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Research Article

Effects of Reentry Plasma Sheath on GPS Patch Antenna Polarization Property

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A plasma sheath enveloping a reentry vehicle would affect performances of on-board antenna greatly, especially the navigation antennas. This paper studies the effects of reentry plasma sheath on a GPS right-hand circularly polarized (RHCP) patch antenna polarization property during a typical reentry process. Utilizing the algorithm of finite integration technique, the polarization characteristic of a GPS antenna coated by a plasma sheath is obtained. Results show that the GPS RHCP patch antenna radiation pattern distortions as well as polarization deteriorations exist during the entire reentry process, and the worst polarization mismatch loss between a GPS antenna and RHCP GPS signal is nearly 3 dB. This paper also indicates that measures should be taken to alleviate the plasma sheath for maintaining the GPS communication during the reentry process.

1. Introduction

A reentry vehicle reentering the Earth's atmosphere at a high Mach number speed is enveloped by a plasma sheath due to the shock wave heating of surrounding air and the ablation of heat shield materials, causing the ionizing of air molecules and heat shield materials [1]. The plasma sheath contains so many free electrons and ions that it can attenuate RF waves greatly through reflection and absorption effects. The primary problem associated with the reentry plasma sheath is the "communications blackout" during which performances of on-board electromagnetic systems can be severely degraded [2]. One of many important effects that contribute to the "blackout" problem is the failure of on-board antennas which have been affected greatly by the reentry plasma sheath [3].

The characteristic of on-board antennas covered by a reentry plasma sheath has been studied by several authors for several decades. Swift et al. [4–7] analyzed the characteristics of S/C band telemetry slot and waveguide antennas radiating into reentry plasma sheath. Galejs [8–10] analyzed and measured the admittance of homogeneous and inhomogeneous plasma-covered slot antenna using the variational method. Villeneuve [11] calculated the admittance of a rectangular waveguide radiating into a homogeneous plasma layer through an application of the reaction concept of Rumsey. Fante [12] described a simple technique for the admittance and the radiation pattern calculations of thin plasma slabs based on the impedance sheet notion. Hodara [13] analyzed the radiation characteristics of slot antennas covered with a magnetized plasma sheath. Qian and Chen [14] analyzed C-band microstrip patch antenna covered by plasma sheath using PLRC-FDTD algorithm, unfortunately, the plasma sheath used there is assumed to be uniform which is not the case for practical reentry plasma sheath. Recently, Bai et al. [15, 16] have studied the admittance and radiation characteristic of GPS and Beidou navigation patch antenna covered by reentry plasma sheath.

It is believed that the plasma sheath affects not only antenna admittance characteristics and radiation power pattern but also the polarization property. Although, the radiation property and impedance characteristic of plasma-covered antenna have been studied well. However, the deteriorations of antenna polarization property have not been payed much attention to and few works of literature have concentrated on the changes of GPS RHCP patch antenna polarization property in the reentry plasma environment. Consequently, analysing the effects of reentry plasma sheath on GPS patch antenna polarization property is also significant to the reentry blackout research and on-board electromagnetic systems design.

In this paper, a practical inhomogeneous plasma sheath profiles data from NASA's report and a dynamic stratified medium modeling method according to electron density profiles are adopted. The RHCP gain, polarization property, and polarization mismatch loss of a GPS RHCP microstrip patch antenna covered by a plasma sheath at different altitudes during a typical reentry process are analyzed utilizing the algorithm of finite integration technique.

2. Simulation Model

2.1. Reentry Plasma Sheath. Generally, a plasma sheath consists of equal numbers of positive ions and free electrons together with a large number of neutral particles. It is well known that the plasma can be characterised by two parameters which are electron density and collision frequency. The natural oscillation frequency of free electrons is the plasma frequency, and the frequency of free electrons colliding with ions and neutral particles is called the collision frequency. The relation between electron density N_e and the plasma frequency ω_p is defined as follows:

$$\omega_p = \left(\frac{N_e e^2}{\varepsilon_0 m_e}\right)^{1/2}, \quad (1)$$

where e is the electronic charge, m_e is the mass of the electron, and ε_0 is the dielectric coefficient of free space.

In practice, the reentry plasma sheath is inhomogeneous and varies with different altitudes. As indicated in the technical note [17], in the vehicle rear region where telemetry and navigation antennas are located, the distribution variations perpendicular to vehicle surface are larger than the variations along vehicle surface greatly; thus, a regular laminar model for the plasma is valid. Electron density distributions perpendicular to vehicle surface at the position of antenna window at different altitudes are obtained from NASA RAM-C data [18], shown in Figure 1. It is clear that shapes and peak values of the electron density distribution profiles change significantly at different altitudes, and it can be inferred that the variation of reentry plasma is tremendous during the entire reentry process.

The collision frequency distribution of reentry plasma sheath perpendicular to vehicle surface is believed to be approximately uniform [2], and the collision frequencies associated with clean air at different reentry altitudes are obtained by Bachynski et al. [19] as follows:

$$\nu = 3 \times 10^8 \left(\frac{\rho}{\rho_0}\right) \times T, \quad (2)$$

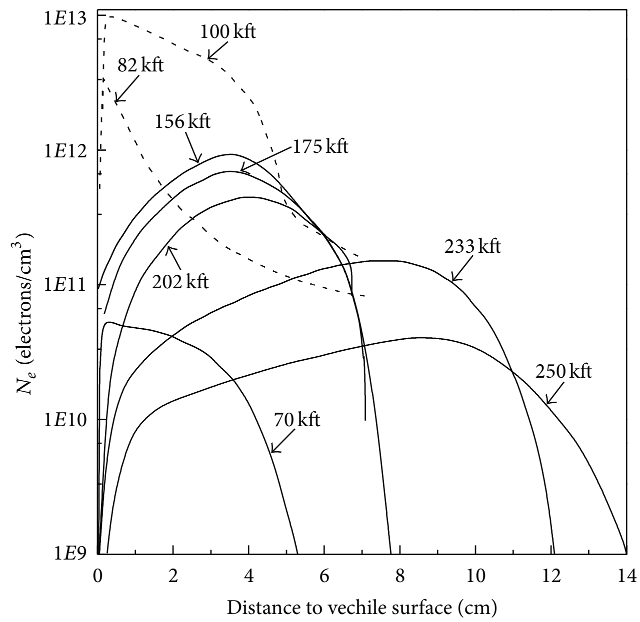

Figure 1: Electron density profiles at different altitudes for RAM-C vehicles (reprinted courtesy of NASA).

where ρ/ρ_0 the density ratio and T is the temperature in Kelvin degrees. The collision frequencies from 250 kft to 50 kft depend on the surrounding air temperature and change by four orders of magnitude. Throughout the reentry phase, the air temperature used in this paper for simulation is 2000 K according to the typical conical reentry vehicle surface temperature [20]. Thus, the collision frequencies at different typical altitudes during RAM-C reentry process adopted in this paper are listed in Table 1.

2.2. Inhomogeneous Plasma Sheath Stratified Modeling. The reentry plasma sheath is reflective, refractive, lossy, and frequency-dispersive medium. Thus, accurate analysis of the interaction of reentry plasma sheath with patch antenna is quite complicated. However, by some simplification, the inhomogeneous reentry plasma sheath can be modeled approximately by several adjacent homogeneous thin plasma slabs according to the electron density distribution profile. The degree of accuracy of this modeling method depends upon the number of slabs chosen to approximate the actual electron density and collision frequency distributions. To achieve excellent simulation accuracy and prevent the simulation mesh from being superabundance, the electron density discrepancy between the adjacent thin plasma slabs is limited to be less than 10%. As a result, in the region where the gradient of electron density distribution is large, the plasma slab width is thinner than the plasma slab width in the region where the gradient of electron density distribution is small.

Accordingly, the electromagnetic characteristic of reentry inhomogeneous plasma sheath can be established by the plasma frequency ω_p and collision frequency ν of each homogenous plasma slab. Assuming that the reentry plasma

Table 1: Collision frequencies in different typical altitudes (T = 2000 K).

Altitude/kft	70	82	100	156
Collision frequency/GHz	23.00	13.18	5.71	0.42
Altitude/kft	175	202	233	250
Collision frequency/MHz	175.0	49.92	11.82	5.37

sheath is divided into n layers, the complex relative dielectric coefficient of the mth plasma slab is established by

$$\varepsilon_r^m = \left[1 - \frac{\omega_{p,m}^2}{\omega^2 + \nu^2} - i\frac{\omega_{p,m}^2(\nu/\omega)}{\omega^2 + \nu^2}\right]. \quad (3)$$

In which $\omega_{p,m}$ is the plasma frequency in the mth layer, and ν is the collision frequency at the calculating altitude.

A schematic diagram of the stratified model which divided an electron density distribution profile of 250 kft into 40 layers is shown in Figure 2. In the regions 0–3 cm and 12–14 cm where the gradients of electron density distribution are large, the plasma slab width is thinner than that in the region 3–12 cm where the gradient of electron density distribution is small. Similarly, electron density profiles of inhomogeneous plasma sheath at others altitudes can be approximated in this stratified modeling method as well.

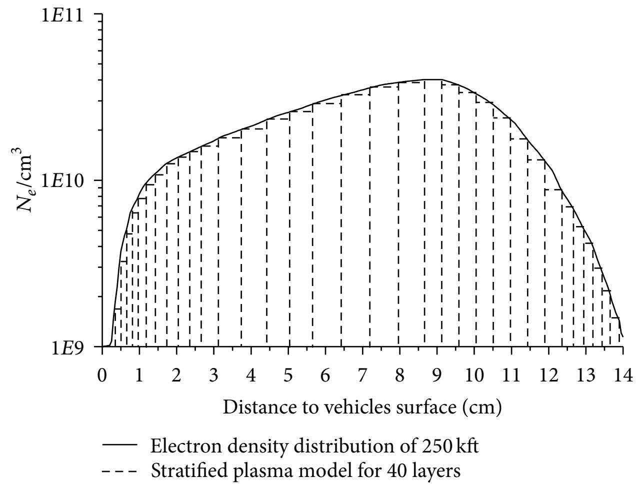

Figure 2: Inhomogeneous plasma sheath stratified models.

2.3. Plasma-Covered Antenna Simulation Technique. An RHCP square patch antenna [21] with two corners truncated is designed. The basic structure and dimensions of the designed patch antenna with an off-center point feeding are shown in Figure 3(a). The antenna operating frequency is designed to be 1.575 GHz with the 3 dB axial ratio bandwidth being 20 MHz. The electromagnetic simulation model of an inhomogeneous plasma-covered patch antenna is shown in Figure 3(b). Although the on-board patch antenna is usually conformed to the vehicle conducting surface, the entire vehicle actually has a small effect on the antenna radiation property since the vehicle is much larger than the antenna. Thus, the simulation model which only consists of a patch antenna and reentry plasma sheath excluding the entire vehicle can be employed approximately in studying the interactions of plasma sheath with a GPS patch antenna polarization property. And the interaction of the plasma sheath with patch antenna is analyzed using the algorithm of finite integration technique.

The finite integration technique (FIT) was proposed in 1977 by Thomas Weiland and was elaborated in the literature [22]. The key idea behind the FIT was to use, in the discretization, the integral, rather than the differential form of Maxwell's equations. This method stands out due to its high flexibility in geometric modeling and boundary handling as well as incorporation of arbitrary material distributions and materials such as anisotropic, nonlinearity, lossy and frequency-dispersive medium. Furthermore, the use of a consistent dual orthogonal grid (e.g., Cartesian grid) in conjunction with an explicit time integration scheme (e.g., leap-frog scheme) leads to computable and memory-efficient algorithms, which are especially adapted for transient field analysis in radio frequency (RF) applications.

Here the finite integration time domain algorithm is used to calculate electromagnetic characteristic of an RHCP patch antenna covered by reentry plasma sheath, and the results will be discussed in the following section.

3. Results and Discussion

The RHCP gain, polarization property, and polarization mismatch loss of a RHCP GPS microstrip patch antenna covered by plasma sheath at different altitudes during a typical reentry process are given below.

3.1. RHCP Gain. As the coordinate system for the antenna simulation is shown in Figure 3(b), the origin of coordinates is the feeding point, and the conducting patch is placed in the xoy-plane perpendicular to the z-axis. The RHCP pattern of xoz-plane (phi = 0 deg) and yoz-plane (phi = 90 deg) are cut from the 3D RHCP radiation pattern to indicate the ability of the patch antenna radiating RHCP waves. Since the patch antenna impedance is changing continuously during the entire reentry process [15, 16], it should add the impedance mismatch losses into the RHCP gain. And the results are shown in Figures 4 and 5.

Figure 4 shows the RHCP gain in the xoz-plane of a GPS patch antenna covered by plasma sheath at different typical reentry altitudes, respectively. It can be seen that antenna-realized gain pattern distortions and performance degradations exist during the entire phase of RAM-C reentry process. Due to the reflection, attenuation and refraction effects on electromagnetic waves caused by reentry plasma sheath, antenna forward gain and main lobe are reduced immensely, and meanwhile antenna backward gain as well as the side lobe is increased greatly.

Figure 5 gives the RHCP gain in the yoz-plane of a GPS patch antenna also covered by plasma sheath at different typical reentry altitudes respectively. It can be seen that the

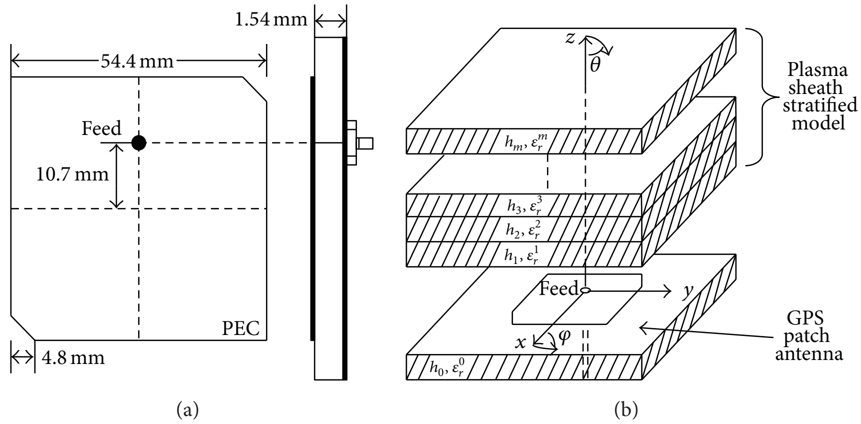

FIGURE 3: Plasma-covered antenna simulation models.

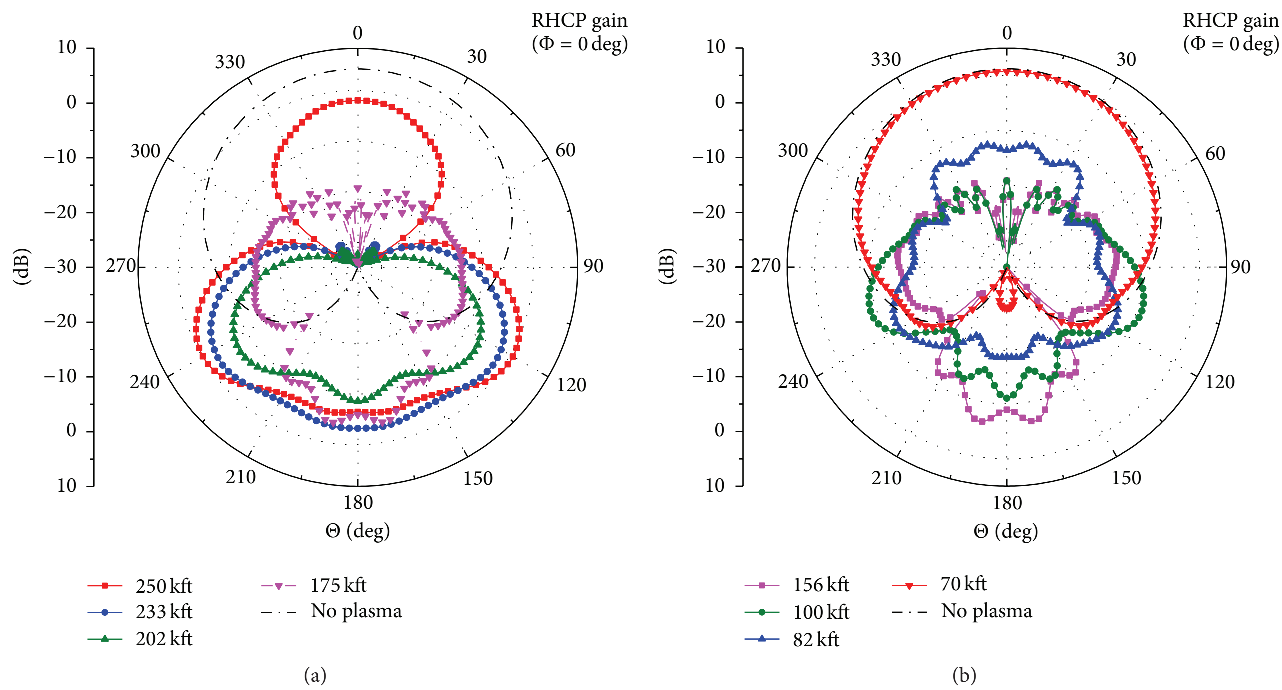

FIGURE 4: RHCP gain (plane of phi = 0 deg) at different altitudes.

distortions of antenna realized gain patterns are similar to that of Figure 4.

Figures 4 and 5 indicate that the GPS RHCP patch antenna forward gain is reduced by 15 dB from the altitudes of 233 kft to 82 kft; then assuming the communication link margin to be 15 dB, it can be concluded that in the perspectives of GPS patch antenna performance degradations the start and the end of GPS frequency reentry blackout altitude are 233 kft and 82 kft, respectively. This conclusion basically agrees well with the L-band RF blackout process of the NASA report [23].

3.2. Polarization Property. Since reentry plasma sheath affects GPS patch antenna-realized gain pattern greatly, the antenna polarization property deteriorations need to be studied as well. When GPS antenna elevation is lower than 60 degrees, the signal transmitted by GPS satellites could not be received efficiently; thus, only the polarization property of antenna elevation less than 60 degrees is studied in this paper. Figures 6 and 7 show GPS patch antenna axial ratio property of *xoz*-plane (phi = 0 deg) and *yoz*-plane (phi = 90 deg) at different typical reentry altitudes.

It can be seen that GPS patch antenna polarization property deteriorates a little only at the altitude of 70 kft; however, at the other altitudes especially 175 kft, and 156 kft the antenna polarization property deteriorates immensely. Consequently, the reentry plasma sheath causes the depolarization effect on the GPS antenna receiving performance, and then polarization mismatch loss may occur between the GPS signal and GPS antenna. Additionally to the degradations of realized gain, polarization mismatch losses reduce the

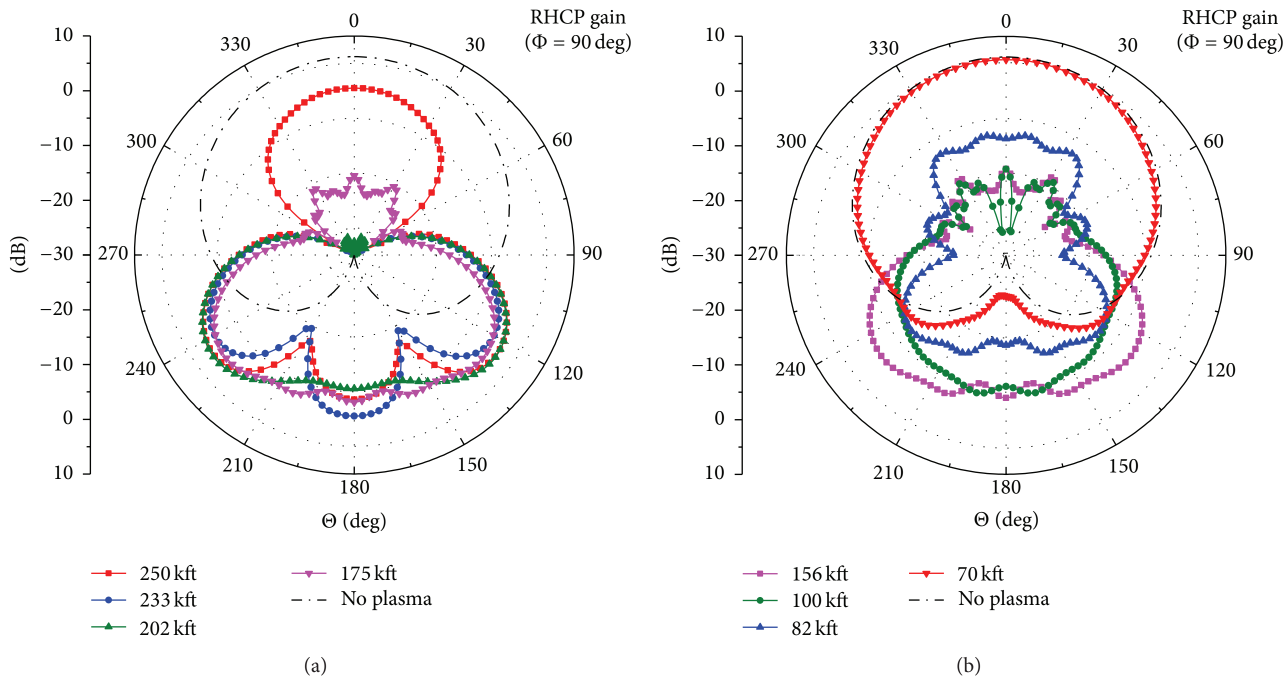

Figure 5: RHCP gain (plane of phi = 90 deg) at different altitudes.

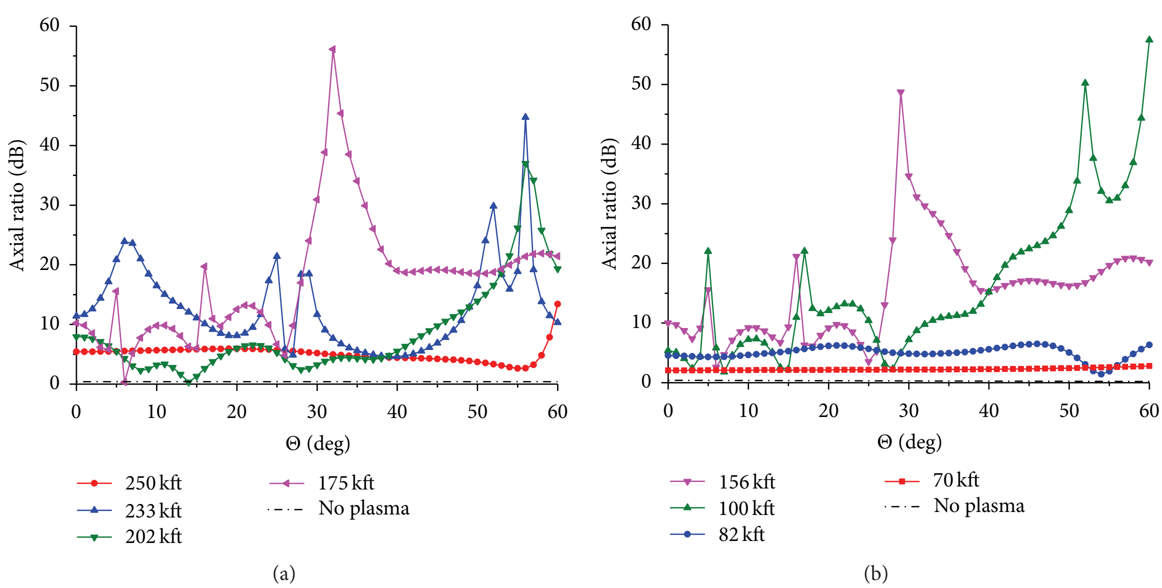

Figure 6: Axial ratio (plane of phi = 0 deg) at different altitudes.

antenna receiving ability further more. Therefore, polarization mismatch losses caused by the reentry plasma sheath should be studied in the following section.

3.3. Polarization Mismatch Loss. Assuming that an RHCP GPS signal is transmitted to this plasma-covered GPS patch antenna, it may cause polarization mismatch loss between the receiving antenna and the RHCP GPS signal due to GPS patch antenna polarization property deteriorations. Figures 8 and 9 show the antenna polarization mismatch loss of *xoz*-plane (phi = 0 deg) and *yoz*-plane (phi = 90 deg) at different typical reentry altitudes, respectively. It can be seen that polarization mismatch loss exists during the entire phase of RAM-C reentry process. The results show that the worst altitudes of polarization mismatch are 175 kft and 156 kft, and the worst mismatch loss is nearly 3 dB. As a result, GPS antenna receiving ability is deteriorated due to the polarization mismatch losses, and these worsen the reentry vehicle GPS blackout problem much more.

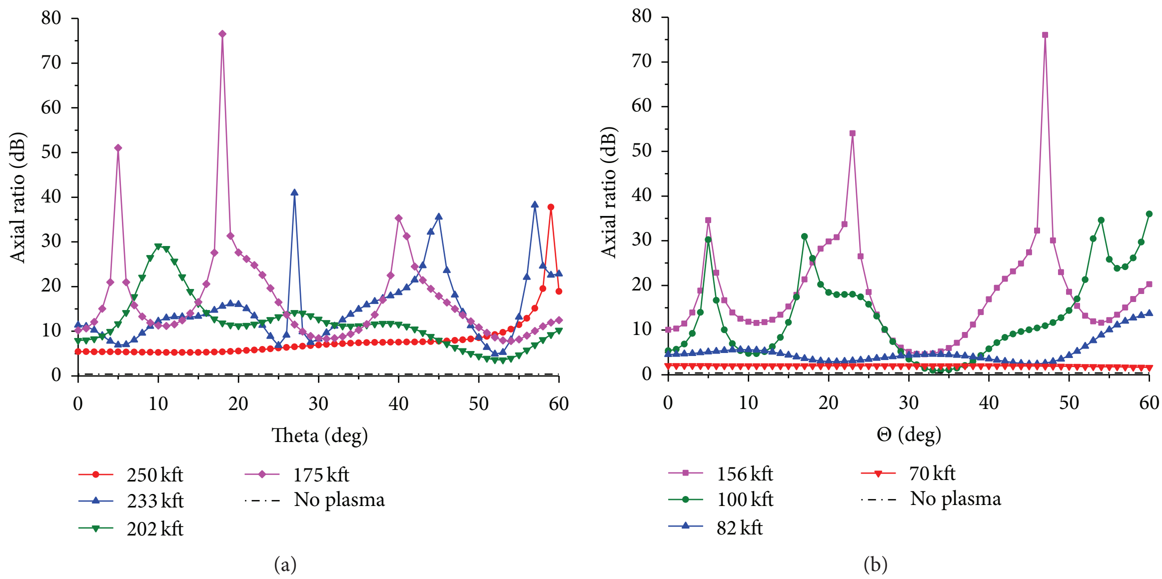

Figure 7: Axial ratio (plane of phi = 90 deg) at different altitudes.

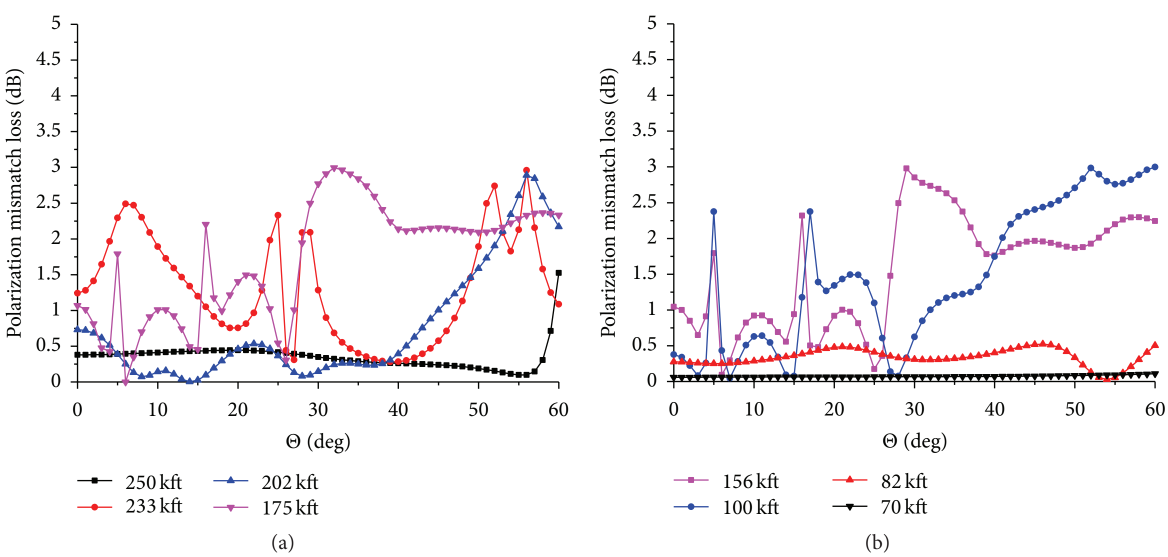

Figure 8: Polarization mismatch loss (plane of phi = 0 deg) at different altitudes.

Noticing that the polarization mismatch loss is below 0.5 dB at the altitudes of 70 kft, for the plasma sheath is not severe enough, measures should be taken to alleviate the plasma sheath for maintaining the GPS communication during the reentry process.

4. Conclusions

This paper utilizes a dynamic stratified modeling method to establish electromagnetic simulation models of reentry inhomogeneous plasma sheath and then studies the effects of the reentry plasma sheath on a GPS RHCP patch antenna polarization property. The electron density distribution and collision frequency data got from the NASA report are used to assess the performance of the GPS patch antenna; as a result, the process of RAM-C GPS reentry blackout can be reproduced basically from the perspective of GPS patch antenna performance degradation. Moreover, in addition to the degradations of antenna-realized gain pattern, antenna polarization property deteriorations and polarization mismatch losses are also important in the reentry vehicle GPS communication system designing. Consequently, it should attract much more attention to antenna polarization property in the reentry vehicle electromagnetic system design. Finally, the results indicate that it should take measures to alleviate the plasma sheath for maintaining the GPS communication during the reentry process; meanwhile, in order to calculate the on-board antenna radiation property affecting the entire

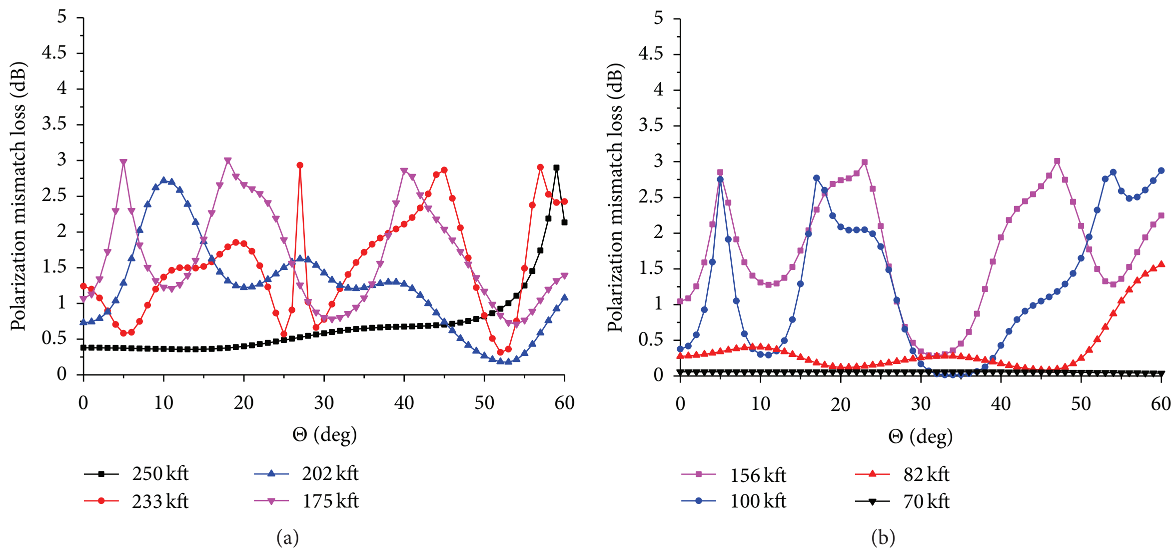

Figure 9: Polarization mismatch loss (plane of phi = 90 deg) at different altitudes.

reentry vehicle and overall plasma sheath accurately, an electrically large simulation technique should be proposed in the future.

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