

Mitigation of Communication Blackout during Re-entry Using Static Magnetic Field

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Abstract—During re-entry into earth's atmosphere, a spacecraft suffers from loss of communication with the ground control station, known as communication blackout, due to formation of plasma around the re-entry spacecraft. This paper presents the theory and analysis of the communication blackout and its mitigation using static magnetic field method. The interaction between electromagnetic waves and plasma in presence as well as absence of magnetic field is described to determine the effects of plasma sheath on the spacecraft re-entering into the atmosphere. An analysis is done to determine the effectiveness of this mitigation technique for a typical re-entry spacecraft and the strength of magnetic field required to establish the communication link between the re-entry spacecraft and the ground station is obtained.

1. INTRODUCTION

When a reusable launch vehicle or manned/unmanned space flight re-enters the atmosphere of earth, a layer of plasma is formed around the vehicle, known as plasma sheath. It is a result of shock wave produced due to excessive heating of air surrounding the vehicle. This plasma can interrupt the radio communication between the re-entry vehicle and the ground based stations. This critical period of time when the communication between the re-entry spacecraft and the ground stations is lost is known as Communication Blackout, which can vary from few seconds to several minutes, depending upon various factors, like vehicle configuration, flight velocity, atmospheric density and angle of attack [1]. The loss of communication between the re-entry vehicle and its ground station is critical due to following reasons:

- (i) This period of time may coincide with the vital portion of manoeuvre phase of the re-entry spacecraft.
- (ii) The absence of communications and control during these few critical minutes, when spacecraft encounters the most extreme temperatures and pressures, is highly undesirable.
- (iii) In the event of an accident/failure during re-entry, the data collected during this phase may be invaluable for diagnosing the cause of failure and improving flight safety in future missions.

Hence due to its criticality, it becomes necessary to understand the phenomenon behind communication blackout and the methods for its mitigation. Several works has been done in the direction of understanding the concepts behind the plasma formation and its impact on communication between the re-entry vehicle and ground stations [2, 3]. Simulation models for communication blackout and attenuation of electromagnetic waves have also been proposed [4]. Various methods have been suggested for mitigation of communication blackout during re-entry [5–9] which includes high frequency method, aerodynamic shaping, injection of coolants, use of magnetic field, or combined electric and magnetic field. The high frequency method aims at avoiding the plasma attenuation region by using communication frequencies higher than the plasma frequencies [10]; however the use of higher frequencies is associated

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with higher losses in communication link. The aerodynamic shaping [11] and injection of coolants [12] reduces the concentration of electrons; however the aerodynamic shaping may affect the aerodynamic stability of the vehicle and injection of coolants is associated with complexity in storage and insertion of coolants in proper direction. Recently a new mitigation technique based on matching approach utilizing a double-positive (DPS) material layer surrounding a hypersonic vehicle antenna has been proposed [13].

Application of static magnetic field [14–17], or combined electric and magnetic field [18–20] reduces the interaction of electromagnetic waves with the plasma sheath by altering its properties. Recently, the use of time varying magnetic field for communication blackout mitigation has also been proposed [21]. Some theoretical and very few practical works have been done to analyse the effectiveness of magnetic field method, which seems to be a promising solution for mitigating communication blackout during re-entry.

This paper describes the theory and analysis for plasma formation along with brief introduction of various mitigation techniques for communication blackout. The present work focuses on static magnetic field mitigation method and its impact on communication blackout. The significance of this method is established by quantifying the reduction in plasma attenuation in presence of static magnetic field. An analysis has been done, for a typical re-entry spacecraft having blunt-shaped configuration, to establish communication link between the spacecraft and its ground station.

2. PLASMA SHEATH AND ITS SIGNIFICANCE

During the re-entry of a spacecraft into the earth's atmosphere, it is associated with large amount of energy, due to its position and velocity. This results in the formation of shock-wave around the spacecraft causing heating and compression of the air present in that region. This process results in conversion of spacecraft's kinetic energy into heat energy, which in turn increases the temperature of air surrounding the spacecraft. As a result, the air molecules become dissociated and ionized, which generates non-uniform and non-equilibrium electron-ions profiles, resulting into a layer known as plasma sheath.

Within this layer, the charged particles maintain equilibrium due to their electrostatic fields. However if an electron moves away from its equilibrium position, an electric field is formed causing the electron to be attracted towards the ions. As electron travels towards ions, it moves beyond its equilibrium position, and the electric field pulls it back. As a result the electron starts oscillating in plasma sheath due to the electrostatic force of neighbouring charged particles. This frequency of oscillation is known as *plasma frequency* or *plasma resonant frequency* (ω_p). For the case of electrons, it is termed as *electron plasma frequency* and is given in radians as [1]:

$$\omega_p = \sqrt{\frac{N_e e^2}{\epsilon_0 m_e}} \quad (1)$$

where, ω_p is the plasma frequency, N_e the electron density (per m^3), e the electron charge (C), m_e the mass of an electron (kg), and ϵ_0 the permittivity of free space. Hence the electron plasma frequency depends on the electron density in the plasma sheath. The plasma frequency for ions can also be determined in a similar way, but due to their excessive mass as compared to electrons, the ion plasma frequency is much below the microwave range and hence can be ignored. Referring to the electron oscillations in the plasma sheath, an electron can collide with neutral particles. The frequency of this collision is called as *collision frequency* (ν). It can be determined from the temperature and pressure at a particular point in plasma sheath, using this simplified equation [22]:

$$\nu = \frac{5.814 \times 10^{12} p}{T^{1/2}} \quad (2)$$

where T is the temperature (K) and p is the pressure (atmosphere).

2.1. Interaction of E.M. Wave and Plasma Sheath

When an electromagnetic (e.m.) wave is incident on plasma sheath, the free electrons of plasma are accelerated along the electric field of e.m. wave. The incident electromagnetic wave acts as driving force

on the electrons, which start oscillating, resulting in the formation of forward and backward travelling waves. This phenomenon is responsible for attenuation of e.m. waves inside the plasma sheath. Also, the oscillating electrons interact with neutral molecules through collisions. During elastic collisions between electrons and neutral molecules, the energy transfer takes place from e.m. wave to plasma sheath, resulting into further attenuation of e.m. wave. Depending on the frequency of electromagnetic wave w.r.t. plasma frequency, one of the following conditions arises:

- (i) *Frequency of electromagnetic wave less than the plasma frequency:* If the driving frequency is considerably less than the plasma frequency, and damping due to collision of electrons is small, inertial effects are small and the electron will oscillate at the driving frequency. Hence the electromagnetic wave gets attenuated and cannot propagate through plasma.
- (ii) *Frequency of electromagnetic wave greater than the plasma frequency:* If the frequency of electromagnetic wave is much greater than the plasma frequency, and collision frequency is very small, the electrons possess large inertia and oscillate weakly at driving frequency, resulting in propagation of electromagnetic wave without attenuation. But in presence of collision frequency, attenuation of e.m. wave takes place.
- (iii) *Frequency of electromagnetic wave equal to the plasma frequency:* If the driving frequency is exactly equal to the plasma frequency, and collision frequency is small, the incident electromagnetic wave is totally reflected from the plasma sheath and does not penetrate plasma at all. However, in presence of collision some propagation does take place.

Hence, when an electromagnetic wave is incident upon the plasma sheath, the attenuation and reflection of the electromagnetic wave depend on its frequency relative to the plasma frequency, and the collision frequency can alter this behaviour.

2.2. Attenuation and Phase Coefficients

The behaviour of electromagnetic waves in a plasma sheath depends on the frequency of electromagnetic wave, plasma frequency and collision frequency. This can be determined by a quantitative analysis of the interaction between electromagnetic waves and plasma. The propagation constant (γ_p) for the electromagnetic wave propagating through the plasma sheath can be expressed in terms of attenuation coefficient (α_p) and phase coefficient (β_p) as,

$$\gamma_p = \alpha_p - j\beta_p \quad (3)$$

The attenuation coefficient α_p (Neper/m), and phase coefficient β_p (radian/m) are expressed as:

$$\alpha_p = k_0 \sqrt{\left((K_r^2 + K_i^2)^{1/2} - K_r \right) / 2} \quad (4)$$

$$\beta_p = k_0 \sqrt{\left((K_r^2 + K_i^2)^{1/2} + K_r \right) / 2} \quad (5)$$

$$K_r = 1 - \frac{\omega_p^2}{\omega^2 + \nu^2} \quad (6)$$

$$K_i = \frac{\omega_p^2(\nu/\omega)}{\omega^2 + \nu^2} \quad (7)$$

where, ω_p is the plasma frequency, ω the frequency of operation, $k_o = \omega/c$ the wave number for free space, and c the velocity of light.

For the case of collision less plasma, i.e., $\nu = 0$, the attenuation coefficient α_p reduces to zero and the phase coefficient β_p reduces to

$$\beta_{p(\nu=0)} = k_0 \sqrt{1 - \frac{\omega_p^2}{\omega^2}} \quad (8)$$

Equation (8) shows that when $\omega > \omega_p$, the e.m. wave propagates through the plasma sheath with no attenuation. When $\omega < \omega_p$, the e.m. wave decays exponentially inside the plasma and does not penetrate through the plasma sheath. When $\omega = \omega_p$, the phase coefficient β_p also becomes zero, and the e.m.

wave is totally reflected from the plasma surface. When collisions are present within the plasma sheath, the attenuation coefficient is not zero. Hence the e.m. wave suffers attenuation at all frequencies inside the plasma sheath. Total attenuation and phase shift can be determined by integrating the attenuation coefficient and phase coefficient over the thickness of plasma sheath using (9) and (10), respectively.

$$A_{\text{dB}} = 8.686 \int_0^{\delta} \alpha_p dy \quad (9)$$

$$\theta_{\text{deg}} = \frac{180}{\pi} \int_0^{\delta} \beta_p dy \quad (10)$$

where, A is total attenuation (dB), θ the total phase shift (deg), and δ the thickness of the plasma sheath.

For a typical case of electron density of $4.96 \times 10^{18} \text{ m}^{-3}$ which correspond to plasma frequency of 20 GHz, the attenuation coefficient (dB/m) and the phase coefficient (deg/m) are plotted against the frequency of operation, for various values of normalized collision frequency ν/ω_p and shown in Fig. 1 and Fig. 2 respectively. The results show that the behaviour of plasma sheath to incident electromagnetic wave is analogous to a high pass filter for RF waves, with plasma resonant frequency equivalent to the cut-off frequency of filter. This means that collision less plasma cannot support wave propagation at frequencies below ω_p . Thus two specific regions are seen in Fig. 1.

- (i) $\omega < \omega_p$: This region is analogous to the stop band of a high pass filter. The attenuation is very high for lossless plasma and communication is not possible in this region. Even if collision is present and collision frequency is less than plasma frequency, communication is difficult. However, when the collision frequency is comparable to plasma frequency, attenuation decreases at the very low frequencies.
- (ii) $\omega > \omega_p$: This region depicts the pass band of a high pass filter. The attenuation value gradually decreases in this region, and is very less for frequencies sufficiently higher than the plasma frequency. However, an increase in collision frequency increases the attenuation in this region.

Thus, increase in collision frequency w.r.t. plasma frequency is favourable in region $\omega < \omega_p$, where as it is unfavourable in region $\omega > \omega_p$ for communication link to be established. Fig. 2 shows the graph for phase shift of electromagnetic wave. As the collision frequency increases, the phase shift decreases in region $\omega < \omega_p$. However in region $\omega > \omega_p$, the phase shift changes linearly with frequency of operation and does not change with variation of collision frequency.

This behaviour is in accordance with the theory described in Section 2.1, which states that as long as frequency of electromagnetic wave is higher than the plasma frequency, with very small collision frequency, the communication link can be established through plasma sheath. However, for the case of electromagnetic wave frequency lesser than plasma frequency, it is difficult to establish a communication link and communication black-out occurs. Hence, a mitigation method is required for propagation of electromagnetic wave in this region.

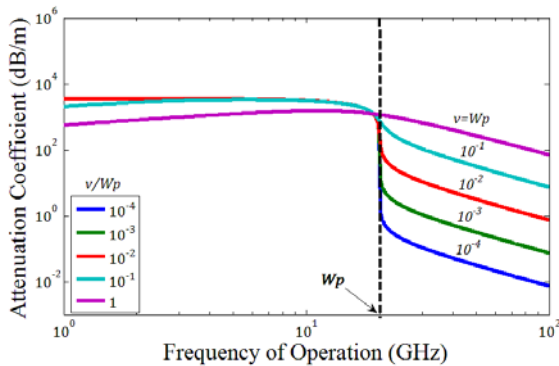


Figure 1. Attenuation coefficient vs frequency of operation.

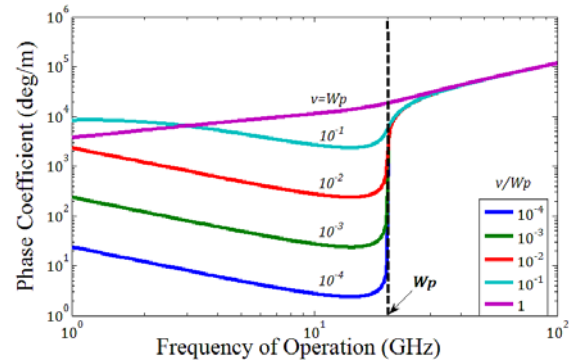


Figure 2. Phase coefficient vs frequency of operation.

3. MITIGATION TECHNIQUES

The communication blackout during re-entry of a spacecraft can be alleviated in various ways as suggested by [1, 5–7]. Some of these methods along with their merits and demerits are discussed below:

- (i) By avoiding attenuation region in plasma sheath: Higher Frequency method.
- (ii) By reducing concentration of electrons in plasma sheath: Aerodynamic shaping, Injection of coolants.
- (iii) By altering the properties of plasma to minimize its interaction with the e.m. waves: Magnetic Field Method.

Higher Frequency method: The attenuation due to the plasma sheath is very less for the frequencies higher than the plasma frequency and hence high frequency operation can be used for mitigation of communication blackout during re-entry. However, there are certain disadvantages of using this method. For typical re-entry missions, the plasma frequency is very high, of the range of Ku-band or higher bands; depending on re-entry parameters. The beam-width at these frequencies is very narrow; hence the communication system requires tracking terminals on-board spacecraft as well as on ground. Moreover, the attitude of spacecraft is usually varying during the re-entry; hence it may be difficult to align the spacecraft antenna towards the ground station. Alternatively there may be requirement of large number of on-board antennas as well as large number of ground stations to maintain the communication link. Higher atmospheric attenuation at these frequencies further complicates the problem. Hence, it is advantageous to operate at lower frequency bands like S-band, where nearly omni-antennas can be used on-board spacecraft and a communication link can be easily established.

Aerodynamic Shaping: The concentration of electrons in the plasma sheath can be reduced by aerodynamic shaping of the re-entry spacecraft. Its basic principle is to modify the vehicle shape to change the flow field, which reduces the thickness of the plasma sheath in the vicinity of the antenna or reduces the electron density in the plasma sheath, or both. However, the inherent problem of this method is to maintain aerodynamic stability of the vehicle during re-entry.

Injection of coolants: The concentration of electrons can also be reduced by injection of coolants. The basic principle behind this technique is that if sufficient coolant (like hydrogen, water, helium, propane) is injected into the shock layer and if the resulting mixture is brought to thermodynamic equilibrium, the resulting electron density would be low enough that communication would be possible. However, it increases the complexity of system to high extent since the coolants need to be stored on-board and injected in proper direction.

Magnetic Field method: The properties of plasma sheath can be altered in a way so that its interaction with the electromagnetic waves can be minimized. This can be done using static magnetic field in a direction perpendicular to the incident e.m. waves. By applying suitable magnetic field strength it is possible to establish communication link at lower frequency bands.

Considering the pros and cons of various mitigation methods, the magnetic field method is chosen for detailed analysis.

3.1. Magnetic Field Method

In the magnetic field method, a suitable static magnetic field is applied in the direction of propagation of electromagnetic waves. This alters the properties of plasma in a way to minimize the interaction of electromagnetic waves with the plasma sheath. When sufficiently strong magnetic fields are applied, the signal attenuation can be reduced to negligible levels.

3.1.1. Interaction of E.M. Wave and Plasma in Presence of Magnetic Field

When a d.c. magnetic field is applied in the direction of signal propagation, it alters the motion of electrons in a plane perpendicular to the applied magnetic field and the electrons start rotating in a circular pattern. This reduces the ability of the free electrons to interact with the electric field associated with the incident e.m. wave and in this way the attenuation due to plasma reduces [15]. The frequency

of this circular motion of electrons is known as *gyro-frequency or cyclotron frequency* (ω_c). The cyclotron frequency increases directly with the strength of magnetic field and is given by

$$\omega_c = \frac{-eB_0}{m} \quad (11)$$

where B_0 is the magnetic field strength (T), e the charge of electron (C), and m the mass of electron (kg). The radius of the circle electrons exhibit is known as *gyro-radius or cyclotron radius*. It is inversely proportional to the strength of magnetic field and is given by

$$r_c = \frac{mv_e}{eB_0} \quad (12)$$

where v_e is the velocity perpendicular to the direction of magnetic field.

In the absence of magnetic field, no propagation is possible at frequencies below the plasma resonant frequency. As the magnetic field increases, the cyclotron frequency increases and the radius of circular motion of electron decreases. When B_0 is infinite, the cyclotron frequency becomes infinite and gyro-radius becomes zero. In such a case, the electron is fixed in the transverse plane which means there is no movement of electron in the plane perpendicular to the magnetic field. Thus, no interaction takes place between the incident e.m. wave and plasma electrons and hence the electromagnetic wave is propagated through the plasma sheath. When a linearly polarized wave is incident on the air-plasma interface in the presence of magnetic field, it generates two circular modes of propagation due to circular motion of electrons in the plane transverse to the magnetic field. The modes generated are Right handed circularly polarized (RHCP) and Left handed circularly polarized (LHCP). However, if a circularly polarized wave is incident on the air-plasma interface, the transmitted wave is also circularly polarized and has same sense of polarization (LHCP/RHCP) as the incident wave. In this case, only one mode of propagation is generated inside the magneto-active plasma sheath due to which, the relative power of transmitted wave will be 3 dB higher than the case of linearly polarized wave.

The properties of electromagnetic plasma can be expressed in terms of three basic parameters: electron-plasma resonant frequency (ω_p), electron collision frequency (ν) and cyclotron frequency (ω_c). The propagation constant for RHCP and LHCP modes inside the magneto-active plasma is given by [17]:

$$\gamma_{\text{LHCP}} = \alpha_{\text{LHCP}} + j\beta_{\text{LHCP}} \quad (13)$$

$$\gamma_{\text{RHCP}} = \alpha_{\text{RHCP}} + j\beta_{\text{RHCP}} \quad (14)$$

where,

$$\alpha_{\text{LHCP}} = k_0 \sqrt{\frac{(K_1^2 + K_2^2)^{1/2} - K_1}{2}} \quad (15)$$

$$\beta_{\text{LHCP}} = k_0 \sqrt{\frac{(K_1^2 + K_2^2)^{1/2} + K_1}{2}} \quad (16)$$

$$\alpha_{\text{RHCP}} = k_0 \sqrt{\frac{(K_3^2 + K_4^2)^{1/2} - K_3}{2}} \quad (17)$$

$$\beta_{\text{RHCP}} = k_0 \sqrt{\frac{(K_3^2 + K_4^2)^{1/2} + K_3}{2}} \quad (18)$$

$$K_1 = \frac{1 - [(\omega_p/\omega)^2(1 - (\omega_c/\omega)^2 + (\nu/\omega_p)^2)] - [2(\omega_p/\omega)^2(\omega_c/\omega)(\nu/\omega_p)]}{[1 - (\omega_c/\omega)^2 - (\nu/\omega_p)^2]^2 + 4(\nu/\omega_p)^2} \quad (19)$$

$$K_2 = \frac{[(\omega_p/\omega)^2(\omega_c/\omega)(1 - (\omega_c/\omega)^2 - (\nu/\omega_p)^2)] - [(\nu/\omega_p)(\omega_p/\omega)^2(1 + (\omega_c/\omega)^2 + (\nu/\omega_p)^2)]}{[1 - (\omega_c/\omega)^2 - (\nu/\omega_p)^2]^2 + 4(\nu/\omega_p)^2} \quad (20)$$

$$K_3 = \frac{1 - \left[(\omega_p/\omega)^2 (1 - (\omega_c/\omega)^2 + (\nu/\omega_p)^2) \right] + \left[2(\omega_p/\omega)^2 (\omega_c/\omega) (\nu/\omega_p) \right]}{\left[1 - (\omega_c/\omega)^2 - (\nu/\omega_p)^2 \right]^2 + 4(\nu/\omega_p)^2} \quad (21)$$

$$K_4 = \frac{- \left[(\omega_p/\omega)^2 (\omega_c/\omega) (1 - (\omega_c/\omega)^2 - (\nu/\omega_p)^2) \right] - \left[(\nu/\omega_p) (\omega_p/\omega)^2 (1 + (\omega_c/\omega)^2 + (\nu/\omega_p)^2) \right]}{\left[1 - (\omega_c/\omega)^2 - (\nu/\omega_p)^2 \right]^2 + 4(\nu/\omega_p)^2} \quad (22)$$

where ω is the frequency of operation ($2\pi f$), k_0 the the wave number, given by $k_0 = \omega/c$, and c the velocity of light. The behaviour of E.M. waves in plasma sheath in presence of static magnetic field can be determined using (13) to (22). Considering plasma resonant frequency of 20 GHz corresponding to electron density of $4.96 \times 10^{18} \text{ m}^{-3}$, the attenuation coefficient in presence of magnetic field is plotted for various values of normalized collision frequency. The magnetic field strength is varied from 0.01 T to 5 T. The graphs of Fig. 3 give the value of attenuation coefficient per meter for LHCP mode of propagation. Total attenuation can be calculated by integrating it over the sheath thickness using (9).

Figures 3(a) to 3(d) show the plots of attenuation coefficient vs normalized collision frequency for various frequencies of operation. The peaks and valleys observed in the plots are corresponding to the cyclotron frequency (ω_c), which in turn depend on magnetic field strength. When the collision frequency is negligible as compared to plasma frequency, as shown in Figs. 3(a) and 3(b), it is observed that with the increase in the strength of magnetic field, the plasma attenuation decreases in the region $\omega < \omega_p$. However, this decrease in plasma attenuation is seen for $\omega < \omega_c$ (i.e., to the left of cyclotron peak). Hence a window is created on frequency axis which passes the e.m. waves through magnetized plasma. The location of this window is independent of the plasma resonant frequency and depends

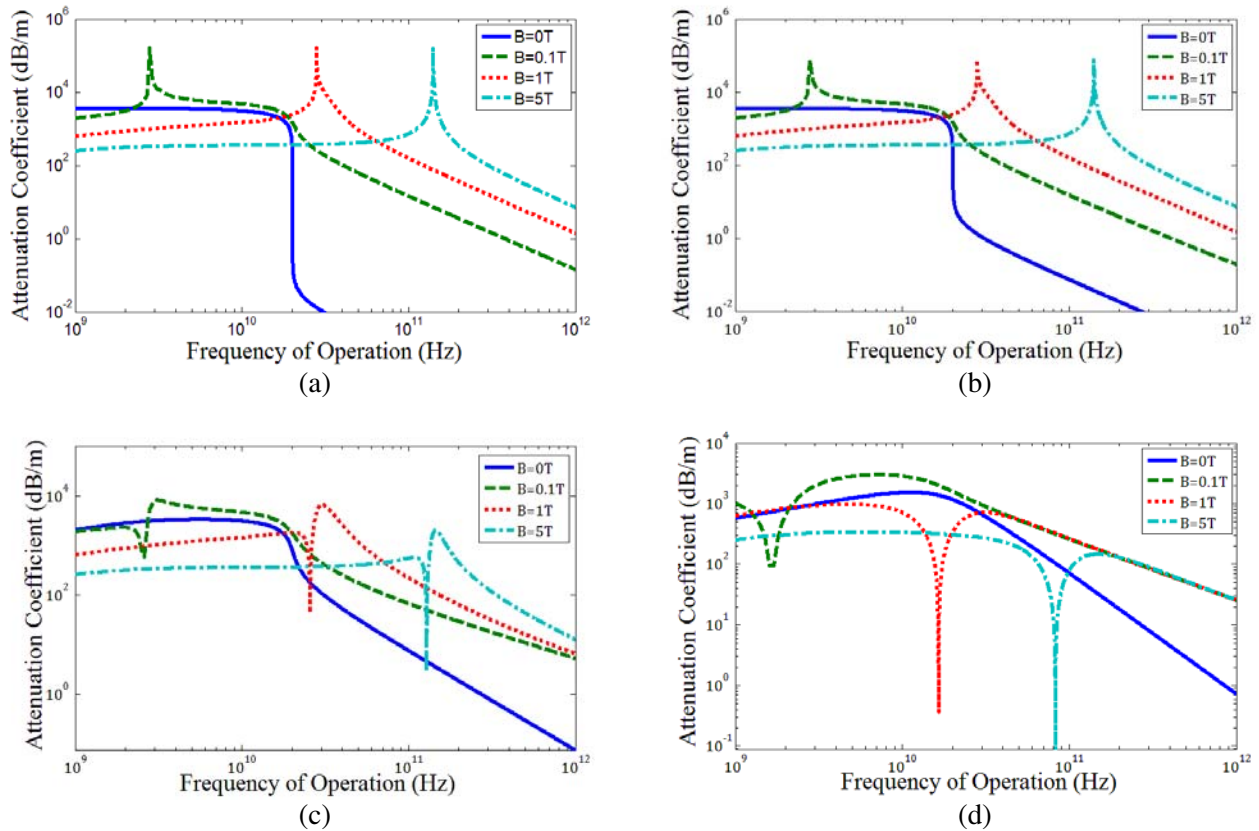


Figure 3. Plasma attenuation coefficient in presence of magnetic field. (a) $\nu/\omega_p = 10^{-5}$, (b) $\nu/\omega_p = 10^{-3}$, (c) $\nu/\omega_p = 10^{-1}$, (d) $\nu/\omega_p = 1$.

only on cyclotron frequency which in turn depends on magnetic field strength. The e.m. waves having frequencies corresponding to this window on frequency axis can pass through magnetized plasma with lesser attenuation. When collision frequency is comparable to plasma resonant frequency, as shown in Figs. 3(c) and 3(d), higher magnetic field strength is required to reduce the plasma attenuation. For mitigation of communication blackout using this method, it is important to derive the minimum magnetic field required for plasma attenuation.

3.1.2. Minimum Magnetic Field Required

The location of magnetic window on frequency axis is dependent on the cyclotron frequency, as discussed in Section 3.1.1. The minimum strength of magnetic field required to reduce the plasma attenuation for a given frequency of operation is derived using (11) and can be written as:

$$B_{\min} = 0.0357f \quad (23)$$

where B_{\min} is the minimum Magnetic Field (T) and f the frequency of operation (GHz). In Fig. 4, the minimum magnetic field strength is plotted over the frequency of operation. For magnetic field method to be effective, the magnetic field strength B_0 should be greater than B_{\min} as depicted by *region of operation*. Table 1 shows the value of B_{\min} for typical communication frequency bands. The magnetic field strength shown in the table is the minimum values for static magnetic field method to be effective. However the actual magnetic field strength required for mitigation of plasma attenuation in practical cases depends on the required reduction in attenuation and the available system margin in the communication link.

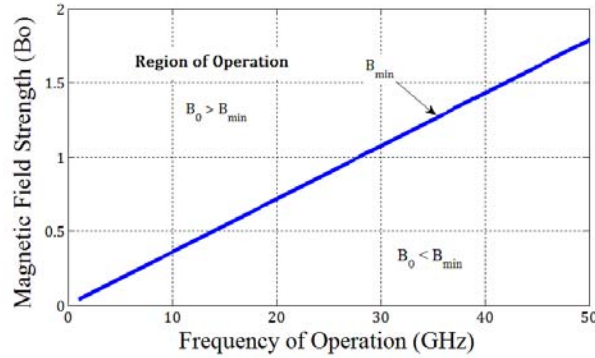


Figure 4. Minimum magnetic field strength for various frequencies of operation.

Table 1. Minimum field strength for typical communication frequencies.

Frequency of operation, f (GHz)	Minimum magnetic Field Strength, B_{\min} (T)
2 (S-Band)	0.1
6 (C-Band)	0.2
10 (Ku-Band)	0.4
20 (K-Band)	0.7
30 (Ka-Band)	1.0

3.1.3. Reduction in Plasma Attenuation due to Magnetic Field

The reduction in plasma attenuation due to static magnetic field as compared to plasma attenuation without magnetic field, for collision less plasma, is derived using (4) to (7) and (15) to (22) and given in Fig. 5. It is observed that with the increase in the strength of magnetic field, the reduction in plasma

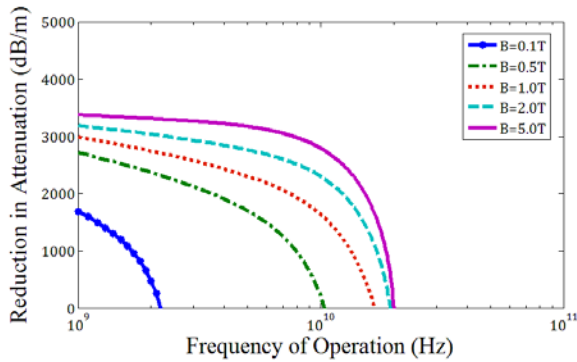


Figure 5. Reduction in plasma attenuation for various magnetic field strengths (*in absence of collision frequency*).

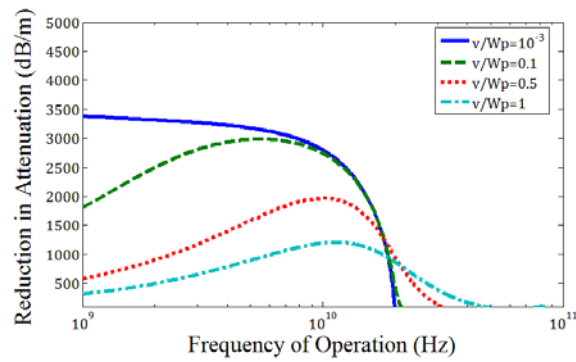


Figure 6. Reduction in plasma attenuation for various normalized collision frequencies (*magnetic field strength=5 T*).

attenuation increases. Hence depending upon the absolute plasma attenuation in absence of magnetic field and the system margin available in the communication link, the strength of magnetic field is chosen for mitigation of communication blackout.

However, in presence of electron collision, the reduction in plasma attenuation due to static magnetic field also depends on collision frequency in addition to the magnetic field strength. Fig. 6 shows the reduction in plasma attenuation for various normalized collision frequencies, with static magnetic field strength of 5 T. It can be seen that for smaller values of ν/ω_p , significant reduction in plasma attenuation is seen. However, for collision frequency comparable to plasma frequency, higher magnetic field strength is required to overcome plasma attenuation.

In order to establish the effectiveness of static magnetic field method for mitigation of communication blackout, an analysis is done for a typical re-entry spacecraft.

4. ANALYSIS OF COMMUNICATION BLACKOUT IN A RE-ENTRY SPACECRAFT

An analysis for the attenuation due to plasma formation between a re-entry Spacecraft and a ground station is performed and the impact of static magnetic field for the mitigation of communication blackout is established. A typical re-entry spacecraft having blunt-shaped configuration has been considered as shown in Fig. 7. The re-entry parameters in terms of electron density, temperature and pressure as a function of altitude are shown in Fig. 8. Following are the assumptions for analysis:

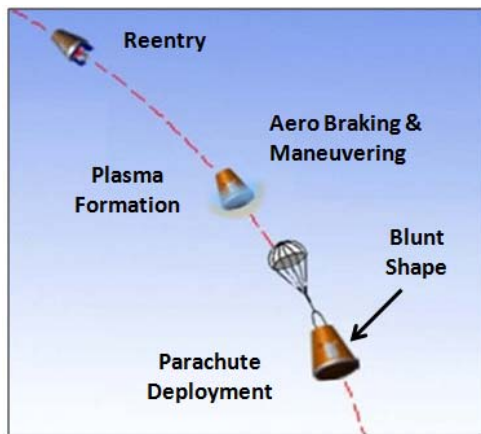


Figure 7. Blunt-shaped spacecraft re-entry.

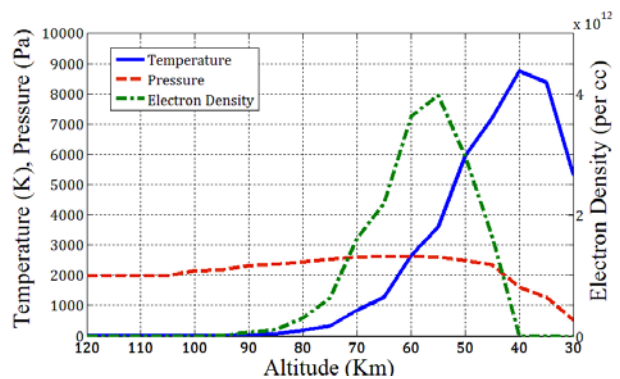


Figure 8. Spacecraft re-entry profile.

- a Communication Link Frequency is 2.2 GHz (S-band).
- b Uniform Plasma Sheath Thickness of 0.5 inches.
- c System margin for attenuation due to plasma in the communication link is 5 dB (i.e., plasma attenuation upto this limit is acceptable).

The plasma attenuation and the strength of magnetic field required for establishing the communication link through plasma sheath during re-entry of spacecraft is obtained in the following way:

- i For the spacecraft having re-entry profile as given in Fig. 8, the plasma frequency profile and collision frequency profile are derived using (1) and (2).
- ii Then the plasma attenuation coefficient is calculated along the re-entry path using (4), (6) and (7).
- iii Using (9), total attenuation in absence of magnetic field is calculated for the uniform plasma sheath thickness, along the re-entry path.
- iv The impact of static magnetic field strength on the plasma attenuation along the re-entry path is calculated using (15) to (22).

The results are shown in Figs. 9 to 11. Fig. 9 shows the derived plasma frequency profile and the collision frequency profile for the considered spacecraft. The attenuation coefficient and hence total attenuation is calculated at various altitudes along the flight path and shown in Fig. 10. Fig. 11 shows the total attenuation profile, in the presence of magnetic field.

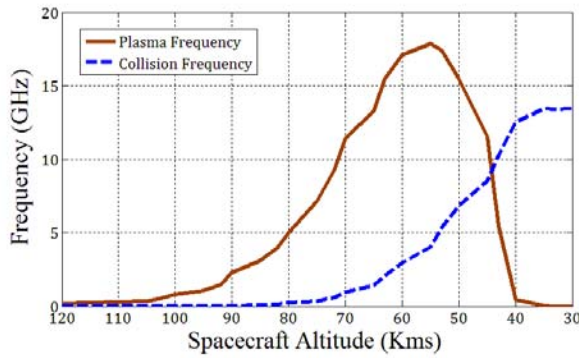


Figure 9. Plasma frequency and collision frequency profiles.

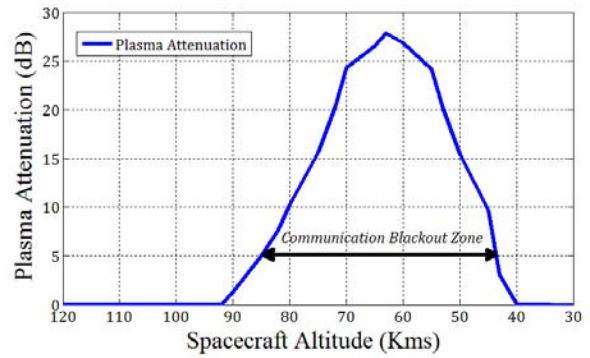


Figure 10. Plasma attenuation along the re-entry path (*no magnetic field*).

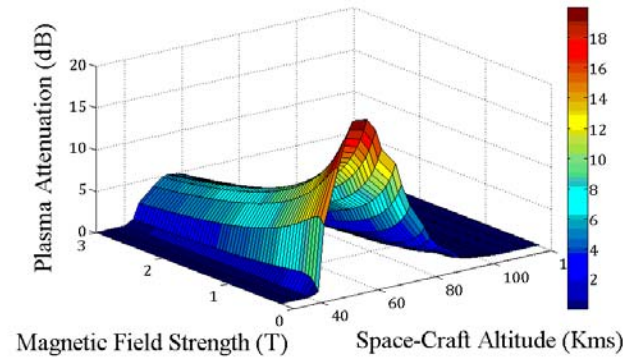


Figure 11. Plasma attenuation profile with magnetic field strength along the re-entry path.

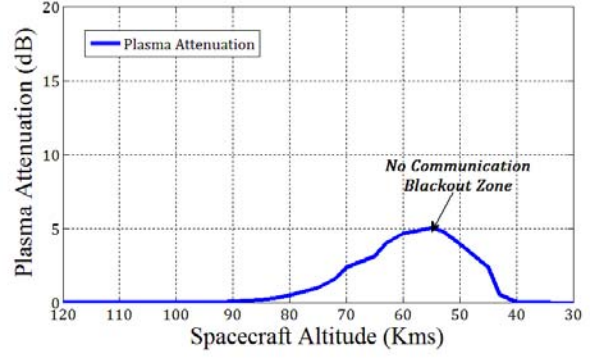


Figure 12. Plasma attenuation along the re-entry path (*magnetic field=3 T*).

5. RESULTS AND DISCUSSION

The analysis results show maximum plasma frequency of 18 GHz, which is very high as compared to the communication link frequency in S-band. For operating frequency of 2.2 GHz, the maximum attenuation, in absence of any mitigation method, is 28 dB. Since the system margin allowed for attenuation due to plasma is only 5 dB, it shows that in the absence of any suitable mitigation technique, it is not possible to establish any communication between the altitudes 85 kms to 45 kms, referred as *Communication Blackout Zone*.

The static magnetic field method is considered for mitigation of plasma attenuation. The strength of magnetic field is increased from 0.1 T (B_{\min}) until the plasma attenuation reduces to allowable limits defined by system margin. It is seen that when magnetic field strength is low, the maximum plasma attenuation is very high and Communication black-out zone exists. However, as the magnetic field strength increases, the attenuation due to plasma decreases. With the magnetic field strength of 3 T, the maximum attenuation is reduced to 5 dB and hence the communication Black-out zone diminishes, as shown in Fig. 12. Therefore, by using static magnetic field method, the communication link is established throughout the re-entry path. By using advanced technologies like carbon nano-tubes, and superconductors supporting higher current densities for space based magnets, the mass required to generate the required magnetic field is < 10 kg [23].

6. CONCLUSION

The phenomenon of the communication black-out due to plasma formation is discussed in detail, and the significance of static magnetic field method for the mitigation of communication blackout has been established. The analysis for communication blackout in a typical re-entry spacecraft proves that the application of static magnetic field significantly reduces the attenuation due to plasma formation and mitigates the communication blackout zone. Hence the communication link is established between the re-entry spacecraft and the ground station.

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