# Compact Infrared Camera (CIRC) for earth observation adapting athermal optics

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## ABSTRACT

We have developed the compact infrared camera (CIRC) with an uncooled infrared array detector (microbolometer) for space application. The main mission of the CIRC is the technology demonstration of the wildfire detection using a large format (640×480) microbolometer. Wildfires are major and chronic disasters affecting numerous countries, especially in the Asia-Pacific region, and may get worse with global warming and climate change.
Microbolometers have an advantage of not requiring cooling systems such an a mechanical cooler, and is suitable for resource-limited sensor systems or small satellites. Main characteristic of the CIRC is also an athermal optics. The thermal optics compensates the defocus due to the temperature change by using Germanium and Chalcogenide glass which have different coefficient of thermal expansion and temperature dependence of refractive index. The CIRC achieves a small size, light weight, and low electrical power by employing the athermal optics and a shutter-less system.
Two CIRCs will be carried as a technology demonstration payload of ALOS-2 and JEM-CALET, which will be launched in JFY 2013 and 2014, respectively. We have finished the ground calibration test of the CIRC Proto Flight Model (PFM). Athermal optical performance of the CIRC have been confirmed by measuring modulation transfer function (MTF) in a vacuum environment and at environmental temperature from -15 to 50 °C. As a result, MTF was found to be effective at capturing clear images across the entire range of operating temperatures. We also provide an overview of the CIRC and radiometric test results in this presentation.

**Keywords:** remote sensing, thermal infrared imaging, microbolometer, wildfire, ALOS-2, CALET

## 1. INTRODUCTION

Microbolometers are widely used in commercial and military applications. Their advantage is that they do not require a cooling system, such as a mechanical cooler. Sensors without a cooling system for a detector are small in size, lightweight, and consume less power. Although the sensitivity of a microbolometer is lower than that of an HgCdTe-based photonic infrared detectors, its advantage of not requiring a cooling mechanism makes it suitable for small satellites or sensor systems whose resources are limited.
We have developed the Compact Infrared Camera (CIRC)[1,2,3] as a technology demonstration payload for thermal infrared imaging from space using a microbolometer. The main mission of the CIRC is to detect wildfires, which are a major and chronic disaster that affects many countries, especially those in the Asia-Pacific region. There are also suggestions that this situation will get worse with global warming and climate change. In the Sentinel Asia project, which will share disaster information in almost real time across the Asia-Pacific region, wildfire detection has been chosen as one of the important activities to be monitored. Therefore, their early detection is important. An effective means of early detection is to increase their observation frequency. Our aim is to realize frequent observations by loading CIRCs in as many satellites as possible by taking advantage of their small size, low weight, and low power consumption. Other mission targets of the CIRC are volcanoes or heat island phenomena in a city. The CIRC will be carried as a technology demonstration payload of the Advanced Land Observing Satellite-2 (ALOS-2)[4], and CALorimetric Electron Telescope (CALET)[5], which will be attached to the Japanese Experiment Module (JEM-EF) at the International Space Station (ISS).
In this paper, we present the verification results of the athermal characteristics and the calibration of the shutter-less system with the CIRC Proto Flight Model (PFM). In section 2, we describe ALOS-2 and CALET. The specifications of

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the CIRC is described in section 3. In section 4, the ground calibration results of the CIRC PFM onboard ALOS-2 and CALET is presented. The airborne observation with the CIRC ground test model is shown in section 5. In section 6, the conclusion is provided.

## 2. ALOS-2 AND CALET

ALOS-2 is a follow-up mission to ALOS, which has been contributing to cartography, regional observation, disaster monitoring, and resource surveys since its launch in 2006. JAXA is conducting research and carrying out development activities to improve the wide and high-resolution observation technologies developed for ALOS to further fulfill social needs. These social needs include (1) disaster monitoring of damage areas, both in considerable detail and when these areas may be large; (2) continuous updating of data archives related to national land and infrastructure information; (3) effective monitoring of cultivated areas; and (4) global monitoring of tropical rain forests to identify carbon sinks. ALOS-2 will be launched in 2013. ALOS-2 succeeds the L-band synthetic aperture radar (SAR) observation of ALOS PALSAR with enhanced capabilities. Table 1 lists the baseline specifications of ALOS-2. The mounting location of CIRC is shown in Figure 1. Basically, CIRC will take images of the target area when the SAR is pointing to the right at an off-nadir angle of 30°.

CALET is an international program of the ISS that will search for signatures of dark matter and provide direct measurements of the highest energy of the cosmic ray electron spectrum to observe discrete sources of high-energy particle acceleration in our local region of the galaxy. CALET will address many outstanding questions, including (1) the nature of the sources of high-energy particles and photons through the high-energy spectrum, (2) the details of particle transportation in the galaxy, and (3) signatures of dark matter in either the high-energy electrons or the gamma ray spectrum. It will also be capable of monitoring gamma ray transients and solar modulation. CALET will be launched in 2014. The baseline specifications of CALET are listed in Table 1. CIRC will be mounted on the bottom of CALET, which is shown in Figure 1.

Table 1. Baseline specifications of ALOS-2 and CALET.

| Satellite | ALOS-2 | CALET |
|---|---|---|
| Size | 9.9 m×16.5 m×3.4 m | 1.0 m×0.8 m×1.85 m |
| Mass | <2000 kg | <500 kg |
| Bus power | >5200 W | >500 W |
| Communication | <800 Mbps | <300 kbps |
| Orbit | 628 km | 407 km (nominal) |

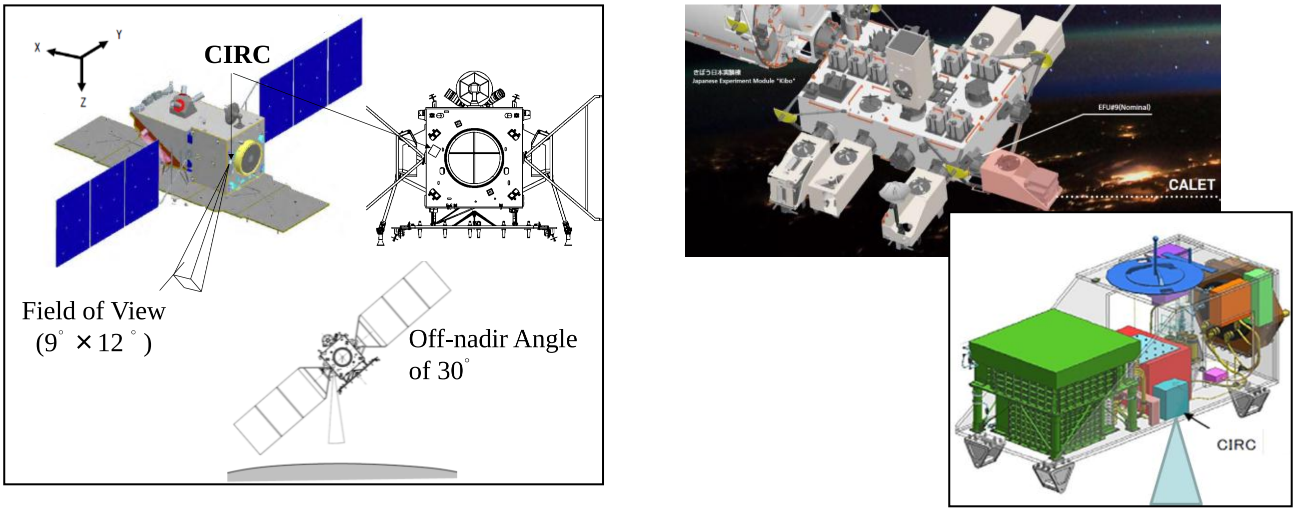


Figure 1. Schematic view of ALOS-2 (left) and CALET(right), and the mounting location of CIRC.

# 3. COMPACT INFRARED CAMERA (CIRC)

The main mission of CIRC is to demonstrate the technology for detecting wildfires using a microbolometer. The CIRC has the characteristics of athermal optical and shutter-less systems. The athermal optical system of the CIRC was designed by combining two infrared materials: germanium and chalcogenide. The temperature does not need to be controlled using a heater. Thus, we realized a CIRC with a small size, light weight, and low power consumption. Moreover, the CIRC design was based on a commercial infrared camera and employs commercial-off-the-shelf (COTS) parts to reduce cost and time for development. It is also possible to increase the observational frequency of wildfires if CIRCs are carried on various satellites, which can take advantage of its small size, lightweight, and low power consumption.

## 3.1 Specification of the CIRC

The baseline specifications of the CIRC are listed in Table 2. We set the baseline specifications to meet requirements for wildfire detection. The detector has a large format (640 × 480 pixels) to obtain a wide field of view. The spatial resolution is an important factor for wildfire detection. The spatial resolution is 200 m from an altitude of 600 km (ALOS-2) and 130 m from an altitude of 400 km (CALET). Eliminating the cooling system reduces the size (110 mm × 180 mm × 230 mm) and electrical power (<20 W). The CIRC PFM onboard ALOS-2 is shown in Figure 2. The CIRC is based on a commercial infrared camera. We modified the hardware design so that it can be applicable for a space application. CIRCs have key technologies, i.e., microbolometer, athermal optics, and shutter-less system, for achieving small size, low weight, and low power consumption.

## 3.2 Microbolometer

We adopted microbolometers as an infrared (IR) focal plane array (FPA) of the CIRC. Microbolometers are based on the principle of detecting infrared energy as minute changes of the IR absorber temperature when an infrared photon enters it. Their advantage is that they do not require a cooling system, such as a mechanical cooler. Sensors without a detector cooling system can be made to have a small size, low weight, and consuming less power.

The CIRCs have a 640 × 480 pixel silicon-on-insulator (SOI) diode uncooled IR FPA developed by MELCO. Its pixel size is 25μm square. The noise equivalent differential temperature (NEDT) is 40mK with f/1 optics. Drive and readout circuits are almost the same as those of the commercial IR camera. For a space application, we performed a radiation damage test, and a screening of commercial devices.

Table 2. Specifications of CIRC

| Parameter | Specifications |
|---|---|
| Size | 110 mm × 180 mm × 230 mm |
| Mass | 3 kg |
| Detector | Uncooled infrared detector |
| Wavelength | 8–12 μm |
| Number of pixels | 640 × 480 |
| Spatial resolution | <200 m @600 km (ALOS-2)<br><130 m @400 km (CALET) |
| Field of view | 12° × 9° |
| Exposure | 33 ms |
| Dynamic range | 180-400 K |
| NEDT | 0.2 K @ 300 K |
| FPN | 0.3 K @ 300 K |
| Temperature accuracy | 4 K (goal : 2K @ 300 K) |

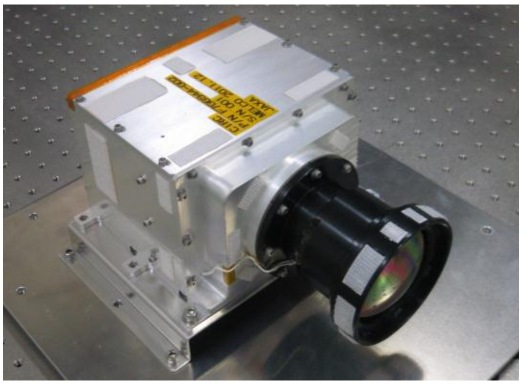

Figure 2. CIRC PFM onboard ALOS-2.

### 3.3 Athermal Optics

The optics of the CIRC are f/1.2 refractive optics. The focal length of the optics is 78 mm. The temperature of the CIRC is changed on orbit. The temperature change of the optics will cause a defocus because refractive indices of lens materials are highly dependent on temperature. In order to compensate for this defocus, we have to employ a focus mechanism or a heater to keep the optics temperature constant. However, such mechanisms increase sensor resources. Athermal optics can compensate for the defocus due to the temperature change without such mechanisms.

Figure 3 shows the optical design of the CIRC. The athermal optics of the CIRC compensate for the defocus by utilizing a combination of different lens materials and diffractive lenses. The optics of the CIRC use a germanium and a chalcogenide glass (GASIR®1). Figure 4 shows the calculated MTF of the CIRC optics versus the ambient temperature from -15ºC to 50ºC. The MTF is constant over the wide range of temperatures.

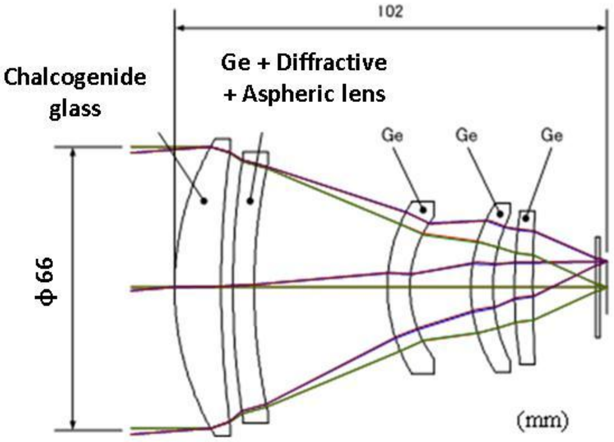


Figure 3. Optical Design of the CIRC.

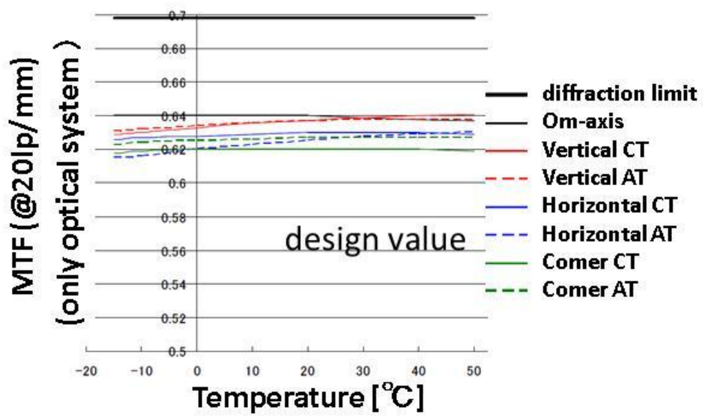


Figure 4. Calculated MTF of the CIRC Optics in the Ambient Temperature from -15ºC to 50ºC.

### 3.4 Shutterless system

We eliminated the mechanical shutter from the CIRC. This enables us to downsize the CIRC. A mechanical shutter is more commonly used as a calibration source. Therefore, we devised a way to achieve temperature calibration and stray-light correction from the inside the CIRC. We obtained images of various temperature blackbody with different CIRC temperatures in order to perform stray-light correction by temperature of the CIRC. The details are show in section 4.

## 4. GROUND CALIBRATION OF THE CIRC PFM ONBOARD ALOS-2 AND CALET

We carried out a ground calibration test of the CIRC PFM onboard ALOS-2 and CALET at the facility in Tsukuba Space Center in JAXA. The aims of this calibration were (1) to construct a data correction algorithm and (ii) to confirm the imaging quality and the radiometric quality.

### 4.1 Constructing data correction algorithm

The stray light (i.e., the overall radiation except that from the target) had to be removed, because a dark image cannot be taken as a result of the shutter-less system. We constructed a calibration data table (stray light correction coefficient and gain coefficient) and algorithm using blackbody images at various temperatures (–10°C to 50°C) obtained with CIRC PFM at various environmental temperatures (–15°C to 50°C). A flow chart of the data correction is shown in Figure 5.

① Bad pixel correction
A bad pixel is a pixel that has a brightness lower or higher than the surrounding pixels. We correct the brightness of a bad pixel by substituting the mean brightness of the normal surrounding pixels.

② Dummy correction
The electrical background is subtracted using dummy pixels, which have no sensitivity to incident infrared rays.

③ Stray light correction
Stray light correction is performed for each pixel by using the stray light correction coefficient.

④ Gain correction
Sensitivity correction is performed for each pixel by using the gain coefficient.

The experimental setup for the construction of the calibration data table is shown in Figure 6. The CIRC was installed in a vacuum chamber and enclosed a shroud to control its ambient temperature with a heater and cooler. The blackbody was set up in the front of the lens.

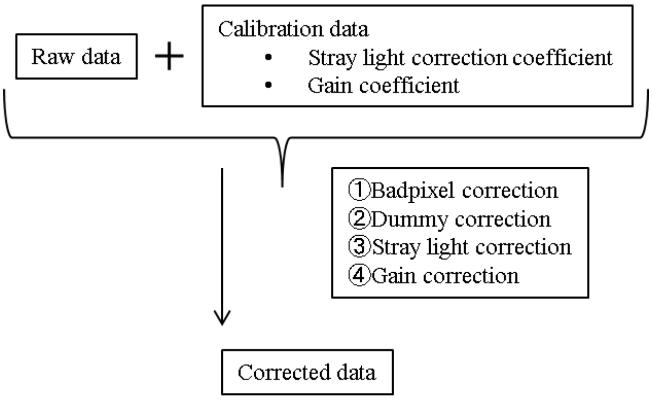


Figure 5. Flow chart of data correction.

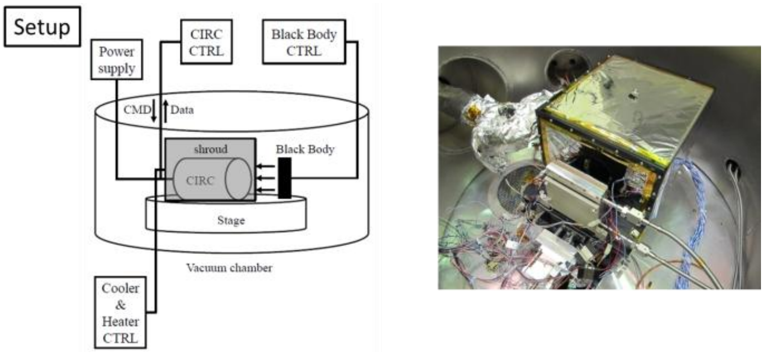


Figure 6. Experimental setup for construction of the calibration data table.

### 4.2 Confirming performance

We confirmed the imaging quality and radiometric quality of image after the data correction discussed in section 4.1.

#### 4.2.1 Imaging quality

The modulation transfer function (MTF) was measured in order to evaluate the imaging quality of CIRC at various operating temperatures (–15°C to 50°C). The experimental setup for MTF measurement is shown in Figure 7. The collimated infrared rays passed through a germanium window on the side of the vacuum chamber. The CIRC was able to capture images of the four-bar target. Figure 8 shows the measurement points of the four-bar target for MTF, at the center, ±5° in the cross-track (CT) direction, and ±3.5° in the along-track (AT) direction.

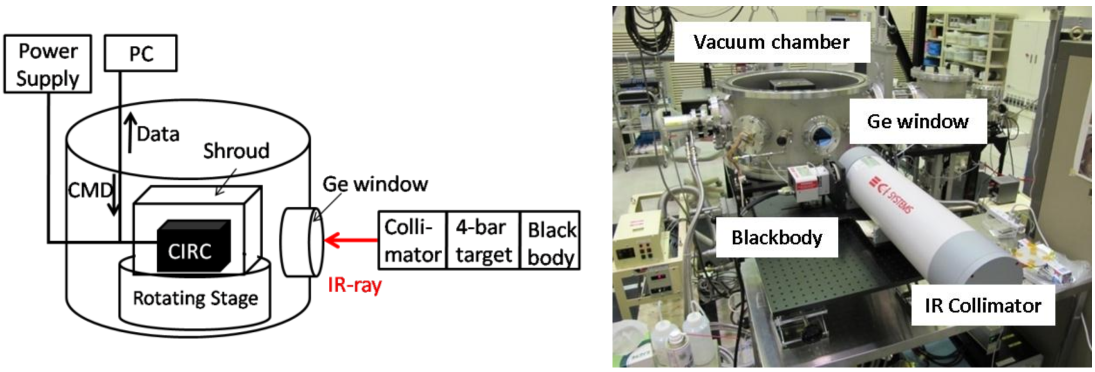


Figure. 7 Experimental setup of MTF measurement.

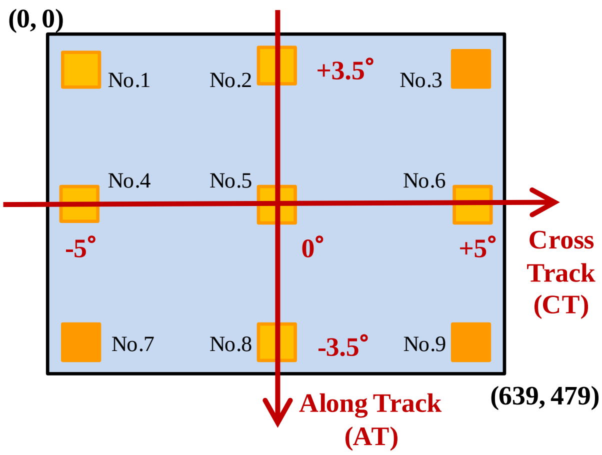


Figure 8. Measurement points of MTF on image acquired by CIRC

Figure 9 shows the MTF results of CIRC PFM for ALOS-2 and CALET. The MTF in the CT direction for ALOS-2 (Figure 9 (a)) is constant with the value of 0.2 ~ 0.39, which is regardless of the environmental temperatures. In contrast, the MTF in the AT direction (Figure 9 (b)) is slightly lower in low-temperature environments. In the case of CIRC PFM for CALET, the MTF are 0.24 ~ 0.33 in the CT direction (Figure 9 (c)) and 0.34 ~ 0.54 in the AT direction (Figure 9 (d)), respectively. The trend of the environmental temperature dependence is the same as the results of CIRC PFM for ALOS-2. MTF was found to be effective at capturing clear images across the entire range of operating temperatures for both CIRC PFM. We confirmed the athermal optical performance of the CIRC.

#### 4.2.2 Radiometric quality

The noise equivalent differential temperature (NEDT) and flat pattern noise (FPN) were estimated, shown in Table 3. These are the results expected from the design of the CIRC, and satisfied its specifications.

Figure 10 shows a comparison between a raw image and corrected image obtained by PFM for ALOS-2. Performing data correction makes it possible to capture smooth images without using a shutter system. The temperature accuracy is less than 2 K in a comparison of the brightness temperature of the corrected image and the actual blackbody temperature. This is within the specification for the temperature correction accuracy. In the case of CIRC PFM for CALET, the temperature accuracy is 0.5 ~ 2.8K, which is also within the specification.

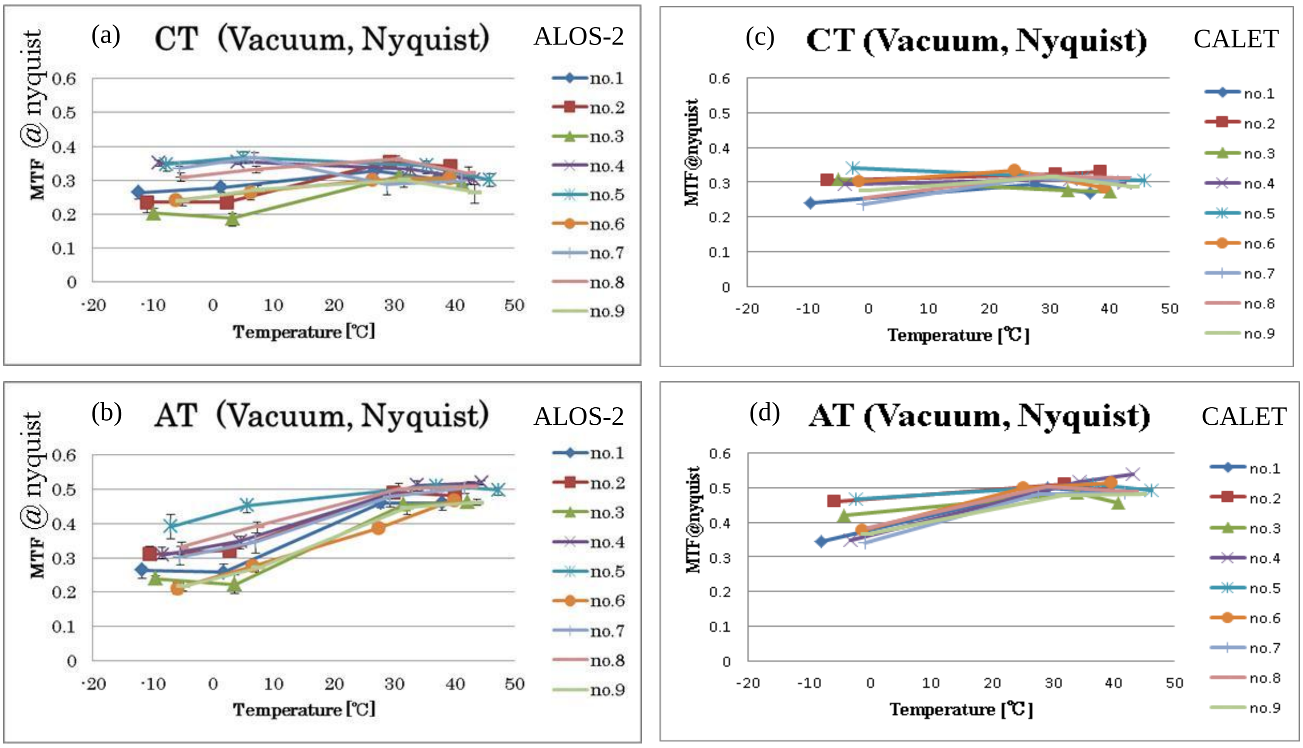


Figure. 9 Measurement results of MTF onboard ALOS-2 (left) and CALET (right).
(top) MTF in the CT direction, (bottom) MTF in the AT direction.

Table 3. Results of NEdT and FPN

| | NEdT [K] | FPN [K] |
|---|---|---|
| for ALOS-2 | 0.19 | 0.27 |
| for CALET | 0.18 | 0.21 |

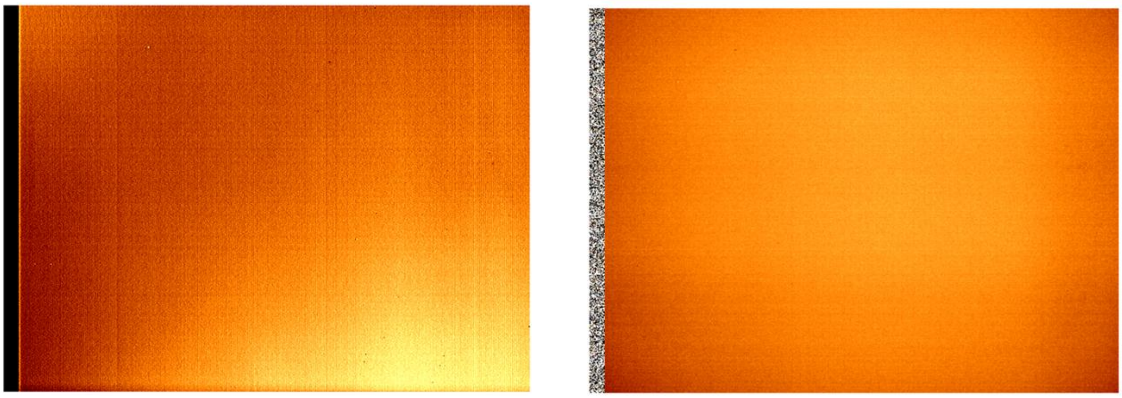

Figure 10. Blackbody image obtained by CIRC onboard ALOS-2.
(top) raw image and (bottom) corrected image.

# 5. AIRBORNE OBSERVATION WITH THE CIRC GROUND TEST MODEL

We carried out airborne observations using the ground test model (GTM) of CIRC, which has optical and radiometric performances equivalent to the corresponding PFM. Observational flight was carried out on March, 22 and 28, 2012. The aircraft was a “Cessna172 Sky hawk” made by the Cessna Aircraft Company. The observation area was Tsukuba City, Tsuchiura City in the south of Ibaraki Prefecture, and Narita City in Chiba Prefecture, all in Japan. The flight altitude ranged from 300 m to 750 m. The ground sample distance (GSD) at these altitudes ranged from about 10 cm to 25 cm.

Figure 11 shows the aerial image of Tsukuba Space Center, which is a facility in JAXA, captured from an altitude 750 m with a compact digital camera. The yellow rectangle is field of view of the CIRC. Figure 12 shows a comparison between the raw image and corrected image captured by an airborne observation from an altitude of 750 m. We confirmed that the data were corrected in the shutter-less system and that the actual images could be corrected by using the ground calibration data.

The temperature correction accuracy was checked using the image of the pond area shown in Figure 12 with the white box. The temperature of the pond measured using a water temperature gauge was about 11°C. The corrected data obtained by CIRC GTM revealed a temperature of 11.5°C, with the assumption that the emissivity of the water was 0.98. The temperature correction accuracy was about 0.5°C, which is within the specification of 2 K with the environmental temperature of ~ 300K.

Figure 11. Aerial image of Tsukuba Space center from 750m above.

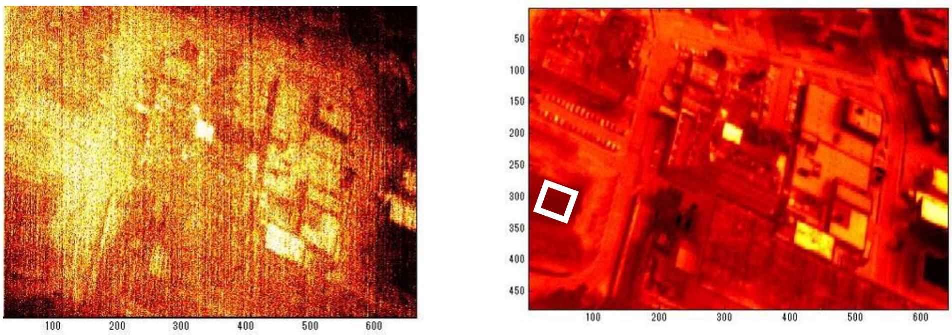


Figure 12. Image captured by airborne observation:
(left) raw image and (right) data corrected image, where white box shows pond area.

# 6. CONCLUSION

CIRC is an instrument equipped with an uncooled infrared array detector, which will be launched in JFY 2013 onboard ALOS-2, and in JFY 2014 onboard JEM/CALET. We have finished the ground calibration test of the CIRC onboard ALOS-2 and CALET, and have confirmed that its performance is as expected and sufficient for launch. We have also performed data correction using a shutter-less system by analyzing the data obtained through airborne observations. The temperature correction accuracy was about 0.5°C, which is within the specification of 2 K.

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