Development of the Compact Infrared Camera (CIRC) for Earth Observation

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***Abstract*— The Compact Infrared Camera (CIRC) is an instrument equipped with an uncooled infrared array detector (microbolometer). We adopted the microbolometer, because it does not require a cooling system such as a mechanical cooler, and athermal optics, which does not require an active thermal control of optics. This can reduce the size, cost, and electrical power consumption of the sensor.**

The main mission of the CIRC is to demonstrate the technology for detecting wildfire, which are major and chronic disasters affecting many countries in the Asia-Pacific region. It is possible to increase observational frequency of wildfires, if CIRCs are carried on a various satellites by taking advantages of small size and light weight.

We have developed two CIRCs. The first will be launched in JFY 2013 onboard Advanced Land Observing Satellite-2 (ALOS-2), and the second will be launched in JFY 2014 onboard CALorimetric Electron Telescope (CALET) of the Japanese Experiment Module (JEM) at the International Space Station(ISS). We have finished the ground Calibration of the first CIRC onboard ALOS-2. In this paper, we provide an overview of the CIRC and its results of ground calibration.

***Index Terms*—CIRC, ALOS-2, CALET, microbolometer, wildfire**

I. 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.

For this reason, microbolometers begin to be applied for various space applications. In planetary missions, the Thermal Emission Imaging System (THEMIS)[1] onboard Mars Odyssey spacecraft used a microbolometer focal plane array (FPA). The Longwave IR camera (LIR) onboard Venus Climate Orbiter (PLANET-C)[2], which was launched in 2010, also uses a microbolometer array.

In earth observation missions, the Infrared Spectral Imaging Radiometer (ISIR)[3] experiment tests the potential of microbolometer for applications to thermal infrared imaging. The ISIR was flown as a hitchhiker experiment on the space shuttle in 1997. Recent missions to measure the atmosphere vertical profiles like CALIPSO[4] and EarthCARE[5] also use a microbolometer as an imaging infrared instrument. In 2011, NIRST[6] was launched onboard Aquarius/SAC-D. NIRST is an infrared radiometer based on uncooled microbolometer detectors. JAXA began a research for application of microbolometer to earth observation since 2000. The Wide-Angle Multi-band Sensor – Thermal Infrared (WAMS-TIR)[7], aboard the station-keeping test airship (SPF-II) for the stratospheric platform project, is a thermal infrared multi-band radiometer using a microbolometer FPA.

We have developed the Compact Infrared Camera (CIRC) [8] 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; 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 there 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)[11], and CALorimetric Electron Telescope (CALET)[12], 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). The mission and details of the CIRC are described in section 2 and section 3, respectively. In section 4 and section 5, the measurements and the initial calibration results of the CIRC PFM are presented. In section 6, the results of airborne observations is reported, and in section 7, the summary is provided.

II. Mission Of The CIRC

The main mission of CIRC is to demonstrate the technology for detecting wildfires using a microbolometer. As mentioned earlier, wildfires are disasters that affects many countries in the Asia-Pacific region, and there are 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. The other objectives of CIRC mission are to monitor volcanoes and heat island phenomena in a city. Observing these with a thermal infrared imager will be useful in monitoring volcanoes and solving the heat island problem.

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 glass. As the temperature does not have to be controlled using a heater, we realized a CIRC with its small size, low weight, and low power consumption. Moreover, the CIRC design was based on a commercial infrared camera, and it employs commercial-off-the-shelf (COTS) parts to reduce cost and time for development.

It is possible to increase the observational frequency of wildfires if CIRCs are carried on various satellites by taking advantage of its small size, low weight, and low power consumption. Two CIRCs will be launched, one in JFY 2013 and the other in JFY 2014. The first one will be carried on Advanced Land Observing Satellite-2 (ALOS-2)[11] in JFY 2013, and the second will be in JFY 2014 onboard CALorimetric Electron Telescope (CALET)[12] of the Japanese Experiment Module (JEM) at ISS.

The orbits of ALOS-2 and ISS are shown in Fig. 1. The green lines represent the ALOS-2 orbit; this is synchronous sub-recurrent orbit at an altitude of 628km. In contrast, the white lines represent the ISS orbit. It has an orbital inclination of 52.8 degree; it is located at an altitude of about 400km.

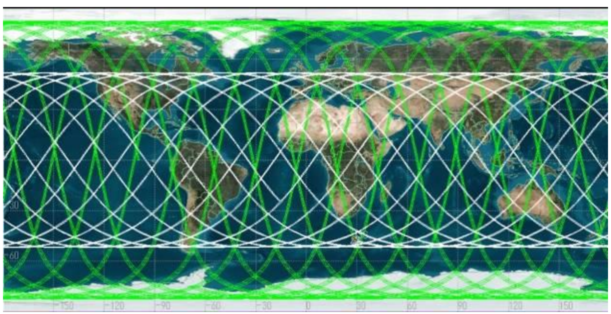

Fig. 1. Orbits of ALOS-2 and ISS

The schematic views of ALOS-2 and ISS/CALET equipped with CIRC are shown in Fig.2 and Fig3. 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. ALOS-2 has a Phased Array L-band synthetic aperture radar (SAR) , which is called PALSAR-2. 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.

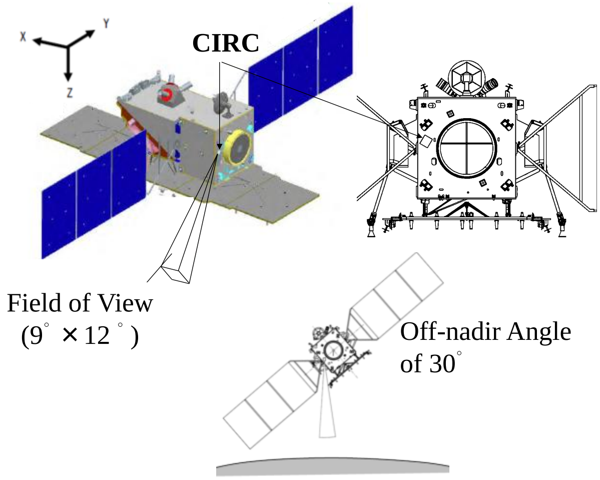

Fig. 2. Schematic view of ALOS-2

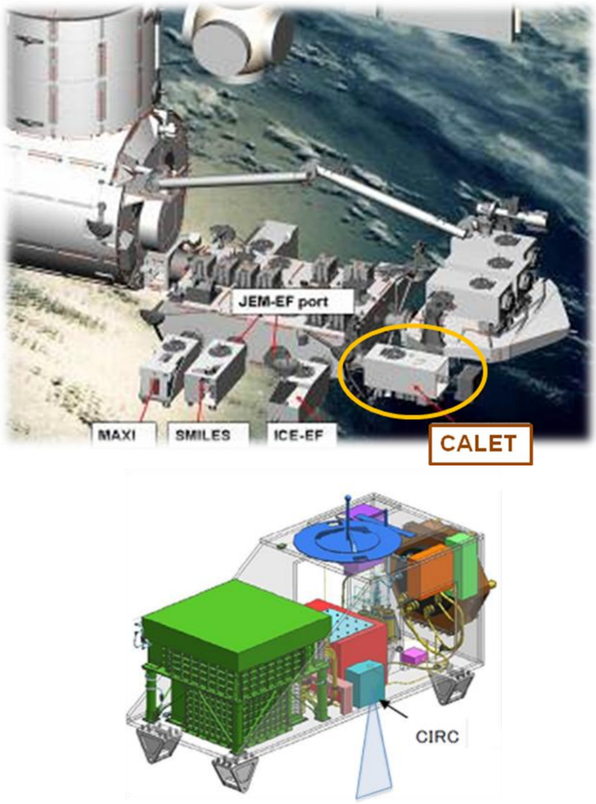

Fig. 3. Schematic views of ISS (top) and CALET (bottom)

III. DESIGN OF THE CIRC

The baseline specifications of the CIRC[8,9,10] are listed in Table 1. We set the baseline specifications to meet the requirements for wildfire detection. The detector has a large format (640 × 480 pixels) to capture a wide field of view. Spatial resolution is an important factor for wildfire detection; it 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 the consumption power (<20 W) of the CIRC.

The CIRC PFM onboard ALOS-2 is shown in Fig.4. The CIRC is based on a commercial infrared camera developed by Mitsubishi Electric Corporation (MELCO). 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. These are described in the subsequent paragraphs.

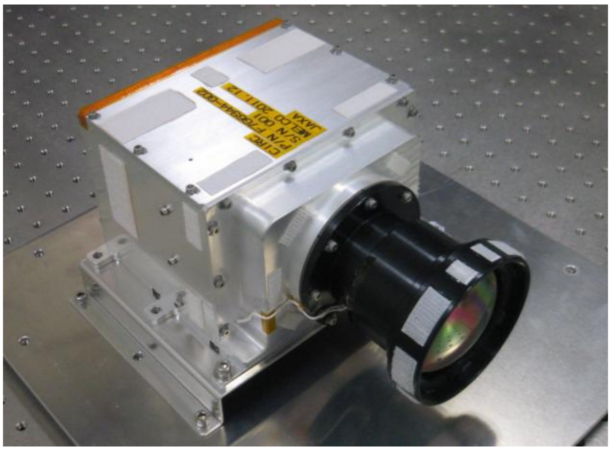

Fig. 4. CIRC PFM onboard ALOS-2

TABLE I. 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) <130 m @400 km (CALET)
Field of view	12° × 9°
Exposure	33 ms
Dynamic range	180−400 K
NEDT	0.2 K @300 K

A. 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 enter 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 SOI diode uncooled IR FPA uses a single-crystal silicon pn-junction diode as a temperature sensor. The single-crystal sensor based on silicon large-scale integration (LSI) technology gives it a low-noise characteristic. 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.

B. Athermal Optics

The optics of the CIRC is an f/1.2 refractive infrared optics. The focal length of the optics is 78mm. The temperature of the CIRC changes on orbit. The temperature change of the optics causes a defocus because refractive indices of lens materials are highly dependent on temperature. In order to compensate for this defocus, we need to employ a focus mechanism or a heater to maintain a constant optics temperature. However, such mechanisms increase sensor resources. An athermal optics can compensate for the defocus due to the temperature change without requiring such mechanisms.

Fig. 5 shows the optical design of the CIRC. The athermal optics of the CIRC compensates for the defocus by using a combination of different lens materials and diffractive lenses. The optics of the CIRC uses a germanium and a chalcogenide glasses (GASIR®1) and is designed in such a way that its modulation transfer function (MTF) changes only slightly when the ambient temperature changes from -15ºC to 50ºC.

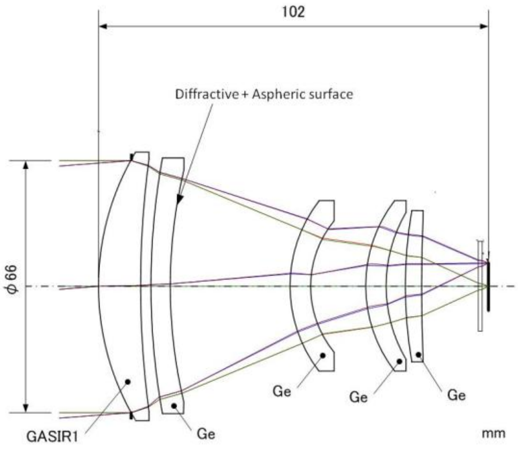

Fig. 5. Optical design of the CIRC

C. 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.

IV. Calibration Instruments Of The CIRC PFM

We carried out the ground calibration test[9,10] of the first CIRC onboard ALOS-2. Here, we report the result of the calibration test.

We measured the modulation transfer function (MTF) in order to evaluate the optical performance of CIRC at various operating temperatures of the CIRC. Further, we evaluated the noise equivalent differential temperature (NEDT) and flat pattern noise (FPN) in radiometric tests.

We carried out ground calibration tests of CIRC at the facility in Tsukuba Space Center in JAXA.

A. Esperimental setup for MTF meaurements

The schematic view and experimental setup for MTF measurement are shown in Figs. 6 and 7, respectively. The CIRC was installed in a vacuum chamber and enclosed a shroud to control its ambient temperature with a heater and cooler. During the experiment, the pressure in the vacuum chamber was ~10^{-5} Torr. Infrared rays were emitted by a blackbody (CI Systems SR800) and passed through the four-bar targets (as shown in Fig. 8) installed in the reflective collimator system (CI Systems ILET-5-1.1). 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. A image of four-bar target captured by CIRC is shown in Fig.9. And a rotating stage under the CIRC enabled it to capture the four-bar target images at any positions on the image of the CIRC.

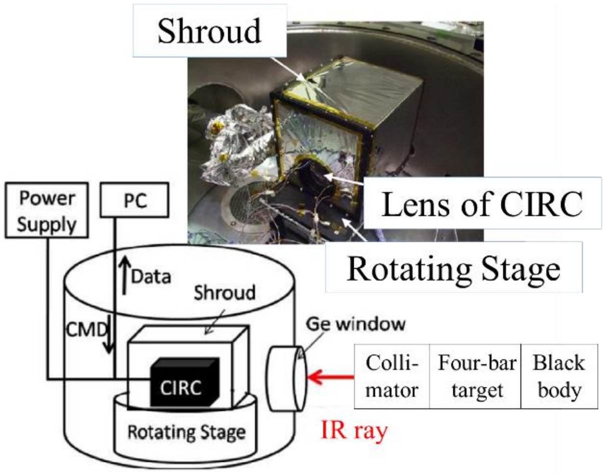

Fig. 6. Schematic view of MTF measurement

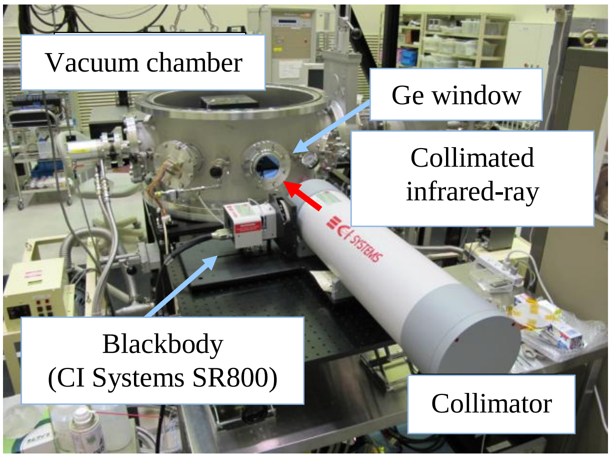

Fig. 7. Experimental setup of MTF measurement

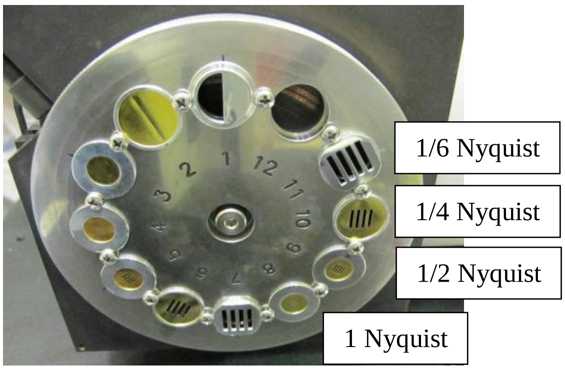

Fig. 8. Four-bar targets mounted on the collimator system

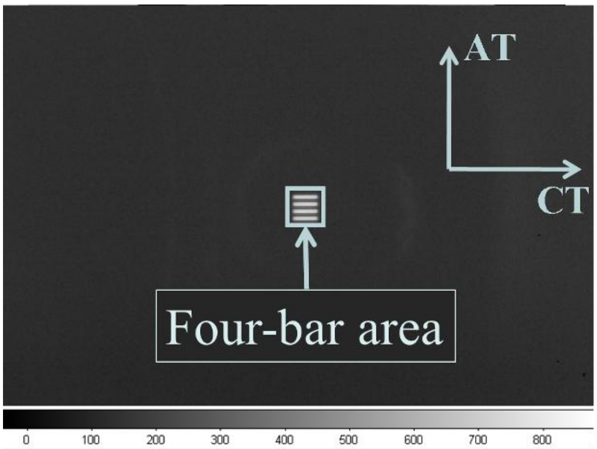

Fig. 9. Image of four-bar target as captured by CIRC for evaluation MTF

We evaluated the MTF of the CIRC from images of the four-bar target. We measured the MTF in a vacuum at a Nyquist frequency, which is 20 line pairs par mm in the case of the CIRC, at the whole image of the CIRC, and we measured the MTF of the CIRC at temperatures ranging from -15°C to +50 °C under changing ambient temperature of the CIRC. Ambient temperature was controlled by controlling the temperature of the shroud enclosing the CIRC. This ambient temperature range is the operational temperature range of the CIRC. We monitored the temperature of the lens barrel and the detector package of the CIRC.

Fig. 10 shows the measurement points of the four-bar target for MTF were at the center, ±5° in the cross-track (CT) direction, and ±3.5° in the along-track (AT) direction. The MTF in the CT/AT directions was measured by rotating the four-bar target.

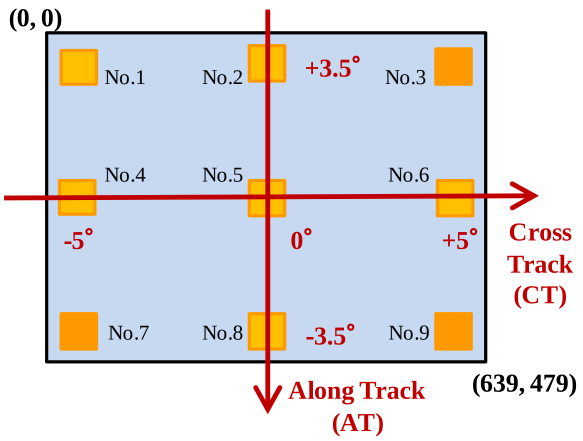

Fig. 10. Measurement points of MTF on image acquired by CIRC

B. Radiometric calibration tests

Fig. 11 shows the schematic view of the experimental setup for radiometric calibration tests. It was the same as that for the MTF experiments except for the blackbody was placed in front of the CIRC.

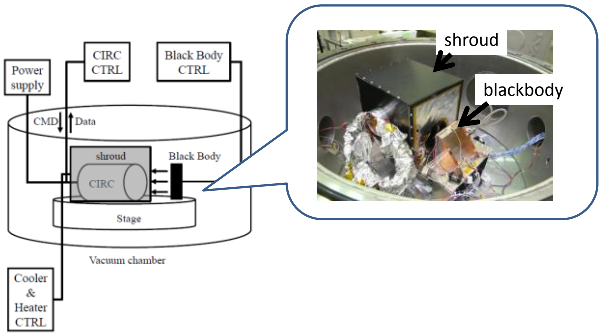

Fig. 11. Schematic view of experimental setup for radiometric measurements

We measured the radiometric performance of the CIRC in a vacuum environment and captured images of the blackbody at temperatures ranging from -10°C to +50 °C under changing ambient temperature of the CIRC, which ranged from -15°C to 50°C. We performed sensitivity and stray-light corrections from the images of various temperature blackbody at different ambient temperature. It is important to correct stray-light from inside the CIRC because it does not have a mechanical shutter.

V. Calibration Results Of The CIRC PFM

A. Results of MTF measurements

The measurement results of the MTF at Nyquist frequency are show in Fig. 12. Each line in the figure represents a mesurement point in Fig.10.

The MTF in the CT direction (Fig. 12. top) was constant regardless of the environmental temperatures. In contrast, MTF in the AT direction was slightly lower in low-temperature environments. However, this results is no problem to capture clear images in the entire range of the operating temperatures of the CIRC. This confirm the athermal optical performance of the CIRC.

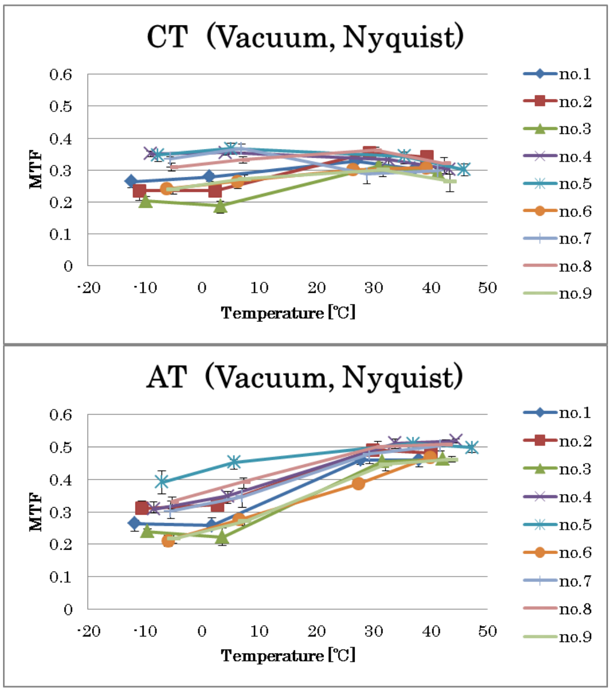

Fig. 12. Measurement results of MTF. MTF in the CT direction (top). MTF in the AT direction (bottom)

B. Results of radiometric calibration tests

We also verified the radiometric performance of the CIRC with shutter-less system. First, we estimated the noise equivalent differential temperature (NEDT) and flat pattern noise (FPN). We performed stray-light correction from the data of the same temperature blackbody images at different ambient temperatures, ranging from -15°C to 50°C. We defined the mean temperature of the lens barrel and detector package as the ambient temperature. In addition, we performed sensitivity correction using the data on different temperature blackbody images. Analysis of the data revealed the NEDT and FPN to be 0.19K and 0.27K,respectively[9]. This is the expected result from the design of the CIRC, and satisfied with the specifications of the CIRC.

Next, we performed background correction along with stray-light correction and sensitivity correction. Fig. 13 shows a blackbody image before background correction. And Fig.14. shows the image of the same blackbody after background correction. Background correction[10] is performed in the following steps.

1) Subtract the electrical background by using dummy pixels, which has no sensitivity to incident infrared rays. CIRC has 20 × 480 dummy pixels besides 640 × 480 effective pixels. The left twenty pixels in Fig.13 are dummy pixels.

2) Perform stray-light correction for each pixel by using the same temperature blackbody data at different ambient temperatures.

3) Perform sensitivity correction for each pixel by using detector gain devised by different temperature blackbody images.

The corrected image (Fig. 14) is smooth for all the effective pixels; we confirmed that the temperature accuracy is below 2K as compared to the brightness temperature of the corrected image and actual blackbody temperature.

Performing background correction by using the blackbody data corresponding to the ambient temperature of the CIRC enables capture of smooth images. We confirmed that it is possible to correct the background without using a shutter system. We will continue to search ways to correct images that would improve the correction accuracy.

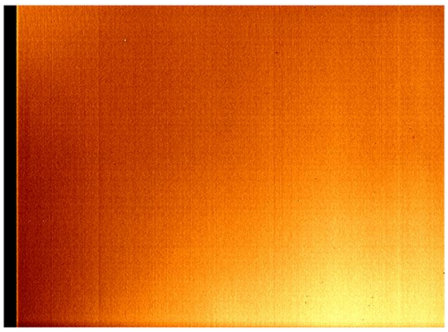

Fig. 13. Raw image of blackbody of CIRC

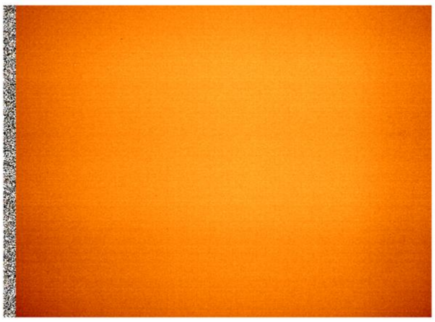

Fig. 14. Corrected image of blackbody of CIRC

VI. Airborne Observation With The CIRC Ground Test Model

We carried out airborne observations with the ground test model (GTM) of CIRC. Fig. 15 shows the CIRC GTM, which has optical and radiometric performances equivalent to the corresponding PFM[8]. The model was constructed for establishing a way to perform ground calibration and carry out field observations before fabrication of the 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 (see Fig.16). It is one of the best-selling single engine aircraft in the world and can carry four passengers, including the pilot. 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 300m to 750m. The Ground sample distance(GSD) in this altitude was about from 10cm to 25cm.

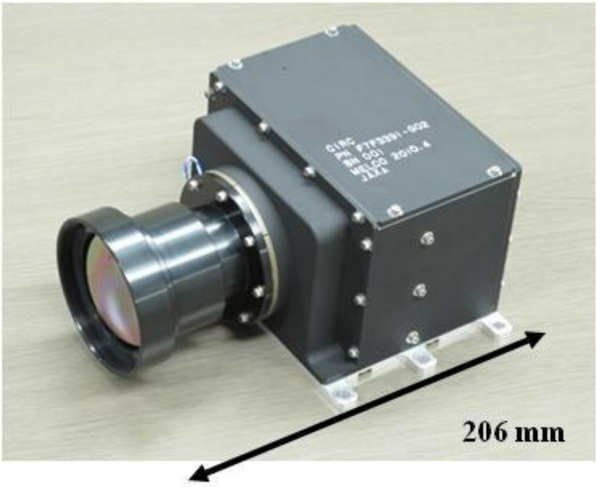

Fig. 15. CIRC Ground Test Model (GTM)

Fig. 16. “Cessna172 Sky hawk” used for airborne observations

Fig.17 shows the aerial image of Tsukuba Space Center, which is a facility in JAXA, captured from an altitude 750m with a compact digital camera. The yellow rectangle is a field of view of the CIRC, and Fig.18 shows the raw infrared image captured with the CIRC GTM at the location shown in Fig.17.

We performed a background correction of the images as previously mentioned in section 5. The result of background correction is shown in Fig.19. We were able to get a clear image. On the other hand, we obtained dark images before capturing images with a shutter, and we subtracted this dark image from raw image (Fig.18) to compare it with the background corrected image (Fig.19). The image subtracted dark image is shown in Fig.20. Both Fig.19 and Fig.20 was a similar clear images. We confirmed that the background was corrected in shutter-less system and that the actual images were able to be corrected by using the ground calibration data.

Fig. 17. Aerial image of Tsukuba Space center from 750m above

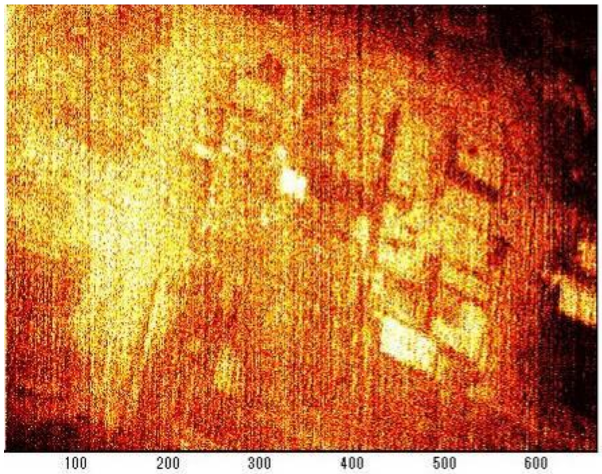

Fig. 18. Raw image of CIRC captured by Airborne observation

(Tsukuba Space Center from 750m above)

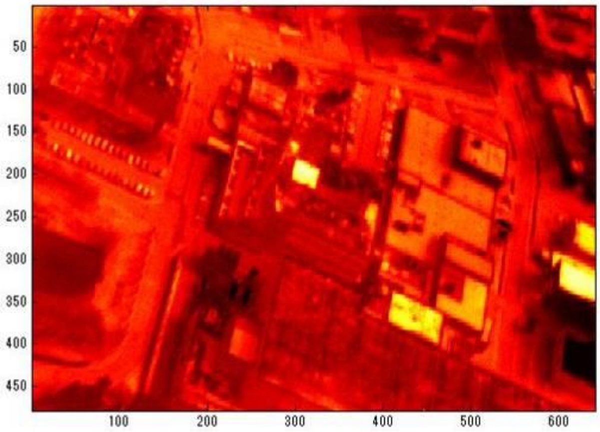

Fig. 19. Background correction for Fig.18

(with shutter-less system)

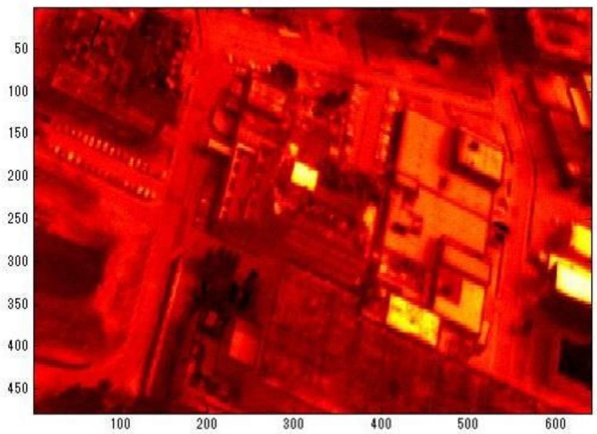

Fig. 20. Image subtracted dark image from Fig.18

(with a shutter)

VII. SUMMARY

We have developed two CIRCs, both of which are thermal infrared imagers equipped with an uncooled infrared array detector (called microbolometer). The first one will be launched in JFY 2013 onboard ALOS-2, and the second will be launched in JFY 2014 onboard CALET at ISS. We have finished the ground calibration of the first CIRC onboard ALOS-2, and have confirmed that the performance of the CIRC is as expected and sufficient for launch. We have also performed background correction using a shutter-less system by analyzing the data obtained through airborne observations.

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