Suitability of COTS InGaAs detectors for ground based exoplanet detections around nearby M-dwarfs

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ABSTRACT

In the search for exoplanets, the TESS mission shifts much of the focus in transit detection towards observing nearby cool stars.[1] Many of the M-dwarf systems identified can be followed up from the ground with meter class telescopes or smaller to confirm the presence of rocky planets.[2,3] However, while space-based missions can easily justify the expensive mercury cadmium telluride (HgCdTe) detectors that perform well at the emission peaks of M-dwarfs, ground based searches at small facilities with modest budget need an alternative.[4] Deep depletion charged-coupled devices (CCDs) are commercially available, but do not have good sensitivity beyond 1000 nm. Commercial off the shelf (COTS) indium gallium arsenide (InGaAs) detectors offer an alternative, but work needs to be done to characterise them, and adapt them to astronomical use. Towards this effort, we code automation software in Python for a commercially available unit and test the performance for typical use in astronomical instruments. We also integrate a unit into a spectroscopy instrument and demonstrate it on sky at near-infrared (NIR) ranges.

Keywords: exoplanet, transits, InGaAs, infrared, Princeton IR Tech, M-dwarfs, Python, Astronomy

1. INTRODUCTION

The most common detectors found for professional astronomical use are based on CCD technology. These have been proven from widespread deployment in astronomy for applications like spectroscopy and photometry. Due to the proliferation of consumer digital cameras, detectors based on complementary metal-oxide-semiconductor (CMOS) technology have exploded in development and gained traction, especially in astrophotography. The CMOS sensor has pinned photodiodes and processing circuitry on chip and is read out line by line. CCDs are usually read out whole frames at a time. In both cases, the circuitry is usually made from poly-silicon, which has a steep drop in sensitivity to detecting near-infrared photons at around 1000 nm.

With the unsuitability of silicon based photodiodes, we are left with two options when working in the infrared, photodiodes with chemistry based on mercury cadmium telluride and indium gallium arsenide. Detectors utilizing HgCdTe such as Hawaii-2RGs and Hawaii-4RGs from Teledyne show excellent noise performance and quantum efficiency, and are in fact found in most ground and space based NIR instruments.[5] They offer large detector area, with 10 and 15 μm pixel size options. However, these devices are very costly and their use is restricted by export control, putting them out of reach for many projects.

As an alternative to HgCdTe detectors, commercially available InGaAs detectors contain photodiodes which also reach into the infrared. U.S. based vendor, Princeton Infrared Technologies (PIRT) manufactures such

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detectors with the largest frame size available as of this writing. The 1280Scicam does not fall under U.S. International Traffic in Arms Regulations (ITAR) and is exportable to Australia. The frame size is 15.4 x 12.3 mm, similar to a micro four thirds system consumer CMOS chip. This size is still only about 1/9 of the area captured by a Hawaii-4RG detector. The detector has a pixel size of 12 μm and has built in thermo-electric cooling, which can either use fans or liquid circulation to transport away the generated heat.

For M-dwarfs, the peak spectral emission occurs in the J-band. This coincides with typical indium gallium arsenide detectors like the 1280Scicam which has a peak quantum efficiency range at 1200 to 1600 nm, see figure 1.[6]

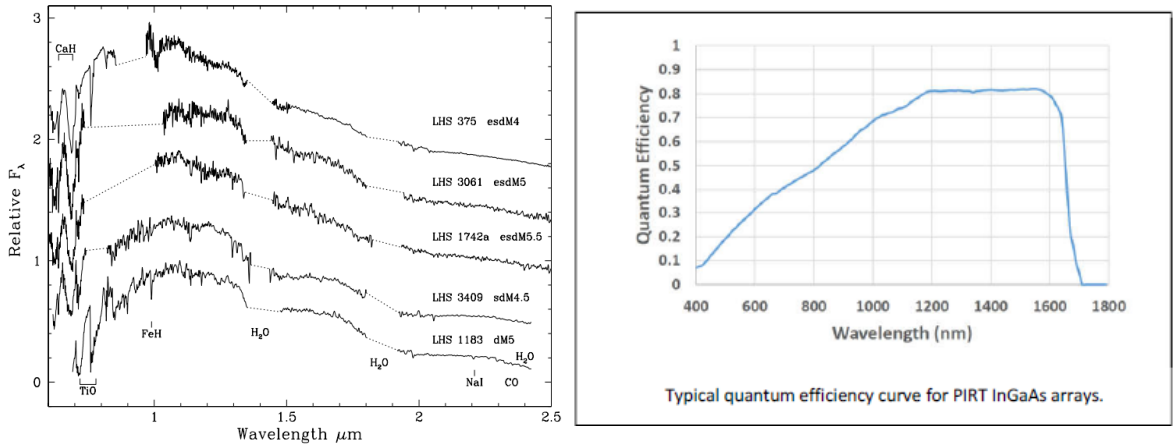

Figure 1. (left) M-dwarfs have their peak spectral emission in the J-band, which coincides with the peak quantum efficiency of the 1280Scicam.[6] (right) Manufacturer data for quantum efficiency of the PIRT 1280Scicam.

2. DETECTOR HOUSING

2.1 Variations and instrument integration

The detector housing is a hexagonal bar shape with a mass of 8 kg, although there are a few revisions including one with a cylindrical body and hexagonal ends, see figure 2. As of 2020, there is also a 3rd form factor from a second generation release of the 1280Scicam (not shown).[7] With the two versions that we have evaluated, the required back focal distance differed between 21.675 mm and 19.36 mm. The face plates which protect the anti-reflective (AR) coated front window were also not interchangeable.

We install the detector on a bench, to use with a spectrograph. The detector frame is in landscape orientation (the frame is wider than it is tall) when resting on a hexagonal edge. When a hexagonal vertex points towards the bench, then the detector is in portrait orientation, and the center of the frame is 82.55 mm above the bench. For our spectroscopic instrument at Macquarie Unviersity, Iranti, we set the optical height to 90 mm. Details on Iranti can be found in these proceedings (Kuo Tiong, et. al., *IRANTI, a compact flexible configuration infrared échelle spectrograph integrating emerging technologies for precise radial velocity measurements*).

2.2 AR coating

The front window serves as a vacuum seal and keeps contamination out of the InGaAs substrate and chip. The window came in two variations. The original unit that Macquarie University received did not have a mask that partially blocked off the window, as seen in figure 3 (left). This unit developed a leak and condensation would form on the window when the detector was turned on, see figure 3 (left). The replacement unit masks the window with the exception of the square detector frame behind. The window on the new system is anti-reflection coated; PIRT provides a profile of the AR coating in figure 3 (right).

Figure 2. PIRT 1280Scicam variations. (left) Front of detectors. The front windows have slight variations, one type has a mask covering all but the square frame. (middle) Chassis variations. (right) Front plates removed.

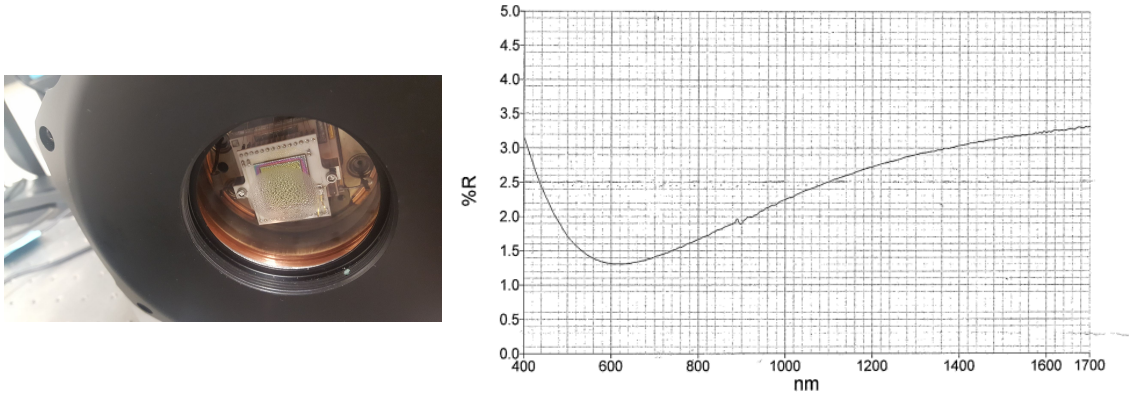

Figure 3. (left) Condensation on the 1280Scicam due to a seal leak. (right) Manufacturer data for vacuum window AR coating.

3. CONTROL SOFTWARE

The camera was delivered by PIRT with a GUI for taking manual exposures and setting parameters and checking diagnostics; however, further software support and functionality is limited. After PIRT technicians helped us set up and configure the detector, we decided to write a software interface to work for our typical use case. To be useful in an observatory setting, the detector needs command line functionality for automation of commands and batch processing of data acquisition. The detector communicates at high speed with a PC via Camera Link interface through a framegrabber. The framegrabber used for this setup comes from National Instruments, an NI-1427.

Writing interfacing routines to command the detector and conduct data acquisition depends on the framegrabber available. The NI-1427 only has drivers for Microsoft Windows, so an additional dependence on the operating system exists. Other framegrabbers such as a VisionLink F4 from EDT have cross platform support. For this implementation, National Instruments has a well documented application programming interface (API) that we use to access the Windows drivers to send serial commands, which control the detector and capture an exposure.[8] Since different framegrabbers have different APIs, any code written to communicate with the detector will be highly dependent on the framegrabber manufacturer.

We use Python as a wrapper around the C Windows drivers to interface with the detector, and the Astropy package to store exposures in Flexible Image Transport System (FITS) files. PIRT has documented the serial commands as well as header bit formats, and we also code these routines into Python. Those are available at a Github repository (github.com/blaisekuo/pirt-1280cam).[9] Some framegrabbers allow sending the serial commands to a standard serial I/O port address, however with National Instruments, it needs to pass through the framegrabber drivers using their API.

3.1 Data acquisition scripts

Two scripts, *scicam-setexp.py* and *scicam-expose.py* run on the detector host PC to trigger exposures on the PIRT detector. Both directly interface to the manufacturer C drivers from National Instruments.

set-exptime.py - Takes one argument, the desired exposure time in seconds, and converts it into a clock frequency and integration time value. The detector interprets an exposure time in terms of those two values, so a serial call is made to the detector with the pair.

Example: set exposure time to 0.5 seconds.

```
> python3 scicam-setexp.py --exposure 0.5 seconds
```

scicam-expose.py - Takes a series of arguments including the exposure time, type of exposure, filename, and intervals. Makes a call to the National Instruments IMAQ API to take an exposure, fill out FITS headers and write data to FITS files using the Astropy FITS package.[10]

Example: Take three consecutive solar exposure of 1.0 seconds every minute for four hours and gives them a file name prefix of "solar".

```
> python3 scicam-expose.py --imagetype "science" --name "solar"
--samples 3 --shots 240 --interval 60.0 --inttime 1.0
```

3.2 Data structure and header information

Each FITS file is 2.5 MB and for each sequence in our use case with the spectrograph, we take 5x bias, 5x flats, 5x calibrations, 5x darks of typically 3 different exposure times. The minimum data size per run for these overhead files is 75 MB. A basic header field is populated below for keeping track of the start of exposures and setting keywords that may be needed later for extraction.

Example: basic fits header fields.

```
SIMPLE   = T / conforms to FITS standard
BITPIX   = 16 / array data type
NAXIS    = 2 / number of array dimensions
NAXIS1   = 1280
NAXIS2   = 1024
EXTEND   = T
BSCALE   = 1
BZERO    = 32768
EXPTIME  = 1.0
DATE     = '2020-10-15T01:26:17.347494'
OBJECT   = 'solar'
OBSERVER = 'blaise'
IMAGETYP = 'science'
CCD-TEMP = -60.0
INPUTFMT = 'FITS' / Format of file from which image was read
```

The detector collects additional hardware status header information, and the fields have been well documented by PIRT. We also maintain code snippets to extract those fields.

4. COOLING

Like most InGaAs detectors, the PIRT detector has high dark signal, so we run it at the coolest possible setting, -60° C. A temperature of -40° C can be reached at room temperature with the fan, however to reach -60° C requires liquid cooling. We initially attempt the cooling with an inexpensive PC liquid cooler, PIRT recommended using distilled water as the heat exchange fluid. This is a simple device with an impeller pump that moves fluid between the detector and a radiator. With the built in cooling fan disabled, the detector fails to reach cooling set points. For our spectrograph, the detector and instrument share an enclosure, so we require it to run fanless so as not to disturb the stability with vibration and heat. Both the instrument and detector operate in an insulated enclosure which is temperature controlled at 24.6° C using a PID controller. To run fanless, we switched the cooling setup to a Solid State Cooling Systems thermo-electric chiller (TEC) with a 25% propylene glycol mixture. The external TEC chills the mixture to 10° C and circulates the fluid through the detector. With the chilled fluid, the detector can reach the desired set point in 5 minutes. We also insulate the tubing with foam to isolate the cool piping from the spectrograph. Since the TEC within the detector package does not extend to the detector electronics, those components run warmer at 57-59° C when operating fanless. With fan cooling, the electronics typically run at 30° C. Thus far the detector has been able to operate at the -60° C set point for days at a time.

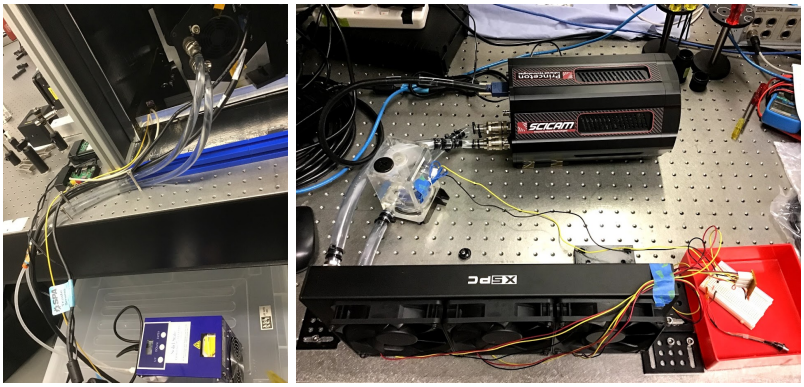

Figure 4. (left) Solid State Cooling Systems TEC using a mixture of distilled water and propylene glycol. (right) PC cooler with distilled water.

5. PERFORMANCE

5.1 Read Noise and Dark Signal

We charted the read noise performance of the 1280Scicam in 2018.[11] Bias exposures had levels at 58 e-/pixel when operating the detector at -60° C and short 1 ms exposure times.

The detector has three TEC cooling set points, -20° C, -40° C, and -60° C. The gain, measure by the manufacturer, of the Macquarie University unit is 4.2 e-/count, at the coolest -60° Cset point. At room temperature and internal TEC set at -60° C, the detector has a dark signal of 284 e-/s, which is linear through to a 60 second exposure. The 1280Scicam does not monitor or dump to headers the cooling set point status, although an indicator light on the chassis can notify when the set point is reached. It is not possible to change the temperature set points in software. The only way to change the set point is through hardware dip switches on the rear of the chassis. However, changing the set points through software is available in the second generation units.

In raw counts, a typical 60 second dark exposure has pixel counts of about 3,700 analog to digital unit (ADU) out of a full well of 16,384 ADU, which effectively limits the detector to taking exposures up to a few minutes. The detector electronics also do not reliably take exposures for exposure times longer than 60 seconds. However, it can continuously take gapless consecutive exposures nearly indefinitely. The shortest exposures we take are for 0.5 seconds for bright flat exposures from broadband calibration lamps. We have taken consecutive exposure at fixed intervals for up to 28 hours.

Better dark signal is achievable on the 1280Scicam by lowering the ambient temperature. We tested one unit at Australian National University at an ambient temperature of -13° C at the three TEC set points of -20° C, -40° C, and -60° C. The dark signal observed was 2,937 e-/s, 559 e-/s, and 68 e-/s respectively, see table 1. The dark signal of 68 e-/s at low ambient temperature outperforms the manufacturer measured figures of 300 to 500 e-/s, which was only conducted at room temperature. Our previous tests at room temperature confirms the manufacturer dark signal data.

Table 1. Dark Signal for 1280Scicam various units

				TEC setting, dark signal (e-/s)		
unit	gain (e-/ADU)	read noise (e-/s)	ambient temp (° C)	-20° C	-40° C	-60° C
Macquarie	4.2	58	≈ 22	1024	382	284
Penn State	3.6	72-79	≈ 22		1000	330
ANU	4.3	75	-13	2937	559	68

5.2 Artifacts and imperfections

The 1280Scicam has CMOS architecture with line by line readouts, and flux variations appear as striations in raw dark frames. Bias subtraction effectively reduces the noise, which trends with higher counts on one side of the frame, see figures in 5.

Noticeable glow also appears on the right side of the frame, likely due to detector electronics. Similar artifacts also commonly appear in CMOS sensors for amateur astronomy on dark exposures. The counts in the glow region are elevated by 200 counts for the PIRT. The PIRT unit in our Macquarie University lab also started developing a hot column at around the 400th pixel column, with the counts in the column about 400 counts higher than adjacent regions, see figure 6.

6. CONCLUSION

The 1280Scicam is an interesting option that allows astronomical near infrared observations in J and H band with 1280x1024 pixels at a cost that puts this wavelength range in reach of smaller facilities, for example, to observe M-dwarf targets for exoplanetary research, or other NIR science cases. However, the dark signal properties limit the exposure times to minutes. We have been able to make the detector suitable for remote and automated work flows and have tested it for exposures from 0.5 to 60 s. It also operates with stability under liquid cooling for multiple days. With the ability to continuously take exposures without readout gaps, it is possible to stack longer exposures.

ACKNOWLEDGMENTS

A few groups have also been working to integrate PIRT 1280Scicams into astronomy projects. Peter Pendersen from the SPECULOOS Southern Observatory project has been instrumental in starting a user group of 1280Scicam users at https://1280scicam.slack.com. Karsten Schindler from Deutsches SOFIA Institut has also tested the detector in low ambient temperatures and on-sky. We also thank Hai Nguyen from PIRT for his technical support and troubleshooting with the detectors.

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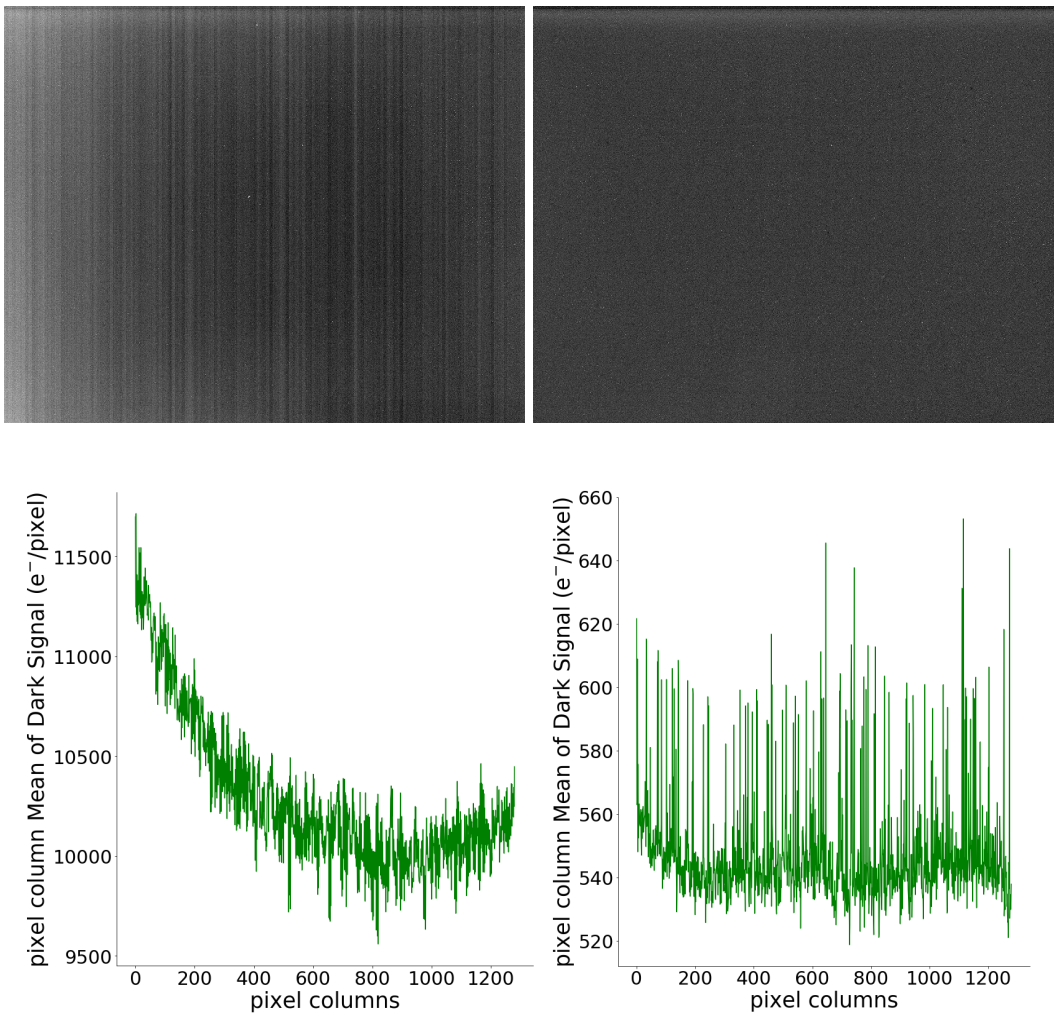

Figure 5. (top left): 1 sec frame at -40 C; (top right): 1 sec frame at -40 C with master bias correction applied; (bottom left): 1 sec frame at -40 C column averages; (bottom right): 1 sec frame at -40 C column averages with master bias correction applied.

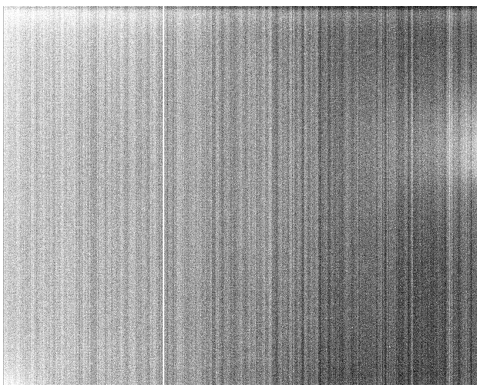

Figure 6. 0.5 sec dark frame on the PIRT showing a hot column and faint glow on the right region.

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