharp-tipped RVs. The trajectory of sharp RV which lacks blackout phase is an ideal condition. After multiple flight tests, it has been observed that blackout is inevitable, irrespective of the vehicle class. The zone of interest in this comparison is the difference in the trajectories of RpK OV and Space shuttle, which projects that the OV maintains comparatively higher speeds at each consecutive altitude. The space shuttle experiences an inordinate amount of blackout time (16 min.) when compared with RpK OV (1 min.), which arises from the fact that the space shuttle travelling in space re-enters into the earth's atmosphere maintaining a 40° angle of attack to decelerate at high altitudes, reduce the heat transfer and protect itself from thermal ablation effects. Meanwhile K – 1 predominantly follows a supersonic ballistic trajectory, resulting in only one min. of re-entry phase where blackout recovery is possible.



Vehicle	Blackout duration, minutes
Shuttle	16
RpK OV	1
Ram C	0.5
Sharp RV	0

Figure 12. Blackout trajectories for four class re-entry vehicles.

Although onset of the blackout for all vehicles under consideration starts at almost equal altitudes, but the offset is different for each vehicle depending on the re-entry vehicle's aerodynamic shape, re-entry velocity and angle of attack. The factors that determine the blackout are all interdependent such as, the temperature of the flow field depends on the re-entry velocity, and the degree of ionization in the flow depends on the temperature[28].

4. BLACKOUT MITIGATION TECHNIQUES

Ever since Yuri Gagarin in 1961 circled the earth and re-entered, humans have been trying numerous strategies to eliminate or mitigate the blackout effect on the re-entry vehicle. There are eight mitigation techniques that have been identified, studied, simulated and tested as potential solutions for the blackout phenomenon. These mechanisms are switching to aerodynamic shaping of the re-entry vehicle, higher frequencies, electrophilic liquid quenchants injection into plasma sheath, magnetic field application, communicating with a satellite and metamaterial antennas. These approaches will be discussed in detailed manner in the next section[29].

4.1 Aerodynamic Shaping

To reduce the thickness of the plasma sheath as much as possible, the aerospace R&D and defence organisations have espoused aerodynamic shaping designs. The plasma sheath forming around a sharp tipped re-entry vehicle is very thin when compared with blunt nose re-entry vehicle. But the disadvantage of sharp tipped vehicle is that, reduced payload capacity, however it gives a relief to the aerodynamic heating problem[30].

A potential design of this technique is shown in Fig.13[31]. In this prototype, an antenna located on top of a slender, sharp probe protrudes from the front of the re-entry vehicle and extends outside of the shock wave region of the blunt

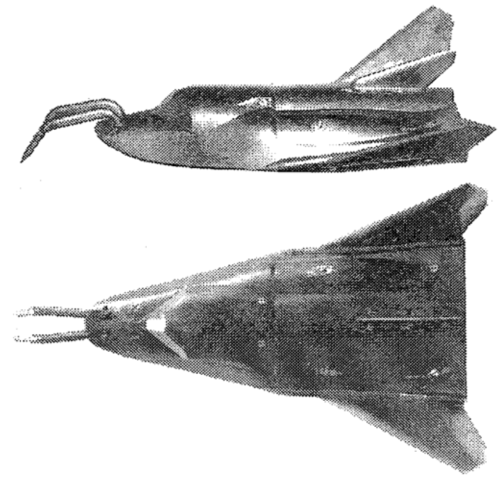


Figure 13. Sharp probe projecting ahead of the blunt nose vehicle shock bow region.

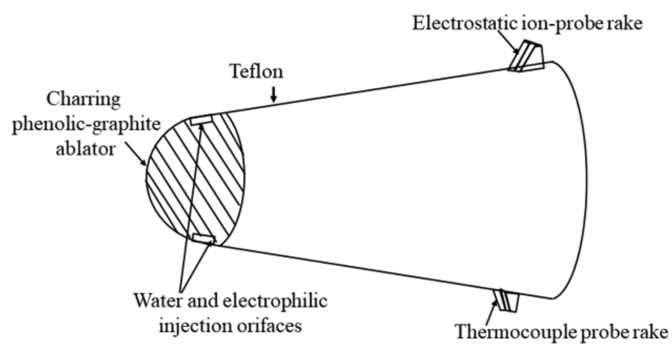


Figure 14. RAM C – III flight re-entry vehicle.

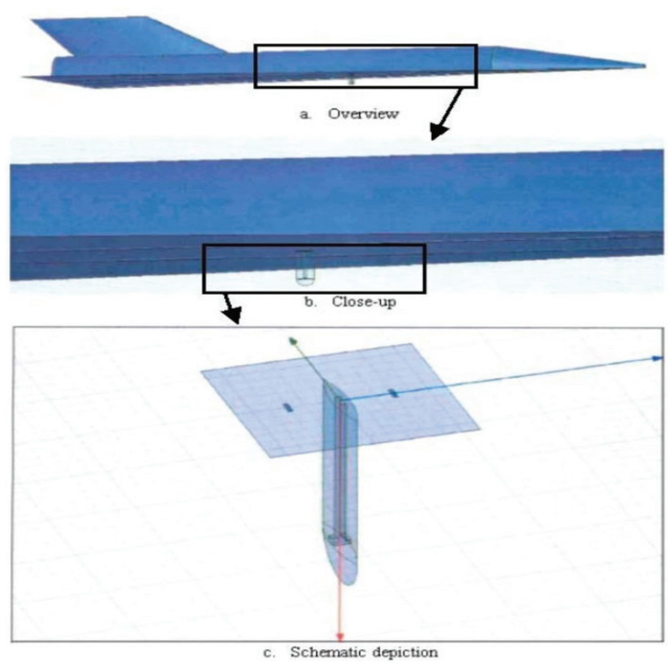


Figure 15. Blade configuration.

nose re-entry vehicle. Experimental evaluation and Finite Element Analysis (FEA) of the re-entry vehicle, pertaining to heat transfer conditions, structural simulations, aerodynamic studies and location of the antenna on the re-entry vehicle, for obtaining adequately low electron density plasma flowing aft. The probe is intentionally manufactured with porous sintered metal that can store cold gas for survival and is designed to be a sharp-nosed cone. Another example of aerodynamic shaping, as shown in Fig.14 and Fig.15[32], is done with RAM C. In 1970, NASA has tested this approach on RAM C-III. Two blades were attached on the either side of the re-entry vehicle. These blades contain electrodes for measurement purposes. One blade contains electrostatic ion probes, that are used to measure the electron density of the plasma and another blade contains thermocouple which measures temperature in the boundary layer. The blades are designed in such a manner that they did not disturb the laminar flow distribution. The blade was also designed to bear a slot antenna at the end of the blade or in the either of the two faces. When the plasma sheath is formed around the re-entry vehicle, the blades are protruded out of the re-entry vehicle and extended beyond to extent that the electrodes measure negligible electron density. Once the tip of the blade which contains a slot antenna or a microchip antenna, is protruded outside the plasma sheath, which essentially reduces attenuation of the RF signals[33].

When the re-entry vehicle reaches lower altitudes, due to the increased electron neutral collisions, the blackout phenomenon gradually perishes. As the attenuation is decreased, the blades are retracted back into the re-entry vehicle. According to the tests conducted by NASA using RAM C III, at 47 Kms the tip of the blades were only 6 centimetres away from the surface of the re-entry vehicle and at 30 Kms, the plasma sheath started to perish gradually due to the electron neutral collisions.

4.2 Higher Frequencies

The attenuation of the RF signals takes place when the operating frequency is less than the plasma frequency. To decrease the attenuation and resume the communications, the operation must be switched to a higher frequency mode which is greater than the peak plasma frequency. This concept is better expressed using the below expressions[34].

$f_o < f_P$ ⇒ Exponential decay in the transmission of the signal

$f_o = f_P$ ⇒ 100 % reflection of the signal

$f_o > f_P$ ⇒ 100 % transmission of the signal

The following graphs are the simulated results of the plasma frequency along the re-entry phase, against the operating frequency to calculate the attenuation offered by the plasma.

It can be comprehended from the graphs as shown in Fig. 16, Fig. 17, and Fig. 18[35] that as the operating frequency band is shifted to a higher mode, the attenuation offered by the plasma is decreased. Although the attenuation is reduced, this does not imply that the RF communications are resumed[36]. It can be only perceived that the communications are still distorted beyond recognition. For the RF communications to be completely restored with good quality, it is necessary that the operating frequency should be higher than the plasma frequency. However, this method of opting for higher frequencies introduces a snag[37]. As the operation mode is switched to higher frequencies, the power requirement is also increased. Consequently, the cost of securing and installing huge batteries in large quantities and other various equipment makes this technique prohibitively expensive. Another disadvantage is that by increasing the number of equipment, the weight of the payload is increased, decreasing the vehicle’s range.

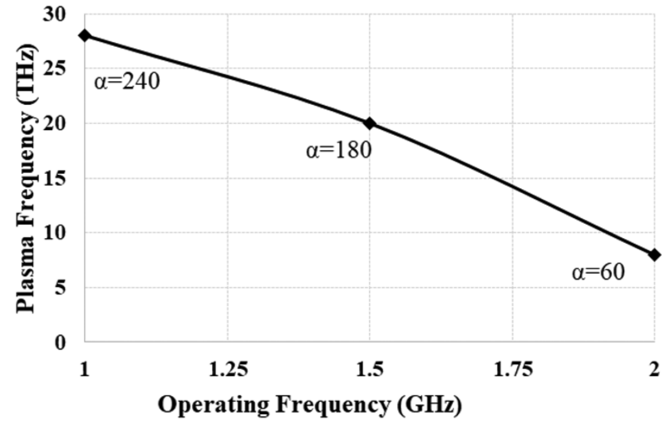


Figure 16. L–Band operating frequency (vs) Plasma frequency.

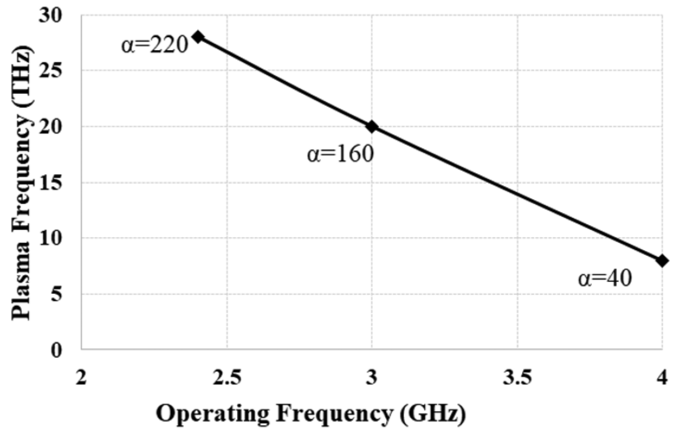


Figure 17. S–Band operating frequency (vs) Plasma frequency.

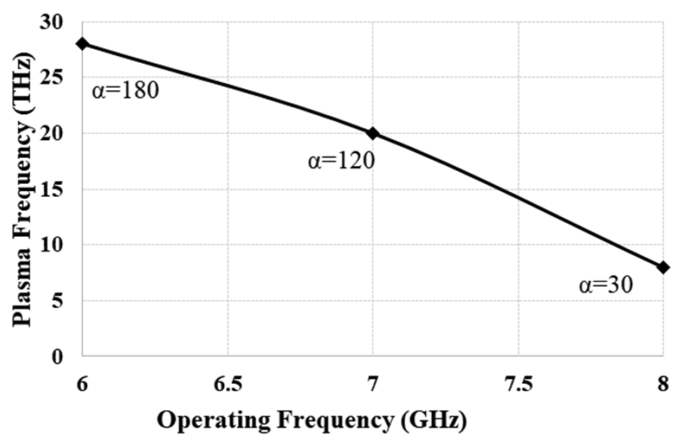


Figure 18. C–Band operating frequency (vs) Plasma frequency.

4.3 Quenchants/Electrophiles

The high temperature produced by the friction on the surface of the re-entry vehicle ionizes the air and converts it into plasma. By decreasing this temperature, the blackout issue can be brought under control. Releasing electrophilic molecules into the atmosphere which immediately combine with the free electrons of the plasma and form negative ions. This process significantly lowers the temperature of the atmosphere, thus resulting in a decrease in the plasma frequency. Theoretical research suggests that injecting a foreign dust particle of the size of a micrometer into the plasma would result in lowering the electron density and, consequently, the plasma frequency. Experiments in the laboratories have proven that sulfur hexafluoride, carbon dioxide, molecular oxygen, and nitrous oxide are useful electrophiles[38].

Now the question arises, as to which kind of matter to release as the electrophile and three cases come up. The injection of quenchants as a gas into the plasma sheath is not physically possible since there is no method that can facilitate a gas to penetrate through an ionized layer of plasma, at least beyond the boundary layer of the re-entry vehicle. Correspondingly, injection of solid particles is also impractical, because solid particles tend to reach higher temperatures at a rapid rate. Eventually, this leaves liquid as the only option[39].

Upon experiments, the injection of liquid electrophiles was found to be the most reasonable and physically possible method because liquids injected at high jet speeds can easily penetrate through the plasma which is forming around the re-entry vehicle, travelling at hypersonic speeds. The nozzles through which the quenchants are injected have a throat diameter of 0.05 mm and is situated near the antenna in an upstream direction.

At first, water was extensively investigated as the first liquid quenchant and was found to be reducing the electron density significantly. But later on, several chemical compounds developed in laboratory such as carbon tetrachloride, boron tribromide, acetone and freon were found to be more effective than water in reducing the electron density.

The effectiveness of various electrophilic quenchants was tested using RAM C-III during multiple re-entry flight tests. The graph illustrated by Fig. 19[40] describes the effect of quenchants on different antennas. The dark region within the attenuation bar indicates the injection effects observed on the antenna.

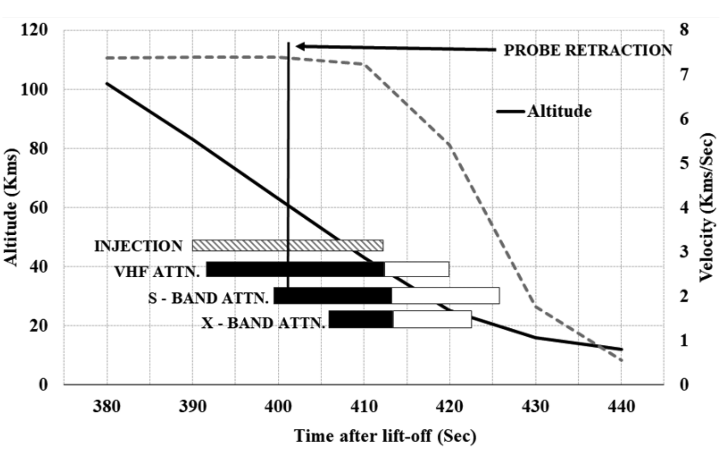


Figure 19. Electrophilic quenchants injection effects on different band antennas.

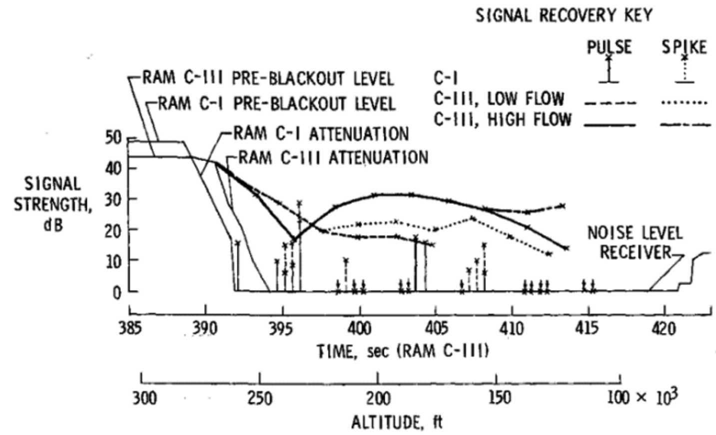


Figure 20. Comparison of RAM C-I & RAM C-III flight's blackout alleviation technique using water injection.

The signal recovery after overcoming blackout using the electrophilic quenchants in two different flight trails with RAM C-I and RAM C-III is demonstrated in the graph illustrated by Fig. 20[41]. The graph conveys that, the original signal which is at 45 dB will undergo attenuation due to blackout and gets decreased to 0 dB; but by using electrophilic quenchants, the signal can be recovered up to 30 dB[42].

It was proven that the injection of the quenchants, was the most reliable technique to mitigate the blackout problem. But this technique comes with its own disadvantages. Firstly, a thorough knowledge about the plasma properties is required to decide which chemical compound is required to be used as a quenchant. To study the plasma properties, high precision electromagnetic sensors are required to be placed on the surface of the re-entry vehicle. Even so, the characteristic of the plasma is such that it rapidly changes it properties, eventually making it difficult to find a pattern in the properties of the plasma[43].

Secondly, the required mechanism to carry and inject the quenchants by the re-entry vehicle increases the payload weight and cost, eventually decreasing the range of the vehicle. Hence, to use this technique, certain aspects must be compromised[44].

4.4 Magnetic Window

The strong electron-dense plasma attenuates or reflects back the entire RF signals emitting from the re-entry vehicle. To counter this strong electron-dense sheath, if equally strong magnetic field lines are oriented in such a way that the electrons are attracted to the magnetic field lines and are tightly bound to the magnetic field lines through gyration and do not influence their electric charge on the RF signals coming through them, then there is a chance that a window generated by the magnetic field can provide a path for the RF signals so that they can pass through[45].

The simulation results shown by Fig. 21[46] of the discussed hypothesis prove that when the plasma is subjected to a force generated by a magnetic field intensity, there is, not only a significant reduction in the attenuation offered by the plasma but also the rate of reduction is increased.

However, the drawback that comes by employing this technique is, again, the additional weight of the equipment,

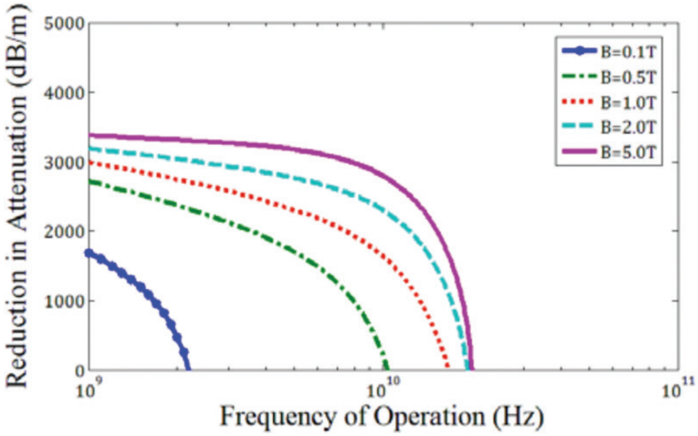


Figure 21. Reduction in attenuation (vs) operating frequency.

required to generate magnetic field lines that will significantly increase the weight of the payload, hence decreasing the range of the flight vehicle[47].

4.5 Employing Satellites

As discussed earlier, there are five regions of the re-entry vehicle, out of which four regions are influenced by the plasma. The wake region is the only region that is not affected by the plasma because it is not directly exposed to the air, which is converted in the shock bow region. Hence this area can be used for communications. Antennas can be flushed on the surface of the wake region and could be used for communications as shown in Fig. 22[48]. However, the signals emerging from the antenna are highly directional and are directed in the opposite direction of the descent, making it difficult for the ground stations to receive those signals. To receive these signals, satellites must be used to receive these signals, amplify and relay them back to the ground stations. This process is arduous, involving many equipment such as satellites, relays, etc. Hence, employing this technique is tedious, time-consuming, and not optimum.

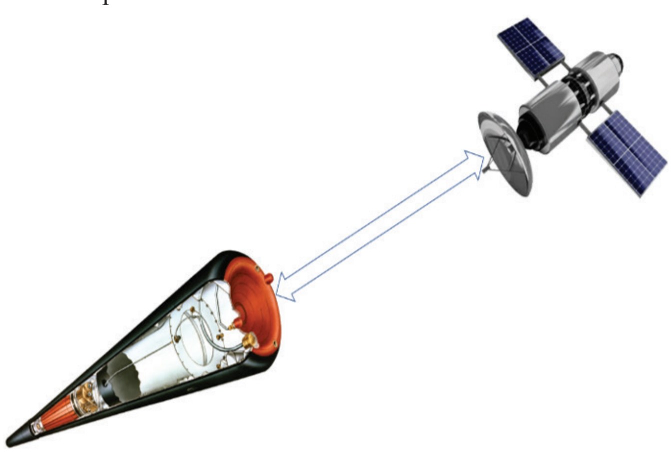


Figure 22. Employing satellite from payload antenna.

4.6 Metamaterials

Metamaterial is not some rare earth materials or something made out of different chemicals. The properties of a metamaterial are not defined by its chemical composition, rather it is defined by its physical structure. A material becomes meta by the difference in its physical structure[49].

Metamaterials are the kind of materials that exhibit abnormal behavior when compared with normal materials. This abnormal behavior is very useful for several applications such as super lenses, cloaking, negative thickness, etc. One of the applications is in antennas. Metamaterials produce a negative permeability magnetic field that is analogous to the negative permittivity electric field of the plasma sheath. Basically, the application of metamaterials is a derivative of the magnetic window. When both permittivity and permeability of the atmosphere is negative, it allows the RF signals to pass through. If the former or the latter is different from one another, RF signals will be attenuated completely. Hence, metamaterial has a significant application in antennas, which can operate in the presence of highly dense electron plasma[50].

The advantages of this technique are that metamaterial is easy to procure and manufacture, lightweight, and easy to install and operate. If this technique is practically proven, metamaterials will become the prime solution for the RF communications blackout issue.

5. COMPARISON OF DIFFERENT MITIGATION TECHNIQUES

As discussed in the earlier sections, there are numerous approaches to counter the RF communications blackout problem, out of which six approaches have high probability of success. But each approach has its own advantages and disadvantages. Comparing each technique with one another will bring out the best strategy.

By comparing the techniques, aerodynamic shaping and satellite communication counters the blackout issue, but the former compromises the payload capacity, and the latter increases the complexity. Now, when other strategies are compared, such as switching to higher frequencies, injection of quenchants, creating a magnetic window, and employing a higher power source, it is observed that all these techniques were able to counter the blackout problem except the technique involving the employment of the high-power source. But all these techniques come with the disadvantage of decreased range, which is not desirable. The only solution that does not offer any disadvantage but also counters the blackout issue without compromising any aspects of a typical re-entry vehicle is the application of metamaterial in antennas. Although this solution is only theoretically hypothesized, metamaterial will be a revolutionary solution to the RF communications blackout phenomenon if proven practically[49-50].

6. CONCLUSION

Multiple rockets and flights have been flown into space and brought back to earth, to study and solve the blackout issue. To study the blackout issue, firstly, it is required to study the physical and chemical properties of the plasma sheath. To study these properties, high-precision electromagnetic sensors are to be installed on the surface of the re-entry vehicle to record the data of various parameters. Once the plasma's behaviour is understood, any mitigation should be adopted which is suitable for the application. For instance, a ballistic flight vehicle containing a re-entry vehicle will undergo the blackout phenomenon during the re-entry phase

Table 1. Comparison of different mitigation techniques

Factors→ Techniques↓	Signal recovery time (Sec)	Attenuation experienced (dB)	Efficiency	Additional payload weight
Aerodynamic shaping 40° AoA to 20° AoA	900	NIL	Very low	No
Higher frequencies VHF to X band	9.4	14	Very high	Yes
Quenchants (water)	300	20	Moderate	Yes
Magnetic window 0.075 Tesla	NIL	40	Moderate	Yes
Satellite communication	NIL	NIL	Very high	Yes
Metamaterial	NIL	5-10	Very high	No

of the trajectory. The appropriate mitigation method that must be used that does not increase the payload weight, cost, and complexity is metamaterials in the antenna.

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