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Effects of Reentry Plasma Fluctuation on Polarization Properties of Electromagnetic Waves

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Abstract—Fluctuations of the reentry plasma sheath can affect the propagation of Electromagnetic waves. The relations between fluctuations and the propagation of electromagnetic waves are analyzed. The effects on polarization properties in L-band, S-band and Ka-band during a typical reentry process are studied using methods derived by synthesizing the compressible turbulent flow theory, plasma theory, and electromagnetic wave theory together. Results show that in L-band and S-band, the effects increase with the altitude, while in Ka-band, the effects decrease with altitude. The effects at high altitude above 60 km are prominent in L-band and S-band, while the effects at middle and low altitude below 60 km in Ka-band are obvious. The effects in L-band and S-band are much bigger than that in Ka-band and can affect the signal properties of TT&C systems significantly, while the effects in Ka-band are much milder. The waves with large oblique incident angle can encounter much more severe conditions than that with small angle.

1. INTRODUCTION

A supersonic spacecraft reentering the Earth's atmosphere produces intense shock-wave heating and causes a plasma sheath enveloping the vehicle. This plasma sheath contains enormous unbound electrons which can interact with the electromagnetic field. Thus, the plasma sheath can strongly attenuate the Electromagnetic (EM) waves and causes severe deterioration of the signals between the vehicle and ground base stations. At the worst conditions, the plasma sheath can even cause a complete loss of the signals. This phenomenon is known as "communication blackout" and often sustains several minutes during a typical reentry process. The blackout is one of the worst situations for tracking, telemetry and command (TT&C) [1]. Therefore, researchers have been spending considerable efforts to analyze the propagation properties of the RF waves transmitting the plasma sheath [2–8].

Since the 1960s, the National Aeronautics and Space Administration (NASA) have conducted series of programs [9–11], which studied the blackout both theoretically and experimentally. Methods of numerical calculation of the flow were proposed. Cases of blackout were researched. Attenuation of EM wave was estimated roughly. Mitigation methods were proposed, and reentry crafts were launched. Besides, researchers have focused on the influence of plasma on EM wave propagation theoretically, experimentally or resorting to numerical calculations. Vidmar [12] utilized the Epstein electron density distribution model to analyze the interaction between plasma and radar waves. Laroussi and Roth [13] derived the relationship of electron density, collision frequency, and incident angle with absorbed power and reflected power in unmagnetized plasma using the WKB method. Petrin [14, 15] analyzed the nonlinear mechanism between EM waves and plasma by studying the left-hand polarized wave and right-hand polarized wave, respectively. Kim and Boyd [16] got the attenuation and reflection of reentry signals in different electron densities and collision frequencies. Lontano and Lunin [17–19]

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derived the coefficients of reflection and transmission of EM waves propagating through a non-uniform, unmagnetized plasma sheath. Cerri et al. [20] discussed the relation between electron density, plasma sheath thickness and coefficient of reflection in detail when wave frequencies are between 1 GHz and 20 GHz. Recently, Bai et al. [21] discussed the transmission properties of polarized wave.

Most of the researches mentioned above take the plasma sheath as a steady dielectric medium. However, the reentry plasma sheath is fiercely unsteady [22, 23]. This induces the fluctuations of the plasma parameters and causes the fluctuations of the dielectric properties of the plasma sheath. Thus the method which takes the plasma sheath as steady medium is not sufficient in TT&C system design. For more reliable communications, the worst conditions must be considered.

In this paper, compressible turbulent flow theory, plasma theory and EM wave theory are used together to establish the relation between plasma parameter fluctuations and the fluctuations of the dielectric parameters. On these bases, the influences of plasma parameter fluctuations on the EM wave propagation properties are estimated with the actual plasma sheath data of blunt-nosed reentry craft launched by NASA.

2. RELATIONS BETWEEN PLASMA PARAMETERS AND WAVE PROPAGATION

2.1. Relations between Fluctuations of Plasma Parameters

For compressible turbulent flow, the fluctuations of plasma parameters have the relation as below [24]:

$$\frac{\Delta p}{\bar{p}} = n\frac{\Delta \rho}{\bar{\rho}} = \frac{n}{n-1}\frac{\Delta T}{\bar{T}} \tag{1}$$

where the overbar of a quantity $\overline{(\bullet)}$ represents an averaged quantity; a preceding Δ represents a perturbation from the averaged quantity; n is a polytropic coefficient. A great deal of simulation results indicate that n is approximately equal to the specific heat ratio λ.

For plasma conditions, the electron density fluctuation and temperature fluctuation have the relation as below [25]:

$$\Delta N_e = \bar{N}_e\left(\frac{1}{4} + \frac{E_i}{2K\bar{T}}\right)\frac{\Delta T}{\bar{T}} \tag{2}$$

where N_e is the electron density, K the Boltzmann constant, and E_i the ionization energy of plasma. For reentry conditions, one can take $E_i/2K\bar{T} \approx 29$ as an estimate [26].

At the rear of the reentry craft where the TT&C antenna windows are located, the plasma collision frequency ν is expressed as below [27–31]:

$$\nu = 2.71 \times 10^7 P\,[\mathrm{Pa}]\,T\,[\mathrm{K}]^{-1/2} \tag{3}$$

According to Equation (3), one can get the relation of plasma collision frequency fluctuation and the fluctuations of temperature and pressure:

$$\Delta\nu = 2.71 \times 10^7\left(\bar{T}\,[\mathrm{K}]^{-1/2}\,\Delta P - \frac{1}{2}\bar{P}\,[\mathrm{Pa}]\,\bar{T}\,[\mathrm{K}]^{-3/2}\,\Delta T\right) \tag{4}$$

Equation (4) can be transformed as below:

$$\begin{aligned}\Delta\nu &= 2.71 \times 10^7\left(\bar{T}^{-1/2}\Delta P - \frac{1}{2}\bar{P}\bar{T}^{-3/2}\Delta T\right)\\ &= 2.71 \times 10^7\left(\bar{T}^{-1/2}\frac{\lambda}{\lambda-1}P\frac{\Delta T}{\bar{T}} - \frac{1}{2}\bar{P}\bar{T}^{-3/2}\Delta T\right)\\ &= 2.71 \times 10^7\left(\frac{\lambda}{\lambda-1}\bar{P}\bar{T}^{-3/2}\Delta T - \frac{1}{2}\bar{P}\bar{T}^{-3/2}\Delta T\right)\\ &= 2.71 \times 10^7\left(\frac{\lambda}{\lambda-1} - \frac{1}{2}\right)\bar{P}\bar{T}^{-3/2}\Delta T\\ &= 2.71 \times 10^7\frac{\lambda+1}{2(\lambda-1)}\bar{P}\bar{T}^{-3/2}\Delta T\end{aligned} \tag{5}$$

If the average plasma collision frequency is known, Equation (5) can be expressed as:

$$\Delta\nu = \bar{\nu} \cdot \frac{\lambda + 1}{2(\lambda - 1)} \frac{\Delta T}{\bar{T}} \tag{6}$$

2.2. Relations between Fluctuations of Plasma Electron Density, Collision Frequency and Dielectric Constant

Plasma is a kind of lossy dielectric medium, and its dielectric constant ε_r can be expressed as [32]:

$$\varepsilon_r = 1 - \frac{\omega_p^2}{\omega^2 + v^2} - i\frac{\omega_p^2(v/\omega)}{\omega^2 + v^2} \tag{7}$$

where ω_p is the plasma frequency [25]:

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \tag{8}$$

with e the electronic charge and m_e the mass of the electron.

Assume that the frequency of EM wave is constant. The fluctuation of dielectric constant $\Delta\varepsilon_r$ can be expressed as:

$$\Delta\varepsilon_r = \frac{\partial\varepsilon_r}{\partial\omega_p}\frac{\mathrm{d}\omega_p}{\mathrm{dN_e}}\Delta N_e + \frac{\partial\varepsilon_r}{\partial\nu}\Delta\nu \tag{9}$$

Thus, the relation between fluctuation of dielectric constant and fluctuations of electron density and collision frequency is:

$$\begin{aligned}
\Delta\varepsilon_r &= \left[\frac{2\omega_p}{\omega^2+\nu^2}\cdot\frac{1}{2}\left(\frac{e^2}{\varepsilon_0 m_e}\right)^{-1/2} N_e^{-3/2}\Delta N_e + \frac{2\nu\omega_p^2}{\left(\omega^2+v^2\right)^2}\Delta\nu\right] \\
&\quad -j\left[\frac{\nu}{\omega}\frac{2\omega_p}{\omega^2+\nu^2}\cdot\frac{1}{2}\left(\frac{e^2}{\varepsilon_0 m_e}\right)^{-1/2} N_e^{-3/2}\Delta N_e + \frac{\omega_p^2}{\omega}\frac{\omega^2-v^2}{\left(\omega^2+v^2\right)^2}\Delta\nu\right] \\
&= \left[\frac{1}{\omega^2+\nu^2}\cdot N_e^{-1}\cdot\Delta N_e + \frac{2e^2}{\varepsilon_0 m_e}\cdot\frac{\nu}{\left(\omega^2+v^2\right)^2}\cdot N_e\cdot\Delta\nu\right] \\
&\quad -j\left[\frac{\nu}{\omega\left(\omega^2+\nu^2\right)}\cdot N_e^{-1}\cdot\Delta N_e + \frac{e^2}{\varepsilon_0 m_e}\cdot\frac{\omega^2-v^2}{\omega\left(\omega^2+v^2\right)^2}\cdot N_e\cdot\Delta\nu\right]
\end{aligned} \tag{10}$$

With the equations above, the relation between fluctuation of dielectric constant and fluctuations of plasma parameters can be derived. One can use this relation to estimate the influences of the plasma sheath parameter fluctuations on EM wave propagation.

3. BLUNT-NOSED REENTRY PLASMA MODEL

3.1. Blunt-Nosed Reentry Plasma Conditions

The plasma conditions of a reentry craft are closely related to the shape of the craft. And the conditions of the blunt-nosed reentry crafts are unique. This paper takes one of the most representative blunt-nosed reentry crafts, the reentry capsule of the RAM CII experiment, as an example to study the effects of plasma fluctuation on EM waves.

Several plasma parameters are most concerned for the study. They are plasma electron density and its distribution, collision frequency and its distribution. In consideration that this paper concerns the effects of plasma fluctuation, the fluctuation patterns of electron density and collision frequency are also important.

Analyze the electron density and its distribution firstly. In practice, the reentry plasma sheath is isotropic and varies with altitude. For telemetry and navigation, the plasma parameters in the antenna window region are most interesting. In the RAM CII reentry vehicle, they are located at the rear region.

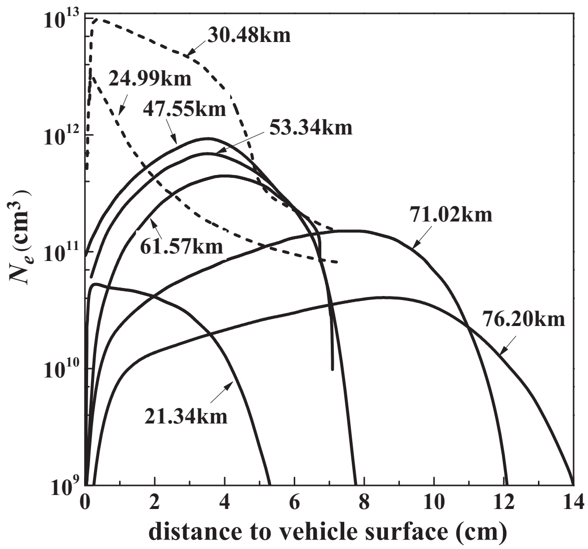

Figure 1. Electron density profiles at different altitudes from NASA RAM-C data.

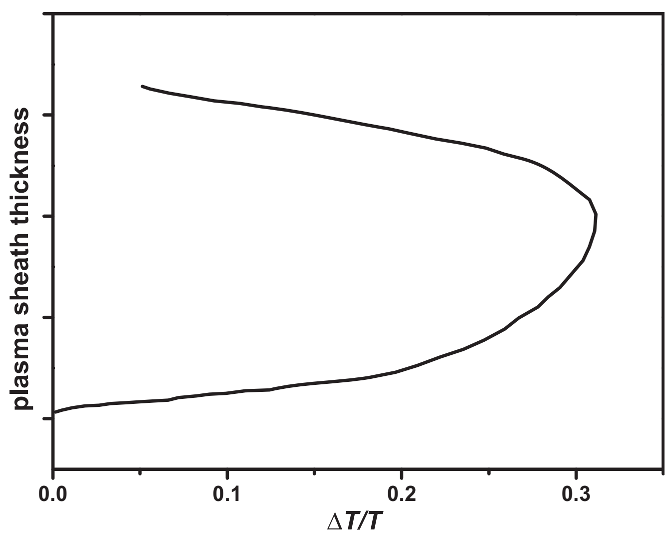

Figure 2. Fluctuation pattern.

As indicated in the technical note [33], the electron density distributions at the antenna window region for different altitudes are shown in Figure 1. We take these distributions as the average electron density distributions.

Secondly, we analyze the collision and its distribution. As Rybak noted, the collision frequency distributions of reentry plasma sheath normal to the vehicle surface are believed approximately uniform [34]. Thus, we can take the collision frequency at each altitude as constant and use the data calculated by Bachynski et al. as the average collision frequency [35, 36]. The adopted collision frequencies are listed in Table 1.

Table 1. Collision frequencies at different typical altitudes.

Altitude/km	Collision Frequency/GHz	Altitude/km	Collision Frequency/MHz
21.34	23.00	53.34	175.0
24.99	13.18	61.57	49.92
30.48	5.71	71.02	11.82
47.55	0.42	76.20	5.37

Thirdly, we analyze the fluctuation pattern. The parameter fluctuations of the blunt-nosed reentry plasma sheath have a unique pattern. As Lin and Sproul indicate in [25], the variations of the temperature fluctuation distributions normal to the vehicle surface are considerably obvious and approximately obey the double-Gaussian distribution. The peak intensity of the fluctuation is about $\Delta T/T = 0.3$, as shown in Figure 2. According to the fluctuation pattern of T, we can use Equations (2) and (6) above to obtain the fluctuation pattern of electron density and collision frequency, and consequently obtain the fluctuation of dielectric constant. Thus, we assume that the distributions of the fluctuations are the double-Gaussian distribution, and the peak intensity of the fluctuation is $\Delta T/T = 0.3$. The thicknesses of the plasma sheath at different altitudes are taken from the data of Figure 1.

Use the relations of different parameter fluctuations and the blunt-nosed reentry plasma conditions introduced above, the effects of plasma parameter fluctuation on EM wave propagation can be estimated.

3.2. Stratified Layering Model of Plasma Sheath

Adopting some simplifications, the inhomogeneous reentry plasma sheath can be layered approximately by several adjacent homogeneous thin plasma slabs, shown in Figure 3. Each slab's thickness depends on the spatial variation of the electron density distribution. The plasma parameters of each layer are a number of mean values of the distributions. The accuracy of this modeling method depends on the number of slabs chosen to approximate the actual electron density distributions. To achieve accurate simulations, the electron density discrepancy between the adjacent slabs should be small. Consequently, to divide the sheath reasonably, the plasma slabs in regions where the gradient of the profile is sharp should be thinner than that in regions where the gradient is slow.

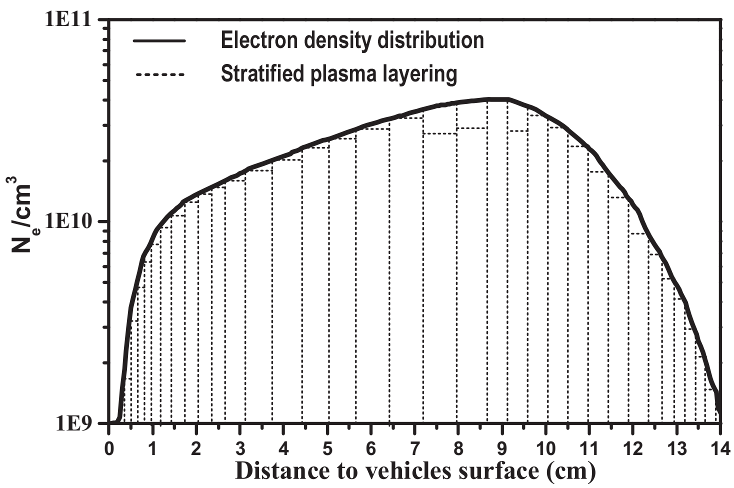

Figure 3. Stratified layering model of plasma sheath.

3.3. Polarization Properties

A wave penetrated through the plasma sheath can be orthogonally decomposed into a pair of perpendicular polarized wave and parallel polarized wave. Its penetrated electric field $\vec{E}^t$ is expressed as [21, 37]:

$$\vec{E}^t = E^t_{\parallel}\vec{v}_{\parallel} + E^t_{\perp}\vec{v}_{\perp} = E^i_{\parallel}T_{\parallel}\vec{v}_{\parallel} + E^i_{\perp}T_{\perp}\vec{v}_{\perp} \tag{11}$$

where $\vec{v}_{\parallel}$ is the unit vector along the parallel polarization direction and $\vec{v}_{\perp}$ the unit vector along the perpendicular polarization direction. The superscripts i and t represent the incident and penetrated fields, respectively.

Because of discrepancies in the transmission coefficients between the perpendicular and parallel polarized waves, the polarization properties of the penetrated wave are altered.

To analyze the oblateness of the penetrated wave, the axial ratio is appropriate. Take the axial ratio of the righthanded polarized wave as negative and the left-handed polarized wave as opposite. The axial ratio of the penetrated wave is described as [21, 37]:

$$AR = \tan\left(\frac{1}{2}\arcsin\left(\frac{2|E^i_{//}T_{//}||E^i_{\perp}T_{\perp}|\sin\phi^t}{|E^i_{//}T_{//}|^2 + |E^i_{\perp}T_{\perp}|^2}\right)\right) \tag{12}$$

where $|E^t_{//}|=|E^i_{//}T_{//}|$ and $|E^t_{\perp}|=|E^i_{\perp}T_{\perp}|$ are the amplitudes of the penetrated parallel and perpendicular polarized waves.

ϕ^t is the phase difference between the perpendicularly polarized component and parallelly polarized component of the penetrated wave. With this parameter, one can assess the influences of lossy medium on the phase characteristics of the incident wave without a priori knowledge of initial phase. For an incident RHCP wave, the phase difference is $-90°$, and after penetrated from the plasma sheath, the phase difference will probably change.

For a full description of the penetrated wave, Stokes parameters are useful [21, 37]:

$$\begin{cases} g_0^t = \left|E_{//}^i T_{//}\right|^2 + \left|E_\perp^i T_\perp\right|^2 \\ g_1^t = \left|E_{//}^i T_{//}\right|^2 - \left|E_\perp^i T_\perp\right|^2 \\ g_2^t = 2 \cdot \left|E_{//}^i T_{//}\right| \cdot \left|E_\perp^i T_\perp\right| \cdot \cos\phi^t \\ g_3^t = 2 \cdot \left|E_{//}^i T_{//}\right| \cdot \left|E_\perp^i T_\perp\right| \cdot \sin\phi^t \end{cases} \tag{13}$$

The difference between the incident wave and penetrated wave can induce the polarization mismatch between the transmitting and receiving antennas that will bring in additional mismatch loss. Thus polarization mismatch loss is needed to investigate.

Assume that the Stokes parameters of the receiving antenna in the arrival direction of the penetrated wave are [21, 37]

$$\begin{bmatrix} g_0^r & g_1^r & g_2^r & g_3^r \end{bmatrix} \tag{14}$$

The polarization match coefficient between the receiving antenna and penetrated wave is expressed as [21, 37]:

$$m_p = \frac{g_0^t g_0^r + g_1^t g_1^r + g_2^t g_2^r + g_3^t g_3^r}{2 \cdot g_0^t g_0^r} \tag{15}$$

Then, the polarization mismatch loss is [21, 37]

$$Loss = 10 \cdot \log_{10}(m_p) \text{ dB} \tag{16}$$

4. RESULTS AND DISCUSSION

As the L-band and S-band are widely used in telemetry and navigation and the Ka-band is thought to be a means of overcoming the blackout, propagation properties at 1.575 GHz (L-band), 2.4 GHz (S-band) and 3 GHz (Ka-band) for different altitudes are analyzed, and the incident angles selected are 30° and 60°. Results are given below.

4.1. Effects on Axial Ratio of Penetrated Wave

The effects of reentry plasma fluctuations on axial ratios of penetrated waves with different incident angles are presented in Fig. 4 to Fig. 6. The y-axes in these figures are the differences of axial ratios of penetrated waves between postulated conditions with and without reentry plasma fluctuations. The x-axes in these figures are altitudes.

From these figures, one can find that the effects of reentry plasma fluctuations on axial ratios of the penetrated waves change with altitudes. The effects are complicated and changeable. But from the general change trend, one can find that in L-band and S-band, the effects increase with the altitude, while in Ka-band, the effects decrease with altitude. The effects at high altitude above 60 km are prominent in L-band and S-band, while the effects at middle and low altitude below 60 km in Ka-band are obvious.

Comparing the effects in L-band, S-band and Ka-band, the effects of reentry plasma fluctuations on axial ratios in L-band and S-band are much bigger than that in Ka-band, while the effects in L-band and S-band are similar. It means that the distortions of the TT&C signals are much severe in L-band and S-band than Ka-band.

Comparing the effects with an incident angle of 30° and 60°, the former is much smaller than the latter. It means that the TT&C signals will encounter a much more severe distortion in a large oblique angle condition.

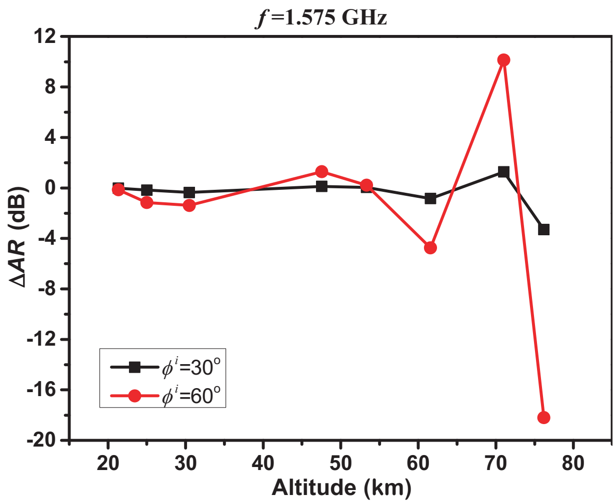

Figure 4. Effects on axial ratio of penetrated wave in L-band.

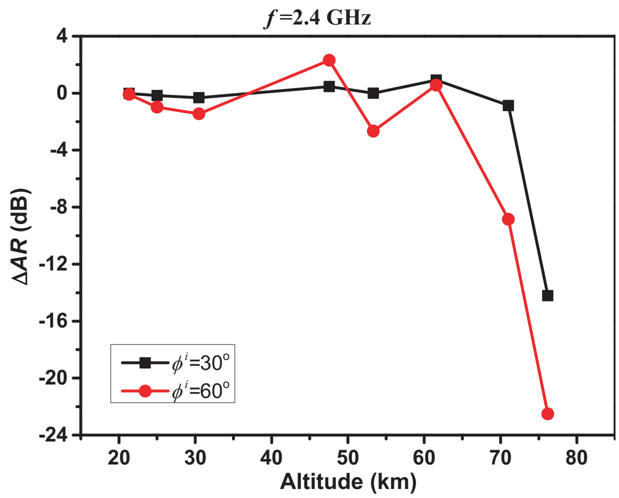

Figure 5. Effects on axial ratio of penetrated wave in S-band.

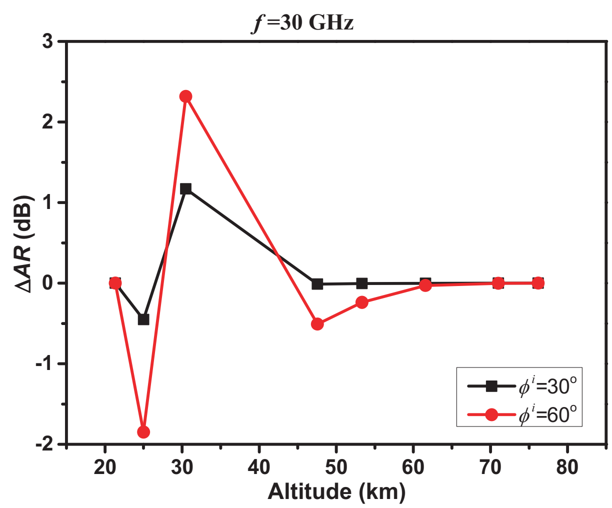

Figure 6. Effects on axial ratio of penetrated wave in Ka-band.

4.2. Effects on Phase Difference between Perpendicular Polarized Component and Parallel Polarized Component of Penetrated Wave

The effects of reentry plasma fluctuations on phase difference between perpendicular polarized component and parallel polarized component of penetrated waves with different incident angles are presented in Fig. 7 to Fig. 9. The y-axes in these figures are the phase difference between postulated conditions with and without reentry plasma fluctuations. The x-axes in these figures are altitudes.

Form the figures, one can find that the general change trend is similar to the effects on axial ratios. The effects increase with the altitude, while in Ka-band, the effects decrease with altitude. The effects at high altitude above 60 km are prominent in L-band and S-band, while the effects at middle and low altitude below 60 km in Ka-band are obvious. The effects in L-band and S-band are much bigger than that in Ka-band. And the effects with an incident angle of 6° are bigger than that with a 3° incident angle.

In L-band and S-band, the maximum effects are close to 120°, which can affect the signal properties of TT&C systems significantly, while in Ka-band, the influences are much milder.

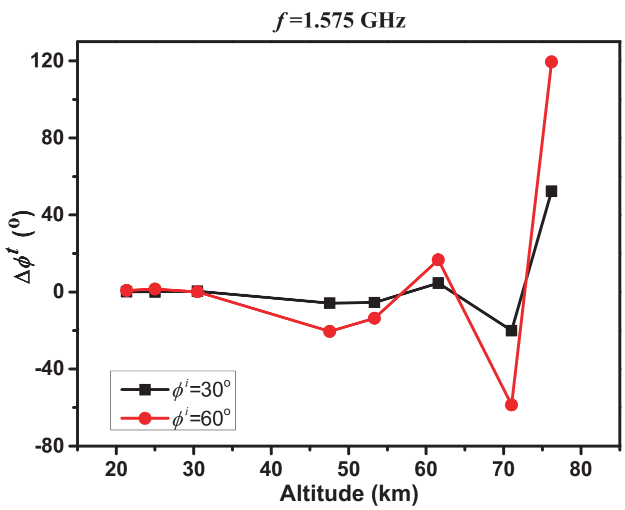

Figure 7. Effects on phase difference in L-band.

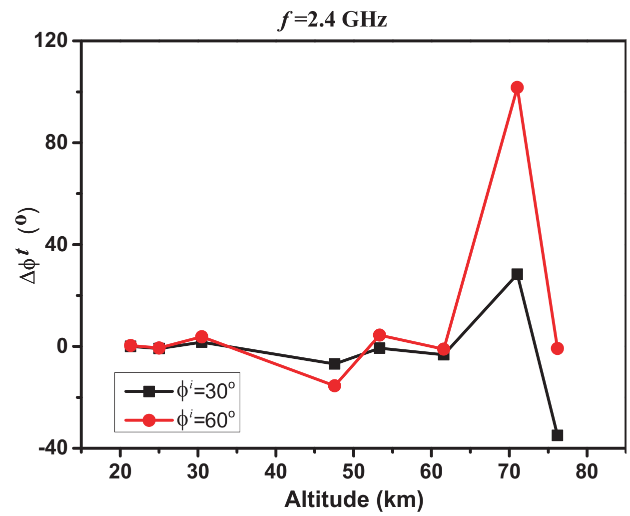

Figure 8. Effects on phase difference in S-band.

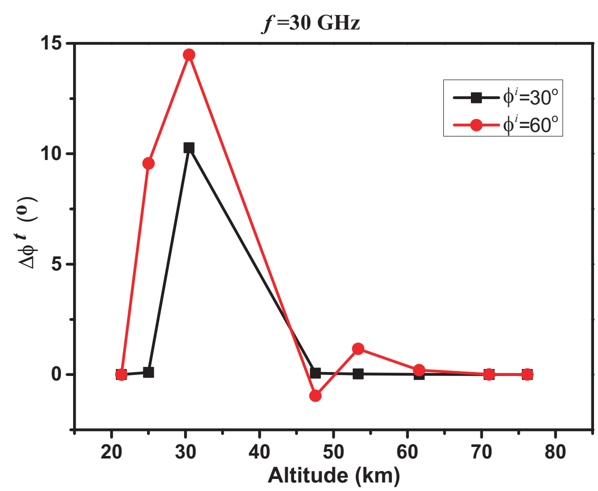

Figure 9. Effects on phase difference in Ka-band.

4.3. Effects on Polarization Mismatch Loss between Penetrated Wave and Receiving Antenna

The effects of reentry plasma fluctuations on polarization mismatch loss between penetrated wave and receiving antenna with different incident angles are presented in Fig. 10 to Fig. 12. The y-axes in these figures are the differences of polarization mismatch loss between postulated conditions with and without reentry plasma fluctuations. The x-axes in these figures are altitudes.

Form the figures, one can find that the general change trend is similar to that on axial ratios and phase difference. The effects increase with the altitude, while in Ka-band, the effects decrease with altitude. The effects at high altitude above 60 km are prominent in L-band and S-band, while the effects at middle and low altitude below 60 km in Ka-band are obvious. The effects in L-band and S-band are much bigger than that in Ka-band. And the effects with an incident angle of 6° are bigger than that with a 3° incident angle.

In L-band and S-band, the maximum effects are close to 3 dB, while in Ka-band, the maximum effects are less than 0.2 dB.

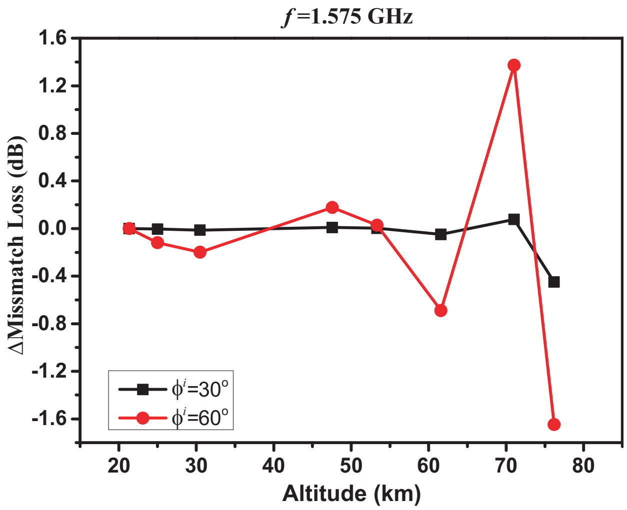

Figure 10. Effects on polarization mismatch loss in L-band.

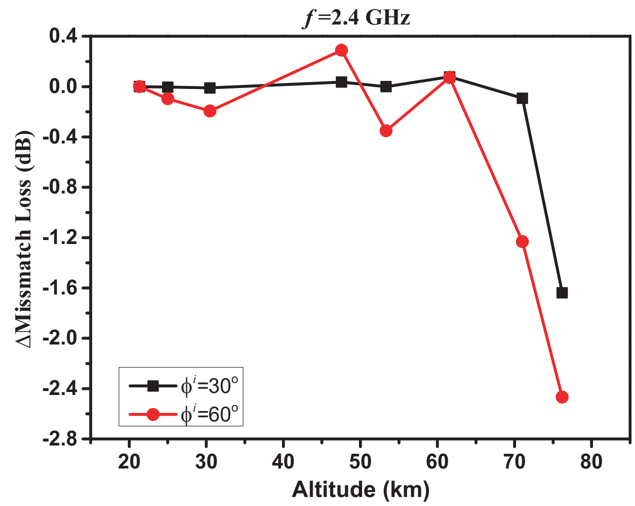

Figure 11. Effects on polarization mismatch loss in S-band.

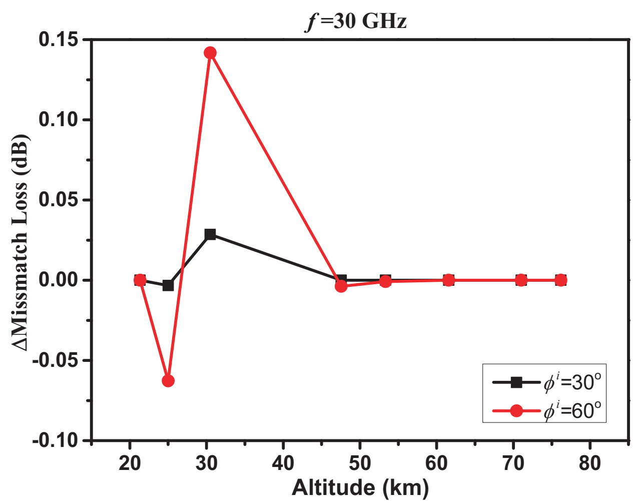

Figure 12. Effects on polarization mismatch loss in Ka-band.

5. CONCLUSIONS

This paper combines the compressible turbulent flow theory, plasma theory, and electromagnetic wave theory together to study the relationship between the parameter fluctuation of reentry plasma sheath and the fluctuation of the dielectric constant. On this basis, the effects of parameter fluctuations on polarization properties of transmitted EM waves can be estimated. In this framework, the effects of reentry plasma fluctuations on transmitted EM waves in L-band, S-band and Ka-band in a typical reentry process of blunt-nosed craft (RAM C-II reentry process) are analyzed. To simulate the reentry plasma sheath, a stratified modeling method is used. From the simulation results, one can get that the effects of reentry plasma fluctuations on polarization properties of transmitted EM waves change with altitudes. The effects are complicated and changeable. But from the general change trend, one can find that in L-band and S-band, the effects increase with the altitude, while in Ka-band, the effects decrease with altitude. The effects at high altitude above 60 km are prominent in L-band and S-band, while the effects at middle and low altitude below 60 km in Ka-band the effects are obvious. The effects in L-band and S-band are much bigger than that in Ka-band and can affect the signal properties of

TT&C systems significantly, while the effects in Ka-band are much milder. A larger oblique incident angle wave can encounter a more severe condition than that of a smaller one.

This suggests that the communication links between the reentry vehicles and the base stations could be susceptible to the plasma parameter fluctuations, and the effects should be taken into consideration to mitigate the blackout.

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