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Shinen2, an Ultra-Small Deep Space Probe: Thermal Design, Analysis and Validation

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SUMMARY

Shinen2 is a deep space probe, developed by Kyushu Institute of Technology (Japan) in collaboration with Kagoshima University (Japan), which was launched on 3rd December 2014, being the first ultra-small deep space probe in the world which uses an amateur radio communication system in deep space. It has a quasi-spherical shape which allows a more uniform heat transfer compared to a cubic shape. If for the most of the deep space missions, consisting of large spacecrafts, an active thermal design can be implemented, for Shinen2, there are some challenges regarding the thermal design: the deep space probe will pass through very different thermal environments, its size is only 500 mm in diameter and an active thermal control is difficult to implement because it requires large equipment. For these reasons, instead of an active thermal control, a passive thermal control is used for temperature management. The thermal analysis is realized with the help of SINDA solver and to verify the validity of the thermal analysis, the results are compared with the results from the thermal vacuum tests and with the telemetry data, in this way a thermal design method for ultra-small spacecraft which flies in deep space being realized.

KEY WORDS: thermal design; deep-space probe

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NOMENCLATURE

SCU = Shinen2 Control Unit
PCU = Power Control Unit
CCU = Communication Control Unit
PEEK = Polyether ether ketone
CFRP = Carbon Fiber Reinforced Plastic
CFRTP = Carbon Fiber Thermoplastic
STM = Structure-Thermal Model
EM = Engineering Model
FM = Flight Model

1. INTRODUCTION

Shinen2 was developed by Kyushu Institute of Technology in collaboration with Kagoshima University (Japan) and it carries a radiation sensor as payload. Shinen2 was launched with an H-IIA rocket of the Japan Aerospace Exploration Agency (JAXA), on 3rd December 2014 and it represents an experimental-shaped probe, its quasi-spherical shape allowing a more uniform heat transfer compared to a cubic shape (Fig. 1) [1].

Shinen2 has 3 main objectives as a space mission:

1) Demonstration of a communication system based on ham radio in deep space;
2) Demonstration in deep space of a structure made of PEEK and Epoxy CFRP materials.
3) Measuring radiation using Radiation Detector Sensor.

For achieving these three main objectives, thermal design plays a very important role due to the fact that it must assure the survival of electric components including the communication system through which the ground stations are kept in contact with the space probe [1]. The main function of the thermal subsystem is to keep the equipment and the satellite structure in a given temperature range for various phases and operating modes of spacecraft during its lifetime [2].

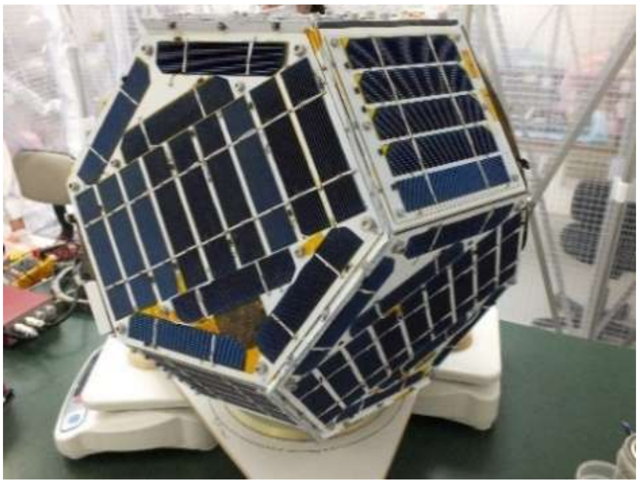

Figure 1 Flight model of Shinen2

For a deep space mission, CFRP materials are very suited since they have low thermal conductivity, making them good insulator materials.

Most of the deep space missions consists of a relative big spacecraft for which an active thermal design can be implemented. The most important challenges in thermal design of Shinen2 are the fact that the deep space probe will pass through very different thermal environments (between 0.9 and 1.1 AU), its size is only 500 mm in diameter, its weight is about only 17 kilograms and an active thermal control is difficult to implement because it requires large equipment [1]. For these reasons, instead of an active thermal control, a passive thermal control is used for temperature management.

For thermal analysis of Shinen2 in deep space, SINDA equations-solver has been used. SINDA is a thermal analyzer which uses a conductor-capacitor network representation, providing a powerful thermal programming language [3].

To verify the validity of the thermal analysis, the results are compared with the results from the thermal vacuum tests and with the telemetry data, in this way a thermal design method for ultra-small spacecraft which flies in deep space being realized.

2. THE THERMAL CONSTRAINTS FOR SHINEN2 MISSION

For obtaining an optimum performance and assuring the success of the mission, the thermal control plays a very important role. If the temperature of a component is too low or too high, the respective component can be damaged or its performance can be severely affected.

When a passive thermal system is used, the complexity of a satellite is greatly reduced, and the limited resources available on small satellites can be better used for payload function.

The most applied means for realization of passive thermal control satellite design are the multilayer insulation, painted surfaces, optical coatings, heat conductive elements, heat insulation supports and thermal conductive gaskets [4].

In case of Shinen2, the passive thermal control system will consist of painted surfaces, in this way, the simplicity of thermal system being assured and the costs being kept at minimum. The passive thermal control system of Shinen2 consists mainly in using a combination of white and black paint. To assure more storage of heat inside, the inside components are painted black. For the outer surfaces, the white paint is used in order to prevent too much heat from the Sun to enter inside the space probe [1].

The heat transfer inside is accomplished by conduction and radiation. To allow more heat transfer between internal components and outer panels, the structure of the main frame was changed after STM model [1]. Instead of having a big case for main frame, for EM and FM models there are four strong pillars which host inside the two batteries and Radiation Detector Sensor (Fig. 2). Before this change, there was a big difference in temperatures between 0.9 and 1.1 AU (of around 40 degrees), but for the EM and FM models, the difference is of only 14 degrees between the worst hot case and worst cold case scenarios.

In case of Shinen2, the most delicate devices are batteries and the payload (Radiation Detector Sensor), which can be seen in Fig. 3. The heat generation inside Shinen2 is between 10 and 15 W.

Also, another important aspect is that the solar cells are body-mounted, they are placed on CFRP panels, being attached on all lateral sides of the satellite and on the top panel.

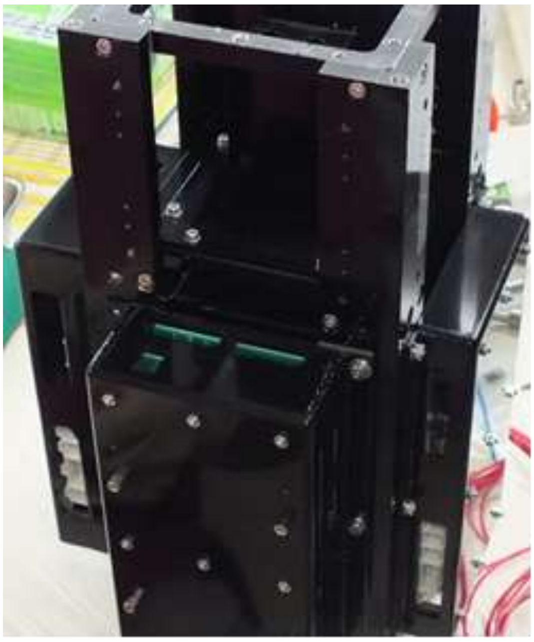

Figure 2 **The internal structure of Shinen2 (EM Model)**

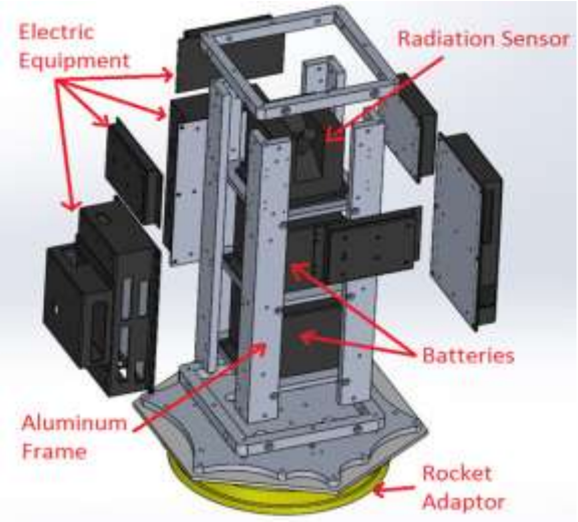

Figure 3 **Overview of the internal structure of Shinen2**

3. Methodology for Orbit Calculation

To know the position of Shinen2 in time and space is very important for the thermal design and for the communication system. The input data provided by JAXA are presented in Table 1. The parameters of Table 1 correspond to the separation phase. Based on this parameters, the trajectory of Shinen2 around the Earth, then the orbit around the Sun can be deduced.

Table 1 **Input parameters from JAXA**

Time of separation (after launch)	6835	seconds
Distance from the center of Earth	9244.915	km
Latitude	0.034	degrees North
Longitude	189.94	degrees East
Inertial Velocity	10357.221	m/s
inertial velocity Elevation angle	34.644	degrees
inertial velocity Azimuth angle	119.877	degrees
Japan time of launching	13:22:48	3-Dec-14

For achieving the minimum mission success, Shinen2 must be able to communicate with the ground stations when it is beyond Moon orbit and for achieving success, Shinen2 must be able to communicate with the ground stations when it is beyond 1,000,000 km. The communication succeeded until about 2,250,000 km. In Fig. 4, the distance between Shinen2 and Earth soon after the launch can be seen as a function with time.

The trajectory is composed by 2 important stages: the hyperbolic escape trajectory around the Earth (until 925000 km from the center of Earth, this location corresponding to the edge of Earth's sphere of influence) and the elliptical orbit around the Sun. For the hyperbolic orbit, the influence of Sun's gravitational force is neglected and only Earth is considered as the attracting body. After escaping from the Earth's sphere of influence, Shinen2 will follow an elliptical orbit around the Sun (Fig. 5) and, for its calculation, the Earth's gravitational influence will be neglected.

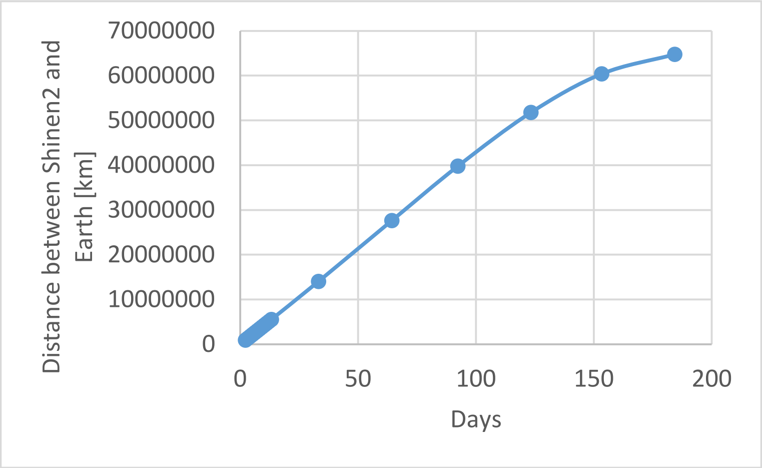

Figure 4 **Distance between Shinen2 and Earth after launch**

Since the distance from Earth, the latitude and longitude angles, the inertial velocity and its angles for the separation phase are known, the position and velocity in the Geographic Coordinate System can be deduced. The X-axis of the Geographic Coordinate System is given by the intersection of Greenwich meridian and geographic equator and the Z-axis is towards the Geographic North Pole. The Y-axis completes a right-handed Cartesian triad.

Because it is desirable to calculate the trajectory of Shinen2 independently of Earth's rotation around its own axis, a transformation from the Geographic Reference System (GEO) to the Geocentric Equatorial Inertial System (GEI) is required. GEI System has the X-axis pointing towards the First Point of Aries and the Z-axis towards the Geographic North Pole. For performing the transformation mentioned above, the time in Julian centuries, corresponding to the separation time, must be calculated first. The Greenwich Mean Sidereal Time (GMST) can be calculated based on the Julian Day number and, after knowing the GMST, the position and the velocity of Shinen2 in GEI coordinate system can be found out [5].

After the separation, Shinen2 will go into an escape hyperbolic orbit around the Earth, until it will reach the edge of the Earth's sphere of influence, located at about 925,000 km. Based on the orbital parameters and true anomaly for the location at 925000 km away from Earth, the position and the velocity at that location can be calculated.

Knowing the position and velocity at the boundary of the Earth's sphere of influence, the elliptical orbit around the Sun ca be deduced. First, a transformation between GEI (Geocentric equatorial inertial) reference system to GSE (Geocentric solar ecliptic) reference system is required. The time of reaching 925,000 km from Earth is December 5, 10:27:36 UTC. From GSE, a coordinate transformation to the Heliocentric Earth Ecliptic (HEE) and then to Heliocentric Aries Ecliptic (HAE) is necessary and the orbital elements for the elliptic orbit around the Sun can be calculated.

The distance between Shinen2 and the Sun will vary (Fig. 6), the perihelion being at 0.9 AU and the aphelion at 1.1 AU. The thermal environments for 0.9 AU and 1.1 AU are quite different, the Solar Constant being 1699.11W/m^2, respectively 1137.42 W/m2 (Table 2). Because Shinen2 has an elliptical orbit around the Sun, the most important environmental factor will be the Sun's influence.

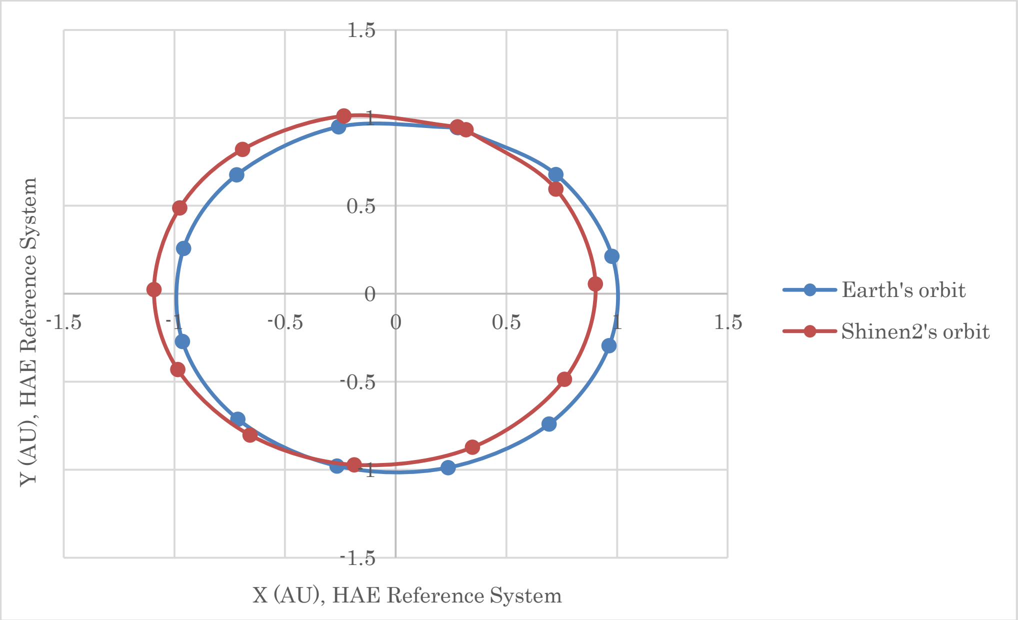

Figure 5 **The orbit of Shinen2 and Earth for one year**

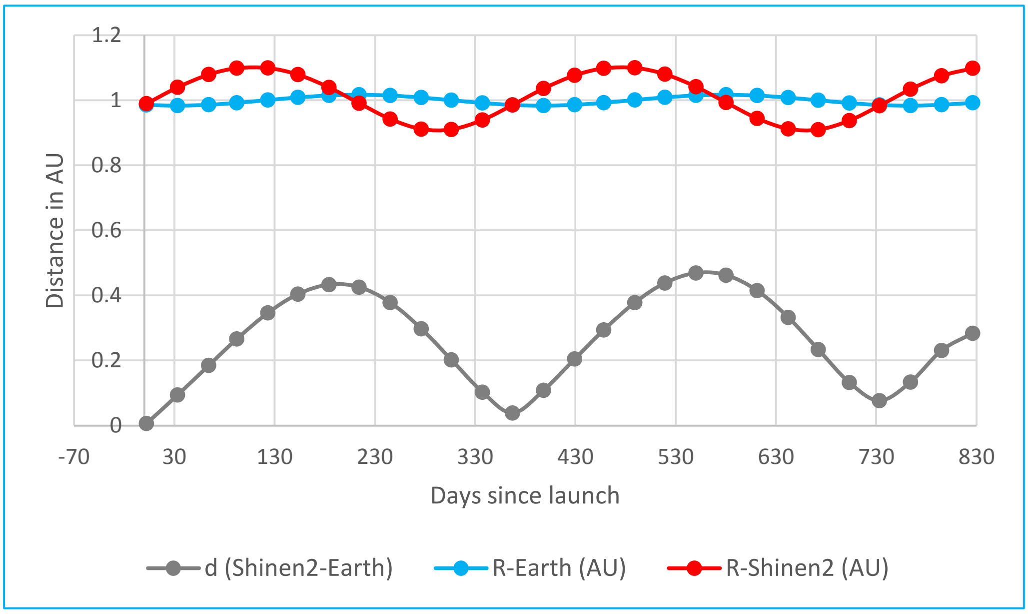

Figure 6 **Distance between Sun and Earth (R-Earth), Sun and Shinen2 (R-Shinen2) and distance between Earth and Shinen2 (Δd) expressed in km, for a period of time of about 830 days**

Table 2 **Variation of Solar Constant for Shinen2 mission**

	Near Earth (1 AU)	Worst hot case (0.9 AU)	Worst Cold case (1.1 AU)
Solar Constant (W/m^2)	1376.0	1699.1	1137.4

4. THERMAL ANALYSIS FOR SHINEN2

Performing thermal analysis is the primary mean by which can be verified if a thermal subsystem meets the design requirements [2]. In case of Shinen2, a SINDA model was developed to help predict the temperatures of the components.

For thermal analysis, a SINDA model of 47 nodes was built. In the thermal design of spacecraft, several parameters, like absorptivities and emissivities of the outer structures, emissivities of the inner components and structure, the thermal conductances, the heater powers generated inside, need to be determined so that the components will stay in their design temperature ranges [6].

For estimating the optical properties of the outer surfaces, the presence of solar cells was carefully considered and the averaged optical properties are described in the Table 3.

Table 3 Averaged values of Optical Properties of outer panels

	Average absorptance (α)	Average emissivity (ε)
White Paint	0.39	0.75
Black Paint	0.69	0.75

Two cases were considered previously: one with the outer panels painted in white and one with the outer panels painted in black. After performing thermal analysis, it was found out that, for the white model, the internal temperatures for the electric components, payload and batteries are in the operating range, while for the black model, the internal temperatures are exceeding the operating range (Table 3). Both cases were performed assuming that the interior components are painted in black and assuming also the internal heat generation inside Shinen2 (Table 4).

In Table 5, the survival range and operational range of temperatures are shown. The two kinds of range are frequently defined in case of thermal design. Operational limits are the limits within which the components must remain while operating and survival limits are the limits in which the components must remain at all times, even when not powered [7].

It was decided to use white paint for outer surfaces and black paint for the internal equipment. The optical properties of the materials used for Shinen2 can be seen in Table 6.

Regarding the materials, Epoxy CRRP and PEEK CFRP were used for the outer panels and Aluminum for the internal equipment. The properties of the materials are described in Table 7. Also, the PCB plates on which solar cells are mounted, were carefully taken into consideration in thermal analysis.

Table 4 The internal heat generation

Component	Heat Power [W]
Radiation Detector Sensor	1.25/0.1
Top Battery	0.5
Bottom Battery	0.5
TX top, -z (1)	0.1
TX top, -z (2)	0.1
A_CCU_PCU	0.2
TX, +z	5
B_PCU_CCU, +z	0.1
A_PCU_IF, -y	0.2
TX, +y	5

Table 5 Survival and Operation Range of Temperatures

Component	Survival Range (Power off), (°C)	Operational Range, (°C)
Radiation detector sensor	-30→60	-20→50
Batteries	-10→50	0→40
TX & RX	-30→60	-20→50
SCU, PCU, CCU	-40→80	-30→70

Table 6 The optical properties

Material	Absorptivity (α)	Emissivity (ε)	α/ε
Aluminum	0.13	0.30	0.43
PCB	0.25	0.88	0.28
PEEK	0.94	0.91	1.03
EPOXY	0.85	0.85	1.00
White Paint	0.25	0.88	0.28
Black Paint	0.90	0.80	1.13

Table 7 The properties of the materials

Material	Density (kg/m^3)	Thermal conductivity (W/m/K)	Specific Heat (J/kg/K)
Aluminum	2700	167	896
PCB	1300	0.274	1421
PEEK	1520	0.766	913
EPOXY	1600	0.766	1000

The SINDA model consists of 47 nodes between which the heat transfer was modelled (conduction and radiation). To assure the survival of electric components and batteries, the SINDA program was run for the two cases: the worst hot case (0.9 AU) and the worst cold case (1.1 AU).

The results consist of temperatures between about 10 and 50℃ during one orbit (Fig. 7) and these results are in the allowable and working temperature range.

In Fig. 8, the temperatures of Radiation Detector Sensor and of batteries are represented for one year (the orbit period of Shinen2) and, in Table 8, the exact values for the radiation detector sensor and batteries are described in case of the worst hot and cold cases.

The results show that all components operate within their safe temperature limits.

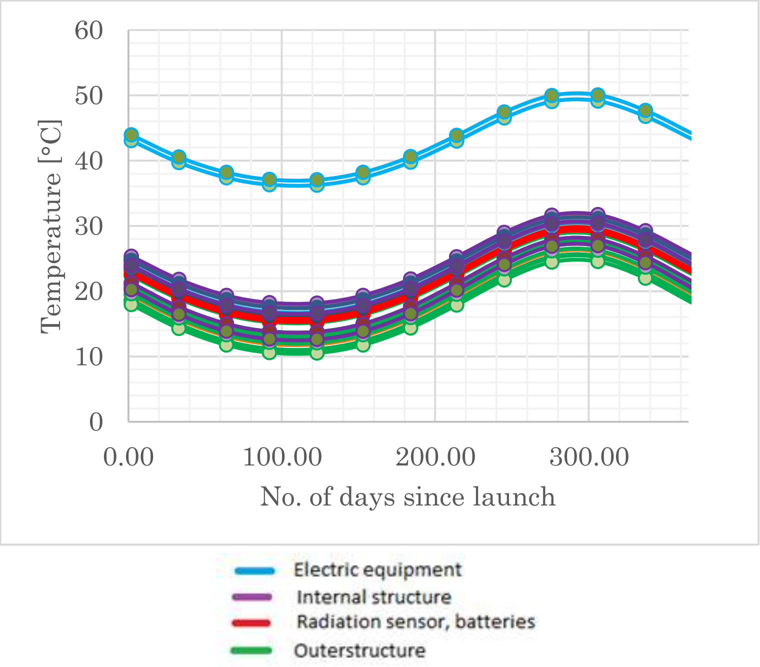

Figure 7 The analysis results in temperatures for one year period of time

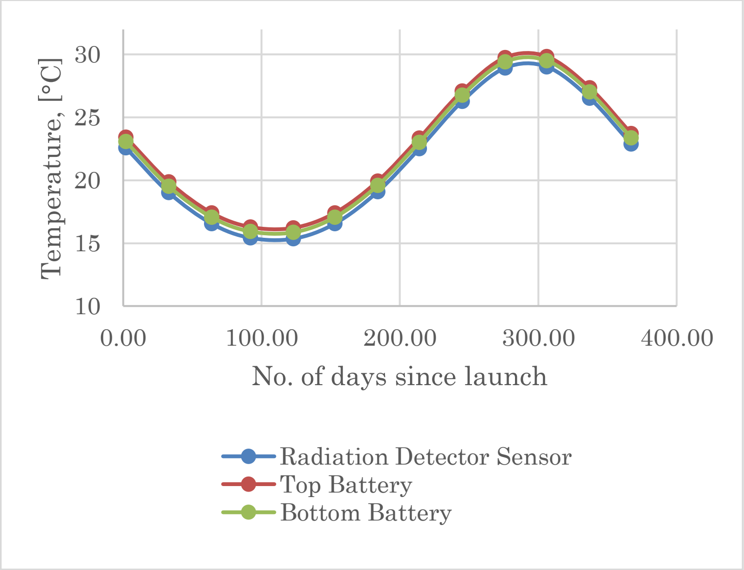

Figure 8 The analysis results in temperatures for one year period of time, in case of Radiation Sensor and batteries

Table 8 The temperatures for the worst cold and hot case, for Radiation Detector Sensor and batteries

	Worst cold case (0.90 AU)	Worst hot case (1.10 AU)
Radiation Detector Sensor	15.36°C	29.02°C
Top Battery	16.22°C	29.84°C
Bottom Battery	15.87°C	29.51°C

5. VALIDATION OF THE THERMAL ANALYSIS FOR SHINEN2

The SINDA model was validated by the thermal vacuum tests, but also by the telemetry data. In thermal vacuum tests, 50 thermocouples were used (Fig. 9-a), positioned almost in the same location as the nodes in the SINDA model. A heaters cage was used to provide power (Fig. 9-b).

During the tests, the heaters were turned on and they have been kept working until the temperatures inside Shinen2 reached more than 35 degrees Celsius. Afterwards, the heaters were turned off, the temperatures dropped to the room temperature and then the cooling system was activated. The temperatures of batteries were kept at 5 degrees Celsius 21 hours (time of reaching the Moon orbit).

In SINDA, there were implemented the same conditions as for thermal vacuum tests and the differences are of maximum 4 degrees Celsius (Table 9). The small differences show that the SINDA model represents accurately the real model so that it can be used to estimate the thermal environment in deep space.

On the flight model of Shinen2, 9 thermal sensors were attached inside the probe (Fig. 10). After launch, Shinen2 was able to communicate with different ground stations and in the downlink data there were also temperature data. Using Sinda model, the same conditions as during the communication time were simulated and the results of the thermal analysis are in good agreement with the measured data (presented in Table 10 as averaged values of several measurements).

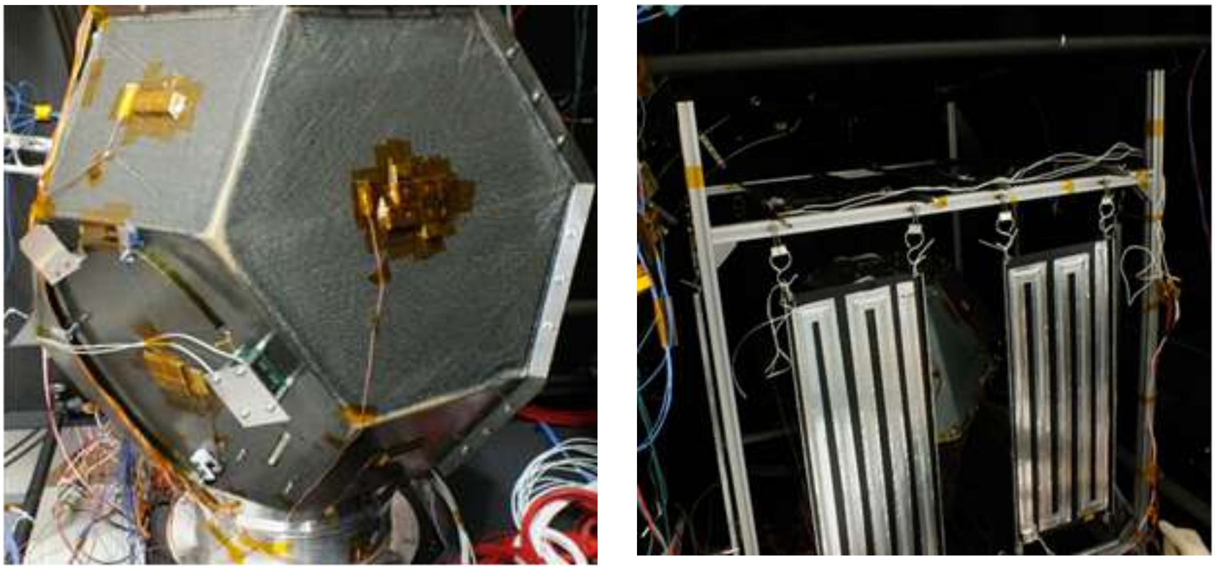
(a) (b)

Figure 9 **Thermal vacuum tests: (a) Preparations of EM model (with thermocouples attached in 50 locations) for thermal vacuum tests; (b) Heaters cage for thermal vacuum tests**

Table 9 Validation of Thermal Analysis Model

Component	Thermal tests results Temp. (C)	Sinda results Temp. (C)	Difference in Temp. (° C)
Top Battery, top	36.0	34.3	1.7
Top Battery, bottom	35.8	34.3	1.5
Top Battery, lateral side	34.8	34.3	0.5
Top Battery, inside	36.0	34.3	1.7
Bottom Battery, top	35.5	34.1	1.4
Bottom Battery, bottom	35.7	34.1	1.6
Bottom Battery, lateral side	35.7	34.1	1.6
Bottom battery, inside	36.9	34.1	2.8
Radiation sensor, top	36.3	32.5	3.8
Radiation sensor, bottom	35.9	32.5	3.4
Top panel	32.8	31.4	1.4
SUBPCU	34.8	35.1	0.3
Bottom plate, CFRTP	31.3	33.5	2.2
CCU	34.9	34.6	0.3
SCU	35.9	36.6	0.7
TPD TX	34.3	34.9	0.6
TPR PCU -z	35.4	35.9	0.5
Main Transmitter	33.4	34.4	1.0
Access panel	29.4	28.7	0.7
Main Frame	34.4	33.7	0.7
Bottom Aluminium plate	35.0	33.8	1.2
Morse Transmitter	40.2	42.6	2.4

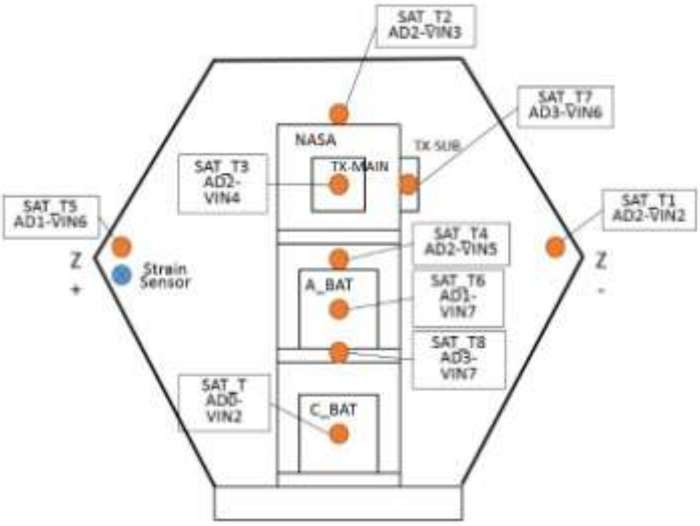

Figure 10 Position of the thermal sensors inside the Flight Model

Table 10 Validation of the thermal analysis using telemetry data (near Earth position, 1367 W/m2 Solar Constant)

	Measured value of temperature in Flight (°C)	Value of temperature from thermal analysis (°C)	Difference (°C)
Top Battery (inside measurement)	23.2	22.5	0.7
Top Battery (lateral side measurement)	21.6	22.5	0.9
Top Battery (bottom side measurement)	27.2	22.5	4.7
Bottom Battery (inside measurement)	-	22.3	-
Radiation sensor (top measurement)	21.5	26.6	5.1
Outside panel (+z)	20.4	18.0	2.4
Outside panel (-z)	20.4	17.5	2.9
Main transmitter	31.6	36.1	4.5

6. CONCLUSION

The thermal analysis was validated by the thermal vacuum tests and by comparing the calculated results with the in-flight measurements. Because the results of thermal analysis are in the operational and survival temperature range for electric components and batteries, the solution with white paint outside and black paint inside is considered a good solution for the thermal control system of Shinen2. The solution can be used for similar future deep space missions, with similar mission requirements and orbital parameters.

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