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# KASINICS: Near Infrared Camera System for the BOAO 1.8 m Telescope

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**Abstract**

We developed Korea Astronomy and Space science Institute (KASI) Near Infrared Camera System (KASINICS) to be installed on the 1.8 m telescope of Bohyunsan Optical Astronomy Observatory (BOAO) in Korea. We use a $512 \times 512$ InSb array (Aladdin III Quadrant, Raytheon Co.) to enable $L$ band observations as well as $J$, $H$, and $K_s$ bands. The field-of-view of the array is $3'.3 \times 3'.3$ with a resolution of $0''.39$/pixel. We adopt an Offner relay optical system, which provides a cold stop to eliminate thermal background emission from the telescope structures. Most parts of the camera, including the mirrors, were manufactured from the same ingot of aluminum alloy to ensure a homologous contraction from room temperature to 80 K. We also developed a readout electronics system for the array detector. Based on preliminary results from test observations, the limiting magnitudes are $J = 17.6$, $H = 17.5$, $K_s = 16.1$, and $L$(narrow) $= 10.0$ mag at a signal-to-noise ratio of 10 for an integration time of 100 s.

**Key words:** infrared: general — instrumentation: detectors — techniques: photometric

## 1. Introduction

KASINICS (KASI Near Infrared Camera System) is one of the KASI (Korea Astronomy and Space science Institute) research and development projects to develop astronomical infrared observation systems. The development of KASINICS was a three-year project from 2004. In the first year, we decided on the design of the instrument, after discussions about scientific merits for Korean Astronomy and on technical issues with Japanese astronomers. We employed the Offner system (Offner 1975) for KASINICS, following the SIRIUS camera (Nagashima 1999; Nagayama 2000; Nagayama et al. 2003). The detailed design and the manufacturing were carried out in the second year. In the final year, system construction and integration tests were performed in the laboratory, and then the first light was obtained in 2006 December.

KASINICS is optimized for the BOAO (Bohyunsan Optical Astronomy Observatory) 1.8 m telescope to cover wavelengths from 1 to 5 $\mu$m with an InSb Aladdin array. The filter wheel is equipped with the $J$, $H$, $K_s$, and $L$ standard broadband filters (Simons & Tokunaga 2002; Johnson 1965; Cohen et al. 1992) and the $H_2$ (2.12 $\mu$m), $H_3^+$ (3.53 $\mu$m) narrow band filters. A new readout controller has also been developed for operating the InSb array. It works under a Microsoft Windows based personal computer with USB2.0 and TCP/IP communication. More details on the development process should be referred to the reports of Cha et al. (2006a) and Cho et al. (2006).

In this paper, we describe the design of the instrument in section 2, present results from test observations in section 3, and report on the system performance in section 4.

## 2. Instrument Design

### 2.1. Optics

Figure 1 shows the configuration of the optical system. Since the BOAO 1.8 m telescope is designed for optical observations, it is necessary to form a cold Lyot stop for blocking unwanted radiation from the telescope. We chose Offner relay optics (Offner 1975), which provides a cold Lyot stop. The secondary mirror (M2 in figure 1) eliminates thermal background noise. The Offner optics makes the optical system simple and compact, and decreases the spherical and chromatic aberration effectively. Table 1 presents the specifications of the Offner optics optimized for the 1.8 m telescope (F/8). The average seeing at the telescope site is about $1''.8$ at 0.5 $\mu$m (Kyeong et al. 1997). Assuming a wavelength dependence of $\lambda^{-0.2}$, we expect that the seeings are $1''.5$ and $1''.2$ in the $J$ and $L$ bands, respectively. Thus, the image sizes correspond to 84 to 105 $\mu$m, or 3 to 4 pixels at the Cassegrain focus (F/8) of the

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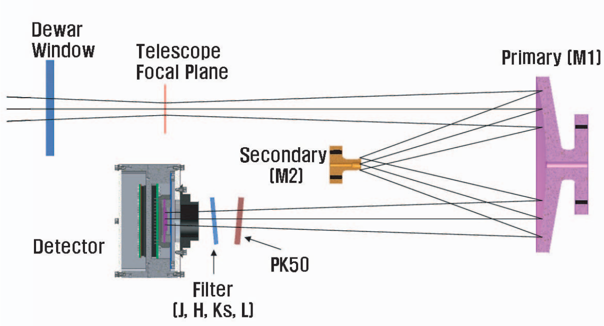


**Fig. 1.** Configuration of the optical system. KASINICS is equipped with Offner optics.

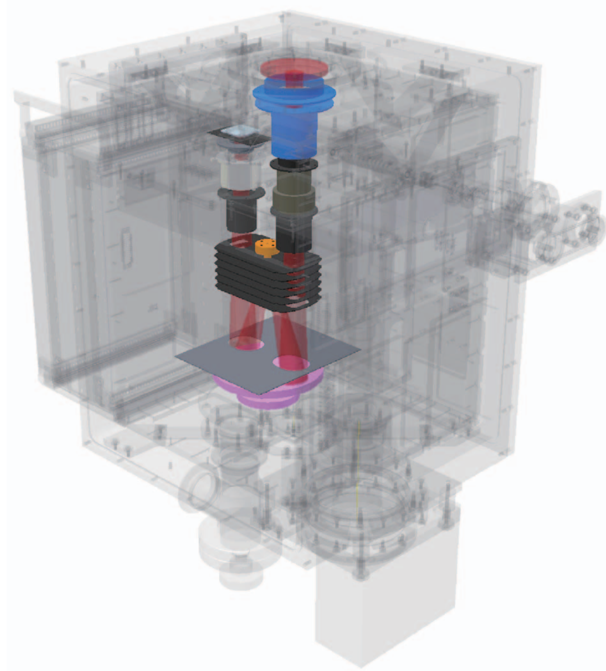

**Fig. 2.** Baffle design. These baffles reduce the stray light into the cold Lyot stop and the detector.

**Table 1.** Specification of the Offner optics optimized for the BOAO 1.8 m telescope.

| Item | | Value |
|---|---|---|
| Primary (M1) | Type | Concave spherical |
| | Radius of curvature | −300 mm |
| | Diameter | 154 mm |
| Secondary (M2) | Type | Convex spherical |
| | Radius of curvature | 150 mm |
| | Outer diameter | 17.6 mm |
| | Inner diameter | 4 mm |
| Optical axis offset (telescope − Offner) | | 45 mm |
| Distance (M1 − M2) | | 148.3 mm |
| Distance (M1 − focal plane) | | 301.7 mm |

BOAO 1.8 m telescope.

A filter wheel containing eight filter modules currently includes the MKO filter system for the $J$, $H$, and $K_s$ bands (Simons & Tokunaga 2002), the standard filter system for the $L$ band (Johnson 1965; Cohen et al. 1992), two narrow band filters [$H_2$ (1–0) S(1) 2.12 $\mu$m and $H_3^+$ R(3,3) 3.53 $\mu$m], and one blank position for a shutter and dark. The broad-band filters are tilted by 5° to avoid the ghost problem (Lee et al. 2005).

Many baffles are employed to block stray light (figure 2). These baffles are arranged along the beam path; cylindrical baffles are located on the filter box, the optical box, the cold box, and the detector box. Seven layers of thin plates are also placed for baffling stray light in the optical box.

All mirrors and mounting parts are made of the same material, aluminum 6061–T6. This minimizes the stress of thermal contraction during cooling down to the operation temperature of 80 K, and our FEM (Finite Element Method) analysis guarantees the optical alignment to be better than one pixel size of the detector (Cha et al. 2006a).

### 2.2. *Mechanics and Cryogenics*

The cryostat is a rectangular box of $390 \times 400 \times 500$ mm, so as to allow easy assembly and convenient access. Figure 3 presents the internal structure of KASINICS. The cold box is supported by G10 glass-epoxy composite plates on the front and rear walls in the cryostat. The bottom plate of the cold box plays the role of an optical bench to align the optical components. The filter wheel is driven by an external DC servo motor through rotary motion feed-through. Figure 4 shows pictures of the filter wheel and the detector.

We employed a low vibration GM cryocooler (RF50D, Suzuki Shokan Co., Ltd.) with a cooling capacity of 18 W at 80 K for the first stage and 4.7 W at 20 K for the second stage. We inserted the Urethane and bellows between the wall of the cryostat and the refrigerator to reduce vibration due to the refrigerator. The first stage of the cooler is connected to the cold box by copper straps. The second stage is linked to the detector box with a copper bar and copper straps, and the detector box is cooled down to 30 K. A monitoring device module provides information for the vacuum level of the cryostat and the temperature values of several parts in real time (Cha et al. 2006b). The temperature of the detector box is controlled within $\pm 0.005$ K by a temperature controller (Model 332, Lakeshore Inc.). It takes about 65 hr to cool down the cold box from room temperature to 80 K.

### 2.3. *Electronics*

Figure 5 shows a block diagram of the KASINICS readout controller and figure 6 shows the communication process of the KASINICS observing system at BOAO. The detector of KASINICS is an InSb $512 \times 512$ format array (ALADDIN III Quadrant, Raytheon Co.). Table 2 gives the specifications of the detector. The readout controller was newly developed for KASINICS (Cho et al. 2006). It consists of a DSP (Digital Signal Processor) board, a bias board, two clock boards, and two video boards. The power, data, and command signal lines

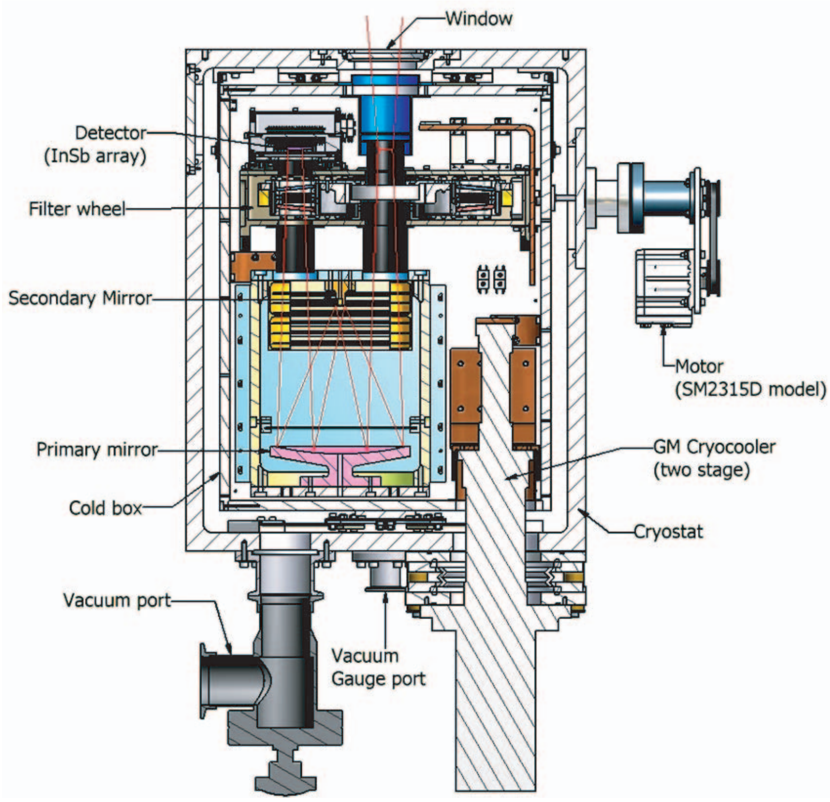


**Fig. 3.** Mechanical drawing of the KASINICS internal structure.

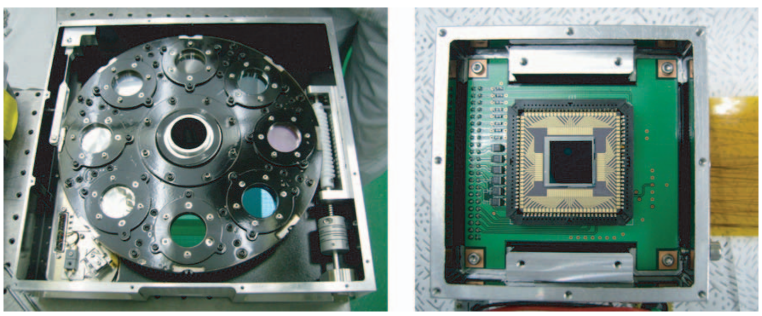

**Fig. 4.** Photograph of (left) the assembled filter box and (right) the assembled detector. The filter wheel contains 8 filter modules, each of which can be equipped with double filters; e.g., one bandpass filter plus one PK50 filter for thermal blocking.

of each board are connected to the standard 3U VME bus backplane. The bias board and the clock board have their own DAC parts, so users are able to easily adjust the output voltage range.

The DSP board contains a floating-point DSP (TMS320C6713), FPGA, USB interface, SDRAM, and DPRAM. We download clock patterns from the PC and save them to the DPRAM. This board transmits 15 clock patterns for the clock board and 1 for the video board. It then receives the digital data from the video board and delivers them to the host PC memory. For communication between the controller and the PC, either the USB2.0 interface or the TCP/IP interface can be used. This board also includes a 16-bit digital I/O for sensing the positions of the filter wheel.

**Table 2.** Detector specification of KASINICS.

| Parameter | Value |
|---|---|
| Model | ALADDIN III Quadrant |
| Material | InSb (Raytheon co.) |
| Spectral response | 1–5 $\mu$m |
| Pixel size | 27 $\mu$m $\times$ 27 $\mu$m |
| Array format | 512 $\times$ 512 pixels |
| Detecting area | 13.8 mm $\times$ 13.8 mm |
| Field of view (BOAO) | $3'\!.3 \times 3'\!.3$ |
| Pixel scale (BOAO) | $0''\!.39$/pixel |

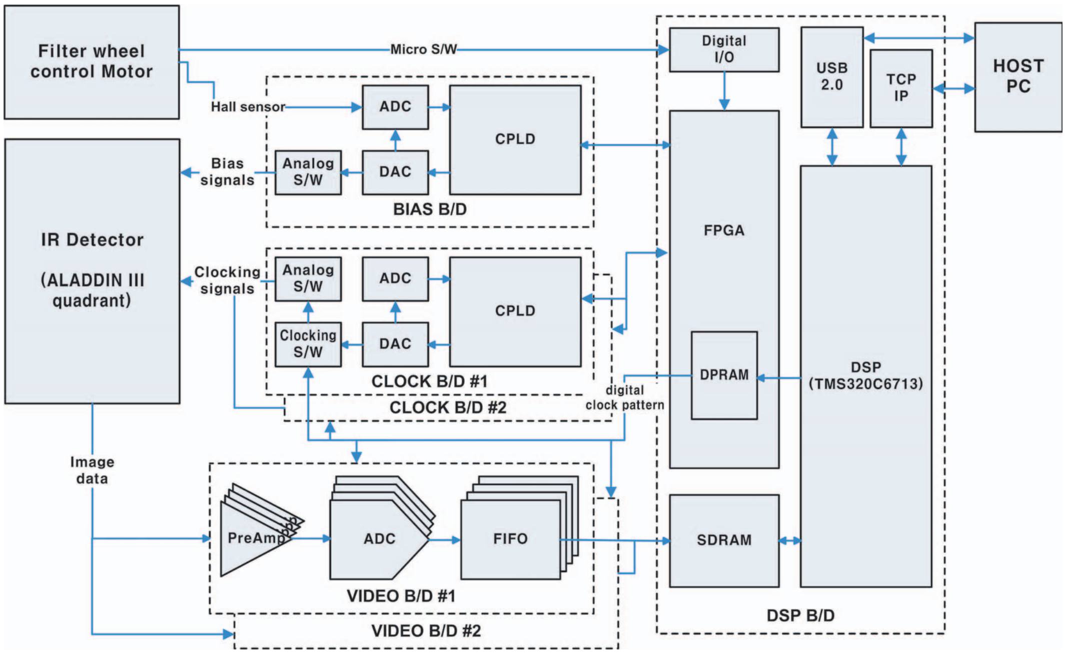


**Fig. 5.** Block diagram of the KASINICS readout controller.

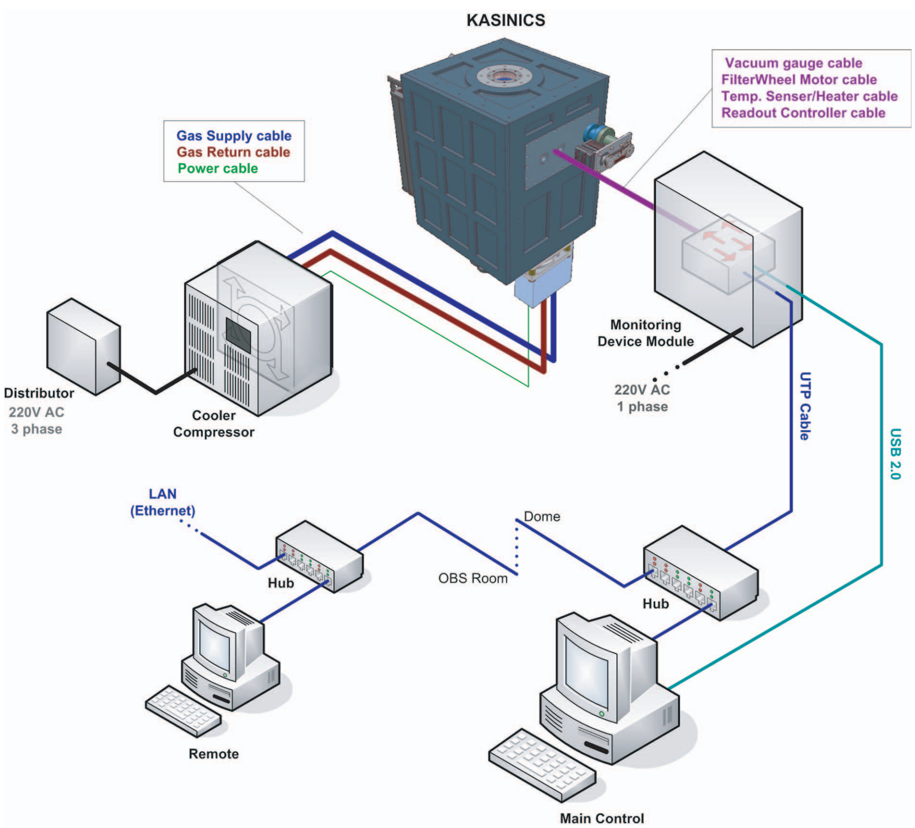


**Fig. 6.** System configuration at BOAO. We can use either USB2.0 or TCP/IP for communication with the PC.

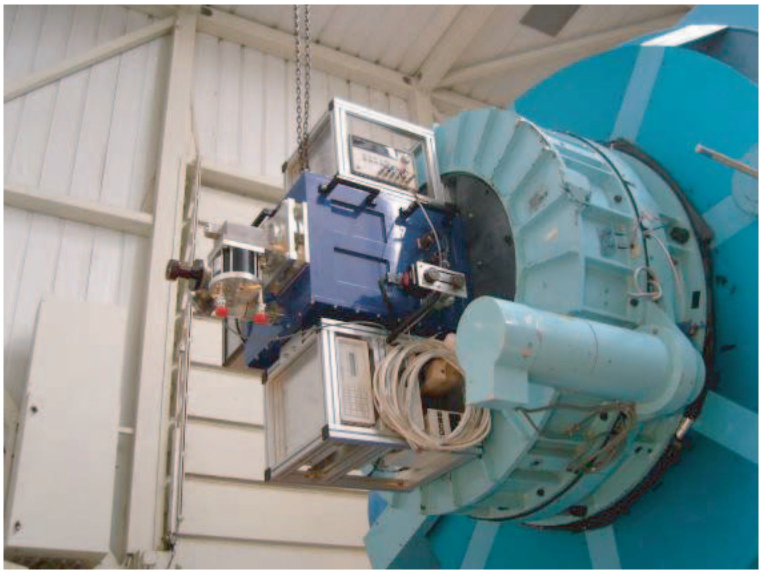

**Fig. 7.** KASINICS installed on the BOAO 1.8 m telescope.

The observation software is coded in C language with the Labwindows/CVI tool and is operated in window-based GUI.

## 3. Test Observations

Test observations were carried out twice in 2006; once from August 23 to 29 with the engineering-grade detector, and next from December 15 to 20 with the science-grade one. Figure 7 shows KASINICS installed on the BOAO 1.8 m telescope for observations. In an observing run with the science grade, targets were chosen to confirm the performance of the system: standard stars, NGC 7789, OMC-1, NGC 2024, HH 10, IC 443, NGC 2903, Sh 2-294, and Saturn. The observed images were preprocessed using the IRAF[1] package.

In $L$-band observations, the broadband images were saturated within a minimum integration time of 1 s of the correlated double sampling (CDS) mode through the broad-band filter, so we tried observations in a single-sampling mode with an integration time shorter than 0.2 s. Figure 8 shows the $L$ band images of Saturn in a single sampling mode and a standard star with a narrow-band $H_3^+$ filter.

To evaluate the possibility of $L$-band observations, we quantitatively investigated the atmospheric condition above BOAO at the beginning of the development (Moon et al. 2004). The absorption and emission by telluric water vapor becomes serious in the bands longer than 3 $\mu$m. Using the GPS PWV (precipitable water vapor) measurement system of KASI, we measured PWV above BOAO to be 3.8–4.7 mm during the winter season (Lee et al. 2007). This value encourages us concerning the possibility of $L$ band imaging in winter season. We plan to remedy this saturation problem in the near future.

1 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

**Fig. 8.** (Left) $L$ band image of Saturn. The image size is $158 \times 105$ pixels. (Right) $H_3^+$ (3.53 $\mu$m) filter image of a standard star, V 569 (4.93 mag in $L$). FWHM of the star is $1\farcs2$ and the signal-to-noise ratio is about 78 (1 s exposure).

## 4. Current Performance

### 4.1. *Imaging Quality*

The imaging quality was verified by observing NGC 7789, an open cluster. Stars of this cluster are evenly distributed within the FOV of the detector. Figure 9 shows an image of NGC 7789 in the $J$ band. The FWHMs of stars throughout the field were measured to be $1\farcs5$ to $1\farcs7$ in $J$, $H$, and $K_s$, similar to those extrapolated from the optical seeings at BOAO. The distortion of the image was evaluated to be smaller than one pixel over a field-of-view of $3\farcm3 \times 3\farcm3$, from measurements of the positions of members of an open cluster, Sh 2-294.

### 4.2. *System Throughput*

The system throughput of KASINICS is theoretically estimated to be $\sim 26\%$ in $J$, $\sim 26\%$ in $H$, $\sim 25\%$ in $K_s$, and $\sim 21\%$ in $L$. This estimation includes the atmospheric transmittance, the reflectivity of the primary and secondary mirrors of the telescope, the transmittance of the camera window, the reflectivity of the Offner optics, the transmittance of the filters, and the quantum efficiency of the detector (see table 3). We also measured the system throughput from test observations as

11% in $J$, 13% in $H$, 13% in $K_s$, and 8% in $L$ (for the 3.53 $\mu$m $H_3^+$ narrow band filter).

### 4.3. Readout Noise, Gain, and Dark Current

The readout noise of KASINICS was measured from the dark frames in the CDS readout mode. We sampled a region of $100 \times 100$ pixels from the image after removing bad pixels, and the standard deviation of each individual pixel in 10 frames was calculated. From the measurement, the readout noise was estimated to be about 15 ADU, or 38 electrons (figure 10).

According to photon statistics, the relationship between the noise and the signal is described as

$$\mathit{Noise}\,(\mathrm{ADU}) = \sqrt{{N_\mathrm{r}}^2 + \frac{S}{g}}, \tag{1}$$

where $N_\mathrm{r}$ is the readout noise in units of ADU, $S$ is the signal in ADU, and $g$ is the system gain. When photon noises are more dominant than the readout noise at higher flux levels, the system gain is calculated from a mean–variance plot. The mean and the variance values for individual pixels are calculated over 10 flat images and averaged over $100 \times 100$ sample pixels for one data point in the plot (figure 11). The gain was estimated to be $2.56\,\mathrm{e}^-/\mathrm{ADU}$ from flat images in the $J$ band.

The dark current was measured to be $18\,\mathrm{e}^-\,\mathrm{s}^{-1}$ at 30 K, much higher than expected from the detector specification ($\leq 1\,\mathrm{e}^-\,\mathrm{s}^{-1}$) or thermal radiation from the cold shutter ($0.2\,\mathrm{e}^-\,\mathrm{s}^{-1}$).

### 4.4. Linearity and Full Well

We measured the linearity and the full well by taking flat images in the laboratory. The experiment was performed under a dome-flat condition with increasing exposure time in the $J$, $H$, and $K_s$ bands. Three CDS images for each exposure were taken and averaged after removing bad pixels.

Figure 12 shows the relation between the exposure time and the signal with the bias voltage set at 600 mV. In this figure, the linearity within 1% is ensured from 4000 to 16000 ADU and the signals are saturated at 22500 ADU.

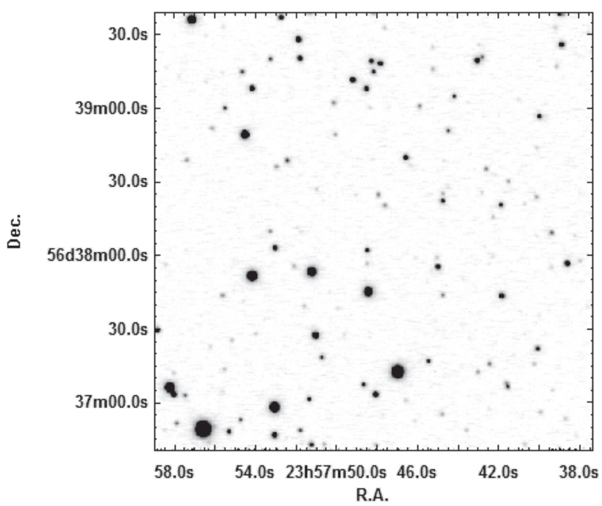


**Fig. 9.** $J$ band image of NGC 7789 (90 s integration).

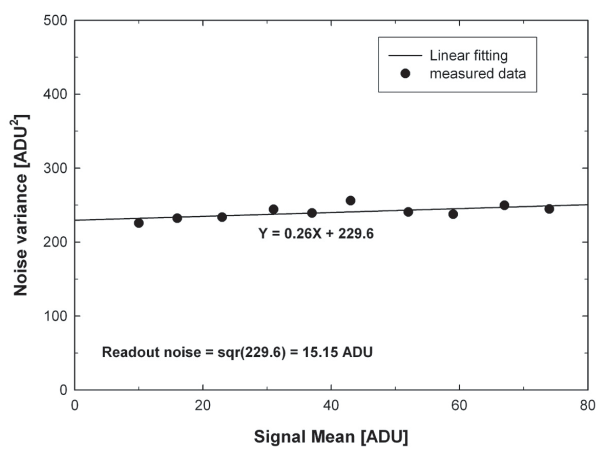


**Fig. 10.** Readout noise measured from dark frames. The approximate value from the linear fitting is about 15 ADU (38 electrons).

**Table 3.** System throughput of KASINICS.

| Item | $J$ | $H$ | $K_s$ | $L$ |
|---|---|---|---|---|
| Wavelength ($\mu$m) | 1.25 | 1.64 | 2.15 | 3.50 |
| Bandwidth ($\mu$m) | 0.16 | 0.29 | 0.32 | 0.60 |
| Atmospheric transmittance* | ~ 95% | ~ 95% | ~ 85% | ~ 70% |
| Telescope (reflection × 2) | ~ 72% | ~ 72% | ~ 72% | ~ 72% |
| Window | ~ 95% | ~ 95% | ~ 95% | ~ 95% |
| Offner (reflection × 3) | ~ 61% | ~ 61% | ~ 61% | ~ 61% |
| Blocking filter 1 | ~ 91% | ~ 90% | — | — |
| Band-pass filter 1 | ~ 80% | ~ 80% | ~ 80% | ~ 80% |
| Quantum efficiency | ~ 90% | ~ 90% | ~ 90% | ~ 90% |
| KASINICS (estimation) | ~ 26% | ~ 26% | ~ 25% | ~ 21% |
| KASINICS (measurement) | 11% | 13% | 13% | 8%† |

* Average values in winter at BOAO (Moon et al. 2004).
† In case of the 3.53 $\mu$m $H_3^+$ narrow band filter.

### 4.5. *Limiting Magnitude*

For a point source with an integration time of 100 s at $S/N = 10$, we estimated the limiting magnitudes to be 18.6 in $J$, 17.7 in $H$, 18.0 in $K_s$, and 12.9 mag in the $L$ band (Moon et al. 2004). We observed 8 standard stars selected from the UKIRT standard-star catalog (Hawarden et al. 2001). The limiting magnitudes were measured to be 17.6 in $J$, 17.5 in $H$, 16.1 in $K_s$, and 10.0 mag in the $L$ (the narrow $H_3^+$ filter) band under the same conditions.

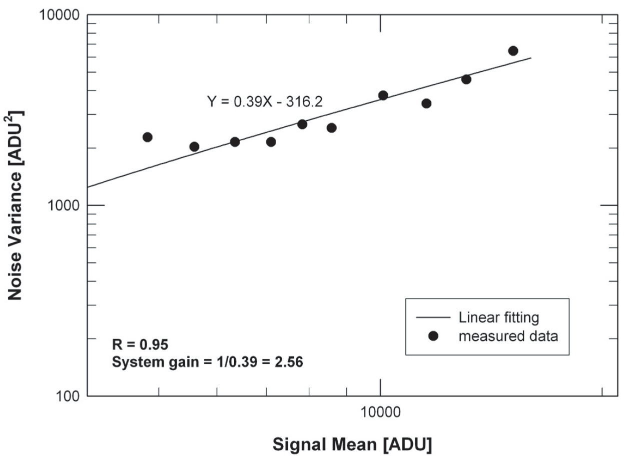


**Fig. 11.** System gain measured from flat images at the $J$ band. The estimated value from the linear fitting is 2.56 $e^-$/ADU.

## 5. Summary

We have developed a near-infrared camera, KASINICS, for observations in the $J$, $H$, $K_s$, and $L$ bands. It employs Offner relay optics to meet the performance requirements for infrared observations with the 1.8 m BOAO optical telescope. It covers a field of view of $3'.3 \times 3'.3$ with a $512 \times 512$ InSb detector.

From laboratory tests, linearity within 1% is guaranteed from 4000 to 16000 ADU with a full well of 22500 ADU at a 600 mV bias voltage and the readout noise of 38 electrons. From test observations, the limiting magnitudes are 17.6 in $J$, 17.5 in $H$, 16.1 in $K_s$, and 10.0 mag in $L$ (the narrow $H_3^+$ filter) band with an integration time of 100 s at $S/N = 10$. In the near future, KASINICS will be optimized for general observers to operate the system conveniently.

We would like to thank all staff members of the BOAO who helped us during test observations. We also thank engineers and scientists of Nagoya Univeriosity. This work was supported by Korea Astronomy and Space Science Institute (KASI) under the "Development of infrared technology" project.

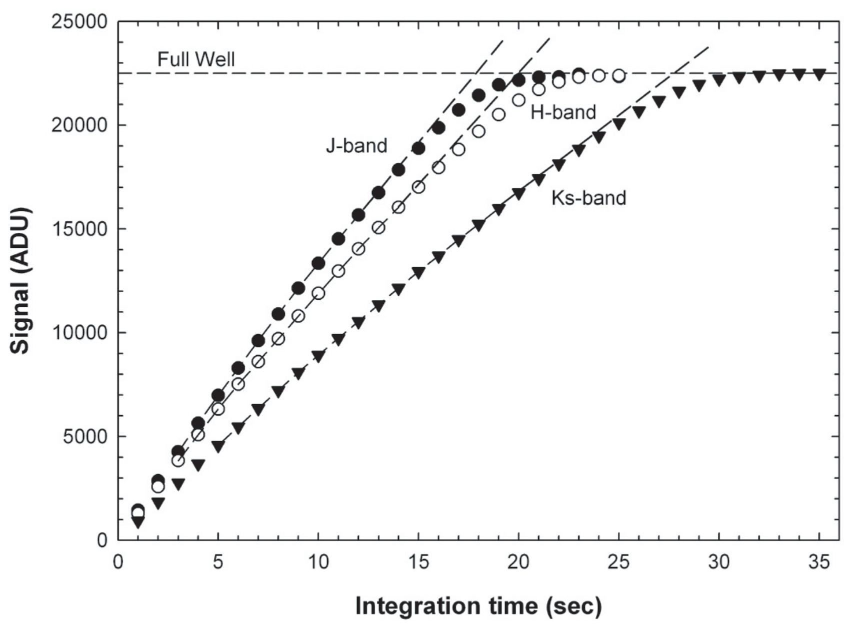


**Fig. 12.** Linearity and fullwell of the KASINICS detector at 30 K and bias voltage of 600 mV. The filled circles, the open circles, and the filled triangles represent the measured values in the $J$, $H$, and $K_s$ bands, respectively. In the signal range from 4000 to 16000 ADU, the linearity is ensured within 1%.

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