Thermal design of the Soft Gamma-ray Detector for the next X-ray astronomical satellite ASTRO-H

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January, 2011
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Abstract

Compton Camera is a main detector in the Soft Gamma-ray detector onboard ASTRO-H, and consists of semi-conductor layers. Their resolutions strongly depend on their temperature, so we must keep them to be below $-15^\circ$C. However, the Compton Camera generates total 4.3 W inside a small volume of 124 mm × 124 mm × 120 mm. Therefore, a thermal design to realize an efficient heat transport is necessary.

We suggested to use graphite sheets in lateral direction, and four copper poles in vertical direction, as new effective heat paths. In addition, we considered that an electro-magnetic shield wall and a bottom frame also can be utilized as heat paths.

To verify the effects of these new heat paths, we constructed a thermal mathematical model (TMM), and calculated the temperature distributions in the Compton Camera. As a result, the new thermal components were found to fulfill the thermal requirements. However, the TMM has systematic errors arising from uncertainties in the assumed the thermal contact conductances.

We prepared two thermal dummies, and carried out experiments in a vacuum chamber. As a result, the contact conductance between the graphite sheet and the copper pole, by double faced tape, was confirmed to be almost the same as our assumption. Those between metals, by screws, were estimated to be four times as large as our assumptions.

Using these the contact conductance values obtained in the experiments, we calibrated TMM, and re-calculated the temperature distribution of the actual Compton Camera. As a result, we succeeded in keeping the temperatures of the all layers between $-16^\circ$C and $-20^\circ$C. Therefore, our thermal design of the Compton Camera fulfills the thermal requirements.
Chapter 1

INTRODUCTION

ASTRO-H is the 6th X-ray astronomical satellite in Japan to succeed Suzaku, and is scheduled for launch 2014. The subject of this Thesis is thermal design of Soft Gamma-ray Detector (SGD), which covers the highest energy band of 50–600 keV, 50–600 keV among instruments onboard ASTRO-H. The SGD utilizes, as its main detectors, six Compton Camera, each consisting of densely stacked 40 layers of semi-conductor imaging devices. To read their signals, each Compton Camera utilizes 208 ASICs (Application Specific Integrated Circuit), with a total power of 4.4 W (or 0.021 W per ASIC) in a small volume of $124 \times 124 \times 120$. Although these Compton Cameras need to be operated in a temperature range of $-20^\circ C$ to $-15^\circ C$, the required thermal condition would not be realized unless the heat can escape efficiently from each ASIC to a cold plate which is connected heat pipes to a radiator. Therefore, the thermal design of SGD, in particular its Compton Camera, is of vital importance.

To solve this issue, new heat paths made of metals are introduced to each Compton Camera. Then, we construct a thermal mathematical model, and numerically calculate the temperature distribution in Compton Camera to examine whether the required thermal condition is fulfilled. However, in the thermal mathematical model, contact resistances at all contact points are subject to large uncertainties. To reduce these uncertainties and calibrate the thermal mathematical model, we prepare dummies which are thermally equivalent to the Compton Camera, and carry out calibration experiments.

In this Thesis, general concept of a thermal design is described in Chapter 2, and ASTRO-H and the SGD are in Chapter 3. Thermal requirements of the Compton Camera and our suggestions to realize them are given in Chapter 4, together with the research plan. We construct thermal mathematical models and calculate the temperature distributions of the Compton Camera in Chapter 5, and the obtained results are verified and calibrated by thermal dummy experiments in Chapter 6. In Chapter 7, we conclude the present study.
Chapter 2

THERMAL DESIGN OF SATELLITE-BORNE INSTRUMENTS

In this Chapter, we show how the temperature of each part of an instrument onboard a near-Earth satellite is determined, and review the basic concept in the thermal design of such an instrument. In §2.1 and §2.2, we describe basics of heat transfer such as heat conduction and radiation, and typical thermal environment of a near-Earth orbit, respectively. Section 2.3 explains how we control thermal conditions of satellite-borne instruments.

2.1 General Thermal Terms

As well known, heat transfer takes place in three forms, namely, conduction, convection, and radiation. Among them, convection is very efficient on ground, but it does not work in a satellite environment due to the absence of atmosphere.

2.1.1 Conductive heat transfer

A thermal gradient between parts of an object drives heat transfer from high temperature parts to low temperature parts. The heat flow $\dot{Q}$ which goes through a cross-sectional area $A$ in the object per unit time is proportional to the temperature gradient $\frac{\partial T}{\partial x}$, and can be written as

$$\dot{Q} = -\kappa A \frac{\partial T}{\partial x}.$$

This relation is called Fourier law. Here, $\kappa$ (W/m/K) is thermal conductivity, and represents how easily the material under consideration can transfer heat. It is not necessarily constant, but often varies largely, depending on the temperature of the object. In table 2.1, we list conductivity of typical materials, together with other physical properties of them at normal temperature. Gas has the lowest conductivity, and liquid has the second, while metals have the highest values. Differentiating partially both sides of eq.(2.1) with $x$, and employing the equation of continuity
Table 2.1: Properties of solid

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (K)</th>
<th>Density (kg/m³)</th>
<th>Isobaric specific heat (J/kg/K)</th>
<th>Thermal conductivity (W/m/K)</th>
<th>Thermal diffusivity (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentine (Ag)</td>
<td>300</td>
<td>10.490</td>
<td>0.237</td>
<td>427</td>
<td>×10⁻⁵</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>300</td>
<td>2.688</td>
<td>0.905</td>
<td>237</td>
<td>9.68</td>
</tr>
<tr>
<td>Gold (Au)</td>
<td>300</td>
<td>19.30</td>
<td>0.129</td>
<td>315</td>
<td>12.8</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>300</td>
<td>8.880</td>
<td>0.386</td>
<td>398</td>
<td>11.7</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>300</td>
<td>7.870</td>
<td>0.422</td>
<td>80.3</td>
<td>2.27</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>300</td>
<td>1.737</td>
<td>1.02</td>
<td>156</td>
<td>8.74</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>300</td>
<td>8.899</td>
<td>0.447</td>
<td>90.5</td>
<td>2.29</td>
</tr>
<tr>
<td>Platinum (Pt)</td>
<td>300</td>
<td>21.460</td>
<td>0.133</td>
<td>71.4</td>
<td>2.52</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>300</td>
<td>2.330</td>
<td>0.713</td>
<td>148</td>
<td>8.80</td>
</tr>
<tr>
<td>Titanium (Ti)</td>
<td>300</td>
<td>4.506</td>
<td>0.522</td>
<td>21.9</td>
<td>0.925</td>
</tr>
<tr>
<td>Tungsten (W)</td>
<td>300</td>
<td>19.250</td>
<td>0.133</td>
<td>178</td>
<td>6.62</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>300</td>
<td>7.131</td>
<td>0.389</td>
<td>121</td>
<td>4.16</td>
</tr>
</tbody>
</table>

\[
0 = \frac{\partial Q}{\partial t} + \text{div}(\dot{Q}) = A \rho C \frac{\partial T}{\partial t} + \frac{\partial \dot{Q}}{\partial x}, \tag{2.2}
\]

we can obtain

\[
\frac{\partial T}{\partial t} = \frac{1}{A \rho C} \frac{\partial}{\partial x} \left( \kappa \frac{\partial T}{\partial x} \right), \tag{2.3}
\]

where \( \rho \) (kg/m³) is the density and \( C \) (J kg⁻¹ K⁻¹) is specific heat of the material. Generalizing this to three dimensions, we can write as

\[
\frac{\partial T}{\partial t} = \frac{\kappa}{\rho c} \nabla^2 T, \tag{2.4}
\]

where \( A \) and \( \kappa \) are assumed to be constant for simplicity. This equation shows the way of conductive heat transfer and is called \textbf{equation of heat conduction}. The invariable, \( \frac{\kappa}{\rho c} \) (m⁻² s), is called thermal diffusivity, and is substance-specific quantity. In the case of steady state heat conduction, the left side of eq.(2.2) and eq.(2.3) are 0, and the equation of heat conduction becomes

\[
\nabla^2 T = 0. \tag{2.5}
\]

Solving eq.(2.4) under an initial condition \( T(x, 0) \) and a boundary condition \( T(x_0, t), T(x, t) \) is completely determined at a given position \( x \) and time \( t \). However, it is generally hard to analytically solve eq.(2.4), unless the object has a simple shape. Therefore, in practical applications, eq.(2.3) is solved numerically, as described in §2.1.3.
In an object, the flow of heat between a position $x_1$ at a temperature $T_1$ and another position $x_2$ at a temperature $T_2$ is expressed, from eq.(2.1), as

$$\dot{Q} = K_{21}(T_2 - T_1),$$

(2.6)

where $K_{21}$ (W/K) is called thermal conductance. Thus, $\dot{Q}$ is proportional to the temperature difference $\Delta T$ between the two points. If we relate $\dot{Q}$ with electric current, $\Delta T$ with potential difference, and $K_{21}^{-1}$ with electric resistance, eq.(2.6) can be considered as analogous to the Ohm’s law.

### 2.1.2 Radiative heat transfer

Every object consists of molecules and atoms, which are moving harder as the temperature gets higher. Because of this motion, the object emits electromagnetic waves. The radiative energy emitted per unit time and unit area from a surface of an object is called emissive power, and is denoted here as $E$ (W/m$^2$). Thermal radiation from any object is emitted in various wavelengths, and when the energy included in an wavelength interval $\lambda \sim \lambda + \Delta \lambda$ is $E_{\lambda}d\lambda$, $E$ can be written as

$$E = \int_{0}^{\infty} E_{\lambda}d\lambda.$$  

(2.7)

Here, $E_{\lambda}$ is called spectral emissive power. When the object is a complete black body, the spectral emissive power $E_{b\lambda}$ follows a Planck distribution, and the emissive power $E_b$ can be written as

$$E_b = \sigma T^4,$$

(2.8)

from Stephan-Boltzmann law. In this equation, $\sigma = 5.67 \times 10^{-8}$ (W/m$^2$/K$^4$) is the Stephan-Boltzmann constant, and $T$ is again the temperature of the object.

Thermal radiation of a general object is different from the black body radiation both in shape and intensity. However, taking a black body radiation of the same temperature as a reference, $E$ and $E_{\lambda}$ can be expressed in the ratio from as

$$E = \varepsilon E_b = \varepsilon \sigma T^4,$$

(2.9)

$$E_{\lambda} = \varepsilon_{\lambda} E_{b\lambda},$$

(2.10)

where $\varepsilon$ ($0 < \varepsilon \leq 1$) is called emissivity, and $\varepsilon_{\lambda}$ is monochromatic emissivity. Obviously, a black body has $\varepsilon = 1$ and $\varepsilon_{\lambda} = 1$ at any $\lambda$.

Radiation energies incident upon a surface of an object are either absorbed, reflected, or going through. The fraction of the absorbed energy is called absorptivity, and denoted as $\alpha$. Like the case of emissivity, we can also define monochromatic absorptivity, $\alpha_{\lambda}$. A black body is characterized as

$$\alpha = \alpha_{\lambda} = 1,$$

(2.11)
and general objects have $0 < \alpha < 1$ and $\alpha_{\lambda} < 1$.

Because thermal radiation of an object results from thermal motion of molecules constructing the object, an object which strongly absorbs radiation at a particular wavelength also emits strongly at the same wavelength. Therefore, we have

$$\alpha_{\nu} = \epsilon_{\nu}, \quad (2.12)$$

which is called Kirchhoff’s law.

Some caution is needed about absorption. The emissivity $\epsilon$, the monochromatic emissivity $\epsilon_{\lambda}$, and the monochromatic absorptivity $\alpha_{\lambda}$ are intrinsic properties of an object, but the absorptivity $\alpha$ depends on the property of the incident radiation. Namely, when energy incident upon a surface of an object in $\lambda \sim \lambda + \delta \lambda$ is $H_{\lambda}d\lambda$, all energy is written as $H = \int_{0}^{\infty} H_{\lambda}d\lambda$, so $\alpha$ is expressed as

$$\alpha(T) = \frac{\int_{0}^{\infty} \alpha_{\lambda}H_{\lambda}d\lambda}{\int_{0}^{\infty} H_{\lambda}d\lambda}. \quad (2.13)$$

In particular, in the case of incident energy from a black body, $H_{\lambda}(T) = \epsilon(T)\epsilon_{\lambda}(T_b)$, and when the temperature of the object is the same as that of a black body, $T_b$,

$$\alpha(T) = \epsilon(T) \ (T = T_b), \quad (2.14)$$

from eq.(2.12).

### 2.1.3 Finite difference method

In numerically calculating a temperature distribution, we divide the object into $n$ finite elements and define flow of heat between every part of nodal points $i$ and $j$, $\dot{Q}_{ij}$.

Let the temperature $T(x)$ be a continuous function of the position $x$. Using discrete values of $T$, $T_{i-1}$, $T_i$, and $T_{i+1}$ at discrete values of $x$, $x_{i-1}$, and $x_i$, $x_{i+1}$, respectively, we approximate the differential coefficient of $T(x)$ at $x_i$ by differences as

$$\frac{\partial T}{\partial x} \bigg|_{x_i} = \frac{T_{i+1} - T_i}{\Delta x} + O(\Delta x), \quad (2.15)$$

$$\frac{\partial T}{\partial x} \bigg|_{x_i} = \frac{T_i - T_{i-1}}{\Delta x} + O(\Delta x), \quad (2.16)$$

$$\frac{\partial T}{\partial x} \bigg|_{x_i} = \frac{T_{i+1} - T_{i-1}}{2\Delta x} + O(\Delta x^2), \quad (2.17)$$

as shown in figure 2.1. These ways of expression are called finite difference; in particular, eq.(2.12) is called forward difference expression, eq.(2.13) is called backward difference expression, and eq.(2.14) is called central difference expression. $O(\Delta x)$ and $O(\Delta x^2)$ shows truncation errors in the order of $\Delta x$ and $\Delta x^2$. Thus, the central difference is more accurate than the others.

In a similar way, the second-order difference coefficient is expressed as...


Figure 2.1: Difference expression of the derivative of a continuum function (JSME text series Heat transfer figure 2.37).

\[
\frac{\partial^2 T}{\partial x^2} |_{x_i} = \frac{T_{i+1} - 2T_i + T_{i-1}}{2\Delta x^2} + O(\Delta x^2).
\] (2.18)

Adopting a two-dimensional case for simplicity, let us solve the thermal conduction equation, eq.(2.3), through the difference method. If heat is not generated, and physicality values are constant at any point in an object, eq.(2.3) is expressed as

\[
\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right),
\] (2.19)

where \(\alpha\) stands for \(\kappa/\rho c\). When the \((x,y)\) plane is divided in directions \(x\) and \(y\), step sizes of \(\Delta x\), \(\Delta y\), respectively, we can divide the object into internal elements and boundary elements. As shown in figure 2.2, let us consider an internal element which is \(i\)-th in \(x\)-direction, and \(j\)-th in \(y\)-direction. Denoting the temperature at \(t = n\Delta t\) as \(T^n_{i,j}\), eq.(2.15) is expressed, from eq.(2.13) and eq.(2.16), as

\[
\frac{T^{n+1}_{i,j} - T^n_{i,j}}{\Delta t} = \alpha \left( \frac{T^n_{i-1,j} - 2T^n_{i,j} + T^n_{i+1,j}}{2\Delta x^2} + \frac{T^n_{i,j-1} - 2T^n_{i,j} + T^n_{i,j+1}}{2\Delta y^2} \right),
\] (2.20)

where \(\Delta t\) is a time step. In this equation, the temporal differentiation is expressed as forward difference expression, and the space differentiation is expressed as central difference expression. This includes a truncation error of \(O(\Delta x^2, \Delta y^2)\). When we set


Figure 2.2: A difference approximation of inner elements in an object (JSME text series Heat transfer figure 2.39).

\[ r_x = \alpha \Delta t / \Delta x^2, \quad r_y = \alpha \Delta t / \Delta y^2 \]  

(2.21)

the equation (2.17) becomes

\[
T_{i,j}^{n+1} = T_{i,j}^n + r_x(T_{i+1,j}^n - 2T_{i,j}^n + T_{i-1,j}^n) + r_y(T_{i,j+1}^n - 2T_{i,j}^n + T_{i,j-1}^n).
\]

(2.22)

Eq. (2.21) is used in two representative context. One is initial value problems, wherein we specify \( \{T_0^{i,j}\} \), and calculate evolutions of these temperatures by a step of \( \Delta t \). The other is boundary condition problems, in which we fix the temperatures of certain nodes to specified volumes, and repeat the iteration of eq.(2.21) until \( |T_{i,j}^{n+1} - T_{i,j}^n| \) becomes sufficiently small. This corresponds to a steady state condition \( \partial T / \partial t = 0 \) in eq.(2.4), in either case, the heat flow \( \dot{Q}_{ij} \) is easily obtained from the solution \( \{T_{i,j}^n\} \) through eq.(2.6).

### 2.1.4 General heat transport equation

Generally, a variation of the temperature of an node \( i \) is written as

\[
C_i \frac{\Delta T_i}{\Delta t} = \sum_{j \neq i} \dot{Q}_{ji} = \sum_{j \neq i} \dot{Q}_{ji},
\]

(2.23)

where \( C_i \) is specific heat of node \( i \). Here, by using eq. (2.6) and eq. (2.8), a heat transported from node \( j \) to \( i \) in eq. (2.23) can be expressed as

\[
\dot{Q}_{ji}^C = K_{ji}^C(T_j - T_i)
\]

(2.24)

\[
\dot{E}_{ji} = K^R(T_j^4 - T_i^4).
\]

(2.25)
Eq.(2.23) can be utilized not only node connection in an individual object, but also that between different materials.

![Figure 2.3: A temperature drop by a contact resistance.](image)

as shown in figure 2.3, surfaces of different materials 1, 2 cannot be completely in contact to each other. This is because they have concavities and convexities, so they are not parallel on small scales. When the surfaces contact only partially, a significant resistance $R_c$ is generated there, which is called **thermal contact resistance**. Using temperatures of the two objects at the contact points, $T_{2A}$ and $T_{2B}$ (figure 2.3), $R_c$ is expressed as

$$\dot{Q} = \frac{T_{2A} - T_{2B}}{R_c}.$$  \hspace{1cm} (2.26)

Because the heat flow $\dot{Q}$ in $x$-direction is the same at any point,

$$\dot{Q} = \kappa_1 A \frac{T_1 - T_{2A}}{L_1} = \frac{T_{2A} - T_{2B}}{R_c} = \kappa_2 A \frac{T_{2B} - T_3}{L_2},$$  \hspace{1cm} (2.27)

where $\kappa_1$, $\kappa_2$ are conductivities, while $L_1$, $L_2$ are lengths of the two objects (figure 2.3).
2.2 Thermal Control Actuators

Elements which control temperatures purposely (e.g., heating or cooling) is called thermal control actuators. Elements which utilize active devices such as heaters and heat pipe are called active control actuator, while those which do not utilize active devices are called passive control actuator. The thermal control actuators related with the SGD are described in §3 in detail. Here, review general concept of thermal control actuators.

2.2.1 Passive control actuator

Passive thermal control is realized by radiation control and conductivity control. The former consists of absorptivity/emissivity ($\alpha/\varepsilon$) control, carried out by selecting surface properties of materials so as to minimize or maximize the radiative heat transport, depending on the purpose.

As a typical example of the $\alpha/\varepsilon$ control, let us describe the technique of radiative cooling, which is used to cool space-borne instruments including the SGD itself, as well as CCD cameras on ASCA and Suzaku. For this purpose, we need to let heat efficiently escape from the instrument to the external space, and to reduce heat input from external space as much as possible. This requires the thermal emissivity $\varepsilon$ in infrared region should be high, and the absorptivity $\alpha_s$ to solar radiation and terrestrial albedo should be small, so sun face materials which have $\alpha_s/\varepsilon \sim 0$ is better. We obtain $\alpha_s/\varepsilon \sim 0.3/0.8$ when we paint the surface white. However, a much better performance is realized when aluminum which has a small $\alpha_s$ is placed on the internal side (satellite side), and a cover which has a high $\varepsilon$ and optical transparency (e.g., a thin plastic film) is placed on the external side (space side). Aluminized plastic films are typical materials with this property. Alternatively, thin teflon films, backed up silver-evaporated layer, are utilized. In order to intercept far-infrared radiation from other parts of the spacecraft which is usually kept at near room temperatures, thermal blanket is utilized. A typical thermal blanket is Multilayer Insulation (MLI), in which aluminum is interleaved by polyester-evaporated sheet and polyester net (to avoid contacts between sheets).

Typical techniques used for conductivity control, include heat sink which moderates rapid temperature variations, thermal thin filer which increases conductance at a contact point, thermal insulation spacers which decrease thermal conductance are, and high-conductivity elements (aluminum, copper, graphite etc.) used to increase conductive heat flows.

2.2.2 Active control actuator

Controlling the temperature by only passive control actuators is often limited for those instruments which generates a significant amount of heat, or those which have time-variable heat generation (e.g., when it is put on and off), or those which is temperature critical, or those which experience largely different thermal environments (e.g., planetary missions). Then, we utilize active control actuators and control the temperature positively.
A typical active control actuator is thermal louver in which we can change $\alpha_s/\epsilon$ by opening or closing shutter blade (either manually by commands, or automatically using bimetal switches/torgures). When we would like to keep the temperature, we close the shutter and expose the surfaces with high $\alpha_s/\epsilon$, and when we would like to radiate heat out, we open it and make surface with low $\alpha_s/\epsilon$ visible.

For active conductive control, heat pipes and fluid controls are often utilized. In particular, heat pipes are good thermal conductor by utilizing latent heat of phase variation and capillary action. Heat pipes have been utilized in the *Suzaku* HXD.

### 2.3 Thermal Environment of the Satellite

A satellite on its orbit receives heat inputs from the Sun and the Earth (albedo and far-infrared emission), and at the same time, it radiates heat as determined by its temperature to space with a temperature of 2.7 K. The temperature of the satellite is naturally determined by the balance between these thermal input and output in its thermal environment.

#### 2.3.1 Solar radiation

The Sun has a radius $R_\odot = 6.96 \times 10^5$ km, located $D = 1.5 \times 10^8$ km ($\equiv 1$ AU) distant from the Earth, and its radiation can be approximated by a black body with an effective temperature $T_\odot = 5780$ K. Therefore, the solar radiation flux near the Earth is

$$S_\odot = 4\pi R_\odot^2 \sigma T_\odot^4 / 4\pi D^2 = \sigma T_\odot^4 = (1353 \pm 21) \times (1^{+0.034}_{-0.0325}) \sim 1353^{+46}_{-44}$ W/m$^2$, \quad (2.28)$$

where the $\pm 21$ W of the right hand side reflects a range of the observation data. The second factor represents the effect of the season variation, and it becomes maximum at the perihelion point (3rd January), and minimum at the aphelion point (4th July).

#### 2.3.2 Earth albedo

Of all the solar heat input to the Earth, some fraction goes back to space by atmospheric scattering and reflection by clouds or the Earth’s surface (including sea). This is called Earth albedo. An energy density of the albedo $S_a$ is expressed as

$$S_a = a S_\odot, \quad (2.29)$$

where $a$ is an albedo coefficient. This albedo coefficient is affected strongly by conditions of the scattering object, so it varies between 0.1 and 0.8, depends on the season, the position, and the existence of clouds. Usually, its average is estimated as

$$a = 0.30^{+0.30}_{-0.15}. \quad (2.30)$$

The wavelength distribution of the albedo is the same as that of the Sun.
2.3.3 Earth infrared radiation

The Earth has an equatorial radius $R_E = 6378$ km. The temperature of the Earth is determined by a heat budget between the thermal input from the Sun and and thermal output of itself, described as

$$S_\odot (1 - a) \times \pi R_E^2 = \epsilon \sigma T_E^4 \times 4\pi R_E^2,$$

where $\epsilon$ refers to the infrared emissivity of the Earth. Approximating that the Earth is a block body ($\epsilon = 1$), this equation yields

$$T_E = 254 \text{ K},$$

and the radiation from the Earth is in an infrared wavelength region. In addition, the flux of the infrared radiation can be expressed as

$$\varphi_E = \epsilon \sigma T_E^4 = 237^{+28}_{-97} \text{ W/m}^2.$$

However, considering the greenhouse effect, the temperature of the geosphere is high than (2.21).

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Chapter 3

ASTRO-H AND THE SOFT GAMMA-RAY DETECTOR (SGD)

3.1 ASTRO-H

The X-ray astronomy satellite, ASTRO-H, which is the successor to Suzaku, is scheduled for launch in the fiscal year 2013. It carries onboard two types of telescopes; the Hard X-ray Telescope (HXT) and the Soft X-ray Telescope (SXT), and four kinds of detectors; the Soft X-ray Imager (SXI), the Soft X-ray Spectrometer (SXS), the Hard X-ray Imager (HXI), and the Soft Gamma-ray Detector (SGD). The spacecraft will experience a typical near-Earth thermal environment (§2), because it will be put into a near-circular orbit with a perigee of ∼550 km.

3.1.1 Observational capability of ASTRO-H

Outstanding capabilities of ASTRO-H include:

- The first imaging spectroscopic observations in energies above ∼12 keV up to ∼80 keV, to be realized by the HXT and the HXI.

- The first ultra high-resolution spectroscopic observation by the SXS, with an energy resolution of 4.7 eV at 6 keV. This was ∼120 eV previously.

- An extremely broad energy band realized by a collaboration of these instruments. The softest end (0.3 − 12 keV) is covered by the SXT + SXI and the SXS, the intermediate range (5 − 80 keV) by the HXT + HXI, and the hardest end (50 − 600 keV) by the SGD. Although the overall bandpass is nominally the same as that of Suzaku, the sensitivity at ≥ 10 keV is significantly improved.

The basic parameters of all instruments onboard ASTRO-H are summarized in Table 3.1.
<table>
<thead>
<tr>
<th>Instrument Type</th>
<th>Focal Length</th>
<th>Effective Area</th>
<th>Energy Range</th>
<th>Angular Resolution</th>
<th>Effective FOV</th>
<th>Energy Resolution</th>
<th>Timing Resolution</th>
<th>Detector Background</th>
<th>Operating Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hard X–ray Imaging System (HXT+HXI)</strong></td>
<td>12 m</td>
<td>300 cm$^2$ (at 30 keV)</td>
<td>5–80 keV</td>
<td>$&lt;1.7$ arcmin (HPD)</td>
<td>$\sim 9 \times 9$ arcmin (12 m Focal Length)</td>
<td>$&lt;1.5$ keV (FWHM, at 60 keV)</td>
<td>several 10 $\mu$s</td>
<td>$&lt;1-3 \times 10^{-4}$ cts s$^{-1}$ cm$^{-2}$ keV$^{-1}$</td>
<td>$\sim -20^\circ$C</td>
</tr>
<tr>
<td><strong>Soft X–ray Spectrometer System (SXT–S+XCS)</strong></td>
<td>5.6 m</td>
<td>210 cm$^2$ (at 6 keV)</td>
<td>0.3–12 keV</td>
<td>$&lt;1.7$ arcmin (HPD)</td>
<td>$\sim 3 \times 3$ arcmin</td>
<td>7 eV (FWHM, at 6 keV)</td>
<td>80 $\mu$s</td>
<td>$&lt;6 \times 10^{-3}$ cts s$^{-1}$ cm$^{-2}$ keV$^{-1}$</td>
<td>50 mK</td>
</tr>
<tr>
<td><strong>Soft X–ray Imaging System (SXT–I+SXI)</strong></td>
<td>5.6 m</td>
<td>360 cm$^2$ (at 6 keV)</td>
<td>0.4–12 keV</td>
<td>$&lt;1.7$ arcmin (HPD)</td>
<td>$\sim 38 \times 38$ arcmin</td>
<td>$&lt;150$ eV (FWHM, at 6 keV)</td>
<td>4 sec</td>
<td>$&lt;$a few$\times 10^{-3}$ cts s$^{-1}$ cm$^{-2}$ keV$^{-1}$</td>
<td>$\sim -120^\circ$C</td>
</tr>
<tr>
<td><strong>Soft Gamma–ray non–Imaging System (SGD)</strong></td>
<td></td>
<td></td>
<td>a few 10 keV–600 keV</td>
<td></td>
<td></td>
<td>$\sim 2$ keV (FWHM, at 40 keV)</td>
<td></td>
<td></td>
<td>$&lt;$a few$\times 10^{-6}$ cts s$^{-1}$ cm$^{-2}$ keV$^{-1}$ (100–200 keV)</td>
</tr>
</tbody>
</table>

Table 3.1: Specification of instruments.
3.1.2 Expected achievements of ASTRO-H

As an example of a large number of research highlights to be expected with ASTRO-H, we select one particular subject, Active Galactic Nuclei (AGN). Figure 3.1 shows the simulated broad band spectra of the typical bright Type I Seyfert galaxy, Mrk 509, actually observed with Suzaku and simulated for ASTRO-H. The energy range is both $0.3 - 600$ keV. We can see that the sensitivity of ASTRO-H is much better than that of Suzaku, particularly in the hard X-ray band which are covered by the HXI and the SGD. Because the HXD has a sensitivity of a few mCrab at around $50 - 200$ keV, the expected high energy cutoff of AGNs may not be easily observed. However, by using the SGD and the HXI, it is clearly observed as shown in figure 3.1. The wide energy band with high sensitivity will reveal spectral components in the hard X-ray spectra of many types of AGNs and identify their nature (e.g., Noda et al. 2011[7]).

In the soft X-ray band, the SXS can be utilized to resolve narrow Fe-K line or Fe-K edge. Using these parameters, the intensity of secondary components scattered far from the central BH will be accurately determined. Furthermore, ionized absorbers which are reported to exist in many AGNs can be individually resolved. These observations will provide a key to clarifying will whether the relativistically broadened Fe-K lines reported in Seyferts such as MCG–6-30-15 are real or not.

![Figure 3.1: Broad band spectra of the typical Type I Seyfert Mrk 509. Panel (a) shows actual Suzaku spectra, while (b) the simulated ASTRO-H spectra.](image)

3.2 The Soft Gamma-ray Detector (SGD)

The Soft Gamma-ray Detector (SGD) covers an energy range of $60 – 600$ keV, which is the highest part among the detectors onboard ASTRO-H. The SGD consists of two units of detectors called SGD-S, and an electronics called SGD-E. As shown in figure 3.2, each SGD-S consists of three Compton Cameras, active BGO shields, front-end electronics, thermal harness, and structure. The
Figure 3.2: One unit of SGD-S, comprising three Compton Camera, displayed by 3D CAD. (left) An overall view, including the radiator panel (purple). (right) An expanded view of the three Compton Cameras, surrounded by active shields (green).

two SGD-S units are attached to outer face of the spacecraft side panels, so that they are exposed to direct Sunshine, or to the 2.7 K space. Therefore, it requires very careful thermal design, although the present thesis focus on thermal design of a single Compton Camera rather than the entire SGD-S. The SGD is being developed by the Stanford University, Nagoya University, JAXA, The University of Tokyo, Hiroshima University, and Saitama University.

3.2.1 Compton Camera

Figure 3.3: The concepts of the Compton reconstruction in the Compton Camera. (a) Compton kinematics. (b) Algorithm of source detection. (c) A Compton Camera with a collimated field of view.

The Compton Camera (identical $3 \times 2$ units in total) is the detection part of SGD-S, and works as one of the world’s first detectors that utilize Compton kinematics. Each camera consists of 32
Si layers, 8 CdTe layers, and 8 side CdTe layers. All of them are solid-state detectors with fine position resolutions, and are accommodated tightly in a small volume of 124 mm×124 mm×120 mm. Basically, Compton-scatters an incident gamma-ray photon at one of the Si layers, and photo-absorbs the scattered photon at CdTe layers. Let the position and energy recorded at the scattering site \( r_1 \) and \( E_1 \), respectively, and those at the absorbing site \( r_2 \) and \( E_2 \). The scattering angle \( \theta \) between the incident direction and \( r_1 - r_2 \) is expressed as

\[
\cos \theta = 1 + \frac{m_e c^2}{E_1 + E_2} - \frac{m_e c^2}{E_2} \tag{3.1}
\]

from Compton kinematics. Solving this equation inversely for \( \theta \) utilizing the two energy measurements \((E_1, E_2)\), and further using the two interaction points \((r_1, r_2)\), the incident direction of the photon is constrained to be a circle as shown in figure 3.3a. The source direction can be determined as a point at which a large number of circles overlap, as shown in figure 3.3b. In addition to this Compton kinematics, the field of view of each Compton Camera is both actively and passively collimated to \( 9^\circ.7 \times 9^\circ.7 \) and \( 34' \times 34' \), respectively (figure 3.3b; also see below). By requiring each valid event to arrive through this small aperture, we can make each Compton circle an arc, and hence narrow down the source location. Using this Compton re-construction, we can also reject events which have inconsistent arrival directions, such as events due to decays of radio-active materials created in orbit, and neutron scattering signals, because they are basically isotropic. As a result, we can decrease back ground in the Compton Camera. Even though its detection efficiency is relatively low, 15\% at \( \sim 100 \) keV, a combined use of \( 3 \times 2 \) cameras will provide an order of magnitude higher sensitivity than with the Suzaku HXD.

### 3.2.2 Active shields and fine collimators

Any satellite-borne radiation detector needs some kind of radiation shield, because the radiation background in space is considerably higher than that on ground. However, conventional passive shields, such as lead blocks, are too heavy to utilize. Therefore, we use active shields of BGO (Bi\(_4\)Ge\(_3\)O\(_{12}\)) crystal scintillators. Thanks to time information of optical photons emitted by BGO, we can remove events in the Compton Camera that have simultaneous hits in BGO. By this anti-coincidence technique, we can remove such background components as; charged particles penetrating SGD-S; secondary photons produced by cosmic-ray interactions with the detector materials; and background \( \gamma \)-rays that scatter in the shield and enter the Compton Camera. The active shield also works to remove those signal photons which are scattered in the Compton Camera, and escaped out. In addition, BGO can stop protons which have energies of less than 100 MeV, and reduce activation of detector materials by such protons. Similarly, BGO absorbs photons (up to \( \sim 300 \) keV) that comes from outside the narrow shield opening (including cosmic background photons and other celestial sources). That is, BGO can also behave as passive shields.

Like in the Suzaku HXD, the SGD active shields have a tightly collimated configuration, leaving only a narrow opening (field of view) used to observe target object. However, it is difficult to make
this field of view narrower by using BGO crystals. It is made of phosphor bronze, and has a thickness of 100 μm, so it can stop photons of up to 150 keV energies. The field of view (FOV) is \(34' \times 34'\). After re-construction by the Compton kinematics in the Compton Camera, if directions of incident photons are out of the FOV, we can judge that they are background events, particularly decay of activated isotopes (figure 3.3c), and remove.

3.2.3 Thermal environments and requirements of the SGD

In the SGD, mainly, two components are temperature critical. One is the Compton Cameras (§3.2.2), in which the temperatures of all semi-conductor layers must be below \(-15^{\circ}\)C. This is the main theme of the present thesis, and the detailed thermal design is explained on in Chapter 4–6. The other is the active shield (§3.2.2), which must also be used preferably in temperature below \(-15^{\circ}\)C. This has merits; one is that the APD leak current gets lower, at lower temperatures, and hence the APD noise is reduced. Another is that we need a less bias voltage to obtain a required APD gain. Finally, the BGO light output increases toward lower temperatures. In short, both the Compton Cameras and the active shields need a low temperature at \(-15^{\circ}\)C to \(-20^{\circ}\)C.

Inside one SGD-S, the three Compton Cameras generate total 17.6 W heat, the four charge sensitive amplifiers (APD-CSAs, figure 3.2 blue parts) total 5.2 W, the High Voltage box (HV) 1.0 W, and the Point of Load (POL) 3.0 W. Therefore, a total 25.8 W heat is generated inside. In addition, because the SGD is fixed outside the satellite body (§3.2), the Solar radiation and the Earth Albedo, the Earth far-infrared radiation (§2.6) are directly incoming. Furthermore, in the worst case, the temperature of the Solar Array Paddles (SAP) reaches 100\(^{\circ}\)C, and it radiates heat to the SGD as a black body (§2.2).

![Figure 3.4](image)

Figure 3.4: Appearances of (a) radiator and heat pipes and (b) cold plate (light green).

To keep the temperature of the SGD low enough under such a tough environment, thermal harnesses such including a radiator and two heat pipes are utilized (§2.5). They are illustrated in figure 3.4a. The heat pipes transport the heat from SGD-S to the radiator panel, where it is
radiated (§2.2.2) to space. As shown in figure 3.4b, we use a “cold plate”, made of aluminum from the Compton Cameras to lead the heat to the bottom plate.
Chapter 4

THERMAL REQUIREMENTS AND RESEARCH PLAN

4.1 Thermal requirement for the Compton Camera

Performance of semi-conductor devices such as Si and CdTe depends on its temperature strongly. Generally, thermal noise increases as the temperature gets higher. In the case of CdTe, in addition, the detector gain decreases on a considerably shorter time scales at higher temperatures, due to an enhanced trapping of carries in impurity level (Polarization). In any case, the energy resolution of semi-conductor devices gets worse, as the temperature increases, so their temperatures must be kept low enough. To realize the resolution of the Compton Camera of 2 keV (FWHM) at 40 keV, its temperature must be below $-15^\circ$C from top to bottom.

The SGD team defines the temperature of the cold plate to be $-20^\circ$C, so we must design the Compton Camera so that all its components must be kept in a temperature between $-20^\circ$C and $-15^\circ$C.

4.2 Thermal problems in the Compton Camera

As illustrated in figure 4.1, each Compton Camera consists mainly of 20 swastika-shaped “trays”, each carrying on its both sides pixellated $(16 \times 16)$ semiconductor devices; the top 16 trays have Si-detectors, whereas the bottom 4 CdTe-devices. In each tray, the 512 $(16 \times 16 \times$ two sides) output signals are read by 4 ASICs, which are placed at the four corners of the tray. Their power consumption is 0.021 W per ASIC, 0.16 W per tray, 0.82 W per corner, and 3.2 W in total. In addition, ASICs for side CdTe detectors generate heat of 0.252 W per one corner, so total 1.01 W in every surface. Then, to make the temperature gradient within the Compton Camera less than $5^\circ$C (§4.1), we need to transport efficiently the heat at each corner vertically down to the cold plate at the bottom.

Figure 4.1 shows how the 20 trays are stacked; thus, each tray (pink) touches the upper and lower neighbors. Employing the simplest thermal design which utilizes only these contacts for a
heat path, let us quickly estimate by hand temperature distribution in the Compton Camera by. Here, the contact area between the adjacent trays is assumed as 100 mm$^2$ and the thickness of tray is 7 mm. Even if the trays on which the semi-conductors and ASICs are placed are made of aluminum, and ignoring contact resistances between the trays, the temperature of the top layer tray was found to become $-10^\circ$C (That is, $\Delta T = 10^\circ$C). However, aluminum cannot be utilized as a tray material, and because aluminum photo-absors $\sim10\%$ of photons after Compton-scattering at Si layers. Therefore, we must choose a nonconductor and low-Z material like a plastic which are sufficiently transparent to the scattered signal photons. If we instead use, for example Poly Benz Imidazol (PBI), which is one of plastic materials, the vertical temperature gradient would amount to $>200^\circ$C, in inverse proportion to the thermal conductivity between Al and PBI. Thus, the thermal design of the Compton Camera encounters a serious problem.

### 4.3 Suggested Solutions

To solve the problem shown in §4.2, we need new efficient heat paths which enable heat of the ASICs to flow toward the aluminum cold plate with a much smaller temperature difference. Such the heat
paths can be divided into vertical ones, which go through all trays and reach the aluminum cold plate, and parallel ones, which run from individual ASICs to the vertical ones. The vertical paths should be high-conductive poles because all heat of the trays (0.82 W each) gathers into them, while the parallel ones should be thin enough to be laid under Front End Card (FEC). Therefore, we have decided to use as our baseline design, metals for the vertical ones, and thin heat-conductive sheets for the parallel ones.

For the vertical path, which metal is the most appropriate? Although silver is the most heat-conductive material \( \kappa = 427 \text{ W/m/K} \), it is much less suited machining than copper which is the second heat-conductive one \( \kappa = 398 \text{ W/m/K} \). Therefore, we employ copper as the material of the vertical heat paths. For the parallel paths, thin sheets which have a high heat conductance along their plane are appropriate. One candidate is power supply paths for the ASICs, which are 100 \( \mu \text{m} \) thin copper layers set between glass epoxy boards in FEC. However, they are connected by some thin through holes, so the temperature difference between an ASIC and a copper pole becomes \( \sim 3^\circ \text{C} \) if we rely only on this path. Therefore, have decided to significantly strengthen this path by adding a 100 \( \mu \text{m} \) thick graphite sheet which have a high conductivity of 700 W/m/K along its plane.

As shown in figure 4.2, the Compton Camera has box-shaped side wells, made of aluminum plate of 2 mm thickness. Because this shield can be considered as an additional vertical heat path, an attractive design is thermally couple these side plates to the proposed copper poles, in an attempts to increase the overall vertical thermal conductivity. The aluminum bottom frame (figure 4.2) can be utilized as yet bottom heat path, which is particularly suited in extracting heat out of the side CdTe detectors.

### 4.4 Research Plan

The principal objective of the present thesis is to solve the serious thermal issue of the SGD Compton Camera (§4.2), by pursuing the suggested solutions described above (§4.3). Specifically, we attempt to fix the baseline thermal design of the Compton Camera, which will be utilized to fabricate an engineering model (EM) of SGD-S. The EM design, with a minimum modification, will be then fed to the production of the flight model (FM) to be actually put in orbit.

Following the general procedure of thermal design of satellite-borne instruments, in §5 we first construct a thermal mathematical model. Such a calculation is particularly effective in cases like this, because we can ignore convective heat transfer, which is the most difficult to model numerically. Thus, we construct a thermal mathematical model, and search the most appropriate thermal design which fills the thermal requirements by changing parameters in that model. However, it has a significant shortcoming, that contact conductances (contact resistances) at each contact point must be assumed.

To measure the actual contact conductances, and to verify the overall validity of the design, we
Figure 4.2: The same as figure 4.2, but the aluminum side plates (green), the copper pole for heat conduction (purple), and the graphite sheets (blue) are added. This becomes our baseline thermal design.

perform in §6 a verification experiment. This utilizes thermal dummies which have the same main heat paths as the thermal mathematical model.

These dummies have the same size as the actual Compton Camera, and fed with the same heat input as from the ASICs. By measuring temperature distributions of the thermal dummy, we can calibrate the thermal mathematical model, and estimate in particular the contact conductances.

Finally, we can use the calibrated thermal mathematical model to finalize our thermal design of the Compton Camera. Furthermore, if any change in design of the Compton Camera because of some of the electrical or mechanical requirements, we can easily predict the expected impact on the thermal condition.
Chapter 5

THERMAL MATHEMATICAL MODEL OF THE COMPTON CAMARA

In this Chapter, a thermal mathematical model (TMM) of the Compton Camera is constructed, and is used to calculate temperature distributions therein. First, we explain the software used in simulation, Thermal Desktop (TD), and next, assume contact conductances at several contact points. Then, we calculate temperature distributions of the Compton Camera in different cases step by step, and fix its baseline thermal design which fulfills the thermal requirements.

5.1 Thermal Desktop (TD)

Thermal Desktop (TD) is a software to construct a numerical model of a thermal design, and to calculate steady-state temperature distributions and heat flows, as well as their time variations in dynamical (time-varying) applications. We can build up a geometry of an instrument in autoCAD, and divide each part into some nodes as many as we would like to. Then, we can assign any heat input at each node, and specify conductive and radiative couplings between any pair of nodes. After constructing the geometry, a temperature distribution can be calculated by an analysis code called SINDA/FLUINT, which utilizes finite difference method (§2.1.2). The result of calculation can be displayed by color contours which specify the temperature.

5.2 Mathematical Model Construction

5.2.1 Model components

As shown in §4.2, the graphite sheets provide the main parallel heat paths in the Compton Camera, and the copper poles are main vertical ones. In addition, the aluminum side shield and the aluminum bottom frame are considered to provide additional heat paths. Therefore, we construct models of these components as shown in figure 5.1 left. The figure also shows a semi-conductor
Figure 5.1: Left figure shows thermal parts of the one-side Compton Camera. A semiconductor (blue), a ASIC (red), a graphite sheet (black), a copper pole (orange), a bottom frame (purple), and an aluminum electro-magnetic shield (grey) are placed at their position in the actual Compton Camera. Right shows a crude shape of the graphite sheet, in which a dashed line shows a fold line, and it is utilized by being folded at this line.

device as well as the input heat generated by ASICs. A piece of graphite sheet is folded at the center as shown in figure 5.1 right, and put on the both surfaces of the tray. Our major task is how we thermally connected these components together.

The Compton Camera has a 90° rotational symmetry, and all the four sides are considered to have same the temperature distributions; so we display only one side of the Compton Camera. Furthermore, Although we model all the 40 trays in the same manner, for simplicity, we hereafter display only the top layer, which has the highest temperature of all 40 layers.

5.2.2 Node division

Each component shown in figure 5.1 is divided into a certain number of nodes. The number of the nodes in each component is decided, depending on how finely we would like to know a temperature distribution therein. However, when the number increases, the calculation time also increases. Therefore, the node division should be optimized by a balance between the model resolution and the calculation time.

Figure 5.2 shows our node division of each component in the one-side Compton Camera. Each
semi-conductor device is divided into $5 \times 5$ nodes, a graphite sheet into $(2 \times 3 + 3 \times 5) \times 2$ nodes, the copper pole into $4 \times 50$, the bottom frame actually its quarter into $8 \times 8 + 8 \times 5$, and the side shield panel into $13 \times 50$.

5.2.3 Node couplings

In a TMM, the divided nodes must be properly connected to one another. There are three forms of node couplings: conductive coupling, radiative coupling, and contact coupling. Here, we limit “conductive coupling” to mean heat conduction within the same material, and use the term “contact coupling” to mean that between two materials across a certain interface (e.g., a simple contact, glue, adhesive tapes, etc). This is because contact thermal resistance can be major obstacles of heat transport under the absence of convection.

The conductive coupling between a pair of nodes is calculated as,

$$K = \frac{A}{d} \times \kappa, \quad (5.1)$$

where $A$ is contact area, $d$ is separation between them, and $\kappa$ is conductivity of a material of the component.

The wattage transferred by radiation from one node with a temperature $T + \Delta T$ to another with a temperature $T$, is calculated as,

$$E = \epsilon_1 \epsilon_2 \sigma A ((T + \Delta T)^4 - T^4) \times \Omega/2\pi \quad (5.2)$$

$$\sim 4 \epsilon \sigma A T^3 \Delta T \times \Omega/2\pi, \quad (5.3)$$
where $A$ is area on a surface of radiating node, $\Omega$ is a solid angle viewing the surface, $\epsilon_1, \epsilon_2$ are emissivities of the radiating node and receiving nodes. $\Delta T \ll T$ is assumed, in the transformation of this equation.

Between a pair of nodes which are in contact with each other, a contact resistance appears, and becomes the dominant coupling between them; so in constructing a TMM, these contact resistances must be assumed. The way of estimating them is explained in the next subsection.

### 5.2.4 Assumption on screw-contact conductances

The present TMM involves two types of contact conductances. One is between a graphite sheet and a copper pole, and the other is between metals. These two types of contact conductances are considered to be both related to sizes of screws which fix the two surfaces together.

Table 5.1 shows empirical contact conductances, from two literatures ([3],[4]), between two aluminum plates with clean mill rolled surface finish, bolted together with a screw using standard torque for spacecrafts. It is assumed that heat flows from one plate to the other through a compressed area around the screw, rather than through the screw itself.

The values in Table 5.1 are visualized in figure 5.3. Thus, the contact conductance increases with the screw diameter, because a larger area is pressed together with larger force. We can also see that thicker plates give higher conductances. However, the two literatures are inconsistent with each other, one reporting rather linear dependences on the screw diameter, whereas the other parabolic relations.

In constructing our TMM, we adopt a parabolic dependence as,

$$K = 0.05 \times (0.4 \times D)^2 \text{ (W/K)},$$

where $D$ is the diameter of screw in mm. This relation is utilized in thermal designs in industries, and corresponds nearly to the worst case in figure 5.3. Table 5.2 shows the contact conductance values as a function of $D$, calculated by eq.(5.4). We start constructing our TMM using tentatively these values at every contact point, even though it is not clear if they are applicable to graphite sheets.

### 5.2.5 An equivalent thermal circuit

Figure 5.4 shows a thermal equivalent circuit of the one-side Compton Camera. For simplicity, we ignore low-conductive connections that are parallel to highly-conductive ones.

Let us show a few examples of conductive coupling calculations. Trays, which are made of PBI, have 0.41 W/m/K conductivities, so the tray conductance from semi-conductor device to the graphite sheet with $A \sim 7 \text{ mm} \times 1 \text{ mm}$ and $d \sim 3 \text{ mm}$, is calculate from eq.(5.1) as

$$K = \frac{7 \text{ (mm)} \times 1 \text{ (mm)}}{3 \text{ (mm)}} \times 0.00041 \text{ (W/mm/K)} = 0.001 \text{ (W/K)}.$$  

(5.5)
Table 5.1: Contact conductances between two aluminum plates bolted together with a screw, measured for different plate thicknesses and bolt diameters (Spacecraft Thermal Control Handbook, P266, Table 8.6). TRW and LM specify reports employed.

<table>
<thead>
<tr>
<th>Diam (mm)</th>
<th>TRW Large Thin Surface</th>
<th>LM Plate Thickness (mm)</th>
<th>TRW Small Stiff Surfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>0.13</td>
<td>0.08</td>
<td>-</td>
</tr>
<tr>
<td>3.5</td>
<td>0.18</td>
<td>0.15</td>
<td>0.45</td>
</tr>
<tr>
<td>4.2</td>
<td>0.26</td>
<td>0.22</td>
<td>0.67</td>
</tr>
<tr>
<td>4.8</td>
<td>0.53</td>
<td>0.33</td>
<td>1.00</td>
</tr>
<tr>
<td>6.4</td>
<td>1.05</td>
<td>0.48</td>
<td>1.43</td>
</tr>
<tr>
<td>7.9</td>
<td>-</td>
<td>0.67</td>
<td>2.00</td>
</tr>
<tr>
<td>9.5</td>
<td>-</td>
<td>-</td>
<td>2.5</td>
</tr>
<tr>
<td>11.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.2: Values of assumed contact conductance

<table>
<thead>
<tr>
<th>Screw Diameter (mm)</th>
<th>Contact conductance (W/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>0.128</td>
</tr>
<tr>
<td>3</td>
<td>0.072</td>
</tr>
<tr>
<td>2</td>
<td>0.032</td>
</tr>
<tr>
<td>1.4</td>
<td>0.01568</td>
</tr>
</tbody>
</table>

On the other hand, conductance of the aluminum wire bondings (ϕ 50 μm × 64) is calculated as,

\[
K = \frac{0.05 \text{ (mm)} \times 0.05 \text{ (mm)} \times \pi \times 64}{3 \text{ (mm)}} \times 0.237 \text{ (W/mm/K)} = 0.04 \text{ (W/K)},
\]

which is 40 times larger than the conductances of trays. We therefore neglect the former.

Assuming ε₁ ~ ε₂ ~ 1 and \(T_0\sim-15^\circ\text{C}\). we obtain the \(E/\Delta T\) to the next layers from eq.(5.3) as

\[
E/\Delta T \sim 4.0 \times 5.7 \times 10^{-14} \times 600 \times 258^3 \sim 0.0024 \text{ W/K},
\]

where \(A \sim 600 \text{ mm}^2\), and \(\Omega \sim 2\pi\). The temperature difference between a pair of adjacent layers is less than 0.5°C, so the radiated heat is 0.0012, which is ~5% of the heat generated by ASIC. For these reasons, hereafter, we ignore the conduction of trays and the radiative coupling between a pair of adjacent layers.
Figure 5.3: Relations between the screw diameter and the contact conductance per screw in various cases ([3], [4]). The aluminum plate thickness is specified by colors. The purple line represents eq.(5.4).

5.3 Temperature Distribution Simulated By TD

In Chapter 4, we suggested that copper poles and graphite sheets are needed to enhance the vertical heat paths in the Compton Camera. In order to examine whether this concept is successful, we use the TMM family constructed in §5.2 to calculate the temperature distribution within the Compton Camera. After a brief evaluation of lateral heat transport in §5.3.2, we begin with the case of only a copper pole (§5.3.2), the adding an aluminum shield plate (§5.3.3), and finally incorporating a bottom aluminum frame. The results are shown as the color contour related with temperatures.

5.3.1 Graphite sheet connection to the copper pole

Between an ASIC and the proposed graphite sheet, there is a Front End Card (FEC) which four electrode layers separated by three glass epoxy layers. The FEC has 35 (just under ASIC) + 80 through holes, made of copper, which directly connects the top and bottom electrode planes, also made of copper. The 35 through holes just below the ASIC individually have a diameter of 0.2 mm, a well thickness of 0.05 mm, and a length of 0.4 mm. We can calculate total heat conductance $K_{T,H}$ as

$$K_{T,H} = 35 \times \frac{0.2 \text{ (mm)} \times \pi \times 0.05 \text{ (mm)}}{0.4 \text{ (mm)}} \times 0.391 \text{ (W/mm/K)} = 1.1 \text{ (W/K)}$$

(5.8)

from eq. (5.1). Compared to this, conduction through the bulk of FEC (glass epoxy with $K = 0.08 \text{ W/K}$) is negligibly small. The thermal coupling between ASIC and the top electrode plane,
and between the bottom electrode plane and the graphite sheet, are both achieved by double-faced tapes. The tape is assumed to have a conductivity 0.0002 W/mm/K. We assume the contact area to be 50 mm² between the ASIC and the top electrode plane, that to be 250 mm² between the bottom electrode plane and the graphite sheet, and the thickness of the tape to be 100 μm. Combing these conductances (i.e., summing up the corresponding thermal resistance), the overall conductance between ASIC and the graphite sheet is calculated to be 0.15 W/K. Beneath FEC, graphite sheet, which has a conductance of 0.047 W/K, is laid.

Because the copper pole cannot be thicker than 4 × 20 mm² (due to space limitation), we tentatively connect the graphite sheet to the copper pole by M1.4 screws, the smallest ones that are usually available. This means a contact conductance to be 0.016 W/K, according to table 5.2. With these assumptions, we calculated, with TD, the temperature distribution from ASIC to the connection point to the copper pole. In this calculation, as a boundary condition, the contact point on the copper pole is fixed to be 0°C. Figure 5.5 shows the result, and the color contours represents ΔT from the copper pole. The semi-conductor device takes the same temperature as the
heat input points on the graphite sheets, because the semi-conductor is connected to nowhere else. Thus, the temperature difference between the ASIC-side and the copper-pole-side on the graphite sheet is 1.3°C, showing that the graphite sheet is very effective. However, the temperature drops across the contact point with the copper pole is 2.7°C, which is significant when compared to the total temperature difference between the Si semi-conductor device and the copper pole, 4°C. The contact conductance by a M 1.4 screw, between the graphite sheet and the copper pole, is too small.

![Figure 5.5: The temperature distribution in color scale in the Si semi-conductor device and the graphite sheet. in the case of a M1.4 screw contact between a graphite sheet and the copper pole not shown. The 0.021 W heat from an ASIC is input to the Si semi-conductor device end of each graphite sheet. The base temperature is fixed at 0°C, and only one layer of tray is considered. Since tray has a Si device and an ASIC on its either side, the model involves two graphite sheets, although only one of the two Si devices are shown for simplicity.](image)

To make the lateral heat paths more efficient, let us consider an alternative case wherein we use the a double-faced tape which has a conductivity of 0.2 W/m/K, and it has an area of 3 (mm)\times10\ (mm)=30\ (mm^{2}), and a thickness of 0.1 mm. Then, the contact conductance there is calculated as

$$K = \frac{3\ (\text{mm}) \times 8\ (\text{mm})}{0.1\ (\text{mm})} \times 0.0002\ (\text{W/mm/K}) = 0.05\ (\text{W/K}).$$

(5.9)

from eq.(5.1) The result of this calculation is shown in fig 5.6. Because each of ASICs generate 0.042 W, the temperature difference becomes 0.8°C at the contact point, between the graphite
sheet and the copper pole. Thanks to this new design, the temperature difference between the top Si semi-conductor device and the copper pole is 2°C, which is nearly half as large as before. From here, the TMM utilizes the tapes to fix the graphite sheet,

![Graphite Sheet Attached](image)

Figure 5.6: The same as figure 5.5, but the graphite sheet is attached to the copper pole using a double-faced tape with a high thermal conductivity.

### 5.3.2 Case1: only a copper pole

In §5.3.1, we focused on the lateral thermal conduction. Hereafter, the vertical one is examined. Here the temperature distribution was calculated in the case of using only a copper pole as the vertical main heat path. First, only a M5 screw was utilized to connect the copper pole to the aluminum cold plate. The result of a TD simulation, performed with this condition together with the lateral path considered in §5.3.1, is shown in figure 5.7. The result is displayed with color contours related to temperatures. Because the figure becomes hard to see if all layers are included, we showed only the top layer, but included all heat which all layer generate. The temperature of the top part of the copper pole became −13.4°C, while that of the bottom part −15.8°C. Their temperature difference is thus 2.4°C. Because the contact conductance between the copper pole and the aluminum cold plate was assumed to be 0.2 W/K (Table 5.2), a large temperature difference of 4.2°C is needed to conduct the total 0.84 W heat. Due to this offset, the temperature of the Si semi-conductor device becomes −11.2°C, and the thermal requirement is not fulfilled.

Then, we added another M5 screw to the contact point between the copper pole and the aluminum cold plate; there are now two M5 screws at that point, and the contact conductance
Figure 5.7: The temperature distribution in the top Si semi-conductor, the graphite sheet, and the copper pole. The graphite sheet is connected to the copper pole by a double-faced tape, and the copper pole is connected to the aluminum cold plate by a M5 screw. A 0.021 W of heat is to each graphite sheet of every layer. The base temperature which is the temperature of the aluminum cold plate is fixed at $-20^\circ$C. Although the model incorporates 20 trays, only the top one is shown for clarity.

there is doubled to, 0.4 W/K. The simulation result of this case is shown in figure 5.8. Thus, the temperature gradient along the copper pole is the same as before, namely 2.2$^\circ$C, the temperature drop from the copper pole to the aluminum cold plate was halved, to became 2.2$^\circ$C. Therefore, the temperature of the top Si device becomes $-13.4^\circ$C, which is 2.2$^\circ$C lower than the former case. Hereafter, we call this design “Case 1”.

Although this design does not yet meet the thermal requirement, the number of screws between the copper pole and the aluminum cold plate cannot be increased, because of the space limitation. Therefore, we must improve the vertical bulk heat paths, for example, by increasing thickness of the copper pole. Due to similar space limitation, it is not feasible to make the copper pole thicker than this, either.

5.3.3 Case 2: a copper pole and an aluminum shield plate

To enhance the vertical heat flow, let us consider using the aluminum electro-magnetic side shield plate as an additional heat path. As shown in figure 4.2, each of the four side shield plates has a thickness of 2 mm, a breadth of 120 mm, a length of 120 mm, and a conductivity of 138 W/m/K.
Thanks to this large cross section and the high thermal conductivity of aluminum (A5052), one shield plate has an almost same thermal conductance as that of a copper pole. However, in their originated design, they were not connected thermally to the trays. We hence consider connecting the copper pole to the shield plate tightly, using thirteen M2 screws, and connect the shield plate to the aluminum cold plate using three M3 screws. The number of these screws are maximized considering the space available for them.

We modified the TMM including these changes, and re-calculated the temperature distribution of the Compton Camera. The result is shown in figure 5.9. Thus, the temperature gradient along the copper pole has decreased to 1.2°C, while that between the top and bottom part of the aluminum shield is 0.4°C. Since the former is nearly halved from the previous Case 1, the copper pole and the aluminum shield plate are estimated to have comparable contributions to the vertical heat flow, with the M2 screws working efficiently. Thanks to this additional heat path, the temperature difference between the copper pole and the aluminum cold plate became 1.4°C, about two thirds of Case 1. The temperature of the top Si device becomes −15.0°C, which is by 1.6°C lower than Case 1. This satisfies the thermal requirement of the Compton Camera, so including the aluminum shield as a vertical bulk heat path is considered to be very efficient. Hereafter, we call this design “Case 2”.

Figure 5.8: The same as figure 5.7, but a M5 screw is added between the copper pole and the aluminum cold plate.
Figure 5.9: The same as figure 5.8, but the 2 mm-thick aluminum side plate is added.

5.3.4 Case 3: Inclusion of side CdTe detectors

Although the TMM based on the above Case 2 design meets the thermal requirements, this is not enough for the whole thermal design of the Compton Camera. This is because on each side, side CdTe devices are placed, and 48 ASICs which generate total 1.08 W heat (or 0.252 W per side) are placed there to read signals. Their heat must be included into our TMM.

The heat from ASICs for the side CdTe devices can be transported directly to the bottom frame, which is placed under lowermost tray. For this purpose, we connect the aluminum bottom frame to the cold plate by two M5 screws. Hereafter, this version of TMM is called Case 3.

Figure 5.10 shows the TMM results for Case 3, and figure 5.11 shows more detailed temperatures at some points of the one-side Compton Camera. The temperature distribution has been somewhat improved from Case 2. This is because the bottom frame has a large cross-section area, and it is tightly connected to the cold plate by a M5 screw. Therefore, it can conduct not only the heat from the side CdTe ASICs, but some fraction of the heat from the 40 trays.

Thus, we have achieved a thermal design which fulfills the thermal requirements. This design, namely Case 3, incorporates a graphite sheet per tray, a copper pole per side, an aluminum electromagnetic shield plate per side, and an aluminum bottom frame. The temperatures of all layers can be less than $-15^\circ$C. However, it must be kept in mind that the results obtained here depend strongly on the assumed contact conductances among some nodes of the TMM. We summarize these assumptions in figure 5.11 (b), as a help to Chapter 6 where verification experiments are
Figure 5.10: The same as figure 5.9, but the aluminum bottom frame is added. The 0.252 W heat which is generated by the side CdTe ASICs is input to this frame.

carried out.
Figure 5.11: Temperature (green boxes) at some points calculated by our TMM for Case 3.
Chapter 6

VERIFICATION EXPERIMENTS

The verification experiment is divided into two parts, which utilize different thermal dummies of the Compton Camera. One is meant for measurements of the contact conductance between a graphite sheet and a copper pole, using a simple thermal dummy. The other is for measurements of the vertical heat conductance, using a more faithful one.

6.1 Setup of Thermal Experiments

![A photograph of a vacuum chamber in our laboratory (Upper Right).](image)

Figure 6.1: A photograph of a vacuum chamber in our laboratory (Upper Right).

6.1.1 Vacuum chamber

To eliminate the effects of convection, the present experiment must be carried out in vacuum with a pressure less than $10^{-3}$ Torr. For this purpose, we utilize a general-purpose vacuum chamber in our laboratory. As shown in figure 6.2, the chamber is made of stainless steel, having a cylindrical shape.
of 240 mm (diameter) \times 250 mm (height). As illustrated in figure 6.2, it is evacuated to $10^{-5}$ Torr by a turbo-molecular pump (50 l/sec), backed up with a rotary pump (100 l/min). The chamber pressure is measured with a Pirani gauge and an ionization vacuum gauge. The temperature of the chamber is almost the same as that of our experiment room, $\sim 25^\circ C$.

6.1.2 Heaters and thermometers

To supply heat input to a thermal dummy, 100 $\Omega$ flat-package resistors are used as heaters, because they are easily attached to surfaces of the thermal dummy. A constant voltage of 8.9 V is applied to each resistor to generate a heat of 0.8 W, which is the same value as the heat generated by all the ASICs in the one-side Compton Camera. By monitoring the current, and examining whether it is constant at 89 mA, we can confirm if the exact power is provided.

To measure temperatures at various points on the thermal dummy, Pt resistance thermometers are used. Their resistances depend on the temperature as

$$R_{Pt} (\Omega) = 100 + 0.38T,$$

where $T$ is the temperature in $^\circ$C. Therefore, the temperature is known from the resistance. To measure the resistance of each thermometer, we form a bridge circuit shown in figure 6.3, apply a constant voltage of 0.50 V (not to heat up the thermometer), and read the voltage difference of the bridge using a differential amplifier with a voltage gain of $1.5 \text{ M}\Omega / 10 \text{ k}\Omega = 150$. The temperature is expressed by the output voltage $V_{out}$ of the amplifier as
\[ T \ (K) = \left[ \frac{250 + V_{\text{out}}/150}{(250 - V_{\text{out}}/150)/100} - 100 \right]/0.38. \] (6.2)

When attaching these heaters and thermometers on a thermal dummy, a double-faced adhesive tapes, which have high thermal conductivity of \( \sim 5 \text{ W/m/K} \), are used.

Figure 6.3: A differential circuit to measure the resistance of a Pt thermometer. This circuit amplifies by 150 times, the voltage drop across at the Pt resistor.

6.1.3 Readout system

Figure 6.4 shows the read out system for our experiments. The heaters and Pt thermometers are attached to a thermal dummy in the vacuum chamber, and their power of the heaters or signal lines are led out of the chamber using vacuum feed throughs, installed on two vacuum flanges. The power lines of the heaters are connected to a common DC power supply, while the signal lines to a circuit box in which signals are differential amplified (§6.1.2), and multiplexed. Those analog signals are AD converted and recorded in digital scope DL708E which has a resolution of 12 bits (a voltage resolution of 2 mV for an employed voltage range of 8 V), and the digital signals are recorded by a PC. The output voltages are converted to temperatures using eq.(6.2).

Before starting experiments, we carried out calibrations of 16 thermometers. They were set onto a piece of 1 mm thick aluminum plate, which has a unified temperature all over, and recorded output voltages of individual thermometers over 1000 samples. By changing the plate temperature from \(-20^\circ\text{C}\) to \(20^\circ\text{C}\) with a step of \(5^\circ\text{C}\), we repeated the measurements, and fitted the outputs from each thermometer with a linear function of the temperature. As a result, After this calibration, these thermometers were confirmed to have an accuracy of \(0.2^\circ\text{C}\), in terms of standard deviation around the linear fit.
6.2 Thermal Dummies

In our verification experiments, two thermal dummies are utilized. One of them is a simplified in-house version, consisting of a piece of graphite sheet, a copper pole, and an aluminum heat sink. Its photograph is shown in figure 6.5. The heat sink has a size of 120 mm$\times$120 mm$\times$50 mm, to which the copper pole is connected by a M5 screw torqued at 29.4 kg\cdot f\cdot cm (a standard for satellite-borne instruments). This simple thermal model is utilized for measurements of the contact conductance between the graphite sheet and the copper pole.

The other, shown in figure 6.6, is a more faithful thermal dummy, which consists of four copper poles, a 2 mm thick aluminum electro-magnetic shield box, an aluminum bottom frame, an aluminum cold plate, and an aluminum heat sink. The sizes of these components are given in caption of figure 6.6. These parts are strictly the same in shape as the actual Compton Camera, except that the legs of the cold plate are 50 mm shorter than those of the actual Compton Camera, due to limited size of the vacuum chamber (§6.1.1). In order to emulate the Case 2 TMM (§5.3.3), each copper pole is connected to a side of the aluminum shield wall by thirteen M2 screws, and connected to the aluminum cold plate by two M5 screws. The bottom frame is connected to the four sides of the aluminum shield wall by four M3 screws (one screw per side), individually, and connected to the cold plate by eight M5 screws altogether. The aluminum shield is connected to the cold plate by three M3 screws per side. Finally, the cold plate is connected to the aluminum heat sink at two sides by ten M5 screws each. These screw settings are visualized in figure 6.10. This strict thermal model is utilized for verification of the contact conductances by screws.
6.3 Measurement of Conductance between Graphite Sheet and Copper Pole

6.3.1 Purpose of the experiment

In the TMM for the Compton Camera, the lateral conduction is realized by graphite sheets, which are connected to the four copper poles. However, the contact conductance between these graphite sheets and the copper poles is subject to large uncertainties (§5.3.1), and our assumptions employed in constructing the TMM must be calibrated experimentally. In addition, graphite sheets generally have highly anisotropic conductivity, which depends on how they are fabricated. Therefore, it is also important to verify that the particular type of graphite sheet, employed here, can perform as expected from their catalogued specifications.

6.3.2 Experimental setup

In this experiment, the simple thermal dummy (§6.2) is utilized, in a configuration shown in figure 6.7. The graphite sheet has a width of 20 mm, a length of 30 mm, a thickness of 100 μm, and a
Figure 6.6: Top-view (left) and side-view (right) photographs of the more faithful thermal model of the Compton Camera, which has four copper poles, an aluminum electro-magnetic shield wall, an aluminum bottom frame, an aluminum cold plate, and an aluminum heat sink. The pole has a size of $\sim 3 \text{ mm} \times 20 \text{ mm} \times 120 \text{ mm}$, the shield has a size of $2 \text{ mm} \times 120 \text{ mm} \times 120 \text{ mm}$ per side, the bottom frame has almost the same size as the tray except for its thickness of 35 mm, the cold plate is 5mm-thick, and the heat sink is $120 \times 240 \times 50 \text{ mm}^3$ in size.

conductivity of 700 W/m/K (catalog specification) along its plane. We attached a 100 $\Omega$ resistor (heater) onto one end of the graphite sheet, fix its opposite end to the copper pole with a 50 $\mu$m thick double-faced adhesive tape, with an area of $10 \text{ mm} \times 20 \text{ mm}$, and set seven thermometers at positions indicated in figure 6.7.

After setting the heater and the thermometers, the setup is put into the vacuum chamber, which is evacuated to a pressure less than $10^{-3}$ torr. Then, the 8.9 V voltage is applied to the resistor, as described in §6.1.3. As also described therein, we record the voltages every 4 sec with a resolution of 2 mV.

Through this measurement, using eq.(2.6), the heat flow, which runs from the graphite sheet to the copper pole, can be calculated as

$$\dot{Q} = K_{Cu} \times \Delta T_{Cu},$$

(6.3)

where $K_{Cu} = 0.23 \text{ W/K}$ is the conductance of the copper pole, and $\Delta T_{Cu}$ is its vertical temperature difference as read from thermometers 5 and 7. We can then calculate the contact conductance $K$ between the graphite sheet and the copper pole as

$$K = \frac{\dot{Q}}{\Delta T},$$

(6.4)

where $\Delta T$ is the temperature difference between the graphite sheet and the copper pole.
In the present experiment, radiative heat flow out of the graphite sheet may not be negligible. In fact, assuming the graphite to be a perfect radiator ($\epsilon = 1$) which couples to a black body heat bath, and assuming a small temperature difference, its radiative conductance is estimated as

$$K^R \sim 4\sigma T_0^3 A \sim 0.006 \text{ (W/K)}$$  (6.5)

where $A = 1000 \text{ mm}^2$ is the unobscured graphite surface area (on both sides), and $T_0 \sim 300 \text{ K}$ is the ambient temperature (eq. (5.3)). Although this value is not necessarily negligible compared to $K_{Cu}$ and $K$, eq.(6.3) and eq.(6.4) are considered to be still valid, because $\dot{Q}$ is the conductive heat flow along the pole rather than the heater power itself, and because radiative loss from the copper pole should be much lower because of its low emissivity.

### 6.3.3 Results

Figure 6.8 (left) shows variations of the temperatures, measured with the 7 thermometers (figure 6.7), while the right shows variations of the temperature differences with respect to the heat sink (#8). The heater is turned on at 0 sec, and then all the temperatures increase steeply for about $\sim 200$ seconds, which is consistent with the heat capacity of the copper pole of $27 \text{ J/K}$. Afterwards, the temperatures start saturating, and the temperature differences among the 7 thermometers
Figure 6.8: (left) Time variations of the temperatures measured by the thermometers indicated in figure 6.7. Red plots (#1) shows the temperature of the heater point, and black shows that of the aluminum heat sink (#8). Green (#3), and blue (#4) are on the graphite sheet, while magenta (#5), cyan (#6), and yellow (#7) are on the copper pole. (right) variations of the temperature in the form of differences from that of the heat sink (#8).

Table 6.1: Temperature difference from the thermometer #8 in figure 6.8.

<table>
<thead>
<tr>
<th>Thermometer number</th>
<th>$\Delta T$ (°C) from #8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19.6</td>
</tr>
<tr>
<td>3</td>
<td>8.5</td>
</tr>
<tr>
<td>4</td>
<td>4.0</td>
</tr>
<tr>
<td>5</td>
<td>2.4</td>
</tr>
<tr>
<td>6</td>
<td>1.2</td>
</tr>
<tr>
<td>7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

become approximately constant, as shown in figure 6.8 right.

We fitted the data of each thermometer with a straight line, $f_n(t) = a_n t + b_n$ ($n = 1, 3, \cdots, 7$ is number of the thermometers), between 3500 sec and 4500 sec. As a result, $a_n$ were all found to be identical within 90% errors, so we employed $f_n(4500)$ as the temperature differences. In table 6.1, we show the temperature differences between the heat sink and the others. The temperature drop between the top and the bottom parts of the copper pole is 2.4°C, so eq. (6.3), yields $\dot{Q} = 0.54$ W. This, together with the measured $\Delta T = 1.6$°C across the contact point between the graphite sheet and the copper pole,

$$K = 0.34 \text{ (W/K).}$$

(6.6)

The temperature difference between the positions of thermometers #1 and #3 is 11.1°C, so we can calculate the conductance of the graphite sheet as
\[ K_{G.S.} = 0.050 \, (W/K), \quad (6.7) \]

also by using eq.(6.4).

### 6.3.4 Implications of the results

In this experiment, the contact area between the graphite sheet and the copper pole was 200 mm\(^2\), while that in the actual Compton Camera is 24 mm\(^2\). Therefore, the actual contact conductance between the graphite sheet and the copper pole is calculated from eq.(6.6) as,

\[
K = \frac{24 \, (\text{mm}^2)}{200 \, (\text{mm}^2)} \times 0.34 \, (W/K) = 0.041 \, (W/K).
\quad (6.8)
\]

This value is 80\% of value, 0.05 W/K, which we estimated in §5.3.1.

The measured conductance of the graphite sheet is 30\% lower than the specification value of 0.070 W/K. However, this is probably due to radiative heat loss from the graphite. In fact, the heat flow along the pole, \(\dot{Q} = 0.54\, W\), is lower by \(\sim 30\%\) from the applied heat input, 0.80 W. The difference, \(\sim 0.2\, W\), can be attributed to radiation, approximately because eq.(6.5) predicts \(E \sim 0.12\, W\) for \(\Delta T = 20^\circ C\).

![Figure 6.9: TD reproduction of the present experiment, including the effect of radiation. See text for the condition of simulation.](image)

To reproduce the measurement considering radiation from the surface of the dummy, we carried out a TD calculation including radiation. The contact conductance between the graphite sheet and
the copper pole is 0.34 W/K, as obtained in §6.3.4. The boundary temperature at the bottom part of the copper pole is set 22°C, and that of the vacuum chamber 20°C. The emissivity of copper pole was assumed to be 0.05, while that of graphite sheet to be 1.0. Figure 6.9 shows the result. The calculated temperature distribution well reproduces our experimental result, and the temperature difference between the top and the bottom parts of the copper pole is 2.6°C. The calculated heat flow in the copper pole is 0.6 W, so rest 0.2 W (~ 30% of all) is radiated.

6.4 Verification of Screw Contact Conductance

In order to measure contact conductances due to screws, we performed an experiment, which is similar to that in §6.4, but using the faithful dummy.

6.4.1 Experimental setup

![Figure 6.10: A 3D CAD picture of the more faithful thermal dummy of the Compton Camera. The positions of the heaters are shown by red circles, and those of the thermometers by numbers.](image)

In the present experiment, the more faithful thermal model of the Compton Camera (§6.2) is used. As shown in figure 6.10, four heaters were attached directly to the top of the four copper poles, and 7 thermometers were arranged on one side of the dummy; #1 (heater point), #6, and #7 are on the pole; #3, #4, #5 are on the aluminum shield wall; #8 on the cold plate. The rest
of the experiment is the same as performed in §6.3.

### 6.4.2 A result of the experiment

![Figure 6.11](image)

Figure 6.11: (left) Variations of the temperatures of the faithful dummy, measured by the thermometers indicated in figure 6.10. Red (#1) shows the temperature of the heater point, and black (#8) that of the cold plate. Green (#3), blue (#4) and purple (#5) are on the aluminum shield wall, while cyan (#6) and yellow (#7) are on the copper pole. (right) Temperature differences from the cold plate (#8).

<table>
<thead>
<tr>
<th>Thermometer number</th>
<th>$\Delta T(^{\circ}\text{C})$ from #8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1.9 - 2.4$ (our best estimation 2.1)</td>
</tr>
<tr>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
</tr>
<tr>
<td>6</td>
<td>0.7</td>
</tr>
<tr>
<td>7</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 6.2: Temperature difference from thermometer #8 in figure 6.11.

Figure 6.11 left shows variations of the 7 temperatures of figure 6.10. The temperatures behave in a similar manner to figure 6.8, except that the gradual increase (after $\sim 500$ sec) is steeper because 4 heaters, instead of one, were used.

The temperature of the thermometer #7 (yellow) does not become parallel to the others until $\sim 4000$ sec, because the cold plate touches the heat sink directly, and its temperature variation is influenced by that of the heat sink which has a large heat capacity of $\sim 3800$ J/K. Applying a linear fit to these data traces over $t = 5000 - 6000$ sec, just as we did in §6.3.3, we determined the temperatures at $t = 6000$ sec. In table 6.2, we summarize the temperature differences between the cold plate (#8) and the others.

The temperature of the thermometer #1 (red) increases in parallel to the others (except for
until 2000 sec. However, between 2000 sec and 6000 sec, its slope became \( \sim 10\% \) smaller than those of the others, and \( f_1(6000) - f_8(6000) = 1.9^\circ \text{C} \) is considered to be underestimated. Actually, when we perform the fitting over 1000 – 2000 sec, the result became \( f_1(6000) - f_8(6000) = 2.4^\circ \text{C} \), which would be an overestimation. Therefore, we decided to use \#3 as a relay point; fitting over 1000 – 2000 sec gives \( f_1(2000) - f_3(2000) = 1.2^\circ \text{C} \). Adding it to the that between \#3 and \#8 in a range of 5000 sec and 6000 sec, i.e., \( f_3(6000) - f_8(6000) = 0.9^\circ \text{C} \) (table 2), we obtain the more reasonable value of 2.1^\circ \text{C} (the value in brackets in table 6.2). This value is utilized to estimate the contact conductances in next subsection.

6.4.3 Implications of the results

we constructed another TMM which simulate the faithful dummy, and calculated the temperature distributions as we change the screw-contact conductances. Comparing the experimental results with the simulations, we can find the best estimates of the contact conductances.

![Figure 6.12: A TD-calculated temperature distribution of the faithful dummy, when we put 0.8 W heat into a top of the copper pole. This is based on a TMM meant to reproduce the faithful dummy (§6.4.2).](image)

Figure 6.12 shows the temperature distribution simulated by our new TMM (§6.4.2), when the contact conductances are the same as our assumption in §5.2. It shows that the temperature difference between the top of the copper pole and the cold plate is 3.7^\circ \text{C}, and which is higher than the experimental value, 2.1^\circ \text{C}. This means that we over-estimated the contact conductances.
Figure 6.13: The simulated relation between the contact conductances and the temperatures on the more faithful dummy. The unit of the horizontal axis is the screw contact conductance, expressed in its ratio to the value assumed in eq. (5.4).

We repeated the TD calculation by changing the contact conductances, and show in figure 6.13 the predicted temperatures as a function of the contact conductances. Comparing the experimental results (table 6.2) with the results of the sensitivity analysis (figure 6.13), we find that the actual screw contact conductances should be ∼4 times larger than the worst case of eq.(5.4) which we assumed in the TMM in §5.2.4. This factor 4 difference appears reasonable from figure 5.3, where the other estimates are larger by a factor of 1.5 to 10 than eq.(5.4).

However, all of the experimental temperatures of aluminum shield well are smaller than estimated ones by 0.2°C. This is considered to be because the large area not pressed by screws are contact to the cold plate, and heat is conducted there.

6.5 Calibration of TMM

In §6.4, the contact conductance between the graphite sheet and the copper pole is confirmed to be 0.04 W/K. On the other hand, the actual contact conductances by screws are estimated to be four times larger than our assumption, eq.(5.4). Including these actual measurement values into the TMM, the temperature distribution in the actual Compton Camera was re-calculated. Figure 6.14 shows the result of the calculation, using this “calibrated” TMM. We confirm that the temperature of the top Si semi-conductor is −16.0°C, which fulfills the thermal requirements. Figure 6.15 summarizes the predictions of the calibrated TMM.

Although our experiment indicated a significantly better contact conductance for screws, the
result in table 6.2 is obviously subject to systematic errors. If, e., we take $\Delta T = 2.4^\circ \text{C}$ between #1 and #8, the implied contact conductance is only twice larger than eq.(5.4). Therefore, we represented the TMM calculation, and formed that the top semi-conductor becomes $-15.5^\circ \text{C}$. Therefore, our conclusion remains unaffected by these systematic errors.

Figure 6.14: A temperature distribution calculated by the calibrated TMM. In this model, the contact conductance between the graphite sheet and the copper pole is 0.05 W/K, and the contact conductances by screws are four times larger than our original assumption.
Figure 6.15: The same as figure 5.11, but using the calibrated TMM.
Chapter 7

CONCLUSION

In the present thesis, we developed, both numerically and experimentally, the thermal design of the Compton Cameras, which work as the main detectors of the Soft Gamma-ray Detector onboard ASTRO-H. Our main objective is how to reduce the anticipated vertical temperature gradient, and hence to make the temperature of the Compton Camera lower than $-15^\circ$C from top to bottom.

We suggested to put graphite sheets under every ASIC to distance heat from semi-conductor devices in lateral direction, and four copper poles which go through all layers and carry heat generated at them to the cold plate in vertical direction. In addition, an electro-magnetic shield wall and a bottom frame can also be utilized as effective heat paths.

To verify the effects of these new heat paths, we constructed a thermal mathematical model (TMM), and calculated the temperature distributions in the Compton Camera. In this calculation, we assumed the thermal contact conductances at all contact points, related with the sizes of screws and a double faced tape which are utilized there. As a result, the new thermal components were found to fulfill the thermal requirements. However, the TMM has systematic errors arising from uncertainties in the assumed the thermal contact conductances.

We prepared two thermal dummies; one is to verify the thermal contact conductance between the graphite sheet and the copper pole, by double faced tape, and the other is to verify those between metals, by screws. Then, we carried out the verification experiments in a vacuum chamber. As a result, the contact conductance by double faced tape, was confirmed to be almost the same as our assumption. Those by screws, were estimated to be four times as large as our assumptions.

Utilizing these contact conductance values obtained in the experiments, we calibrated TMM, and re-calculated the temperature distribution of the actual Compton Camera. As a result, we succeeded in keeping the temperatures of the all layers between $-16^\circ$C and $-20^\circ$C. Therefore, our thermal design of the Compton Camera including the new heat paths which we suggested are verified to fulfill the thermal requirements.
Bibliography


I would like to express my thank all the people who have supported my graduate student life. Especially, I am grateful to the Professor Makishima to his supports and advices to my study. Without his help, I could not complete this theses. Hereafter, I hope to learn more about astrophysics and experimental physics from him.

I would like to thank Lecturer Nakazawa who taught me how the satellite-borne instruments are made. Many discussions with him made me interested in designing such instruments.

I would like to give special thanks to my parents, my brothers, my colleagues, my friends, and Ayaka Morita who strongly supported me any time in my graduate school life.