Progress In Electromagnetics Research, Vol. 123, 321–336, 2012

CHARACTERISTIC OF PLASMA SHEATH CHANNEL AND ITS EFFECT ON COMMUNICATION

L. Shi[1,*], B. L. Guo[1], Y. M. Liu[2], and J. T. Li[3]

[1]ICIE Institute, Xidian University, Xi'an 710071, China

[2]MCI Institute, Xidian University, Xi'an 710071, China

[3]School of Science, Xidian University, Xi'an 710071, China

Abstract—The plasma sheath communication blackout issue for hypersonic or reentry vehicles is addressed from a channel characteristic perspective. Different from previous research, this paper emphasizes the importance of plasma sheath channel in the study of plasma communication blackout, and the discussion on transmission and phase shift characteristic of plasma sheath channel and their effect on communication performance was made with detail. A mathematical plasma sheath channel model is proposed and following the roadmap about how to obtain channel characteristic parameter is given. Flow field simulation of a blunt conical body physical was made, and the electron density and collision frequency profile got from flow field result under different incident angle at Mach 10–20 are presented thoroughly. The performance for QPSK based communication system under the established plasma channel is evaluated finally. It is indicated in our research that channel attenuation feature variation regularity is consistent with that of incident wave or Mach number, but the phase shift variation regularity with incident frequency or Mach number appears fall into chaos because of multiple 360 degree removal of original phase shift from communication view and complicated ratio relationships among incident wave, plasma frequency and collision frequency. Communication simulations result show that bit error rate agree with phase shift chaos well and phase shift exert large influence on present typical racking, telemetry, and command system. Some useful implications obtained from this study to improve communication performance include high frequency, high power and further rapid acquisition/tracing phase-locked loop compensating large phase shift.

Received 2 November 2011, Accepted 7 December 2011, Scheduled 29 December 2011

[*] Corresponding author: Lei Shi (shilei2002yoda@163.com).

1. INTRODUCTION

Vehicles traveling at hypersonic speed experience degradation of radio communications including telemetry and GPS navigation, because of effects from plasma sheath caused by the free electrons in the gas, including signal attenuation, phase shift, noise, etc. [1]. Plasma sheath is referred to a plasma layer formed around the hypersonic or reentry spacecraft and is created by the shock wave formed at the front of hypersonic vehicles, which will compress the air and converts much of the vehicle's kinetic energy into heat increasing the air temperature to some degree that is sufficient to make air molecules dissociated and ionized. The electron density of the plasma layer is about $10^{14}/\mathrm{m}^3$ to $10^{19}/\mathrm{m}^3$, and this density is high enough to cause so-called radio blackout [2].

The blackout phenomenon first came to researchers' attention during the 1950's [3]. NASA Langley Center and The Air Force Research Laboratory [4] have been involved with many efforts in computational simulation, ground experimental test and inflight test with the goal of characterizing and predicting the effects of hypersonic plasmas on propagation of electromagnetic wave from the 1960's to the 1970's. Research work mainly focuses on the numerical computation analysis, electromagnetic wave interaction with plasma, inflight diagnostic, ground simulation facilities, and mutual verification between theory and experiment test. Previous work by NASA has provided an overview of the reentry communications problem. Emphasis is particular placed on developing 1) an understanding of the causes and nature of the reentry plasma sheath, 2) the interaction between electromagnetic waves and plasmas and 3) proposed means of alleviating the reentry communications blackout. The plasma sheath diagnosis technology with different types of antennas has developed, and the impact on the antenna performance has been discussed as well. Many different methodologies to reduce the plasma sheath effects on radio communication attenuation or blackout have been proposed and studied simultaneously [2]. Of these methods, the most promising mitigation technologies are aerodynamic shaping, electrophilic injection, and the utilization of magnetic fields, but they are not so satisfactory because of many limitations at that time though many techniques sound promising. Unfortunately, most of the research results in these areas are classified, thus not published in the open literature. Despite this, a good understanding of the breadth of current research areas is still possible, as they have changed little in the last 50 years. As yet, available literatures still endeavor to make progress in those fields mentioned above [5–13], and rarely, study focuses on plasma blackout from the point view of communication and signal characteristic. What makes communication blackout is not only signal energy loss large alone, but also the inconsistence between the channel model used currently and the actual plasma channel characteristic. Thus the purpose of this paper is to establish and analyze plasma channel features including large scale fading (attenuation or power transmission coefficient) and small scale fading factor (phase shift) for hypersonic environment. At the same time, it is necessary to pay close attention to and evaluate its influence on typical tracking, telemetry, and command (TT&C) system as well.

The remainder of this paper is organized as follows. Section 2 outlines plasma channel environment, the roadmap and methods with which to acquire transmission coefficient and phase shift characteristic for plasma sheath channel in details. The simulation of plasma sheath channel impact on typical TT&C system is presented in Section 3. The overall conclusion of plasma channel feature and communication degradation countermeasures are reported in Section 4.

2. PLASMA SHEATH CHANNEL CHARACTERISTIC

2.1. Research Progress on Plasma Sheath Communication

In addition to propulsion, aerodynamic, and control issues, the ability to communicate through a plasma layer remains a critical area of research in hypersonic flight. The accurate knowledge of vehicle position, velocity, flight path angle, and monitoring of overall vehicle health becomes especially important. The plasma around vehicles is an electrically charged gas consisting of both ionized molecules and free electrons and is often considered as the fourth state of matter. The dissociation of oxygen (above temperatures of about 2,000 K) and nitrogen (above temperatures of about 4,000 K) populates the plasma field with NO+, N+, and O+ ions, along with neutralizing free electrons. Classical theory assumes that the plasma consists of equal numbers of positive ions and free electrons together with a number of neutral particles. If an electron or ion moves away from its equilibrium position slightly then an electric field will form, causing the electron and ion attracted to each other. Since the ion appears infinitely massive to the electron, it can be held that only the electrons move. As it is traveling beyond the equilibrium position, an electric field is formed, which begins to pull it back. In this way, the electrons oscillate in plasma, much like a mass on a spring, at the so-called "plasma frequency" [3]

$$\omega_p = (N_e e^2/\varepsilon_0 m_e)^{1/2} \tag{1}$$

where ω_p is the plasma frequency, N_e the electron density, e the electron charge, m_e the mass of an electron, and ε_0 the electric constant in free space.

During the communication blackout period, the plasma can be characterized by electron concentrations and collision frequency profile depending on the configuration, flight velocity, trajectory, and location within the shock layer. It is the free electrons that attenuate or absorb the electromagnetic wave, especially when the transmission frequency approximates to the plasma frequency. Successful transmission through the plasma sheath requires transmission frequencies above the plasma frequency. Therefore, one solution to this problem is to enhance the transmission frequency to Ku (12.5–18 GHz) or Ka (26.5–40 GHz) band [14].

However, plasma sheath structure and electromagnetism parameter depend strongly on flight vehicle's contour, speed, altitude, ablating rate, and their couple relations are highly complicated. It is difficult to establish a uniform formula for different vehicles when establishing plasma sheath physical model. Previous research had been performed in the United States generally focused on blunt body reentry vehicles, such as the RAM C blunt conical body, Gemini and Apollo capsules of the works done in this area. Little has been published in the open literature due to security concerns. Fortunately, some well acknowledged qualitative results can be seen from a few public literatures. Generally, for a typical blunt conical vehicle, there are five main regions used to describe its flowfield: stagnation region, intermediate region, aftbody region, wake region, and boundary layer. The most severe plasma condition occurs in the stagnation region in the front of the vehicle where a nearly normal shock generating high temperatures and pressures in this region resulting in the highest levels of ionization. While the plasma condition in the aft body region is much less severe than those in the stagnation and intermediate region for the ionization in the aft body region is primarily the result of gases that pass through the oblique shock. To this end, the general agreement among the researchers is that the vehicle antennas should be placed at aftbody or as far from the stagnation region as possible where the environmental conditions are generally orders of magnitude less severe.

2.2. Mathematical Channel Model for Plasma Sheath

As mentioned above, plasma sheath internal flowfield is complex making electron density distribution, pressure distribution, and temperature distribution complicated and time-variable. These bring big variability to the channel characteristic analysis for different hypersonic vehicles. Fortunately, from channel characteristic consideration macroscopically, what is needed is large scale fading and small scale fading when electric wave transmit through plasma. Large and small scale fading features are almost without difference in communication for vehicles with various shapes and different flight conditions. Thus focus can only be made on these two key factors without emphasizing flowfied that much.

These two items in plasma sheath were defined as follows. Large-scale fading of the plasma sheath is characterized by average power loss/factor caused by energy reflection and absorption on the entire thickness of sheath; small-scale fading is characterized by phase shift and spectrum scattering caused by reflection and refraction by heterogeneous micro-object within sheath [15]. These two critical factors for channel modeling are directly related to the plasma frequency, collision frequency, and plasma width. Since electromagnetic wave attenuation and phase shift are related to plasma electrical parameters, plasma physical parameters can be ignored. It is reasonable in this paper to just focus on blunt conical vehicles and make communication performance for typical TT&C system without paying attention to flowfied for specific vehicles with different shapes. Now what is needed to characterize plasma sheath channel is power attenuation (or transmission coefficient) and phase shift feature of the plasma sheath for electromagnetic wave.

The effects of plasma sheath on the signal transmission can be mathematically modeled as

$$\tilde{y}(t) = |T_{rans}(t)|\,|\tilde{x}(t)|\cos(wt + \varphi + \varphi_{shift}(t)) + n_{plasma}(t) \qquad (2)$$

where $\tilde{x}(t)$, $\tilde{y}(t)$ is the input band pass signal and output signal that transmit through plasma sheath, respectively. $T_{rans}(t)$ is electromagnetic wave power transmission coefficient at some carrier frequency, φ the initial phase of signal, $\varphi_{shift}(t)$ the phase shift that generated after the signal passes through the plasma, and $n_{plasma}(t)$ the plasma noise.

The plasma sheath noise cannot be ignored and can be measured by equivalent noise temperature. According to [1, 2, 16, 17], it is indicated that the level of plasma sheath temperature ranges in 1500 K–5000 K and that the noise factor calculated by the equation below is 7.9 dB–12.6 dB.

$$N_F(\mathrm{dB}) = 10\lg\left(1 + \frac{T}{T_i}\right) \qquad (3)$$

in which T_i is the room temperature degrees in Kelvin, about 290 K, and T is total equivalent effective temperature in plasma, including the temperature as well as other collision effects.

2.3. Attenuation and Phase Shift Theory

Channel characteristic acquisition roadmap for plasma sheath is given in Figure 1. If the physical model of plasma sheath, including input conditions such as hypersonic vehicles configuration, Mach number, angle of attack, background pressure, background temperature, and flowfield model, is given, the electron density and collision frequency can be obtained by computational simulation with CFD software Fluent. Since plasma sheath electric feature is known, plasma sheath complex dielectric constant and wave propagation constant in plasma sheath can be derived. Finally, the transmission coefficient and phase shift are obtained with the usage of FDTD algorithm and stratified method.

Knowing the electron density and collision frequency profile, the next step is to solve the Maxwell equations concerning EM wave propagation in ionized air. Assuming that an EM wave propagating through a dielectric medium is a plane wave with the form $E \sim e^{(ikx-i\omega t)}$, Heald and Waharton [18] gave the expression of the values of effective dielectric constant or wave number, and the plasma index of fraction n satisfies Equation (4)

$$n = \frac{kc}{\omega} = \sqrt{1 - \frac{(\omega_p/\omega)^2}{1+(v/\omega)^2} + i\frac{(\omega_p/\omega)^2(v/\omega)}{1+(v/\omega)^2}} \tag{4}$$

where v is neutral particle collision frequency ($v \sim PT^{-1/2}$), and k is

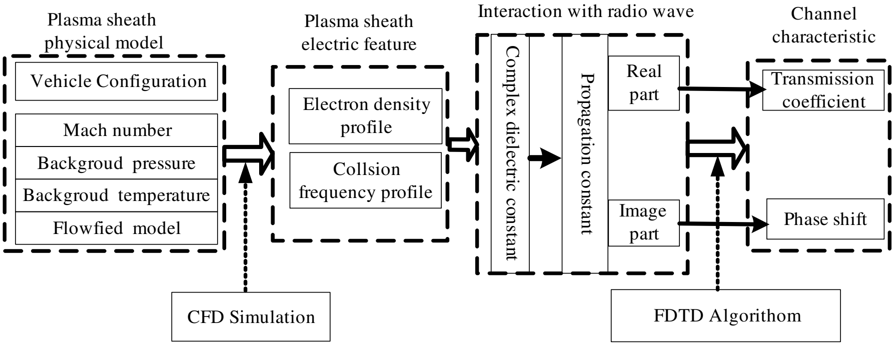


Figure 1. Channel characteristic acquisition roadmap for plasma sheath.

the wave number in plasma, which can be expressed as

$$\begin{aligned} &k = \beta + i\alpha; \quad k_0 = \frac{\omega}{c} \\ &\alpha = k_0 \left(\frac{\sqrt{R^2 + I^2} - R}{2} \right)^{1/2} \\ &\beta = k_0 \left(\frac{\sqrt{R^2 + I^2} + R}{2} \right)^{1/2} \\ &R = 1 - \frac{(\omega_p/\omega)^2}{1 + (v/\omega)^2}; \quad I = \frac{(\omega_p/\omega)^2 (v/\omega)}{1 + (v/\omega)^2} \end{aligned} \tag{5}$$

in which k_0 is the wave number in free space; the real part β is phase constant, and the imaginary part α is attenuation constant. Then the integrated phase shift $\hat{\varphi}$ and transmission attenuation $\hat{T}$ can be estimated as

$$\begin{aligned} \hat{T} &= \textstyle\int \alpha dx \\ \hat{\varphi} &= \textstyle\int \beta dx \end{aligned} \tag{6}$$

Plasma sheath is non-uniform and dispersive medium, thus theoretical integral method is improper and hard to deal with. Here we use stratified approach with each thin plasma layer seeming to be uniform and combine with the FDTD algorithm to achieve electromagnetic wave propagation characteristics in plasma sheath. The transmission/reflection characteristic and phase shift characteristic of each thin uniform plasma were calculated by FDTD algorithm. The FDTD algorithm belongs to the general class of differential time domain numerical modeling methods. The equations are solved in a leap-frog manner: the electric field is solved at a given instant in time. Then the magnetic field are solved at the next instant in time, and the process is repeated over and over again. Thus final propagation features (or channel characteristic) were obtained to combine with the stratified method.

2.4. Channel Characteristic Simulation

In this section, a hypersonic vehicle model [19] similar to NASA RAM C Blunt body as illustrated in Figure 2 is established, and quantitative analysis on plasma electrical feature and plasma channel characteristic will be discussed. The antenna is located aftbody at (0.7 m, 0.247 m) position. Incident angle is defined as an angle between the incident wave direction and body surfaces. 90 degree means that the incident wave is normal to antenna position or body surface. The electron

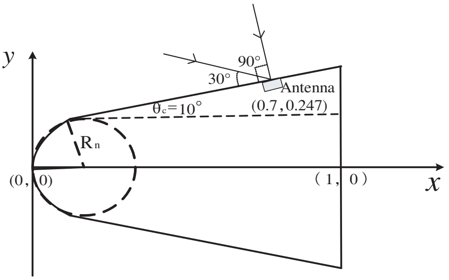


Figure 2. Blunt cone hypersonic vehicle model diagrammatic cross-section.

Table 1. The blunt conical body model parameters.

Vehicle configuration	parameters
Ball radius	$Rn = 0.12\,\mathrm{m}$
half cone angle	$\theta = 10°$
atmospheric background temperature	250 K
atmospheric background pressure	70 pa
Mach number	10–20
wall temperature	1500 K

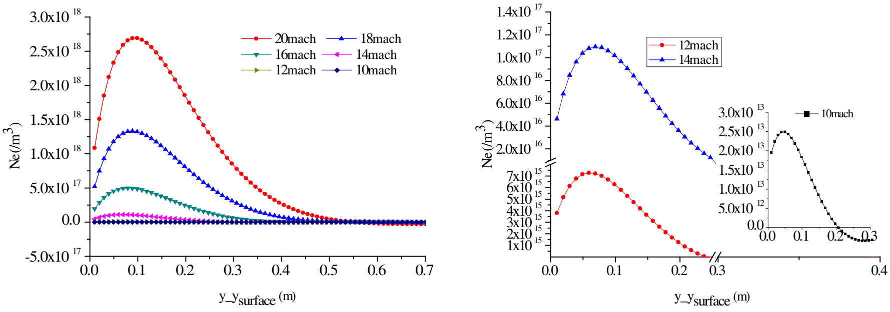


Figure 3. Electron concentration curves under different Mach number when incident wave normal to antenna position (90°).

concentration and collision frequency profile under different Mach numbers and incident angles will be discussed.

The axisymmetric blunt conical body model parameters are listed in Table 1. The temperature model is non-equilibrium gas model, and 5 components Dunn-Kang chemical model was used as air chemistry model.

Figure 3 shows the typical electron density distribution under different Mach when the incident wave is normal to vehicle surface. Generally, electron density increases with rise of Mach number, and the higher is the speed, the wider is the plasma sheath. From the left figure, it can be seen that the peak electron density under Mach 16 is far lower than that above Mach 16, electron density under Mach 16–20 approximately 10^{18} per m^3 level, while as shown in the right figure, about 10^{17} per m^3 level at Mach 14, 10^{15} per m^3 at Mach 12, and 10^{13} per m^3 at Mach 10. Result shows that plasma sheath width may be up to 30 cm with the main effective region that would influence radio wave, and the plasma frequency may range from 50 MHz to 15 GHz. (N_e, the peak value for Mach 10, 12, 14, 16, 20 are $2.5 * 10^{13}/\mathrm{m}^3$, $7 * 10^{15}/\mathrm{m}^3$, $1.2 * 10^{17}/\mathrm{m}^3$, $2.8 * 10^{18}/\mathrm{m}^3$, respectively, and thus plasma frequencies are 50 MHz, 750 MHz, 3 GHz, 15 GHz according to Equation (1)).

The electron density distribution curves under the typical incidence angle (30°–90°) at Mach 15 are given in Figure 4. As the incident angle increases, the peak value points move close to the vehicle surface, and the effective thickness of the plasma becomes thinner but electron density higher, something as compression effect.

The collision frequency distribution curves under different Mach numbers, when the incidence wave is normal to surface, are described in Figure 5. Similar to electron density distribution curves, the larger is the Mach number, the higher is the collision frequency, and the wider is the effective plasma width. The peak collision frequency reaching as high as 240 GHz at Mach 20, and 100 GHz at Mach 18, it is far larger than incident frequency and plasma frequency, and this will

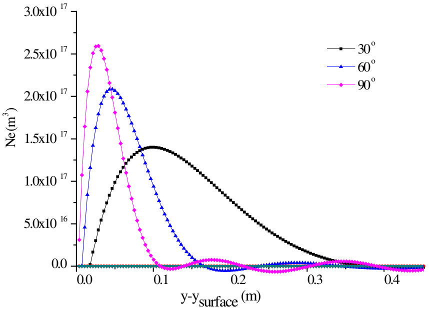


Figure 4. The electron density distribution under different incident angle at Mach 15.

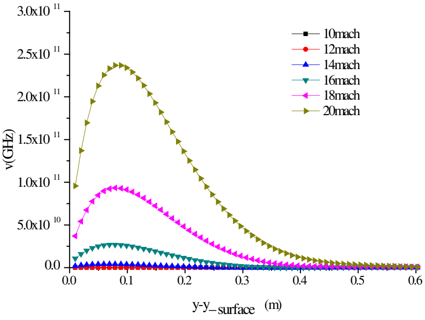
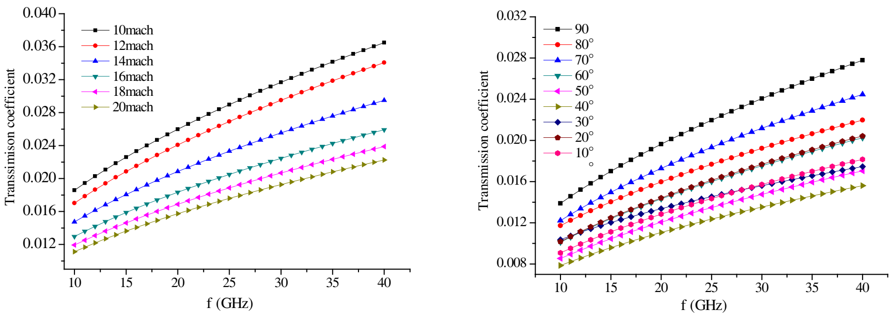


Figure 5. Collision frequency distribution curves under different Mach number when incident wave normal to antenna position.

affect phase shift feature largely, for phase shift is mainly determined by the ratios among incident frequency, plasma frequency and collision frequency as discussed in [2].

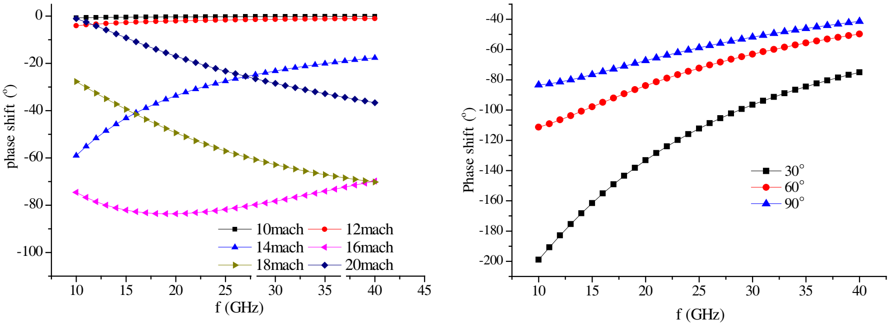
Transmission coefficients characteristics were given in Figure 6. Here the frequency region 10–40 GHz is just considered in order to exceed cutoff frequency for most instances. Figure 6(a) is the transmission coefficient under different Mach numbers when incident wave is normal to surface. It is evident that Mach number imposes big influence on transmission coefficient characteristic. The transmission coefficient decreases when Mach number increases, and generally it increases when incident wave frequency rises for all Mach numbers. Transmission coefficient under different incident angles at Mach 15 is presented in Figure 6(b). In general, the higher is the incident frequency, the better is the transmission effect, but the transmission coefficient variation regularity is inconsistent with that of the incident angle. There is no doubt that the transmission performance at 90 degree is the best, and obviously, other situations are more complex and fall into chaos. The transmission coefficient at 40 degrees is the worst instead of 10 degrees as intuitively imagination, while the transmission coefficient at 60 degrees is almost the same as that at 20 degrees. These situations may be caused by complex factor such as electronic curve shift as shown in Figure 4, thickening oblique incidence layer width and peak value of electronic concentration.

Figure 7 presents phase shift characteristic. The original calculated phase shift data at high Mach may reach hundreds or even thousands of degrees, but for the communication signal, if the signal phase flips 360 degrees, it can be considered the same as the original



(a) (b)

Figure 6. Transmission coefficients characteristic ((a) transmission coefficient under different when incident wave normal to surface, (b) transmission coefficient under different incident angle at Mach 15).



(a) (b)

Figure 7. Phase shift characteristic ((a) phase shift under different Mach number when incident wave normal to surface, (b) phase shift under different incident angle at Mach 15).

signal. The phase shift characteristics given below are processed from communication prospect. In other words, it is the residual value after the original phase shifts data modulo 360 degrees.

It can be seen from Figure 7(a) that the phase shift increases with increase of Mach number and decreases with increase of frequency when Mach number ranges from 10 to 16. But Mach 16 is a dividing line. Overall, the phase shifts at Mach 18–20 become smaller than Mach 16, and the variation trend is almost opposite to that of Mach 10–14 situations. The phase shift decreases with rise of Mach number and becomes larger with increase of frequency. Other than the reason of multiple 360 degrees elimination from original data, another reason that phase shift appears apart from our institution is variation of ratios among plasma frequency, collision frequency, and incident frequency. Figure 7(b) shows the phase shifts under different incident angles at Mach 15. The variation regularity is clear, and with increase of incident angle, the phase-shift increases gradually.

3. EFFECTS ON TYPICAL TT&C COMMUNICATION

This section will evaluate Mach number, incident frequency and SNR (signal to noise ratio) influence on BER (bit error rate) through Monte Carlo simulation. A simple simulation process is as follows: 10^5 random symbols are generated first and QPSK modulated before going through the single path Rician channel and Gaussian white noise (on behalf of space transmission channel), then the modulated and contaminated signal goes through the plasma sheath channel, i.e., signal suffers from attenuation (transmission coefficient) and phase shift effect. The following simulations are conducted under normal incident cases.

As seen from Section 2.3, the phase shift under Mach 10 is almost negligible, so Mach 12 is considered here evaluating BER performance under different incident frequencies and SNRs. Simulation results are shown in Figure 8. It is clear that the overall communication performance is not very good due to the existence of deep attenuation and phase shift. Only at frequency higher than 35 GHz and SNR greater than 40 dB it is possible to achieve voice communication requirements (BER at 10e-3 level).

Figure 9 depicts the BER performance under different Mach numbers and incident frequencies when the initial SNR is fixed at 40 dB. It is evident that the highest error rate occurs at Mach 16, mainly due to the maximum phase shift as shown in Figure 6. Curve mutual cross is observed at Mach 18, 20, consistent with occasions existing in the phase shift in Figure 6. Only under low Mach and high frequency, voice communication requirement can be achieved, such as at Mach below 12 and incident frequency near 40 GHz. Obviously, other occasions appear to be blackout.

The BER performance under different Mach numbers and SNRs, when the incident frequency is fixed at 30 GHz, is shown in Figure 10. Under the precondition that the incident frequency is fixed, the attenuation and phase shift are identified for a specific Mach number. It is indicated in the figure that BER will increase as Mach number increases, and BER will improve largely as SNR increases. It is worth noting that the BER's sudden change occurs at Mach 16 because maximum phase shift occurs which is consistent with the previous

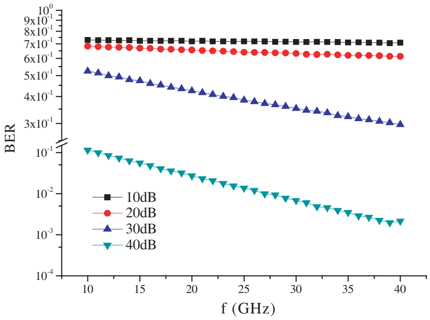


Figure 8. BER curves under different incident frequency and SNR at mach 12.

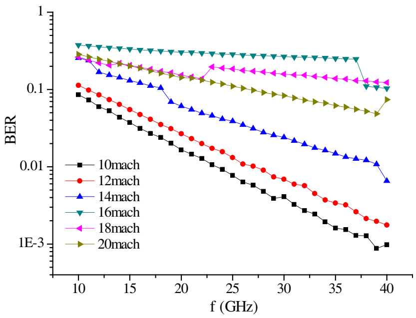


Figure 9. BER curves under different incident frequency and Mach number when SNR is 40 dB.

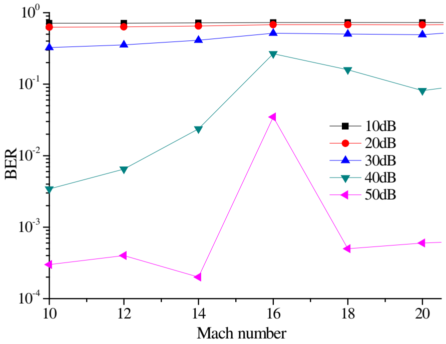


Figure 10. BER curves under different SNR and Mach number when incident frequency is 30 GHz.

phase shift result.

Based on the communication simulation result and analytical investigations above, the following conclusions may be drawn:

(1) Improving the incident signal power to increase SNR will be helpful to compensating deep fading.

(2) Raising the incident frequency will be helpful to enhancing communication performance.

(3) Phase shift exerts a large impact on signal and communication.

It is obvious that the attenuation at Mach 16 is almost the same as that of other Mach numbers, but phase shift differs largely, which leads to the worst BER performance at Mach 16, and BER variation trend is consistent with the irregularity of phase shift as shown in Figure 6.

4. CONCLUSION

This paper analyzes hypersonic aircraft communication blackout problem from the perspective of the plasma sheath channel characteristics, which is characterized by transmission characteristics and phase shift features. The roadmap to obtain transmission coefficient and phase shift is given, and a blunt conical model is simulated. Results about plasma electron density/collision frequency profile and subsequent transmission coefficient/phase shift are presented as well. The deep fading caused by signal attenuation and irregularity in phase shift feature with Mach number were observed. Generally speaking, the transmission coefficient becomes better with lower Mach number and higher incident frequency. However, the phase shift feature variation regularity with Mach number or incident frequency was seemed to be confusing from the view of communication.

This irregularity directly leads to BER confusion as shown in Figures 9 and 10. These irregularities are partially caused by the variation of ratios among plasma frequency, incident frequency, collision frequency.

More communication technologies are needed to overcome communication blackout for the bad environment unavoidable when the plasma sheath characteristic is clear. Deep fading can be overcome with as much communication link margin as possible and combined with efficiency codec, low signal detection technology, high power and high frequency. Phase shift is a big problem and difficult to conquer for present TT&C systems are basically phase modulation-based. As discussed above, in low Mach such as Mach below 12, phase shift is not so large that BPSK may be considered with differential BPSK demodulation method for it can bear phase shift within 180°. However, PSK means have to give up at high Mach situation for large shift. Fortunately, if rapid acquisition and tracking phase-locked loop was used, there is some improving room for communication performance also.

Additionally, except the static plasma occasion discussed in this paper, plasma dynamics caused by rush fight condition change and turbulence exist in plasma sheath, which will cause additional phase jitter or phase noise [20–22]. This will bring new challenges to plasma sheath channel analysis and modeling, and communication performance will worsen. In this case, FSK would be more appropriate in contrast to PSK because it will not suffer from large phase shift and phase noise, but there may also be new receive technology problems that need to be studied further, and it is difficult to replace existing PSK based TT&C facility in practice.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China under Grant No. 61003196, No. 61105066 and Fundamental Research Funds for the Central Universities K50510040004, K50510040007.

REFERENCES

1. Rybak, J. P. and R. J. Churchill, “Progress in reentry communications,” *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 7, No. 5, 879–894, 1971.
2. Hartunian, R. A., G. E. Stewart, S. D. Fergason, T. J. Curtiss, and R.W. Seibold, “Causes and mitigation of radio frequency blackout

during reentry of reusable launch vehicles," Rep. ATR-2007(5309)-1,1-103, Aerosp. Corporation, El Segundo, Jan. 2007.

3. Akey, N. D., "Overview of RAM reentry measurements program," *The Entry Plasma Sheath and Its Effects on Space Vehicle Electromagnetic Systems*, 25–26, 1970.
4. Rawhouser, R., "Overview of the AF avionics laboratory reentry electromagnetics program," *The Entry Plasma Sheath and Its Effects on Space Vehicle Electromagnetic Systems*, Vol. I, 3–17, NASA Langley Research Center, 1970.
5. Li, J.-T., L.-X. Guo, Q.-J. Fang, and W. liu, "Electromagnetic wave propagation in plasma sheath of hypersonic vehicles," *Systems Engineering and Electronics*, Vol. 33, No. 5, 969–973, 2011.
6. Qian, Z. H., R.-S. Chen, K. W. Leung, and H. W. Yang, "FDTD analysis of microstrip patch antenna covered by plasma sheath," *Progress In Electromagnetics Research*, Vol. 52, 173–183, 2005.
7. Yang, H., W. Tang, and X. Kong, "Calculation of the effect on the reflection of the plane electromagnetic wave for non-magnetized plasma with different electron density distributions," *International Journal of Infrared and Millimeter Waves*, Vol. 28, No. 7, 547–556, 2007.
8. Yang, H., X. Duan, and H. Lu, "Simulation of electromagnetic wave reflection on plasma by multiresolution time-domain method," *Journal of Infrared, Millimeter and Terahertz Waves*, Vol. 30, No. 1, 51–55, 2009.
9. Liu, J.-F., X.-L. Xi, G.-B. Wan, and L.-L. Wang, "Simulation of electromagnetic wave propagation through plasma sheath using the moving-window finite-difference time-domain method," *IEEE Transactions on Plasma Science*, Vol. 39, No. 3, 852–855, 2011.
10. Pavelyev, A. G., Y.-A. Liou, J. Wickert, K. Zhang, C.-S. Wang, and Y. Kuleshov, "Analytical model of electromagnetic waves propagation and location of inclined plasma layers using occultation data," *Progress In Electromagnetics Research*, Vol. 106, 177–202, 2010.
11. Ai, X., Y. Han, C. Y. Li, and X.-W. Shi, "Analysis of dispersion relation of piecewise linear recursive convolution FDTD method for space-varying plasma," *Progress In Electromagnetics Research Letters*, Vol. 22, 83–93, 2011.
12. Naz, M. Y., A. Ghaffar, N. U. Rehman, M. Azam, S. Shukrullah, A. Qayyum, and M. Zakaullah, "Symmetric and asymmetric double Langmuir probes characterization of radio frequency inductively coupled nitrogen plasma," *Progress In Electromagnetics*

Research, Vol. 115, 207–221, 2011.

13. Naz, M. Y., A. Ghaffar, N. U. Rehman, S. Naseer, and M. Zakaullah, "Double and triple Langmuir probes measurements in inductively coupled nitrogen plasma," *Progress In Electromagnetics Research*, Vol. 114, No. 113–128, 2011.
14. Chai, L., "Selection of work frequency for near space vehicle TTC and information transmission system," *Acta Aeronautica et Astronautica Sinica*, Vol. 29, No. 4, 1007–1012, 2008.
15. Shi, L., B.-L. Guo, Y.-M. Liu, and L. Zhao, "Research on integrated channel model for Near-space hypersonic vehicle," *Yuhang Xuebao/Journal of Astronautics*, Vol. 32, No. 7, 1557–1563, 2011.
16. Rose, D. V., C. H. Thoma, and V. Sotnikov, "Analysis of plasma communication schemes for hypersonic vehicles: Final report," AFRL-SR-AR-TR-09-0129, 1–71, Feb. 25, 2009.
17. Gillman, E. D., J. E. Foster, and I. M. Blankson, "Review of leading approaches for mitigating hypersonic vehicle communications blackout and a method of ceramic particulate injection via cathode spot arcs for blackout mitigation," No. 20100008938, 1–25, NASA/TM-2010-216220, E-17194, Feb. 2010.
18. Heald, M. A. and C. B. Waharton, *Plasma Diagnostics with Microwaves*, John Wiley & Sons Inc., NewYork, 1978.
19. Lei, S., Y. Liu, B. Guo, and S. Jin, "Research on phase shift characteristics of radio propagate through plasma sheath," *2010 9th International Symposium on Antennas Propagation and EM Theory, ISAPE 2010*, IEEE Computer Society Guangzhou, China Nov. 29–Dec. 2, 2010.
20. Lin, T. C. and L. K. Sproul, "Influence of reentry turbulent plasma fluctuation on EM wave propagation," *Computers & Fluids*, Vol. 35, No. 7, 703–711, 2006.
21. Jandieri, G. V., A. Ishimaru, V. Jandieri, and N. N. Zhukova, "Depolarization of metric radio signals and the spatial spectrum of scattered radiation by magnetized turbulent plasma slab," *Progress In Electromagnetics Research*, Vol. 112, 63–75, 2011.
22. Gurel, C. S. and E. Oncu, "Interaction of electromagnetic wave and plasma slab with partially linear and sinusoidal electron density profile," *Progress In Electromagnetics Research Letters*, Vol. 12, 171–181, 2009.