

Readout and cooling of the WINTER InGaAs camera

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ABSTRACT

The Wide-Field Infrared Transient Explorer (WINTER) is a new time-domain instrument which will perform a seeing-limited survey of the near-infrared sky. Deployed on a dedicated 1-meter robotic telescope at Palomar Observatory, WINTER is designed to study transients of particular interest in the near-infrared including kilonovae from gravitational-wave sources, supernovae, tidal disruption events, and transiting exoplanets around low mass stars with surveys to a depth of $J=21$ magnitudes. WINTER’s custom camera combines six commercial large-format Indium Gallium Arsenide (InGaAs) sensors, observing in Y, J, and a short-H (Hs) band filters (0.9-1.7 microns), and employs a novel tiled optical design to cover a >1 degree squared field of view with 90% fill factor. Each wide-format (1920 x 1080 pixels) InGaAs sensor operates at $T = -50^{\circ}\text{C}$ with a thermoelectric cooler, achieving background-limited photometry without cryogenic cooling. The tiled InGaAs sensors result in a wide field-of-view instrument with significant cost savings when compared to HgCdTe sensors. We present WINTER’s novel readout scheme, which includes custom electronics, firmware, and software for low-noise, real-time readout of the InGaAs sensors, including up to a 30x speed up of data reduction using GPUs. This work also outlines the cooling design for warm ($T = -50^{\circ}\text{C}$) operation of the sensors with a two-stage thermometric cooler, copper heat pipes, and liquid cooling. We conclude with updates on the alignment, integration, and test of the WINTER instrument with a projected first light in Fall 2022.

Keywords: WINTER, InGaAs, Infrared detectors, Infrared astronomy, Non-destructive read

1. INTRODUCTION

In spite of the explosion of optical-wavelength surveys in the last decade,^{1–3} no parallel efforts have been made to perform cadenced, deep surveys of the infrared ($1.0\mu\text{m} - 4.0\mu\text{m}$) sky. While infrared astronomy offers unique insights into dusty environments, cool stars, and r-process nucleosynthesis,⁴ the cost and complexity of the conventional hybridized Mercury Cadmium Telluride (HgCdTe) sensors prevent growth in infrared time-domain science. Additionally, HgCdTe sensors require cryogenic cooling of the optics and detectors to minimize dark current.

Indium Gallium Arsenide (InGaAs) hybridized sensors offer an economical alternative to HgCdTe sensors with extensive heritage in defense and surveillance applications and do not require cryogenic cooling. The InGaAs substrate has a wavelength cutoff at $1.68\mu\text{m}$, which sacrifices K-band imaging but allows for low instrumental backgrounds under warm ($T \approx -50^{\circ}\text{C}$) operations. A prototype camera^{5,6} demonstrated sky-background limited InGaAs imaging operating between -40°C and -55°C using a thermoelectric cooler (TEC) with secondary liquid cooling without employing cryogenics or cooling the optics and control electronics.

The Wide-Field Infrared Transient Explorer (WINTER) is a new, seeing-limited infrared survey instrument that tiles six wide-format InGaAs detectors to cover a >1 degree squared field of view with a 90% fill factor (Figure 1).⁷ WINTER will operate on a dedicated 1-meter robotic telescope at Palomar Observatory, surveying

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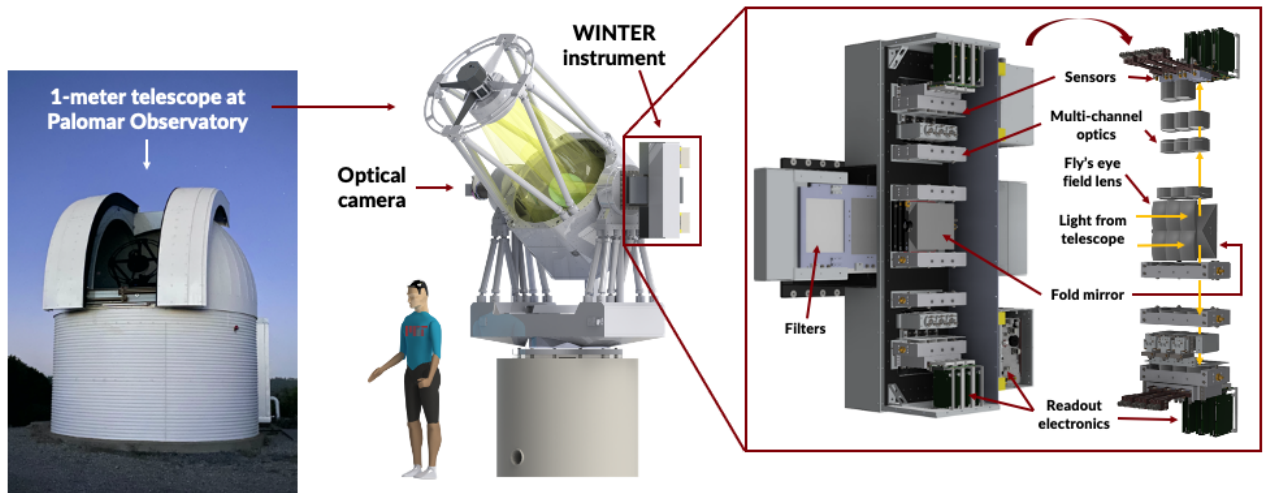


Figure 1: An overview of the WINTER near-infrared survey instrument. Left: The robotic telescope in its 1-meter dome at Palomar Observatory. Middle: A CAD model of the telescope pointing out the placement of the future WINTER camera and an optical camera on the companion port. The telescope has been observing robotically with the optical camera since June 2021. Right: Two cutaway images demonstrating the WINTER’s design. Light from the telescope passes through a filter and is split into six channels by the fly’s eye field lens, three pointing towards the top of the image and three towards the bottom. Each symmetrical half of the instrument features three channels of optics bonded together (as shown at the top right) and placed in adjustable frames (as shown in the bottom right). The light ends at six abutted InGaAs sensors with attached readout electronics. At the top right of the image, one lens group has been removed to show the sensor placement.

the infrared time-domain sky in the Y-band ($1.0\mu\text{m}$), J-band ($1.2\mu\text{m}$), and a shortened H-band ($1.6\mu\text{m}$) to a depth of $J_{\text{AB}} = 21$ magnitudes. A key component of the instrument are the custom readout electronics controlled by a commercially-available field programmable gate array (FPGA) modules, allowing a high level of control over the sensor imaging and readout. By sampling the sensor with multiple non-destructive reads per second (30 Hz), custom firmware and software help reduce read noise with common techniques such as sample-up-the-ramp⁸ in real time.

WINTER’s primary science goal is the study of kilonovae from binary neutron star and neutron-star black hole mergers discovered in gravitational waves and Ref. 9 estimates WINTER will discover up to five new kilonovae during the fourth observing run of the Advanced LIGO, Virgo, and KAGRA interferometers. Other near-infrared transients of interest include transiting exoplanets around low-mass stars, tidal disruption events, supernovae, and stellar mergers. In addition to time-domain astronomy, WINTER will build up a deep co-added reference of the near-infrared sky, contributing to future near-infrared surveys and studying static sky science such as brown dwarfs, galactic structure, and high-redshift quasars.

This paper focuses on the InGaAs detectors central to the WINTER instrument. Section 2 provides an overview of the instrument design, section 3 discusses the InGaAs detectors, section 4 outlines the readout electronics, FPGA firmware, and software, and section 5 summarizes the detector thermal management and prototyping cooling experiments. Finally, section 6 concludes and outlines the upcoming completion of the project.

A companion paper (Ref. 10) provides an overview of the WINTER instrument and observing with the 1-meter telescope, including an in-depth discussion of the optics, mechanics, and robotic observing. Currently, the alignment, integration, and testing of the WINTER instrument is ongoing with an expected first light in Fall 2022. The 1-meter telescope has been observing robotically since June 2021 with an optical-wavelength camera named SUMMER (Studying the Universe with Multi-Messenger and Exoplanet Research) on the companion port (Figure 1).

2. INSTRUMENT OVERVIEW

This section provides a brief introduction to the design of the WINTER instrument. For a more detailed description of the instrument design see Ref. 7 and Ref. 11, for more on the opto-mechanical mounting design see Ref. 12, and for more on the detector architecture and readout electronics see Ref. 13.

WINTER’s design features a nearly continuous focal plane covering 1.19° by 1.02° per image with $1''$ sampling to optimally sample Palomar’s seeing and to match other time-domain surveys. In order to achieve the $1''$ pitch, WINTER’s optics re-image the telescope’s F/6 beam down to an F/3 beam and splits the incoming light into six identical optical channels. Light from the telescope passes through a color filter, is then split into six channels by a fly’s eye field lens (Figure 1a), and then is split further into two sets of three channels by a right-angle fold mirror. Next, the light passes through four groups of re-imaging lenses (Figure 1b) and ends at a set of InGaAs sensors (Figure 1c). To achieve the high-fill field of view, the sensors are closely abutted with custom packaging. A set of readout electronics mount directly to the back of each sensor and are designed to fit within the instrument housing. The closely-packed lenses are truncated on two sides to match the HD-format of each sensor and are bonded together in a tiled lens group and share a rectangular lens frame (Figure 2).

To minimize excess heat in the telescope’s dome, the liquid chiller and most of the instrument computing take place in an adjacent shed. Conduits pass power, data, and liquid coolant between the shed and the dome. Heat pipes draw heat away from the detectors to the closed-loop liquid cooling without risking leaks in the instrument (Figure 2).

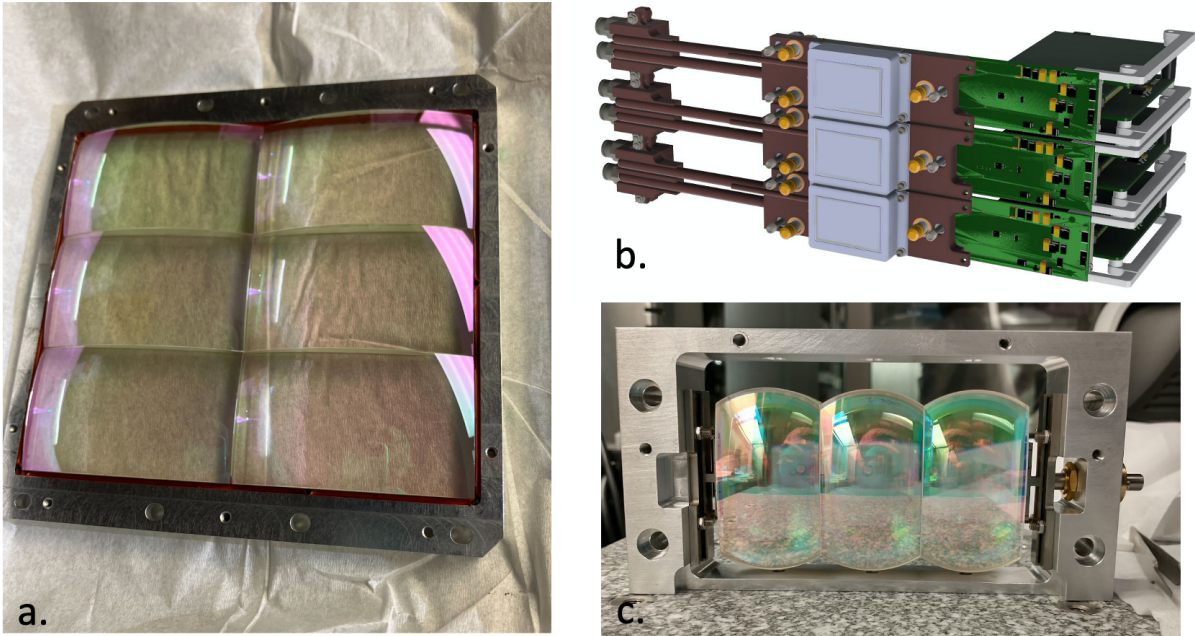


Figure 2: Details of the WINTER design. A: The WINTER fly’s eye field lens, which splits light from the telescope into six channels. B: A CAD model showing three of WINTER’s six sensors, making up half of the total focal plane. The detector packages are modified such that the sensors are closely abutted, leading to an over 90% image fill factor. A pair of copper heat pipes transport heat away from the sensor to liquid cooling. The readout electronics mount on the back of the sensor and are laid out to fit within the constraints of the instrument housing (Figure 1). C: Three channels of WINTER’s truncated lenses bonded together in their frame.

3. DETECTORS

WINTER's six InGaAs detectors are customized AP1020 detectors co-developed by Teledyne-FLIR and Sensor Creations (Figure 3). The hybridized CMOS focal plane arrays feature a high-definition format of 1920 x 1080 pixels and are the largest InGaAs detectors available. The $15\mu\text{m}$ pixels observe in the near-infrared spectral range $0.9\mu\text{m}$ and $1.7\mu\text{m}$ with a K-band cutoff. The photoactive substrate sits on top of a new readout integrated circuit (ROIC) with a capacitive transimpedance amplifier (CTIA) structure featuring eight output data nodes, allowing for sampling at a 30 Hz frame rate. The ROIC is cooled by a two-stage thermoelectric cooler (TEC) inside a vacuum-sealed package, allowing nominal operation at -50°C . The expected dark current at -50°C is $<125\text{ e}^-/\text{pix}/\text{s}$ and the expected read noise is $<45\text{ e}^-$, dominated by Poisson noise from the sky background.

Development of the WINTER imaging system builds on a prototype instrument constructed by the MIT group based on the Teledyne-FLIR AP1121 InGaAs sensor with a single 640×512 pixel detector. The AP1121 detector has a similar pixel architecture to the newer AP1020, which is scaled to a wider format with eight output channels. The prototype camera was deployed on the 100-inch DuPont Telescope at the Las Campanas Observatory in Chile and demonstrated sky-background limited J-band imaging with InGaAs detectors.^{5,6}

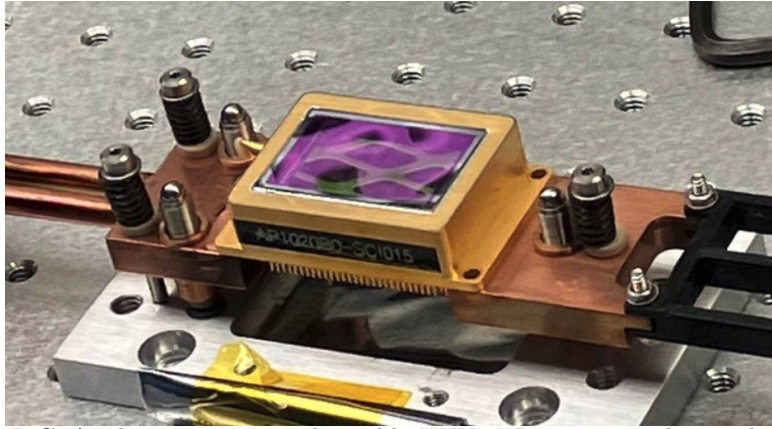


Figure 3: An AP1020 InGaAs detector on its adjustable WINTER mount with attached copper heat pipes to cool the sensor. The detectors, developed by Teledyne-FLIR, have 1920 by 1080 pixels ($15\mu\text{m}$ pitch), making the sensors the largest InGaAs detectors on the market.

4. READOUT

WINTER combines the new InGaAs detectors described in Section 3 with custom readout electronics, firmware, and software to leverage the fast readout of the detectors. With a 30 Hz frame rate sampled non-destructively, each pixel is read continuously throughout an exposure, allowing for noise reduction with techniques such as sample-up-the-ramp⁸ and Fowler pairing.¹⁴ This fast readout scheme requires novel electronics, firmware, and software to keep data acquisition and reduction running in tandem with robotic observing, allowing for real-time transient detection and alerts.

4.1 Electronics

Five boards make up WINTER's focal plane electronics: the sensor board, analog board, FPGA module, digital board, and power board. The optical design of the six WINTER channels, as seen in Figure 1, constrains the geometry of the first four boards. Figure 4 shows one sensor with its readout electronics in the laboratory test set up before it is integrated into the six sensor system. The sensor board plugs directly into the back of the sensor and acts as a motherboard for the analog, digital, and FPGA boards, allowing for direct signal processing without extra cables. The function of each board is as follows:

1. **The sensor board** serves as an interface to the InGaAs sensor with a custom socket interface allowing for cooling hardware to remove heat from the back of the detector. It also provides buffer and preamplifier

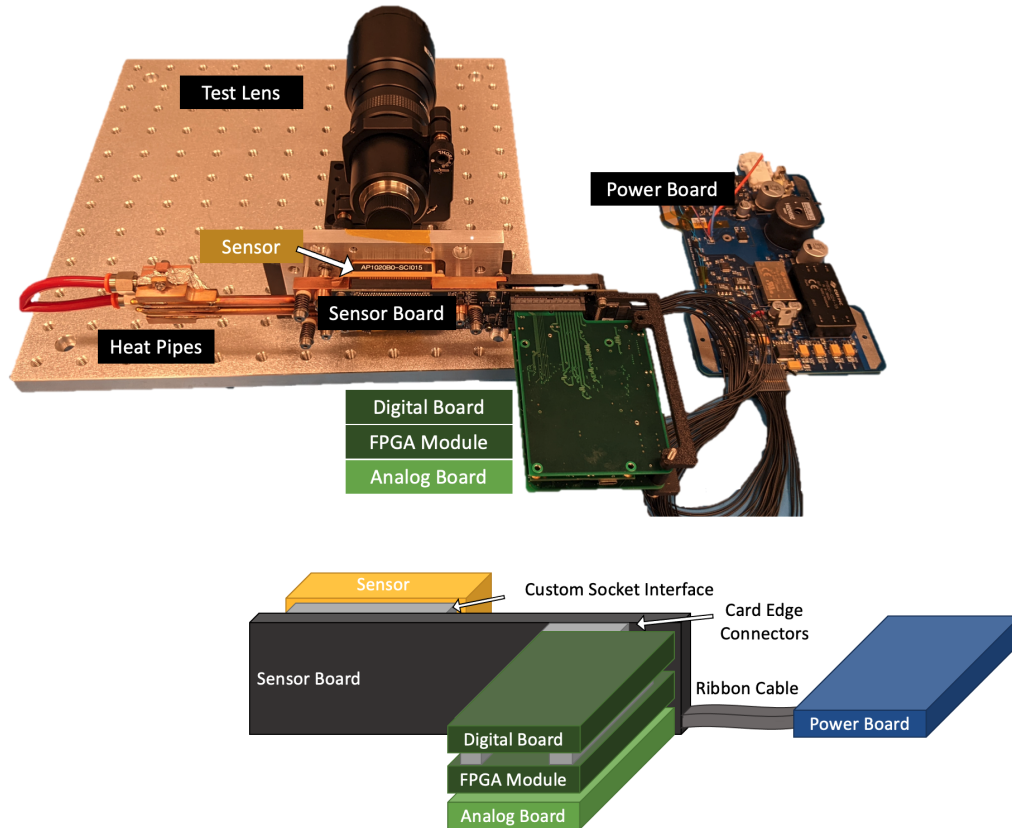


Figure 4: The sensor and readout electronics for one of six WINTER focal plane assemblies. Left: The electronics and sensor in the laboratory test environment with a lens for imaging. Copper heat pipes on the left draw heat away from the sensor to a liquid cooling heat exchanger. Right: A block diagram of the five readout electronics boards demonstrating the connections between the boards and the sensor.

stages with minimal trace lengths, temperature sensors, electrostatic discharge protection, and PCI slot card edge connectors for the analog and digital boards.

2. **The analog board** hosts eight 16-bit differential analog-to-digital converters (ADCs) operating in parallel to convert the eight channels of imaging data.
3. **The FPGA module** is an Opal Kelly XEM7310 board, which features a Xilinx Artix 7 FPGA with 1 GiB of DDR3 RAM, an 200 MHz oscillator clock, and a USB 3.0 interface. The FPGA controls the electronics and detector including power control, housekeeping, detector control, and image readout.
4. **The digital board** provides an interface between the FPGA module and the other electronics via a set of backplane connectors.
5. **The power board** distributes power for the electronics and sensor from the input 12 V power. It also features a custom TEC drive circuit along with housekeeping and temperature monitoring, allowing for a closed-loop temperature control locally regulated by the FPGA.

4.2 FPGA Firmware

The FPGA firmware is responsible for the control, timing, and housekeeping of the sensors, TEC, and focal plane readout electronics assembly along with collection of sensor data and readout to software. Broadly, the firmware provides three main functions: electronics control, sensor control, and interfacing with the software. Figure 5 provides a high-level block diagram of the firmware functions and how the modules interconnect.

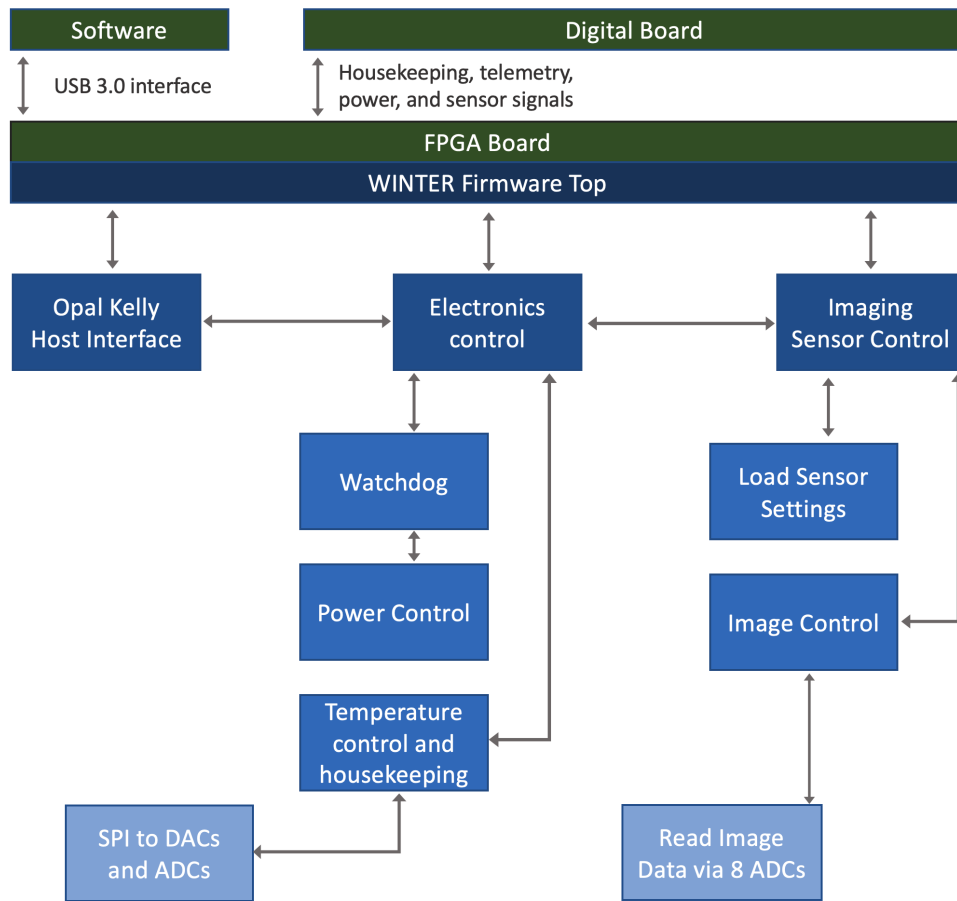


Figure 5: The high-level firmware architecture. The firmware interfaces with the electronics and sensor through signals from the digital board. Software running on a computer in the adjacent shed controls the firmware and receives imaging and housekeeping data via a USB 3.0 over fiber interface. There are three main firmware functions: controlling and clocking the imaging sensor, monitoring the power and temperatures of the readout electronics, and communicating with the software via the Opal Kelly USB 3.0 interface.

1. **Software interface:** The FPGA communicates to the software via a USB 3.0 connection using the Opal Kelly Host Interface as part of the Opal Kelly Front Panel package. The software is always primary and controls the firmware; however the firmware will safely shut down power if the watchdog detects a software outage or if any components on the electronics or sensor overheat.
2. **Electronics control:** The firmware controls power sequencing and monitoring along with providing temperature control and reference voltages. An eight-channel ADC on the power board monitors voltages and temperatures throughout the electronics, which are read into the firmware via serial peripheral interface (SPI). Additionally, the TEC voltage is set via a digital-to-analog converter (DAC) via SPI and reference voltages for the detector bias and the analog offset voltages for the eight sensor readout ADCs are set via SPI on an additional DAC. All of the SPI interfaces for the electronic control—the reference voltage DAC, the TEC DAC, and the housekeeping ADC—are routed on one set of signals to save space.
3. **Image control:** The highly-configurable ROIC for the InGaAs detectors require external control of the sensor clocking and timing, allowing for imaging in correlated double sampling and non-destructive read modes at a range of frame rates. The firmware also programs a range of sensor settings for the ROIC via

SPI, permitting a high level of control over the sensor configuration.

4.3 Software

The six FPGA modules send data from the instrument to a Linux desktop in the adjacent shed via USB 3.0 over fiber at a rate of 320 MB/s. This allows for frames from all six sensors to be stored in RAM for short exposures (≤ 3 seconds) or every other frame for longer exposure to be written directly to disk between frame reads. The software is written in `python` and is multi-processed for simultaneous control of the six detectors, using a custom, pre-compiled `C++` module to handle low-latency interfacing with the detectors.

As an instrument designed for transient discovery, WINTER data needs to be reduced quickly ($\sim$ seconds) to minimize the data storage volume and to make real-time decisions about candidate events and observing strategies. While techniques such as sample-up-the-ramp reduce noise, they also add significant computational overheads. The problem of processing high-definition imaging data quickly is well suited for the architecture of graphics processing units (GPUs).

In order to benchmark sample-up-the-ramp data reduction we compare the processing time for a linear fit for each pixel across six sensors with 128 frames of data. For user accessibility, the linear fits are implemented in `python` with the `numpy` package on a Central Processing Unit (CPU) and the corresponding `cupy` package for GPUs. Figure 6 shows the time to reduce six sensors of data on an Intel Core i7-3770 CPU, a commercial NVIDIA GeForce RTX2070 GPU ($\sim$ \$500), and an industry-level NVIDIA Volta V100 GPU ($\sim$ \$9000). Performing the linear fit directly with the ordinary least squares method with matrix multiplication leads to faster data reduction than using the `numpy.polyfit` and `cupy.polyfit` functions, with a minimum time to reduce six sensors of 8.3, 2.2, and 0.28 seconds for a CPU, commercial GPU, and an industry GPU, respectively.

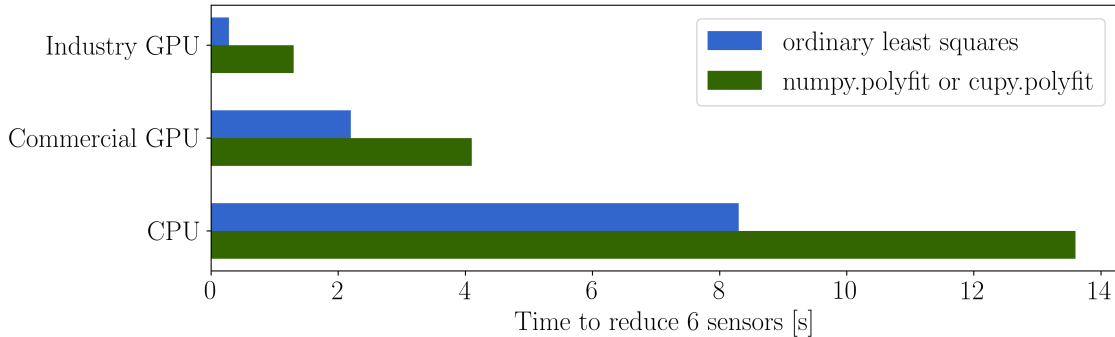


Figure 6: How long it takes to reduce WINTER data from six sensors by performing a linear fit to every pixel in 128 frames of data. An industry-level graphics processing unit (GPU) performs up to thirty times faster than a Central Processing Unit (CPU). The ordinary least squares method of linear fits written in native `python` reduces data up to 4.6 times faster than the `numpy.polyfit` function on a CPU or the `cupy.polyfit` function on a GPU.

5. COOLING

WINTER’s InGaAs detectors operate between -40°C and -55°C , which previous prototyping^{5,6} and modeling¹¹ efforts have shown sufficiently reduces dark current to achieve sky-background limited imaging. Each detector has a two-stage TEC that interfaces to copper heat pipes, which are cooled with a mixture of glycol and distilled water from a chiller in the adjacent shed (Figure 2). The sensors packages are cooled to $\sim 10^{\circ}\text{C}$ with a liquid chiller to remove heat from the TEC while keeping the sensor above the dew point at Palomar Observatory ($\sim 9^{\circ}\text{C}$ at the 90th percentile).⁷ The TECs then cool the backside of the detector another 60°C , generating about 10–12 W to cool the detector to $\sim -50^{\circ}\text{C}$. The FPGA monitors temperatures throughout the instrument and communicates with the software to control the TEC voltage with a proportional-integral-derivative (PID) loop.

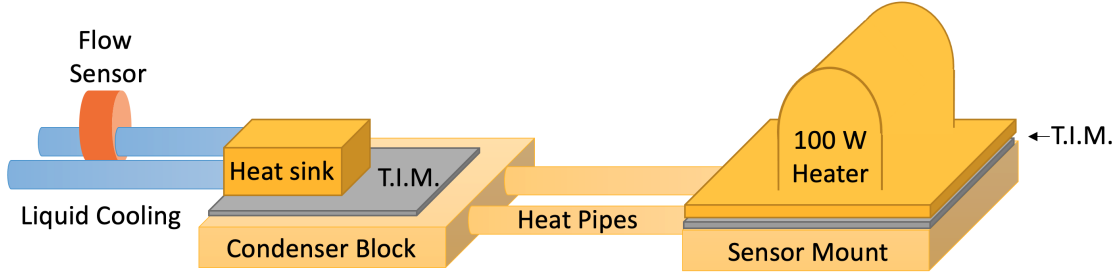


Figure 7: The sensor cooling system with an 100 W heater as a proxy for the sensor and its heat dissipation. The back side of the sensor packaging connects to the sensor mount with a thermal interface material (T.I.M.) to minimize thermal resistance. A pair of copper heat pipes draw heat from the sensor to a condenser block, which attaches to a heat sink and liquid cooling with another layer of the T.I.M. This design allows for cooling of the sensor without risking leaks near the detectors and without convective cooling dumping heat in the telescope dome.

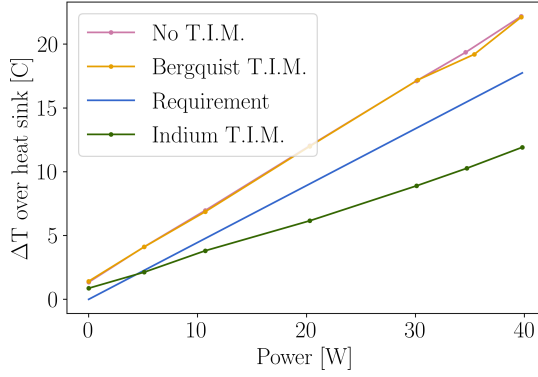


Table 1: Thermal resistance and power dissipated for various thermal interface materials.

	Thermal Interface Material (T.I.M.)			
	Requirement	Indium	Bergquist	No T.I.M.
R ($^{\circ}\text{C}/\text{W}$)	0.466	0.275	0.520	0.532
P_{max} (W)	31.3	48.0	24.4	24.4

Figure 8: Change in heat between the heater and heat sink shown in Figure 7 as a function of power dissipated by the heater. An Indium thermal interface material (T.I.M.) minimizes heat loss and meets the project requirement with a thermal resistance less than $R_{\text{max}} = 0.466^{\circ}\text{C}/\text{W}$.

Copper heat pipes were selected as an intermediate cooling method between the TEC and the closed-loop liquid cooling to balance various project requirements. Liquid near in the instrument risks leaks and convective cooling could contaminate the optics and add heat in the dome, increasing noise for the near-infrared images. As the heat pipes introduce a long thermal path, we conducted prototyping experiments to select a thermal interface material (T.I.M.) which would minimize thermal resistance in the connections between the heat pipes with the sensor and the heat exchanger. Additionally, the experiments demonstrated that WINTER’s thermal design meets the cooling requirement of dissipating 31.3 W of heat per sensor, a conservative requirement derived from the maximum heat able to be dissipated by the two-stage TEC (25 W with a 25% tolerance).

For the experiment, two T.I.M.s were selected—Bergquist 3004 gap filling material and Indium foil—and compared to a control experiment with no material. The Indium foil is textured (also known as Heat-Spring) which reduces the contact pressure needed for low thermal resistance compared to planar foils, limiting the clamping

stress on the sensor package. Grease was not selected due to concerns of longevity and contamination of the optics. The T.I.M. provides an interface between the sensor (modeled with an 100 W heater) and the sensor mount and between the condenser block and a heat sink kept at 10°C by liquid coolant (Figure 7). Meeting the 31.3W of heat dissipated per sensor requires a maximum allowable thermal resistance of $R_{\max} = 0.466^{\circ}\text{C}/\text{W}$, neglecting convective and radiation losses. Figure 8 shows the temperature change between the sensor (heater) and heat sink as a function of power input by the heater, where lower heat loss and less thermal resistance lead to more effective cooling. The Indium T.I.M. meets WINTER’s cooling requirements with a thermal resistance of $R = 0.275^{\circ}\text{C}/\text{W}$, meaning that at the testing temperature of 24°C, the cooling design can remove up to $P_{\max} = 48$ W of heat (Table 1). The Bergquist T.I.M. performs similarly to the design with no interface material and does not meet the cooling requirements. We selected the Indium T.I.M. for WINTER’s thermal management and repeated the experiment with a sensor mount matching the final instrument design and the new configuration still met all cooling requirements.

6. CONCLUSIONS AND FUTURE WORK

WINTER is a new near-infrared survey instrument that covers >1 deg² field of view with 1” pixels. The light is captured by six InGaAs sensors, which offer an economical alternative to the conventional HgCdTe sensors while still achieving background-limited performance with liquid cooling and a thermometric cooler. Custom electronics, firmware, and software enable noise reduction a real-time data readout.

WINTER’s construction is underway, with all optics and sensors obtained and undergoing alignment, integration, and testing. With expected first light in Fall 2022, WINTER will join a new era of near-infrared survey telescopes exploring the dynamic infrared sky.

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