Evaluation of the mid- and near-infrared focal plane arrays for Japanese infrared astronomical satellite ASTRO-F

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ABSTRACT

We report on the extensive tests to characterize the performance of the infrared detector arrays for the Infrared Camera (IRC) on board the next Japanese infrared astronomical satellite, ASTRO-F. The ASTRO-F will be launched early 2004 and the IRC is one of the focal plane instruments to make observations in 2–26 μm . For the near-infrared observations of 2–5 μm , a 512 $\times$ 412 InSb array will be employed, while two 256 $\times$ 256 Si:As arrays will be used for the observations of 5–26 μm in the IRC. Both arrays are manufactured by Raytheon IRO.

To maximize the advantage of the cooled telescope and extremely low background radiation conditions in space, the dark current and readout noise must be minimized. The heat dissipation of the arrays also has to be minimized. To meet these requirements and achieve the best performance of the arrays, we optimized the array driving clocks, the bias voltage, and the supply currents, and evaluated the temperature dependence of the performance. In particular, we found that the voltage between the gate and source of the FET of the multiplexer SBRC-189 had a strong dependence on temperature. This effect becomes a dominant source for the noise unless the temperature is kept within 20mK. We have achieved the readout noises of about 30e[−] and 40e[−] with the correlated double sampling for the flight model readout circuits of the InSb and Si:As arrays, respectively. These noises ensure that the background-limited performance can be achieved for the observations of IRC in the 4–26 μm range in the current observing scheme.

In addition, we are now planning to make scan mode observations with IRC. We have developed a new operation way of the arrays to achieve the stable response and low readout noise in the scanning operation for the first time.

The IRC is now installed in the flight model cryostat and the first end-to-end test has just been completed. We report on the expected performance of the IRC together with the array test results.

Keywords: ASTRO-F, IRC, Near Infrared, Mid Infrared, Detector Array

1. INTRODUCTION

ASTRO-F¹ is the first Japanese space mission solely dedicated to infrared astronomy. InfraRed Camera (IRC)² is one of the focal plane instruments on board the ASTRO-F and make imaging and low-resolution spectroscopy observations in 2–26 μm . The IRC comprises three channels: NIR (2–5 μm), MIR-S (5–12 μm), and MIR-L (12–26 μm). The NIR channel uses a 512 $\times$ 412 InSb array, and 256 $\times$ 256 Si:As IBC arrays are used for MIR-S and MIR-L channels. Both are manufactured by Raytheon IRO. The design and specifications of the IRC are described in Wada et al. (2002)² and the optical performance is in Kim et al. (2002)³ This paper describes the operation and performance of the arrays which are used in the IRC.

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The advantage of the infrared observation from space is the extremely low background radiation compared with the ground-based observation. The reduction of readout noise of the detector is therefore crucial to achieve a high sensitivity. We have optimized the bias voltages and clock patterns to achieve the background limit performance in the mid infrared. We have investigated the dependence of the detector performance on the temperature and examined the optimum temperature range and the temperature stability. IRC is designed originally for pointing observations at fixed targets. In addition we are now planning scan mode observations by IRC. To make the scan observation, the detector array has to be operated in a way different from the usual imaging operation. In this paper we report a new operation method for the scan observation and evaluation of the performance of the detector.

In the scan mode the fast scanner of the detector must be aligned in the vertical direction to the scanning direction. Because of the mechanical design restriction, the NIR array cannot be placed in this way. At present we are planning the scan observation only with MIR-S and MIR-L. We discuss about a possible scanning operation of the NIR array in Sec. 3.3.

2. IMAGING OPERATION

2.1. Brief description of detectors

The InSb/SBRC-189 has a 512×412 format while Si:As/CRC-744 has a 256×256 format. Both have a hybridized structure of the readout integration circuit (ROIC) and the infrared active semiconductor. The detectors have a capability of non-destructive readout, therefore the correlated double sampling (CDS) and the Fowler-n sampling can be used.

Entire pixels on the detector are read as an image as follows. One output line is used to acquire the pixel data by time-sharing. A pixel is selected by two shift registers: the slow scanner (Y-direction) and the fast scanner (X-direction). The fast scanner scans every pixel in the line while the slow scanner is selecting a line. These two scanners have slightly different functions. The slow scanner supplies the power to all pixels in the selected row, while the fast scanner connects the selected column to the output. The signal of the pixel that is supplied the power and connected to the output is read. Each detector has four output lines. Four pixels next to each other can be read at once. For example, to readout one line or one column of Si:As/CRC-744 (256×256) the slow scanner must have 256 increments, but the fast scanner needs only 64 steps. The scanners cannot be operated in the decrement direction.

2.2. Experimental configurations

The detectors were put in the cryostat and cooled down to the LHe temperature. The prototype model (PM) of the IRC control electronics (IRC-E) at room temperature was used to drive the detectors.

The PM of the IRC-E consists of a sequencer and analog boards. The sequencer has two kinds of memory: the program memory to store the bit patterns to drive the detector and the acquisition memory to store the acquired observational data. All bias and active/inactive clock voltages are set in the analog board and supplied to the detector at the timing prepared by the sequencer. The output voltage is amplified by the pre-amplifier, converted into the digital signal by the 16bit analog-digital converters and written on the memory on the sequencer board.

In the cold electronics, all the lines are grounded through resistors for the protection of electrostatic discharge. All the bias lines are grounded also through capacitors to avoid the high frequency noise. A resistor was inserted in series on the I_{gg1} line for the current control.

We stabilized the temperature of the detector module by the heater on the module. The thermal conductance between the detector module and the cold surface of the cryostat is adjusted by the thermal insulator made of Vespel SP-1 and the copper thermal strap. The temperature is monitored every ten mili-second, and we start acquiring the data after it becomes sufficiently stable.

In the performance tests of InSb/SBRC-189, a light source was placed face to face with the detector and a board with a big pinhole was inserted in-between to make a point image. The entire detector unit was masked by aluminium tape to simulate the dark condition. In the performance tests of Si:As/CRC-744, the optical

Figure 1. Illustration of a pixel element of InSb/SBRC-189 and Si:As/CRC-744.

Figure 2. Schematic diagram of the readout circuit of InSb/SBRC-189 and Si:As/CRC-744

system of the IRC/MIR-L camera was used to make a point image. We used a micro lamp of $30\mu\text{m}\times 30\mu\text{m}$ provided by NASA Goddard Space Flight Center (GSFC) as a light source in both experiments.

Figure 3. Configuration for the detector test

Figure 4. Schematic diagram of the data acquisition path

2.3. Array operation

Figure 5. Schematic diagram of the imaging operation

As will be described in Sec.2.6, V_{GS} of the ROIC is quite sensitive to the environmental temperature. Therefore the temperature must be kept constant during the observation. To stabilize the temperature we have developed clock patterns described below.

The fast (X-direction) and slow (Y-direction) scanners are continuously operated during the exposure as the same manner as reading the signal. In other words, the detector is operated continuously and acquired signals

Figure 6. Estimation of the conversion factor for Si:As/CRC-744

are occasionally written on the memory for data acquisition.

Because CRC-744 and SBRC-189 are designed to reset a line of pixels at once, all the pixels can be reset quickly. But we select all the pixels during the frame reset in the same way as the frame reading in order to equalize the generation of the heat during the frame reset and that during the frame reading.

We summarize the bias voltages and currents in Fig.1. We supply a sufficient but minimum power to the detector for its high performance. The capacitance of the long wirings in the cryostat is taken into account for the determination of the currents.

2.4. The conversion factor

We experimentally determined the conversion factors ($\text{e} \cdot \text{ADU}^{-1}$) between the arbitrary data unit (ADU) and the number of electrons for each detector.

The relationship between noise and signal is represented as follows

$$N_{\text{total}}^2 = N_{\text{read}}^2 + \frac{S}{g}, \quad (1)$$

where N_{total} is a total noise in ADU, N_{read} is a readout noise in ADU, S is a signal in units of ADU and g is the conversion factor ($\text{e} \cdot \text{ADU}^{-1}$). According to this equation, the conversion factors are estimated from the slope of the plot of N_{total}^2 against the signal (see Fig.6). We obtain $10 \text{ e} \cdot \text{ADU}^{-1}$ for InSb/SBRC-189 and $6 \text{ e} \cdot \text{ADU}^{-1}$ for Si:As/CRC-744. We use these values in the following discussions.

2.5. Generation of the heat by the detector

Fig. 1 shows the heat generation of the detector in the array operation described above. The upper limit is obtained by the experiments, in which the temperature attained by the self-heating of the detector is reproduced by the heater, while the lower limit is estimated by the formula below.

$$Q_{\text{min}} = (V_{\text{ss1}} - V_{\text{dduc}}) \times I_{\text{ss1}} + (V_{\text{ddo}} - V_{\text{out}}) \times I_{\text{sso}}. \quad (2)$$

The bias voltages and currents are adjusted to achieve a high performance of the detectors, but are kept minimum to minimize the heat dissipation and obtain a high stability (see next section).

InSb/SBRC-189	$Q \simeq 0.5$
Si:As/CRC-744	$Q \simeq 0.8$

Table 1. The generation of heat by the each detector (mW)

Figure 7. Temperature dependence of the performance of InSb/SBRC-189. Dark current (a), readout noise (b), relative responsivity (c), V_{GS} and gain of the source followers (d)

2.6. Dark current, readout noise, photo response and its temperature dependence

The dark current and readout noise are estimated from the average and the standard deviation of ten or more CDS images in the dark conditions.

The gain and V_{GS} of the source followers are estimated from the data obtained with the continuous reset. It shows a relation between the input and output voltages of two-stage source followers.

For InSb/SBRC-189, the temperature dependence of V_{GS} of the ROIC was found to be the most critical. It is stable around 14K but it shows a strong temperature dependence of 120 e-K^{-1} below 13K. Therefore we must keep the temperature in the range of $\pm 20 \text{ mK}$ during the observation, otherwise the change in the gain will exceed the readout noise. The relative responsivity is constant above 10K but rapidly falls below 10K. As a result, the optimum temperature of InSb/SBRC-189 is 14K, or it should at least be operated at temperatures higher than 10K with the stability of 20mK during each exposure.

The temperature dependence of V_{GS} of the ROIC is also strong for Si:As/CRC-744. It is 140 e-K^{-1} in all the temperature ranges tested. We must stabilize the temperature of the detector within 30 mK during the observation, not to have excess noises due to the gain change relative to the readout noise. The dark current

Figure 8. Temperature dependence of the performance of Si:As/CRC-744. Dark Current (a), readout Noise (b), relative responsivity (c), V_{GS} of source followers (d)

increases rapidly for $T > 7.5K$. As a result, Si:As/CRC-744 must be operated below 7.5K and the temperature must be stabilized within 30mK during each exposure.

3. DEVELOPMENT OF SCANNING OPERATION WITH SI:AS/CRC-744

3.1. Background for scanning operation

In addition to the standard imaging operation as described in previous sections, we are now planning to implement the scan mode operation in order to observe the all sky with the IRC. Table 3 shows the detection limits and spatial resolution estimated for the scan mode operation at present. In the scan mode operation, the detectors must be operated differently from the imaging operation. We have developed a special detector operation scheme for the scan mode observation.

ASTRO-F will be put in a solar synchronous polar orbit with a period of about 100 minutes, hence the field-of-views of the IRC quickly moves with a scan rate of 4 arcmin/sec.

It will survey all sky in a half year (Fig.9, most right). In the scan operation, we sample only one row of the pixels in the cross scan direction synchronously with the movement of the view sight while the satellite revolves on its orbit as if the sky were painted by a brush.

The spatial resolution in the in-scan direction is determined by the sampling rate, and that in the cross-scan is fixed primarily by the pixel field of view. The pixel field of view of the MIR-S and MIR-L is $2.34''$. To have

Figure 9. Survey observation with the scan operation of detector arrays

a full spatial resolution a sampling rate of 11 ms is needed. However, the available downlink data rate does not allow the full sampling and thus the spatial resolution has to be degraded.

In the current plan the spatial resolution will be $4.7'' \times 9.4''$, slightly worse than the full resolution ($2.34'' \times 2.34''$).

3.2. Scanning operation

Fig. 10 illustrates a clock pattern for the operation of the detectors, which provides the best performance at present. Fig. 11 shows an example of the scan operation data in the laboratory. The characteristics of this clock pattern are summarized below:

The Si:As/CRC-744 detector array is subject to the cross talk (the contaminating effect from neighboring pixels). In the imaging mode, the pixels at the edge of the array or around the hot pixel show higher outputs level than the average even in the dark configuration. If the lines which are not used in the scan operation are left without operation, they will easily be in the saturation level and affect neighboring sampled pixels. Therefore the unsampled pixels are kept in the reset level by selecting them with the reset pulse being sent.

To avoid the effects of the neighboring pixels, several lines are read but only the data of a middle line are actually stored. It is a kind of partial imaging operation. It takes about 0.5 ms to read one line and the sampling rate can be adjusted by changing the number of the lines to be read with the basic clock speed unchanged.

Both of the fast and slow scanners can be scanned only in one direction. Therefore to repeat reading of the fixed lines requires the re-setup of the scanners. There are two ways to reset the scanner: to activate $\phi 1S$ and $\phi 2S$ simultaneously or to go back to the first line after continuous reading to the end of the scanner. We adopted the latter method, which supplies the power to all lines of the array regularly.

3.3. Possibility of Y-scanning operation

As described in Sect.3.1, the generation of the heat will be concentrated in the used line. What happens if the fast scanner is fixed and only the slow scanner is operated to make the scanning operation (hereafter y-scanning operation)? From the view of the power dissipation, this should be the same as in the imaging operation. The slow scanner is operated for all the lines periodically. If CRC-744 and SBRC-189 have the same characteristics on this point, near-infrared all sky survey with the NIR channel ($2-5\mu m$) may be possible. However because the column of the pixels pointed by the fast scanner is connected to the output and the signals of these pixels are switched by the power supply, the signal may be affected by the signals of the previous pixels.

Figure 10. Scanning operation for Si:As/CRC-744: Map on the detector in scan operation (a), two methods of the reset operation (b), driving clock pattern (c)

Figure 11. Example of the scan operation data

We made the imaging measurements by swapping the operations of the fast and slow scanners (y-imaging). Fig. 12 shows an example of the results. This particular detector has a hot pixel whose output shows always a saturated level and can be used to simulate a bright star. The effect of the hot pixel is extended to only one or two pixels, thus the operation with y-imaging seems possible for actual observations. The measurements were made during the first phase of the MIR-L optical testings and an image like a supernova remnant appears for a pinhole without focus.

3.4. Scanning operation testings result

Table 2 shows the readout noise in 10 sec exposure and Fig. 13 shows a linearity of the response in the imaging mode, scan mode, and y-scan mode. The readout noise and the linearity in the scanning operation are moderate and sufficiently good for actual observations. The shot noise due to the dark current is not significant because the integration time in the scan mode is very short.

Figure 12. Examples of the normal imaging operation (left) and the operation of the slow scanner fast and the fast scanner slow (right)

Operation	Readout noise[e]
Imaging	42
X-Scanning	47
Y-Scanning	43

Table 2. Readout noise of each operation mode (CDS)

If the y-scanning operation is sufficiently evaluated, all sky survey observations with the NIR channel may also become possible.

Figure 13. Output versus time in the dark configuration (left), and in the spot lighted configuration (right)

4. DETECTION LIMIT FOR POINT SOURCES

Table 3 shows the detection limits of each channel for one-pointing observations (8×60 sec exposure) and survey observations of the IRC. We assume that thermal stability of the detector module described in Sect.2 is achieved. We adopt $30 e^-$ and $40 e^-$ for the readout noise of InSb/SBRC-189 and Si:As/CRC-744, respectively.

The efficiency of optics is the designed value. We use the COBE data at $\beta=60^\circ$ for the estimation of the background radiation. Around the ecliptic poles, the detection limit should become better because of the overlapping scan paths of field of views.

The IRC survey will provide the database with the detection limit better by a factor of 2–5 and the spatial resolution higher by nearly two orders of magnitude than the IRAS survey. It will have a similar detection limit at $10\mu\text{m}$ and much better at $20\mu\text{m}$ with higher spatial resolution than MSX, and the IRC survey can provide the data not only for a limited area of the sky but for the nearly all sky.

Fig.14 shows the detection limits and the Spectral Energy Distributions (SEDs) of target objects. For example, Ultra Luminous Infrared Galaxies (ULIRGs) may be detected to the depth of $z=0.05$ in the mid-IR region in the IRC scan observation. We can survey star formation regions in wide areas and a number of young stellar objects at different evolutionary phases should be detected together with the FIS survey.

Channel	Filter[μm]	Detection Limit for Pointing [μJy]	Detection Limit for Survey [mJy]
NIR	1.8–2.7	1.3	–
	2.7–3.7	1.2	–
	3.7–5.05	1.9	–
MIR-S	5.5–8.5	19	–
	6.0–11.5	19	50
	8.5–13.0	51	–
MIR-L	12.5–18.0	101	–
	14.0–26.0	92	100
	22.0–26.0	170	–

Table 3. Detection limit of the IRC for point source

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Figure 14. Detection limit for IRC and SEDs of target objects