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# Thermal Control of Lunar Exploring Spacecraft "SELENE" (KAGUYA)

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Japanese Lunar explorer SELENE (KAGUYA) was successfully launched on September 14, 2007 (JST). The missions are to investigate the Moon's origin and the evolution, and to observe the Moon in various ways for the future mission. The thermal environment in lunar orbit is more severe than that in Earth orbit due to wider variation in planetary infrared radiation and longer lunar eclipse. The thermal control of SELENE was achieved by using passive and active control techniques. This paper describes the thermal environment in lunar orbit, the thermal control concept, thermal hardware and in orbit thermal performance.

**Key Words:** Lunar explorer, SELENE, KAGUYA, Thermal control, Lunar orbit, Infrared radiation, Lunar eclipse

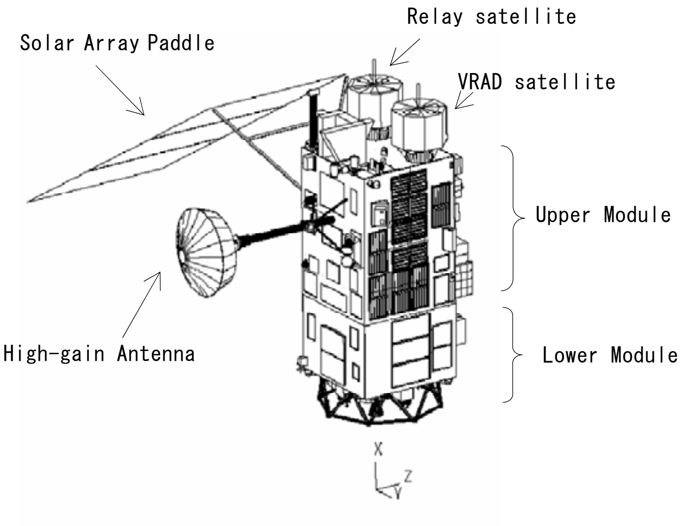
## Nomenclature

| | |
|---|---|
| HCE | : Heater Control Electronics |
| LOV | : Thermal Louver |
| MLI | : Multi Layer Insulation |
| PEI | : Polyetherimide |
| VRAD | : VLBI Radio source |
| UM | : Upper Module |
| LM | : Lower Module |
| LOI | : Lunar Orbit Insertion |
| PCU | : Power Control Unit |
| X-MOD | : X-band Modulator |
| USB-TRP | : Unified S-band Transponder |

## 1. Introduction

SELENE (shown in Figure 1); Japan's lunar explore was successfully launched by H-IIA launch vehicle from Tanegashima Space Center (TNSC) on September 14, 2007. The missions are to investigate the entire Moon in order to obtain information on its elemental and mineralogical composition, its geography, the Moon's origin and the evolution, and to observe the Moon in various ways.

Figure 2 shows the orbit of SELENE schematically from the Earth to the Moon. The first orbit after launch is the phasing orbit for adjustment of time-position at lunar orbit insertion(LOI). At the second perigee, the spacecraft was accelerated to the Moon. On October 3, SELENE reached the Moon and entered to a elliptical polar orbit. On October 18, SELENE reached the nominal observation orbit which is circular and polar orbit with altitude:100 km. On the way to the nominal observation orbit two small satellites Relay satellite (Okina) and VRAD satellite (Ouna) were released into the elliptical orbits of 100 km perilune, and 2400 km and 800 km apolune, respectively. After the checkout of the bus system and the performance test of each instrument, the nominal observation term was started on December 21, 2007.




| SELENE (KAGUYA) Characteristics | |
|---|---|
| Mission | Investigation of entire Moon by using 14 science instruments. |
| Dimensions | 2.1m x 2.1m x 4.8m |
| Mass | 3 tons (include fuel ) |
| Orbit | Altitude : 100 km nominal<br>Inclination : 90 degree |
| Attitude control | Three-axis stabilized (+Z-axis point toward Lunar center) |
| Power | 3.5kW (maximum) |
| Mission period | About 1 year in mission orbit |

Figure 1 Outline of SELENE

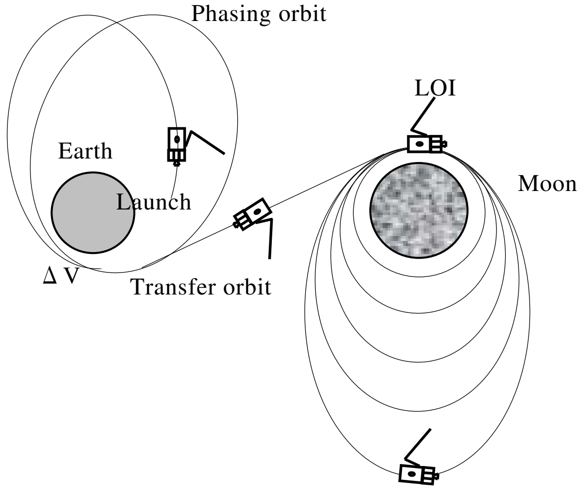



Figure 2 Schematic diagram of the Orbit

## 2. Thermal Environment

From the launch to the end of the mission, the thermal environment is classified into 2 phases. One is the phasing and the transfer orbits, that lasted for approximately 3 weeks. The other is the nominal observation lunar orbit, which continues approximately one year by the end of the mission.

### 2.1. Phasing and Transfer Orbit

During the phasing and the transfer orbit, the only external heat source is the solar heating. In addition, the spacecraft attitude is fixed to the Sun with 45degrees of the sun angle. The sun angle is defined as the angle between the +X axis of the spacecraft and the solar vector, measured from +X-axis toward -Y-axis, as shown in Figure 3.

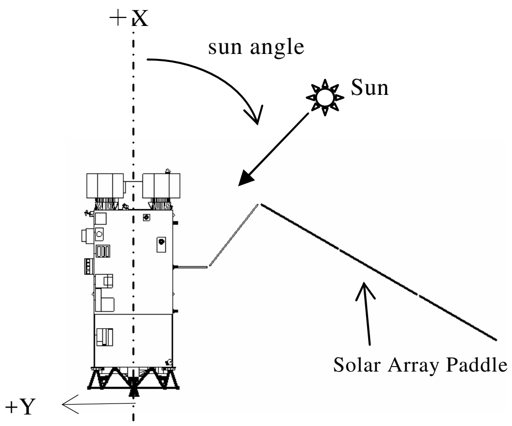



Figure 3 Solar vector in lunar transfer orbit

### 2.2. Lunar orbit

In a lunar orbit, a spacecraft is irradiated by direct sunlight, sunlight reflected of the Moon (albedo), and infrared (IR) energy emitted from the Moon. Due to the lack of the atmosphere and the length of the lunar day, the thermal environment in low lunar orbit is dominated by the planetary infrared. The temperature on the sunlit side of the Moon at the sub-solar point becomes approximately 110 degrees C.[1] Inversely the temperature on the dark side of the Moon becomes about -170 degrees C.[1] Figure 4 shows the lunar surface temperature profile during the lunar day.[3] The spacecraft is therefore exposed to extreme planetary infrared emission above day side. On the other hand, above the night side of the Moon, infrared emission is almost zero. Table 1 shows the thermal environment in lunar orbit applied to the thermal design of SELENE.

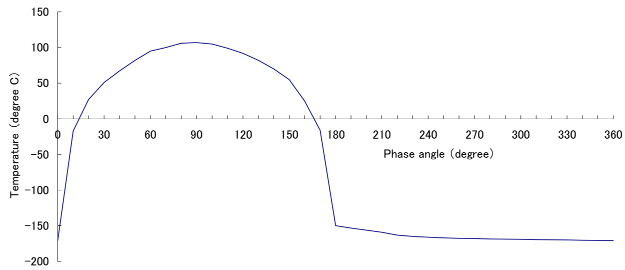



Figure 4 Lunar surface temperature profile

Table 1 Lunar orbital environments

| | |
|---|---|
| Solar intensity(Ps) | Ps = 1289 W/m$^2$ to 1421 W/m$^2$ [2] |
| Albedo(a) | a = 0.073 [4] |
| Infrared Emission($P_{IR}$) | Day side: by next equation<br>$P_{IR}$ = Ps (1-a) cos$\Phi$<br>$\Phi$ : the angle from sub-solar point.<br>ex.: 1317 W/m$^2$ at sub-solar (max.)<br>Night side 5W/m$^2$ [4] |

A lunar eclipse occurs whenever the Moon goes through some portion of the Earth's shadow for every 6 months. At the lunar eclipse, the satellite in low lunar orbit also into Earth's shadow. The maximum duration of umbra and penumbras is up to 5 hours, that consists of one 2.5hours umbra and two 1.25hours penumbrae. Figure 5 shows a schematic diagram of the lunar eclipse.

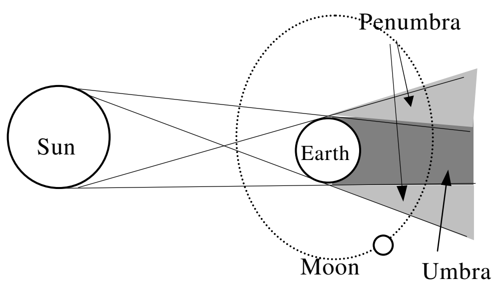



Figure 5 Schematic diagram of the lunar eclipse

## 3. Thermal Control

### 3.1. Design Requirements

The orbit required by SELENE mission is the polar circular orbit at altitude of 100km, and the attitude control is a three-axis stabilized with the +Z-axis points toward the lunar surface during nominal operation.

In the polar orbit, the beta angle varies from 0degree to 90 degrees, where the beta angle is the minimum angle between the orbit plane and the solar vector. Figure 6 shows a schematic diagram of the beta angle. In usual Earth surroundings satellite, when beta-angle is zero degree, the satellite has maximum eclipse factor. That means the satellite is in cold temperature orbit. Inversely, when beta angle is 90degrees a circular orbit appears as a circle as seen from the sun, there are no eclipse.

In case of SELENE, zero in beta angle means that the spacecraft passes above sub-solar point where lunar infrared emission has maximum intensity. In addition, the -Z-panel of SELENE receives the direct solar irradiation at the sub-solar point. In the orbit with 90 degrees beta angle, the infrared emission from the lunar surface becomes negligible small, and there is no eclipse. The infrared emission quantity received by spacecraft depends on beta angle. Furthermore, in beta angle=90degrees orbit, the spacecraft body is shadowed by the solar paddle as shown in Figure 7. In case of SELENE, therefore, beta angle=90degrees is cold worst condition, and inversely the beta angle=0degree orbit is hot worst condition. Figure 8 shows the variation of beta angle in orbit.

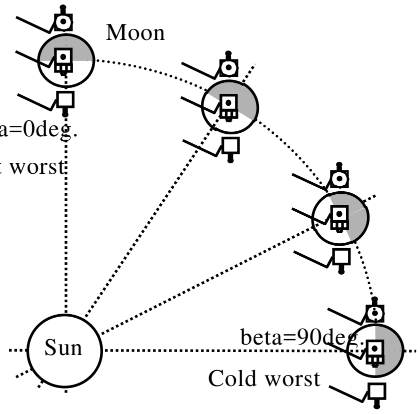



Figure 6 Schematic diagram of the beta angle

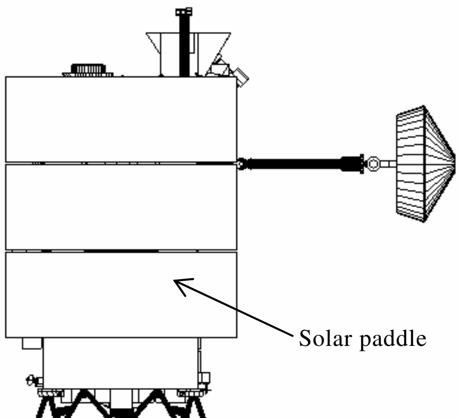



Figure 7 View from –Y axis

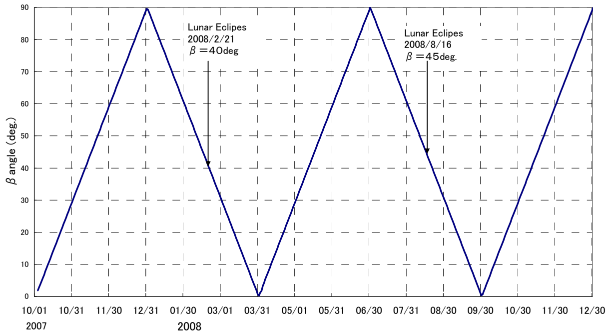



Figure 8 Variations of the beta-angle

There are four typical thermal environments for SELENE. First, the spacecraft is exposed to the solar irradiation from fixed direction in phasing and transfer orbit. Then, in the nominal observation lunar orbit with 90degrees beta angle, the main body of spacecraft is shadowed by the solar paddle this is the cold-case. Next, as the hot-case it is emitted infrared emission from lunar surface, in orbit of the beta-angle=0 degree. Finally the other cold-case environment is long time lunar eclipse.

### 3.2. Thermal Design Concept

The thermal control of SELENE has been achieved by using combination of passive and active control techniques.

As passive techniques, MLI(Multi layer insulation) and radiator are used. Most of the spacecraft surfaces are covered with the MLI except optical apertures, radiators and thermal-louvers (LOV). The spacecraft radiators are mainly located on the –Z-direction (anti-moon side) to avoid the lunar infrared emission. Figure 9 shows the locations of radiators and louvers.

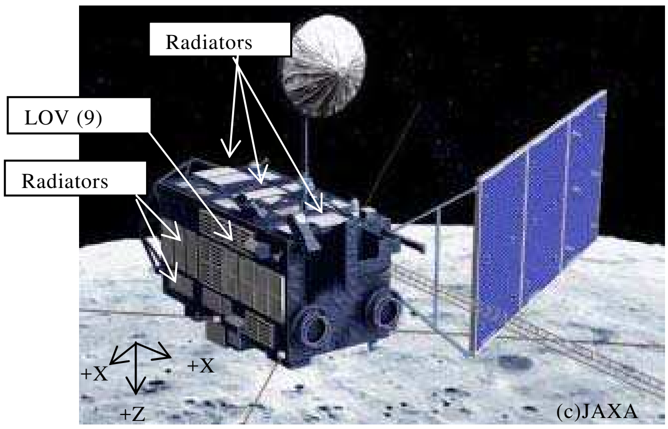



Figure 9 Location of LOV and Radiators

As active thermal control technique, louvers and heaters are used. On the +Y-panel (anti-sun side), 9 louvers are mounted to avoid the direct solar irradiation and to protect the components the under cold-case and the lunar eclipse. Furthermore the heaters are mounted on structures and on components, and the currents of heaters are thermostatically controlled by HCE (Heater Control Electronics).

SELENE consists of two modules, the upper module(UM) and the lower module(LM). The many electrical components such as the communication, data handling, mission electronics unit and so on are mounted in the UM. The electrical components mounted in the UM require not narrow allowable temperature range. So the temperatures of the UM are controlled mainly by louvers that have wide control temperature range, and heaters support them. On the other hand, the components such as the batteries and the propulsion subsystem in the LM required narrower allowable temperature range. The propulsion components (fuel tanks, pipes and valves) are warmed up indirectly by the heaters on LM panels controlled by HCE. This way reduces heater channel, since LM panels require less heater channel than mounting individual heaters on each propulsion components. Figure 10 shows major thermal control devices used on the spacecraft. In addition, the devices of passive thermal control, such as paint and thermal filler, are omitted in this table.

For simplicity of the thermal interface, the instruments mounted on outside of spacecraft are thermally insulated, and thermal design was carried out by component side. However, the heater control channels for those components are provided from HCE.

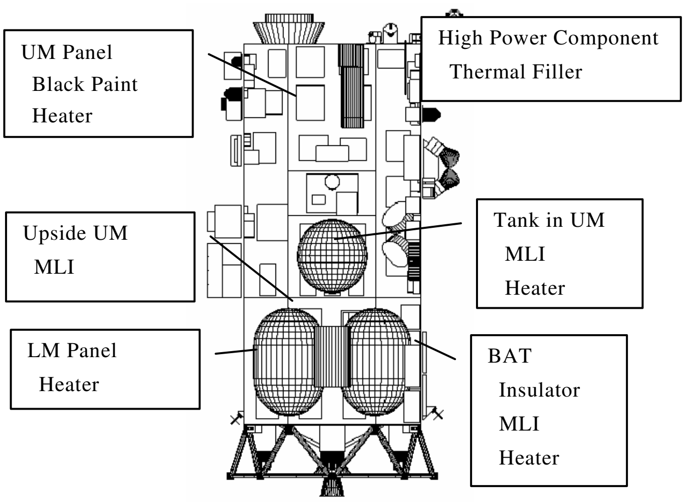



Figure 10 Inner thermal control devices

### 3.3. Thermal Control Hardware

Table 2 shows major thermal control hardware used for SELENE.

MLI uses the black Kapton conductive film in the outer cover sheet. All metalized layers of MLI are grounded.

For the radiator, transparent conductive coated Ag-PEI (low solar absorptance and high infrared emittance) is used. The conductive surfaces of radiators are electrically grounded to the spacecraft structure.

Figure 11 shows the thermal louver (LOV), and Figure 12 shows the characteristics of a LOV. A LOV has six bimetallic actuators in it, and the actuator has two blades on both sides. When the temperature of +Y-panel rises the bimetallic actuators open the blades. Inversely, when the temperature falls, the blades close. The temperature change of 15 degree C is required to drive the blades from the full close to full open position.

Table 2 Major Thermal Hardware

| Item | Descriptions |
|---|---|
| MLI | Outer layer :Aluminized Black-Kapton 0.025mm thickness<br>Electrically conductive<br>Grounding : All metalized layer are grounded.<br>Total area : approximately 52 ㎡ |
| Radiator | Material : Silvernized PEI(Polyetherimide)<br>Thickness : 0.075 mm<br>Coating : Transparent Conductive Coated<br>Solar absorptance : 0.14/0.20(BOL/EOL)<br>Infrared emittance : 0.74 |
| LOV | Dimensions : 800 x 400 x 70 (mm)<br>Mass : 1.42 kg / unit<br>Effective emittance : 0.11(close) to 0.66(open)<br>Heat Control ability :<br>12Watts(close) to 88Watts(open) |
| HCE | Dimensions : 267 x 260 x 230 (mm)<br>Mass : 6.3kg/unit<br>Control channels : 63 channels / unit<br>Maximum current : 1.0A max./ channel<br>Temperature set point : variable by command |

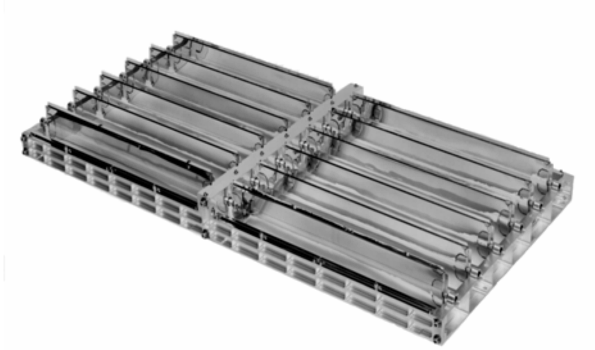


Figure 11 LOV(Thermal Louver)

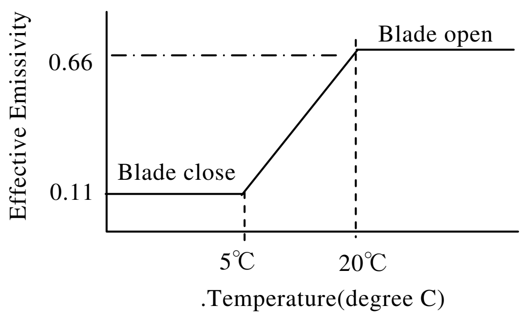



Figure 12 Effective Emissivity of LOV

The inner components are heated up indirectly by structure panel heaters, except for the batteries. The batteries and the external components such as propulsion thrusters, observation sensors and outer bus components are directly equipped the electrical heaters. The heaters are controlled by HCE except for the power subsystem components, batteries and shunts that are controlled by themselves. All heater systems of the bus components and structure panels are redundantly configured with a pair of primary and redundant. A HCE can control 63 heater channels, monitor the temperatures and provide the heater currents for each channel. SELENE uses 4 HECs( 2 as primary and 2 as redundant). The primary heaters have a set point 2 degree C higher than the redundant one so that no ground command operation is needed to switch primary to redundant in case of a failure.

Figure 13　HCE (Heater Control Electronics)

## 4.　Flight Performance of Thermal Control

On September 14, SELENE was inserted into the transfer orbit. Figure 14 shows measured temperatures in the phasing orbit, predicted temperatures and allowable temperature ranges of several key components. The measured temperatures are on 20:07(UT) September 15, about 44 hours after the launch. All components were kept within their allowable temperature range.

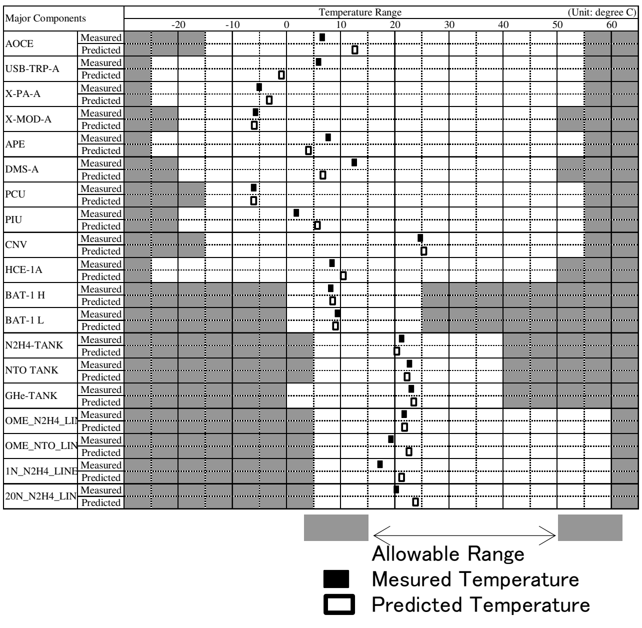



Figure 14 Measured and Predicted Temperature
(Phasing Orbit at Sep. 15 2007 20:07 UT)

On October 18, SELENE has reached the nominal observation orbit (altitude 100 km circular and polar). After the checkout of the bus system and science instruments, nominal observation term has been started on December 21. On January 2, 2008, the beta angle became the 90degree that is one of cold worst condition. Figure 15 shows the measured temperatures and predicted temperatures in the case of beta angle=90degrees of key components. All components were kept within their allowable temperature range in good agreement with prediction.

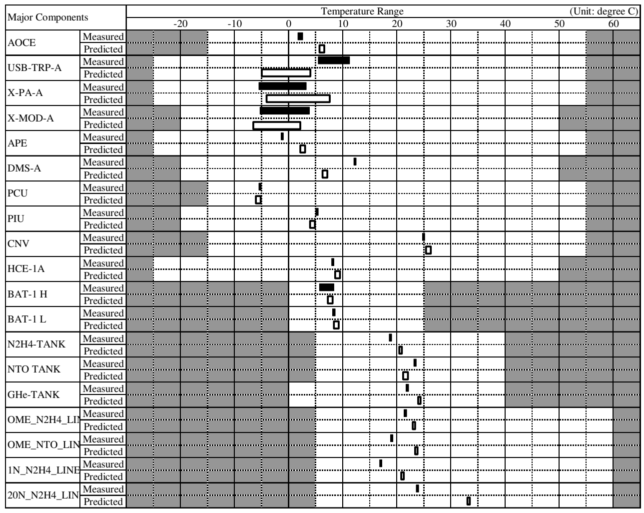



Figure 15 Measured and Predicted Temperature
(Beta angle = 90 deg.　Cold condition)

In the lunar eclipse on February 21, 2008, SELENE has entered the shadows that were caused by the Earth and the Moon respectively. The solar irradiation intensity has varied as shown in Figure 16, and Figure 17 shows the temperature profile of PCU and X-MOD as typical components during the lunar eclipse. The measured temperatures and predicted temperatures of key components are shown in Figure 18, the period between 22:00(UT) February 20 and 10:00(UT) February 21. All components are kept within their allowable temperature range in this period.

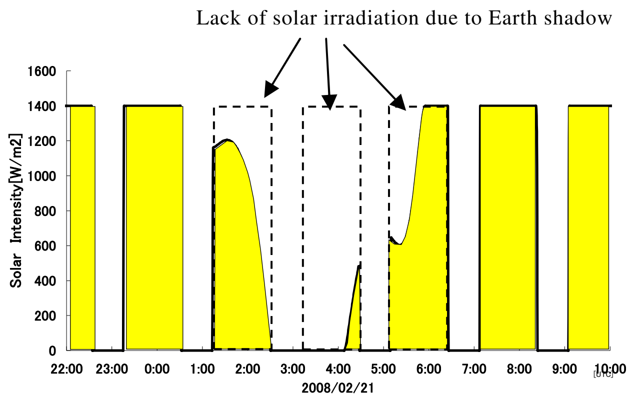



Figure 16 Solar Intensity at Lunar eclipse

On April 2, 2008, the beta angle became zero, that is the hot worst condition. The measured temperatures and predicted temperatures of key components are shown in Figure 19. All components are kept within their allowable temperature range in this period.

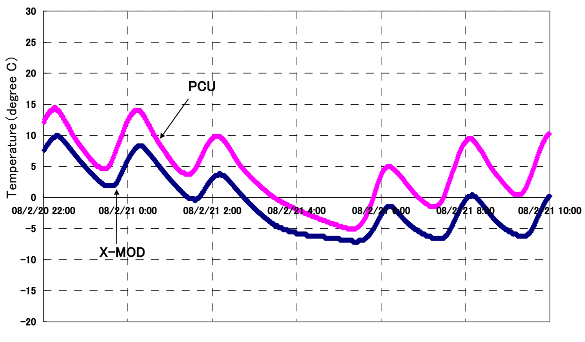



Figure 17　Temperature profiles of PCU and X-MOD at Lunar Eclipse

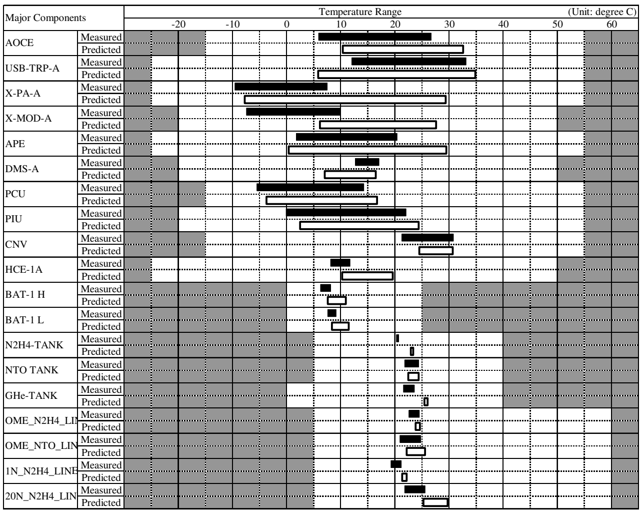



Figure 18 Measured and Predicted Temperature (Lunar Eclipse)

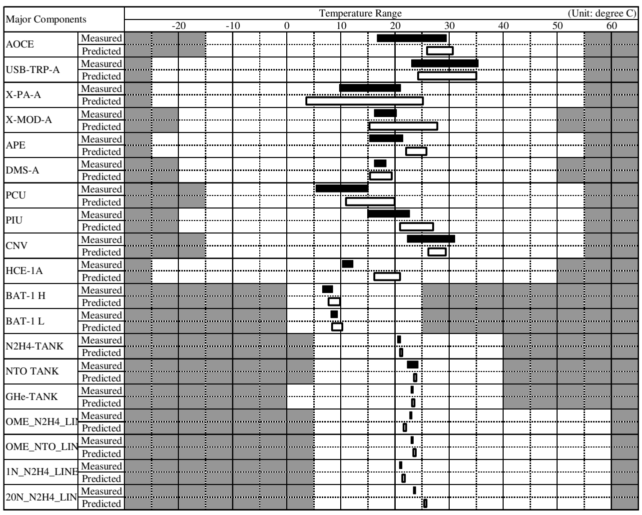



Figure 19 Measured and Predicted Temperature (Beta angle = 0 deg : Hot condition)

Figure 20 shows temperature profile of USB-TRP as typical component from launch to April 5, 2008. It is shown that the temperature in nominal observation phase is lowest at beta-angle=90degree, and highest at beta angle 0 to 30degree, and the spacecraft already overcame the hot and cold worst environments.

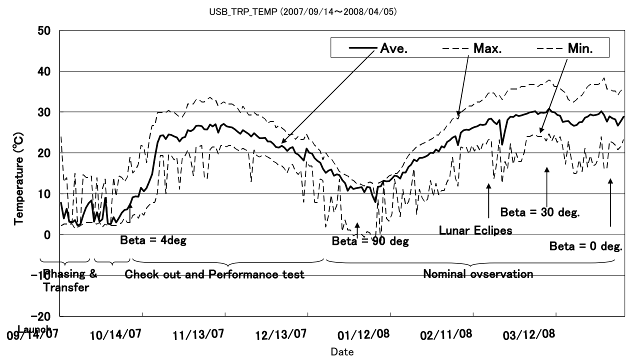



Figure 20　Temperature profile of USB-TRP

## 5. Conclusion

SELENE already has overcome the severe environments, the lunar eclipse and the maximum lunar infrared condition and so on. In addition, the measured temperatures indicated that all components are kept within their allowable temperature range in good agreement with prediction. Now, therefore, authors are sure that the thermal performance of SELENE is satisfactory, and conclude as follows:

(1)The thermal environment in lunar orbit used for SELENE is valid and it would be possible to use in future's project.

(2)The design concept that the radiators are located on the anti-moon direction is valid.

(3) Use of the thermal louver which can reduce the heater electric power under the severe cold case is effective.

(4)The method of warming up indirectly the propulsion system works completely.

## 6. Acknowledgments

The authors gratefully acknowledge for great contribution from all members concerned to development of SELENE thermal control subsystem design, manufacturing, integration and test in this work.

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