A Wide-Field Infrared Camera for the Palomar 200-inch Telescope

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ABSTRACT

The availability of both large aperture telescopes and large format near-infrared (NIR) detectors are making wide-field NIR imaging a reality. We describe the Wide-field Infrared Camera (WIRC), a newly commissioned instrument that provides the Palomar 200-inch telescope with such an imaging capability. WIRC features a field-of-view (FOV) of 4.33 arcminutes on a side with its currently installed 1024-square Rockwell Hawaii-I NIR detector. A 2048-square Rockwell Hawaii-II NIR detector will be installed and commissioned later this year, in collaboration with Caltech, to give WIRC an 8.7 arcminute FOV on a side. WIRC mounts at the telescope's f/3.3 prime focus. The instrument's seeing-limited optical design, optimized for the JHK atmospheric bands, includes a 4-element refractive collimator, two 7-position filter wheels that straddle a Lyot stop, and a 5-element refractive f/3 camera. Typical seeing-limited point spread functions are slightly oversampled with a 0.25 arcsec per pixel plate scale at the detector. The entire optical train is contained within a cryogenic dewar with a 2.5 day hold-time. Entrance hatches at the top of the dewar allow access to the detector without disruption of the optics and optical alignment. The optical, mechanical, cryogenic, and electronic design of the instrument are described, a commissioning science image and performance analyses are presented.

Keywords: Wide-field, Near-infrared

1. INTRODUCTION

The combination of recently available large format near-infrared arrays with large aperture telescopes offers the chance to develop more efficient deep, wide-field imaging in the near-infrared. We are currently commissioning the Wide-field Infrared Camera (WIRC) at the Palomar 200-inch telescope. Mounted at prime focus to take advantage of the telescope's fast f/3.3 primary, WIRC currently provides seeing limited imaging with a FOV of 4.33 arcminutes with its Hawaii-I 1024-square detector and a 0.25 arcsec / pixel plate scale. An upgrade to a Hawaii-II 2048-square detector in August, 2002, in collaboration with Caltech, will increase the FOV to 8.7 arcminutes.

The scientific rationale for such large area near-infrared cameras includes large surveys of the universe at both immense distances and close to the local neighborhood. Galaxies at a z $\sim$ 1 will have their starlight redshifted into the near-infrared, making surveys in this wavelength range crucial for understanding the variation of galaxy and star formation activity with redshift. Closer to home, wide-field near-infrared imaging can help identify low-mass stars and brown dwarfs in nearby open stars clusters so that we can improve our understanding of the luminosity and mass function for low-mass objects.

2. DESIGN

In the following sections we discuss the instrument's optical, mechanical, and dewar design, and the detector and electronics control scheme.

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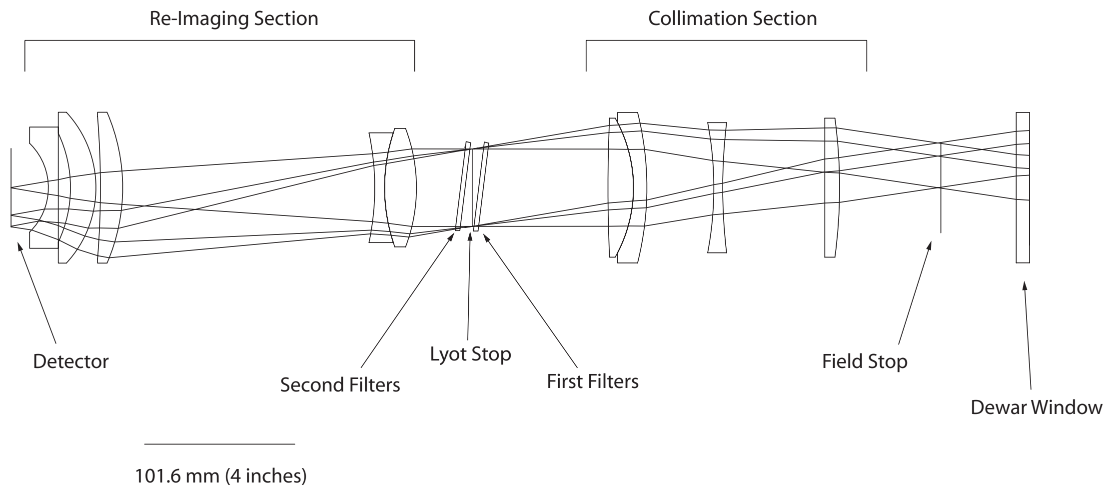

Figure 1. A schematic of the WIRC optical train from the dewar window (right side) to the detector (left side). Three beams are also shown: the on-axis beam and two at the edge of the field.

2.1. Optical

The camera features an all-refractive 9-lens re-imaging system designed and manufactured by Telic Optics, Inc. (N. Billerica, MA). The system is optimized for 1.1 - 2.3 μm, the JHK atmospheric bands. All elements have spherical surfaces with warm (300K) radii of curvature that match test plates in the Telic Optics inventory. With the exception of the dewar window, all elements are contained within the cryogenic dewar. The camera elements are made from the commonly used infrared materials ZnSe, Infrasil and CLEARTRAN (a water free ZnS), and range in diameter from 3.1 - 4 inches.

A schematic of the optical train is shown in Figure 1, along with three beams with various field angles. After reflection from the 200-inch primary mirror, an f/3.3 beam passes through the dewar window and immediately comes to a focus. A square field stop is located at the focus. Past the focus the beam is collimated by a 4-element lens assembly and then passes through two filter wheels that straddle an aluminum Lyot stop. The beam diameter at the Lyot stop is approximately 52 mm. Each filter wheel can contain up to seven 60 mm filters, each tipped at 7 degrees to minimize ghost reflections. Finally, the beam is re-imaged onto the detector by a 5-element lens assembly which includes a three-lens field flattener close to the focal plane. The final f/3.0 beam was selected to give a 0.25 arcsec / pixel scale on a Hawaii-II array (18 μmpixel pitch) thus slightly oversampling the typical seeing-limited point spread function. The 9-lens system also corrects aberrations caused by the primary mirror, primarily coma. Three separate edge-contact doublets are used in the design.

The image quality is predicted to be seeing limited over the entire 8.7 arcmin FOV for almost all seeing conditions at Palomar. Table 1 lists normalized fractional energy contained within 18μm spot radii at various positions on a Hawaii-II array. No instrumental image degradation has been observed thus far out to the edges of the Hawaii-I array in seeing as good as 0.55 arcseconds.

During design consideration was given to the pupil size to minimize the maximum angle of incidence on the filters at the edges of the field to avoid adverse performance while imaging through narrow band filters. The final design has a maximum angle of incidence at the pupil of 14 degrees.

To keep costs manageable the J,H and K bands were allowed to be non-confocal on the detector. Focusing when switching to the various filters is accomplished by focusing the entire telescope, i.e. the prime focus cage, with instrument attached, is moved along the optical axis to focus the selected wave-band. Typically only 0.3 mm focus adjustments are required between bands.

A full suite of astronomical filters fabricated as part of the Mauna Kea Observatory (MKO) near-infrared filter consortium[1–3] are available for use with WIRC. All available filters with respective central wavelength

Table 1. Normalized fractional energy contained within 18μm spot radius.

	Filter		
Focal Plane Position	J	H	K
(Diffraction Limit)	0.93	0.91	0.90
On-axis	0.92	0.89	0.85
Edge of detector	0.84	0.85	0.84
Corner of detector	0.58	0.66	0.62

and manufacturer are listed in Table 2. Normally the second filter wheel (the wheel downstream of the Lyot stop) will contain the broad-band filters J, H, K_S and K', an Infrasil flat, a narrow-band filter, and one empty position. The first filter wheel (the wheel upstream of the Lyot stop) will normally contain an aluminum blocking substrate, 5 narrow band filters and one empty position to allow use of filters in the second wheel.

The Infrasil flat in the second wheel can be used in series with a narrow band filter in the first wheel for the following reasons: First, by design the detector and 5-lens re-imaging optics have been offset from the axis of the Lyot stop and 4-lens collimating optics by $\sim$ 5 mils to compensate for the displacement of the optical axis by the tilted second filter just past the Lyot stop (the filter just before the Lyot stop causes pupil wander but not axis displacement). The Infrasil flat in the second wheel, with index of refraction similar to that of the broad-band filter substrates, can be inserted in series with narrow-band filters in the first wheel to retain the axis displacement and keep proper aberration correction by the downstream optics. Secondly, the first filter introduces a slight coma which can be eliminated by the use of a second filter in parallel just past the Lyot stop.

Table 2. Broad and Narrow-band filters available for use with WIRC.

Filter	$\lambda_{center}(\mu\mathrm{m})^{a,b}$	Manufacturer
J	1.250	OCLI
H	1.635	OCLI
K'	2.120	OCLI
K_S	2.150	Barr Associates
Pa β	1.282	NDC Infrared
J-continuum	1.207	NDC Infrared
Fe-II	1.644	NDC Infrared
H-continuum	1.570	NDC Infrared
CH_4 short	1.570	NDC Infrared
CH_4 long	1.690	NDC Infrared
Br γ	2.166	NDC Infrared
CO (2-0)	2.294	NDC Infrared
K-continuum	2.270	NDC Infrared

[a]Design center wavelength for 77K and 5 degree tilt angle

[b]WIRC filters are tilted at 7 degrees, so filter design wavelengths will be shifted blueward by 0.001-0.002 μm

2.2. Mechanical

The mechanical assembly for the camera was also designed and fabricated by Telic Optics. Each of the collimating and re-imaging systems are mounted within aluminum lens barrel assemblies. A schematic of the WIRC dewar with installed optics is shown in Figure 2. The 4-lens collimating section and the filter wheel assembly can be seen mounted in the dewar in the lab in Figure 3.

Only one material, aluminum, is used for the housings to simplify the mechanical problem of manufacturing lenses and mounting structures at warm temperatures that will ultimately be used at cryogenic temperatures after thermal contraction. To maintain lens centration at warm and cold temperatures a system of Delrin pins are used. The pins center the lenses inside the barrels while warm. As the system cools the large thermal contraction of Delrin (approx. three times that of aluminum) causes the pins to contract away from the lenses. In their place the aluminum lens housing, with inside diameters properly designed, contract and closely surround the lenses to keep them centered.

The two filter wheels and Lyot stop are mounted on the dewar cold plate located between the collimating and re-imaging systems. The ~ 9.4 inch filter wheels can accomodate up to seven 60 mm filters. The wheels, geared on their edges, are driven by cryogenic stepper motors purchased from Phytron (Waltham, MA) at a gear ratio of $\sim 17.7:1$. The steppers motors are operated without feedback although 'home switches' are provided. These are simply micro-switches mounted adjacent to the filter wheels that are tripped as a protruding tab (one on each wheel) passes. The instrument operator can 'home' each wheel remotely when necessary to verify filter wheel position.

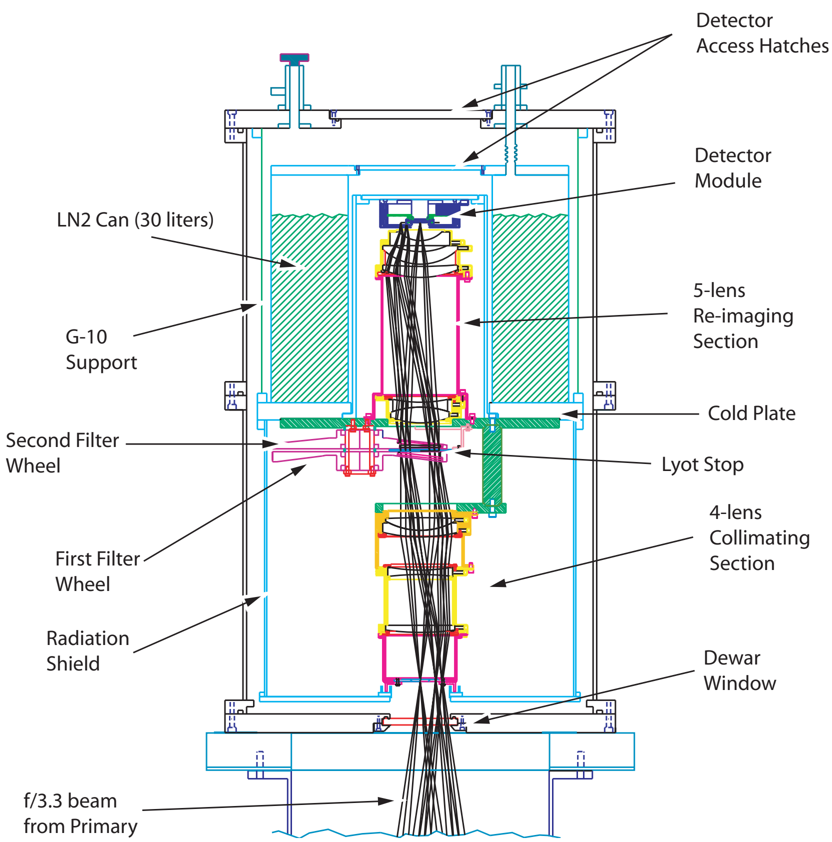

Figure 2. A schematic of the WIRC dewar and optics.

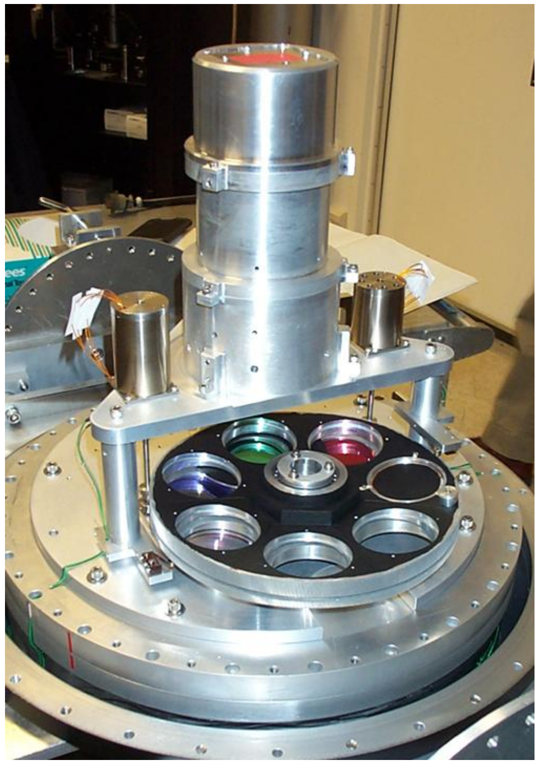

Figure 3. The WIRC dewar opened in the lab. The 4-lens collimating section can be seen in its lens barrel assembly. The two filter wheels straddling the Lyot stop can also be seen just above the cold plate.

2.3. Dewar

The instrument is housed within a cylindrical LN2 cooled cryogenic dewar designed in collaboration with and built by Precision Cryogenics Inc. (Indianapolis, IN). The requirement for a large diameter cold plate (17.5 inch) but long and thin optical assemblies perpendicular to the plate led naturally to the annular LN2 tank that surrounds the final 5-lens re-imaging system and detector. The tank can hold up to 30 liters of LN2 and typical hold times are 60 hours. The detector is mounted at the end of an aluminum cylinder that is directly connected to the cold plate for maximum cooling. The detector can be accessed by two 'hatches' on the top of the dewar. This allows for detector translation or focus adjustments without the need to open the two dewar halves and remove the camera and its components.

Figure 4 shows WIRC mounted at the 200-inch prime focus. Fully loaded with electronics racks and LN2 the instrument weighs approximately 400 lbs.

2.4. Detector & Electronics

The current detector is a Hawaii-I 1024-square HgCdTe engineering grade array produced by Rockwell Scientific. A Hawaii-II 2048-square array is being installed in August, 2002 (see §4). The Hawaii-I engineering grade array has four operational quadrants, three of which are cosmetically very good. The final quadrant has about a quarter of its area marred by bad pixels. The detector is installed on a fan-out board designed and fabricated by the University of Hawaii specifically for the Hawaii-I array. We operate the detector with external (off-chip) J270 JFETs to eliminate the on-chip FET glow typically seen with these devices.[4] The detector is operated with a bias (VRESET) voltage of 0.5 V to give an expected gain of approx 2 e^{-1}/DN.

WIRC currently uses the warm electronics and computer control system of another Palomar instrument built by Cornell, the Palomar High Angular Resolution Observer (PHARO)[5] science camera for the Palomar

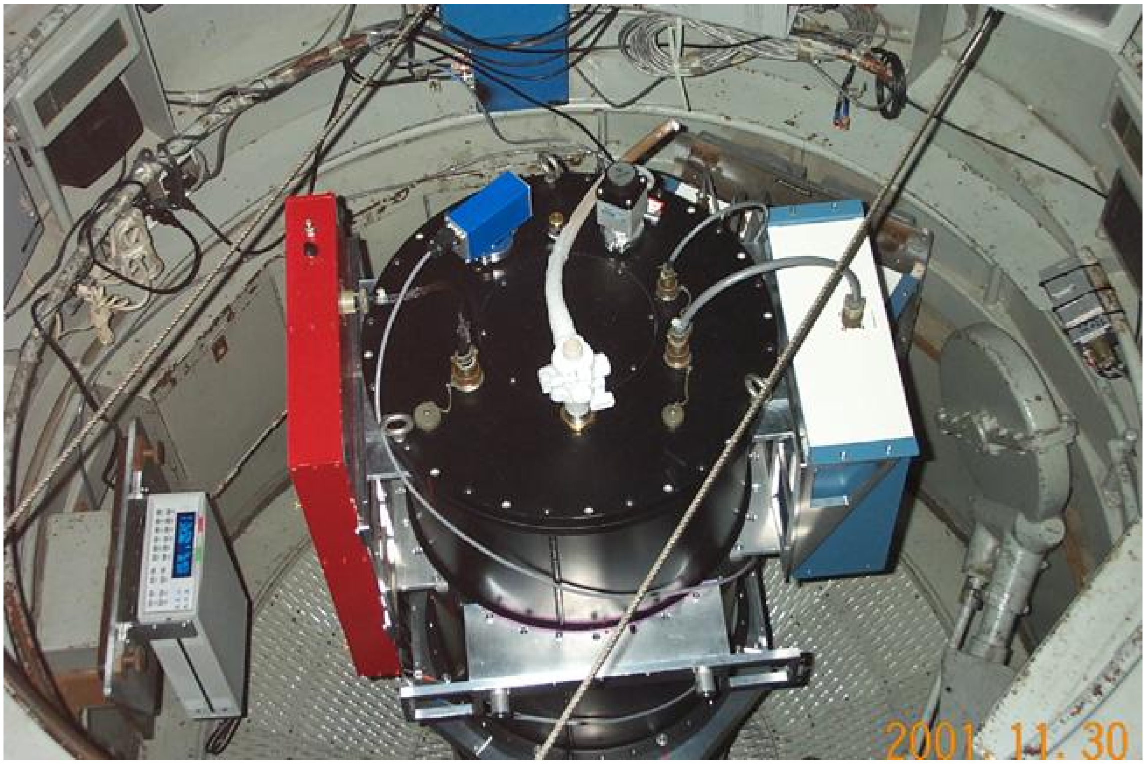

Figure 4. WIRC mounted at the prime focus of the 200-inch telescope for first light.

Adaptive Optics System. Since PHARO also uses a Hawaii-I array, it was relatively simple to use its control system for WIRC as an interim controller. Briefly, the PHARO warm electronics consist of a device driver, preamplifier and 16-bit A/D boards purchased from the University of Hawaii Institute for Astronomy. A fourth control board built by one of us (B.P.) generates the clocking waveforms, controls mechanical hardware via logical I/O, and handles the fiber interface. At the heart of this board is a field programmable gate array (FPGA). In fact it was this board's FPGA-based design that allowed the use of the PHARO electronics for WIRC with no hardware changes. Since WIRC had different hardware control requirements than PHARO (two stepper motors v. five motors and various sensors) the ability to download a new program for the FPGA at power-up allowed the electronics to be shared between the instruments for the past half year.

WIRC has also been able to use the same computer control as PHARO. Its graphical user interface (GUI), called XWIRC, offers similar camera control functionality as the XPHARO interface, except that we now use the open source GTK toolkit in place of the proprietary MOTIF toolkit.

3. PERFORMANCE

WIRC has been in commissioning mode on the Palomar 200-inch since first light in late November, 2001. With the exception of a re-design of the filter wheel drive mechanism and bearing housings to better compensate for thermal contraction effects, the instrument was ready for science starting the first night. The measured point source sensitivities of WIRC in JHK' based upon observations of the HST standard P161-D[6] are shown in Table 3. Backgrounds with the blocker inserted in the beam are $\sim 1\mathrm{e}^{-1}$/sec, including stray light, dark current and read noise. No measurable distortion has been observed across the Hawaii-I array to an upper limit of 0.5 arcsec. Ghost images have only been observed when the Infrasil flat is used in series with narrow-band filters in the first wheel. The ghosts were ~ 5 mags fainter than the source image.

Figure 5. Images of the interacting galaxy pair NGC 4038 and NGC 4039, known as the Antennae galaxies. (left) An HST/WFPC2 true color $UBVI$ composite image of the central region.[7] (right) K' band image of the same image observed with WIRC.

A K' image of the Antennae interacting galaxy pair taken with WIRC (NASA's Astronomy Picture of the Day for April 11, 2002, `http://antwrp.gsfc.nasa.gov/apod/ap020411.html`) is shown in Figure 5. This image is a co-added composite from 160 individual, dithered, 7.3 second integrations for a total integration time of 19.4 minutes. Also shown in Figure 5 is a true color $UBVI$ composite of the same field imaged by HST/WFPC2.[7] Not only does this figure show the imaging capabilities of WIRC, but it demonstrates the importance of near-infrared wide-field imaging in understanding such phenomena as star formation in the highly energetic environments of interacting galaxies.

4. DETECTOR UPGRADE

In collaboration with Caltech, a final science grade 2048-square Hawaii-II HgCdTe array is being installed in the instrument this summer to take full advantage of the camera's design FOV. First light for this array is planned for September, 2002. For approximately six months the Hawaii-II will be controlled by a 4-channel Leach control

Table 3. Measured Point Source Sensitivity

Filter	m for S/N = 5 for 1.8 sec	m for S/N = 5 for 3600 sec [a]
J	18.5	22.6
H	17.9	22.0
K'	17.4	21.5

[a]Extrapolated from 1.8 second measurement

system provided by Caltech. After this time a custom 32-channel detector control system will be installed. This system, designed by one of us (B. P.), will feature differential signal output from each channel to the pre-amp boards, 32 independent A/D converters, and an FPGA based clocking, control and communications board. The system will be capable of ~ 1 Hz array readout speeds.

We decided to produce electronics capable of operating the Hawaii-II detector in 32-channel mode primarily because of the science requirement to be able to observe fields with bright objects. This is needed for example when surveying open star clusters for faint brown dwarfs. The minumum practical array readout speeds of 4-channel and 32-channel electronics are ~ 3 seconds and < 1 second, respectively. The ~ 3 second minimum integration time of the 4-channel electronics would then cause increased persistence due to bright objects and preclude the sub-frame readout mode which is only possible with the Hawaii-II arrays when using 32-channel mode.

The final 32-channel electronics system leverages ongoing detector control development at Cornell for the Faint Object Infrared Camera for the Sofia Telescope (FORCAST),[8] a facility-class mid-infrared camera for the Stratospheric Observatory for Infrared Astronomy (SOFIA). The FORCAST system is being designed to operate 32 channel output (16 each from two 256-square mid-infrared arrays) at 400 Hz frame rates.

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