Testing and Analysis of Astronomical Applications of Domestically Developed Infrared Detectors (Postprint)

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Abstract

In recent years, China has achieved breakthrough progress in the development of infrared detectors. To meet the requirements of astronomical observation, comprehensive testing of all performance metrics relevant to astronomical detection has been conducted on this infrared detector, obtaining important parameters such as readout noise, dark current, full well capacity, dynamic range, nonlinearity, non-uniformity, and quantum efficiency, and thereby assessing the detector's observational capabilities in infrared astronomy. Furthermore, actual on-site observations were carried out using the 1.56 m telescope at Sheshan, Shanghai Astronomical Observatory, Chinese Academy of Sciences, verifying that the performance of this detector in ground-based applications has approached the level of equivalent foreign detectors. This signifies that Chinese infrared astronomy has entered a stage where it can utilize independently developed infrared detectors to conduct astronomical observations in specific near-infrared bands.

Full Text

Preamble

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Testing and Analysis of Astronomical Applications for Self-reliant Domestic Infrared Detectors

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Abstract

Over the past two years, China has achieved significant breakthroughs in the development of infrared detectors. Guided by the demands of astronomical observation, we have conducted comprehensive tests on all astronomical detection parameters of the infrared detector and obtained key indicators such as readout noise, dark current, full well capacity, dynamic range, nonlinearity, nonuniformity, and quantum efficiency. These tests have enabled us to assess the detector' s capabilities in infrared astronomy. Additionally, we utilized the 1.56 m Telescope at the Shanghai Astronomical Observatory' s Sheshan site for real-world observations. These observations confirmed that the detector' s ground-based application performance is comparable to that of foreign detectors, indicating that China's infrared astronomy has advanced to a stage where it can employ domestically developed infrared detectors for astronomical observations in specific near-infrared bands.

Keywords: infrared astronomy; domestic HgCdTe infrared detector; nondestructive reading mode; dark current; read noise

1. Introduction

Infrared astronomy began in the early 20th century with the introduction of lead sulfide (PbS) photoconductive detectors. During the 1960s-70s, the introduction of indium antimonide (InSb) detectors enabled comprehensive infrared astronomical observations. In 1979, the United States built the 3.2 m IRTF telescope and the United Kingdom built the 3.5 m UKIRT, which were the most famous early ground-based infrared telescopes. In the 1990s, optical telescopes such as the American 10 m Keck I and Keck II, the European Southern Observatory' s four 8.2 m VLT telescopes, and Japan' s 8.2 m Subaru telescope were all equipped with infrared cameras and spectrometers. Since the launch of the first infrared astronomical satellite IRAS in 1983, led by the Netherlands, Europe' s ISO, Herschel, and Euclid, Japan' s AKARI, and America' s COBE, Spitzer, and WISE infrared satellites or space telescopes have been launched successively. Particularly noteworthy is the James Webb Space Telescope (JWST), launched in 2021, which represents the largest aperture (6.5 m) and most expensive ($10 billion) space infrared telescope to date, ushering in a new era of space infrared astronomy.

The rapid development of foreign infrared astronomy has primarily benefited from highly sensitive infrared detectors. The infrared camera for the U.S. IRTF telescope was NSFCAM (1993-2004), which was updated to NSFCAM2 in 2012 using Teledyne Hawaii-2RG infrared detectors, significantly improving detection capabilities. The Hubble Space Telescope’ s (HST) first-generation infrared camera (NICMOS, launched in 1997) used Rockwell (now Teledyne) infrared detectors. The third-generation infrared camera (WFC3, launched in 2009) employed Teledyne infrared detectors operating at a relatively high temperature of 145 K (compared to NICMOS’ s 77 K). Table 1 shows the performance specifications of several focal plane infrared detectors and the detector IR20 001 used in this paper.

Different infrared bands require different detector materials. Near-infrared bands of 1.0-5.5 m generally use HgCdTe, such as in HST’ s NICMOS or WFC3, or InSb, such as in Spitzer’ s IRAC camera for the 3.6 m and 4.5 m channels. Longer wavelengths (above 5 m) typically use doped material detectors such as Si:As or Ge:Ga, as employed in Spitzer, AKARI, and JWST for mid- to long-wave infrared detection.

China’s infrared astronomical observations have lagged primarily due to the lack of domestically developed high-sensitivity infrared detectors, which are strictly embargoed by foreign countries. Chinese researchers began studying infrared astronomical detection in the 1970s. For example, in 1979, a 1-3 m PbS photometer jointly developed by Beijing Normal University and the Yunnan Observatory conducted trial observations at the Purple Mountain Observatory’ s 60 cm telescope. In 1985, a 1.26 m infrared telescope developed by the Nanjing Astronomical Instrument Factory was installed at the Beijing Astronomical Observatory’ s Xinglong Observatory site for trial observations using a single-element InSb infrared detector. During the 1980s, the Shanghai Astronomical Observatory and Purple Mountain Observatory conducted high-altitude balloon infrared astronomical observations and collaborated internationally with Japan. However, due to detector limitations, China’s infrared astronomy failed to make substantial progress. In 2014, Xu Chun utilized HgCdTe infrared array detectors from the Shanghai Institute of Technical Physics for astronomical observations with the Sheshan 1.56 m telescope, achieving a signal-to-noise ratio greater than 100 for stars of magnitude 5, corresponding to detection capabilities for magnitude 9 stars. The infrared detector at that time had a cutoff wavelength of 3.3 m, dark current of 4,000-6,500 e /s, and readout noise greater than 300 e , requiring short-exposure observation modes.

In recent years, driven by the demand for infrared observations from China’ s Space Station Telescope (CSST), the Shanghai Institute of Technical Physics has developed high-sensitivity HgCdTe infrared detectors. The device has a cutoff wavelength of 1.7 m, a format of 640×512, a pixel size of 15 m, readout noise better than 50 e , and detector dark current less than 1 e /s. Following astronomical observation requirements for detector parameter testing, we conducted laboratory tests on another infrared detector with a cutoff wavelength of 2.0 m, designated IR20 001, and performed field trial observations with the

Sheshan 1.56 m telescope. The following sections discuss in detail the parameters of interest for astronomical detection, the testing principles and methods for different parameters, data analysis, and field test results.

2. Astronomical Application Testing Requirements for Infrared Detectors

Following the data analysis procedures of telescopes such as HST and Spitzer, the main parameters requiring testing for astronomical detectors include: detector response band, quantum efficiency, readout noise, dark current, bias, nonlinearity, nonuniformity, full well capacity, dynamic range, gain, sub-pixel effects, and bad pixels. Below are the definitions of these parameters, their impact on astronomical detection, and the reasons they need to be tested.

The detector' s response band refers to the wavelength range of photons that can generate photoelectrons when irradiating the detector. Only photons with energy higher than the detector's bandgap can produce photoelectrons through the photoelectric effect. Since photon energy is inversely proportional to wavelength, there exists a maximum wavelength; photons shorter than this wavelength can excite the detector to produce photoelectrons. This wavelength is the cutoff wavelength of the infrared detector. The efficiency of photoelectron excitation varies with wavelength, meaning quantum efficiency differs at different wavelengths. Through photoelectric efficiency, the number of incident photons can be calculated from the number of photoelectrons to estimate target intensity.

Detector bias refers to the detector output signal (generally corresponding to output voltage) in the absence of photoelectrons and internally generated dark current electrons, or the output signal at zero integration time. The effective output signal of the detector is obtained by subtracting the bias signal from the output signal. Generally, the bias signal shifts with changing observation conditions, necessitating study of its variation characteristics to improve the precision of the detector' s effective output signal.

Readout noise refers to the fluctuation when different readouts give different output values, assuming the actual signal size on the detector is a fixed value. It is determined by the detector' s electronic characteristics and is the most critical parameter affecting detector sensitivity.

Dark current refers to the intensity of spontaneously generated excited electrons in the detector due to thermal effects or material defects when no external photons are incident. Dark current is part of the detector' s output signal and thus affects detection precision and sensitivity. China' s infrared detector level has consistently lagged far behind international standards primarily due to excessive readout noise and dark current.

If a detector' s response were linear, the output signal size would be strictly proportional to the number of accumulated charges on the detector. In reality, due to the influence of accumulated charges on the integration capacitor, the output signal and charge number exhibit nonlinear effects that require precise measurement to accurately calculate the input signal. This correction is particularly important for faint astronomical targets.

For array detectors, the bias and response efficiency differ among pixels and require correction. Response nonuniformity correction is called nonuniformity calibration, which in astronomy is generally referred to as flat-field correction. After flat-field correction, the equivalent response rates of adjacent pixels become consistent, and spatially correlated noise caused by pixel nonuniformity can be suppressed. Flat-field measurement precision primarily depends on instrument stability, test equipment uniformity, and test signal-to-noise ratio.

Astronomical target brightness ranges are enormous, covering 30 magnitudes or a 10^{12} brightness range. Full well capacity refers to the total charge number the detector can accommodate, which is the difference between the output value when the detector no longer increases response with continued exposure and the bias value. For single-exposure imaging mode, dynamic range refers to the ratio of full well capacity to minimum noise. For multiple non-destructive exposure modes, dynamic range is determined by the product of the ratio of total non-destructive exposure time to the shortest initial non-destructive exposure time and the dynamic range of single imaging. Detailed calculations are discussed later.

Gain refers to the ratio of the detector’ s output code value (generally corresponding to voltage) to the charge number. From gain, the charge number on the detector can be calculated, thereby determining the number of incident photons or target brightness.

Sub-pixel effects refer to the imprecision in target brightness calculation caused by different response rates at different sub-pixel positions within a detector pixel. This effect becomes relevant when the optical system’ s point spread function is undersampled. If a point spread function is collected by multiple (more than two) pixels, the imprecision caused by sub-pixel efficiency can generally be ignored.

Bad pixels refer to measurement problems caused by pixel output values that differ significantly from average values during bias, dark current, and flat-field acquisition processes. Generally, the output values of bad pixels need to be eliminated or recovered through other observation or calculation methods.

Astronomical detection is related to all the parameters mentioned above. The measurements in this paper will cover all astronomical detection parameters except sub-pixel characteristics.

3.1 Infrared Detector Signal Characteristics

The detector tested in this paper is an HgCdTe array infrared detector with a format of 640×512, pixel size of 15 m×15 m, and cutoff wavelength of 2.0 m. The detector readout circuit operates similarly to visible-light CMOS devices:

each pixel corresponds to a readout unit that reads the voltage on each pixel' s integration capacitor and then outputs each pixel's signal through a multiplexer. The detector has multiple readout modes, including single-exposure single-frame readout mode and single-exposure non-destructive multiple readout mode.

Infrared detector output signals generally contain several components. First are photoelectrons, which are electron signals formed by the conversion of infrared photons incident on the detector. Photoelectron sources actually include: (1) photons radiated from celestial targets; (2) infrared background from the sky, including collective radiation from unresolved celestial bodies near the target and Earth' s atmospheric infrared radiation (for ground-based observations); (3) instrument infrared background radiation, including infrared radiation from the instrument itself (particularly from various mirrors and structures of the telescope' s infrared camera); (4) the detector' s own thermal radiation or amplifier glow effect, where amplifier glow (or amp-glow) is the infrared luminescence effect caused by internal currents in CCD or CMOS detector amplifiers during readout, which was clearly detected in Hubble' s NICMOS infrared camera. Second is the detector' s dark current, where each pixel generates electrons even without external radiation, output simultaneously with target photoelectron signals. The output signal form is generally the voltage value on the integration capacitor, so the output voltage actually includes the basic voltage of the detector' s electronic system, i.e., the bias. The bias drifts with the detector' s operating environment (such as temperature and power supply) and requires accurate subtraction. Another uncertainty is readout noise, which is the fluctuation around the mean value when reading the same pixel multiple times without incident photons and dark current. This random fluctuation is called readout noise. For infrared detectors used in astronomical observations, the most critical metrics are readout noise and dark current, followed by the stability and traceability of bias and other additional signals. Currently, the most advanced near-infrared detectors internationally, such as the HAWAII series, have readout noise around 10 e and dark current around 0.1 e /s.

Infrared detectors have multiple signal output methods, with correlated double sampling single output and non-destructive multiple output modes being the most common. Single output produces a detection signal after exposure ends, outputting one image per exposure. Non-destructive multiple output reads the voltage on the integration capacitor and outputs signals during the exposure process, but does not reset the integration capacitor after readout. The detector continues exposure, with generated charges continuing to accumulate on the integration capacitor, enabling the next readout. The characteristic of non-destructive readout is that each readout accesses the capacitor's voltage without affecting the voltage value or charge number on the capacitor, allowing multiple voltage values at different exposure moments to be output during a single long exposure. Figure 1 [Figure 1: see original paper] shows a schematic diagram of the non-destructive readout mode, where t is the integration time for frame 1, t + t is the interval integration time between frame i and frame i-1, and t is the time required to read each frame. For the detector in this paper, t is

2 s, meaning the interval integration time for non-destructive readout cannot be less than 2 s. Here, t can be arbitrarily selected according to operational requirements or can be the same time. If only the first frame is read to end exposure, this is the conventional single-readout mode, where integration time t (or t) can be arbitrarily selected within 25 s to 4,095 s. The detector in this paper can operate in either single-frame readout mode or non-destructive multi-frame readout mode, with measurements under different readout modes discussed separately.

3.2 Infrared Detector Testing Principles

Based on the previous discussion, the relationship between detector output signal and input signal is as follows:

$$S_{out} = B + (S_{in} + S_{bk}) \cdot Q \cdot t + I_{dk} \cdot t$$

Here, S_{out} is the collected detector output signal in units of electron number, which can also be written as $S_{out}(e^-)$. It consists of several parts: detector bias (B, in units of electron number e^-), signals generated by detector due to input photons (target signal S_{in} and background signal S_{bk}, in units of s^{-1}) and dark current (I_{dk}, in units of e^-/s), where Q is quantum efficiency and t is integration time.

In actual operation, the detector outputs voltage values or quantized voltage values in units of DN. The quantized voltage signal $S_{out}(DN)$ has a conversion relationship with the electron number signal $S_{out}(e^-)$:

$$S_{out}(e^-) = G \cdot S_{out}(DN)$$

Here, the conversion factor G is the gain, in units of e^-/DN. We measure readout noise, dark current, etc., with raw data in DN units, so this gain value must be measured to obtain standard descriptions in electron units.

If integration time is 0 s, Equation (1) shows that the detector output signal is the bias B. Under the same conditions, collecting B multiple times in single-frame acquisition mode and calculating the mean square fluctuation of B between multiple images for the same pixel gives the readout noise for that pixel, generally denoted as σ_{read}.

If the detector has no external signal input, meaning S_{in} and S_{bk} in Equation (1) are both zero, dark current can be simply obtained as $I_{dk} = (S_{out} - B)/t$. By integrating the detector for a long time without signal input, subtracting the average bias, and dividing by integration time, the dark current value can be obtained. Since infrared detectors are generally packaged in test dewars and warm objects have their own infrared radiation, including the dewar window itself, to make S_{in} and S_{bk} both zero, the dewar must be opened and the detector sealed with a low-temperature structure inside before installing the dewar shell, vacuum pumping, and cooling for dark current testing. Note that the test time must be sufficiently long or multiple tests must be averaged so that readout noise has minimal impact on results.

Another simpler method does not require opening the dewar structure but uses a target source with known radiation intensity (such as a blackbody) covering the dewar window for testing. Assuming background radiation S_{bk} is zero in Equation (1), dividing both sides by t yields:

$$(S_{out} - B)/t = S_{in} \cdot Q + I_{dk}$$

For fixed exposure time, since incident light intensity S_{in} is directly related to blackbody temperature T, selecting several different blackbody temperatures (corresponding to several light intensity values S_{in}) during measurement yields different output signals S_{out}. Equation (3) forms a linear function, where the intercept at $S_{in} = 0$ is the dark current I_{dk}. This method requires accurate temperature measurement and precise measurement of the detector and filter spectral response curves. Where:

$$S_{in} = \alpha \cdot \Omega_F \cdot A_d \cdot t \cdot \int_{\lambda_1}^{\lambda_2} B_\lambda(T) \cdot R_\lambda \cdot \varepsilon_\lambda$$

Here, α is the equivalent blackbody radiation efficiency, Ω_F is the entrance pupil field angle of the optical system, A_d is the area of a single pixel receiving radiation, t is integration time, $B_\lambda(T)$ is the blackbody radiation spectrum at temperature T, R_λ is the filter response curve in this band, and ε_λ is the energy of a single photon in this band. Using Equation (4) and different temperature blackbodies, the average quantum efficiency of the detector in the filter band can also be calculated.

The detector' s gain mentioned earlier has a design value during instrument design. However, the design value requires pre-assumed integration capacitor size, which is difficult to measure accurately. Therefore, gain is actually measured and calculated using the photon transfer curve (PTC) method. The basic principle is as follows: the right side of Equation (1) corresponds to the actual electron number output by the detector pixel, which we denote as S_o, so Equation (1) can be simplified to:

$$S_{out} = B + S_o$$

Taking fluctuations on both sides, i.e., mean square values, and considering the independence between parameters on the right side:

$$\sigma^2_{S_{out}} = \sigma^2_B + \sigma^2_{S_o}$$

Here, σ_{S_o} is the uncertainty in the pixel' s output electron number, belonging to photon shot noise, which follows a Poisson distribution, so $\sigma_{S_o} = \sqrt{S_o}$, thus:

$$\sigma^2_{S_{out}} = \sigma^2_B + S_o$$

Equations (4)-(6) are all in units of electron number. Since actual output signals are generally in DN units, dividing both sides of Equation (6) by G^2 and using the relationship from Equation (2), Equation (7) becomes:

$$\sigma^2_{S_{out}}(DN) = \sigma^2_B(DN) + S_o(DN)/G$$

Collecting multiple images with different output values and calculating the noise variance $\sigma^2_{S_{out}}(DN)$ for each pixel in different images yields a linear relationship with the pixel' s output value $S_o(DN)$. The reciprocal of the slope is the gain G, and the intercept $\sigma^2_B(DN)$ is the square of the previously calculated readout noise. Of course, when calculating G, noise is generally not calculated for individual pixels but statistically for local regions of the detector. Noise is typically calculated through the difference between two images with the same exposure time. Since the image difference includes the sum of readout noise from both images, the noise variance is actually half the statistical fluctuation variance of the image difference.

The above are the basic testing principles for detector parameters including readout noise, dark current, and gain. These are fundamental relationships and methods applicable to both single-element and multi-element devices. Actual testing is for array detectors, with variations in testing methods.

4. Laboratory Testing System

The infrared focal plane detector testing system in this paper (shown in Figure 2 [Figure 2: see original paper]) mainly includes the detector under test, power supply circuits, acquisition electronics, and a host computer. The system enables long-term integration. In non-destructive readout mode, frame intervals can be adjusted from 25-150 s to 0.1-4,095 s, with a maximum of 256 frames collected during a single integration process.

The IR20 001 detector response band is 1.0-2.0 m. A filter is installed above the detector with bandpass FWHM positions corresponding to 1.632 m and 1.754 m, with an average transmittance of 0.78. The filter band is close to the infrared H band but narrower and too close to the atmospheric window absorption edge. The detector is packaged in a vacuum liquid nitrogen dewar. Temperature measurement resistors are installed inside the dewar next to the detector and at the top of the cold shield, with positions shown in Figure 3 [Figure 3: see original paper]. PT1 is the temperature measurement resistor next to the detector, and PT2 is at the top of the cold shield. The relationship between resistor temperature and time is shown in Figure 4 [Figure 4: see original paper]. Based on measurements, the cold shield temperature stabilizes after approximately 100 minutes, with the detector operating temperature around 87 K.

When measuring dark current noise using Method 1, the internal cold aperture window is covered with a cold shield. The temperature at the top of the cold shield is around 130 K. Preliminary estimation assumes a 130 K blackbody surrounding the detector with a solid angle of and pixel size of $= 15\times15$ m^2. The number of photons received per second on a single pixel is 4.4×10^{13}, far smaller than the measured dark current value.

Under this testing method, we collected a series of single short-integration images, short-interval non-destructive integration images, and long-interval non-destructive images to calculate readout noise and dark current.

When using the second method for testing, the sealing cold shield on the cold aperture was removed and a reflective plane mirror was placed over the dewar window. For dark current testing, the ambient temperature near the plane mirror and dewar window needs to be changed, so a thermally conductive aluminum cover was installed near the window, with a semiconductor cooling plate placed above the aluminum cover. A temperature feedback platinum resistor contacts the reflective plane mirror and window to achieve temperature control of the reflective plane mirror and window, as shown schematically in Figure 5 [Figure 5: see original paper].

Under this testing method, we collected images similar to Method 1. Particularly under certain temperature control conditions, we adjusted the interval integration time between frames and collected until detector full well, analyzing data using the PTC method and readout noise analysis. PTC testing is an important method for evaluating detector performance, primarily used to measure key parameters such as detector gain, readout noise, and full well capacity. PTC curves are plots with incident photon number on the x-axis and noise variance on the y-axis.

From February to December 2023, we conducted multiple infrared detector tests under several different operating conditions. The following sections present data analysis results from different tests.

Due to limitations in short-wave infrared HgCdTe detector technology and fabrication processes, the focal plane contains various bad pixels. Inclusion of bad pixels in performance parameter statistics and calculations leads to biased results, so bad pixels must be accurately classified, identified, and eliminated from calculations. Bad pixel classifications found in images include: (1) pixels with excessive response nonuniformity, responding too fast or too slow; (2) pixels with excessive dark current, causing premature saturation; (3) pixels with no or minimal response to photon input, including dead and hot pixels; (4) pixels with excessive readout noise; (5) pixels with abnormal response, specifically showing opposite response and no response within a certain time period. The response of one such pixel under different experimental ambient temperatures is shown in Figure 6 [Figure 6: see original paper].

5.1 Gain Test Data Analysis

Knowing the gain value is necessary for accurate analysis of noise, dark current, and other parameters, so we first discuss gain test data analysis. Data for gain analysis was obtained using the second testing method. First, the dewar was placed at room temperature with only a reflective plane mirror at the window. After temperature stabilization, non-destructive readout integration was performed with a frame interval of 5 s until full well, collecting 255 frames total. This integration process was repeated three times consecutively. Then, two of the integration processes were selected for differential analysis to obtain the photon response curve and calculate gain. Figure 7 [Figure 7: see original paper] shows the detector' s response curve during one integration process, i.e., the relationship between detector output signal and time, with the x-axis representing integration time and the y-axis representing the average value of all pixel responses S_{out} in the focal plane.

During testing, due to long single integration times, systematic differences inevitably exist between different integration processes. The source of these differences is subtle changes in the experimental environment and testing system. Therefore, systematic offsets between the three integration processes must be eliminated before calculating variance; otherwise, variance calculation results will be overestimated. The offset elimination process is as follows: First, select two of the three integration processes. Taking any two frames at the same integration time as an example, labeled frame 1 and frame 2, calculate the average values of all pixel S_{out} for these two frames as M_1 and M_2. Let $M_1 - M_2 = D$, then subtract D from all pixel S_{out} values in frame 1 to complete offset elimination for these two frames at this integration time. Next, repeat this process for the remaining 254 "pairs" of frames to complete systematic offset correction for these two integration processes. For the remaining integration process, pair it with any other integration process to complete the above offset elimination process, thereby obtaining systematic offset correction for all three integration processes.

Only after removing the fixed background offset ($B(DN)$) from the original S_{out} can the average signal S_{out} be plotted, so each integration process subtracts frame 1 from every frame starting from frame 2, resulting in three groups of 254-frame integration processes. The mean-variance curve is then obtained through the following steps: (1) Select two of the three integration processes, subtract corresponding pixel S_{out} values frame by frame at the same integration time to obtain 254 differential frames (to eliminate fixed pattern noise), as shown in Figure 8 [Figure 8: see original paper]; (2) Calculate the variance of all pixel S_{out} values for each differential frame and divide by 2 (to eliminate the extra random noise component), obtaining the variance level at that integration time; (3) Calculate the average of all pixel S_{out} values for the two frames at the same integration time to obtain the average output signal S_{out} level at that integration time; (4) Repeat steps (1)-(3) three times to obtain three different mean-variance curves to reduce systematic errors.

Using the above method, the relationship between mean and variance is shown in Figure 9 [Figure 9: see original paper]. Since output signals at low levels are subject to greater interference from different noise sources and nonlinearity effects become more significant near saturation, we only fit the middle linear region (approximately 20%-70% of full well). The reciprocal of the slope is the detector gain, with values shown in Table 2 .

5.2 Dark Current Test Data Analysis

We measured dark current using both Method 1 and Method 2. Below is the analysis of test results from different methods.

When using Method 1 (cold shield method) for dark current testing, three integration processes were performed in non-destructive readout mode with a frame interval of 5 s, collecting 256 frames per integration process. The detector response curve is shown in Figure 10 [Figure 10: see original paper], with the x-axis representing integration time and the y-axis representing the average value of all pixel S_{out} for that frame.

According to Equation (1), the slope of the linear region fit is the pixel dark current. The histogram of pixel dark current distribution is shown in Figure 11 [Figure 11: see original paper]. Combined with the previously measured gain of 2.28 e /DN, the dark current values are shown in Table 3 .

When using Method 2 for dark current testing, a reflective plane mirror was covered over the window. First, the dewar was placed at room temperature (6.75°C and -0.50°C), and the aluminum cover and plane mirror at the window were cooled to 2.00°C, -5.00°C, and -9.75°C. The temperature curve of the platinum resistor monitoring the reflective plane mirror is shown in Figure 12 [Figure 12: see original paper]. Non-destructive readout mode integration was performed at each temperature (all with 5 s frame intervals). To reduce errors, linear fitting was performed within the 20%-70% full well range to obtain the line slope. Using Equation (4), the incident light intensity S_{in} at different window temperatures was calculated, from which the pixel dark current could be derived.

Using pixel [37, 270] as an example, the dark current level was calculated. Equation (4) was used to calculate the incident light intensity S_{in} at 5 temperature points, with values shown in Table 4 .

The response curve of this pixel at different temperature points is shown in Figure 13 [Figure 13: see original paper]. Linear fitting was performed within the 20%-60% full well range, and the slope obtained was dS_{out}/dt. The array S_{in} and dS_{out}/dt were then linearly fitted as shown in Figure 14 [Figure 14: see original paper], where the vertical axis intercept is the pixel' s dark current level

(7.39 DN/s). Combined with the previously calculated average gain, the pixel' s dark current level is 16.85 e /s.

The same method was used to calculate dark current for all pixels in the focal plane. The histogram of pixel dark current distribution is shown in Figure 15 [Figure 15: see original paper]. Combined with the previously measured gain of 2.28 e /DN, the dark current values measured by Method 2 are shown in Table 5 .

Comparison of test results from Method 1 and Method 2 shows that Method 2' s results (17.48 e /s) are smaller than Method 1' s (23.01 e /s). Preliminary estimates suggest there may be other radiation sources near the detector, currently suspected to be glow. In Method 2, glow radiation partially escapes through the window, reducing measured results but also making them closer to the true dark current. Confirmation of whether this is glow radiation is still underway, but it is certain that the true dark current value is even smaller than the measured values. The dark current image of the detector measured by Method 1 is shown in Figure 16 [Figure 16: see original paper].

5.3 Readout Noise Test Data Analysis

Based on the three integration processes obtained at a certain temperature state in Method 2 for dark current testing, readout noise can be calculated. The calculation method is: starting from frame 2, subtract the previous frame from the subsequent frame, yielding 254 subtracted frames per integration process. Then, for a single pixel, calculate the standard deviation of the 254 values. Since frame subtraction involves noise accumulation, divide by $\sqrt{2}$ to obtain the pixel' s readout noise.

The histogram of calculated pixel readout noise distribution is shown in Figure 17 [Figure 17: see original paper], with specific readout noise values in Table 6 , combined with the previously measured gain of 2.28 e /DN.

5.4 Detector Bias Data Analysis

We analyzed bias characteristics under two conditions: bias features and variations in single-exposure single-readout mode, and bias features and variations in non-destructive readout mode.

For single-exposure single-readout mode, we collected 6 series of bias frames. The first 3 were collected near the same time, and the latter 3 near another time. Exposure time was 25 s, with 100 frames collected each time, obtaining 100-frame average bias. Comparing the 6 bias frames, differences among the 3 simultaneously collected biases were small, about 11.4 DN or 0.04%. The difference between the average of the first 3 and latter 3 was larger, about 54.72 DN or 0.6%. This test demonstrates that detector bias changes significantly with working environment. If bright targets are collected using single-exposure single-readout mode, bias must be collected before and after acquisition as a baseline for subtraction, rather than using long-term average bias as a reference baseline.

For non-destructive readout, we collected 6 image series at different time periods. Each series collected 3 non-destructive images with the same integration time, using the first readout frame as bias. One bias image is shown in Figure 18 [Figure 18: see original paper]. After calculating the average bias at different times, we found irregular variations in bias (see Figure 19 [Figure 19: see original paper]). Sometimes the average values of three consecutive biases were relatively stable, with differences less than 12 DN (such as group 1). Sometimes changes were larger, with differences about 263 DN (such as group 4, frame 10). The fluctuation range of average values was between 8,500-9,200 DN, relatively large. Non-destructive readout clearly cannot perform stable bias subtraction; only by subtracting the first readout frame of a single exposure can actual accumulated charge be calculated. Compared with noise-smoothed average bias, the first frame carries readout noise, increasing system noise. Accumulated charge after subtracting the first frame is more accurate than that after subtracting average bias. Noise in non-destructive readout must be reduced through other methods.

5.5 Detector Nonlinearity Characteristics

Detector nonlinearity characteristics are obtained by analyzing PTC curves. PTC curves are collected at equal time intervals while maintaining stable illumination. If detector response were linear, output values would be completely linear with collection time. In reality, they are not linearly related, so output values must be adjusted to make adjusted values completely linear with collection time. The calculation method is: for each pixel, assume the adjusted value is a polynomial of the output value:

$$f_c = c_0 + c_1 f_o + c_2 f_o^2 + c_3 f_o^3$$

Here, f_o is the detector output value and f_c is the adjusted value. During data analysis fitting, we assume f_c has a strictly linear relationship with exposure time, so we fit the relationship $t = a_0 + a_1 f_o + a_2 f_o^2 + a_3 f_o^3$. After obtaining parameters a_0, a_1, a_2, a_3, divide both sides by a_1 to get $t/a_1 = a_0/a_1 + f_o + (a_2/a_1) f_o^2 + (a_3/a_1) f_o^3$. Replace t/a_1 with f_c, $c_0 = a_0/a_1$, $c_2 = a_2/a_1$, $c_3 = a_3/a_1$ to obtain fitting parameters c_0, c_1, c_2, c_3, where c_1 is forced to be 1.

In actual calculations, multiple acquisition data are combined for fitting, with the fitting range below 90% of full well for more accurate polynomial coefficients. The average difference between f_c and f_o for the IR20 001 detector is about 0.43%. Compared with the nonlinearity of Hubble' s WFC3 infrared detector (>5%), this detector' s nonlinearity effect is very small. The histogram of pixel nonlinearity distribution is shown in Figure 20 [Figure 20: see original paper]. The main reason is that this detector uses CTIA readout circuit, while WFC3 uses SFD readout circuit. SFD has lower noise but higher nonlinearity.

5.6 Detector Full Well and Dynamic Range

Using the same PTC test data, the IR20 001 detector' s maximum output is around 22,000 DN, after which output no longer increases even with extended exposure time. Subtracting the bias value of about 9,000 DN (with large fluctuations) yields a full well of 13,000 DN, or about 30,000 e . Thus, single-exposure dynamic range is about 30,000/41 = 730 (41 e is the typical readout noise level), meaning the brightness ratio between the brightest and dimmest detectable targets is about 730, or 730/3 = 243 based on signal-to-noise ratio of 3 as the detection criterion. For multi-frame non-destructive readout, the brightest target approaches saturation in the first frame, with shortest exposure time of 2 s. Longest exposure time, assuming determined by dark current (charges from dark current plus some instrument background approaching 50% of full well), is 30,000/2/18 = 800 s. At this point, total noise is readout noise plus shot noise of about $\sqrt{15,000} + 41 = 130$ e , with 3-sigma signal-to-noise ratio corresponding to 390 e . Therefore, the ratio between brightest and dimmest targets is $(800/2) \times 30,000/390 = 30,769$, meaning the target dynamic range can exceed 30,000.

5.7 Detector Nonuniformity Characteristics

Detector flat-field (nonuniformity) is obtained by uniform illumination to about half of full well, subtracting bias, and dividing by average intensity. The flat-field range for the IR20 001 detector is 0.95-1.15, relatively uniform. There is a region in the lower right side of the detector with different response. Figure 21b [Figure 21: see original paper] shows a local flat-field, where periodic response variations between pixels can be seen, caused by fabrication defects or process issues during detector manufacturing.

For charge values at half of full well, we measured noise of 1,593.72 e in a 100×100 pixel region before flat-field correction. After flat-field correction, noise V_{rms} was 145.14 e . Theoretically:

$$V_{rms} = \sqrt{(f \cdot D)^2 + N_{read}^2 + D}$$

where D is half well at about 6,500 DN or 14,495 e , N_{read} is typical readout noise of 41 e , and f is residual after nonuniformity correction, with $f \cdot D$ being noise contributed by nonuniformity residual. Calculation yields $f = 0.0048$, with post-correction precision reaching about 0.5%.

5.8 Detector Quantum Efficiency

Using blackbody illumination at different temperatures, we measured the quantum efficiency of the IR20 001 detector in the test filter band (1.7 m). Figure 22 [Figure 22: see original paper] shows the illumination curves of different temperature blackbodies on the detector. For 30°C and 50°C blackbody illumination, the measured slopes of detector output signal (corresponding to radiation intensity) were 31.615 DN/s and 54.012 DN/s, respectively, or an output electron number difference of $(54.012 - 31.615) \times 2.28 = 51.05$ e /s (2.28 e /DN is the gain). Using Equation (3), considering the dewar' s F-number of 8 and detector pixel size of 15 m, and accounting for the filter response curve, the number of photons reaching a single pixel per second can be calculated as 17.3 (30°C blackbody) and 96.7 (50°C blackbody). Therefore, the difference in photons per second is $96.7 - 17.3 = 79.4$. Thus, quantum efficiency is $51.05/79.4 = 64\%$. It should be noted that the filter response curve, blackbody temperature, and measured gain values all have certain errors. Currently, we cannot accurately quantify these errors, so quantum efficiency measurements will have some deviation. Values of 72% quantum efficiency have been obtained in different tests.

Additionally, we statistically analyzed all bad pixels in the IR20 001 detector, including those from bias, dark current, nonuniformity, etc., totaling about 2,970 pixels, accounting for approximately 0.9% of the total 640×512 pixels. Bad pixels vary somewhat between different observation batches. We did not measure sub-pixel effects in this paper, which affect undersampled observations but require complex testing methods using infrared spots smaller than pixel size. Overall, test results for this detector show that domestic infrared detectors have noise levels between 38-41 e in different operating modes, already very close to the typical noise of Hubble' s 1990s infrared camera NICMOS (around 30 e). Minimum dark current is less than 17.48 e /s, which, although higher than NICMOS' s dark current, is already lower than background sky brightness for ground-based observations. Therefore, this detector can fully meet ground-based infrared astronomical observation requirements. Table 7 shows the performance parameters of the IR20 001 detector measured in this paper.

6.1 Infrared Detector Astronomical Observation Capability Analysis

We observed AS21-0 using the Shanghai Astronomical Observatory' s Sheshan 1.56 m telescope with an integration time of 19 s. The measured star image signal covers about 509 pixels. According to the Landolt catalog, AS21-0 has an H-band magnitude of 9.043 mag. Considering atmospheric transmittance, optical system efficiency, filter band and efficiency, and quantum efficiency, the estimated signal generated in the IR20 001 detector is about 3,112,793 electrons. In astronomical observations, signal-to-noise ratio (SNR) is an important indicator of detection capability, defined as the ratio of signal to noise. Total noise σ_{tot} is:

$$\sigma_{tot} = \sqrt{\sigma_{st}^2 + \sigma_{rd}^2 + \sigma_{dk}^2}$$

where all noise units are in electrons, σ_{st} is photon shot noise equal to the square root of signal electrons, σ_{rd} is readout noise in electrons, and σ_{dk} is dark current noise in electrons equal to the square root of dark current signal generated at the current integration time. Thus, SNR is calculated as:

$$SNR = \frac{S_{est}}{\sqrt{S_{est} + B_{sky} \cdot n_{pix} + n_{pix} \cdot \sigma_{rd}^2 + n_{pix} \cdot I_{dk}}}$$

where S_{est} is the estimated number of electrons generated by the target star image in the detector, n_{pix} is the number of pixels covered by the signal, B_{sky} is background sky radiation at about 13 mag/(arcsec)² (corresponding to about 70 e /s, higher than the detector dark current value), σ_{rd} is single-pixel readout noise, and I_{dk} is single-pixel dark current generated at this integration time, with all values in electrons.

Substituting the measured readout noise and dark current values from above, the estimated SNR in this state is 1,177.76.

6.2 Field Astronomical Testing

Using the Shanghai Astronomical Observatory' s Sheshan 1.56 m telescope to observe AS21-0 with an integration time of 19 s, the image obtained after subtracting the first frame of the non-destructive readout process and flat-field correction is shown in Figure 23 [Figure 23: see original paper].

After calculating and subtracting the image background, the total signal was 358,581.03 electrons. The SNR calculation formula is:

$$SNR = \frac{S_s}{\sqrt{S_s + n \cdot \sigma^2}}$$

where n is the number of pixels covered by the signal (509 pixels) and σ is single-pixel noise (87.33 e) calculated from a region near the signal with similar size, containing all noises in the image. Thus, SNR is calculated as 174.13. Based on this SNR, we can estimate that the sensitivity of this infrared detector on the Sheshan 1.56 m telescope with the currently designed band and 19 s exposure time is (3): $9.04 + 2.5 \times \log(174.13/3) = 13.5$ mag. This is already very close to the 15 mag sensitivity of the internationally famous near-infrared survey 2MASS.

The ratio of actual observed SNR to predicted SNR is $174.13/1,177.76 = 1/6.8$, and the ratio of actual observed signal intensity to predicted intensity is $358,581/3,112,793 = 1/8.7$. Clearly, we significantly overestimated the number of photons collected by the telescope. The likely reason is that the efficiency of the telescope and adapter system was overestimated, particularly atmospheric transmittance. In fact, there was obvious moisture in the atmosphere during the field observation period. The system transmittance issue is still under investigation.

7. Conclusion

Performance testing of China' s self-developed near-infrared detector shows that the IR20 001 detector has readout noise of about 38.1 e and dark current below 17.5 e /s, comparable to early foreign infrared detector noise levels. Nonlinearity, astronomical observation dynamic range, flat-field and other characteristics can meet astronomical observation requirements. The detector' s bias and bias variations exhibit some instability, which has certain impacts on data processing in single-frame exposure mode and requires precise calibration, but does not affect astronomical detection in non-destructive readout mode. The non-destructive readout mode of infrared detectors is very useful for long-exposure astronomical observations, helping improve astronomical data processing levels in terms of nonlinearity, readout noise, dynamic range, and other aspects. Field observations show that at Shanghai' s low-altitude, high-moisture site, brief exposures of about 20 s can achieve 13.5 mag sensitivity, approaching the 15 mag sensitivity of the internationally famous 2MASS survey. Performance testing and field trial observations of domestic detectors demonstrate that China' s infrared detectors have reached a new level and can meet the requirements of ground-based infrared astronomical observations.

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Note: Figure translations are in progress. See original paper for figures.