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Mingyang Mao ; Kai Yuan ; Rongxin Tang ; Jiawei Xiong ; Ziyang Zhao ; Xiaohua Deng

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Mingyang Mao,[1,a)] Kai Yuan,[2,b)] Rongxin Tang,[3,c)] Jiawei Xiong,[4,d)] Ziyang Zhao,[3,e)] and Xiaohua Deng[3,f)]

AFFILIATIONS

[1] School of Resources and Environment, Nanchang University, Nanchang 330031, China
[2] School of Information Engineering, Nanchang University, Nanchang 330031, China
[3] Institute of Space Science and Technology, Nanchang University, Nanchang 330031, China
[4] School of Physics and Materials Science, Nanchang University, Nanchang 330031, China

[a)] **Electronic mail:** mingyang_mao@email.ncu.edu.cn
[b)] **Electronic mail:** yuankai@ncu.edu.cn
[c)] **Author to whom correspondence should be addressed:** rongxint@ncu.edu.cn
[d)] **Electronic mail:** jiaweixiong_ncu@163.com
[e)] **Electronic mail:** zhaozy006@163.com
[f)] **Electronic mail:** dengxhua@gmail.com

ABSTRACT

Communication blackouts have been a main threat to hypersonic vehicles for decades. The low frequency communication was considered a potential approach to mitigate the "blackout." Nowadays, low frequency transmitters serving underwater communication have transmission power up to several megawatts. In other words, if low frequency communication signals could penetrate the plasma sheath, it would be a meaningful solution that using modern low frequency transmitters to give service to hypersonic vehicle communication, and the service area could be very large. Although the studies on blackouts using low frequency waves have lasted for many years, it still remains many unclear problems. The present study analyzes the characteristics of different frequency waves passing through a plasma sheath. The analysis revealed that the low frequency signals with high power could penetrate the plasma sheath and mitigate the blackout effectively. According to our simulation results, the transmission coefficient decreased with the flight speed and also increased with magnetic field intensity and the axial distance from the onboard antenna to the nose of the vehicle. Moreover, it is not sensitive to the frequency of signals. At last, two example models of using a ground low frequency station to communicate with the hypersonic vehicle were analyzed, which means that the low frequency communication can significantly be considered in the application of hypersonic vehicles in the near future.

I. INTRODUCTION

Hypersonic vehicles in near space have been suffering from a communication blackout for several decades. Hypersonic vehicles would face communication interruptions in what is called the "blackout" region. The reason is that the vehicles would be enveloped by a dense plasma layer at such a high speed. The electron density in the hypersonic plasma sheath could be up to 10^{20} m^{-3}.[1–3] Radio frequency (RF) signals will be shielded by the plasma layer, then the blackout occurs.

There are many researchers working on solutions and have proposed several potential approaches. Among them, low frequency (LF) communication is considered to be an effective method.[4–6] Using LF communication to mitigate the impact of blackouts was put forward in the 1950s.[7,8] The thickness of the plasma sheath is in the range from 0.2 to 0.5 m, while the wavelength of LF waves is several kilometers for a blunt-coned vehicle.[9] It means that the plasma sheath is "thin" compared with the wavelength of LF waves. In addition, the transmitting power of a LF communication system could be up to several megawatts, so that the signals may be effectively received by the onboard antenna.[10,11]

It should be realized that LF waves have a low attenuation in the waveguide between the Earth's surface and the ionosphere. In addition, modern LF and Very Low Frequency (VLF) signal transmission systems can already achieve high transmission power. It implies that the high power LF communication is stable and mature nowadays. The communication range of LF communication systems could be up to thousands of kilometers. Its serving range is sufficient to maintain wireless communication with hypersonic vehicles by using just a few ground-based LF stations. Although LF communication systems have a low transmission rate, they are still a potential method to transmit some key information when a "blackout" occurs.

Some previous studies have already paid attention to the LF approach to mitigate the "blackout." Liu *et al.* analyzed the attenuation of LF waves in the plasma sheath in 2017,[12] whose theoretical results showed that the magnetic field component had a lower attenuation and it was better to use a magnetic loop antenna. However, the plasma sheath was modeled as a uniform spherical shell in that study, which is different from a real hypersonic plasma sheath since the plasma sheath is significantly inhomogeneous. In addition, the study made a conclusion that a signal below 3 MHz would evade the blackout, and the details about the impacts of signal frequency or signal path were not mentioned. Xie *et al.* verified the propagation theory of the LF waves in hypersonic plasma using a shock tube experiment in 2019.[13,14] Guo *et al.* placed two permanent magnets outside the shock tube, which were perpendicular to each other, to reduce the electron density in 2021.[15] Sun *et al.* analyzed the LF waves in a shared time-varying plasma sheath in 2020.[16] These theoretical and experimental research show that LF waves are able to pass through the plasma sheath. However, these studies focused on the magnetic antenna, and the frequency of these studies was about 10 MHz. Nevertheless, it should be realized that the transmitting power of modern transmitters working in the VLF to LF bands is normally up to several megawatts, which is much greater than that of short wave transmitters. Thus, it is worth being investigated that whether high power LF communication signals are able to penetrate the plasma sheath of hypersonic vehicles.

As the wavelength of LF/VLF waves is much longer than the thickness of the hypersonic plasma sheath, the key point is whether the transmitted signal can be detected by an onboard receiving antenna. In such a case, the present study analyzes the transmission characteristics of LF waves in the plasma sheath of a hypersonic vehicle by using the Transmission Matrix Method (TMM). In addition, the receiving antenna was assumed to be a loop antenna since the large size of LF dipole antennas are impossible to be installed on hypersonic vehicles. It means that the present study only analyzed the uplink of those applications using the ground LF station to send some key command information to the hypersonic vehicles, which could be a standby or emergency mechanism when the high speed communication is interrupted.

It is obvious that the flight conditions and atmospheric conditions would change at every moment during the whole flight. Many researchers have analyzed the impact of one or more factors. Yuan *et al.* analyzed the impact of flight altitudes and angles of attack on the terahertz signals propagation in the plasma sheath.[17,18] However, the impact of flight speed was unclear, while the flight speed was one of the most important factors in a vehicle. In addition, the antenna position is also an essential factor because the plasma sheath is inhomogeneous at different regions of the vehicle. Therefore, the present study focused on the influence of the flight speed, the antenna position, and the wave frequency. Since the key point of blackout is the high electron density of the plasma sheath, setting a magnetic field around the airborne antenna could reduce the electron density significantly, which is called the "magnetic window" method.[19,20] This method is also effective for LF waves in the plasma sheath. The details of the impact of the external magnetic field on the transmission coefficient of LF waves were also analyzed in this study. In addition, the characteristics of the hypersonic plasma sheath were revealed via solving the hydrodynamic model. The antenna was assumed to be on the wall of the vehicle at different distances to the nose; the frequency was between 3 and 300 kHz; and the flight speed was between 3850 and 7750 m/s.

II. IMPACTS OF ANTENNA POSITION

The position of the antenna can obviously affect the transmission of electromagnetic waves, according to the previous study. These studies showed that the most suitable position for the antenna is on the wall near the aft region of the plasma sheath.

To investigate the impacts of antenna position, three points were assigned as the antenna position with 0.41, 0.85, and 1.15 m from the nose of the vehicle in the present study. The wave transmission paths were assumed to be perpendicular to the wall of the vehicle in the region near the antenna (see the dashed lines in Fig. 1).

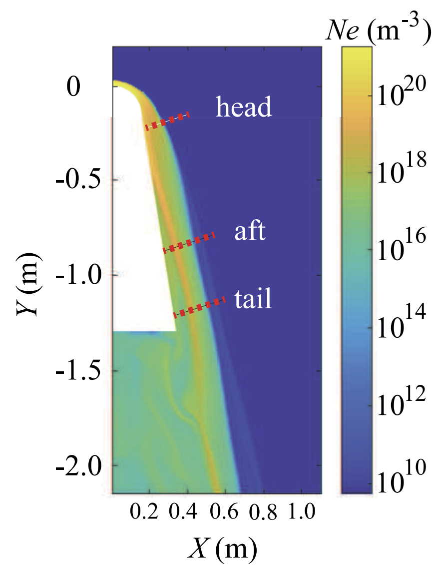

FIG. 1. The plasma sheath and the wave transmission paths.

In the present study, the plasma sheath was based on the flow field model. The flow field of the plasma sheath could be obtained by solving a numerical hydrodynamic model, which has been employed in previous studies.[21,22] The shape of the vehicle was identical to the reentry object involved in the Radio Attenuation Measurement C-II (RAM C-II). The shape of the vehicle is usually considered for theoretical studies nowadays. In the present study, the altitude of the vehicle was 30 km, and the air mass density of the neutral atmosphere around the vehicle was 1.566×10^{-2} kg/m^3.

Electron density (N_e) and electron collision frequency (ν_e) were the most important parameters of plasma. Figure 1 shows the N_e of the plasma sheath around the vehicle at a speed of 5650 m/s. Obviously, the plasma sheath was strongly inhomogeneous in different regions near the wall. Then we can infer that LF waves will show different characters in different transmission paths (it means different positions of the antenna).

The characteristics of wave transmission were reflected by the transmission coefficient (T), absorption coefficient (A), and reflection coefficient (R). A, R, and T of LF waves were calculated with TMM. The basic principle of TMM is to assume that the plasma sheath is divided into N layers. If the T and R in the mth layer were expressed as T_m and R_m, then the recurrence formula can be expressed as

$$\begin{bmatrix} T_m \\ R_m \end{bmatrix} = S_m \begin{bmatrix} T_{m-1} \\ R_{m-1} \end{bmatrix} \tag{1}$$

Then the A was obtained according to T and R

$$A = 1 - R^2 - T^2. \tag{2}$$

More details about N_e, ν_e, and T in the three wave transmission paths is shown in Fig. 2.

In Fig. 2, L was the distance to the surface of the vehicles, v was the speed of the vehicles, and f_c was the frequency of LF waves. Figure 2(a) shows that the electron density stayed the same characteristic in different paths. The distribution of the electron density along all the wave transmission paths was similar to a Gaussian function. In addition, the maximum value of electron density was monotonous with d, where d was the axial distance from the onboard antenna to the nose of the vehicle. It means that the longer the distance between the antenna and the nose of the vehicle, the lower the value of electron density. Similarly, the wave transmission coefficient showed the contrary tendency with d but still stayed monotonous as shown in Figs. 2(c) and 2(d). Furthermore, this tendency was not affected by the flight speed or the wave frequency. Figure 2(b) showed that ν_e was inhomogeneous along the wave transmission paths, and it varied greatly in different paths. Further analysis showed that ν_e had little impact on the propagation of LF waves in the hypersonic plasma sheaths compared with N_e. The details about A, R, and T with different frequencies will be analyzed in the next part.

As the character of the plasma sheath and the homologous transmission coefficient changed monotonously with d, the value range of the electron density or the transmission coefficient could be determined when the characteristics of the plasma sheath in the two paths near the nose and the tail were clear.

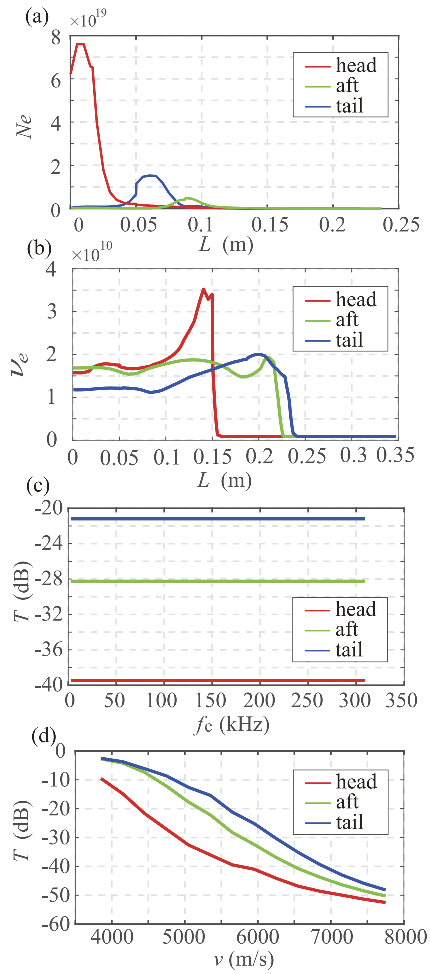

FIG. 2. The characteristics of the plasma sheath (a) and (b) and the wave transmission coefficient (c) and (d) in three wave transmission paths.

In the next part of this study, attention will be focused on the details of these two paths.

III. IMPACTS OF FLIGHT SPEED AND SIGNAL FREQUENCY

The air near the hypersonic vehicles would be ionized due to the friction between the air and the aircraft surface. Based on the previous study, the flight speed can obviously impact the plasma sheath. In that case, the relationship between the A, R, and T of LF waves and these two elements was analyzed in the present study.

Figures 3(a)–3(c) shows the A, R, and T of LF waves in different flight speeds at a signal frequency of 100 kHz. Figures 3(d)–3(f) shows the A, R, and T of waves with different frequencies at a flight speed of 5650 m/s. As shown in Figs. 3(a)–3(c), according to the range of ordinates, the flight speed had a significant influence on the A, R, and T in both paths. The higher the speed, the lower the A and T, and the higher the R. Furthermore, the change range of A was larger than that of R, which means that LF waves were

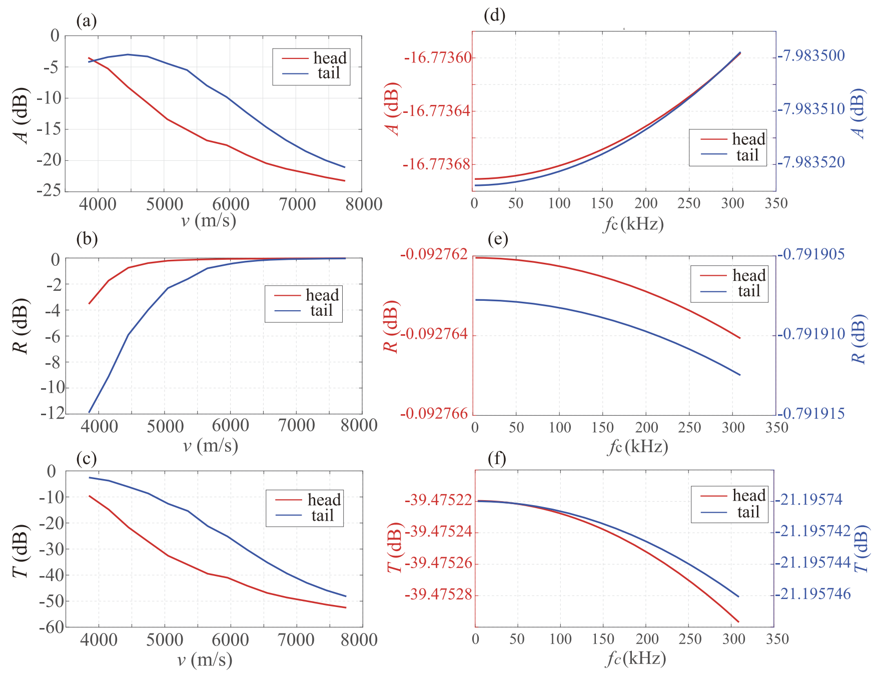

FIG. 3. Impacts of flight speed (a)–(c) and wave frequency (d)–(f) in two paths.

absorbed less as the flight speed increased. In addition, the path near the tail had a higher T and lower R with a speed under 5650 m/s. While the A, R, and T would tend to a stable value when the speed increased, such as beyond 6000 m/s. Approximately, 5650 m/s is the boundary between hypersonic vehicles in near space and reentry vehicles. It means that LF communication was an applicative manner of the hypersonic vehicles in near space but not the reentry vehicles.

According to Figs. 3(d)–3(f), R and T decreased with the wave frequency while A increased with it. It means that the waves with a higher frequency would have lower power after passing through the plasma sheath. However, the impact of wave frequency was insignificant compared with the flight speed due to the range of the ordinates. Furthermore, it can be seen from the ordinates that A and T near the tail part were much higher than the head part, while R had a contrary characteristic. In addition, these characteristics were independent of the wave frequency. It means that the impact of antenna position is more important than wave frequency.

IV. IMPACTS OF EXTERNAL MAGNETIC FIELD

The "magnetic window" method is an effective method to reduce the electron density of the plasma sheath and then mitigate the impact of a blackout. In this section, we analyzed the propagation of LF waves in the hypersonic plasma sheath by adding an external magnetic field.

Figure 4(a) shows the transmission coefficients of 100 kHz waves with different external magnetic fields; B is the magnetic field intensity, and it is assumed to range from 0 to 3 T. It showed that the transmission coefficient would increase with the magnetic field intensity. In particular, when the flight speed was high that it was not conducive to signal transmission because of the low transmission coefficient, it was actually more effective. It means that applying an external magnetic field was an effective method for the high speed vehicles.

As the external magnetic field could significantly improve the transmission coefficient of 100 kHz waves, what about the other frequencies? For this purpose, the waves from 30 kHz to 30 GHz were analyzed and shown in Fig. 4(b). In Fig. 4(b), f_c was the frequency, and T was the transmission coefficient with a flight speed of 5650 m/s. It can be seen that waves of all frequencies were impacted by the external magnetic field and increased with the magnetic field intensity. In addition, the waves beyond 0.1 THz were more sensitive to the changes in frequency and magnetic field intensity. It means that the method of applying an external magnetic field was more effective for waves beyond 0.1 THz. However, it should be noted that applying external magnetic field is still an effective way to mitigate the impact of a blackout on LF communication, and it is unnecessary if the wave frequency is higher than the cut-off frequency of the plasma sheath.

It is known that the propagation of electromagnetic waves in a magnetic field is impacted by polarization. Then the transmission coefficient would be affected by its polarization if using an external magnetic field. Figure 4(c) shows the difference between left-handed and right-handed circularly polarized waves with different flight speeds. In Fig. 4(c), T_d was the difference, v was the flight speed, the wave frequency was assumed to be 30 kHz and the magnetic field intensity was assumed as 1 T. It showed that T_d was

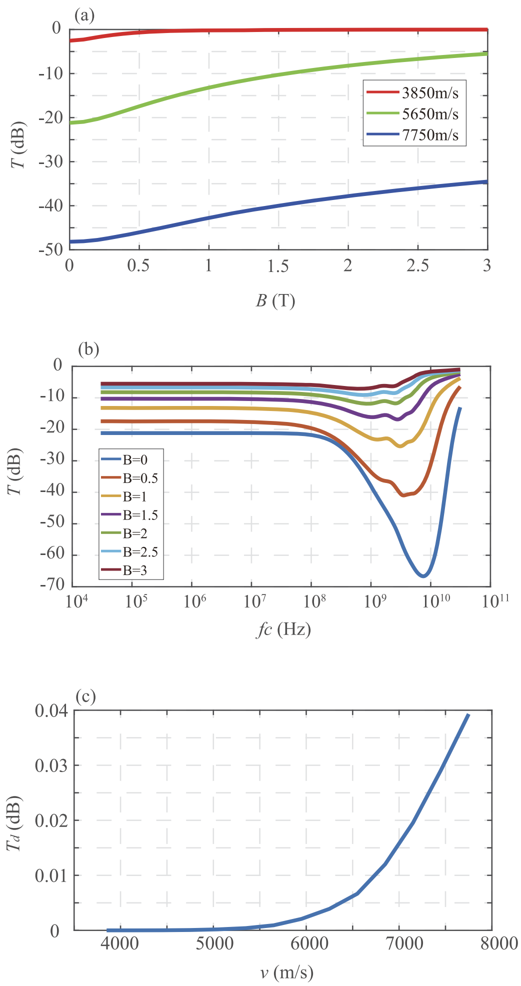

FIG. 4. *T* with different magnetic field intensities (a) and (b) and the difference between left-handed and right-handed circularly polarized waves (c).

very small, but further analysis showed that T_d can increase rapidly with the wave frequency. It means that it is unnecessary to pay attention to the polarization for LF communication, but it is better to choose the right-handed circularly polarized wave if the working frequency is higher than MHz. In addition, Fig. 4(c) also showed that T_d increased with the flight speed, it means that right-handed circularly polarized wave is more appropriate for hypersonic vehicles with higher speed.

V. DISCUSSIONS

According to Fig. 3(f), LF waves had a transmission coefficient of about −21 dB at the tail path. As the transmitting power of modern transmitters working in LF bands is normally up to several megawatts, the signals may be effectively received by the onboard antenna. On the other hand, the frequency had little effect in LF bands, according to this study, which means that it needs no special restrictions on the working frequency of a transmitter. In this

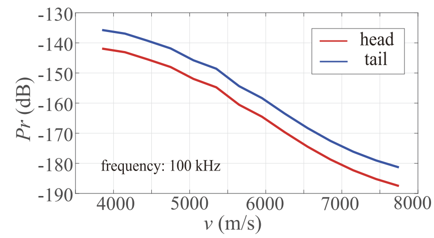

FIG. 5. The relative receiving power with different flight speeds.

section, the situation of using an existing LF transmitter or building a special ground station is analyzed.

Figure 5 shows the relative power (P_r) of LF waves with different flight speeds (v). The transmitting antenna was assumed to be an omnidirectional antenna on the ground, and the working frequency was 100 kHz. As the LF/VLF communication systems have a long communication distance, a LF/VLF ground base station with omnidirectional antennas would be able to provide communication services to many hypersonic vehicles in a large region. Figure 5 shows the situation where the distance from the vehicle to the transmitting antenna was assumed to be 1000 km. It was an example of using existing ground LF stations to communicate with the hypersonic vehicles. According to the simulations above, the receiving antenna was assumed to be a loop antenna at the head or tail part of the vehicle. From Fig. 5, P_r was between −141 and −187 dB at the head path and was −135 to −181 dB at the tail path. It means that if the transmitting power is 1 MW, the reserving power has a maximum value of −45.7 dBm at a flight speed of 3850 m/s and a minimum value of −97 dBm at a flight speed of 7750 m/s. In addition, according to Fig. 3(d), it can be inferred that all the frequencies in the LF part would have a P_r between −135 and −187 dB. It can successfully suggest that, if the onboard antenna can detect a signal higher than −97 dBm, it would be possible to communicate with the hypersonic vehicle.

As the reentry vehicles often enter the atmosphere in a few specific areas for a country, such as a landing site of about 2000 km^2 in Siziwang Banner, Inner Mongolia of China. Thus, it is an effective solution to build a ground LF station for a landing site to communicate with these reentry vehicles. An example model is shown in Fig. 6. Assuming the ground dipole transmitting antenna is set up in the north–south direction because the flight paths are always along the east–west direction. In addition, the electromagnetic wave exited by the antenna is assumed to be a horizontally polarized wave, then the magnetic field component can be detected by the ring antenna, which is set on the tail part of the hypersonic vehicle, and the normal direction of the ring antenna is parallel to the main axis of the vehicle. The radius of the landing site is assumed to be 100 km, and the altitude of the flight path is 30 km. If the transmitting power of the ground station is 1 kW or 1 MW, the receiving power of the onboard ring antenna is shown in Fig. 7.

Figure 7 shows the receiving power of different flight speeds and wave frequencies. v was the flight speed and f_c was the wave frequency. The range of wave frequency here was from 100 kHz to 10 MHz. Figure 7(a) is the receiving power of the 1 kW transmitter, and Fig. 7(b) is the 1 MW transmitter. It showed that the receiving power decreased when the flight speed increased and it

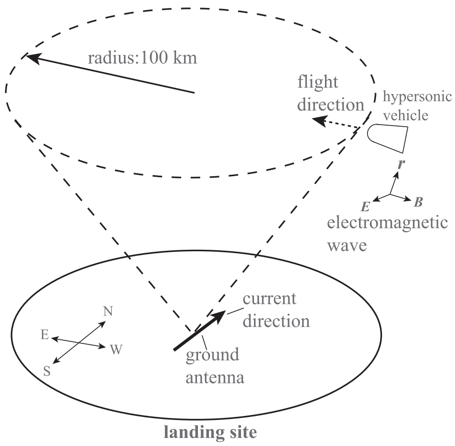

FIG. 6. The model of the centering ground station.

was insensitive to the wave frequency as we analyzed above. However, the receiving power would decrease when the wave frequency increased if the flight speed was higher than 7000 m/s. In addition, Fig. 7 shows that if the receiving ring antenna could detect a signal power higher than −130 dBm, it would be possible to communicate with the hypersonic vehicles by using the ground LF station when the transmitting power is higher than 1 kW. On the other hand, as the wave frequency had little impact on the receiving power when the flight speed was lower than 7000 m/s, it is better to choose a higher frequency to reduce the size of the transmitting antenna. However, the corresponding transmission power should also be considered. In such a case, the system designers could choose the most beneficial strategy based on the above model.

It should be noted that the power of LF transmitters could be higher than 1 MW nowadays, and the distance to the vehicle would be smaller than 1000 km in a normal situation. Thus, the reserving power would be higher than the range above.

Although LF communications have a low communication rate, the hypersonic vehicles only needed to receive some simple instructions when the blackout occurred, which was enough for some emergency communications to pass through the blackout safely. As the wave frequency was not the prime consideration, we should focus on other sides of the LF systems, such as the size of the corresponding antenna, the information transmission rate, and so on. They should be given priority over those with better frequency. On the other hand, LF communication systems can provide a higher transmitting power more than 1 MW, and the transmission power is able to be detected nowadays.

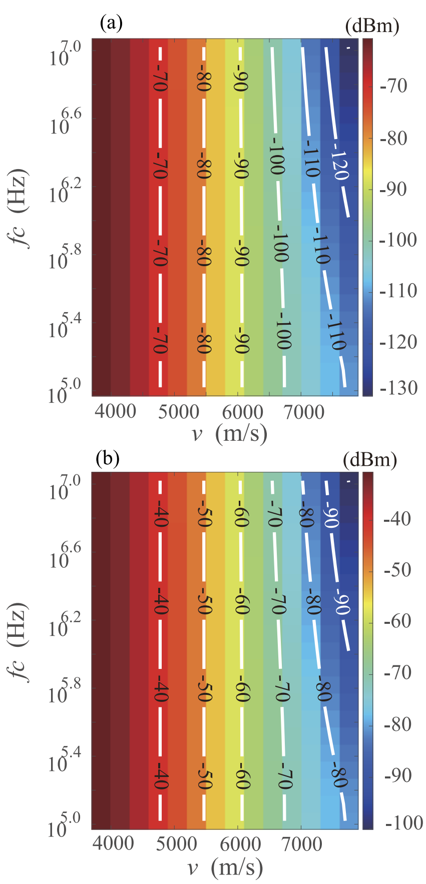

FIG. 7. The receiving power with different flight speeds and wave frequencies.

VI. SUMMARY AND CONCLUSION

In the present study, the propagation of LF waves in a hypersonic plasma sheath was analyzed. The plasma sheath was obtained by solving a numerical hydrodynamic model. The transmission coefficients for different antenna positions, flight speeds, and wave frequencies were calculated using the transmission matrix method. Furthermore, the receiving power of LF waves generated by the ground LF station was detailedly analyzed.

According to the present study, the LF signals could penetrate the plasma sheath effectively. For instance, the power of 100 kHz signals that reach the onboard receiving antenna ranges from −97.0 to −45.7 dBm once a 1 MW transmitter is 1000 km away from the hypersonic vehicle. Furthermore, the receiving power could reach up to −15.2 dBm when the vehicle was directly above the ground LF station. Modern onboard LF receivers could detect the penetrated LF communication signals effectively. In addition, the transmission coefficient increased with the magnetic field intensity and the axial distance from the onboard antenna to the nose of the vehicle, and decreased with the flight speed. Moreover, the present study revealed that the transmission coefficient is not sensitive to the frequency of signals. Therefore, decelerating the vehicle and installing the receiving antenna near the tail part of the vehicle helps to strengthen the received LF communication signals. Our results can significantly improve the system design of LF communication applications for hypersonic vehicles in the near future.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Mingyang Mao: Conceptualization (equal); Data curation (lead); Software (lead); Writing – original draft (lead); Writing – review & editing (equal). **Kai Yuan**: Conceptualization (lead); Data curation (equal); Formal analysis (lead); Writing – review & editing (equal). **Rongxin Tang**: Conceptualization (equal); Formal analysis (equal); Writing – review & editing (lead). **Jiawei Xiong**: Data curation (equal); Software (equal). **Ziyang Zhao**: Data curation (equal); Software (equal). **Xiaohua Deng**: Conceptualization (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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