Numerical Study on the Thermal Control of the TriG Receiver for FORMOSAT-7 Satellite

Chen-Hao Wang*, Jeng-Der Huang, Chia-Ray Chen

Mechanical Engineering Division, National Space Organization (NSPO), National Applied Research Laboratories (NARL), Hsin-Chu 300, Taiwan, Republic of China

Abstract

The FORMOSAT-7 (FS-7) satellite constellation collect atmospheric and ionospheric data primarily for operational weather forecasting and space weather monitoring to fulfill the needs of Taiwan, the US, and the rest of the world. Because of the relative high power consumption and limited temperature requirement, TriG receiver (TriGR) becomes a critical component for thermal control. A thermal model is developed to examine the temperature feasibility of TriGR at the preliminary design phase. Parametric studies including the sizes of radiators, the thicknesses and the lateral thermal conductances of honeycomb panels. Results show that the effect of thermal conduction is more significant than thermal radiation by comparing the influences of the lateral thermal conductance of honeycomb panel and the sizes of radiators. Moreover, it is found that both the thermal conductance between middle platform and wall panels, and the lateral thermal conductance of honeycomb panel are the main factors for thermal control of TriGR. A careful consideration for the bracket used between the middle platform and wall panels is therefore needed to guarantee the performance of it.

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* Corresponding author. Tel.: +886-3-5784208#2209; fax: +886-3-578-8062.
E-mail address: chwang@nspo.narl.org.tw
Nomenclature

| Symbol          | Definition                  |
|-----------------|-----------------------------|
| $A_i$           | surface area               |
| $c_p$           | specific heat              |
| $F_{ij}$        | radiation interchange factor|
| $G$             | thermal conductance        |
| $h$             | thermal conductance per unit area |
| $k$             | thermal conductivity       |
| $Q$             | heat source                |
| $r_k$           | reflectivity               |
| $T$             | temperature                |
| $t$             | time                        |

Greek symbols

| Symbol          | Definition                  |
|-----------------|-----------------------------|
| $\alpha_{ij}$  | absorptance                 |
| $\beta$         | beta angel                  |
| $\beta_{ij}$    | radiation exchange factor   |
| $\delta$        | effective thickness of honeycomb |
| $\varepsilon_k$ | emissivity                  |
| $\varepsilon_{ij}$ | effective radiation emittance |
| $\rho$          | density                     |
| $\sigma$        | Stefan-Boltzmann constant   |
| $\phi_{ij}$     | image factor of energy      |

Subscripts

| Subscript       | Definition                  |
|-----------------|-----------------------------|
| $I$             | TriG receiver interface     |
| $MP-WP$         | between middle platform and wall panel |
| $W$             | overall width of the honeycomb |
| $L$             | overall length of the honeycomb |

1. Introduction

Thermal control (TC) is what allows controlling the temperature level of components, payloads and satellites within the design requirements of space mission to protect flight hardware and to guarantee the optimum performances during the mission lifetime [1]. In space, it would be hardly to correct an overheated problem that could damage the component or affect the performance severely. For TC system, like other space subsystems, it needs to be designed and tested properly to ensure the reliability and performances before launch [2]. Recently, space electronics are becoming miniaturized. High power consumptions increase the challenge of TC.

Based on the highly successful FORMOSAT-3 (FS-3) mission [3, 4, 5], FORMOSAT-7 (FS-7), or so-called Cosmic-2, is planned to collect atmospheric and ionospheric data primarily for operational weather forecasting and space weather monitoring as well as meteorological, climate, ionospheric, and geodetic research [6]. The satellite constellation is constituted by thirteen satellites and will be served as the space qualification platform for the self-reliant key components of NSPO. The mission science payload instrument for FS-7, TriG System (TGRS), is a Global Navigation Satellite System (GNSS) for low earth orbit. Each TGRS flight unit includes main components such as TriG receiver (TriGR), omni-directional Precision Orbit Determination (POD), Radio Occultation (RO) antennas, Low Noise Amplifier Band Pass Filter (LNABPF) Assemblies, and the low loss RF cables. The TriGR is the key component of the overall TGRS design/capability, and it tracks signals from GNSS satellites and measures the phase and group delay of the signals for the purpose of orbit determination and radio occultation studies [7]. However, the relative high power consumption (63.5W on-orbit average power with a peak power of 73.2W at up to
10 minutes duration) and limited temperature requirement (between -5°C and +40°C during operation) makes it becomes the critical component for TC.

For optimizing the space utilization, a middle platform is interposed and the TriGR is set on it based on the consideration of mass distribution. The challenges are encountered not only for the increasing packaging density that limits the volume available for the thermal arrangement, but also the indirect heat transfer between TriGR and the thermal control hardware due to the middle platform presented. To control such parts operating within the temperature requirement, a thermal analysis with the space thermal environment is made to examine the temperature feasibility at the preliminary design phase. In this paper, the influences of the sizes of radiators, the thicknesses and the lateral thermal conductances of honeycomb panels are investigated.

2. Thermal Analysis

At the preliminary design phase, thermal analysis models are established. The temperatures of satellite under different beta angels, $\beta$, and the worst hot condition are investigated. Fig. 1 shows the geometry of the FS-7 mission satellite and the allocation of critical component, TriGR. The principal forms of environmental heating on satellite are direct sunlight, sunlight reflected off Earth (albedo), and infrared (IR) energy emitted from Earth [1]. In addition to external heating form space environment, the internal power dissipations from all components in the different operational modes of the whole mission are considered in our thermal model.

2.1. Environmental heat flux radiation

Thermal Radiation Analyzer System (TRASYS) [8] and System Improved Numerical Differencing Analyzer (SINDA/G) [9] are used for satellite thermal design. TRASYS models are constructed to provide the radiation exchange factors $\beta_{ij}$ among all surfaces, and the transient orbital heating array from the direct sunlight, albedo and IR emitted from Earth. The radiation interchange factors are obtained effectively by solving graybody matrix equations for gray enclosures with $n$ surfaces [10]. The radiation exchange factors can be expressed as

$$\beta_{ij} = \varepsilon_i \phi_{ij} + \sum_{k=1}^{n} r_{ik} \phi_{kj} \beta_{kj},$$

where $\varepsilon_i$ is the emissivity and $r_{ik}$ is the reflectivity. The image factor $\phi_{ij}$ is defined as the fraction of energy that leaves surface $i$ and arrives at surface $j$ both directly and by all possible first-order specular reflection as
\[ \phi_{ij} = F_{ij} + \sum_{k=1}^{n} \phi_{ik} F_{ik(k)}, \]  

where \( F_{ij} \) is the radiation interchange factor that couples surface \( i \) to surface \( j \).

The radiation heat transfer between surfaces \( A_i \) and \( A_j \) with temperature \( T_i \) and \( T_j \), respectively, are therefore determined as

\[ Q_{ij} = \sigma \cdot A_i \cdot \varepsilon_i \cdot \beta_{ij} \left( T_i^4 - T_j^4 \right) = \sigma \cdot A_j \cdot \varepsilon_j \cdot \beta_{ij} \left( T_i^4 - T_j^4 \right), \]  

where \( \sigma \) represents the Stefan-Boltzmann constant.

Accordingly, the total thermal radiations, including heat flux from environment for a satellite in orbit and those between interior surfaces, are calculated by TRASYS.

2.2. Thermal network model

The internal radiation conductance and external heat flux calculated by TRASYS models are then inserted into SINDA/G that takes advantage of a lump parameter approach for conduction and radiation heat transfers. A lumped resistance-capacitance (R-C) thermal network model, which the thermal masses are concentrated on the nodes and they are connected by the linear conduction conductors and nonlinear radiation conductors, is solved by finite-difference method and the energy balance equation is shown as follows,

\[ \rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \nabla \cdot (Q_{ij}) + Q, \]  

where \( T, t, k \) and \( Q \) denote the temperature, time, thermal conductivity and heat source, respectively. The heat capacitance is defined as the product of density \( \rho \) and specific heat \( c_p \).

In our thermal studies of TriGR, an explicit method based on the modified Dufort-Frankel scheme is used to evaluate the temperature distribution [9].

3. Results and Discussions

In this research, thermal cases are performed for different beta angles, orbit altitudes, operating modes, orbit thermal environments and power dissipations to make sure all components are well operated within their temperature requirements. The hot cases of TriGR are presented in the following.

3.1. Parameters and assumptions

3.1.1. Configuration and environmental parameters

The dimension of bus for each FS-7 mission satellite is assumed to be 720 × 880 × 830 mm³ as shown in Fig. 1. The flight direction is defined as the X-axis, the pitch direction is defined as the Y-axis, and the Z-axis is in the nadir direction. Fig. 2(a) shows the orientation and the configuration of satellite. The solar panels are neglected at the preliminary design phase. The internal configuration is sketched in Fig. 2(b). Only components near the TriGR are considered for simplification. The satellite is assumed to be launched into a low Earth orbit of 600 km altitude, and the attitude is controlled as Earth orientation. The beta angle, \( \beta \), is defined as the minimum angle between the orbit plane and the Sun vector, which varies from -52° to +52°. Important parameters, Solar constant, albedo and Earth IR are respectively defined as 1420 W/m², 0.35, and 265 W/m².
3.1.2. Passive thermal control hardware

The TC for FS-7 satellite is achieved mainly through passive hardware, such as Aluminum Second-surface Mirror (Al-SSM) radiators and Multilayer Insulation (MLI) thermal blankets. Heaters are only considered to warm up critical components in the cold condition. Radiators usually have surface finishes with high infrared emittance and low solar absorptance to increase their ability. The emissivity $e_{ij}$ and absorptance $a_{ij}$ of the radiator are 0.79 and 0.15, respectively. MLI consists of highly reflective radiation shields with low thermal conductivity material separating within different layers. The effective radiation emittance, $e_{ij}^*$, of MLI is assumed to be 0.01 for hot cases in our research [11]. All internal components are treated with surface finishes (black paint, both $e_{ij}$ and $a_{ij}$ are assumed to be 0.9) to enhance radiation coupling.

3.1.3. Heat source

To investigate the temperature of TriGR, only the power allocated on the middle platform, 100 W, is considered. The total power dissipation of four Reaction Wheels (RWs) is assumed to be 32 W. Two power dissipations of TriGR, 66.0W and 63.5W, are assumed for comparison, which corresponding to SADM with 2.0 W and 4.5 W, respectively.

3.1.4. Conductance

All the panels are thermally coupled to each other with initial conductance as listed in Table 1. For Case 1 and 2, the TriGR is assumed to be dry and wet mount with typical thermal conductance per unit area, $h = 30$ and $500$ W/Km$^2$, respectively. The corresponding thermal conductance between TriGR and the middle platform, $G_i$, are then obtained (1.62 W/K and 26.97 W/K). For Case 3, an ideal value of $G_i$ (138.89 W/K) is used according the report of TriGR producer Jet Propulsion Laboratory (JPL). The influence of conductance between middle platform and wall panels, and the lateral thermal conductance of middle platform, are discussed in section 3.3.

Table 1. The initial (standard) thermal conductance between panels of FS-7.

| Thermal Conductance (W/K) |  
|---------------------------|
| $G_i$ | Middle Platform $\uparrow$ | Middle Platform $\downarrow$ | Middle Platform $\uparrow$ | Wall Panel $\downarrow$ | Separation Plane $\uparrow$ |
|----|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1  | 1.62 | 0.1 | 0.1 | 0.1 | 0.1 |
| 2  | 26.97 | 0.1 | 0.1 | 0.1 | 0.1 |
| 3  | 138.89 | 0.1 | 0.1 | 0.1 | 0.1 |
3.2. The effect of radiators

To reduce the accumulation heat inside the satellite, radiators are applied on bus panel to radiate the internal waste heat to the space. The effect of radiators on ±X and +Y wall panels with different sizes are investigated as listed in Table 2. Fig. 3. shows the locations of radiators on in our research. The rest wall panels (-Y and ±Z) are covered in MLI.

Table 2. The percentage of Al-SSM radiators on each wall panel.

| Wall Panel | +X | -X | +Y | -Y | +Z | -Y |
|------------|----|----|----|----|----|----|
| R1         | 60%| 76%| 0% | 0% | 0% | 0% |
| R2         | 60%| 76%| 72%| 0% | 0% | 0% |

Fig. 3. The sizes and locations of radiators (marked in gray) on (a) +X, (b) -X and (c) +Y wall panels.

Fig. 4(a) shows the temperatures of TriGR with 66.0W and 63.5W power dissipation for β lie in between ±52°. The ±X panels are the main radiators (case R1) as shown in Fig. 3(a)-(b). The highest temperatures predicted are 59.65 °C and 58.31 °C, respectively. Both of them happened at β = 0°. If the MLI covered in +Y panel are replaced by radiators as case R2, the highest temperatures of TriGR are reduced to 52.59 °C and 51.17 °C respectively as shown in Fig. 4(b). It is found that the highest temperature for both cases are observed at β = -52° because of the present of radiators applied on +Y panel, where it is sensitive to the Solar radiation when β is less than 0°. Accordingly, case R2 was selected, and the worst hot case was determined at β = -52°.

Fig. 4. Temperature distributions of TriGR for different beta angels. The main radiators are (a) ±X and (b) ±X and +Y wall panels.
3.3. The influence of conductance

In addition to consider the sizes of radiators to reduce the temperature of TriGR, the influence of thermal conductance, G, between middle platform and wall panels, and the lateral thermal conductance altered on the thickness and the lateral thermal conductance of panels, are studied as below.

3.3.1. Thermal conductance of TriG receiver interface

Firstly, the influence of GI is investigated. Fig. 5 illustrates the temperature profile of TriGR for three mounting conditions: typical dry mount, typical wet mount and ideal wet mount. Though the ideal wet mount keeps the temperature of TriGR at the lowest level, the temperature difference between typical and ideal wet mount is only 0.76°C. Accordingly, the typical wet mount is good enough considering the extra efforts needed for ideal wet mount.

3.3.2. Thermal conductance between middle platform and wall panels

Though the power dissipated within TriGR is transported by conduction (GI) to the middle platform, the thermal conductance from mounting plate to the radiator panels, i.e. G_{MP-WP} of ±X and ±Y wall panels, is one of the major factors affecting the temperature of TriGR. As shown in Fig. 6, the temperature of TriGR drops rapidly when G_{MP-WP} increases, no matter what kind of mounting conditions is used. It is found that the influence of G_{MP-WP} decays when the value is greater than 10.0 as detailed in Table 3. Accordingly, a suitable choice of G_{MP-WP} is located in between 1 to 10 based on the convenience of bracket design and the operation temperature requirement of TriGR.
Table 3. The temperature difference of TriGR for different GI and GMP-WP.

| GMP-WP | GI   | Temperature Difference (°C) |
|--------|------|----------------------------|
| 0.1    | 1.0  | 7.68 8.65 8.78             |
| 1.0    | 10.0 | 9.57 11.48 11.77           |
| 5.0    | 50.0 | 4.68 6.00  6.22            |

3.3.3. Lateral thermal conductance of middle platform

For satellite and spacecraft design, sandwiched composite structures, as known as honeycomb panels, are used to reduce the mass budget. It consists of three parts: a honeycomb core constructed of thin hexagonal cells in between two face sheets. Because of the construction, honeycomb has directionally dependent conductivities. The major way for the heat generated by electronic components is conducting through honeycomb panels and radiating out of the satellite. The radiation heat transfer is assumed small compared to conduction for aluminium honeycomb panels. Therefore, the effective conductivity through honeycomb core material in different directions, width and length directions, dominate the efficiency of heat transfer by conduction.

The thermal conductance \( G \) is calculated as [1]

\[
G = k \delta \frac{W}{L} = k_i \frac{W}{L},
\]

(5)

where \( \delta \) is the effective thickness of honeycomb. \( W \) and \( L \) are the overall width and the overall length of the honeycomb, respectively. The equivalent lateral thermal conductivity \( k_i \) with given honeycomb thickness can be determined as

\[
k_i = \frac{2k_{FS} \delta_{FS} + k_{core} \delta_{core}}{2t_{FS} + \delta_{core}}.
\]

(6)

Three different sets of \( k_i \) for the middle platform are investigated as listed in Table 4. The properties of case B is for typical honeycomb panel commonly used in satellite. As a comparison, case A and C are the cases for worse and better \( k_i \), respectively.

Table 4. The equivalent lateral thermal conductivity of middle platform honeycomb panel.

| FS [mm] | Core [mm] | \( k_w \) [W/K] | \( k_{al} \) [W/K] | \( k_{avg} = \frac{k_{sw} + k_{al}}{2} \) [W/K] |
|---------|-----------|----------------|-----------------|---------------------------------|
| A       | 0.1       | 12             | 0.0429          | 0.0467                          | 0.0448                          |
| B       | 0.5       | 24             | 0.0867          | 0.0924                          | 0.0895                          |
| C       | 1.0       | 25             | 0.1500          | 0.1500                          | 0.1500                          |

Fig. 7 shows the temperature distribution of TriGR. The power dissipation of TriGR is fixed at 63.5W and the ±X and ±Y panels are the main radiators. It is observed that the influence of \( k_i \) is almost equivalent to GMP-WP, and the effect for both of them are stronger compared with the effect of radiator for FS-7 satellite. In other words, the effect
of thermal conduction is more significant than thermal radiation. Besides, although the temperatures of TriGR in case C with G\(_{MP-WP}\) greater than 1 all achieve the temperature requirement, the cost of mass budget explosion because of the thickened face sheets totally eliminates the advantage. Accordingly, case B with G\(_{MP-WP}\) lie in between 1 to 10 is a suitable choice for FS-7 mission satellite considering the temperature margin and the proper mass budget.

![Fig. 7. Temperature distributions of TriGR for different GI and G\(_{MP-WP}\) with radiators (R2), 63.5W power dissipation and \(\beta = -52^\circ\).](image)

4. Conclusion

A simplified thermal model is developed to study the temperature feasibility of TriGR at the preliminary design phase of FS-7 mission satellite. The influences of the heat dissipation of TriGR, sizes of radiators, the thicknesses and the lateral thermal conductances of honeycomb panels are investigated. Results show that the influence of the lateral thermal conductance of honeycomb panel is more significant comparing with the effect of radiator for FS-7. Both the thermal conductance between middle platform and wall panels, and the lateral thermal conductance of honeycomb panel, are the major factors affecting the temperature of TriGR. This means the bracket design between middle platform and wall panels will be the critical point for TriGR operating within the temperature requirement.

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