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A layered fluctuation model of electron density in plasma sheath and instability effect on electromagnetic wave at Ka band

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ABSTRACT

The effects of plasma sheath on communication signals are not only power attenuation but also multiplicative noise addition because of the sheath's instability. The fluctuation properties of time-varying electron density are crucial to comprehensively understand the blackout problem. In this paper, the fluctuation laws of time-varying electron density are first comprehensively revealed in space–time–frequency domain. A layered fluctuation model of time-varying electron density is then proposed based on these fluctuation laws. The effects of dynamic plasma sheath on electromagnetic (EM) waves at Ka band are calculated by Monte Carlo quasistatic EM numerical method. Results show that the amplitude and phase of time-varying transmission coefficient both follow Gaussian distribution, whereas the spectrum curves follow a bi-Gauss function because of the effect of second mode instability in the hypersonic boundary layer. Furthermore, the means of amplitudes increase with the increasing of the incident EM wave frequency and the decreasing of the peak electron density, while the standard deviations decrease with the increasing of incident EM wave frequency, the decreasing of the peak electron density and the decreasing of electron density standard deviation.

1. Introduction

A spacecraft that moves in the atmosphere at hypersonic speed is enveloped by a plasma layer because of the shock wave that heats the surrounding air and abates the heat shield, thereby causing air molecules and heat shield material to be dissociated and ionized [1–4]. The plasma layer can strongly attenuate electromagnetic (EM) waves and cause communication interruption between vehicle and ground stations [5–7]. This problem is known as the communication blackout, and has not been completely solved [8,9]. Several promising methods have been proposed to alleviate this problem [6,10,11]. The methods include using high frequency, altering aerodynamic shaping, applying a magnetic field, and adding of electrophilic materials. They have a common purpose that increases the ratio of EM wave frequency and plasma frequency (f/f_p) to reduce attenuation.

However, several previous studies reveal that plasma layer is unstable. Plasma parameters fluctuate rapidly because of the influence of turbulence [7,12–14]. Antennas are often installed in the rear of the aircraft where the electron density is lower. However, fluctuation in rear boundary layer is more severe [15] and this strong disturbance also affects the quality of communication. EM waves suffer extra fading in the process of EM wave propagation, which cannot be solved by the alleviation methods. Therefore, the study on the influence of dynamic plasma sheath on EM waves is crucial to understand hypersonic vehicle communication problems.

In recent years, many studies have been done on the dynamic characteristics of plasma sheath. Lin [16] calculated transmission attenuation at 5.6 GHz and 44 GHz, and the result shows that EM wave at high frequency is less influenced by dynamic plasma. Liu [18] developed a novel method to connect pressure variation and relative permittivity of reentry plasma sheath, in which Ka frequency suffers less influence of pressure variation than does GPS frequency. Therefore, with the maturity of technology, using EM waves at high frequency, especially at the Ka band, is more feasible and adaptive than other methods to alleviate the blackout problem. Yang [17] analyzed the influence of plasma on transmitted communication signals by comparing the theoretical derivation and experimental data. Parasitic modulation of EM signals caused by time-varying plasma was observed. He [19] proposed a spatial-time electron density model, and a fluctuation law of transmission attenuation was analyzed preliminarily. However, his model is simple and the assumption on fluctuation laws was based on subsonic flows, which may not be applicable to hypersonic flows.

Few studies have investigated fluctuation laws of electron density and transmission coefficient of hypersonic plasma although they are crucial to high-frequency communication between hy-

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personic vehicle and ground stations. Therefore, this paper reveals these laws based on previous experimental measurement data and theoretical analysis. Characteristics of hypersonic plasma fluctuation are extracted, and a layered fluctuation model of time-varying electron density for dynamic plasma sheath is established. The model contains characteristics of time-varying electron density in space–time–frequency domain and contributes to dynamic plasma EM simulation and signal characteristics analysis. The effects of dynamic plasma on EM waves at Ka band under different conditions are also discussed in this paper. The results are crucial to communication channel modeling and can deepen the understanding of the plasma sheath blackout problem.

The rest of this paper is organized as follows. Section 2 studies the electron density fluctuation laws in hypersonic plasma layers. Section 3 proposes a layered fluctuation model using the laws, and the EM calculation method is introduced as well. The effect of hypersonic plasma on EM wave at the Ka band are given in Section 4, and the overall conclusion is summarized in Section 5.

2. Instability of electron density in hypersonic boundary layer

Plasma sheath has consistently been considered as a steady medium. However, complicated changes of parameters occur because of the disturbance of hypersonic turbulence. Velocity, temperature, and pressure are disorderly in time and spatial domain. Additionally, electron density, the main factor affecting EM wave propagation, also varies randomly. Spatial–temporal electron density at an antenna location $Ne(z,t)$ can be described as follows:

$$Ne(z,t) = \overline{Ne}(z,t) + \Delta Ne(z,t) = \overline{Ne}(z,t)\left(1 + \frac{\Delta Ne(z,t)}{\overline{Ne}(z,t)}\right) \quad (1)$$

where z is the axis normal to the vehicle surface, t is time, overline is the mean value, and Δ is the deviation from mean. For simplicity, a replacement can be made as follows:

$$r(z,t) = \frac{\Delta Ne(z,t)}{\overline{Ne}(z,t)}. \quad (2)$$

The peak value of electron density occurs at a considerable distance from the vehicle at high altitudes. The mean profile of electron density in an outward position from the vehicle surface $\overline{Ne}(z,t)$ can be represented by an asymmetric Gaussian function [20]. As the spacecraft descends, the pressure and temperature increase, the viscosity coefficient becomes larger, and another peak value appears close to the surface. The mean profile can be expressed by mixed Gauss function. When the altitude is lower than 30 km, the outer peak disappears, and the mean profile can be described as a one-sided Gauss function. Mean profiles of electron density at different altitudes in the RAM-C project is shown in Fig. 1 [21]. The general function of $\overline{Ne}(z,t)$ can be expressed as:

$$\begin{aligned}
&\overline{Ne}(z,t) = F_1(z) + F_2(z)\\
&F_1(z) = \begin{cases} Ne_{peak}e^{-c_1(z-z_{peak})^2}, & 0 \le z \le z_{peak} \\ Ne_{peak}e^{-c_2(z-z_{peak})^2}, & z_{peak} < z \le z_{\max} \end{cases} \quad (3)\\
&F_2(z) = Ne'_{peak}e^{-c_3 z^2} \quad (0 \le z \le z_{\max})
\end{aligned}$$

where c_1, c_2, and c_3 are shape parameters, Ne_{peak} is the electron density peak value at a considerable distance from the vehicle, Ne'_{peak} is the peak value near the surface, z_{peak} is the position of Ne_{peak}, and $z_{\max}$ is the thickness of plasma sheath. This function contains three forms: (i) $Ne'_{peak} = 0$, the function is asymmetric Gaussian, (ii) $Ne_{peak} \neq 0$, $Ne_{peak} \neq 0$, the function is mixed Gauss, (iii) $Ne_{peak} = 0$, the function is one-sided Gauss.

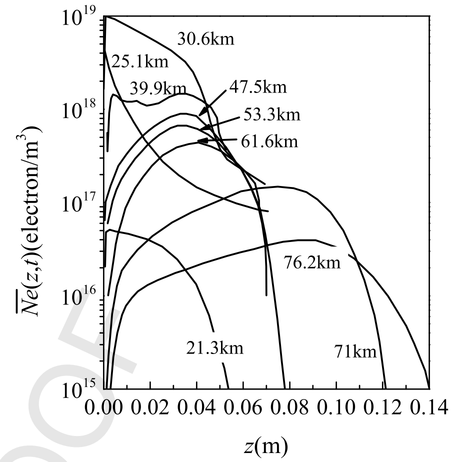

Fig. 1. Mean profiles of electron density at different altitudes of RAM C-III.

The instability of electron density $r(z,t)$ is a two-dimensional function of position z and time t. Fluctuation properties are derivable from hypersonic boundary layer theory and experiment data in literatures. The laws can be revealed in the spatial, temporal, and frequency domains.

2.1. Time domain

In hypersonic boundary layer, the Saha equation correlates the electron density variation magnitude and temperature variation magnitude at an arbitrary position z_m as [17]

$$\frac{\Delta Ne(z_m,t)}{\overline{Ne}(z_m,t)} = \left(\frac{1}{4} + \frac{E_i}{2K\overline{T}(z_m,t)}\right)\frac{\Delta T(z_m,t)}{\overline{T}(z_m,t)} \quad (4)$$

where T is temperature, K is the Boltzmann constant, and E_i is the ionization energy of plasma. When E_i is assumed as a constant, a proportionality between electron density and temperature variation can be obtained:

$$\frac{\Delta Ne(z_m,t)}{\overline{Ne}(z_m,t)} \propto \frac{\Delta T(z_m,t)}{\overline{T}(z_m,t)}. \quad (5)$$

Owen [22] found that temperature variation at arbitrary position $\Delta T(z_m,t)/\overline{T}(z_m,t)$ follows normal distribution in hypersonic wind tunnel experiment. As the direct ratio shown in equation (5), the probability density function of $r(z_m,t)$ would be Gaussian function and can be described as follows:

$$PDF\big(r(z_m,t)\big) = Gauss\big(r(z_m,t), \mu(z_m), \sigma(z_m)\big) \quad (6)$$

where $PDF(\cdot)$ is the probability density function, $Gauss(\cdot)$ is Gauss function, $\mu(z_m)$ is the mean value of $r\ (z_m,t)$, and $\sigma(z_m)$ is the standard deviation. The Gauss function is

$$Gauss(r,\mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(r-\mu)^2}{2\sigma^2}}. \quad (7)$$

2.2. Frequency domain

The first mode wave, namely low frequency disturbance, is in dominate position in the subsonic and supersonic boundary layers. However, references [23–25] indicate that fluctuations of flow field parameters are mainly caused by second mode instability wave in hypersonic boundary layer so that a peak will appears at high frequency in power spectrum. Estorf and Radespiel proved that pressure fluctuations are also affected by second mode instability in hypersonic wind tunnel at Mach 6 [23].

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