SCIENCE CHINA Information Sciences

Sub-THz signals' propagation model in hypersonic plasma sheath under different atmospheric conditions

Kai YUAN[1], Yuhao WANG[2], Linfang SHEN[1], Ming YAO[1], Xiaohua DENG[1]*,
Fuhui ZHOU[2] & Zhou CHEN[1]

[1]Institute of Space Science and Technology, Nanchang University 330031, China
[2]Information Engineering School, Nanchang University 330031, China

Hypersonic vehicle and communication blackout

- Hypersonic vehicle: reentry capsules, ballistic missiles and hypersonic cruise flights.

- Vehicles moving hypersonically in near space are surrounded by dense plasma (hypersonic plasma sheath), which shields the communication signals and leads to the so called ‘blackout’.

- The communication blackout was concerned since 1950s.

- Modern hypersonic cruise flights also suffer from communication blackout.

A potential solution to the 'blackout' problem – sub-THz technology

- **The maximum electron density in the plasma sheath could be up to 10^{20} m^{-3}.**

- **The sub-THz band covers the frequencies in the range from 50 GHz to 1 THz, which are normally higher than the cutoff frequency near the onboard antenna.**

- **According to previous theoretical and experimental studies, carrier waves in Sub-THz band could penetrate dense plasma slab.**

Sub-THz signal propagation in hypersonic plasma sheath

- The electron collisions lead to significant signal attenuation when the carrier frequency is higher than the maximum cutoff frequency.

- The ‘blackout’ would occur once the signal received by the onboard antenna is too weak.

- The plasma sheath is impacted by many factors, including the atmospheric conditions surrounding the vehicle.

- The length of route of a hypersonic cruise flight could be up to thousands of kilometers. The atmospheric conditions along the route are complicated. As the results the propagation of sub-THz signals in the plasma sheath is complicated.

Outline

- The hypersonic plasma sheaths under different atmospheric conditions were obtained with a numerical hypersonic fluid model.
- The relation between the sub-THz signal propagation and the atmospheric conditions was analyzed.
- A new estimation model was developed. The model could be utilized for quick estimation of sub-THz signal propagation in hypersonic plasma sheath under different atmospheric conditions.
- The global distribution of sub-THz signal attenuation in hypersonic plasma sheath was obtained with the new model.

Hypersonic fluid model

- The conservative form of Navier-Stokes equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$

$$\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot \left(\rho \vec{u} \otimes \vec{u} + p \vec{\vec{I}} \right) = \nabla \cdot \vec{\vec{\tau}}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot [\vec{u}(e+p)] = \nabla \cdot \left(\vec{\vec{\tau}} \cdot \vec{u} \right) + \nabla \cdot (k_T \nabla T)$$

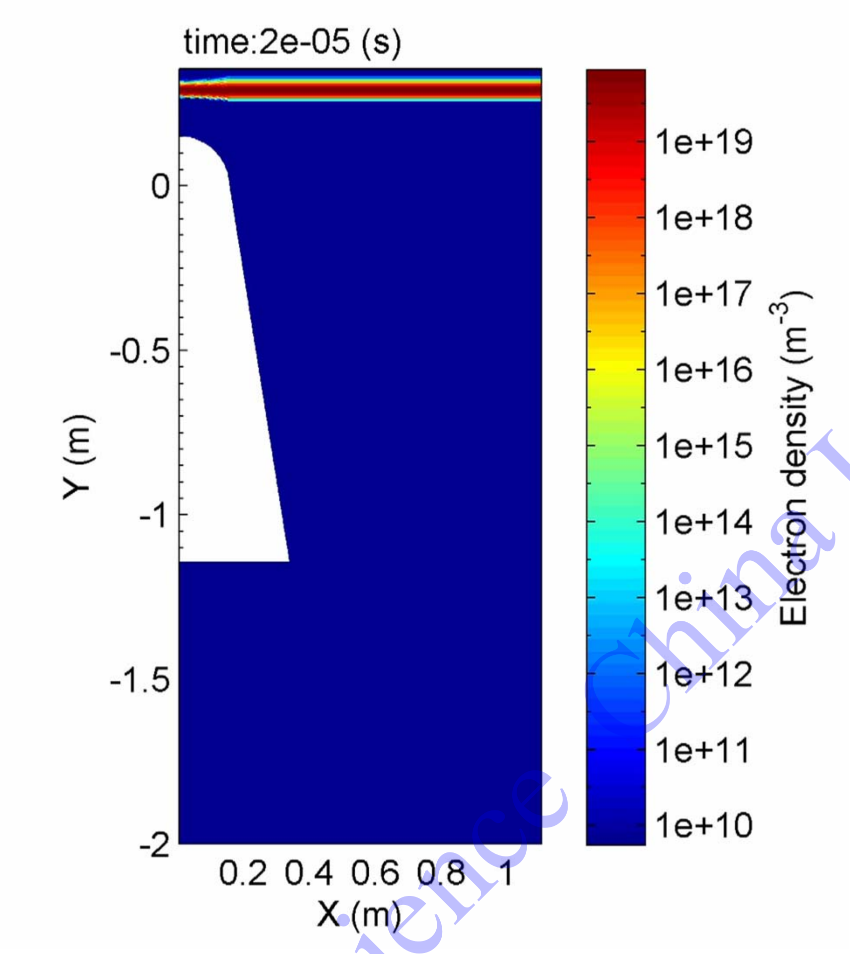
- Number density continuity equation:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \vec{u}) = s_i$$

- Chemical reactions: air 7 species model (N_2, N, O_2, O, NO, NO^+ and e^- (electron))

- Molecular kinetic theories.

The hypersonic plasma sheaths



- The hypersonic plasma sheath was modeled under 11 sets of different atmospheric conditions (see Table 1 in the paper). The atmospheric conditions were obtained from the M-SISE-90 empirical atmosphere model.

- The video shows the generation and the evolution of the hypersonic plasma sheath at equator.

- The electron collision frequency (Bachynski's fomula):

$$f_{en} = 3 \times 10^{8} \left(\frac{\rho}{\rho_0} \right) T$$

The hypersonic plasma sheaths

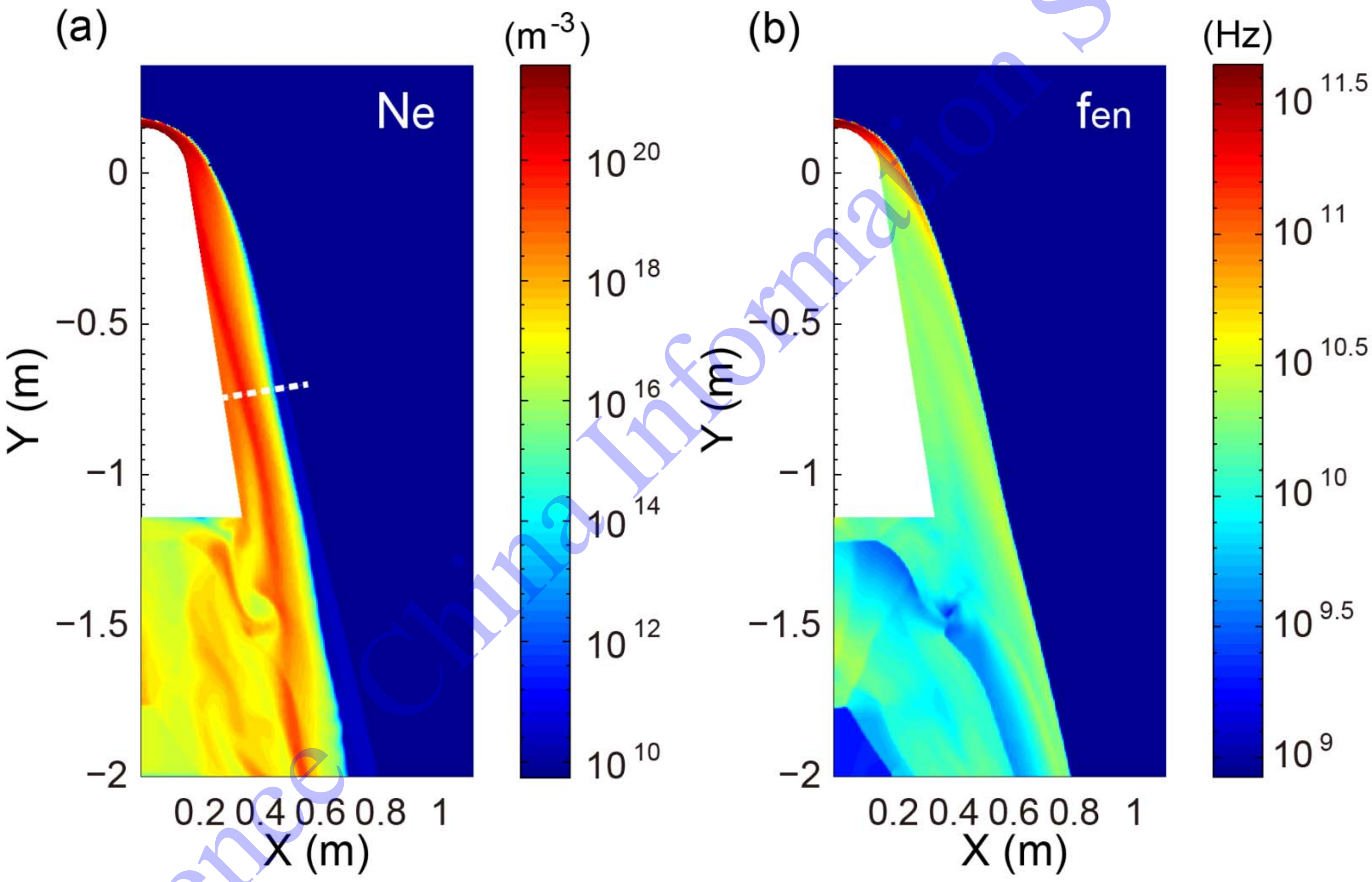


Figure 1 The plasma sheath (at equator).

The hypersonic plasma sheaths

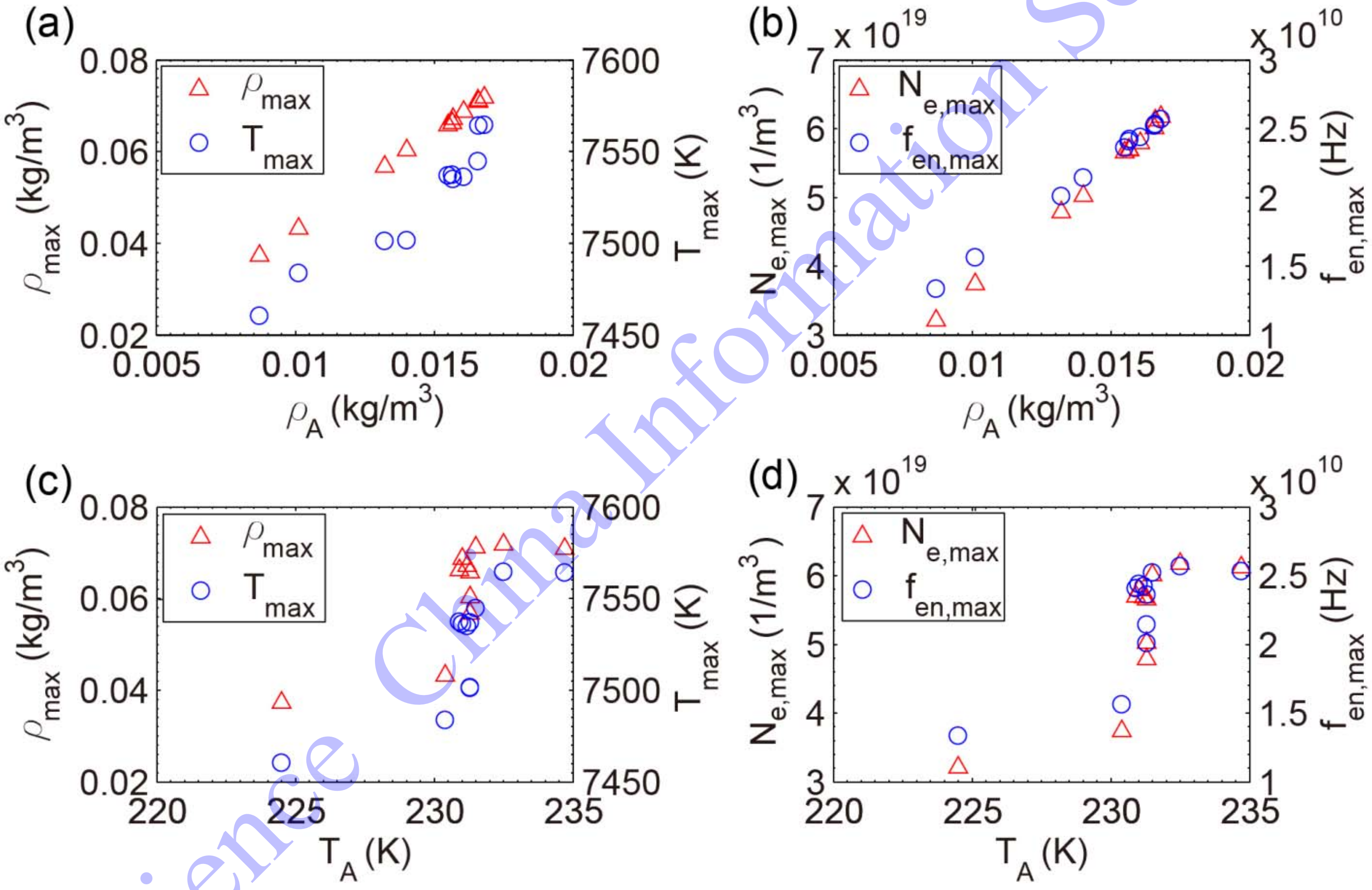


Figure 2 The maxima of plasma parameters near the antenna vs. the atmospheric conditions.

The hypersonic plasma sheaths

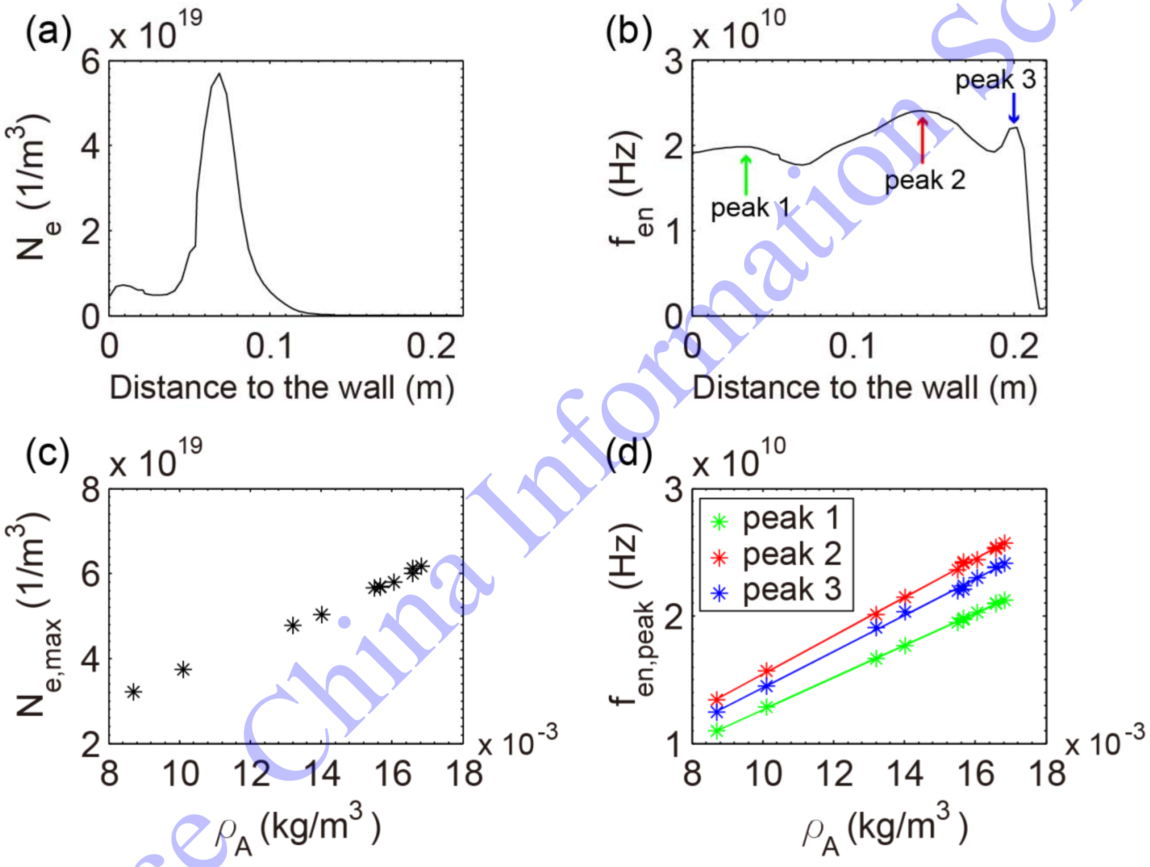


Figure 3 The electron density profile (a), electron collision frequency profile (b), maximum electron density against the atmospheric mass density (c) and the peak values for the electron collision frequency against the atmospheric mass density (d).

The propagation of sub-THz signals

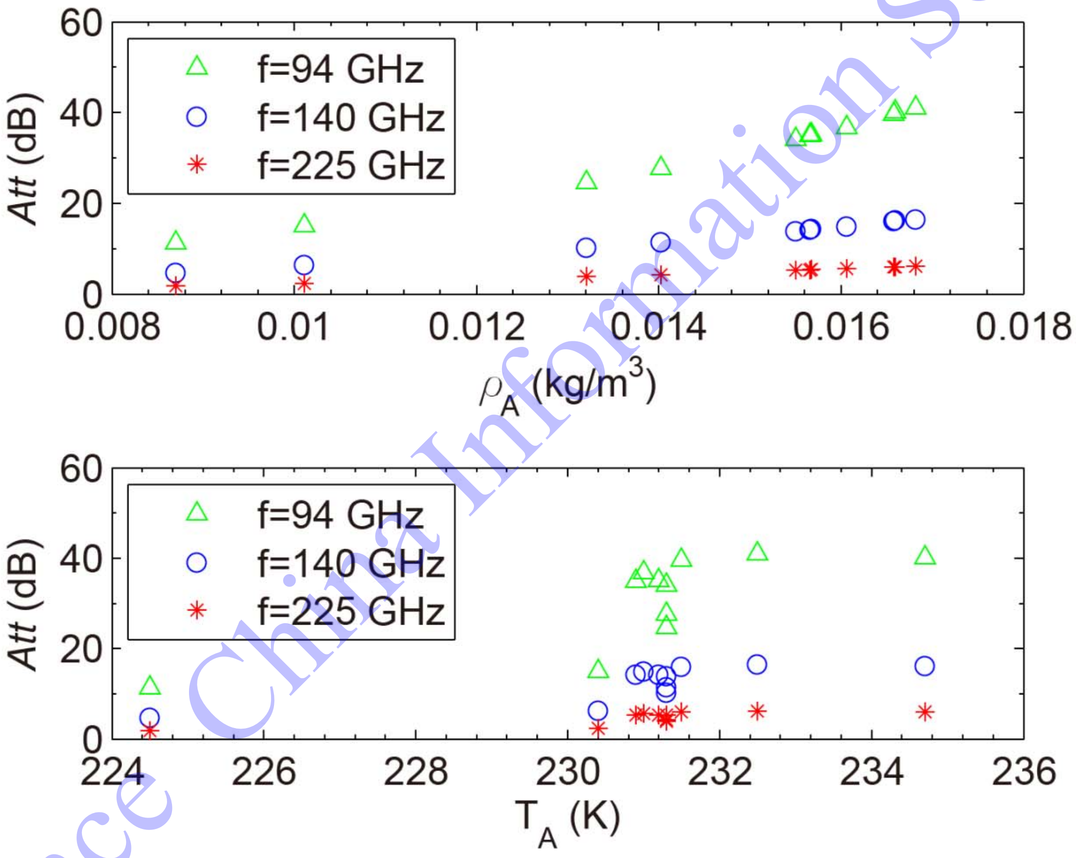


Figure 4 The total signal attenuation vs. atmospheric conditions.

The character of energy loss for sub-THz signals

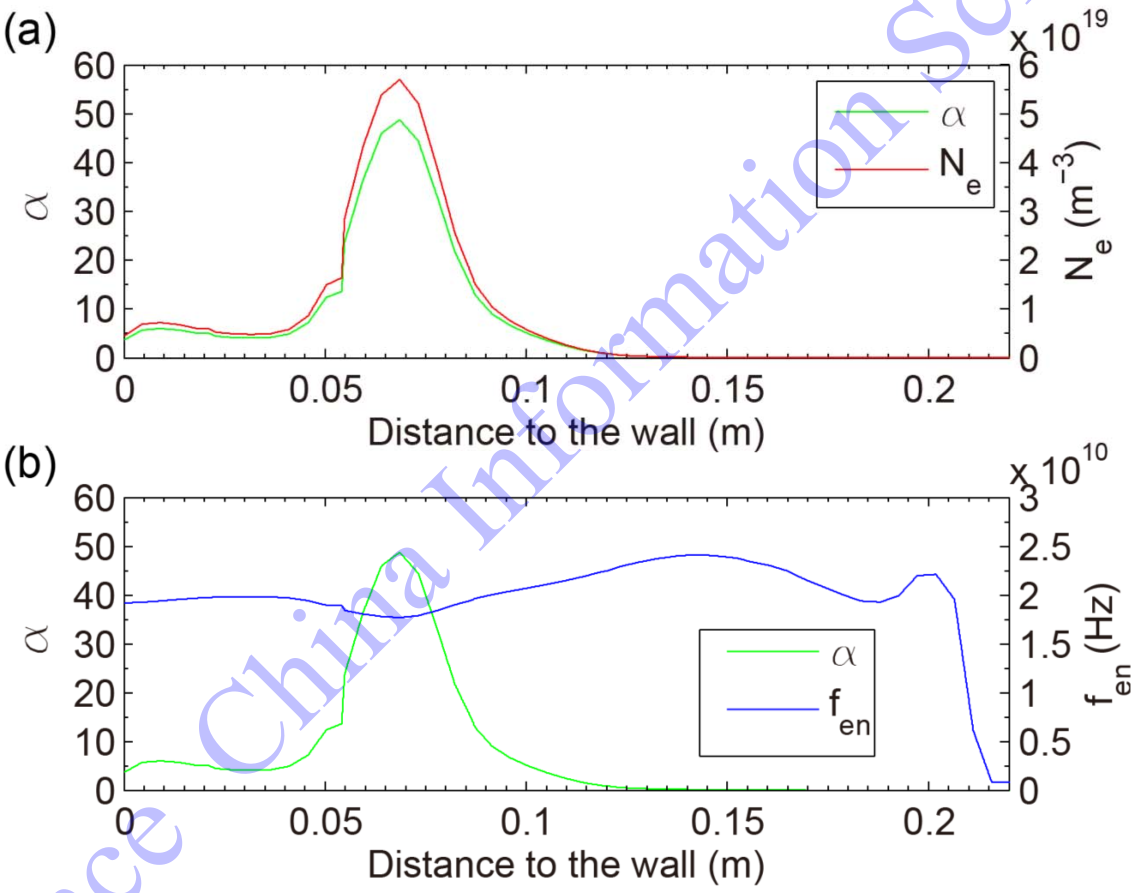


Figure 5 The profiles for the attenuation coefficient, electron density (a) and the electron collision frequency (b).

Complicated global atmospheric conditions

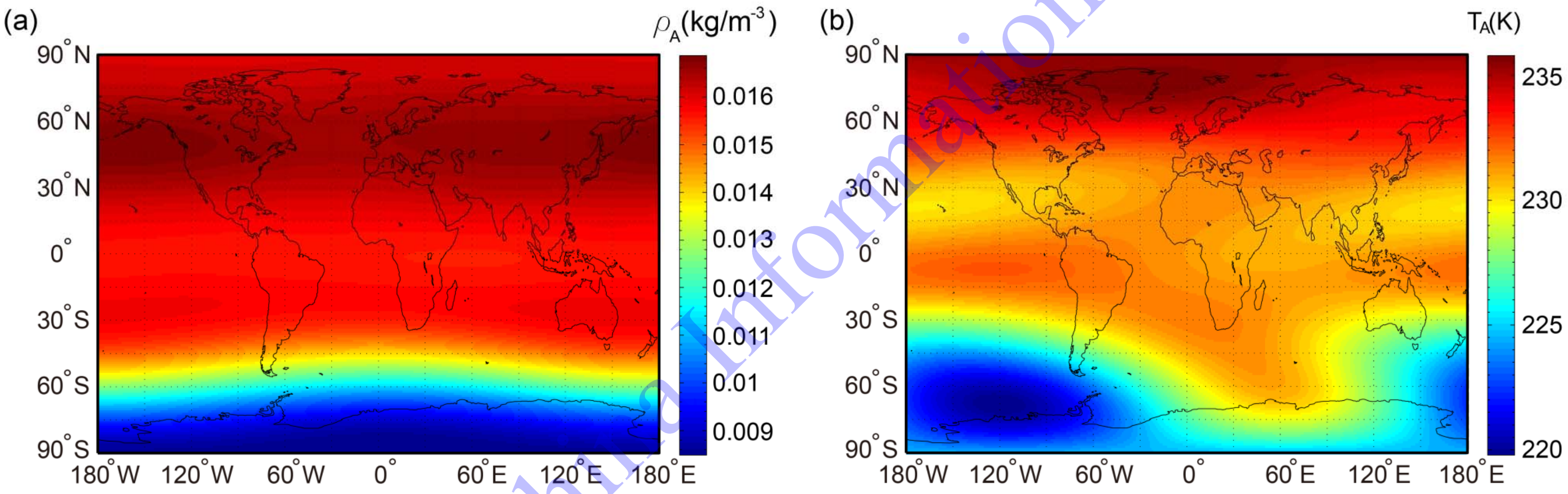


Figure 6 The global distributions of atmospheric mass density (a) and temperature (b). The data was obtained from M-SISE-90 empirical atmosphere model.

A new estimation model for sub-THz signal propagation

- **The peak plasma density near the onboard antenna has a linear relation with the atmospheric mass density.**
- **The shape of the electron density profile along the signal propagation path is similar to a Gaussian function.**
- **The attenuation of sub-THz signals occurs mainly in the region where the electrons concentrate.**
- **The peaks of electron collision frequencies have linear relations with the atmospheric mass density.**
- **The atmospheric mass density was obtained from the M-SISE-90 model.**

◆ Equation for the estimation of electron density along the signal propagation path:

$$N_e(l) = N_{e,peak} \exp\{-[(l - l_{peak})/c_{Ne}]^2\}$$

◆ Equation for the estimation of electron collision frequency along the signal propagation path:

$$f_{en}(l) = f_{en,peak1} \exp\{-[(l - l_{peak1})/c_{c1}]^2\} + f_{en,peak2} \exp\{-[(l - l_{peak2})/c_{c2}]^2\} + f_{en,peak3} \exp\{-[(l - l_{peak3})/c_{c3}]^2\}$$

The coefficients obtained via the curve fitting with the Gaussian functions

	l_{peak}	c_{Ne}	l_{peak1}	c_{c1}	l_{peak2}	c_{c2}	l_{peak3}	c_{c3}
1	0.351	0.01755	0.4344	0.05115	0.4805	0.01166	0.3087	0.1141
2	0.3507	0.01629	0.4348	0.05247	0.4819	0.01061	0.3067	0.1151
3	0.351	0.01723	0.4346	0.05144	0.4807	0.0114	0.3084	0.1138
4	0.3504	0.01663	0.4351	0.0521	0.4819	0.01074	0.3073	0.1175
5	0.3507	0.01638	0.4346	0.05141	0.4815	0.01094	0.3098	0.1121
6	0.3508	0.0162	0.4348	0.05189	0.4818	0.01074	0.3084	0.1121
7	0.3507	0.01656	0.435	0.05195	0.4819	0.01076	0.3078	0.1154
8	0.3508	0.01637	0.4345	0.05197	0.4813	0.01111	0.3076	0.1145
9	0.3507	0.01642	0.4344	0.05218	0.4816	0.01095	0.3064	0.1163
10	0.3507	0.01632	0.4353	0.05152	0.4818	0.01081	0.3094	0.1142
11	0.3508	0.01641	0.4351	0.05202	0.4819	0.01064	0.3082	0.1141

The comparison

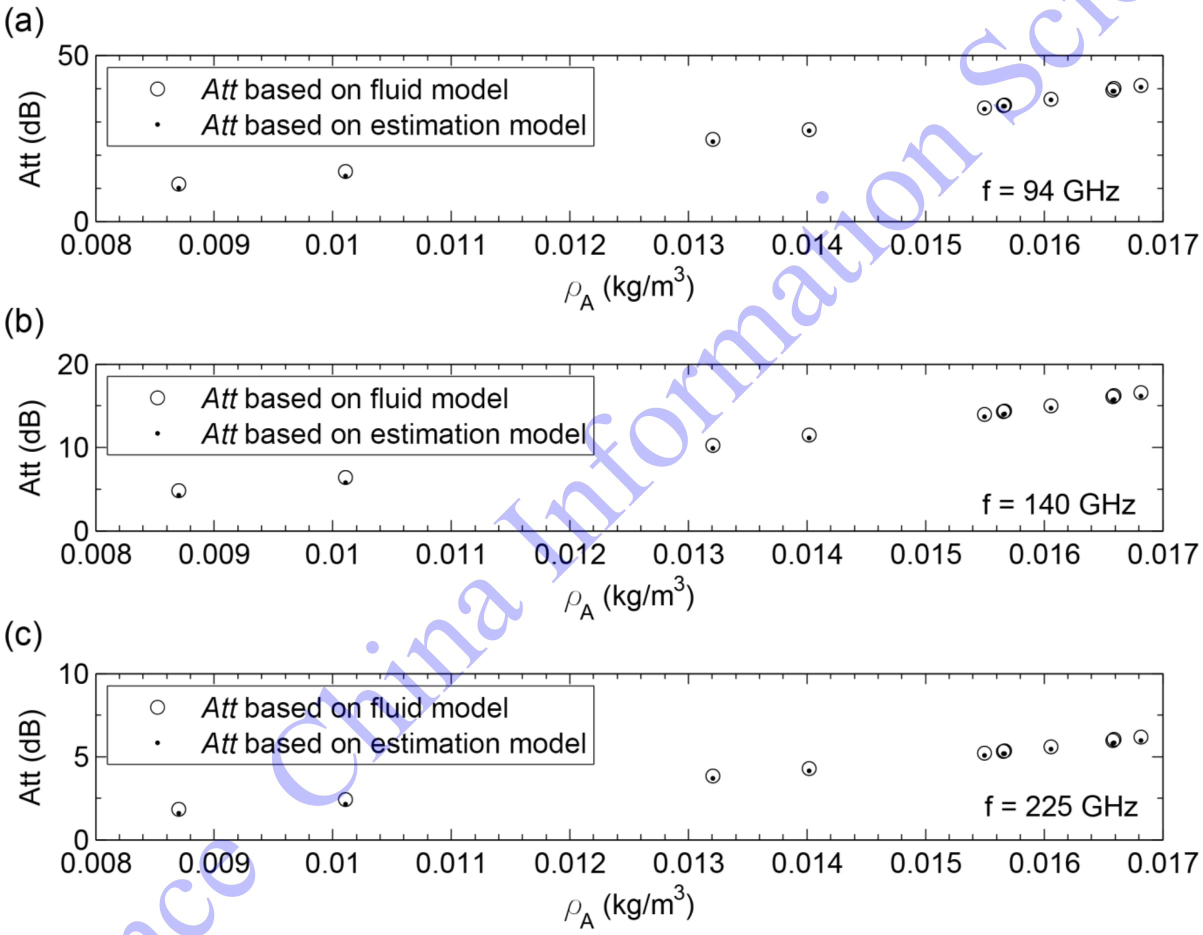


Figure 7 The comparisons between the signal attenuations based on the hypersonic fluid model (dots) and the estimation model (circles).

Complicated global atmospheric conditions

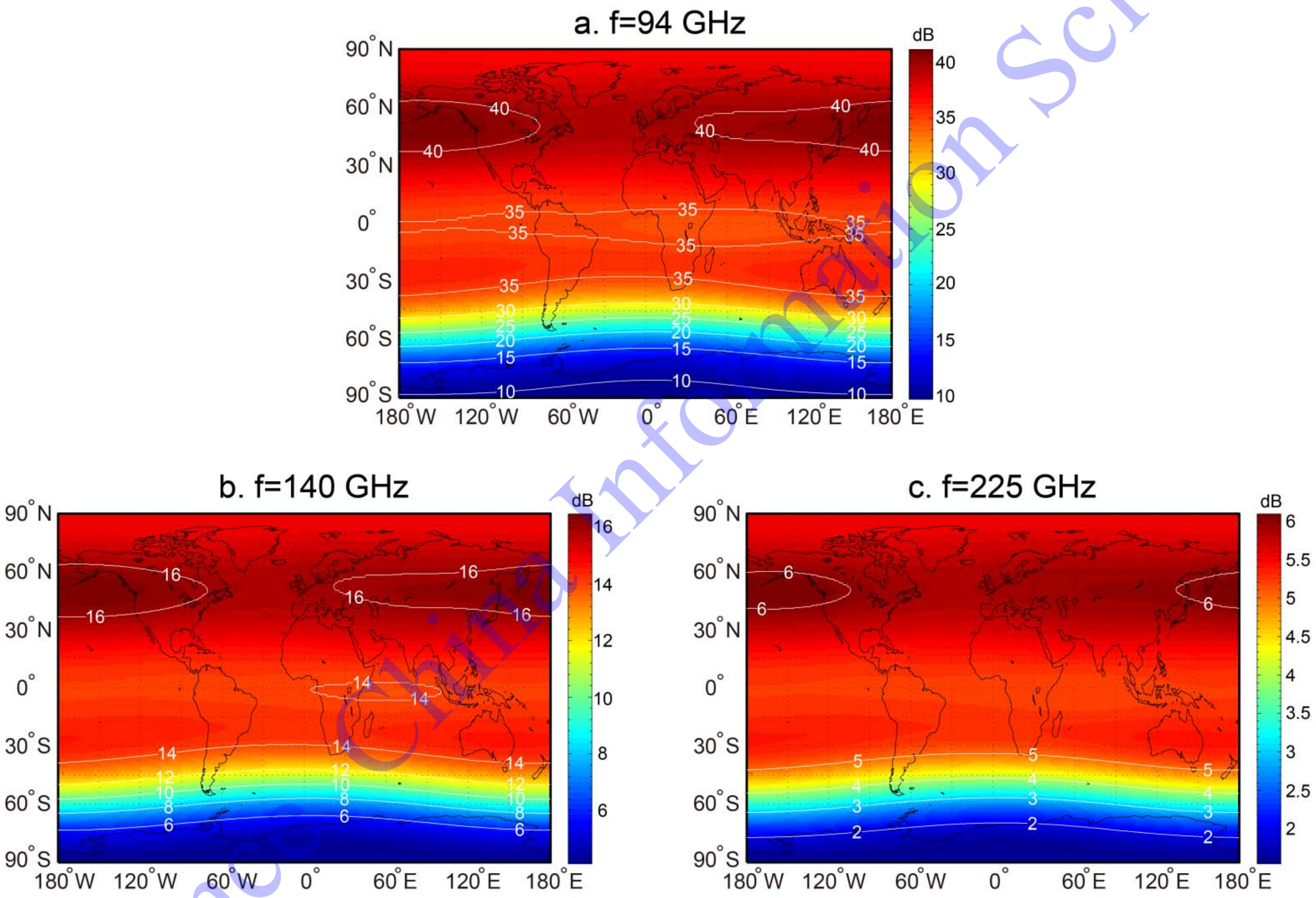


Figure 8 The global signal attenuation of 'atmospheric windows' in hypersonic plasma sheaths.

Conclusion

1. The attenuation of sub-THz signals in hypersonic plasma sheaths is impacted by the atmospheric density. The total signal attenuation in hypersonic plasma sheaths increase with the atmospheric mass density around the flight. The impact led by the atmospheric temperature is ignorable.

2. The peak values of the electron density and the electron collision frequency near the onboard antenna have linear relations with the atmospheric mass density around the vehicle.

3. The attenuation of sub-THz signals in hypersonic plasma sheaths mainly occurs near where the electrons concentrate.

4. Due to the geographical difference of atmospheric mass density, the total attenuation of sub-THz signals in hypersonic plasma sheaths varies with the latitude and the longitude of the flight. For a hypersonic cruise flight, the performance of the onboard sub-THz communication system partly depends on the flight route. Generally the total signal attenuation at northern hemisphere are higher than that at southern hemisphere. The maximum total signal attenuation occurs once the flight is in the region between the latitudes of 45°N to 70°N, which covers parts of Canada, Russia and Alaska of the United States.