

Propagation Path of Radio Waves in Nonequilibrium Reentry Plasma Around a Nanosatellite With an Inflatable Aeroshell

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A communication blackout is one of the major problems that occurs during the reentry of a satellite into the Earth's atmosphere, which is caused by the reentry plasma blocking electromagnetic waves near the satellite for telecommunication. Moreover, it prevents tracking and data transmission, resulting in inaccurate prediction of landing sites and data loss. Therefore, there is a necessity to evaluate the propagation of electromagnetic waves in the reentry plasma and to mitigate the communication blackout. An inflatable aeroshell technology with lightweight and large-area features enables aerodynamic drag at high altitudes to reduce aerodynamic heating and to mitigate communication blackouts. Thus, a nanosatellite mission using such an inflatable aeroshell has been proposed. For the purpose of telecommunication possibilities during the reentry in future nanosatellite missions, a detailed investigation of communication blackout mitigation by inflatable aeroshell is required. In the present article, the plasma flow and electromagnetic wave propagation near the nanosatellite during atmospheric reentry were revealed by using a computational science approach. A low-temperature and low-density wake is formed behind the nanosatellite. Moreover, an electromagnetic wave propagation path is formed in the wake, indicating that this path is maintained during the reentry, and no communication blackout occurs when using the deployable nanosatellite.

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NOMENCLATURE

a	= altitude, km.
$\mathbf{B}$	= magnetic flux density vector, T.
C	= mass fraction.
C_v	= specific heat at constant volume, J/(kg · K).
D	= effective diffusion coefficient, m ² /s.
$\mathbf{D}$	= electric flux density vector, C/m ² .
e	= electric charge, C.
E	= internal energy, J/m ³ .
$\mathbf{E}$	= electric field vector, V/m.
f	= frequency, Hz.
$\mathbf{F}$	= flux vector.
h	= enthalpy, J/kg.
Δh^0	= enthalpy of formation, J/kg.
H	= enthalpy flux transported by diffusion, J/(m ² · s).
$\mathbf{H}$	= magnetic field vector A/m.
i	= imaginary unit.
I	= current, A.
l	= mean free path, m.
J	= diffusion flux, kg/(m ² · s).
$\mathbf{J}$	= current density vector, A/m ² .
k	= reaction rate coefficient, m ³ /(mol · s).
k_B	= Boltzmann constant, J/K.
K^{eq}	= equilibrium constant.
m	= mass, kg.
n	= number density, 1/m ³ , or normal direction coordinate, m.
N_M	= number of molecules.
N_s	= number of chemical species.
p	= pressure, Pa.
q	= heat flux, W/m ² .
$\mathbf{Q}$	= conservative variable vector.
$\mathbf{r}$	= position vector, m.
R	= gas constant, J/(kg · K).
S	= area, m ² .
S_{int}	= internal energy exchange rate, W/m ³ .
t	= time, s.
T	= temperature, K.
$u, \mathbf{U}$	= velocity, m/s.
V	= volume, m ³ .
$\mathbf{W}$	= source term vector.
x	= coordinate, m.
X	= Mole fraction.
γ	= specific heat ratio.
δ_{ij}	= Kronecker delta.
ϵ_r	= relative permittivity.
ϵ_0	= permittivity in free space, N/V ²
Θ_{vib}	= vibrational characteristic temperature, K.
λ	= thermal conductivity, W/(K · m).
μ	= molecular viscosity, N · s/m ²
ν_c	= collision frequency, Hz.
ρ	= density, kg/m ³ .
q	= charge density, C/m ³ .
σ	= conductivity, S/m.
σ_a	= accommodation coefficient.
τ_{ij}	= viscous stress tensor, N/m ² .
ω	= angular frequency, rad/s.

Subscripts

b	= backward.
bd	= boundary.
ele	= electron.
f	= forward.
free	= free space.
p	= plasma.
pa	= plasma attenuation.
r	= relative.
rot	= rotation.
s	= species.
sl	= slip.
trs	= translation.
vib	= vibration.
w	= wall.
∞	= freestream.

Superscripts

eq	= equilibrium.
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I. INTRODUCTION

When a vehicle travels at a hypersonic speed during its reentry into the Earth's atmosphere, a strong shock wave is generated at its front. The reentry vehicle is surrounded by high-temperature plasma, which is composed of electron and ions that cause the attenuation or reflection of electromagnetic waves used for telecommunication, derived from the generated strong shock waves. The electromagnetic waves between the vehicle and ground stations or data relay satellites are trapped by the reentry plasma, resulting in communication blackouts [1], which have been observed in various space missions [2]–[4] and considered as a problem for sample return missions, ballistic trajectories research, and human space exploration. The communication blackout can last for a few minutes wherein the position of the vehicle cannot be tracked and the data cannot be sent or received by the vehicle and the mission control, resulting in the deterioration of the flight path and landing site predictions and loss of data.

To date, several mitigation schemes of communication blackouts have been proposed [5]. The magnet window [6], wherein a magnetic field is used to form a low-dense plasma, is a well-known idea for blackout reduction. The inflatable aeroshell technology [7] has also been proposed to reduce the aerodynamic heating environment, which helps avoid the formation of blackout duration. Belov *et al.* [8] investigated the effect of the remote antenna assembly for moving the antenna out of the high-dense plasma near the vehicle. The plasma propagation behavior of terahertz waves has been investigated by Xu *et al.* [9], [10] and Ouyang *et al.* [11], and is expected to be a potential blackout mitigation method. The split ring resonator based mu-negative sheet [12] and laser-plasma-induced X-ray emissions [13] are also proposed. The surface catalysis effects for the mitigation scheme have been investigated by Takasawa [14] and Takahashi [15], which revealed the detailed mechanism using experimental and analytical

methods. Thus, in recent years, mitigation scheme studies have been actively conducted.

It is necessary to clarify the behavior of the reentry plasma to study the electromagnetic wave propagation near a reentry vehicle and its mitigation scheme. A computational science approach is an effective method for such investigations [16]. The WKB method [17] and the Scattering-matrix method (SMM) [10] have been proposed to reproduce electromagnetic waves propagating in plasmas. Zhang *et al.* [18] proposed the improved SMM, which was robust and accurate, and it solves the singularity problem of SMM. The ray-tracing model [19], [20] has a low computational cost method and is used to study the electromagnetic waves behavior in the flow field near the atmospheric reentry capsule. The multifluid and fully Maxwell's equation coupling has been implemented by Kundrapu *et al.* [21].

In general, communication blackouts occur at high altitudes in low atmosphere density, where the energy exchange between the internal energy modes is not fully completed due to the low frequency of collisions between molecules. At these altitudes, the characteristic times of chemical reactions and flow become comparable. It is important to properly reproduce such thermochemical nonequilibrium flows for communication blackout studies and to capture the strong shock wave formed in the front of the vehicle, the boundary layer near the surface, and the expansion wave formed in the wake because the flow is moving at a hypersonic speed.

Takahashi [22] proposed a communication blackout analysis model by coupling a nonequilibrium plasma flow simulation based on computational fluid dynamics (CFD) and electromagnetic wave simulation based on the finite difference time domain (FDTD) approach. This approach has helped perform a detailed analysis of electromagnetic wave propagation in reentry plasmas with a high degree of freedom. For example, it is possible to predict the time and direction in which communication is possible for the vehicle, to investigate the plasma attenuation in detail, and to propose new methods to reduce the blackout. Although this generally requires a large computational cost, the recent development of high-performance computers has been solving this problem.

The research on inflatable aeroshell technologies has increased significantly. Examples are mitigation schemes of aerodynamic heating [23]–[26] during atmospheric reentry and aerocapture technology [27] by the inflatable aeroshell. The deployable nanosatellite EGG (reentry satellite with gossamer aeroshell and GPS/Iridium) reentered into the Earth's atmosphere based on the orbital deployment mission that was conducted using the Japanese Experiment Module (JEM) Small Satellite Orbital Deployer (J-SSOD) from the JEM Kibo's airlock on the International Space Station (ISS) in 2017 [28]. The EGG had an inflatable aeroshell technology weighing approximately 4 kg with a diameter of 800 mm when the aeroshell is inflated. After the drop from the ISS, the inflatable aeroshell was deployed, and

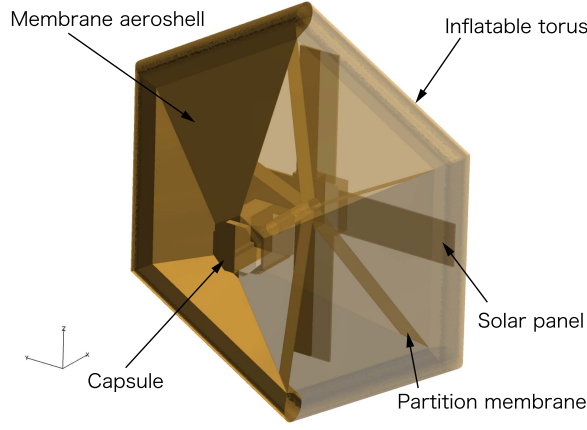


Fig. 1. EGG configuration.

the aerodynamic drag started. During the mission, the communication frequency, satellite position, altitude [29], and aerodynamic heating [30] were measured. Results show that the EGG successfully burnt out below an altitude of 90 km during the atmospheric reentry. The lightweight aeroshell with a large area enables low ballistic coefficient flight, significantly reducing aerodynamic heating and communication blackouts. In addition, the communication in the EGG has been confirmed even at around an altitude of 90 km, and any communication below the altitude is no longer possible due to the damage to the EGG.

Fig. 1 shows the standard triangulated language (STL) model of the EGG, consisting of the inflatable torus, membrane aeroshell, and capsule. In addition, the partition membrane and solar panels are reproduced on the back of the model. The inflatable torus has a tube diameter of 60 mm, and the aeroshell is a regular hexagon with a side of 461 mm and an inscribed circle diameter of 800 mm when projected forward using the inflatable torus. The flare angle is 60°.

EGG was expected to cause no communication blackout during the reentry. However, this was not confirmed by the mission conducted due to it burning out during the reentry process. Currently, various nanosatellites and space missions, such as the atmospheric reentry, have been launched and proposed [31]. It is useful to obtain insight on the mitigation of communication blackouts by deployed nanosatellites for designing future missions. The present analytical model described above helps evaluate detailed communication possibilities in nanosatellites with an inflatable aeroshell. In this study, the plasma flow behavior and electromagnetic wave propagation of EGG during reentry were revealed by numerical analysis.

This article consists of five sections starting with the introduction, including the background, motivation, and purpose of this article. In Section II, the numerical method of the plasma flow is described, while the numerical method of the electromagnetic wave analysis is explained in Section III. Coupling process between the plasma flow and electromagnetic wave simulations are described in Section IV. In Section V, the results obtained by the simulations are discussed. Finally, Section VI concludes this article.

II. PLASMA FLOW MODELING

A. Governing Equations

The flow was assumed to be a continuum, laminar, steady, and in thermochemical condition outside equilibrium, i.e., nonequilibrium. The flow field can be represented by the Navier–Stokes equation, which consists of the total mass, momentum, and total energy conservation laws, and the equation of state, which are extended to thermochemical nonequilibrium flows. Thermal nonequilibrium in the present study was expressed by using Park’s two-temperature model [32], which models both a translational–rotational temperature and a vibrational–electron temperature. Eleven chemical species, including N_2 , O_2 , NO , N_2^+ , O_2^+ , NO^+ , N , O , N^+ , O^+ , and e^- were introduced to consider chemical nonequilibrium, and the species mass conservation laws were added.

The governing equations were composed of conservation laws of total mass, momentum, total energy, species mass, and electron energy; these can be expressed in integral forms as follows:

$$\frac{d}{dt} \int_V Q dV + \int_S (\mathbf{F}_j - \mathbf{F}_{vj}) n_j dS = \int_V \mathbf{W} dV \quad (1)$$

where the conservative vector is expressed as $\mathbf{Q} = [\rho, \rho u_i, E, \rho_s, E_{ele}]^T$. In addition, n_j shows element of the normal vector of area dS . The vectors of the advection flux $\mathbf{F}$, viscous flux $\mathbf{F}_v$, and source term $\mathbf{W}$ in (1) are described as follows:

$$\mathbf{F}_j = \begin{bmatrix} \rho u_j \\ \rho u_i u_j + \delta_{ij} p \\ (E + p) u_j \\ \rho_s u_j \\ E_{ele} u_j \end{bmatrix}, \quad \mathbf{F}_{vj} = \begin{bmatrix} 0 \\ \tau_{ij} \\ q_j + u_i \tau_{ij} + H_j \\ J_{s,j} \\ q_{ele,j} + H_{ele,j} - p_{ele} u_j \end{bmatrix}$$

$$\mathbf{W} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dot{w}_s \\ S_{ele} \end{bmatrix} \quad (2)$$

where δ_{ij} , $\dot{w}_s$, and S_{ele} denote the Kronecker delta, mass production rate, and internal energy exchange rate, respectively. The stress tensor, τ_{ij} , and heat flux, q_j , in (2) can be expressed as follows:

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{ij} \quad (3)$$

$$q_j = (\lambda_{trs} + \lambda_{rot}) \frac{\partial T_{trs}}{\partial x_j} + (\lambda_{ele} + \lambda_{vib}) \frac{\partial T_{ele}}{\partial x_j}. \quad (4)$$

The electron component including the vibrational, q_{ele} , is the second term of the right-hand side in (4). The diffusion flux, $J_{s,j}$, and enthalpy flux transported by the diffusion, H_j , are expressed by

$$J_{s,j} = \rho D_s \frac{\partial X_s}{\partial x_j} \quad (5)$$

$$H_j = \rho \sum_{s=1}^{N_s} h_s D_s \frac{\partial X_s}{\partial x_j} \quad (6)$$

$$H_{\text{ele},j} = \rho h_{\text{ele}} D_{\text{ele}} \frac{\partial X_{\text{ele}}}{\partial x_j} + \rho \sum_{s=M}^{N_m} h_{\text{vib},s} D_s \frac{\partial X_s}{\partial x_j} \quad (7)$$

where D_s , h_s , and X_s are the effective diffusion coefficient, enthalpy, and mole fraction of species s , respectively. In addition, M means the molecular species.

The equation of state is given by

$$p = \sum_{s \neq \text{ele}}^{N_s} \rho_s R_s T_{\text{trs}} + \rho_{\text{ele}} R_{\text{ele}} T_{\text{ele}}. \quad (8)$$

The electron pressure, p_{ele} , is the second term of the right-hand side in (8).

The total internal energy can be calculated as

$$\begin{aligned} E = & \sum_{s \neq \text{ele}}^{N_s} \frac{3}{2} \rho_s R_s T_{\text{trs}} + \sum_{s=M}^{N_m} \rho_s R_s T_{\text{trs}} \\ & + \frac{3}{2} \rho_{\text{ele}} R_{\text{ele}} T_{\text{ele}} + \sum_{s=M}^{N_m} \frac{\rho_s R_s \Theta_{\text{vib},s}}{\exp(\Theta_{\text{vib},s}/T_{\text{ele}}) - 1} \\ & + \sum_{s=1}^{N_s} \rho_s \Delta h_s^0 + \frac{1}{2} \rho u_i u_i \end{aligned} \quad (9)$$

where Δh_s^0 and $\Theta_{\text{vib},s}$ represent the enthalpy of formation and vibrational characteristic temperatures, respectively. The electron and vibrational energy, E_{ele} , is summation of the third and forth terms of the right-hand side in (9).

B. Transport Properties

The transport coefficients, including viscosity, thermal conductivity, and effective diffusion coefficient, in the viscosity term of the governing equations were evaluated based on the first-order Chapman–Enskog approximation [33] and extended to multicomponent and multitemperature gas using Yos' formula [34]. The effective diffusion coefficients were calculated using binary diffusion coefficients based on Curtiss's formula [35]. Moreover, the effect of the ambipolar diffusion on ionized heavy-particles was also considered.

The collision cross-sections used for calculating the transport coefficients were curve-fitted as a function of temperature. In this model, the proposed model by Gupta [36] was used for the collision cross-sections between species, except for e–N and e–O. Moreover, Fertig's model [37] was used between e–N and e–O.

C. Thermal Nonequilibrium

It is necessary to model the energy exchange term, S_{ele} , in the vibration–electron energy conservation law because the energy exchange between internal energy modes was considered to reproduce the thermal nonequilibrium flow. In this analysis, Park's two-temperature model [32] that considers the energy transfers between translation–vibration, translation–electron, rotation–vibration, and rotation–electron was adopted. In addition,

the energy losses due to dissociation and ionization reactions are also introduced.

D. Chemical Nonequilibrium

The flow field is in chemical nonequilibrium when the characteristic time of the chemical reactions is close to that of the flow. Moreover, the species equation needs to be solved along with the source term calculation. In the simulation employed in this study, 49 chemical reactions were considered for 11 chemical species in the high-temperature air to reproduce the chemical reactions in the plasma flow. The forward reaction rate was given by the Arrhenius type as follows:

$$k_{f,r}(T_{f,r}) = C_r T_{f,r}^{n_r} \exp\left(-\frac{\theta_r}{T_{f,r}}\right) \quad (10)$$

where the reaction rate coefficients C_r , n_r , and θ_r were obtained from Park's study [32]. The backward reaction rate was obtained from the ratio of the forward reaction rate and the equilibrium constant.

$$k_{b,r}(T_{b,r}) = \frac{k_{f,r}(T_{b,r})}{K_r^{\text{eq}}(T_{b,r})} \quad (11)$$

where $T_{f,r}$ and $T_{b,r}$ are the effective temperatures of the forward and backward reactions, respectively, expressed as the geometric means of each temperature. These constants and effective temperatures are summarized in Table I. The equilibrium constants, which are functions of only the effective temperature $T_{b,r}$, were obtained by curve-fitting models proposed by Park [38] and Gupta [36].

E. Numerical Implementation

The physical model described in the previous sections was implemented in the high-enthalpy flow solver RG-FaSTAR [22], which is based on the FaSTAR [39] developed by JAXA and included the real gas effect to express the thermochemical nonequilibrium flow. The governing equations were discretized with a finite volume formulation. Moreover, the flow properties were defined at the cell center. Additionally, the spatial gradients were calculated based on the Gauss–Green theory. The SLAU2 scheme [40] was adopted as the numerical flux evaluation for the advection term. In contrast, the viscosity term was given by the average of the spatial gradients of the neighboring cells with a correction to prevent instability. The minmod function was used for the slope limiter. The time integration was performed using the Euler implicit method. The steady-state solution was obtained by the point implicit method [41] for the source term and the coefficient matrix inversion by the LU-SGS method [42].

F. Computational Conditions

Fig. 2(a) and (b) shows the computational domain and grids of the plasma flow simulation, respectively. A tetrahedral mesh, which has a good shape reproducibility and can easily generate computational grids, was used in the simulation since the EGG had a complicated shape. A

TABLE I
Chemical Reactions

r	Forward		Backward	C_r	n_r	θ_r	$T_{f,r}$	$T_{b,r}$
1-6	$N_2 + M_1$	$\rightleftharpoons$	$N + N + M_1$	7.0×10^{21}	-1.60	113,200	T_{f1}	T_{trs}
7-10	$N_2 + M_2$	$\rightleftharpoons$	$N + N + M_2$	3.0×10^{22}	-1.60	113,200	T_{f1}	T_{trs}
11	$N_2 + e^-$	$\rightleftharpoons$	$N + N + e^-$	1.2×10^{25}	-1.60	113,200	T_{ele}	T_{b1}
12-17	$O_2 + M_1$	$\rightleftharpoons$	$O + O + M_1$	2.0×10^{21}	-1.50	59,500	T_{f1}	T_{trs}
18-21	$O_2 + M_2$	$\rightleftharpoons$	$O + O + M_2$	1.0×10^{22}	-1.50	59,500	T_{f1}	T_{trs}
22-26	$NO + M_1$	$\rightleftharpoons$	$N + O + M_1$	5.0×10^{15}	0.00	75,500	T_{f1}	T_{trs}
27-31	$NO + M_2$	$\rightleftharpoons$	$N + O + M_2$	1.1×10^{17}	0.00	75,500	T_{f1}	T_{trs}
32	$NO + O$	$\rightleftharpoons$	$N + O_2$	8.4×10^{12}	0.00	19,450	T_{trs}	T_{trs}
33	$N_2 + O$	$\rightleftharpoons$	$NO + N$	6.4×10^{17}	-1.00	38,400	T_{trs}	T_{trs}
34	$N + N$	$\rightleftharpoons$	$N_2^+ + e^-$	4.4×10^7	1.50	67,500	T_{trs}	T_{trs}
35	$O + O$	$\rightleftharpoons$	$O_2^+ + e^-$	7.1×10^2	2.70	80,600	T_{trs}	T_{trs}
36	$N + O$	$\rightleftharpoons$	$NO^+ + e^-$	8.8×10^8	1.00	31,900	T_{trs}	T_{trs}
37	$N + e^-$	$\rightleftharpoons$	$N^+ + e^- + e^-$	2.5×10^{34}	-3.82	168,600	T_{ele}	T_{ele}
38	$O + e^-$	$\rightleftharpoons$	$O^+ + e^- + e^-$	3.9×10^{33}	-3.78	158,500	T_{ele}	T_{ele}
39	$NO^+ + O$	$\rightleftharpoons$	$N^+ + O_2$	1.0×10^{12}	0.50	77,200	T_{trs}	T_{trs}
40	$O_2^+ + N$	$\rightleftharpoons$	$N^+ + O_2$	8.7×10^{13}	0.14	28,600	T_{trs}	T_{trs}
41	$O^+ + NO$	$\rightleftharpoons$	$N^+ + O_2$	1.4×10^5	1.90	26,600	T_{trs}	T_{trs}
42	$O_2^+ + N_2$	$\rightleftharpoons$	$N_2^+ + O_2$	9.9×10^{12}	0.00	40,700	T_{trs}	T_{trs}
43	$O_2^+ + O$	$\rightleftharpoons$	$O^+ + O_2$	4.0×10^{12}	-0.09	18,000	T_{trs}	T_{trs}
44	$NO^+ + N$	$\rightleftharpoons$	$O^+ + N_2$	3.4×10^{13}	-1.08	12,800	T_{trs}	T_{trs}
45	$NO^+ + O_2$	$\rightleftharpoons$	$O_2^+ + NO$	2.4×10^{13}	0.41	32,600	T_{trs}	T_{trs}
46	$NO^+ + O$	$\rightleftharpoons$	$O_2^+ + N$	7.2×10^{12}	0.29	48,600	T_{trs}	T_{trs}
47	$O^+ + N_2$	$\rightleftharpoons$	$N_2^+ + O$	9.1×10^{11}	0.36	22,800	T_{trs}	T_{trs}
48	$NO^+ + N$	$\rightleftharpoons$	$N_2^+ + O$	7.2×10^{13}	0.00	35,500	T_{trs}	T_{trs}
49	$N_2 + N^+$	$\rightleftharpoons$	$N_2^+ + N$	1.0×10^{12}	0.50	12,200	T_{trs}	T_{trs}

TABLE II
Freestream Parameters Along the Reentry Trajectory of the Deployable Nanosatellite EGG

a , km	U_∞ , m/s	ρ_∞ , kg/m ³	T_∞ , K	C_{∞,N_2}	C_{∞,O_2}	$C_{\infty,O}$
100	7683	4.83×10^{-7}	184.8	7.771×10^{-1}	1.942×10^{-1}	2.872×10^{-2}
95	7529	1.12×10^{-6}	184.8	7.800×10^{-1}	2.084×10^{-1}	1.156×10^{-2}
90	7221	2.72×10^{-6}	193.4	7.796×10^{-1}	2.178×10^{-1}	2.624×10^{-2}
89	7137	3.19×10^{-6}	195.4	7.693×10^{-1}	2.163×10^{-1}	1.744×10^{-3}
88	7043	3.75×10^{-6}	197.4	7.688×10^{-1}	2.175×10^{-1}	1.129×10^{-3}
87	6939	4.39×10^{-6}	199.3	7.681×10^{-1}	2.187×10^{-1}	6.995×10^{-4}
86	6825	5.14×10^{-6}	201.3	7.675×10^{-1}	2.196×10^{-1}	4.143×10^{-4}
85	6700	6.01×10^{-6}	203.1	7.765×10^{-1}	2.233×10^{-1}	2.368×10^{-4}
84	6563	7.02×10^{-6}	204.9	7.661×10^{-1}	2.213×10^{-1}	1.255×10^{-4}
83	6414	8.18×10^{-6}	206.7	7.653×10^{-1}	2.221×10^{-1}	6.402×10^{-5}
82	6252	9.54×10^{-6}	208.4	7.644×10^{-1}	2.227×10^{-1}	3.098×10^{-5}
81	6078	1.11×10^{-5}	210.0	7.638×10^{-1}	2.233×10^{-1}	1.420×10^{-5}
80	5893	1.29×10^{-5}	211.6	7.732×10^{-1}	2.268×10^{-1}	6.259×10^{-6}
75	4780	2.74×10^{-5}	217.8	7.707×10^{-1}	2.293×10^{-1}	4.856×10^{-8}
70	3529	5.76×10^{-5}	221.7	7.687×10^{-1}	2.313×10^{-1}	0.0

detailed region was created near the EGG with a spatial resolution that was locally increased, where the flow field changed rapidly. The number of computational grids was 17 650 727 cells.

The inflow condition at the front of the vehicle, the outflow condition at the rear, and the surface condition were set as boundary conditions in the plasma flow analysis in this study. Specifically, the velocity, density, temperature, and chemical species in the inflow condition at the front of the vehicle were given as freestream flows, which are listed in Table II. In this table, a is the altitude, U_∞ is the freestream velocity, ρ_∞ is the freestream density, T_∞ is the freestream temperature, and $C_{\infty,s}$ is the freestream mass fraction of species s . The atmospheric data were obtained from the NRLMSISE-00 Atmosphere Model [43]. The freestream

velocity was given by the trajectory analysis data obtained by solving the three degree-of-freedom equation of motion of the mass point in a noninertial coordinate system (Earth rotation, Earth fixed coordinates; ECEF) where Earth gravity and aerodynamic forces act. The mass of the point was 4 kg and the drag coefficient set was 1.0 in the trajectory analysis. The flow field computations between altitudes of 100 and 70 km were performed. A gradient-free condition for all the flow properties at the outlet boundary was imposed. No pressure gradient in the normal direction of the surface boundary was given. The angle of attack (AOA) was set to zero.

The boundary condition on the vehicle's surface deviates from the nonslip condition and behaves more like a slip condition when the flow is in a rarefied gas state,

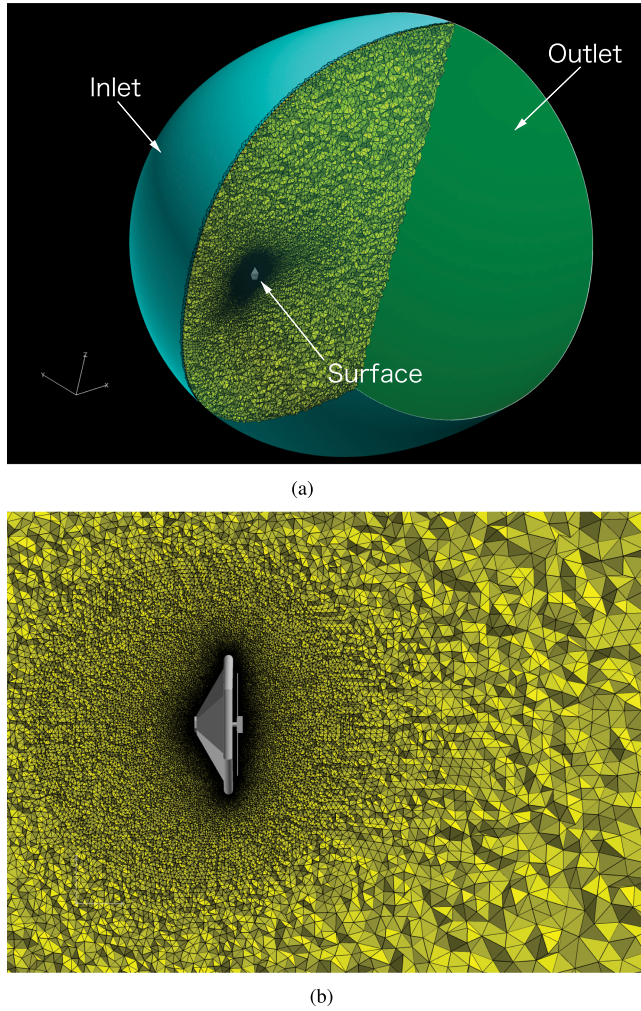


Fig. 2. Computational domain and grids of the plasma flow simulation.

i.e., a high Knudsen number at high altitudes. Therefore, the low-density slip condition [44] was adopted in this simulation as the velocity and temperature boundaries at the surface. This boundary condition was expressed by

$$\sigma_a (u_{sl} - u_w) = 2\ell_u \left. \frac{\partial u}{\partial n} \right|_w \quad (12)$$

$$\sigma_a (T_{sl} - T_w) = 2\ell_T \left. \frac{\partial T}{\partial n} \right|_w \quad (13)$$

where u_{sl} and T_{sl} are the velocity and temperature at the slip surface, respectively. In addition, u_w is the velocity at the wall surface set to 0 m/s and T_w is the temperature at the wall surface set to 300 K. Moreover, the accommodation coefficient σ_a was set to 1.0. The mean free paths ℓ_u and ℓ_T were given by

$$\ell_u = \frac{\mu}{\rho} \sqrt{\frac{\pi}{2RT}} \quad (14)$$

$$\ell_T = \frac{2}{(\hat{\gamma} + 1)} \frac{\lambda_{trs}}{\rho \hat{C}_v} \sqrt{\frac{\pi}{2RT}} \quad (15)$$

where λ_{trs} is the translational component of the thermal conductivity. In addition, $\hat{R}$, $\hat{\gamma}$, and $\hat{C}_v$ are the gas constant,

specific heat ratio, and specific heat at a constant volume of the gas mixture, respectively. These values appearing in the mean free paths were evaluated in the fluid cells neighboring the boundary surface (i.e., low-density slip surface).

III. ELECTROMAGNETIC WAVES MODELING

The electromagnetic wave propagation generally follows the Maxwell's equations. The FDTD method has been widely used as a numerical expression of the equations, while in the case of dispersive medium such as plasma, this method probably shows a large error. In this article, the frequency-dependent finite difference time domain (FD2TD) method [45] was adopted, wherein the electric flux density is calculated as a convolution integral of the dielectric constant and the electric field to account for frequency dispersion. Here, only the dielectric constant was assumed to have frequency dependence, while the magnetic permeability was assumed to be constant.

A. Maxwell's Equations

The following Maxwell's equations can be expressed by

$$\nabla \times \mathbf{E}(\mathbf{r}, t) = -\frac{\partial \mathbf{B}(\mathbf{r}, t)}{\partial t} \quad (16)$$

$$\nabla \times \mathbf{H}(\mathbf{r}, t) = \frac{\partial \mathbf{D}(\mathbf{r}, t)}{\partial t} + \mathbf{J}(\mathbf{r}, t) \quad (17)$$

$$\nabla \cdot \mathbf{D}(\mathbf{r}, t) = \rho(\mathbf{r}, t) \quad (18)$$

$$\nabla \cdot \mathbf{B}(\mathbf{r}, t) = 0 \quad (19)$$

where $\mathbf{E}$, $\mathbf{H}$, $\mathbf{D}$, $\mathbf{B}$, $\mathbf{J}$, and ρ were the electric field, magnetic field, electric flux density, magnetic flux density, current density, and charge density, respectively. Additionally, $\mathbf{r}$ and t are the position vector and time, respectively. The current density is given by

$$\nabla \cdot \mathbf{J}(\mathbf{r}, t) + \frac{\partial \rho(\mathbf{r}, t)}{\partial t} = 0. \quad (20)$$

In this article, the computational domain surrounds the wave source, and the entire domain is divided into small rectangles. Maxwell's equations were spatially discretized on Yee's cell [46] and were solved in the time domain.

B. Dispersive Medium

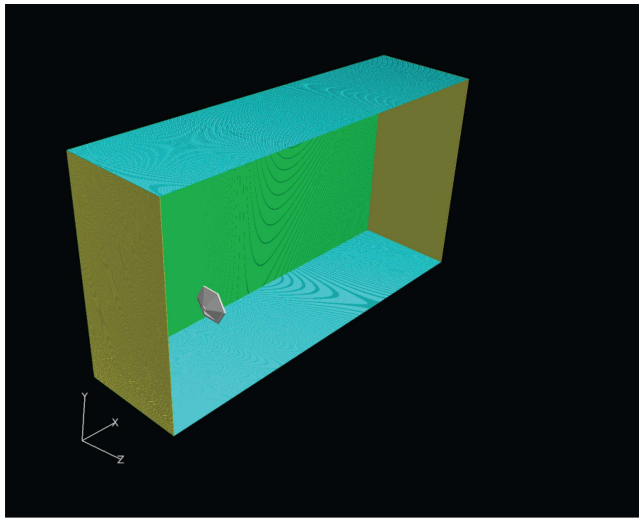
The first-order Drude dispersion to represent the plasma, which is the dispersive medium, was adopted. The complex permittivity based on the relative permittivity and electrical conductivity was expressed as follows:

$$\varepsilon_r^* = \varepsilon_r + \frac{\sigma}{i\omega\varepsilon_0} \quad (21)$$

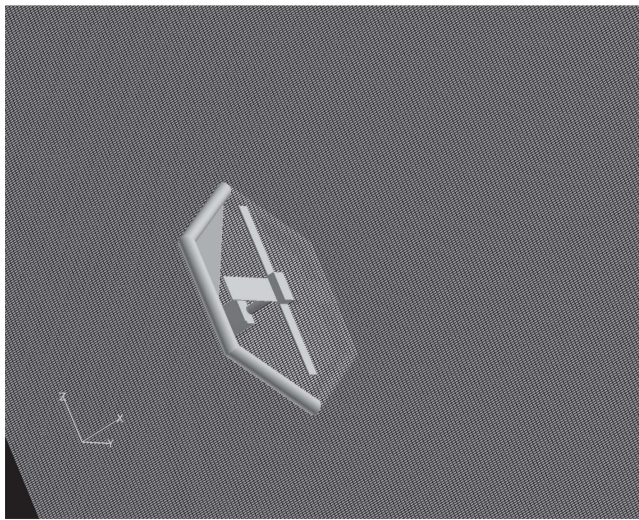
where i , ω , and ε_0 are the imaginary unit, link angular frequency in telecommunication, and permittivity in free space, respectively. In addition

$$\varepsilon_r = 1 - \frac{\omega_p^2}{\omega^2 + \nu_c^2} \quad (22)$$

$$\sigma = \frac{\varepsilon_0 \omega_p^2}{\omega^2 + \nu_c^2} \nu_c \quad (23)$$



(a)



(b)

Fig. 3. Computational domain and grids of the electromagnetic waves simulation.

where ω_p and ν_c show the plasma angular frequency and electron collision frequency, respectively.

C. Computations

Fig. 3(a) and (b) shows the computational domain and grids of the simulation of the electromagnetic waves, respectively. The number of the computational grids was set to 421 875,000 nodes (i.e., $750 \times 750 \times 750$) and the frequency of the communication electromagnetic wave to 1.6 GHz. Additionally, the antenna was assumed to be located at the rear of the capsule, and the Mur's absorption boundary conditions [47] were set for all outer boundaries. The electromagnetic waves were reflected on the surface because the conductivity condition was imposed on the EGG capsule and solar panels. However, the aeroshell and inflatable torus, which are composed of a fabric (i.e., Zylon), were assumed to transmit electromagnetic waves.

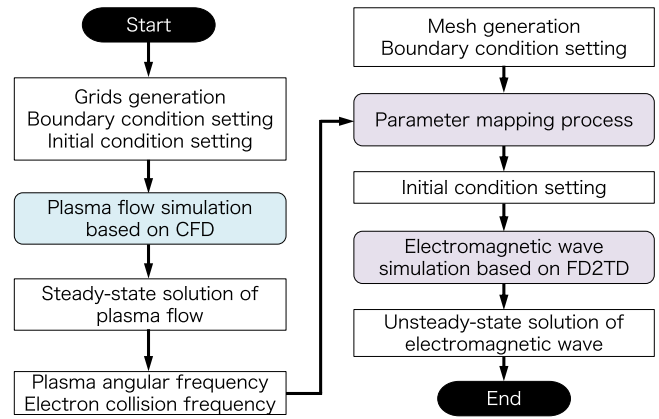


Fig. 4. Flowchart of coupling process between plasma flow and electromagnetic wave simulations.

The electromagnetic wave analysis model based on FD2TD described above was implemented in “Arcflow/Arcwave” code developed by the author.

IV. COUPLING PROCESS

To reproduce electromagnetic waves propagation in reentry plasma, the plasma flow simulation based on CFD and the electromagnetic wave propagation by FD2TD described in previous sections are coupled. Because the characteristic time of the electromagnetic wave is much faster than that of the plasma flow, one-way coupling from the plasma to the electromagnetic wave is sufficient. Thus, the coupling is achieved by mapping the steady-state plasma variables obtained from the CFD simulations to the FD2TD computational domain, and then performing the unsteady electromagnetic-wave simulation in turn. In this coupling, the transfer variables are the plasma angular frequency ω_p and the electron collision frequency ν_c . These are respectively obtained as follows:

$$\omega_p = \sqrt{\frac{e^2 n_{ele}}{m_{ele} \epsilon_0}} \quad (24)$$

$$\nu_c = \sum_{s=1}^{N_s} n_s \pi \Omega_{s,ele} \sqrt{\frac{8k_B T_{ele}}{\pi m_{ele}}} \quad (25)$$

where e is the elementary charge, n_s is the number density of chemical species s , m_{ele} is the electron mass, and k_B is the Boltzmann constant. In addition, $\pi \Omega_{s,ele}$ is the collision cross-section between the species s and electrons, and it is obtained from the results of the plasma flow simulation.

Fig. 4 is a flow chart of the present coupling process between the plasma flow and electromagnetic wave simulations. Because the initial state has no influence on the steady-state solution of the plasma flow simulation, the initial condition is given by values close to the freestream parameters. After obtaining the plasma-flow solution, the plasma angular frequency and the electron collision frequency are transferred to the data mapping process, and then, the initial condition, including the electric and magnetic fields of zero, for the electromagnetic wave simulation

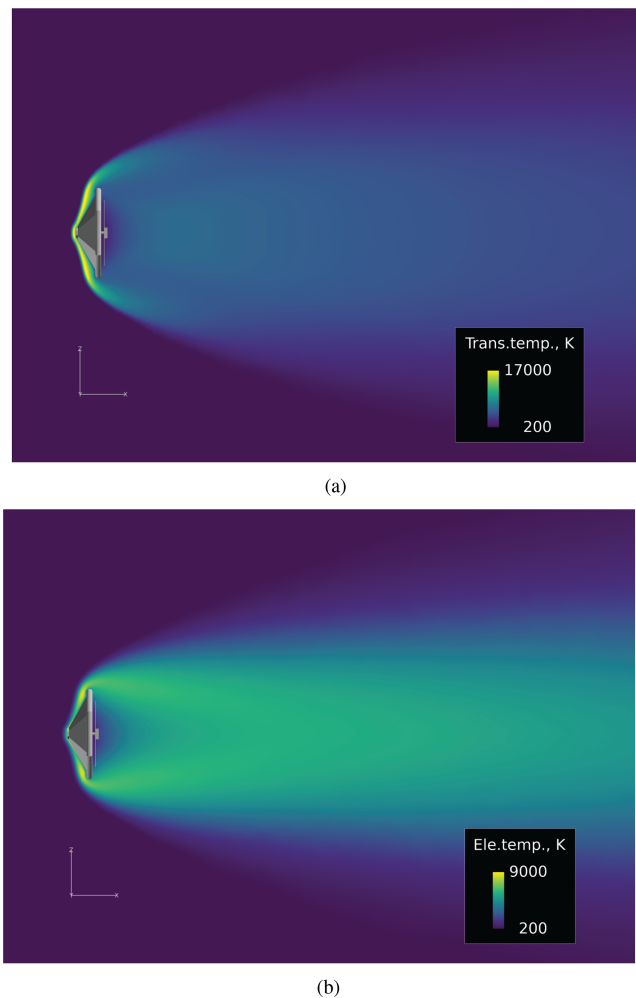


Fig. 5. Distributions of translational and electron temperatures around the nanosatellite at an altitude of 85 km.

is set. The electromagnetic wave simulation is performed, and the time-series solutions for wave propagation in reentry plasma are finally obtained in the coupling calculation.

The present analysis models implemented in RG-FaSTAR and Arcflow/Arcwave code have been validated through comparison with the flight data of RAM-C and the atmospheric reentry demonstration (ARD) of the European Space Agency (ESA) [15], [22].

V. RESULTS AND DISCUSSION

This section presents and discusses the numerical results. The flow field near the EGG nanosatellite is shown from the results of the plasma flow simulations. Meanwhile, the details of electromagnetic wave propagation during the reentry are discussed from the results of the electromagnetic wave simulations. Furthermore, the mechanism of communication blackout mitigation is clarified.

A. Fundamental Structure of Plasma Flow

The translational and electron temperature distributions around the EGG nanosatellite at an altitude of 85 km are shown in Fig. 5(a) and (b), respectively. The freestream

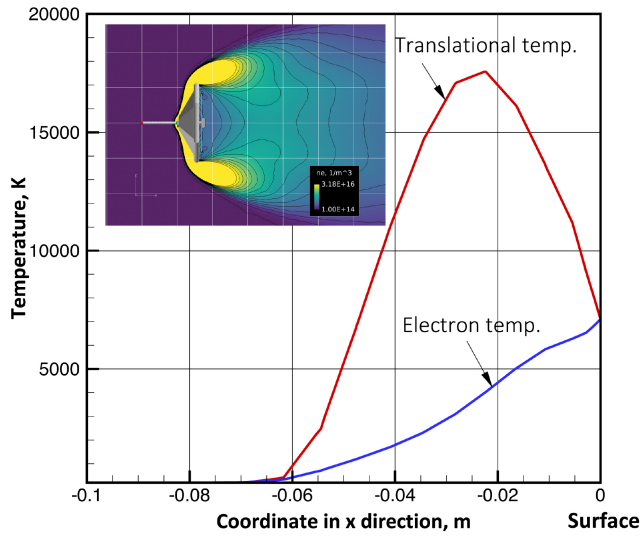
Mach number at this altitude is approximately 24 with a low atmospheric density. A strong shock wave was formed in front of the nanosatellite, and a high-temperature plasma was observed behind the shock wave. The kinetic energy across the shock wave is converted into thermal energy, increasing the translational temperature. Eventually, the electron temperature increases due to the relaxation of the internal energy. Then, chemical reactions started to occur, producing dissociated and ionized species. Moreover, the electron temperature remained low compared to the translational temperature because the atmospheric density was low and the relaxation between particles was insufficient. The flare angle of the membrane aeroshell of the nanosatellite was 60° . From the point of view of shock interaction and aerodynamic heating, it is desirable that a detached shock wave is formed in an inflatable reentry vehicle. Thus, the flare angle should be above a certain value [25]. However, the flare angle of the nanosatellite was small and was set as a tradeoff between the aerodynamic heating and attitude stability. The shape of the shock wave was close to that of the attached shock wave. Because the nanosatellite was supposed to burn out during the atmospheric entry, it is not a major problem in the mission. The high-temperature gas compressed in front of the nanosatellite expanded and accelerated in the inflatable torus, and a relatively low-temperature region was observed behind the nanosatellite. The translational temperature decreased because of the supersonic expansion, and the electron temperature decreased as the translational temperature relaxed. The relatively high electron temperature in the wake was due to the lack of relaxation. The occurrence of the thermal nonequilibrium is a characteristic of reentry plasmas.

In this article, the analysis was performed without AOA as a typical case of the inflatable aeroshell. However, because the EGG in the mission had no attitude control device, the EGG possibly reentered into the atmosphere with an AOA. The behavior of electromagnetic wave in plasma considering AOA is an interesting study. Although this is not within the scope of the present article, the study is also one of the future issues.

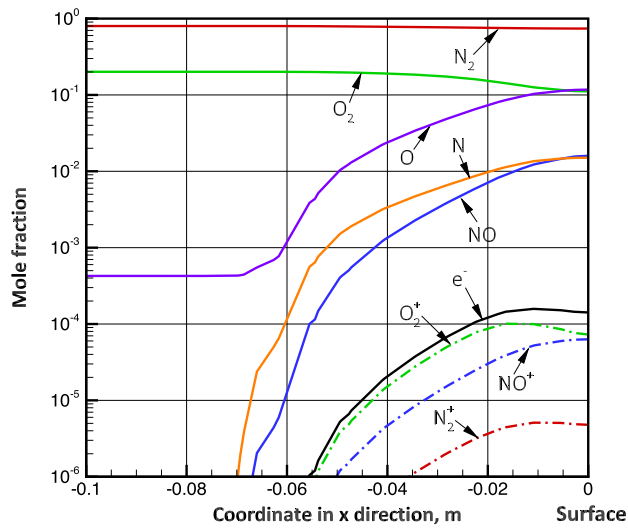
B. Thermal and Chemical Nonequilibrium

The profiles of the temperatures and species mole fractions on the front-side body axis at the altitude of 85 km are shown in Fig. 6(a) and (b), respectively. The shock wave is formed at a distance of approximately 0.06 m from the surface of the nanosatellite. The translational temperature increased across the shock wave at approximately 17 000 K, and the electron temperature increased during relaxation at approximately 6000 K. At this altitude, the nonequilibrium in the shock layer is high and the thermal equilibrium, which is a region where each temperature is expressed as a single value, is not yet formed.

The reaction of chemical species proceeded at slow rates, and the chemical nonequilibrium was observed. N_2 did not significantly dissociate, while O_2 dissociated in the shock layer because its dissociation energy is much lower



(a)

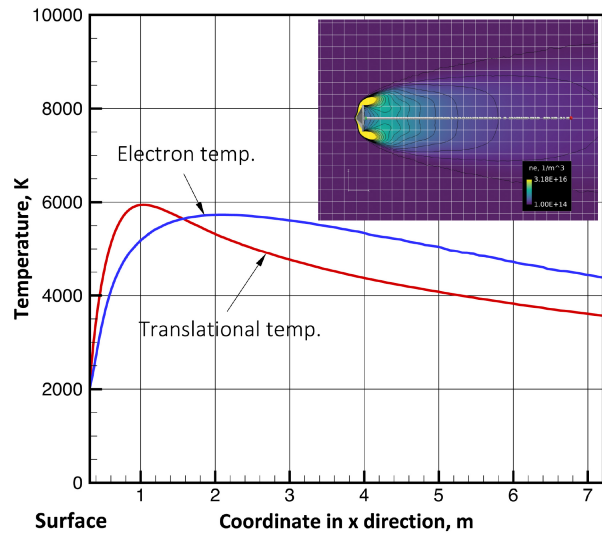


(b)

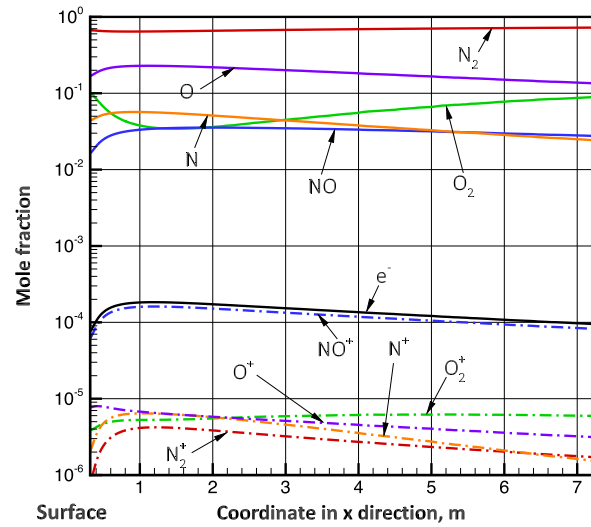
Fig. 6. Profiles of temperatures and mole fractions on the front-side body axis of the nanosatellite at an altitude of 85 km.

than that of N_2 that causes it to dissociate more easily. The dominant chemical species in the shock layer are N_2 , O_2 , and O . The dissociated N_2 generated a small amount of N . On the other hand, nitric oxide, NO , was formed by combining O and N . The ionized species were mostly O_2^+ and NO^+ , and less of N_2^+ . Moreover, N^+ and O^+ did not almost exist. Therefore, the associative ionization reactions produced most electrons ($r=34\text{--}36$ in Table I). The temperature of the flow field suggests that the electron-impact ionization, which generates many N^+ and O^+ , did not occur.

The profiles of the temperatures and mole fractions on the wake-side body axis at an altitude of 85 km are shown in Fig. 7(a) and (b), respectively. The peak translational and electronic temperatures in the wake of the nanosatellite were approximately 6 000 K, which is lower than the temperatures obtained in the front shock layer due to the occurrence of the supersonic expansion that resulted in



(a)



(b)

Fig. 7. Profiles of temperatures and mole fractions on the wake-side body axis of the nanosatellite at an altitude of 85 km.

the conversion of thermal energy to kinetic energy. The relaxation of internal energies was low and nonequilibrium region was observed.

The dominant chemical species in the wake were dissociated species, including N_2 , O_2 , N , and O , with few charged species of ions and electrons. There were almost no chemical reactions. In addition to the low density and frequency collisions between particles, a high velocity reduces the frequency of recombination reactions. The recombinations between ionized species and electrons did not exist in the wake. However, the number of O_2^+ decreased and NO^+ was dominant as an ionized species compared to the front shock layer.

C. Electron Density in the Wake

The electron number density is the plasma parameter that has the greatest influence on communication blackouts.

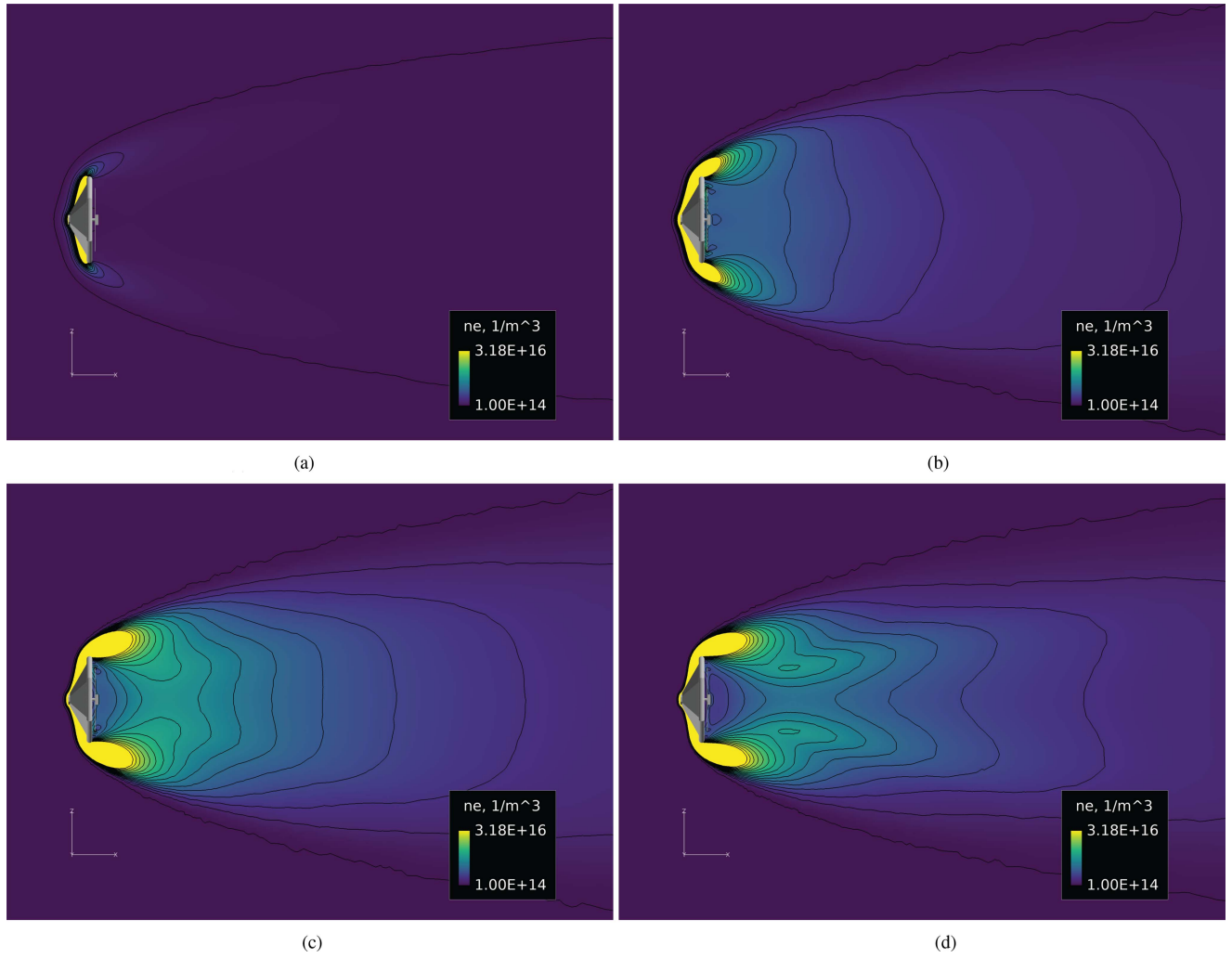


Fig. 8. Distributions of the electron number density around the nanosatellite at each altitude.

Fig. 8(a)–(d) shows the electron number density distributions around the nanosatellite at altitudes of 95, 90, 85, and 80 km, respectively. The maximum value of the legend in the figure shows the critical electron number density of $n_{\max} = 3.18 \times 10^{16} \text{ 1/m}^3$ at the communication frequency of 1.6 GHz calculated based on the equation

$$f_{\text{cr}} = \frac{1}{2\pi} \sqrt{\frac{e^2 n_{\max}}{\epsilon_0 m_{\text{ele}}}}. \quad (26)$$

The electromagnetic waves with frequency below f_{cr} cannot propagate. Moreover, the attenuation, reflection, and diffraction occur near the surface. There was a region behind the nanosatellite with a low electron number density due to rarefaction caused by the supersonic expansion, while the shock layer in front of the nanosatellite showed a high electron number density. At high altitudes, chemical reactions did not occur much due to the very low density, and the number of electrons was quite low. On the other hand, at altitudes below 90 km, a relatively large number of electrons was generated in the shock layer in front of the nanosatellite. However, in both cases, a low-density

region was formed in the wake. This result suggested that electromagnetic waves with a communication frequency of 1.6 GHz cannot propagate in the front of the nanosatellite, but can propagate in the wake. The electron number density peaked at an altitude of 85 km and decreased at lower altitudes. Therefore, as long as no blackout occurred at an altitude of 85 km, blackouts do not occur at other altitudes.

D. Waves Propagation Path

The propagation of electromagnetic waves around the nanosatellite during the reentry was investigated using the FD2TD method. Fig. 9(a) and (b) shows the absolute values of the electric field near the nanosatellite at an altitude of 100 and 85 km, respectively, with a logarithmic scale. There was almost no plasma near the nanosatellite at the altitude of 100 km, causing the wave to travel without reflection or absorption. Therefore, the electromagnetic waves propagated concentrically around the antenna. On the other hand, a strong shock layer was formed in front of the nanosatellite at the altitude of 85 km, and a highly dense plasma appeared. Moreover, electromagnetic waves were reflected, absorbed, and diffracted near the surface because the plasma in the

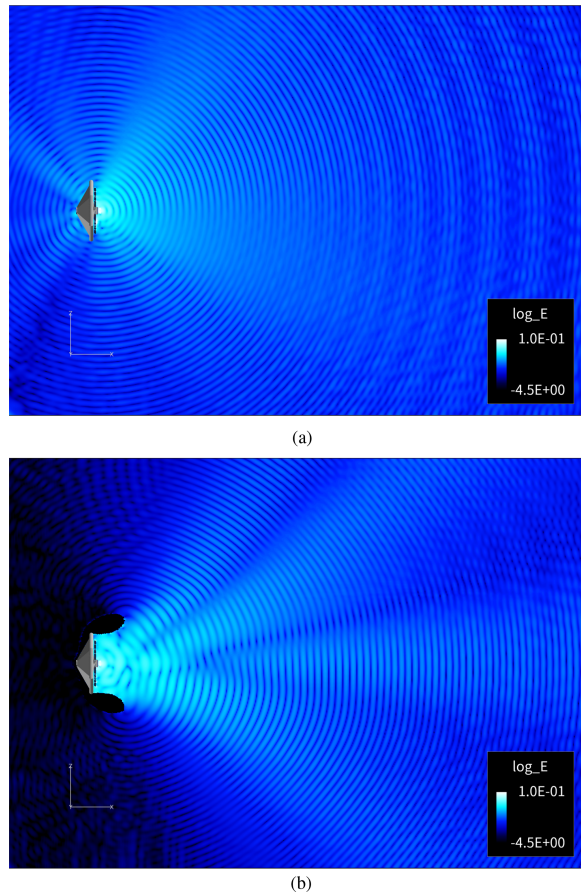


Fig. 9. Distributions of the absolute values of the electric field of electromagnetic waves around the nanosatellite.

shock layer in front of the nanosatellite exceeded the critical electron density. Therefore, the electromagnetic wave propagation to the front surface was almost impossible. This similar situation is also apparent in reentry vehicles that are larger than nanosatellites as shown by ESA ARD [15]. The communication with the vehicle is difficult when the observer is located in front of the vehicle, and a communication blackout or similar situation occurs. In the wake, although the electron distribution did not exceed the critical electron number density, an environment with low permittivity and high conductivity appeared. A high-density plasma was also formed behind the inflatable torus, which formed a horn-shaped reflective region in the wake, resulting in enhanced propagation of electromagnetic waves to the rear. The observer that is located at the rear side is able to capture the electromagnetic wave propagation through the path formed in the wake, avoiding communication blackouts. For example, if the Iridium satellite communication network used in the EGG mission or data-relay satellites can be used, the communication during the reentry is possible. However, this opportunity will be carried by the next mission because of the planned burn out of the EGG mission.

The current density can be calculated when an electromagnetic wave passes through a certain area. Additionally, the current can be obtained by integrating the electromagnetic wave over a specific region. The generated current

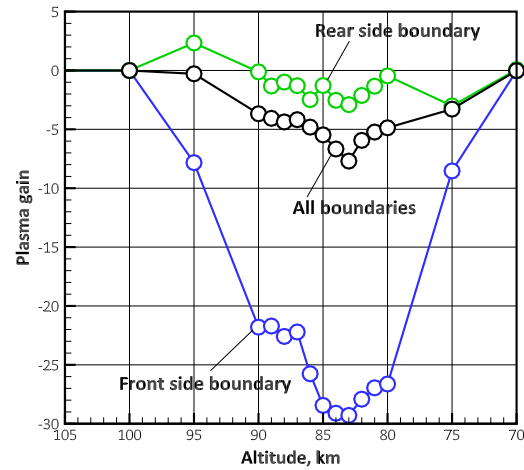


Fig. 10. Plasma attenuation gain profile in the nanosatellite atmospheric reentry.

was calculated over the entire absorption boundary of the FD2TD computational domain. The plasma attenuation gain profile of the electromagnetic wave for the nanosatellite was obtained by dividing the current at an altitude by the current in the no-plasma case, which is defined as follows:

$$G_{pa} = 10 \log \frac{\sum I_{bd}^2}{\sum I_{bd, free}^2}. \quad (27)$$

The attenuation of the electromagnetic wave becomes smaller as the gain value is closer to zero due to the reentry plasma. Conversely, the larger the negative value, the larger the attenuation. Moreover, this value becomes negative and infinite when the electromagnetic wave is surrounded by the plasma and there is no electromagnetic wave passing through the outer boundary, resulting in a communication blackout. In the present simulations, however, such a result was not observed.

Fig. 10 shows the profile of the plasma attenuation gain at each altitude, obtained in the EGG simulations. This figure also includes the gain profiles integrating over the only front-side boundary and rear-side. Attenuation integrated over the entire boundary started at an altitude of approximately 90 km, with a peak attenuation at 83 km. Then, the gain recovered below an altitude of 75 km. The attenuation was almost zero at the altitude of 70 km, indicating that the communication was completely performed. The results show that no communication blackouts occurred in the nanosatellite unless there was a planned burnout. Plasma gain evaluated on the front-side boundary became very small at an altitude from 95 to 75 km. This meant that the electromagnetic waves cannot propagate into the front side, which is caused by the front shock wave discussed above. In contrast, that on the rear-side boundary did not decrease much, and exceeded 0 at altitudes of 95 km. This was attributed to the horn-shaped plasma at the rear.

The EGG resulted in the avoidance of communication blackouts. In contrast, the communication blackout was observed in the ESA ARD, which has a typical shape and trajectory as an atmospheric entry capsule such as the

Apollo command module. This is due to the efficient aerodynamic drag at higher altitude by the inflatable aeroshell, which resulted in relatively slow atmospheric reentry and the formation of a large cold and low plasma region at the rear of the vehicle. This indicated that the inflatable aeroshell is useful in proposing atmospheric entry missions, where communication blackouts do not exist.

VI. CONCLUSION

The plasma flow and electromagnetic wave propagation during the atmospheric reentry of a deployable nanosatellite with an inflatable aeroshell were investigated using a computational science approach. In this study, the numerical analysis models employed consisted of a 3-D thermochemical nonequilibrium flow solver based on the CFD modeling and a dispersive medium electromagnetic wave propagation solver based on the frequency-dependent FDTD method. The electromagnetic wave simulation in reentry plasmas was achieved by mapping plasma parameters, including electron number density, permittivity, and conductivity, obtained by the thermochemical nonequilibrium flow solver. The numerical analysis indicated that the nanosatellite reentered into the Earth's atmosphere at hypersonic speed, forming a strong shock wave ahead of the satellite, which resulted in the generation of high-density plasma, and a flow field with strong thermochemical nonequilibrium. This high-density plasma limited the propagation of electromagnetic waves forward. The inflatable aeroshell caused supersonic expansion near the inflatable torus on the side of the nanosatellite, forming a wake consisting of cold, low-density, and large-scale separation regions. The electron density in the wake was significantly reduced, and an electromagnetic wave propagation path in the wake was formed. The path in the wake was maintained over the reentry, and the deployable nanosatellite did not cause a communication blackout. Thus, a nanosatellite with an inflatable aeroshell can communicate during the reentry by relaying a satellite in orbit, including the Iridium satellite and data relay satellite. This means that data transmission and tracking during atmospheric reentry are possible, leading to flexible space mission design by nanosatellites.

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