http://www.doi.org/10.62341/istj-vol39-1-mm02

Received	**2026/06/10**	**تم استلام الورقة العلمية في**
Accepted	**2026/07/04**	**تم قبول الورقة العلمية في**
Published	**2026/07/06**	**تم نشر الورقة العلمية في**

High-Frequency Electromagnetic Window for Mitigating Blackout-Induced by Plasma During Communication with Spacecraft (Re-Entry)

Majdi Khalfalla [1*], Marai Abousetta [2]

1-Faculty of natural resources engineering - Bir Elghanam

University of Zawia -Libya

[1]https://orcid.org/0009-0008-9516-0950

2-Libyan Academy for Postgraduate Studies -Tripoli, Libya

*majdi.khalfalla@zu.edu.ly

Abstract

In space missions, when spacecraft travels back to Earth with hypersonic speed, it suffers loss of communications with the ground station, which is called communication blackout, due to the friction between its surface and the surrounding air forming the plasma sheath. This blackout blocks vehicle communications up to 10 minutes depending on the angle of re-entry, shape of vehicle and the atmosphere's properties. This blackout results in loss of control and guidance from the ground station, which is critical for crew safety and the vehicle. In this paper, we used the Drude model to calculate the complex relative permittivity of the plasma sheath, and developed a MATLAB simulation to compute the attenuation coefficient of electromagnetic waves ranging from 1 GHz to 300 GHz, using electron density data derived from NASA's RAM-C flight experiments under different plasma conditions to representing various re-entry phases. The results shows that the attenuation at its peak at S-band, and then drops sharply beyond plasma frequency forming a clear high-frequency window. The same drop with Ka, EHF bands. These findings demonstrate that Ka- band and EHF

http://www.doi.org/10.62341/istj-vol39-1-mm02

frequencies represent effective solution to maintain the communications between the spacecraft and ground station during re-entry, offering lower signal attenuation comparing to S and Ku bands.

Keywords: Plasma sheath; Communication blackout; Ka-band; Re-entry; Attenuation coefficient.

نافذة كهرومغناطيسية عالية التردد للتخفيف من انقطاع الاتصال الناجم عن البلازما أثناء الاتصال بالمركبة الفضائية (إعادة الدخول)

مجدي خلف الله[1]، مرعي ابوستة[2]

1- كلية هندسة الموارد الطبيعية – بئرالغنم – جامعة الزاوية – ليبيا

2- الاكاديمية الليبية ، طرابلس، ليبيا

majdi.khalfalla@zu.edu.ly

الملخص

في رحلات الفضاء الاستكشافية وأثناء عودة المركبة لسطح الارض وقبل دخولها الغلاف الجوي بسرعات تفوق سرعة الصوت تتعرض المركبة لانقطاع الاتصال بينها وبين مركز التحكم على الارض وذلك بسبب احتكاك الهواء مع سطح المركبة الفضائية ويصل الانقطاع احيانا الى 10 دقائق ويعتمد على زاوية دخول وشكل المركبة وخواص الطبقة الجوية.

هذا الانقطاع يؤدي الى قطع الاتصال وفقد اشارات التحكم والتوجيه التي يرسلها مركز التحكم الموجود على الارض، وهذا يعتبر فترة حرجة وخطرة على المركبة وطاقمها. في هذه الورقة يتم استعمال نموذج Drude لحساب السماحية الكهربائية النسبية المعقدة لغلاف البلازما وتطوير نموذج محاكاة باستخدام برنامج ماتلاب لحساب معامل التوهين للموجات الكهرومغناطيسية بنطاق من 1 الى 300 جيجا هرتز باستخدام بيانات كثافة الإلكترونات الناتجة من تجارب الرحلة RAM-C التابعة لـ NASA في ظروف بلازما مختلفة تمثل مراحل متعددة من إعادة الدخول.

http://www.doi.org/10.62341/istj-vol39-1-mm02

أظهرت النتائج أن التوهين يبلغ ذروته عند نطاق S–band، ثم ينخفض بحدة بعد تجاوز تردد البلازما مُشكِّلاً نافذة ترددية واضحة عند الترددات العالية. وتُثبت هذه النتائج أن نطاقَي Ka–band و EHF يمثلان حلاً فعّالاً للحفاظ على الاتصال بين المركبة الفضائية ومحطة الأرض خلال مرحلة إعادة الدخول، إذ يوفران توهينا أقل بكثير مقارنة بنطاقَي S–band و Ku–band.

الكلمات المفتاحية: غلاف البلازما؛ انقطاع الاتصالات؛ نطاق S-band؛ إعادة الدخول؛ معامل التوهين.

1. Introduction

Spacecraft during re-entry and when they are at the Earth's atmosphere at hypersonic speed, they experience a sever aerodynamic heat which causes the air in front of the vehicle becomes highly compressed and forming a shock wave. As a result, and with extensive heat, these shock waves ionize the gas, creating plasma sheath in front of the vehicle surface[1,2] .

Plasma around the vehicle blocks communications with the ground station and make it impossible and difficult to track the vehicle's position which is significantly increase the uncertainty to predict the landing site of the vehicle. In addition, flight data such as voice communications, telemetry, and global positioning system (GPS) may be lost, or severely attenuated which putting the safety of the crew and the vehicle at risk [3] .

Many approaches have been presented in order to solve the problem of blackout, such as, aerodynamic modification, quenchant injection, magnetic window, and magnetic field control, etc.; however, the true breakthrough technique has not been achieved. Most of these methods introduce significant mechanical complexity, additional weight, or require technologies that are not yet available for operational use[1].

One of the main reasons for communication blackout is that the electromagnetic wave (EMW) frequency, fEM is below the plasma frequency, fp. According to NASA's Radio Attenuation

http://www.doi.org/10.62341/istj-vol39-1-mm02

Measurement C(RAM-C) flight data, the peak electron density number in plasma layer ranges from 1014 to 1018 m-3 and the corresponding plasma frequency is 0.08985 GHz to 8.985 GHz respectively depending on the altitude of the vehicle and measurement method[4] .

Therefore, electromagnetic waves with frequencies above fp, particularly Ka-band (35 GHz) and EHF (100 GHz), are able to propagate directly through the ionized layers of plasma and make the communication possible even in presence of plasma .

In this paper we investigate the attenuation of electromagnetic waves through the plasma sheath over a range of frequencies of 1 GHz up to 300 GHz using MATLAB- based simulation with Drude model. The simulation data used is taken from NASA's RAM-C experiments and aims to identify the high-frequency electromagnetic window and evaluate the performance of Ka-band and EHF frequencies as a practical solution for re-entry vehicle's communications.

2. Literature review

Several studies have investigated electromagnetic wave propagation through re-entry plasma sheaths and proposed mitigation strategies for communication blackout. Zheng et al. [1] analyzed the effect of plasma on electromagnetic wave propagation and demonstrated that THz-range frequencies can traverse ionized re-entry layers with reduced attenuation, supporting the use of high-frequency bands as a viable blackout mitigation approach. Kundraput et al. [2] modeled electromagnetic wave propagation through the plasma layer surrounding a re-entry vehicle and showed that plasma density profiles significantly influence wave cutoff behavior, reinforcing the importance of frequency selection relative to local plasma frequency.

Webb and Ziolkowski [3] proposed a metamaterial-inspired approach to mitigate radio frequency blackout around re-entry vehicles, demonstrating that engineered material layers can alter the effective permittivity of the plasma sheath environment. Kim [4]

http://www.doi.org/10.62341/istj-vol39-1-mm02

provided a comprehensive theoretical framework linking electron density, plasma frequency, and wave attenuation through electromagnetic manipulation of the plasma layer, which serves as a foundational basis for the Drude-model approach adopted in the present work. Boyd [5] and Scalabrin [6] contributed high-fidelity computational models of plasma formation in hypersonic re-entry flows, providing validated electron density profiles that underpin the RAM-C-based simulation parameters used in this study. The present work extends these contributions by performing a systematic frequency sweep from 1 GHz to 300 GHz across multiple plasma density regimes representative of distinct re-entry phases, and by quantitatively evaluating Ka-band and EHF as practical communication windows.[7]

3. Plasm4.a sheath model

Plasma is considered the fourth state of matter and is formed when a gas is supplied with enormous energy that causes its atoms to ionize, that is, to remove electrons from their atomic orbits. This happen when extensive heat is applied, like in stars where heat could reach thousands or even millions of degrees. Moreover, plasma can be formed in lab by applying a strong electric or magnetic field to a gas, as in neon lamps or inside fusion reactors.[7]

Plasma has direct influence on electromagnetic waves travelling in space. When the plasma frequency f_p becomes higher than the electromagnetic wave frequency f_{EM}, the Electromagnetic wave (EM) signal suffers severe signal attenuation which leads to loss of communications between vehicle and ground station. Therefore, to transmit EM wave in the plasma, the plasma frequency f_p should be less than the electromagnetic wave frequency f_{EM} used in the communication.

The plasma frequency fp is a principal characteristic of plasma, which can be defined as the cutoff frequency below which EM waves cannot propagate, is given by: [8]

$$f_P = \frac{\omega_e}{2\pi}$$

http://www.doi.org/10.62341/istj-vol39-1-mm02

$$= \frac{1}{2\pi}\sqrt{\frac{e^2\, n_e}{\epsilon_0 m_e}}$$

$$= 8.985 \times n_e^{1/2} \;\; Hz \qquad (1)$$

Where n_e is electron number density in m^{-3}, m_e is electron mass, 9.1×10^{-31}kg, ϵ_0 is permittivity of free space, 8.85×10^{-12} F/m^2 and e is electron charge, 1.6×10^{-19}C.
To model the interaction between EM waves and the plasma sheath, the Drude model is used to calculate complex relative permittivity of the plasma. The complex relative permittivity ϵ_r is expressed as: [9]

$$\epsilon_r = 1 - \frac{\omega_p^2}{\omega^2 + \nu^2} - j\,\frac{\nu\,.\,\omega_p^2}{\omega\,(\omega^2 + \nu^2\,)} \qquad (2)$$

Where $\omega_p$is the plasma angular frequency, ω is the EM wave angular frequency, and ν is the electron collision frequency (Hz).
The electron collision frequency is the number of collisions per second that the electrons encounter with other species in the plasma.[10]
The attenuation coefficient α, which represents how rapidly the EM wave loses its power as it propagates through the plasma, is derived from the imaginary part of the complex wave vector and expressed as:[11]

$$\alpha = \frac{\omega}{c}\,.\left|Im\,\sqrt{\epsilon_r}\right| \qquad (Neper/m) \qquad (3)$$

Where c is the speed of light and $Im\,\sqrt{\epsilon_r}$ is the imaginary part of the square root of the complex permittivity.
The attenuation in dB/m is then obtained by: [12]

$$\alpha_{dB} = 20\,\log_{10}(e) \times \alpha \quad (dB/m) \qquad (4)$$

http://www.doi.org/10.62341/istj-vol39-1-mm02

4. Simulation Methodology

In this work, a MATLAB simulation was developed to calculate the attenuation coefficient of EM waves that propagate through the re-entry plasma sheath. The electron density data used in the simulation are based on NASA's RAM-C (Radio Attenuation Measurement C) flight experiments that were conducted in the early 1970s. RAM-C still the most comprehensive publicly available dataset for re-entry plasma electron density measurements at multiple altitudes during hypersonic flight. Although conducted in the early 1970s, no equivalent publicly accessible flight measurement campaign of comparable scope has been published since, and RAM-C data continue to serve as the standard validation benchmark in re-entry plasma research . The simulation sweeps frequencies from 1 GHz to 300 GHz for three electron density values, Table 1.

Table 1. Simulation parameters for different re-entry phases. [12]

Plasma density (m^{-3})	Re-Entry Phase	Plasma Frequency (GHz)
10^{16}	Low density — High Altitude	0.90
10^{17}	Medium density — Mid Phase	2.84
10^{18}	High density — Peak Heating	9.00

The simulation here covers range of altitudes approximately from 20 km to 80 km, which represents the critical re-entry phase where plasma density is at its peak and communication blackout is nearly severe. The shock wave around the vehicle prevents the communication. The electron collision frequency was set to $v = 10^{10}$ Hz, and it represents a peak of re-entry conditions.

5. Results and discussion

The simulation results of EM wave attenuation through the re-entry plasma sheath across different frequency bands and electron density conditions are presented in this section.

In figure 1, the blue line represents frequency of electromagnetic wave, f_{EM}, less than frequency of plasma, f_p, (red dashed line) it is

http://www.doi.org/10.62341/istj-vol39-1-mm02

clear that the attenuation here is flat and at its peak where can reach about 1320 dB/m. At this point, plasma sheath acts as a high-pass filter reflecting most of the incident energy causing communication blackout observed in S-band and Ku-band frequencies. However, increasing f_{EM} higher than f_p, the attenuation gradually and becomes significantly lower for frequencies above 100 GHz, forming a clear low-attenuation window suitable for communication.

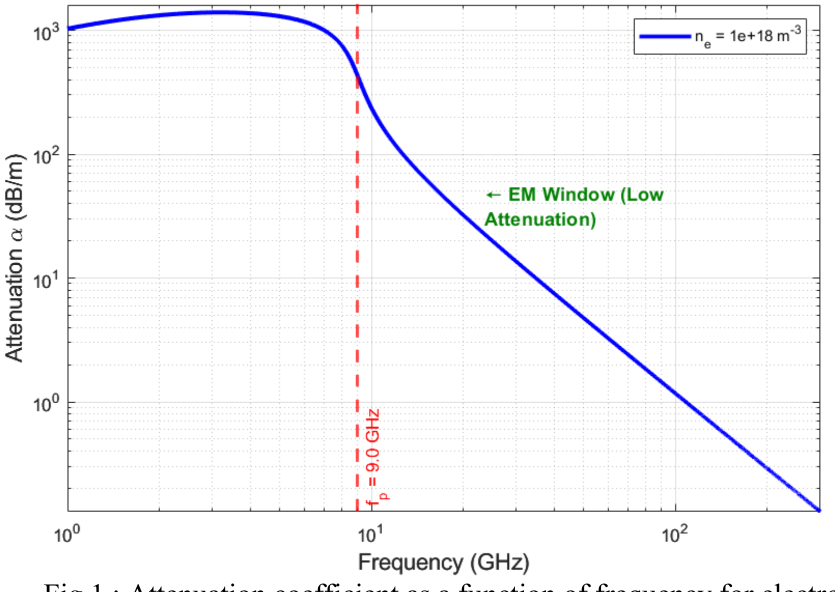

Fig.1 : Attenuation coefficient as a function of frequency for electron density $n_e = 10^{18}$ m^{-3}

In figure 2, the attenuation against different plasma densities was plotted. Low, medium and high electron densities were represented by green, dashed and red lines respectively to simulate different altitudes ranging from 20 – 80 km above earth's surface. It can be seen that at high electron density, the attenuation is well above 1000 dB/m, medium and low electron densities have less attenuation. The graph clearly demonstrates the proportional relationship where higher electron density (peak heating) results in significant increase in attenuation constant α. A critical transition of the graph can be

http://www.doi.org/10.62341/istj-vol39-1-mm02

seen at plasma frequency (fb ≈ 9 GHz). In the other hand, when operating frequency goes beyond plasma frequency and for all density levels, the attenuation drops sharply. This clearly indicates why moving towards high frequencies.

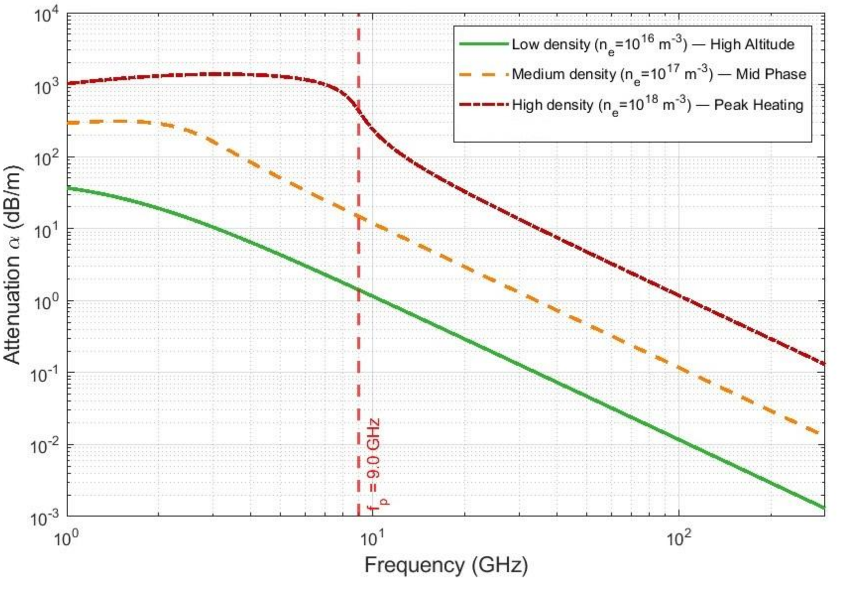

Fig. 2: Attenuation coefficient as a function of frequency for different electron density levels

Finally, figure 3 shows the relationship between the altitude of the vehicle and the minimum required frequency to penetrate through plasma sheath. The graph shows that as the vehicle descends from 80 km to 20 km, the required frequency increases as a result of rising of electron density at lower altitudes caused by aerodynamic heating. For S-band blackout can occurs at altitude below 42 km where plasma frequency exceeds electromagnetic frequency. However, higher bands like Ku-band can offer better performance at altitudes from 20 - 30 km. Ka-band is on the right of the graph which means that this frequency can penetrate plasma at all altitudes without any blackout.

http://www.doi.org/10.62341/istj-vol39-1-mm02

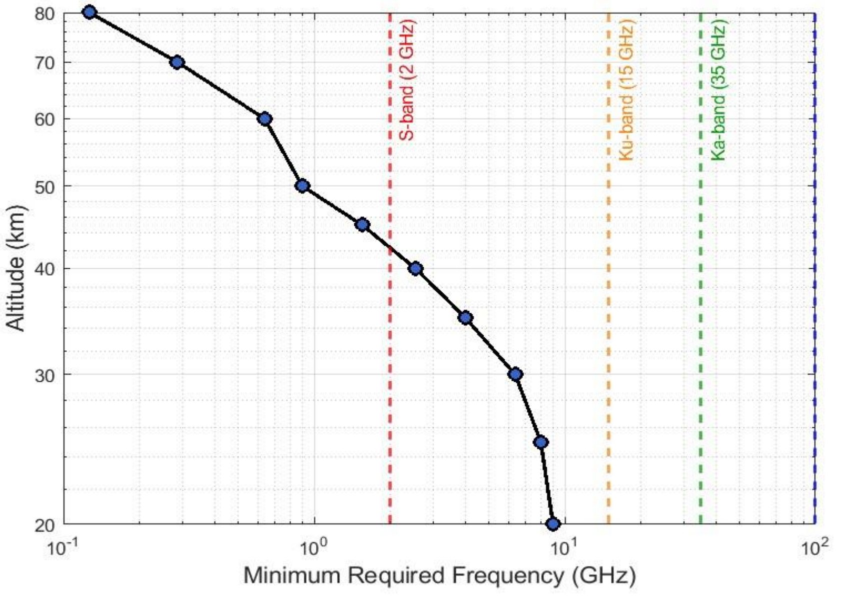

Fig. 3: Minimum required transmission frequency as a function of re-entry altitude

6. Conclusion and future work

The effect of plasma on the propagation of electromagnetic wave signal has been investigated, which showed that communications using Ka-band and extremely high frequency band provides a solution for blackout problem.

The results showed that at higher electron density (10^{18} m^{-3}) the plasma frequency can reach 9 GHz, below which complete communication blackout occurs. In the Results and Discussion section, Figure 1 shows that at peak plasma density ($n^e = 10^{18}$ m^{-3}), the attenuation at S-band (2.4 GHz) reaches approximately 1320 dB/m, confirming total signal blockage. Ka-band (35 GHz) exhibited an attenuation of approximately 9 dB/m, while EHF (100 GHz) reached as low as 0.9 – 1 dB/m — a massive reduction compared to S-band. Figure 2 confirms that this trend holds across

http://www.doi.org/10.62341/istj-vol39-1-mm02

all three plasma density levels, with the attenuation dropping sharply above the plasma frequency for each case. Figure 3 further shows that as the vehicle descends from 80 km to 20 km altitude, the minimum required transmission frequency increases from below 1 GHz to approximately 9 GHz, placing Ka-band and EHF well above the blackout threshold throughout the entire re-entry trajectory.
Future work should focus on the practical implementation of Ka-band and EHF communication systems for reentry vehicles, such as antenna design, link budget analysis, and experimental validation under real reentry plasma conditions.

7. References

[1] Zheng, L., Zhao, Q., Xing, X.J. ,2015, Effect of plasma on electromagnetic wave propagation and THz communications for reentry flight, The Applied Computational Electromagnetics Society Journal (ACES), 30, 1241–1245.
[2] Kundraput, M., Loverich, J., Beckwith, K., Stoltz, P., Shashurin, A., Keidar, M. ,2014, Electromagnetic wave propagation in the plasma layer of a reentry vehicle, arXiv:1407.4431.
[3] Webb, B.A., Ziolkowski, R.W. ,2020, A Metamaterial-Inspired Approach to Mitigating Radio Frequency Blackout When a Plasma Forms Around a Reentry Vehicle, Photonics, 7, 88.
[4] Kim, M.K. ,2009, Electromagnetic manipulation of plasma layer for re-entry blackout mitigation, Doctoral dissertation, University of Michigan.
[5] Boyd, I.D. ,2007, Modeling of plasma formation in rarefied hypersonic entry flows, 45th AIAA Aerospace Sciences Meeting and Exhibit.
[6] Engheta, N., Ziolkowski, R.W. ,2006, Introduction, history, and selected topics in fundamental theories of metamaterials, In: Engheta, N., Ziolkowski, R.W. (Eds.), Metamaterials: Physics and engineering explorations, pp. 5–9.
[7] Scalabrin, L.C. ,2007, Numerical simulation of weakly ionized hypersonic flow over re-entry capsules, Doctoral dissertation, University of Michigan

http://www.doi.org/10.62341/istj-vol39-1-mm02

[8] D'Angola, A., Colonna, G., Gorse, C., Capitelli, M. ,2008, Thermodynamic and transport properties in equilibrium air plasmas in a wide pressure and temperature range, The European Physical Journal D, 46, 129–150.

[9] Sawicki, P., Chaudhry, R.S., Boyd, I.D. ,2022, Influence of chemical kinetics models on plasma generation in hypersonic flight, AIAA Journal, 60, 31–40.

[10] Anderson, J.D. ,2006, Hypersonic and High Temperature Gas Dynamics (2nd ed.), AIAA Education Series.

[11] Chen, F.F. ,2016, Introduction to Plasma Physics and Controlled Fusion (3rd ed.), Springer International Publishing.

[12] Takahashi, Y., Yamada, K., Abe, T. ,2014, Examination of radio frequency blackout for an inflatable vehicle during atmospheric reentry, Journal of Spacecraft and Rockets, 51, 430–441.