Computer experiments on radio blackout of a reentry vehicle

H. Usui, H. Matsumoto, F. Yamashita, M. Yamane, and S. Takenaka

Radio Science Center for Space & Atmosphere, Kyoto University, Uji, Kyoto 611-0011, Japan

Abstract. We examined the radio blackout of a reentry vehicle by performing electromagnetic PIC (Particle-In-Cell) simulations. We focused on (1) blackout phenomenon and its avoidance with static magnetic field applied to the plasma, and (2) measurement of the reentry plasma layer with radio waves. Regarding (1), we could clearly show that the radio blackout occurs when the plasma frequency of reentry plasma exceeds the frequency of radio wave emitted from the vehicle. To avoid the radio blackout, we applied static magnetic field to the reentry plasma, which modifies the wave dispersion relation. We found that the radio waves can penetrate the reentry plasma mainly by whistler mode. Regarding (2), we found that the reflectometry method is applicable to the estimate of the spatial profile of the plasma layer, which utilizes the information of phase difference between the waves emitted from the antenna and reflected against the plasma layer. We can also obtain the maximum plasma density by searching for abrupt decrease in the field spectra of the reflected waves.

Introduction

In the reentry of spacecraft to the earth's atmosphere, a dense plasma layer is created due to the ionization of neutral particles by the shock wave heating near the vehicle nose. The density of the plasma layer becomes as dense as $10^{18} - 10^{19} / m^3$ and it causes so called radio blackout [MaCabe and Stolwyk, 1962; Huber and Sims, 1964; Rybak and Churchill, 1971]. During the blackout, radio waves emitted from the reentry vehicle cannot reach ground stations because they are reflected against the plasma layer.

The theoretical analysis of the radio blackout is difficult because the reentry plasma has very steep gradient in space in a short distance compared to the wave length. Meanwhile active experiments in space provide significant data regarding the radio blackout. However, we cannot perform the experiments so often because they take a long time for the preparation and cost very much. In the present study, we analyzed the radio blackout by performing computer experiments with an electromagnetic PIC (Particle-In-Cell) code which solves the equation of motion for the plasma dynamics and Maxwell's equations for the associated electromagnetic fields at each time step.

We also examined a method of blackout avoidance. Various methods concerning the blackout avoidance have been proposed mainly in the U.S. Although most of them are classified in the military and not open to the public, the simplest method is to apply magnetic field to the reentry plasma and locally modify the wave dispersion relation. We will examine the capability of this method by computer experiments.

In the research of the radio blackout, we need to understand the parameters of the reentry plasma such as the density profile and the maximum density. Conventionally the density of the reentry plasma has been measured by using a probe with a help of CDF (Computational Fluid Dynamics) analysis. However, the probe data obtained in the temperature more than 500 degree is not reliable due to the breakdown of insulation. Instead of using a probe, we use radio waves to measure the reentry plasma. In the present study, we adopted the reflectometry method which is used in the fusion plasma measurement [Simonet, 1985]. In the reflctometry we actively emit radio waves to plasma and obtain the reflected waves for the density measurement. The advantage is that the plasma environment is not perturbed by probe insertion. In the HYFLEX experiment [Itoh *et al.*, 1996] this method was utilized to measure the density of the reentry plasma by using two different antennas. To examine the capability of this method in detail, we perform one-dimensional computer experiments with PIC (Particle In Cell) model.

Radio Blackout and its avoidance

In the computer experiments, we use an electromagnetic particle code called KEMPO which has been developed in the space plasma group of Kyoto university [Matsumoto et al., 1985]. This simulation code basically solve the Maxwell equations for the fields and the equation of motion for the particles in the model region and enables us to trace not only linear but also nonlinear evolution of phenomena of interest. The model region for one-dimensional computer experiments is schematically illustrated in Figure 1. We focus on the vicinity of a reentry vehicle including a dense plasma layer. The y-z plane at x=0 corresponds to the vehicle surface. The reentry plasma is placed in front of the vehicle surface with a Gaussian distribution in space. By current oscillation at the vehicle surface, we radiate radio wave which propagates along the x direction. The electric and magnetic field components of the radiated wave oscillate in the y and z directions, respectively. In this model, we neglects the effects of the geomagnetic field and the collision frequency against neutral particles.

To see the radio blackout in the computer experiments, we examined the wave transmission ratio through the reentry plasma by changing $\Pi_{e\max}/\omega_0$ where $\Pi_{e\max}$ and ω_0 denote the maximum plasma frequency in the layer and the frequency of the

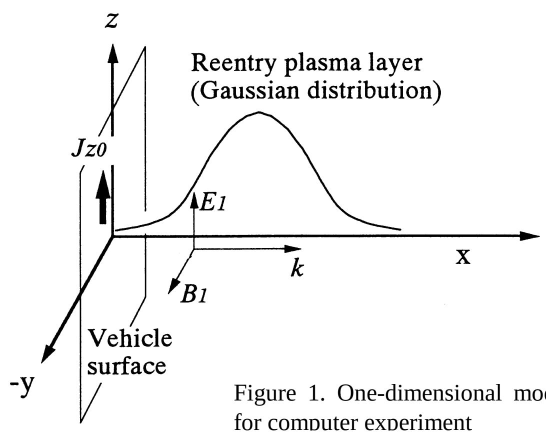

Figure 1. One-dimensional model for computer experiment

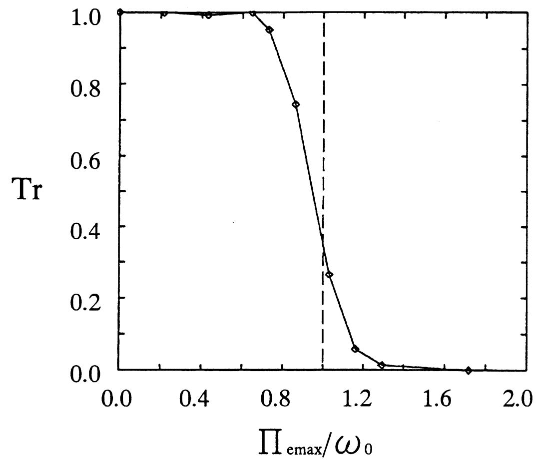

Figure 2. Transmission ratio of radio wave emitted from a reentry vehicle

radiated wave, respectively. In the experiments, we varied $\Pi_{e\max}$ keeping ω_0 constant. As clearly shown in Figure 2, the transmission ratio abruptly decreases near $\Pi_{e\max}/\omega_0 = 1.0$. Namely the radiated wave cannot penetrate the plasma layer when ω_0 is smaller than $\Pi_{e\max}$. Partial penetration of the wave is observed even if $\Pi_{e\max}/\omega_0 > 1$ because the width of the plasma layer is thinner than the wave length. Perfect penetration is not realized when $\Pi_{e\max}$ is slightly smaller than ω_0 because there is some reflection against the plasma layer even if the density is low.

Next we examined the blackout avoidance. As stated earlier, we applied static magnetic field B_0 to the plasma layer. Prior to the computer experiments, we analyzed the wave dispersion relations for the parallel propagation at each point in the plasma layer. The dispersion relation of the electromagnetic wave propagating along B_0 is given as

$$\omega^2 = \frac{\Pi_e^2}{1 \pm \Omega_e/\omega} + k^2c^2 \qquad (1)$$

where Ω_e, Π_e, c denote the electron cyclotron frequency, the plasma frequency, and the speed of light, respectively. In the equation, Ω_e has a negative value and + and – signs represents the R and L mode waves, respectively. In addition to these waves, we have whistler mode (R mode) whose resonance frequency is Ω_e. When we increase the intensity of B_0, the cut-off frequency ω_L (frequency at k=0) of the L-mode wave decreases. When ω_L becomes smaller than ω_0, the radiated wave can propagate through the layer as the L-mode wave. In addition, the wave can also propagate as whistler mode when Ω_e is larger than ω_0.

Figure 3 shows the wave dispersion relations in $\omega - k$ diagrams at different positions in the plasma layer. The intensity of the

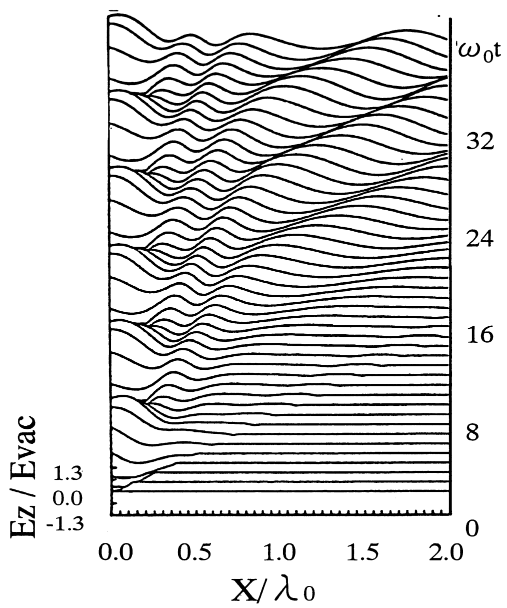

Figure 4. Snapshots of spatial profile of Ez component at different times superimposed vertically.

applied magnetic field is constant as $|\Omega_e|/\omega_0 = 1.8$. The dashed line in each $\omega - k$ diagram represents the frequency of the radiated wave. As shown in panel (b) and (c) corresponding to low density, ω_L becomes lower than ω_0 and the wave can propagate as the L-mode wave. Around the center of the plasma layer corresponding to panel (a), however, the mode branch of the L-mode exists in the frequency range larger than ω_0, which implies evanescent wave. One significant finding is that whistler wave can cover ω_0 at any point of the layer as long as $|\Omega_e|/\omega_0 > 1$ is satisfied while the high frequency R-mode does not cross at ω_0. In result, we expect the radiated wave from the reentry vehicle can penetrate the plasma layer as whistler mode.

To verify the wave penetration discussed above, we performed computer experiments with the same model as shown in Figure 1. We applied B_0 along the x direction with the intensity $|\Omega_e|/\omega_0 = 1.8$. The maximum plasma frequency in the plasma layer is approximately three times larger than the wave frequency ($\Pi_{e\max}/\omega_0 \approx 3$). Figure 4 shows snapshots of spatial profile of Ez component at different times superimposed vertically. In the region of the plasma layer ($0.3 < x/\lambda_0 < 1.2$), the phase velocity is less than the speed of light and agrees with that of the whistler wave. After the plasma layer ($1.2 < x/\lambda_0 < 2.0$), the phase velocity increases and becomes the speed of light. In result the radiated wave penetrates the plasma layer as whistler wave and is converted to the light mode wave in the vacuum region. In the vicinity of the antenna around $x/\lambda_0 = 0$, a standing wave is observed, which is due to the reflection of the L-mode component

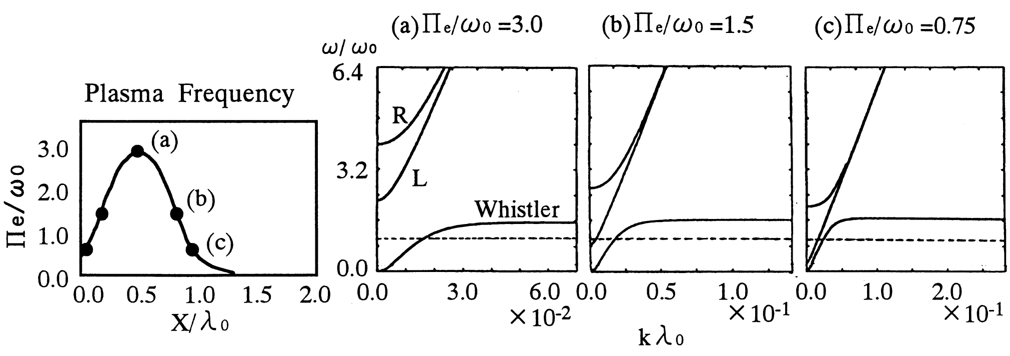

Figure 3. $\omega - k$ diagram corresponding to each position of the reentry plasma layer. The dashed line in each panel represents the frequency of the radiated wave ω_0

in the radiated wave. Forward and backward propagating L-mode waves cause the standing wave between the plasma layer and the vehicle surface.

Reentry plasma measurement

The reflectometry method provides the wave reflection point

$$\varphi(\omega) = 2\omega \int_0^{r_c(\omega)} \frac{dr}{v_{ph}} - \frac{\pi}{2}$$

$$= \frac{2}{c} \int_0^{r_c(\omega)} (\omega^2 - \Pi_e^2)^{1/2} dr - \frac{\pi}{2} \qquad (2)$$

with the information of the phase difference $\varphi(\omega)$ between the emitted and reflected waves observed at the vehicle surface. $\varphi(\omega)$ is given as

where c, $r_c(\omega)$, ω, Π_e, and v_{ph} denote the speed of light, the

$$r_c(\omega) = \frac{c}{\pi} \int_0^{\omega} \frac{d\varphi}{d\omega'} (\omega^2 - \omega'^2)^{-1/2} d\omega' \qquad (3)$$

distance between the antenna and the reflection point, the wave frequency, the plasma frequency, and the phase velocity of the wave, respectively. By modifying Eq. (2), we obtain $r_c(\omega)$ as If we can sweep the frequency from 0 to ω and measure $d\varphi/d\omega'$, we can evaluate $r_c(\omega)$ where the local plasma frequency Π_e is equal to ω. The plasma density n is then obtained from the relation $\Pi_e = nq^2/\varepsilon_0 m$ where q, m, and ε_0 denote the charge, mass of electron, and the dielectric constant in vacuum, respectively.

To examine the capability of the reflectometry to the estimate of the spatial profile of the reentry plasma, we performed computer experiments. The model is the same as used in the previous experiments. As shown in Figure 5, we assumed three models for the plasma layer with (x/λ_0 , w/λ_0) = (3.5, 0.67), (4.6, 0.67), and (3.5, 0.47) where x/λ_0 and w/λ_0 denote the distance between the center of the plasma layer and the vehicle surface and the width of the plasma layer. The distance and width are normlized to the wave length in vacuum corresponding to the frequency $\Pi_{e\max}$ in the layer.

To obtain $r_c(\omega)$ in the reflectometry, we need the phase difference $\varphi(\omega)$ for each frequency as given in Eq.(3). To measure $\varphi(\omega)$ in one simulation run, we use a pulse current source for the vehicle antenna. The pulse includes no DC components and is expressed as $d/dt[(t/T)^4 e^{-t/T}]$ where t and T

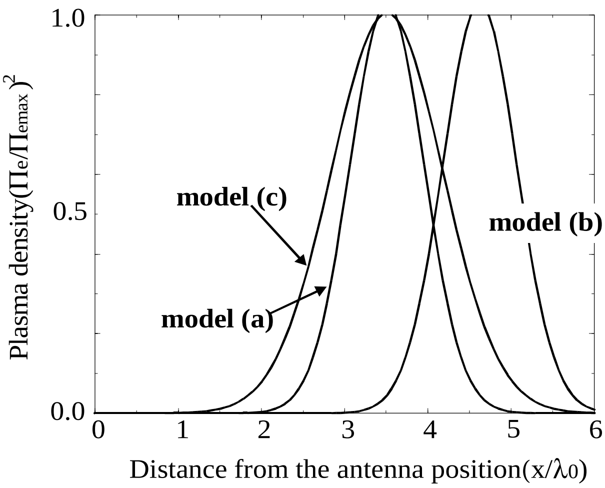

Figure 5. Models of plasma layer used in the computer experiments

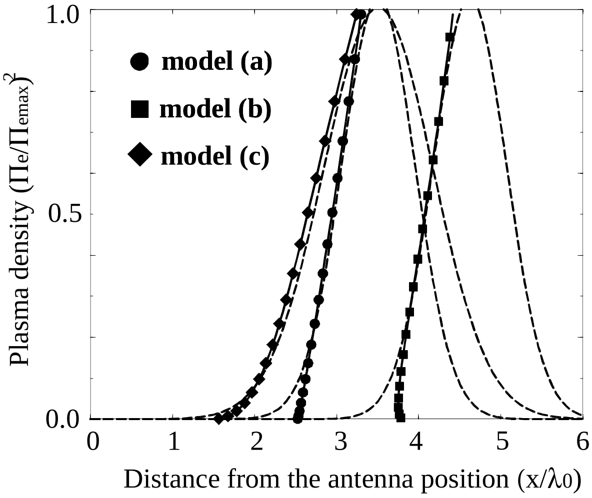

Figure 6. Spatial profiles of plasma density obtained in the computer experiments.

denote the time and the inverse of the center frequency f_c, respectively [Hashimoto and Abe, 1996]. In the computer experiments, we take f_c 1.7 times as large as $\Pi_{e\max}$. Since this pulse has a broad band frequency spectra, we can obtain $\varphi(\omega)$ by performing only one computer experiment. At the vehicle surface, we observed the time series of the field data which includes both the emitted pulse wave and reflected one. Since we know the time function of the emitted wave, we subtract it from the observed data to obtain the reflected wave. Then we perform the Fourier transformation to the emitted and reflected wave data to obtain $\varphi(\omega)$ at each frequency.

Although not shown, $\varphi(\omega)$ is obtained as a smooth function of frequency for each case. We calculate $d\varphi/d\omega$ and insert it to Eq. (3) to obtain $r_c(\omega)$. The results are indicated in Figure 6. The marked lines correspond to the results given by Eq. (3) and the dashed curves indicate the profiles of the plasma layers used in computer experiments. As obviously shown in the figure, the estimate of the plasma density profile agrees very well with those of the model layer.

We present the spectra of the reflected waves for each case in Figure 7. Note that the spectra drastically decrease at $\omega/\Pi_{e\max} = 1.0$ for all the cases. This results implies that wave components with $\omega > \Pi_{e\max}$ can penetrate the layer but the other components are reflected back to the antenna position. By using this result, we can estimate $\Pi_{e\max}$ or the maximum plasma density

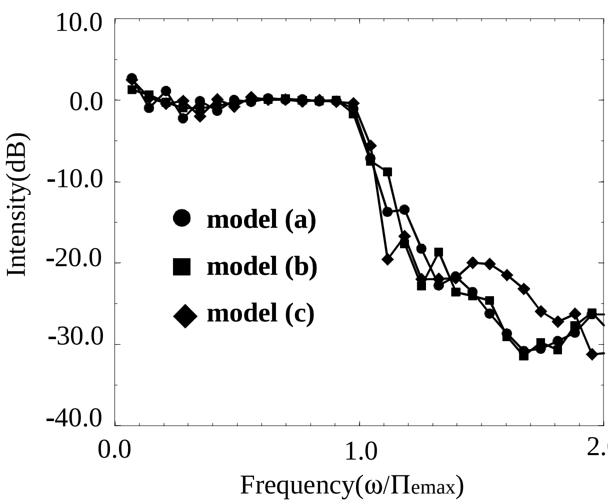

Figure 7. Spectra of waves reflected against the plasma.

in the layer.

Discussion

We showed that radio wave can propagate as whistler wave when we apply magnetic field to the reentry plasma. In the present experiment, we used the magnetic field intensity corresponding to $|\Omega_e|/\omega_0 = 1.8$. If we assume that the frequency of wave emission $\omega_0/2\pi$ is 2.3 GHz, $|\Omega_e|/2\pi$ is approximately 4.1GHz, which corresponds to 1,500 gauss. If we can apply the magnetic field with 1,500 gauss to the reentry plasma, we will be able to avoid the radio blackout by using whistler mode wave as shown in the present study. Although not displayed, the same results are obtained in a two dimensional model. However, the transmission rate of the whistler wave through the plasma layer becomes approximately 0.65 which is less than that in the one dimensional model. This is due to the wave field component propagating obliquely to the applied magnetic field which is uniform in the layer. Since the antenna is assumed as a point , the emitted radio wave propagates in a radial direction, not as a plain wave as shown in the one dimensional model. The oblique component of the whistler wave is damped when the angle between the propagation direction and B_0 becomes large. Meanwhile, the propagation of the L-mode wave is little affected by the direction of B_0 in the plasma layer because the L-mode wave has longer wave length than the whistler wave. In result the transmission rate of the L-mode wave is almost the same as that obtained in the one dimensional model.

Regarding the measurement of the reentry plasma by radio waves, we showed that the reflectometry is very effective, which uses the information of the phase difference between the emitted and reflected waves as a function of frequency.

The reflectometry method is based on the W.K.B. approximation. The relation of the W.K.B. approximation is given

$$\left|\frac{3}{4n^4}\left(\frac{dn}{dx}\right)^2 - \frac{1}{2n^3}\frac{d^2n}{dx}\right| \ll k_0^2$$

as [Maeda and Kimura, 1985]

where n and k_0 denote the refractive index and the wave number in vacuum, respectively. We define Δx as a spatial difference between the position of $\omega = \Pi_e$ and that which satisfies the condition that the R.H.S. of the above relation is 10 times larger than the L.H.S. for the same ω. In the low frequency region, Δx increases because the corresponding wavelength becomes as large as the width of the plasma layer and it becomes hard to determine the exact reflection point. In this situation, the W. K. B. approximation may be violated and the wave data obtained in the low frequency may cause some errors in the evaluaion of Eq.(3) . As in Figure 6, however, we succeed in estimating the spatial profile of the plasma layer with the reflectometry. This result implies that the large Δx in the low frequency region affects very little on the mesurement of the plasma. Taking into an account that Δx is directly related to the wavelength, we need to evaluate Δx as a relative value to the corresponding wavelength. We, for instance, assume a plasma layer which has the maximum plasma frequency 3GHz, the distance between the center of the plasma layer and the vehicle surface 45 cm, and the width of the plasma layer 10 cm. In this situation, $\Delta x/\lambda$ corresponding to the wave frequency of 1GHz and 0.1GHz are respectively 1×10^{-2} and 4×10^{-3} where λ denotes the wavelength in vacuum for simplicity. In result, Δx can be negligible to the corresponding wavelength, which does not affect the measurement of the plasma profile as explained earlier.

Summary

In the present study, we investigated the radio blackout and its avoidance by performing computer experimnets. We could clearly show that the radio blackout occurs when the plasma frequency of reentry plasma exceeds the frequency of radio wave emitted from the vehicle. To avoid the radio blackout, we applied static magnetic field to the reentry plasma, which modifies the wave dispersion relation. We found that the radio waves can penetrate the reentry plasma mainly by whistler mode [Matsumoto et al, 1997].

We also examined the remote measurement of reentry plasma with the reflectometry method by performing one-dimensional computer experiments with PIC model. We clarified that the spatial profile of the reentry plasma can be estimated by the reflectometry which uses the information of the phase difference between the emitted and reflected waves as a function of frequency. We could also show that the maximum density in the reentry plamsa is estimated from the cut-off in the spectra of the reflected waves. In the present model, we treat a one-dimensional plain wave. In a realistic three-dimensional model, however, radio waves transmitted from the vehicle antenna basically propagate in the radial direction. Therefore the power of the reflected waves observed at the vehicle surface will decrease, which may cause an error in the estimate of phase difference used in the reflectometry. In order to examine this point quantitatively, we need to proceed in multi-dimensional computer experiments, which is left as a future work.

References

Hashimoto, O., and T. Abe, Introduction to Finite Difference Time Domain method, *Morikita Publishing Company*, Japan, 1996.

Huber, P. W., and T. E. Sims, The entry communications problem, Astronautics & Aeronautics, 30-40, October, 1964.

Itoh, K., R. Takagi, and K. Teraoka, The measurement of plasma density around an reentry vehicle with a reflectometer, HYFLEX/HOPE symposium, Japan, 1994.

MaCabe, W. M., and C. F. Stolwyk, Electromagnetic propagation through shock ionized air surrounding glide re-entry spacecraft, *IRE Trans. On Space Electronics and Telemetry*, December issue, 257, 1962.

Maeda, K., and I. Kimura, Electromagnetic waves, Ohm Publishing Company, Japan, 1984

Matsumoto. H., and Y. Omura, Particle simulation of electromagnetic waves and its application to space plasmas, *Computer Simulation of Space Plasmas*, Terra Scientific Publishing Company, 1985.

Matsumoto, H. H. Usui, and S. Takenaka, Computer experiments on radio blackout of a re-entry vehicle and its evasion with magnetic field applied to the re-entry plasma , Trans. Inst. Electron. Inf. Commun. Eng. B-II (Japan) vol.J80B-II, no.3, 257-64, 1997.

Rybak, J. P., and R. J. Churchill, Progress in reentry communications, *IEEE Trans, on Aerospace and Electronic System, AES-7, 5,* 879-894, September, 1971.

Simonet, F., Measurement of electron density profile by micro wave reflectometry on tokamaks,, *Rev.Sci.Instrum, 56,* 664, 1985.