HOKKAIDO UNIVERSITY

Proposal Procedure of Thermal Design for Micro and Nano Satellite pointing to Earth with Body-mounted Solar cells

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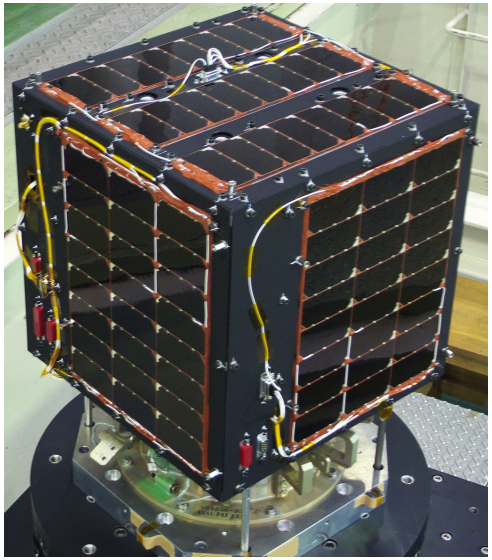
Motivation (1/2)

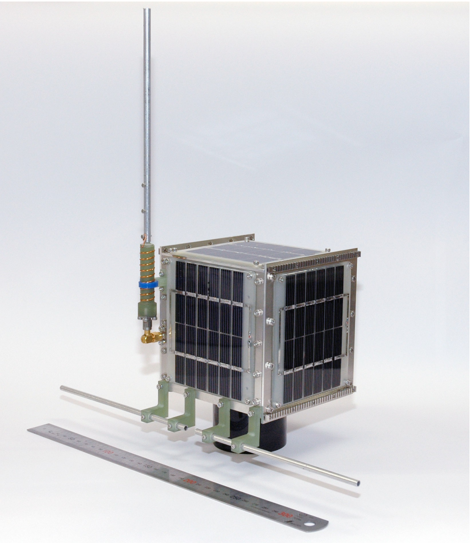
- It has taken a long period for the development of a satellite, for about ten years in normal-sized spacecraft.
- The long developing period of a spacecraft has blocked newcomer's access in Japan.
- Newcomers hope that the developing period of micro and nano satellites is shortened to realize missions as soon as possible after an order entry.
- In the thermal design of spacecraft, many parameters should be decided in such a way that the temperatures of units become within the design temperature ranges.

Motivation (2/2)

- It is easy to change the temperature of micro and nano satellite because the heat capacity of micro and nano satellite is small.
- The resource of electricity assigned to the temperature control subsystem is not enough to control the temperature of all units actively.
- The goal in this study is that the thermal design is completed within one year despite difficulties of low heat capacity and low assigned electric power.



UNITEC-1



HIT-SAT

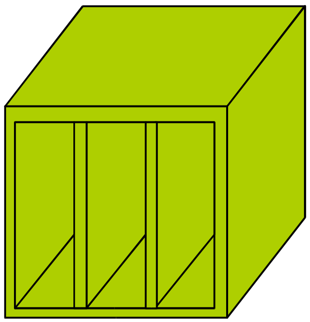
To shorten the developing period

- A simple design is required to shorten the developing period of micro and nano satellites.
- A simple design leads to a simple analysis, the fabrication for a short time and small number of thermal test items.

Proposal procedure of thermal design

Concept 1

to decrease the temperature change using the whole thermal capacity of the micro and nano satellite.



- The heat transfer between units and structures and the heat transfer between structures by thermal conduction and radiation are enhanced.
- A thermal conductive sheet is inserted between units and structures, and between structures in order to decrease the influence of the contact thermal resistance.

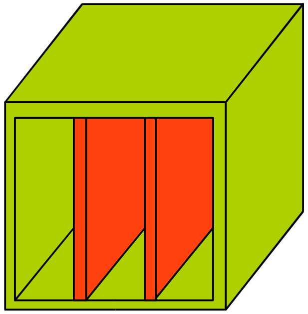
Analysis method

One nodal analysis

- One nodal analysis that the whole of a satellite has one node is adequate for Concept 1.
- The thermal conductance between units and structures, and between structures are set to infinity implicitly.
- The parameter survey of $\alpha_{O\text{-}out}$, $\varepsilon_{O\text{-}out}$ can be carried out in a short period.

Concept 2

to decrease the temperature change of the inner structure which the units with the narrow design temperature range are mounted on and which is insulated conductively from the outer structure



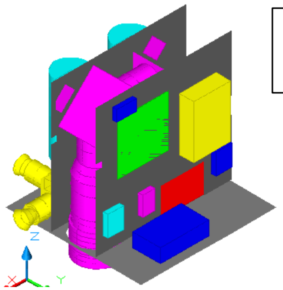
- The heat transfer between the outer structure and the inner structure by thermal conduction is insulated.
- The heat transfer between units and the inner structures and the heat transfer between inner structures by thermal conduction and radiation are enhanced.

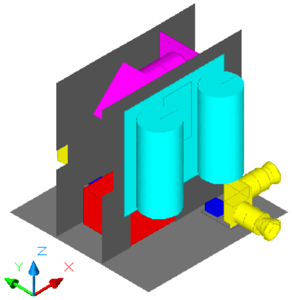
Analysis method

Two nodal analysis

- Two nodal analysis that the outer structure has one node and the inner structure has one node is adequate for Concept 2.
- The thermal conductance between inner structures and outer structures is set to 0.
- The parameter survey of $\alpha_{\text{O-out}}$, $\varepsilon_{\text{O-out}}$, $\varepsilon_{\text{O-in}}$, ε_{I} can be carried out in a short period.

After parameter survey of one nodal or two nodal analysis





Multi nodal analysis

- The parameters adopted in one nodal analysis or two nodal analysis are used at first.
- If the temperatures of all units are within the design temperature range, the thermal design is completed.
- If not, the emissivity of the units whose temperature is beyond the design temperature range is modified and the conductive and radiative heat transfer between the inner plate and those units are modified.

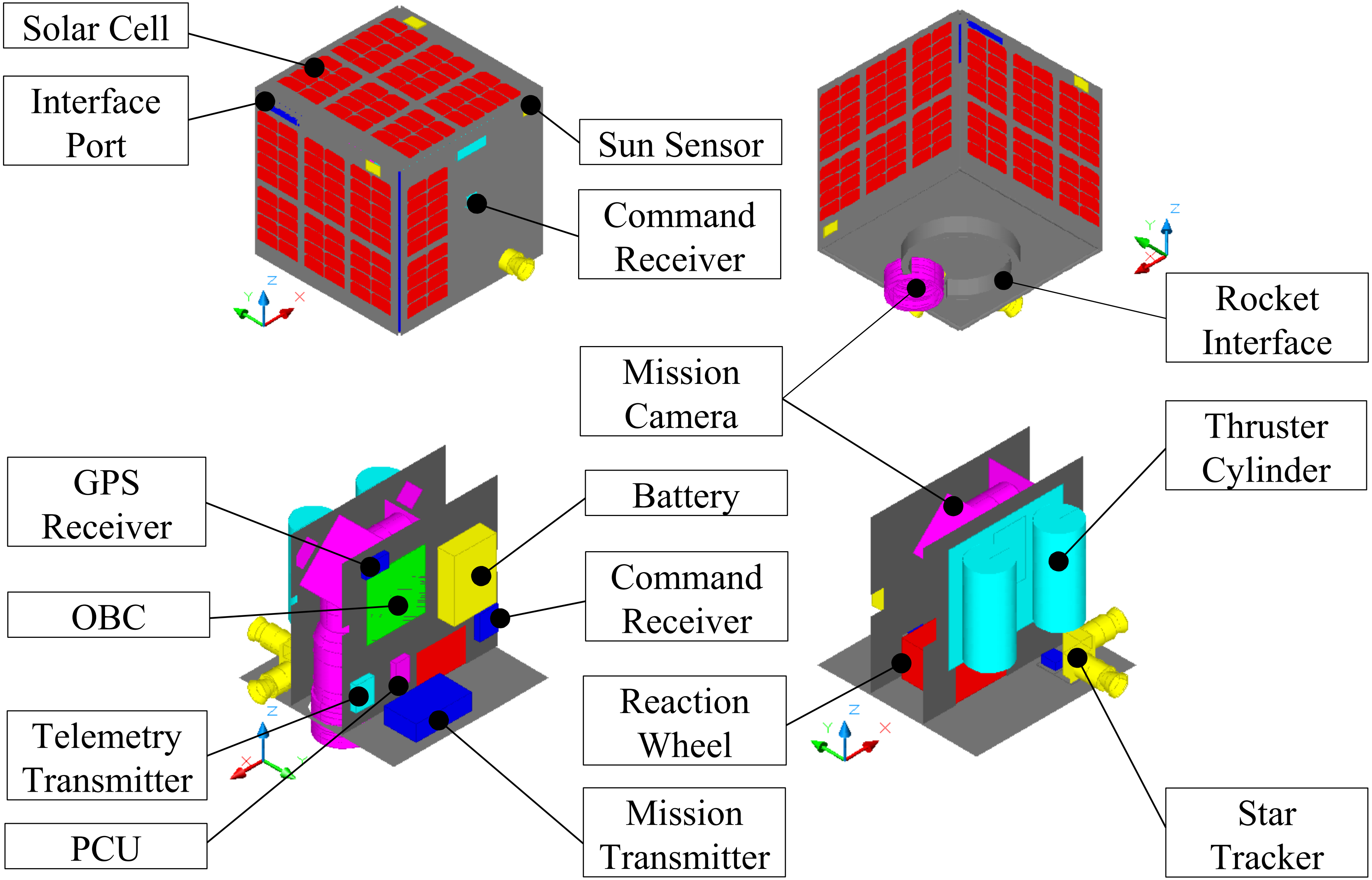
In the thermal design of satellites

- What takes long period of time is a parameter survey using multi nodal analysis and the measurement of the contact thermal resistance between the structures and units, so on, in a thermal vacuum test.

In this proposal procedure of the thermal design

- The parameter survey is carried out using a simple nodal analysis such as one nodal analysis or two nodal analysis, and the influence of the contact thermal resistance decreases by a thermal conductive sheet or an insulator.

Satellite Model : Hodoyoshi-1 satellite



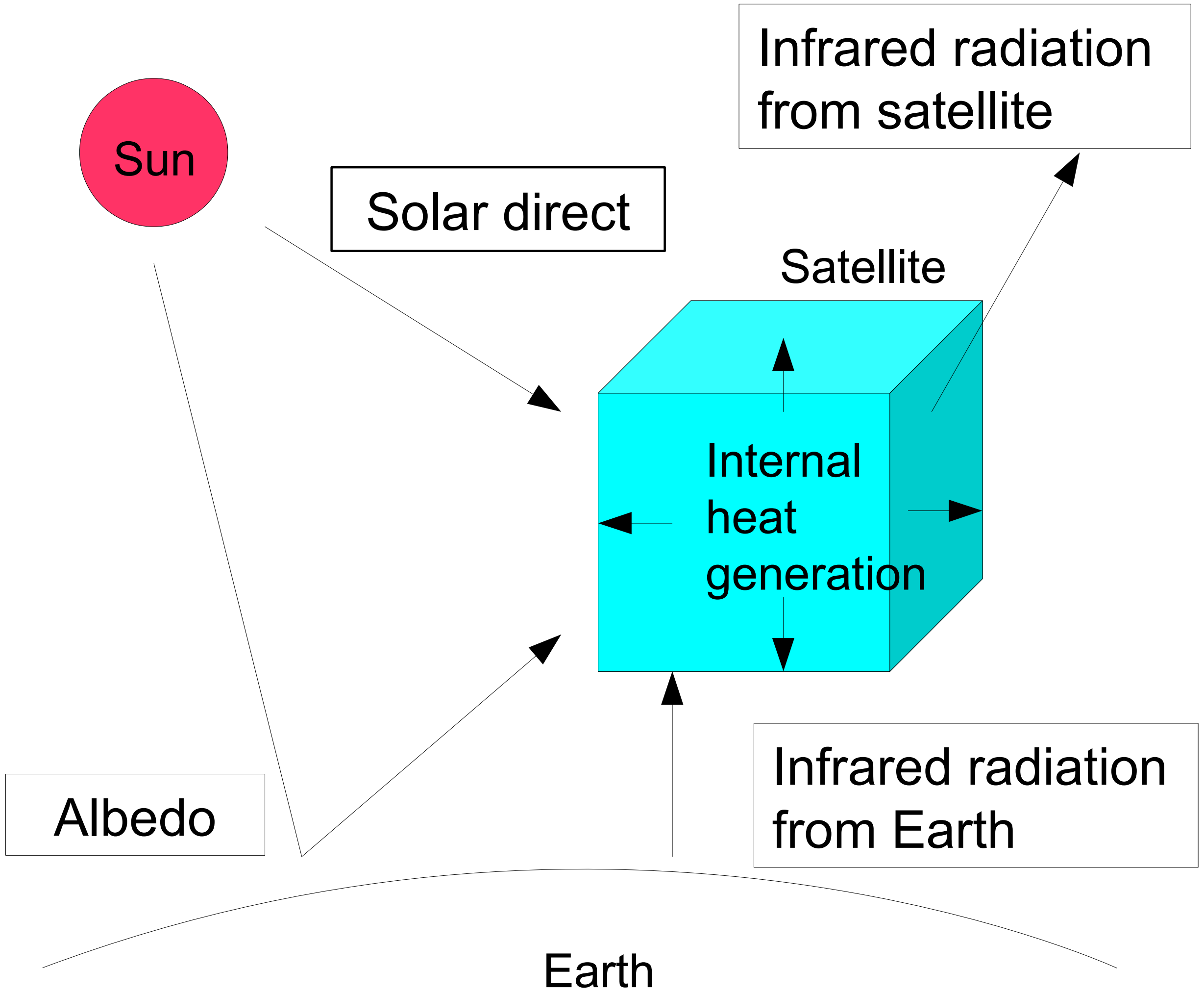
Specifications of Hodoyoshi-1 satellite

Items	Specifications
Mass, kg	49.6
Size, m	0.5 × 0.5 × 0.5
Inner Structure	2 plates
Orbit	Sun-synchronous and circular
Altitude, km	500
Local Time of Descending Node	11:00 AM
Attitude	Earth-pointing
Power Generation	Ultra triple junction solar cell
Setting Method of Solar Cell	Body-mount
Battery	Lithium-ion battery
Shunt	Sequential shunt

Analytical Condition

One Nodal Analysis

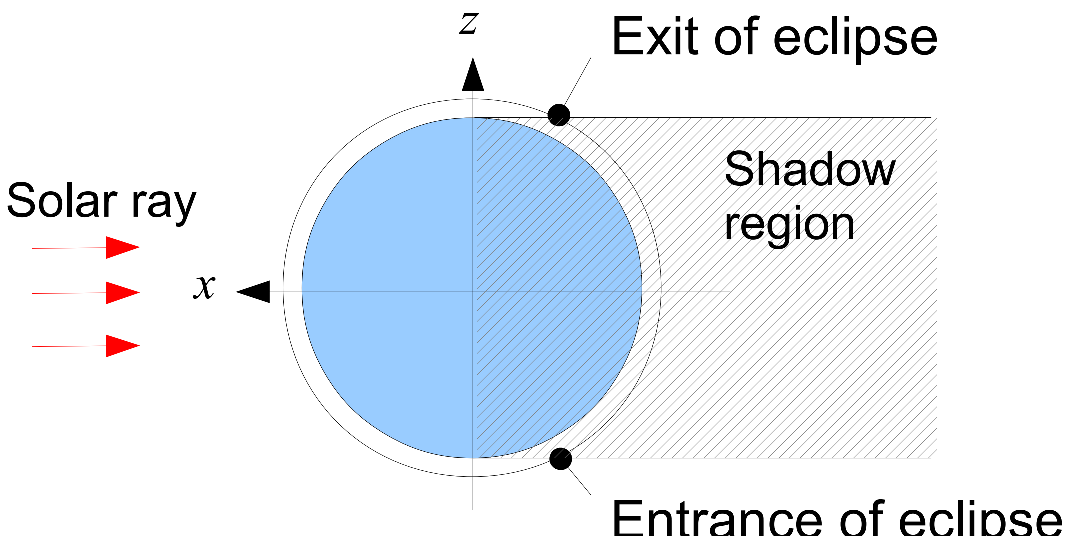
Items	Values
Mass, kg	49.6
Size, m	0.5 × 0.5 × 0.5
Specific heat, J/(kg K)	720
Thermal conductance between inner and outer structure, W/K	∞
Heat dissipation, W	15.35
Design temperature range, deg.C	10 - 40


Infrared radiation
from satellite
Sun
Solar direct
Satellite
Internal
heat
generation
Albedo
Infrared radiation
from Earth
Earth

Worst cold case and worst hot case

One nodal analysis and two nodal analysis

	Worst cold case	Worst hot case
Earth IR radiation q_{IR} [W/m^2]	189	261
Solar constant G_s [W/m^2]	1309	1414
Albedo factor a	0.20	0.40
Initial temperature [deg. C]	10	25
Initial position	Entrance of eclipse	Exit of eclipse



Result of one nodal analysis

- There is no combination of the solar absorptivity, $\alpha_{O\text{-}out}$, and the infrared emissivity, $\varepsilon_{O\text{-}out}$, of the outside of the outer structure, which the temperature of the satellite becomes within the design temperature range.
- It is clarified from this result that Concept 1 can not keep the temperature of the satellite model within the design temperature range.

Analytical Condition

Two Nodal Analysis

Mass, kg	Outer structure: 20.7 Inner structure: 28.9
Size, m	0.5 × 0.5 × 0.5
Specific heat, J/(kg K)	720
Thickness of structural panel (Aluminum honeycomb), m	Outer structure: 0.01 Inner structure: 0.01
Inner structure	2 plates
Distance between inner plates, m	0.16
Thermal conductance between inner and outer structure, W/K	0
Heat dissipation, W	Outer Structure: 10.02 Inner Structure: 5.33
Position of shunt	Outer Structure
Design temperature range, deg.C	Outer Structure: -20 to 40 Inner Structure: 10 to 40

Result of two nodal analysis

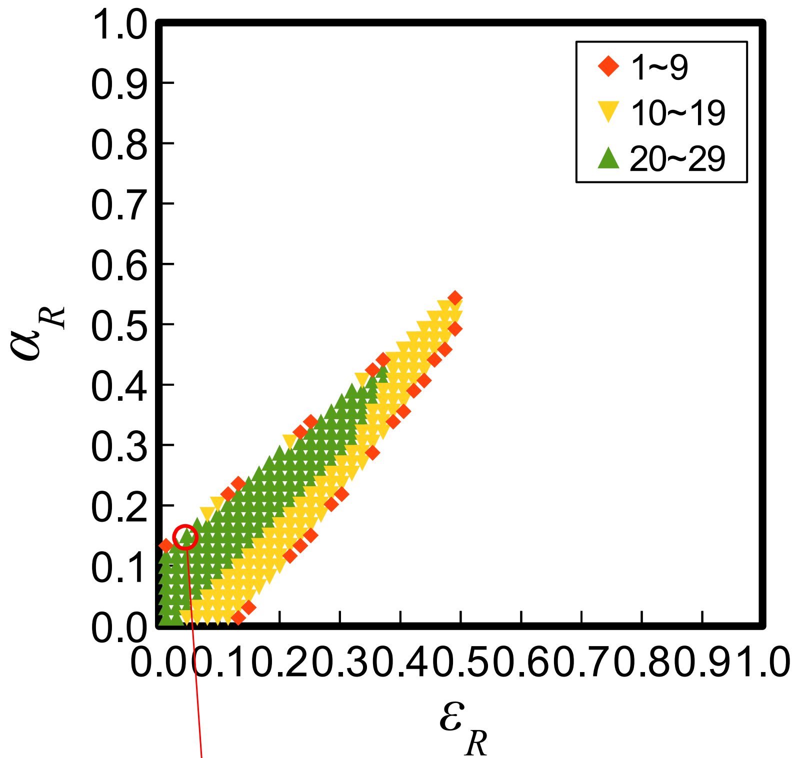


Figure 6. Combinations of α_R and ε_R in case that temperatures of satellite keep within design temperature range under worst hot case and worst cold case.

Alodine 1000	
$\alpha_{\mathrm{O-out}}$	0.15
$\varepsilon_{\mathrm{O-out}}$	0.038

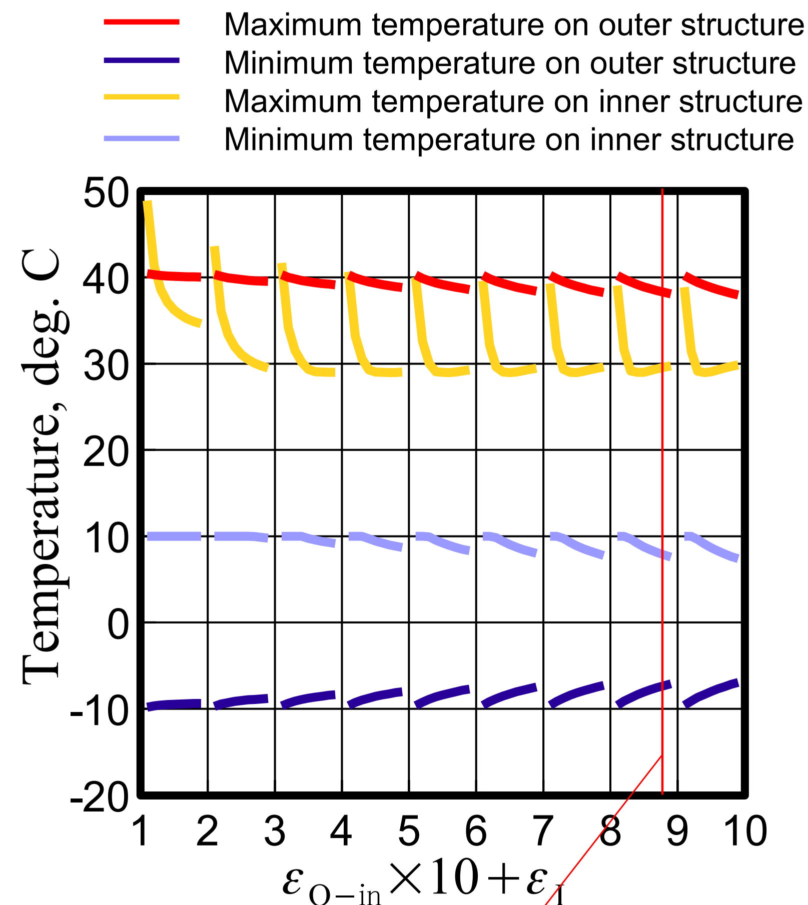


Figure 7. Maximum and minimum temperature on outer and inner Structure; $\alpha_R = 0.15$, $\varepsilon_R = 0.038$.

Black alumite	
ε_{I}	0.88
$\varepsilon_{\mathrm{O-in}}$	0.88

Worst cold case and worst hot case

Multi nodal analysis

	Worst cold case	Worst hot case
Earth IR radiation q_{IR} [W/m^2]	189	261
Solar constant G_s [W/m^2]	1309	1414
Albedo factor a	0.20	0.40
Initial temperature [deg. C]	10	25
Initial position	Entrance of eclipse	Exit of eclipse
Shift of local time descending node	+1 hour LTDN: 12:00	-1 hour LTDN: 10:00
Production error	Alodine 1000 ε: 0.038 → 0.060	Alogine 1000 α: 0.15 → 0.20
Degradation	-	White alumite α: 0.24 → 0.68 ε: 0.76 → 0.88

Design temperature range

Units	Design temperature range, deg. C
On-board computer	-25 to 55
GPS receiver	-25 to 65
Telemetry transmitter	-25 to 80
Mission transmitter	-25 to 75
Command receiver	-25 to 80
Battery	5 to 35
Gyro sensor	-35 to 80
Sun sensor	-35 to 80
Magnetic sensor	-40 to 70
Magnetic torquer	-35 to 80
Star tracker	-15 to 35
Reaction wheel	-15 to 45
Thruster	-15 to 125

Analysis software for multi nodal analysis

- Thermal Desktop SINDA/FLUINT/RadCad version 4.8 has been used.

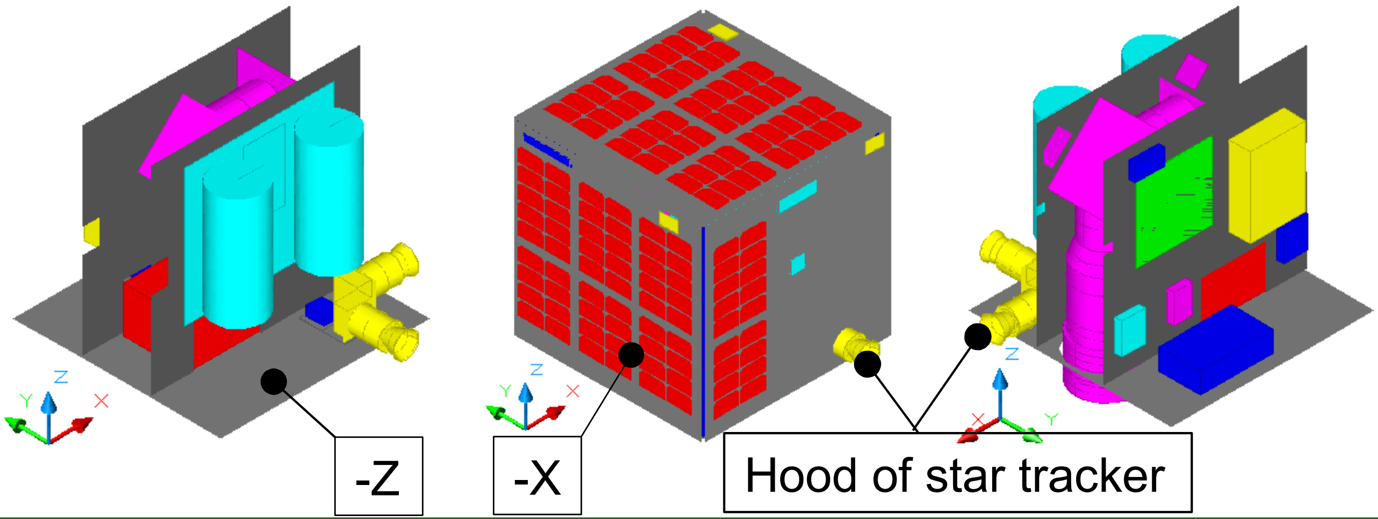
Units	Number of nodes	Units	Number of nodes
On-board computer	1	-X	24
GPS receiver	1	+X	35
Telemetry transmitter	1	-Y	44
Mission transmitter	1	+Y	20
Command receiver	1	-Z	30
Battery	1	+Z	22
Gyro sensor	3	Inner plates	56
Sun sensor	5	Columns	12
Magnetic sensor	1	Solar cells	26
Magnetic torquer	15	Output port	11
Star tracker	30	Thruster	6
Reaction wheel	1	Mission camera	53
		Total	400

Result of multi nodal analysis

Units	Worst Cold Condition	Worst Hot Condition
On-board computer	-0.6 to 11.3	24.3 to 41.5
GPS receiver	-4.6 to 11.1	19.3 to 41.5
Telemetry transmitter	-3.3 to 10.7	21.1 to 41.2
Mission transmitter	-7.0 to 11.7	17.1 to 42.7
Command receiver	-3.6 to 11.8	20.7 to 42.0
Battery	-0.7 to 11.3	24.2 to 41.5
Gyro sensor	-7.0 to 11.6	16.9 to 42.3
Sun sensor	-9.2 to 13.8	14.0 to 44.3
Magnetic sensor	-9.2 to 12.2	14.0 to 42.8
Magnetic torquer	-9.1to 13.5	14.1 to 44.1
Star tracker	-7.2 to 11.9	16.5 to 41.8
Reaction wheel	-6.7 to 11.8	17.6 to 42.6
Thruster	0.78 to 4.8	27.5 to 33.8

Modification of thermal design

- The conductive control material between Earth pointing surface (-Z) and the inner structure is changed from the insulator to the thermal conductive sheet.
- The surface finishing on the outside of the hood of the star tracker is changed from Alodine 1000 to Black Alumite.
- The conductive thermal material between the battery and the inner structure is changed from the thermal conductive sheet to the insulator.
- The surface finishing on the outside of -X plate in the outer structure is changed from Alodine 1000 to White Alumite.



Result of multi nodal analysis

Units	Worst Cold Condition	Worst Hot Condition
On-board computer	-7.6 to 6.6	17.5 to 37.5
GPS receiver	-12.5 to 7.7	10.9 to 39.1
Telemetry transmitter	-10.0 to 6.3	14.3 to 38.3
Mission transmitter	-8.2 to 6.3	16.8 to 37.3
Command receiver	-8.8 to 6.7	16.1 to 37.9
Battery	-2.4 to 2.0 4.1 to 8.3 with 2.9 W heater	24.8 to 31.0
Gyro sensor	-8.7 to 6.4	16.1 to 37.3
Sun sensor	-17.3 to 11.0	4.8 to 42.9
Magnetic sensor	-16.9 to 9.3	5.4 to 41.0
Magnetic torquer	-17.1 to 10.7	5.1 to 42.8
Star tracker	-9,9 to 6.8	14.3 to 35.0
Reaction wheel	-8.2 to 6.3	16.8 to 37.3
Thruster	-4.4 to 0.2	22.3 to 29.7

Result of multi nodal analysis

- The temperature range of the battery becomes from 4.1 to 8.3 deg. C. in the worst cold case with the heater of 2.9 W.
- The project leader made the judgment that there is no problem although the battery temperature of 4.1 deg. C is lower than the design temperature range of the battery.
- This thermal design has been completed for a short period of ten months including the development of one nodal and two analysis programs and the development of the satellite model for the multi nodal analysis.

Conclusions

- The procedure of the thermal design of micro and nano satellites has been proposed in order to complete the thermal design of micro and nano satellites about 1 year.

- The procedure of thermal design is applied to Hodoyoshi-1 satellite that is about 50 cm wide, 50 cm deep, and 50 cm high, is about 50 kg in mass, has two inner plates, has solar cells on the body, flies on the sun-synchronous orbit of the 500 km of altitude, and is pointing to the Earth.

- This thermal design has been completed for a short period of ten months including the development of one nodal and two nodal analysis programs and the development of the satellite model for the multi nodal analysis.

Surface finishes

	α	ε	α/ε
Alodine 1000	0.15	0.038	3.95
Alodine 1200	0.39	0.068	5.74
White alumite	0.24	0.76	0.32
Black alumite	0.68	0.88	0.77

Thermal properties

	Conductivity
Glass epoxy	0.471 W/(m･K)
DENKA BFG20	4.1 W/(m･K)

Basic equation

Energy equation

- One nodal analysis

$$m_W c_W \frac{dT_W}{dt} = \dot{Q}_{ex} - P_{gen} + P_W + \dot{Q}_{sh\_W}$$

- Two nodal analysis

$$m_O c_O \frac{dT_O}{dt} = \dot{Q}_{ex} - P_{gen} + P_O + \dot{Q}_{sh\_O} + \dot{Q}_{I-O}$$

$$m_I c_I \frac{dT_I}{dt} = P_I + \dot{Q}_{sh\_I} + \dot{Q}_{O-I}$$

Net heat rate between space and satellite

- One nodal analysis

$$\dot{Q}_{ex} = \alpha_{O-out} G_s A_{p/l} l^2 + \alpha_{O-out} G_s a F_a l^2 + \varepsilon_{O-out} q_{IR} F_{s-e} l^2 - \varepsilon_{O-out} 6 l^2 \sigma T_W^4$$

- Two nodal analysis

$$\dot{Q}_{ex} = \alpha_{O-out} G_s A_{p/l} l^2 + \alpha_{O-out} G_s a F_a l^2 + \varepsilon_{O-out} q_{IR} F_{s-e} l^2 - \varepsilon_{O-out} 6 l^2 \sigma T_O^4$$

$$\alpha_{O-out} = (1-\rho_C)\alpha_R + \rho_C \alpha_C$$

$$\varepsilon_{O-out} = (1-\rho_C)\varepsilon_R + \rho_C \varepsilon_C$$

Net heat rate between space and satellite

$$F_{s-e} l^2 = F_{ns-e} l^2 + 4 F_{ps-e} l^2$$

$$F_{ns-e} = \left(\frac{R_e}{R_e + H} \right)^2$$

$$F_{ps-e} = \frac{1}{\pi} \left(\tan^{-1} \frac{1}{\sqrt{\left(\frac{R_e + H}{R_e} \right)^2 - 1}} - \frac{\sqrt{\left(\frac{R_e + H}{R_e} \right)^2 - 1}}{\left(\frac{R_e + H}{R_e} \right)^2} \right)$$

$$F_a = \begin{cases} F_{s-e} \cos\theta_{za} & if \quad \cos\theta_{za} > 0 \\ 0 & if \quad \cos\theta_{za} \leqslant 0 \end{cases}$$

Basic equation

Heat transfer rate between inner structure and outer structure

$$\dot{Q}_{I-O} = \dot{Q}_{I-O\,r} + \dot{Q}_{I-Oc}$$

$$\dot{Q}_{O-I} = \dot{Q}_{O-I\,r} + \dot{Q}_{O-Ic}$$

$$\dot{Q}_{I-O\,r} = \sum_{enclosed\ region} \frac{\sigma\left(T_I{}^4 - T_O{}^4\right)}{\left(1/\varepsilon_{O-in} - 1\right)/A_O + \left(1/\varepsilon_I - 1\right)/A_I + 1/\left(A_I F_{I-O}\right)}$$

$$\dot{Q}_{I-O\,r} = \sum_{enclosed\ region} \frac{\sigma\left(T_I{}^4 - T_O{}^4\right)}{\left(1/\varepsilon_{O-in} - 1\right)/A_O + \left(1/\varepsilon_I - 1\right)/A_I + 1/\left(A_I F_{I-O}\right)}$$

$$\dot{Q}_{I-O\,c} = kA_{sp} \frac{T_I - T_O}{L}$$

$$\dot{Q}_{I-O\,c} = kA_{sp} \frac{T_O - T_I}{L}$$

Basic equation

Power control term

The generation and dissipation of electric power are separated to the following four condition: [1] eclipse, [2] the generation of electric power is smaller than the dissipation, [3] the generation of electric power is larger than the dissipation and the battery is not full charge and [4] the generation of electric power is larger than the dissipation and the battery is full charge.

$$P_{gen} = \begin{cases} \rho_C \eta_C G_s (A_{p//} + aF_a) l^2 & if \quad case[2],[3],[4] \\ 0 & if \quad case[1] \end{cases}$$

- One nodal analysis

$$\dot{Q}_{sh\_W} = \begin{cases} P_{gen} - P_W & if \quad case[4] \\ 0 & if \quad case[1],[2],[3] \end{cases}$$

- Two nodal analysis

$$\dot{Q}_{sh\_I} + \dot{Q}_{sh\_O} = \begin{cases} P_{gen} - P_I - P_O & if \quad case[4] \\ 0 & if \quad case[1],[2],[3] \end{cases}$$

Comparison between 2 nodal and multi nodal

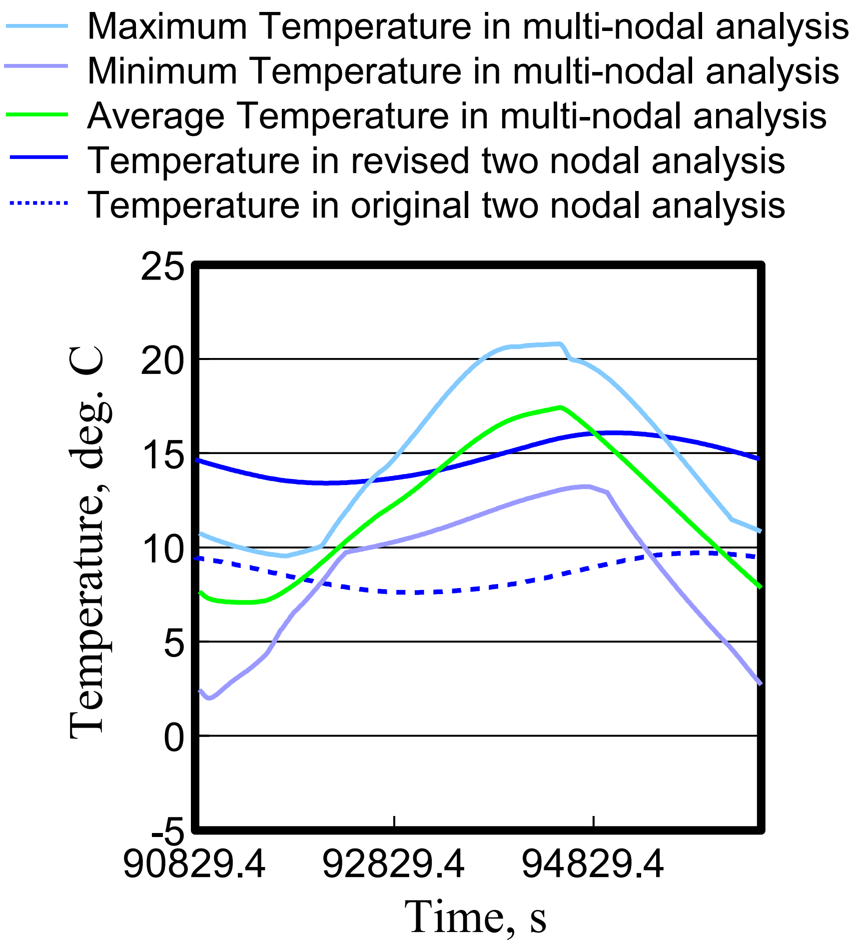


Figure 16. Comparison of temperature history at inner structure under worst cold case between two nodal analysis and multi-nodal analysis.

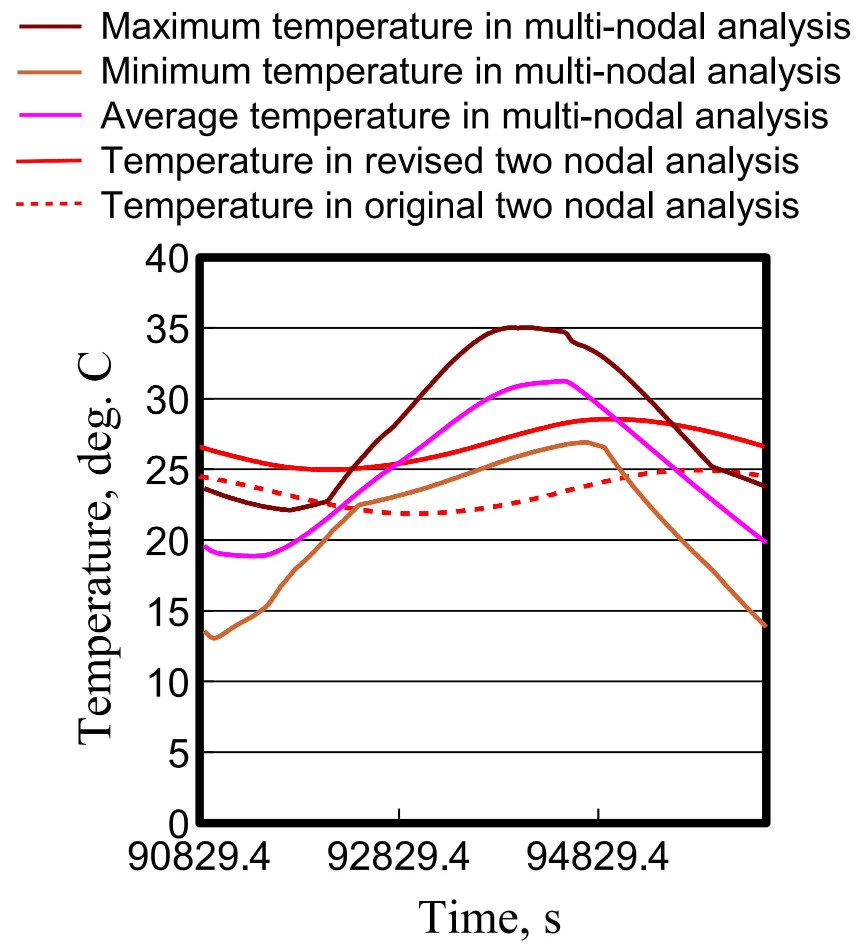


Figure 15. Comparison of temperature history at inner structure under worst hot case between two nodal analysis and multi-nodal analysis.