Detector architecture of the wide-field infrared transient explorer (WINTER) InGaAs camera

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ABSTRACT

We present the InGaAs detector system of the Wide-Field Infrared Transient Explorer (WINTER), a new infrared instrument operating on a 1 meter robotic telescope at the Palomar Observatory. These commercially produced sensors are cooled to -50 °C by a thermo-electric cooler integrated into a room temperature package. These warm InGaAs sensors represent a dramatic reduction in cost and complexity over HgCdTe systems and achieve sky background-limited performance across our science bands for exposures greater than a few seconds. We present the design and implementation of the WINTER detector system and readout electronics.

Keywords: WINTER, InGaAs, infrared detectors, large-format infrared sensors, sample-up-the-ramp, non-destructive read, commercial sensors, infrared astronomy

1. INTRODUCTION

While numerous transient survey telescopes operate in the visible light range, there are relatively few wide-field telescopes operating in the near-infrared (1.0 µm to 4.0 µm) range.[1–3] One driving reason for this absence is the expense and complexity of HgCdTe detectors, as well as their attendant electronics and cooling apparatuses. The Teledyne HAWAII-2RG and HAWAII-4RG have dominated infrared astronomy for almost two decades due to their tunable bandgap, low dark current, and low read noise. However, these sensors are typically run at less than 80°K to achieve the required dark current and require the use of a low-temperature application-specific integrated circuit (ASIC) to perform preamplifier functions, which increases the engineering and logistical difficulty of constructing and operating semi-autonomous survey telescopes using this technology, thereby increasing both the setup and operating costs of such instruments.

The focal plane design of the Wide-Field Infrared Transient Explorer (WINTER) was enabled by warm Indium Gallium Arsenide sensor technology from FLIR Electro-Optical Systems that circumvents these limitations. The modified AP1020 sensors are less than one-third the cost of comparable format HgCdTe sensors. Previous prototyping efforts[4,5] have demonstrated that similar detectors can achieve sky-noise limited operation in the -40°C to -55°C range, allowing them to use an integrated two-stage thermo-electric cooler (TEC) instead of a cryogenic system. Other than the amplifier stages integrated on the ROIC inside the sealed vacuum housing, all other control electronics can operate in air and at room temperature.

By making a number of design choices related to focal plane format, field of view, and geometry, these sensors will allow WINTER to provide sky noise-limited wide-field images on a 1-meter telescope with 120-240 second time resolution in the Y, J, and a shortened H-band (Hs) tuned to the 1.7 µm InGaAs bandgap. Our models (see Ref. 6) show that this should be sufficient to localize the optical counterparts of neutron star-neutron star mergers detected in the LIGO-Virgo fourth observing run (O4) at distances up to 190 Mpc under optimal conditions,[5] directing fast follow-up studies.

Hardware development of the WINTER focal plane is well underway: A full schematic design of the focal plane electronics exists and has passed design review, and prototype boards are currently being fabricated and tested. The InGaAs sensors are in production, and expected to be integrated early in 2021.

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1.1 Optical layout

WINTER consists of a commercial 1-meter corrected Dall-Kirkham telescope from Planewave Instruments, with the optics and focal planes mounted directly to one of the two Nasmyth port as shown in Fig. 1. The InGaAs sensors used by WINTER are packaged in narrow vacuum housings that can be be tiled along their short axis, but require additional space along the long axis to accommodate mounting hardware and the volume of the readout electronics. To facilitate this, the WINTER optics use a reflective rooftop prism to split the 3x2 mosaic into two arms of three channels, thereby increasing accessible volume for focal plane electronics, cooling interfaces, and interconnects, as shown in Fig. 1 Additional details on the layout of the WINTER instrument and optical system can be found in Refs. 7 and 8.

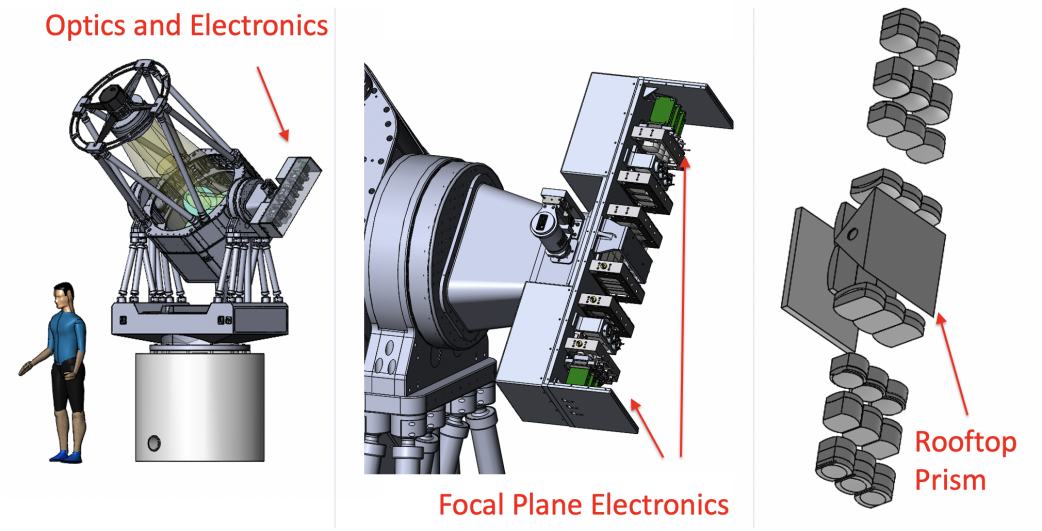

Figure 1. Basic structure of the WINTER. Left: CAD model of the full instrument. Center: Detail of optical and focal plane housing. Right: WINTER optics, showing rooftop prism used to split the focal plane.

1.2 Geometry of readout electronics

Fig. 2 shows the position of the readout electronics and thermo-electric cold block relative to the InGaAs sensor. The sensor is plugged directly into the preamplifier card, which acts as a motherboard for the FPGA and analog-digital converter boards. This allows all of the analog signal processing to be done without external cabling.

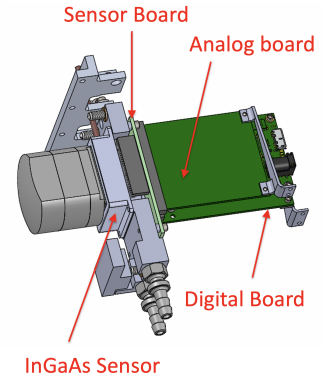

Figure 2. Relative positions of the InGaAs readout circuit boards and heat exchanger relative to the InGaAs sensor.

2. INGAAS SENSORS

The InGaAs detectors for WINTER are customized AP1020 units under fabrication by FLIR systems. These sensors are 1920 by 1080 pixel devices mounted on an internal proprietary read-out IC (ROIC), on top of a two-stage thermo-electric cooler, inside a sealed vacuum housing. This cooler will allow the sensor to operate in between -40°C and -50°C, which previous modeling[6] and prototyping[4,5] efforts have shown to be sufficient to achieve sky-noise limited observation in the Y, J, and Hs bands, all of which fall within the InGaAs sensor's 0.9 µm to 1.7 µm range.Table 1 shows the key metrics of the FLIR sensors used in the WINTER focal plane.

Table 1. Key parameters of the FLIR AP1020 sensors used in WINTER focal plane.

Parameter	**Value**
Sensor Format	1920x1080 pixels
Pixel Size	15 µm
Amplifier Type	CTIA on onboard ROIC
Nominal Input Referred Noise	25 e-
Spectral range	0.9 µm - 1.7 µm
Minimum Operating Temperature	-50°C
Expected Dark Current at Operating Temperature	<125 e-/pix/s
Output nodes	8
Operating frame rate	30 Hz

2.1 Amplifier parameters

The capactitive trans-impedence amplifier (CTIA) in the AP1020 sensors has been modified to allow for non-destructive readout, which in turn enables various noise reduction techniques such as Fowler pairs[9] or sample-up-the-ramp [10] . The nominal read noise for the AP1020 is 25 e-, whereas the infrared sky background is estimated[6,11] to be 320 e-/pix/s, 1686 e-/pix/s, and 2823 e-/s/pix for the Y, J, and Hs-bands respectively. The dark current at the operating point of the AP1020 is expected to be less than 125 e-/pix/s. This means that for exposures longer than approximately 60 seconds (in the worst case), the noise in the image will be dominated by the Poisson noise of the sky background.

2.2 Sensor outputs and clocking

In order to allow a significant number of frames to be accumulated during short exposures for sample-up-the-ramp processing, a 30 Hz framerate specification was chosen to drive the design of the readout electronics. With 8 outputs used to read out a 1920x1080 pixel area, a pixel sampling frequency of less than 10 million samples per second can be used, provided each output is hooked up to its own analog-digital converter.

3. ELECTRONIC DESIGN

The major components of the focal plane electronics and their interconnections are summarized in Fig. 3. The AP1020 sensor itself connects to the sensor board, and the analog and digital board with its integrated Opal Kelly module. The power board is mounted on the outside of the focal plane housing.

3.1 Sensor Board

The two primary functions of the sensor board are to provide an electronic interface between the InGaAs sensor and other boards, and to provide buffer and buffer and differential preamplifier stages to the sensor's eight signal outputs. The InGaAs sensor housing is plugged in to a custom socket extension on the sensor board to allow room underneath the sensor housing for cooling hardware so that waste heat can be removed from the hot side

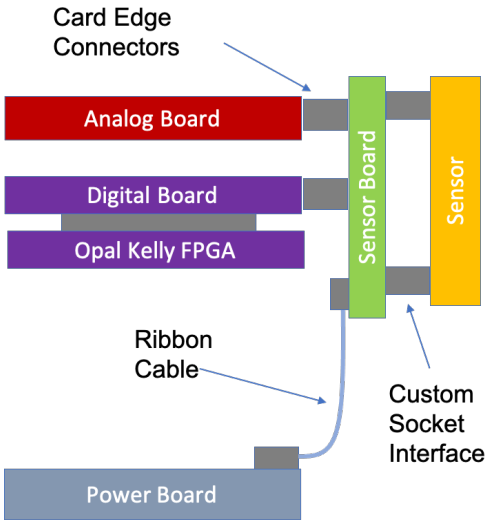

Figure 3. Block diagram of the major components of the WINTER focal plane electronics.

of the sensor TEC. The analog and digital boards are connected to the sensor board using standard right-angle PCI slot card edge connectors.

The buffer and preamplifier stages are positioned on the sensor board to minimize the trace length from the sensor outputs in order to maintain optimal signal integrity. The differential amplifier is configured to scale the sensor output to the range of the analog-digital converters on the analog board, with an offset voltage added to tune the zero point.

The sensor board also has two other secondary functions. First, circuit protection hardware is integrated with the sensor voltage rails to protect the sensor from electrostatic discharge (ESD) and from lightening events in the area around the telescope dome. Second, the sensor board also contains temperature sensor drivers for the sensors in the InGaAs sensor housing and for board housekeeping sensors.

3.2 Analog Board

The analog board contains eight AD7626 16-bit differential analog-digital converters (ADCs) and their attendant voltage references. The AD7626 was chosen because of its extremely low signal-to-noise ratio of 91.5 dB, and because this ADC family had also been successfully used in a previous prototype. Because the maximum sampling frequency of the AD7626 is 10^7 samples per second, we were required to design the analog board with eight ADCs in parallel in order to achieve the 30 Hz sensor sampling speed specification on the two megapixel InGaAs sensor.

Digital signals between the ADCs and the Opal-Kelly FPGA module are in 2.5V LVDS format. In order to minimize the number of signals, each ADC has its own dedicated data lines, but the clock and conversion signals from the FGPA are distributed using low-delay fanout chips.

3.3 Digital Board and FPGA Module

The digital board primarily as a signal-mapping interface between the sensor board and an Opal-Kelly XEM7310 FPGA integration module via the module's backplane connector. The XEM7310 is the primary controller for all focal plane module functions, including sensor clocking, image readout, turn-on sequencing, and temperature control. The XEM7310 implements an Artix 7 FPGA along with FPGA flash memory and 1 Gib of external RAM in addition to the FGPA's 13,140 Kib of internal RAM. The XEM7310 also implements a native USB-3 interface, which is used for data readout in conjunction with an external USB to fiber link. The USB-3 interface gives us sufficient bandwidth to download 30 raw 16-bit frames per second during prototyping and commissioning, while the FPGA RAM is sufficient to hold multiple frames in memory simultaneously, which will allow pre-processing or sample-up-the-ramp calculations to be done in real time using the FPGA's parallel processing capabilities.

3.4 Power Board

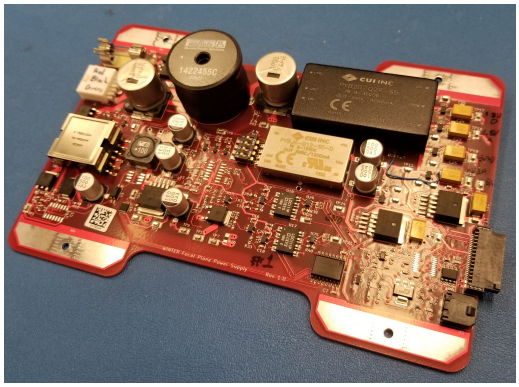

Figure 4. Photo of prototype WINTER Focal Plane power board.

The WINTER power board (shown in Fig. 4) is one of the most complicated components of the WINTER focal plane electronics. While this board performs a number of functions its primary purpose is to convert the 12 V input power into the relevant voltages for operation of the sensor and converters. To minimize electromagnetic interference and protect against transient events, the power board keeps all voltages that go to the rest of the circuit offline isolated. The circuit uses DC-DC switching converters to downconvert the input voltage to a value close to the use voltage, then uses linear regulators to achieve the actual voltages that are used by the rest of the circuit. This method keeps power efficiency high by using switching regulators to handle the larger part of the voltage drop, while also achieving the low noise on the DC rails by leveraging the high line regulation of the linear regulator components. All of the linear regulators have enable lines, allowing the FPGA to sequence voltages on startup, which prevents start-up transients from damaging the InGaAs sensor.

The power board also contains a custom TEC-drive circuit that uses a variable-setpoint switched-mode DC supply to provide a low-noise, high-efficiency conversion of the 12V supply voltage to whatever output voltage is needed on the TEC. The voltage setpoint is written by the FPGA over an SPI interface, allowing full closed-loop temperature control on each focal plane module without communication from the control computer.

Lastly, the power board also contains an 8-channel ADC for housekeeping and monitoring functions. Since the majority of the voltages and currents being monitored originate on the the power supply board, and because the power board is the least space-constrained, it is most efficient in terms of signal routing to perform analog-digital conversion on the power board.

3.5 Hardware Fabrication, Testing, and Integration Plan

The current hardware development roadmap has been designed to prioritize components that will enable multiple development efforts to take place simultaneously.

The first hardware component to have a full layout is the power board, since the voltages it provides are necessary for operating all of the other components, and since having a functional TEC driver enables temperature testing of cooling fixtures with dummy sensor/TEC packages. After that, the addition of a digital board enables FPGA development as it pertains to sensor cooling and voltage sequencing. A test connector has been added to the digital board design that allows the FPGA to interface with the power board in the absence of the sensor board interconnects for firmware development purposes.

The sensor and analog boards will need to be developed, reviewed, and tested more concurrently, since these are the parts making actual contact with a working sensor. Once the behavior of all sensor-facing signals has been verified, another internal review will clear the focal plane electronics for integration with engineering-grade sensors.

4. CONCLUSIONS

By leveraging knowledge gained by previous prototyping and simulation efforts, we have made significant headway in the expansion of our previous 640x512 single-output InGaAs sensor designs into a focal plane array of 2k x 1k InGaAs devices capable of sky-noise limited observation. A full electrical schematic for the focal plane electronics exists, and prototyping efforts are underway for all of the component circuit boards and cooling hardware. We expect that the focal plane electronics will be built, tested, and ready for integration with the AP1020 InGaAs sensors when production is finished in the first half of 2021.

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REFERENCES

[1] Sutherland, W., Emerson, J., Dalton, G., Atad-Ettedgui, E., Beard, S., Bennett, R., Bezawada, N., Born, A., Caldwell, M., Clark, P., and et al., "The visible and infrared survey telescope for astronomy (vista): Design, technical overview, and performance," *Astronomy & Astrophysics* **575**, A25 (Feb 2015).

[2] Casali, M., Adamson, A., Alves de Oliveira, C., Almaini, O., Burch, K., Chuter, T., Elliot, J., Folger, M., Foucaud, S., Hambly, N., Hastie, M., Henry, D., Hirst, P., Irwin, M., Ives, D., Lawrence, A., Laidlaw, K., Lee, D., Lewis, J., Lunney, D., McLay, S., Montgomery, D., Pickup, A., Read, M., Rees, N., Robson, I., Sekiguchi, K., Vick, A., Warren, S., and Woodward, B., "The UKIRT wide-field camera," A&A **467**, 777–784 (May 2007).

[3] De, K., Hankins, M. J., Kasliwal, M. M., Moore, A. M., Ofek, E. O., Adams, S. M., Ashley, M. C. B., Babul, A.-N., Bagdasaryan, A., Burdge, K. B., and et al., "Palomar gattini-ir: Survey overview, data processing system, on-sky performance and first results," *Publications of the Astronomical Society of the Pacific* **132**, 025001 (Jan 2020).

[4] Sullivan, P. W., Croll, B., and Simcoe, R. A., "Precision of a Low-Cost InGaAs Detector for Near Infrared Photometry," *Publications of the Astronomical Society of the Pacific* **125**, 1021 (Sept. 2013).

[5] Simcoe, R. A., Fűrész, G., Sullivan, P. W., Hellickson, T., Malonis, A., Kasliwal, M., Shectman, S. A., Kollmeier, J. A., and Moore, A., "Background-limited Imaging in the Near Infrared with Warm InGaAs Sensors: Applications for Time-domain Astronomy," *The Astronomical Journal* **157**, 46 (Feb. 2019).

[6] Frostig, D. and The WINTER Collaboration, "Design requirements for the wide-field infrared transient explorer (winter)," in [Proc. SPIE], **11447**(113) (2020).

[7] Lourie, N. P., Baker, J. W., Brown, J., Burruss, R. S., Fűrész, G., Frostig, D., Garcia-Zych, A. A., Ganciu, N., Haworth, K., Hinrichsen, E., Kasliwal, M., Karambelkar, V. R., Malonis, A., Piotrowski, J., Simcoe, S., and Zolkower, J., "The wide-field infrared transient explorer (WINTER)," in [Proc. SPIE], **11447**(55) (2020).

[8] Hinrichsen, E. and The WINTER Collaboration, "Opto-mechanical mounting design of the wide-field infrared transient explorer (WINTER) "fly's eye" camera lenses," in [Proc. SPIE], **11447**(115) (2020).

[9] Fowler, A. M. and Gatley, I., "Demonstration of an Algorithm for Read-Noise Reduction in Infrared Arrays," *The Astrophysical Journal* **353**, L33 (Apr. 1990).

[10] Chapman, R., Beard, S., Mountain, M., Pettie, D., Pickup, A., and Wade, R., "Implementation of a charge integration system in a low background application.," in [*Instrumentation in Astronomy VII*], Crawford, D. L., ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **1235**, 34–42 (July 1990).

[11] Roth, K. C., Smith, A., Stephens, A., and Smirnova, O., "Measurements of airglow on Maunakea at Gemini Observatory," in [*Observatory Operations: Strategies, Processes, and Systems VI*], Peck, A. B., Seaman, R. L., and Benn, C. R., eds., **9910**, 421 – 440, International Society for Optics and Photonics, SPIE (2016).