Smithsonian Widefield Infrared Camera

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ABSTRACT

The Smithsonian Widefield Infrared Camera (SWIRC) is a Y-, J-, and H-band imager for the f/5 MMT. Proposed in May 2003 and commissioned in June 2004, the goal of the instrument was to deliver quickly a wide field-of-view instrument with minimal optical elements and hence high throughput. The trade-off was to sacrifice K-band capability by not having an internal, cold Lyot stop. We describe SWIRC's design and capabilities, and discuss lessons learned from the thermal design and the detector mount, all of which have been incorporated into the upcoming MMT & Magellan Infrared Spectrograph.

Keywords: Infrared camera, HAWAII-2

1. INTRODUCTION

Ground-based infrared (IR) observations address many high-impact questions in astronomy, from the formation of planets and stars in our own Galaxy, to the formation of the first galaxies at high redshift and the star formation history of the Universe. Astronomers at the Smithsonian Astrophysical Observatory (SAO) have designed and are now using the *Spitzer Space Telescope* Infrared Array Camera (IRAC) to image large areas of sky to faint flux limits. *Spitzer* has two key limitations, however: *Spitzer* does not observe at near-IR wavelengths $\lambda < 3.5$ μm, and it has poor 1.2 arcsec resolution. Thus there is a critical need for ground-based, near-IR observations to fill the "wavelength gap" between optical and *Spitzer* observations, and to study the near-IR morphology of *Spitzer* sources.

The SAO Widefield Infrared Camera (SWIRC) was proposed in May 2003 to deliver quickly a wide field-of-view instrument to the 6.5m MMT telescope. The design trade-off was to give up K-band capability (which requires cold re-imaging of the pupil) in order to construct the instrument cheaply and quickly. The result is that SWIRC is a direct imager with minimal optical elements and very high throughput, 2.5-3 times that of FLAMINGOS on the MMT. SWIRC uses a 2048$\times$2048 HAWAII-2 HgCdTe array with a 0.150 arcsec/pixel plate scale that allows it to fully sample the best seeing at the MMT. SWIRC's 5.12$\times$5.12 arcminute field of view is well matched to the 5 arcminute field of IRAC. SWIRC was commissioned in June 2004, 6 months after *Spitzer* began science operations and only 13 months after SWIRC was originally proposed.

2. INSTRUMENT DESCRIPTION

2.1 Optical Design

SWIRC's optical design is an achromatic doublet that acts as a field flattener and provides the desired plate scale. Table 1 presents the as-built optical prescription. There are a limited number of optical materials that work in the near-IR.[1] Because SWIRC's optics are outside the dewar vessel, we cannot use hygroscopic crystals such as BaF_2 and LiF. Instead, we chose CaF_2 and IR Fused Quartz, and use the IR Fused Quartz element, the second lens, as the pressure window.

Our CaF_2 / IR Fused Quartz doublet provides excellent image quality: the geometric RMS spot diameters are 12.4 μm on-axis and 17.6 μm at corner of the field. The HAWAII-2 array has 18 μm pixels, thus the RMS spot diameters are less than one pixel in size.

SWIRC's optical design has forgiving tolerances that allow us to align the optics mechanically. Sensitivity calculations predict a 10% spot size change for a $2'$ lens tilt or a 0.25 mm lens de-center from the optical axis. In practice, we can mechanically locate the optics with a precision of $0.5'$ in tilt and 0.02 mm in centration.

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Table 1. SWIRC Optical Prescription.

Comment	Radius mm	Thickness mm	Diameter mm	Comment
MMT Primary	-16255.3	-6179.877	6500	Conic = -1
f/5 Secondary	-5150.89	7707.042	1587	Conic = -2.6947
SWIRC Lens 1	256.362	20.067	139.7	CaF_2
	-724.103	70.503	139.7	
SWIRC Lens 2	-464.439	15.083	116.0	Herasil
	427.906	64.6	116.0	
SWIRC Filter	Inf	7.0	70.0	BK7
	Inf	30.0	70.0	
SWIRC Detector	Inf			

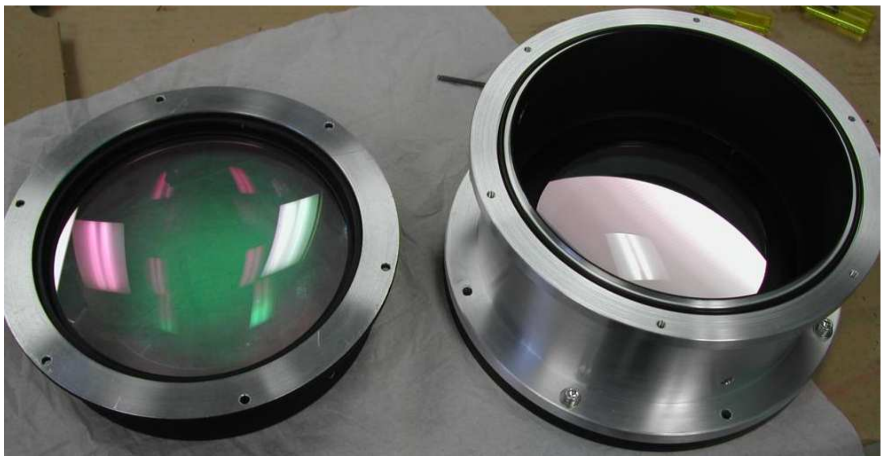

Figure 1. Lens 1 (left) and lens 2 (right) are athermally mounted in aluminum bezels with RTV GE560 full-edge bonds.

2.2 Lens Mounts

Figure 1 shows the SWIRC lenses in their aluminum bezel lens mounts. The two lenses were centered in the bezels with precision dowel pins, and bonded in place using RTV GE560 (see Figure 1). The height and thickness of the RTV bonds was chosen to compensate for the different thermal expansion coefficients of the materials so that the overall design is athermal.

We prevent condensation forming on the dewar window lens surface by sealing dry nitrogen between the doublet. As sketched in Figure 2, the two lens bezels are machined with slip-fit pilot diameters, and mated with a Viton o-ring. Two 1/2-inch valves access the volume between the two lenses, and dry nitrogen is periodically blown through the valves to purge the air of water vapor.

The lens assembly is aligned with a pilot diameter machined onto the dewar cover and bolted to the dewar. The IR Fused Quartz lens provides a 0.076 mm pre-load onto a series 2-155 Viton o-ring and seals the dewar.

2.3 Filters

SWIRC has three 70 mm diameter science filters: a Y-band (1.02 μm), J-band (1.2 μm), and H-band (1.6 μm), plus a dark position. The filters are inside the dewar and at cryogenic temperature. Because SWIRC does not have a cold Lyot stop, the filters must reject all out-of-passband light. Transmission scans showed all three filters have excellent $< 10^{-4}$ out-of-passband transmission on-axis. However, out-of-passband rejection at large incidence angles is also very important.

During commissioning, we discovered that our original J-band filter had 15 times larger background than expected. We ruled out scattered light and unwanted light sources, and concluded that the filter itself was at

Table 2. SWIRC on-sky performance.

Filter	Detected (e-/s) for 15th mag star, Vega-relative	Sky background (e-/s/pix)	Exposure time (s) to observe 20th mag point source at S/N=10
Y	26,000	650	90
J	33,000	470	40
H	37,000	2600	170

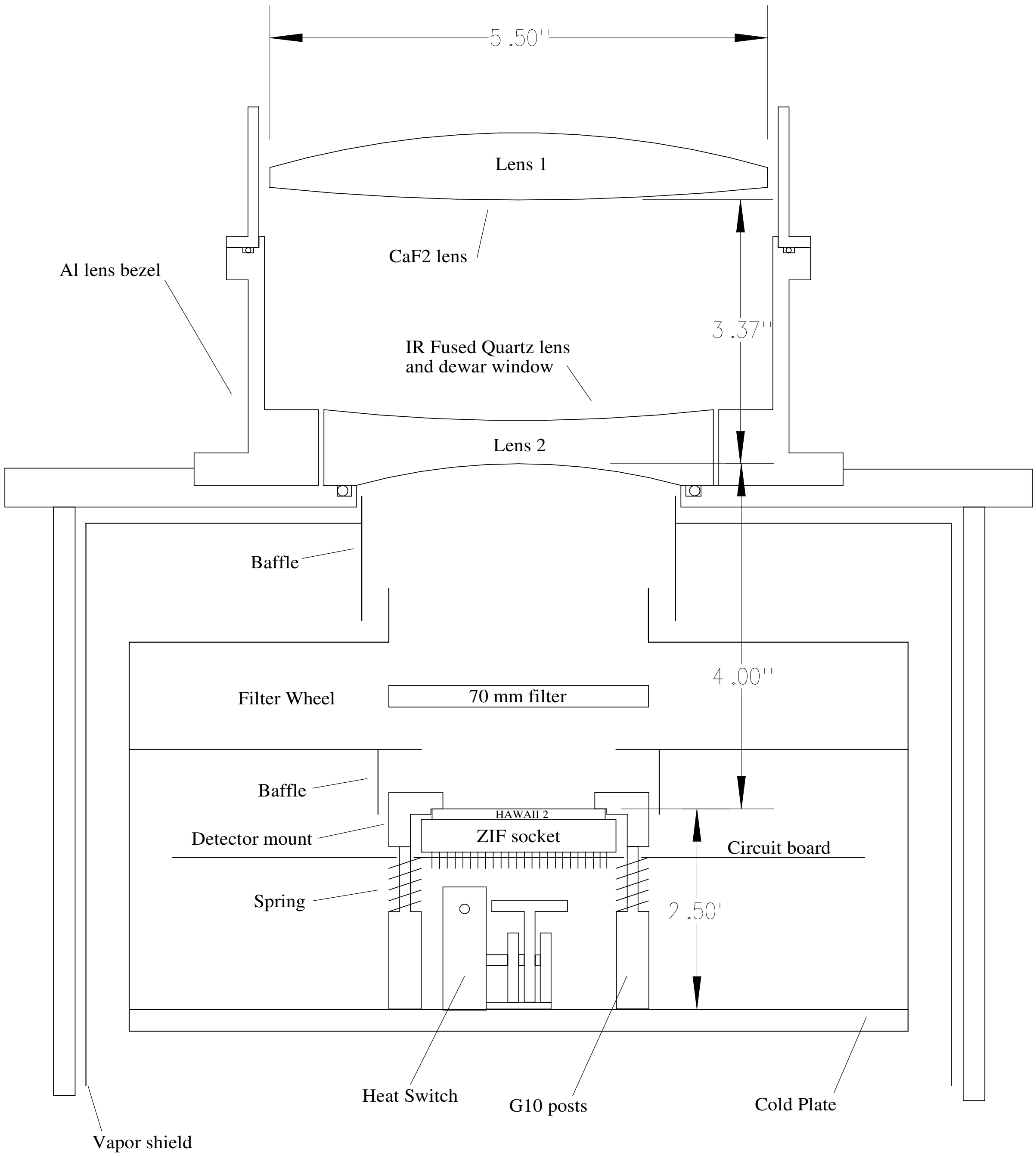

Figure 2. Sketch of the SWIRC optics, detector, and cryogenic dewar.

fault. The filter sees room-temperature up to a 40° incidence angle, and a subsequent transmission scan obtained at 40° incidence angle revealed a 10% transmission window in the 2.6-2.7 μm region of the J-band filter. The HAWAII-2 has enough sensitivity at these wavelengths that the J-band filter was compromised. Thus we were forced to obtain a second J-band filter with tighter specifications on out-of-passband rejection at large incidence angles.

2.4 On-Sky Performance

Table 2 presents SWIRC's on-sky performance. The final column gives the total exposure time required to reach a signal-to-noise $(S/N) = 10$ for 20th magnitude (Vega-relative) point sources. Because observations are background limited, longer exposures are made by stacking a series of shorter exposures together. The exposure time for the sky background to reach half the linear regime (80,000 electrons) is 90, 120, and 20 seconds for the Y-, J-, and H-band filters, respectively.

2.5 SWIRC Dewar

The SWIRC filters and detector are housed in an inverted-fill IR Labs ND-10 (10-inch diameter) liquid nitrogen dewar (see Figure 2). The dewar's 10.6 liter liquid nitrogen tank provides a 36 hr hold-time at vertical, which means our Cassegrain-mounted instrument has enough cryogen to last through even the longest observing night at horizon-pointing orientation.

2.6 Filter Wheel

SWIRC's only moving part is an IR Labs cryogenic filter wheel. The filter wheel mounts on a light-tight can attached to the cold plate. Thermal tests show that the filters equilibrate at 85 K. The filters are positioned mechanically, with a spring-loaded roller that presses into indentations on the outer diameter of filter wheel. The filter wheel is rotated via a feed-through to a Compumotor stepper motor outside the dewar. We power up the motor only during moves, and allow the spring-loaded roller to hold the position of the filters during observations. A rotary encoder on the motor shaft provides continuous position information, and a home switch inside the dewar (at the H-band position) provides an absolute reference position.

SWIRC's single mechanical failure in 4 years of operation occurred when a set screw on the stepper motor shaft loosened. This caused the motor shaft to disengage from the feed-through, and the filter wheel was stuck in the H-band position. We machined a second flat on the shaft for an opposing set screw, and placed a G10 washer to make sure the linkage cannot fully disengage again.

2.7 Detector Mount

SWIRC has an unique detector mount design. Our design goals were to maintain the detector's tip/tilt to better than $2'$ while providing (passive) temperature control to protect the HAWAII-2 from rapid temperature changes that might destroy the device. We also wanted to minimize wiring inside the dewar. Figure 3 shows the entire assembly.

Our solution was to push the corners of the HAWAII-2 chip carrier against an aluminum reference surface (as shown in Figure 3). The aluminum reference surface is spatially located by three G10 posts, which also serve to thermally isolate the detector mount from the cold plate. We set the tip/tilt of the aluminum reference surface using shims under the G10 posts. We also shimmed the liquid nitrogen tank to set the correct cold plate-to-dewar window (lens 2) distance. Tests show that the detector tilts $< 40''$ between room temperature and 77 K.

To minimize wiring, we solder the detector's zero-insertion-force socket directly onto our pre-amp board, and spring-load the entire assembly onto the aluminum reference surface. The 5-lb springs allow for thermal contraction but prevent the detector from moving off the aluminum reference surface for up to 10 g accelerations.

To protect the HAWAII-2 from cooling faster than 0.25 K/min, we use a heat switch (essentially a miniature clamp) to conductively isolate the detector from the cold plate during cool-cown. Our hope was that opening the heat switch during cool-down would allow the detector to radiatively cool at an acceptable rate. As discussed below, the heat switch is difficult to use in practice, and the radiative cool-down rate is dominated by the large ~ 0.3 m^2 surface area of the pre-amp board soldered to the detector.

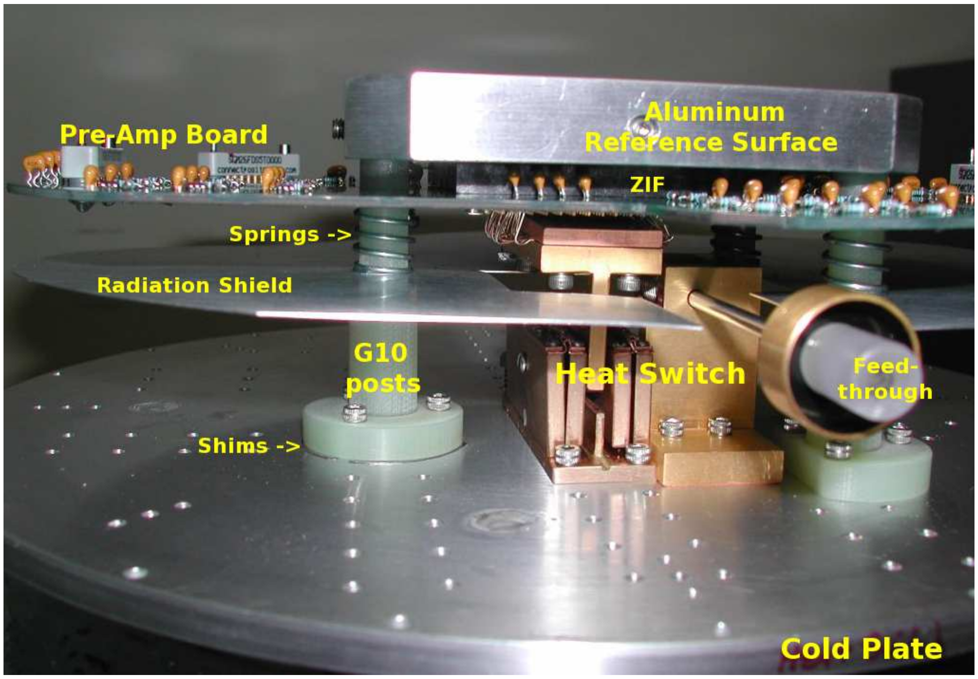

Figure 3. Side view of the SWIRC detector mount, pre-amp board, and heat switch on the cold plate.

The heat switch provided by IR Labs works by opening or closing copper jaws onto a copper piece shaped like a T (see Figure 3). Copper wires connect the T to the detector's thermal pins. There is a trade-off between maximizing the conductive heat transfer rate (proportional to the cross-sectional area of copper divided by its length, A/l) and making the whole assembly too stiff to move. In the end, we added a G10 guide (not shown) to prevent the T from touching the heat switch and creating a thermal short. When open, the heat switch conductively isolates the detector from the cold plate very well. When closed, the detector runs $\sim$7 K warmer than the cold plate with the electronics on.

The pre-amp board radiatively cools very rapidly during cool-down, which is unfortunate because the detector is soldered to the board. We added radiation shields above and below the pre-amp board (see Figure 3) to mitigate the radiative heat load on the board. In the end, we are forced to cool the dewar in three steps (first to 240 K, then to 180 K, and finally to 77 K) over the course of 12 hrs to maintain the desired cool-down rate < 0.25 K/min on the detector. The detector reaches 90 K about 36 hrs after the cold plate reaches 77 K, at which point we use the heat switch to conductively clamp the detector to the cold plate. The entire cool-down process takes approximately 48 hours. We have not lost a detector pixel in over 20 cool-downs.

2.8 Electrical Design and Detector Settings

The HAWAII-2 output signals pass through three stages: a cryogenic unity-gain buffer, a room-temperature preamplifier, and 32 channels of parallel analog-to-digital conversion. The cryogenic header board carries one OPA357 CMOS op-amp per channel, configured as a unity-gain buffer, which serves to drive approximately 0.4m of constantan wiring to two hermetic connectors, which each handle two quadrants of the imaging array. Soldered to the outside of each hermetic connector is an 16-channel preamplifier board, which feeds its output to the backplane of the camera controller via coax cables. The 32 output signals are processed by eight 4-channel A/D boards, derived from our CCD signal processors but slightly modified for DC coupling. The resulting data stream is fed to the data acquisition computer via a commercial EDT fiber-optic interface system.

We read the HAWAII-2 in 32 channels at 180 kHz, for a total read time of 0.7 seconds. We operate BIASGATE at 3.4 V and VRESET at 0.75 V. Readnoise is 31 electrons, and dark current is 16 electrons/s/pix. The HAWAII-2 has excellent linearity (better than 0.1%) to 160,000 electrons, and has a full-well depth of 190,000 electrons.

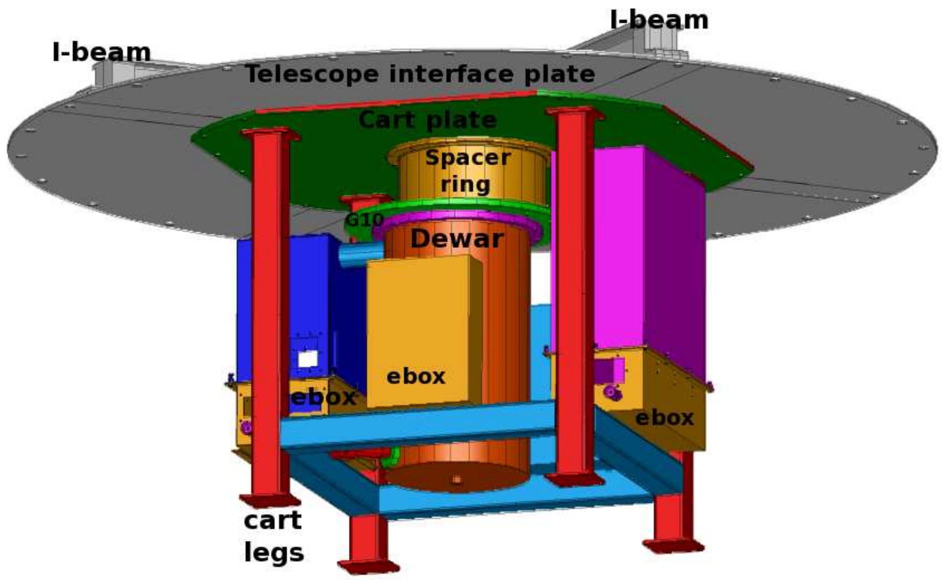

Figure 4. SWIRC instrument cart and telescope interface plate.

There is no shutter in SWIRC; rather, each line is cleared before being read the first time. Images are created by differencing a pair of non-destructive reads. The HAWAII-2 is put in a continuous clear mode between exposures.

We see the same HAWAII-2 reset-anomaly reported by others,[2] which is caused by a capacitive relaxation of the voltage level in the array after reset. Because the reset-anomaly is repeatable but non-linear, we remove it by subtracting dark exposures of identical length as the science exposures. We also find anomalous statistics in the first image obtained after exiting the continuous clear mode, and so we often throw away the first science image in an observing sequence.

2.9 Instrument Cart and Telescope Interface

The SWIRC dewar is attached to a wheeled instrument cart for ease of handling. The top of the cart is a 12.7 mm thick steel plate (the green square in Figure 4) that supports the dewar. The dewar sits 147 mm below the steel plate on a spacer support ring, and is electrically isolated from the cart with a G10 interface plate. SWIRC's electronic boxes are attached to the cart legs, and place no gravity load on the dewar.

A telescope interface plate mounts the instrument cart to the MMT rotator flange. The interface plate consists of a pair of crossed I-beams, with a hole in the middle, that supports the entire load of the instrument (see Figure 4). The large circular skirt protects the instrument from stray light. Finite element modeling of the entire assembly predicts the detector focal plane will deflect 0.1 mm when horizon-pointing, well within our 1 mm tolerance.

2.10 Observing Interface

Observers control SWIRC using the MMT ICE (MICE) graphical user interface (GUI), the same software package used to control all of SAO's f/5 MMT instruments. The upper half of the MICE GUI displays instrument status; the lower half is the observing interface. The infrared sky is both bright and variable, and so the typical observing strategy is to obtain sets of exposures in a dither pattern. MICE provides a straightforward interface for loading dither catalogs, and specifying filter and exposure time. The dither mode allows the observer to directly control telescope pointing, up to 1 degree offsets from the catalog position. The total overhead per exposure is $\sim$5 seconds, including readout and telescope dither motion.

SWIRC images are unguided, yet the MMT tracks so well that we observe no point-spread-function smearing in 90 second exposures taken in $0.4''$ seeing. SWIRC is used every trimester on the MMT, and nearly every SWIRC run has nights of $0.4''$ seeing.

2.11 Data Reduction Pipeline

We have developed an in-house data reduction pipeline to process the SWIRC images. The pipeline is a script that calls a series of IRAF tasks and stand-alone C programs. After dark subtraction and flat fielding (we use sky flats, obtained 5-10 minutes after sunset), the sky background for each image is determined by median-stacking the 15 nearest images in a given filter. Residual sky structure is seen in images obtained with the J filter; we fit and remove this structure using Source Extractor[3] with a background mesh size of 32 pixels. One channel in the HAWAII-2 exhibits intermittant ± 76 e^- bias fluctuations; we check for and correct any systematic offset in this channel with respect to the rest of the image. We establish the astrometric solution for each image using WCSTools.[4] There are typically enough 2MASS stars in SWIRC's field of view to provide astrometric solutions with RMS $\pm 0.2''$, which allows us to align and stack the reduced images using the world coordinate system. A mask image excludes cosmetics and high dark-current regions from the final stacked image.

3. CONCLUSION

SWIRC is a modest yet productive instrument. It has been used to study objects ranging from planet debris disks[5] to the highest redshift quasars[6] and galaxy clusters.[7] The instrument web site is:
http://www.cfa.harvard.edu/mmti/swirc/.

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