Design and Implementation of a Thermopile-Based Earth Sensor


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(Received July 31st, 2015)

In recent years, microsatellites have attracted great attention for their low cost, rapid development, and utilization capability. Demand for more requirements is increasing, and reliable attitude control is indispensable for secure operation. An Earth sensor is typically used to detect the direction of Earth’s center relative to the spacecraft’s attitude. Unlike Sun sensors, an Earth sensor can be functional even in the eclipse region in orbit, which enables a spacecraft to determine its attitude regardless of orbital position. The thermopile-based Earth sensor developed in this research is designed to have full sky coverage, i.e., it is operational independent of satellite attitude. Therefore, it can be used in safe-hold-mode operation. As a result of this research, an Earth sensor is realized by utilizing multiple thermopile sensors. The geocentric vector can be determined from the output voltages of thermopiles that are mounted on the entire satellite in a distributed manner and pointed in different directions. In order to establish a data processing algorithm, the output voltage and angle characteristics of the sensors were investigated analytically and experimentally. A numerical model of the sensor was developed, and its performance in orbit was evaluated in a software-based simulation and verification environment.

Key Words: Microsatellite, Earth Sensor, Thermopile

Nomenclature

\[ \begin{align*}
A & : \text{area} \ [m^2] \\
F & : \text{view factor} \ [-] \\
N & : \text{Earth direction vector} \\
n & : \text{normalized vector of Earth sensor} \\
R & : \text{radius} \ [m] \\
T & : \text{temperature} \ [K] \\
V & : \text{voltage} \ [V] \\
d, r & : \text{distance} \ [m] \\
\epsilon & : \text{emissivity} \ [-] \\
\theta, \gamma & : \text{angles} \ [^\circ] \\
\alpha & : \text{active layer} \\
ds & : \text{deep space} \\
c & : \text{Earth} \\
i & : \text{sensor identification number} \\
sat & : \text{satellite} \\
rl & : \text{reference layer}
\end{align*} \]

Subscripts

- al: active layer
- ds: deep space
- c: Earth
- i: sensor identification number
- sat: satellite
- rl: reference layer

1. Introduction

The Space Robotics Laboratory (SRL) of Tohoku University has been very active in the field of small-satellite development for many years. Tohoku University has successfully developed, launched, and operated SPRITE-SAT, its first scientific microsatellite (renamed RISING-1 after the launch); CubeSat RAIKO; and is completing its second and third microsatellite projects RISING-2\textsuperscript{1–5} and RISESAT.\textsuperscript{6} In particular, the RISESAT (Rapid International Scientific Experiment Satellite) is a 50-kg-class international scientific microsatellite that is equipped with various international payload instruments. Some of these instruments require high-precision attitude control pointing either toward Earth or to planetary objects, while others focus on stable operation rather than high-attitude control accuracy. The attitude control system of RISESAT is designed to meet all these requirements. According to a requirement analysis and system design, it was determined that an Earth sensor with full sky coverage is necessary for stable and reliable operation of the satellite without depending on star sensors, which have operational restrictions such as Sun and Earth blinding. This is necessary to, e.g., prevent optical payload components from directly observing Sun when the satellite is entering the dayside out of an eclipse. According to this background, SRL has started a research and development project for a new Earth sensor with collaborative support from the Department of Aerospace Science and Technology of Politecnico di Milano in Italy. This paper describes the design, implementation, and ground verification results for the new Earth sensor.

2. Design Trade-Off of Earth Sensors

The Earth sensor developed in this research utilizes one of the most commonly used Earth detection methods, namely, observation in the infrared (IR) radiation range. In this way, the sensor can tell the existence of Earth (~300 K) against cosmic background radiation (~3 K). Because this observation is independent of the visible wavelength, Earth’s direction can be detected regardless of orbital position.

From the mechanical point of view, there are two different ways to implement an IR sensor: dynamic and static. The dynamic way of implementation uses a mechanism such as
mirrors, which are rotated or vibrated to scan or track Earth’s rim. This is considered a direct determination. This type of sensor is widely used in larger satellites such as those in geostationary orbit and is often too large for microsatellites. Furthermore, having moving parts inside the sensor is not desired for microsatellites owing to reliability issues (hence cost) and mechanical disturbance vibration and torque. On the contrary, in static implementation, multiple IR sensors are installed in a distributed method with some angle offsets from each other. By either comparing or coupling the output data from these sensors, one can estimate the direction of Earth’s center. This method is considered an indirect determination. This method is more suitable for microsatellite applications.

For indirect methods, it is difficult to achieve high precision and large field of view (FOV) at the same time. Indeed, most Earth sensors that use this approach have sensitivity only in the nadir direction. To use these sensors, a satellite first needs to achieve a rough nadir acquisition maneuver by means of other sensors. It is clear that these types of Earth sensors are not suitable for use in safe-hold mode. Consequently, this project aims to develop an Earth sensor with a 4π sr FOV and relatively low determination accuracy. Although the accuracy is low (initially estimated at 20°), the high availability of this sensor plays a significant role in coarse attitude control to achieve reliable operation.

3. Thermopile-Based Full-Sky-Coverage Earth Sensor

In this section, the mechanism of a thermopile sensor and the configuration of the developed Earth sensor are described in detail.

3.1. Thermopile sensor

A thermopile sensor is composed of two plates linked by a high thermal resistance. One of these plates irradiates freely toward the sensor FOV and has a negligible heat capacity; therefore, we can consider it to always be in the equilibrium state. (The characteristic time of the system is much lower than the one required for a change in attitude.) This plate is generally labeled as an active layer. The other plate is called a reference layer, and it is assumed to have the same temperature as the satellite. A thermopile is able to measure the temperature difference between the plates using some thermocouples connected to them. The output voltage of the thermopile is therefore proportional and, in a certain range, linear to the difference in temperatures between those two plates. Figure 1 illustrates the internal structure of a thermopile and a photograph of an exemplary thermopile with a cap mounted atop it.

![Fig. 1. Thermopile structure scheme (left) and a photograph of exemplary thermopile sensor with cap.](image)

Fig. 1. Thermopile structure scheme (left) and a photograph of exemplary thermopile sensor with cap.

3.2. Sensor field of view

Usually, thermopile sensors for terrestrial application are covered by caps and filters, as illustrated in Fig. 1, in order to intentionally narrow the FOV and limit sensitive wavelengths. However, because the cap temperature can become extremely high or low in the space environment, the existence of the cap can influence the performance of the Earth sensor. Moreover, this Earth sensor only aims to distinguish the temperature contrast between Earth and deep space; no specific filter is required. Based on these reasons, a thermopile sensor without a cap or filter was selected for use.

The relations between the thermopile sensor’s FOV and the Earth view angle are illustrated in Fig. 2, where the satellite altitude is selected as 600 km. As illustrated in the figure, Earth is visible from the thermopile sensors by an off-nadir angle of up to approximately 150°.

3.3. Constellation of distributed thermopile sensors

Theoretically, the more distributed sensors a satellite has, the better determination accuracy it can achieve. The international scientific microsatellite RISESAT is the first microsatellite to carry this new Earth sensor. Considering its mass, envelope, and power resources, it was decided that thermopile sensors would be divided into four units, and each unit would have seven thermopiles, as illustrated in Fig. 3. Within a unit, two pairs of four thermopiles are oriented on a plane with an angle distribution of 30° from each other by sharing one thermopile in the middle for both planes. RISESAT carries four of these sensor units, which are mounted in a tetrahedron configuration as illustrated in Fig. 4. Because each sensor unit can have a different reference temperature depending on the temperature distribution of the satellite’s main structure, each unit has temperature sensors, and this information is utilized to calibrate the output voltage level of each thermopile sensor.

![Fig. 2. Relations between thermopile sensor FOV and Earth view angle with an orbit altitude of 600 km.](image)

![Fig. 3. Orientation of seven thermopile sensors mounted on a single sensor unit: (left) CAD overview and (right) engineering model of the Earth sensor. (This unit is also combined with two pairs of slit-type sun sensors.)](image)
4. Analytical Evaluation

In order to analytically estimate the output voltages of the thermopile sensors, the temperatures of both active and reference layers must be determined. This can be done by calculating the heat balance between the plate and the objects present in its FOV, such as Earth and deep space (here Sun is neglected). Assuming that the active-layer plate is always in the equilibrium state, the heat balance equation of the active layer becomes

\[
\frac{\sigma(T_{\text{al}}^4 - T_{\text{ds}}^4)}{A_e e_e + \frac{1}{A_{\text{al}} e_{\text{al}}}} = \frac{\sigma(T_{\text{al}}^4 - T_{\text{ds}}^4)}{1 - e_{\text{al}} + \frac{1}{A_{\text{al}} e_{\text{al}}}}
\]

(1)

where \(\sigma\) is the Stefan–Boltzmann constant, and \(e_{\text{al}}\) and \(e_e\) are assumed to be 1. The view factor of Earth seen by the active layer \(F_{\text{al-e}}\) can be described as

\[
F_{\text{al-e}} = \frac{1}{\pi} \int_{A_e} \frac{\cos(\theta_{\text{al-e}}) \cos(\theta_{\text{e-al}})}{d^2} dA_e
\]

(2)

where \(\theta_{\text{al-e}}\) is the angle between the normal vector of the active layer and the direction toward the infinitesimal area \(dA\) of Earth, \(\theta_{\text{e-al}}\) is the angle between normal vector of the infinitesimal area \(dA\) and the direction toward the satellite, and \(d\) is the distance between the infinitesimal area \(dA\) and the satellite. These are illustrated in Fig. 5. By numerically solving these equations, one can calculate the estimated temperature of the active layer. The temperature of the reference layer can be considered as equal to the local temperature of the satellite’s structure.

5. Experimental Calibration and Evaluation

The only remaining unknown factor is the scale factor between the sensor output voltage and the temperature difference between the active and reference layers. To determine this relationship, an experimental measurement has been conducted in a thermal vacuum chamber using the test setup illustrated in Fig. 6.

As illustrated in Fig. 6, a thermopile sensor was fixed on a rotation table, which was placed in front of a circular copper plate with the same Earth view angle as in orbit. The diameter of the copper plate was 200 mm, and the distance between the sensor and the plate was set to 57.7 mm to achieve a view angle of approximately 120°. During the test, the copper plate was heated, and the temperature was kept at 285 K to emulate Earth, while the temperature of the plate around the thermopile was kept at 293 K to emulate the temperature of the satellite body. The ambient temperature during this test was 253 K. The comparison between the output voltages of the simulated thermopile model and the real measurement is illustrated in Fig. 7.
The scale factor of the calculated curve using the numerical thermopile model was selected so that the maximum values meet the measurement values when the offset angle is equal to zero. As can be seen in Fig. 7, the calculated and measured values overlap with quite good precision. From this result, it could be concluded that the analytical evaluation of the mechanism accurately reflects the reality. Owing to the limited capability of the test facility, angle dependency characteristics of the sensor could not be measured in different temperature conditions. Thus, an assumption was made that the above identified scale factor can be applied to different kinds of temperature conditions. The most important revealed fact is that the thermopile sensor does indeed have an angle dependency as foreseen, and owing to this characteristic, it will be possible to detect the Earth center direction by means of the suggested method with distributed thermopile sensors.

6. System Simulation Result

SRL has been developing a software-assisted development, verification, and integration environment for microsatellites to realize rapid and cost-effective development of reliable microsatellite systems. Based on the abovementioned analysis and experimental measurements, the software model of the Earth sensor has been developed and implemented in this simulation environment for ground testing. This simulation environment is comprehensive and is capable of hardware-in-the-loop simulation with satellite components such as attitude control computers, as illustrated in Fig. 8.

Using this environment, the reproducibility of the Earth center vector from the thermopile sensor output voltage values was evaluated. The reproduction algorithm calculates the weighted center of the incoming IR radiation energy from the 4π sr FOV by summing the sensor vectors multiplied by the corresponding normalized sensor output $\hat{V}_i$. This can be described as follows:

$$N = \sum_i \hat{V}_i n_i \quad (3)$$

In this simulation, the Earth center reproduction algorithm was implemented in the satellite’s attitude control computer connected to the simulation environment.

Earth sensor output values were emulated by the real-time simulation environment and fed to the attitude control computer while the satellite conducted a nadir acquisition maneuver. A comparison between the real and reproduced values of the azimuth and elevation angles of the Earth’s direction against satellite body coordinates, as well as the absolute error angle of Earth’s direction, are illustrated in Fig. 9.

The estimation error of the azimuth angle is less than 3°.
throughout the simulation period, whereas that of the elevation angle has a clear bias offset up to approximately $10^\circ$ in the region around both the minimum and maximum elevation ranges. From this comparison, the elevation angle error seems to be the dominant contribution to the absolute estimation error. Figure 9 indicates that the absolute error angle of the Earth center detection is estimated to be less than approximately $10^\circ$ most of the time. This accuracy is better than that of the estimated value mentioned in Section 2. It should also be noted that the absolute error of the angle becomes very small around the region where the elevation angle is around zero. In this situation, the Earth vector is on the X–Y plane of the satellite body coordinates, where the population of thermopiles is the sparsest, and their distribution is symmetric in regard to the X–Y plane. Because both the azimuth and elevation angle errors are the smallest in this condition, it is indicated that the distribution of the sensors shall be as symmetric as possible in any direction to achieve better accuracy independent of the satellite’s attitude.

A detailed investigation of the effects of the quantities and distribution configuration of the sensors will bring further improvements, as well as insight for the utilization of this method in the future. In addition, because the bias offset on the estimated elevation angle has a clear trend and seems dependent on the elevation angle, this effect can be calibrated and the error can be possibly decreased during actual operation.

7. Conclusion

As the result of this research, Earth sensor technology for microsatellite applications is developed. This technology utilizes multiples of distributed thermopile sensors pointed in different directions around the entire satellite without a moving element inside the sensor unit. The characteristics of the thermopile sensor were analytically investigated and validated by experimental measurements on the ground. A hardware-in-the-loop simulation with a model-based simulation and verification environment illustrated that the geocentric vector can be determined with an accuracy of less than approximately $10^\circ$. The in-orbit performance of this Earth sensor will be evaluated by a planned microsatellite mission in near future. The developed Earth sensor enables stable and reliable operation of microsatellites.

Acknowledgments

This research was supported by a Grant-in-Aid for Scientific Research on Innovative Areas KAKENHI: 24760658 from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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