Microwave Telemetry Breakdown Caused by Rocket Plume

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Abstract

A black-out phenomenon of the microwave transmission from a launched rocket to the ground station was investigated focusing on the phenomenon observed for the M-V rocket launched in July 1998. The primary candidate for the cause is found to be the exhaust plume generated from the solid fueled motor. It is shown that the microwave transmission through the plume suffers a strong self-interaction, which is the cause of the local attenuation of the microwave that was observed as a black-out phenomenon at the ground station.

1 Introduction

When a rocket is launched, a down-link telecommunication from the launcher to the ground support station is inevitable in order to monitor the health condition of the rocket during the ascent. However it is reported that the telecommunication system sometimes suffered a black-out which is believed to be caused by the rocket exhaust plume. But the cause for the black-out phenomenon has not yet been confirmed. When the M-V rocket was launched from Kagoshima space center at July 1998, a similar black-out of the telecommunication was observed during the 3rd stage engine was burning[1]. Fortunately enough, since the detailed record of the received telecommunication signal level was preserved completely, we can utilize the record to confirm an investigation for the cause. In the present paper, we present the result of the investigation for the cause, comparing with the flight data.

2 Flight Data

The M-V rocket is a solid-fueled 4-staged rocket. Since the altitude at the third stage burn is high enough, the exhaust plume for the 3rd stage motor (M34 motor) is fully expanded into a low pressure atmospheric environment. For a telemetry data down-link from the rocket to the ground station, a microwave of 2280.5 MHz is employed while a 5.6 GHz microwave is used for the radar transponder for radar tracking. As depicted in Fig. 2, during the 3rd stage flight of the M-V rocket, the recorded AGC level of these microwaves shows a significant reduction of the signal level during a time interval from X+270 sec to X+317 sec; the time corresponding to the rocket motor burned out. That is, during the time interval, we suffered a so-called black out of the microwave of both 2280.5 MHz and 5.6 GHz. When we replot the AGC level against the angle defined between the axisymmetric axis of the rocket and the line between the rocket and the ground support station; i.e., an eye-line toward the rocket from the ground support station, it was clear that this level reduction occurs when the angle is smaller than a certain threshold, as shown in Fig. 1. This suggests us that the phenomenon was caused by the rocket exhaust plume because the eye-line is interrupted by the rocket exhaust plume when the angle becomes smaller.

For the analysis of the cause, we must remind that the motor of the M-V rocket is a solid fueled one and its exhaust plume includes not only a plasmas due to the hot plume gas but also a solid particles of aluminum oxides (alumina) of which size is approximately 1 micron order. Hereafter, in section 3, we present, based on the flow field calculated at the typical flight condition, an estimation of the plasma and the solid particle density distribution in the exhaust plume flow. The effect of the solid particles and the plasmas on the microwave transmission will be presented in Section 4, 5, respectively.

3 Plume flow field prediction

The flow inside the combustion chamber and nozzle, and the plume flow outside the nozzle is computed using a general-purpose CFD solver, NS3D, for the flight and combustion conditions of the M34 motor shown in Table 1. The flow field is assumed to be axisymmetric.
FIG. 2: Dependency of the AGC level on the eye-line angle from the ground station.

about the center axis of the rocket motor, and the gas is treated as a compressible and non-viscous ideal gas composed of single species having the unique thermophysical properties shown in Table 1.

3.1 Particle density prediction

The trajectory of alumina particles is computed using the flow field obtained by the CFD calculation described above. Here, the flow field is assumed to be uninfluenced by the presence of particles, and the interaction between alumina particles is neglected. On the surface of propellant inside the combustion chamber, particles are assumed to be injected in the direction normal to the surface at the same velocity as the combustion gas injected from the combustion surface. In the flow field, the trajectory of the particle is determined by integrating the equation of motion according to the fluid dynamic force exerted on the particle.

The alumina particles are assumed to be spherical. The drag coefficient of the particle is calculated by the method of Henderson[2]. In this calculation, the viscosity of the combustion gas is described by

$$\mu = 6.43 \times 10^{-7} T^{0.8} \text{ [Pa.s]}$$  \hspace{1cm} (1)

The trajectory calculation is conducted for four different radii of the particle, 0.1, 0.5, 1.0, 5.0 μm, which are typical values observed at the combustion test of the rocket motor in the ground facility. The density of the alumina particles is set as 3.2 g/m³.

The particle number density becomes maximum on the center axis, and decreases gradually in the radial direction. Calculated number densities of the alumina particle at the center of the nozzle exit are summarized in Table 2. Because of the momentum of particles, the particle trajectory does not spread so much as the flow does in the downstream area of the nozzle exit, forming a clear conical boundary outside of which the particle stream does not exist. The conical divergent angle of such particle stream depends on the diameter of the particle. For example, it is approximately 20 and 40 degree for the particle diameters of 5.0 and 1.0 μm, respectively.

### Table 2: Calculated number density of alumina particles at the center of the nozzle exit.

<table>
<thead>
<tr>
<th>Diameter [μm]</th>
<th>Number density [m⁻³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>$3.8 \times 10^{10}$</td>
</tr>
<tr>
<td>1.0</td>
<td>$4.7 \times 10^{12}$</td>
</tr>
<tr>
<td>0.5</td>
<td>$3.8 \times 10^{13}$</td>
</tr>
<tr>
<td>0.1</td>
<td>$4.7 \times 10^{15}$</td>
</tr>
</tbody>
</table>

3.2 Electron density and collision frequency prediction

**Approximate estimation**

Because the flow field is computed by assuming the propellant to be a single-component ideal gas, we have to introduce another approximation to determine the electron number density in the plume. In a very rough approximation, the electron density may be calculated by assuming an equilibrium condition with the temperature and the pressure obtained with the flow field computation described above. Based on the chemical element composition of the propellant, the equilibrium composition of hot gas in the flow is calculated by means of CHEMIKIN. In this way, the electron number densities are estimated to be $9.0 \times 10^{19}$ m⁻³ in the combustion chamber, and $1.7 \times 10^{10}$ m⁻³ at the throat exit, for example.

However, it is clear that this approach significantly underestimates the electron density in the downstream area of the nozzle exit, because, in reality, the electron recombination processes decreases rapidly along the nozzle due to a decrease in electron collision frequencies. In order to take this effect into account, we consider a non-equilibrium flow model, in which it is assumed that 1) the electron recombination processes freezes at a certain position along the nozzle, and 2) from the certain point, the mole concentration of chemical components is maintained over the downstream area. In the present study, the freezing point is assumed at several locations; the throat exit, and the point in the nozzle where the expansion ratio (ER) is equal to 4.

The electron collision frequency is calculated with

$$\nu = \sqrt{\frac{8 k_{B} T_{e}}{\pi m_{e}} \sum_{i} N_{i} Q_{i,m}}$$  \hspace{1cm} (2)

where $N_{i}$ and $Q_{i,m}$ are the number density and the collision cross section of species $i$, respectively, and $\sum_{i}$ stands for the sum over all chemical species. Downstream of the throat, the major chemical species of the combustion gas is calculated to be H₂ and CO, whose collision cross sections are approximately regarded to be $10^{-19}$ m² for the electron temperature range of interest[3]. The cross sections for other minor species
TABLE 1: Conditions for flow field computation.

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
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<tbody>
<tr>
<td>Free-stream</td>
<td>Altitude</td>
</tr>
<tr>
<td>Velocity</td>
<td></td>
</tr>
<tr>
<td>Combustion gas</td>
<td>Molecular weight</td>
</tr>
<tr>
<td></td>
<td>Ratio of specific heats</td>
</tr>
<tr>
<td>Motor</td>
<td>Propellant</td>
</tr>
<tr>
<td></td>
<td>Combustion pressure</td>
</tr>
<tr>
<td></td>
<td>Combustion temperature</td>
</tr>
<tr>
<td></td>
<td>Combustion speed</td>
</tr>
<tr>
<td></td>
<td>Propellant density</td>
</tr>
</tbody>
</table>

TABLE 3: Conditions for electron density and collision frequency calculation.

<table>
<thead>
<tr>
<th>Ionization frozen at</th>
<th>Electron temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 throat</td>
<td>$T_e = T$</td>
</tr>
<tr>
<td>Case 2 throat</td>
<td>$T_e &gt; 1,000$ [K]</td>
</tr>
<tr>
<td>Case 3 ER = 4</td>
<td>$T_e = T$</td>
</tr>
<tr>
<td>Case 4 ER = 4</td>
<td>$T_e &gt; 1,000$ [K]</td>
</tr>
</tbody>
</table>

are also commonly assumed to be this value in order to simplify the calculation. The electron temperature is determined based on the two different assumptions. One is that the electron temperature is equilibrated with the heavy species temperature, and the other is that the electron temperature is assumed not to decrease below the threshold value. The latter is based on the fact that the energy exchange between electron and the heavy species is much slower than between the heavy species due to the small mass of electron, which prevents the electron temperature from decreasing quickly like the heavy species temperature does.

Based on the previous assumptions, we have computed the electron number density and the electron collision frequency for the four cases listed in Table 3. The calculated electron density distribution along the center axis is shown in Fig. 3. The electron density is found to strongly depend on the position at which the ionization and recombination processes are frozen. This suggests that much more attention should be paid for ionization and recombination processes in the nozzle, which will be discussed in the next section. On the other hand, the electron collision frequency is only weakly dependent on the electron temperature in the temperature range of interest, as shown in Fig. 4. This is because the collision frequency is proportional to a square root of the electron temperature.

**Nonequilibrium effect on electron density estimation**

As discussed previously, we must consider the effect of the finite ionization and ionic recombination reac-

tion rates to obtain a more accurate estimation for the electron number density distribution. Here we predict the electron density at the nozzle exit considering the nonequilibrium effect due to the finite rate ionization and recombination rate, and evaluate the accuracy of the previously estimated values.

We consider the same condition for combustion and flight with the one employed previously, as listed in Table 1. The gas in the flow is assumed to consist of electrons, ions of the same amount with the electrons and neutral heavy particles having the same molecular weight with the ion. The effective molecular weight, specific heat ratio for the heavy particles and the ions, and the number density of the electrons at the reservoir are determined to be 29.5 g/mol and 1.166, $9 \times 10^{18}$ m$^{-3}$, respectively, assuming an equilibrium flow.

For simplicity, we assume a quasi-one-dimensional flow with the reservoir condition noted above. The governing continuity, momentum, energy and electron num-

![FIG. 3: Calculated electron density distribution along the center axis.](image-url)
The governing equations are solved using the time-marching finite-difference method. The electron number density and the temperature distributions along the nozzle are shown in Fig. 6. The ionic ratio is frozen at the nozzle exit. The electron number density at the nozzle exit is calculated as around $7 \times 10^{13} \text{ m}^{-3}$. This value corresponds to the one obtained previously, assuming the freezing of the recombination reaction at the location in the nozzle where the nozzle expansion ratio equals to 4. Although the present analysis is still a preliminary one, this coincidence suggests that our previous estimation is reasonable.
where \( \varepsilon_i \) and \( \varepsilon_r \) are the imaginary and the real parts of the permittivity; \( \varepsilon = \varepsilon_r + i \varepsilon_i \).

Combining both the scattering and the absorption effect due to the particles, the attenuation of electromagnetic wave \( \gamma \) becomes

\[
\gamma = 4.343\sigma n \quad [\text{dB/m}],
\]

where \( \sigma = \sigma_{\text{scatter}} + \sigma_{\text{absorb}} \) and \( n \) is the particle number density. Since, for the M-34 motor, the typical particle diameter is 5 \( \mu \)m, and the particle number density in the exhaust plume is \( 10^{10} \text{ m}^{-3} \) at most, the scattering cross section, the absorption cross section and the attenuation ratio are estimated to be \( 10^{-24} \text{ m}^2 \), \( 10^{-18} \text{ m}^2 \) and \( 4 \times 10^{-3} \text{ dB/m} \), respectively, for the microwave frequency of 2GHz. Here the permittivity of Aluminum oxide is assumed to be \( \varepsilon = 8.5 + 1.7i \).

Based on the value obtained above, we can estimate the attenuation of the microwave transmitted from the launcher. When the region size over which the particles are distributed is estimated as 1 km, which is unlikely large, the present attenuation ratio gives the total attenuation of 4 dB, which is still negligible for the observed attenuation of a few tenths dB. Hence, we can conclude that the attenuation caused by the alumina particles in the plume can have a negligible contribution on the observed attenuation of the microwave.

### 5 Plasma effect

In this section, we consider a plasma effect on the microwave transmission emitted from the rocket. To see the interaction between the plume plasma and the microwave propagation from the antenna on the rocket, we simulate an electromagnetic wave propagation in the plasma. In the simulation we will preserve a wave characteristics of the electromagnetic wave. This is because the wavy AGC level behavior observed in the flight, as shown in Fig. 1, suggests a self-interaction of the microwave. Hence the governing equation for the present simulation should be the Maxwell equation instead of the ray tracing equation which can preserve only the attenuation and diffraction effect along the propagation ray of the microwave.

Interaction of the electromagnetic (EM) wave with the plasma plume can be described by the Maxwell equations with the permittivity of plasma, \( \varepsilon \), which can be expressed as

\[
\varepsilon = 1 - \frac{\omega_{pe}^2}{\omega(\omega + i\nu)}
\]

where \( \omega_{pe} \) is the angular plasma frequency directly related to the electron density as

\[
\omega_{pe} = 56.5\sqrt{n_e}.
\]

Here \( \omega \) is the angular microwave frequency, and \( \nu \) is the electron collision frequency. Equation (8) is valid for non-magnetized cold plasma without a thermal effect of electrons, and this model is applicable to describe a electromagnetic wave propagation through the plume plasma. Using the electron density and electron temperature distributions predicted previously, the profile of the plasma permittivity can be easily obtained based on Eq. (8). The simulation for the EM wave propagation was conducted for this permittivity distribution using full electromagnetic equations with an assumptions of periodic oscillation at a given frequency, and solving the FEM program PHOTO-WAVE[6]. The simulation region used for the analysis is depicted in Fig. 7. To simulate the generation of the EM wave from the antenna, a periodic oscillation of the electric field was imposed at the location. The EM wave will then propagate in every direction. The rocket motor surface was treated as a perfect conductor; that is, symmetrical boundary conditions were imposed, and other boundaries consist of non-reflecting absorbing surfaces to avoid any reflection back to the calculation region. These absorbing boundaries was employed to simulate the condition at an infinite distance. From the computer memory limitation, only a small region around the motor, including the antenna and part of the plasma plume, was considered for the simulation. A 300 x 100 mesh was used for x (axial) and y (radial) direction, but only one element was used for z direction (corresponding to circumferential direction) and at z surface a natural boundary condition is imposed. The model can treat the microwave absorption, reflection and diffraction in the radial and the axial direction.

Calculated results for the case of 2.0 GHz downlink are plotted in Fig. 8. Case A and B represent a low and a high electron density case, and corresponds to case 1,2 and case 3,4 in the previous section, respectively. For the case B whose maximum electron density at the throat exceeds \( 1.0 \times 10^{19} \text{ m}^{-3} \), the microwave penetrating into plasma region is reflected at the plume edge in the downstream region \( z > 3.5m \). No such reflection was found for the case A. For the case B, in spite that the maximum electron density along the microwave transmission doesn’t reach the cutoff density of 2 GHz (\( 5 \times 10^{16} \text{ m}^{-3} \)), the direction of wave propagation is changed, and as a result, the EM wave is inhibited to propagate in the rocket exhaust direction. Also, one can see weak fringe patterns inside the region because of the interaction of two kinds of EM waves: one goes directly toward the downstream region, the other is once reflected from the wall. These two characteristics are summarized in Fig. 9, in which the cross sectional plot at the radial line at \( x=4.5 \text{ m} \) was depicted. As the electron density of the plume arises, only a small portion of EM wave can penetrate into the plume but most of the wave is reflected. In particular, when the electron density at the plume edge exceeds the microwave cutoff density, almost no EM wave can penetrate the plume, which is demonstrated in the artificial case (case C) where the electron density was assumed twice as much as that for the case B. The attenuation level estimated for the case B is not, however, as significant as observed for the M-34 motor firing. The observed reduction is rather compara-
Fig. 7: Calculation region.

6 Conclusions

Our analysis strongly suggests that the cause of the black-out observed at the launch of the M-V rocket was a plasmas in the rocket exhaust plume. This was confirmed at least qualitatively. Speaking quantitatively, there is still some discrepancy which may be attributed to enhancement of plasma, which is probably caused by the impurity in the fuel in the solid motor. The investigation for the impurity effect is under way.

Acknowledgement

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References

1ISAS internal report (1998).