A NEW MID-INFRARED CAMERA FOR GROUND-BASED ASTRONOMY AND AN INFRARED STUDY OF PLANETARY NEBULAE

by

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ABSTRACT

This dissertation is composed of two parts. The first part is a description of the Mid-Infrared Array Camera (MIRAC), a new camera for ground-based astronomy. The second part of this dissertation is an infrared study of planetary nebulae utilizing observations with the new camera.

MIRAC is a collaborative effort among the University of Arizona, Smithsonian Astrophysical Observatory, and Naval Research Laboratory. It currently utilizes a Hughes 20x64 Si:As IBC detector array, which is sensitive to infrared (IR) radiation from 2 to 26 µm. The camera is equipped with 10% bandwidth filters at 2.2, 3.8, 4.6, 8.8, 9.8, 11.7, and 12.5 µm, and a wide band 8.0 to 12.8 µm "N" filter. There is also a 20% filter at 20.5 µm, and a 8-14 µm CVF with a resolution of 1.8%. The MIRAC electronics provides timing signals and coadds successive frames at a maximum rate of 10 KHz for the full array, and higher rates for a partial array readout. The data are transferred via a serial interface to a PC for storage and further processing. The camera recently achieved a NEFD of .010 Jy/arcsec^2 at 8.8, 11.7, and 12.5 µm for a 900 second on-source integration on the Steward Observatory 1.5 m telescope.

Planetary Nebulae (PN) are formed when a star is in the post-Asymptotic Giant Branch stage of evolution. The ejection of circumstellar material is an important enrichment mechanism for the interstellar medium. In many PN, there is an excess of emission in the IR, indicating the presence of dust. There are several different components seen in the IR emission, including a family of unidentified IR (UIR) emission features at 3.3, 6.2, 7.7, and 11.3 µm. Images in the near- and mid-IR are presented here for the following PN: IC 418, BD+30°3639, J 900, NGC 2392, NGC 6543, AFGL 2688, and M 2-9. In IC 418 and BD+30°3639, the SiC and UIR emission is seen to be spatially distinct from the IR continuum. In NGC 2392 and NGC 6543, evidence for excess emission is seen in the distribution of the near-IR flux. In the bipolar nebulae AFGL 2688 and M 2-9, structures in the IR emission are seen that could be related to the equatorial density enhancements that have caused the bipolar morphology.

PART 1: THE MID-INFRARED ARRAY CAMERA

1.1 Introduction

The first part of this dissertation describes the Mid-Infrared Array Camera (MIRAC). The introduction discusses some results from previous instruments and possible astronomical applications of the camera. Then each component of the camera system is described in detail, including the cryostat, optics, detector array and electronics, the computer interface and control program, and the guider box. Following the camera description are the results of several tests of the system carried out in the lab and on the telescope. The final section describes ongoing and future projects that will add to the capabilities and effectiveness of MIRAC.

MIRAC is a collaborative program among the University of Arizona (U/A), Smithsonian Astrophysical Observatory (SAO), and the Naval Research Laboratory (NRL). The principal investigators are William Hoffmann (U/A), Giovanni Fazio (SAO), and Kandiah Shivanandan (NRL). The responsibilities for each institution and the sources of funding are outlined in Appendix 1. With William Hoffmann as my graduate advisor, I participated in the parts of the program that were carried out at U/A. These include the review of the dewar design by Infrared Labs, the initial tests of the detector with the prototype electronics, the installation and alignment of the dewar optics, the testing and optimization of the final controller and signal processor electronics, and the subsequent lab tests and astronomical observations using MIRAC described here. I developed the microprocessor program for the array processor, which provides the interface between the MIRAC electronics and the IBM PC-compatible computer and controls the telescope chopper motion while coadding images in memory. I also developed the MIRAC program for the PC which controls the camera operation and the display and recording of data.

1.1.1 MIRAC program goals

MIRAC was designed for mid-infrared imaging of astronomical sources from ground-based telescopes using normal bandwidth infrared (IR) filters, without saturating the readout or detector, and to achieve a sensitivity comparable to or better than the best discrete or array detector systems currently in use. It was intended to replace the system that we had been using, the Goddard Space Flight Center (GSFC) 10 μm Camera, which was used to obtain broad-band mid-IR images of a variety of sources (Hoffmann *et. al* 1987). MIRAC was to allow us to obtain similar images with the state-of-the-art mid-IR arrays currently being developed.

There were a number of other goals for the new camera system. We wanted to take advantage of the increased spectral range of the available Si:As array to observe at wavelengths in the 20 μm atmospheric window and at near-

IR wavelengths, as well as the 8-13 μm atmospheric window. In addition to broad band imaging (at a resolution of ~10), we wanted the ability to image sources at higher spectral resolution of ~50 with a CVF filter, and resolutions of up to 10000 using a Fabry-Perot spectrometer (FPS) currently being modified to use with MIRAC. The MIRAC had to have the proper scales to image large emission regions on the sky efficiently, yet allow us to obtain high resolution images of compact sources. The camera also had to be easily configured and transported to the different telescopes we were likely to use, including the Steward (IRTF), and the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope, as well as the Kuiper Airborne Observatory (KAO) or the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the 6.5 m Multiple Mirror Telescope replacement. The dewar and electronics had to be free from extraneous noise and as efficient as possible to allow us to use the detector to its full capability.

1.1.2 Astronomical Applications

There are many astronomical applications for which this camera is well suited. The study of planetary and protoplanetary nebulae conducted with the GSFC 10 μm camera has yielded valuable information on the nature of the dust emission in several nebulae (Arens *et. al* 1985, Tresch-Fienberg 1985, Jaye *et. al* 1989, Hora *et. al* 1990, Deutsch 1990, Deutsch *et. al* 1991). Many of these nebulae exhibit emission from the "unidentified" infrared (UIR) features, usually attributed to carbonaceous dust or molecules. Images in the mid-infrared have shown the spatial distribution of emission from the UIR features to differ from the emission from the ionized zone of the nebula. Determining the location of the emitting regions relative to the central star is important in evaluating models of dust formation, composition, and evolution. Because of its better sensitivity, the MIRAC will allow this study to be extended to many more nebulae, including nebulae in later stages of evolution, which are spatially more extended and diffuse. Its increase in spectral sampling and coverage will enable a more thorough investigation of the UIR features near 10 μm and the cool dust emission at 20 μm. High spectral resolution images of the [NeII] (12.8 μm) line will yield information on the velocity structure and dynamics of these nebulae.

Another area of interest is star-formation regions. Observations with a mid-infrared camera are very effective in determining the spatial distribution, color temperature, and optical depth of warm dust emission surrounding young star- forming regions. Circumstellar disks, which are predicted by stellar formation models and indicated by the observed emission at far-infrared wavelengths, may be resolvable in the mid infrared in nearby protostellar regions. If the camera is used in conjunction with a high resolution FPS, observations of H_2 lines at 12.279 and 17.034 μm would permit the study of shocked gas in these regions at high spatial resolution. Images of the sources in the lines would yield the distribution and velocity structure of shocked gas in these star forming regions.

A third area of investigation is star formation processes in extragalactic nuclei. Mid- and far-infrared studies of galaxies have shown that strong star formation may be common in the nuclei of normal spiral galaxies. Studies of two IR-bright galaxies M82 and NGC 253 (Rieke *et al.* 1980, Ho *et al.* 1988) have shown that the infrared emission is associated with indicators of recent star formation. In active galactic nuclei, non-thermal sources of emission may contribute to the mid-infrared flux from these objects. In the Seyfert galaxy NGC 1068, two point-like sources have been detected in the central kiloparsec at several mid-infrared wavelengths (Tresch-Fienberg *et al.* 1986), one at the center of the nucleus and the other 100 pc to the northeast. This spatial and spectral information is important in understanding the processes taking place in galactic nuclei.

These are examples of some of the many possible uses of the MIRAC. The camera was designed with these and other potential uses in mind, maximizing the flexibility and usefulness of the instrument. In the description of the camera below, I have tried to point out as much as possible how these goals influenced the decisions made in the design of the camera. Many of the choices made are compromises between opposing opportunities, because of the impossibility of doing everything at once, and the practical limits of cost and ability. However, we believe that the instrument that has resulted from this effort will prove to be extremely useful and a productive astronomical camera.

1.1.3 Definitions of terms

There are a number of definitions that I will make here to clarify the descriptions of the data and image processing below. The array is composed of 20 **columns** by 64 **rows** of discrete detector pixels. Each signal processor board contains 2 **channels**, and each channel is connected to a single column on the array. A **frame** is an image consisting of the pixels from a single readout of the entire array. A **coimage** is several frames added together in the coadder buffer of the signal processor board. An **observation** is a number of coimages that have been added together in the array processor board (APB). This could consist of two phases of a chop pair, etc. A data file on the PC contains one complete observation. A **picture** or **image** is a set of coimages from an observation or many observations that have been processed in the PC computer to be displayed on the screen. Two chop phases could have been subtracted, and/or the picture flat-fielded or masked.

The following terms designate regions of the infrared spectrum. Near-IR denotes the region from 1-5 µm, mid-IR is the region from 5-25 µm, and far-IR is above 25 µm. The following direction abbreviations are used: N=north, S=south, E=east, and W=west. All images presented here have N at the top and E to the left, unless otherwise noted. Position angles (PA) of source structures are defined, unless otherwise noted, as degrees E of N, relative to the center of the source. All personnel mentioned by name are U/A, unless stated otherwise. The symbol " = arcsec. The unit of flux Jansky (= 10^{-26} W m^{-2} Hz^{-1}) is abbreviated Jy, and .001 Jy = 1 mJy.

1.2 MIRAC Dewar and components

1.2.1 Cryostat

The MIRAC dewar, shown in Figure 1.1, is a modified HD-3 cryostat built by Infrared Laboratories Inc. (IR Labs). The modifications were designed by Bob Kurtz of IR Labs. The case is a standard 6-inch inside diameter (I.D.) aluminum cylinder with hexagonal outer surface, with liquid nitrogen (LN_2) and liquid helium (LHe) reservoirs that occupy the entire upper section of the dewar. A 7-inch I.D. extension holds all the optics, electronics, and mechanisms in the camera. The support for the reservoirs and the mechanisms in the extension is provided by a rigid support structure between the cryogen vessels and the top of the dewar. A radiation shield extends from the nitrogen vessel and encloses the helium vessel and shield. Inside the helium temperature shield, the volume is divided into two parts by a plate that separates the section containing the detector and filter wheels and the section containing the optics. The optics (described below) are mounted inside a housing mounted to the plate that divides the sections. A baffle tube with a baffle on both ends extends from the housing to the helium temperature shield. A second baffle tube extends from the nitrogen shield to near the helium temperature shield and tube. Inside the housing is the pupil stop mechanism. The only opening into the upper section where the detector is located is through the selected pupil hole.

The array, mounted on a 68 pin chip carrier, is inserted into a socket on a circuit board as shown in Figure 1.1b. There are two 31 pin miniature connectors on the circuit board where the electrical connections are made, one for the bias voltages and clock signals, the other for the analog output signals from the detector. A heater resistor and temperature sensor diode are stycast to the bottom of the copper detector mount to provide for detector temperature monitoring and control.

The volumes of the nitrogen and helium reservoirs are 0.8 and 2.0 liters, respectively, allowing for a hold time of 17.5 hours for the liquid helium and 18 hours for LN_2. This is sufficient for more than an entire night of observing without having to interrupt to fill. The position of the nitrogen fill tube also allows for tilting the telescope to high airmass without unnecessarily spilling LN_2. Our method of measuring a gain matrix involves taking images of blank sky at low and high airmass, so this feature is important, especially at the beginning of the night when the dewar is full.

The MIRAC dewar was designed so that the filters, magnification positions, and pupils can be changed externally, minimizing the need for disassembly under normal operating conditions. However, a dewar is always opened much more often than planned, so the dewar was also designed for ease of disassembly and reassembly. The disassembly proceeds from the bottom, first by removing the bottom plate and the lower case extension. Next the LN_2 and helium shields are removed. This exposes the optical housing and the area where the detector is mounted. At this point all major mechanisms and components are exposed. The detector stage can be removed, wiring checked and repaired, filter wheel mechanisms examined, optics adjusted, etc. Everything within the helium shield is attached to a plate which is in turn attached to the bottom of the helium reservoir. If desired, this plate can be removed from the cold plate by removing six bolts. The entire assembly can then be removed. This is useful when aligning the optics or working on the filter wheel mechanisms, or to protect the array and optics when working on the upper section of the dewar.

Another design goal was to have a portable dewar. This was achieved by designing the dewar to be as compact as possible, and protecting the connectors and external actuators from damage. The 6-inch I.D. IR Labs dewar was chosen for compactness, instead of the 8-inch I.D. dewar. If the bottom plate with the actuators and filter motors is replaced by a blank plate, the MIRAC dewar meets airline size restrictions for carry-on luggage. The actuator mechanisms and the vacuum valve are mounted on the bottom plate of the dewar. The dewar stand attached to the bottom plate has the same profile as the dewar extension, and along with the standoffs used to attach it forms a cage which protects the mechanisms. The electrical connectors are mounted on the top, and act as a stable support when the dewar is inverted on the workbench.

1.2.2 Optics

The MIRAC optics were designed with the following goals in mind: to provide two different magnifications, to enable use of the full 2-20 µm range of detector sensitivity, and to be as simple, compact, and efficient as possible. The optics also had to be easily configurable to the different telescopes with which MIRAC may be used. For all magnifications and pupil sizes to be used, the geometrical image size had to be much less than the 100 µm pixel size over the full array. An additional constraint was to allow for the potential use of larger format arrays in the MIRAC dewar without significant modifications. The optics were designed by William Hoffmann and the ellipsoid element was fabricated by Dick Sumner.

A drawing of the MIRAC optics is shown in Figure 1.2. The optical elements are a gold-coated flat and a tilted off-axis ellipsoid mirror, and a pupil stop. The central ray enters the dewar through the window and passes through baffles to the flat inside the optical housing. The ray is reflected first down to the ellipsoid, then directly upward, normal to the work surface of the dewar. The ray passes through the center of the pupil, filter wheel 1 and 2, and intercepts the center of the array normal to the surface. The only opening to the compartment of the dewar where the detector is located is through the pupil stop. This minimizes the amount of off-axis radiation reaching the detector. The inside of this compartment, along with the optics housing, is painted black to reduce scattering of stray light on to the detector.

A reflective system has many advantages over a refractive system. The reflective optics accomodate the wide range of wavelengths that the detector is sensitive to without need for adjustment. This simplified the design considerably and reduced the volume necessary inside the dewar to contain the optics. There is only one active element, an off-axis ellipsoid located at the bottom of the optics housing. Propagation losses through the system are minimized by having only two gold-coated reflective surfaces. Any system of lenses would have reflective losses from the lens surfaces and absorption loss in the lens material. Changes in magnification are accomplished by moving the position of the detector and refocusing the telescope. This allows the optics to remain fixed and aligned, and eliminates the need for a mechanism to slide or shift the optical elements. One drawback of having a single off-axis ellipsoid is that it causes a small amount of pincushion distortion at the detector. The amount of distortion, however, is small (see §1.7.7 below) and has been calibrated, so the distortion can be removed in the data reduction process.

Since the central ray is normal to the work surface, the array can be translated vertically to change magnifications. The low magnification position is when the detector is moved to the closest position to the pupil stop, 19.95 mm, and in high magnification, the array is moved farthest from the pupil stop, 40.84 mm. The detector image focus is located outside the dewar for both magnification positions, 13.72 cm for low and 1.176 cm for high magnification.

The optical design was optimized for minimum image blur at the edges of the array at the f/36 IRTF. This was a compromise between the f/45 of the Steward telescopes and the faster telescopes on which the MIRAC could be used. The design has a calculated maximum rms image blur of 8 µm over the array at low magnification, and 5 µm at high magnification. The maximum pincushion field distortion at the corners is 45 µm at low magnification and 23 µm at high magnification. The pixels are 95 µm square, on 100 µm centers.

The filter wheels, shown in Figure 1.1e, are made from 12.7 cm diameter aluminum gears in which counterbored holes have been machined on a 8.052 cm diameter to hold the filters. The wheel nearest the pupil stop holds nine .953 cm diameter filters and blockers and the CVF segment. The second wheel holds 10 1.588 cm filters. Figure 1.1e shows the position of the filter wheels in the dewar. The filter wheel containing the CVF is located as close to the pupil as possible, to provide a sharp wavelength-defining aperture. It is also desirable to have the other filters near the pupil stop.

Table 1.1 gives a list of the filters in the MIRAC dewar. In each wheel there is a position with no filter installed, and in both wheels there is an aluminum blank installed in one position. The filters were all purchased from Optical Coating Laboratories, Inc. (OCLI), and the information is based on data supplied by OCLI, except for a few filters and the dewar windows which were measured at room temperature with the Beckmann Acculab 6 Spectrophotometer at NOAO. See Appendix 2 for a spectral scan of each of the filters.

Table 1.1 MIRAC Filters

Wavelength[1] [HP width] (μm)	Trans-mission[2] (%)	Substrate	Size (cm)	Blocker[3]	Comments
Wheel #1					
8.82 [.87]	75	Ge	.959	CaF_2	OCLI "O" astr.
9.8 [.96]	76	Ge	.959	BaF_2	OCLI "P" astr.
11.7 [1.13]	72	Ge	.959	BaF_2	OCLI "R" astr.
12.5 [1.16]	64	Ge	.959	BaF_2	OCLI "S" astr.
10.6 [4.8]	80	Ge	.959	BaF_2	OCLI W10575-9
4.62 [.59]	85		.959		OCLI W04711-4
Sapphire			.959		1 mm thick
7.9-14.5 CVF [~1.8%]	70	Ge	1.37[4]		OCLI 15-1395-970
Wheel #2					
2.17 [.35]	67		1.715		OCLI W02206-7
3.85 [.62]	92		1.715		OCLI "L" astr.
20.6 [4.2]	31		1.715		OCLI W-19500-9, L18180-8A
N.D.	.33		1.715		
N.D.	1.0		1.715		
N.D.	5.0		1.715		
N.D.	20		1.715		
		BaF_2	1.715		1 mm thick

[1]The wavelength data from the OCLI 295°K scans were shifted to adjust for a temperature of 4K. The OCLI 77°K data were not adjusted, since most of the wavelength shift occurs from room temperature to 77°K. All of the scans were multiplied by the detector response to derive the effective wavelength given here. N.D. = Neutral Density filter.

[2]For filters, effective peak transmission. For CVF, average peak transmission over the usable range. For N. D. filters, the trans-mission is the average value over the range 2-26 μm.

[3]The filters with blockers listed have a 1 mm blocker of the same diameter installed in the same wheel, separated by a .25 mm thick gold-coated copper spacer ring.

[4]The CVF is a 1.37 cm wide, 90° segment of a circle of diameter 8.052 cm (circle through the center of the CVF).

Two windows were fabricated for use with MIRAC, one of KrS5 and the other of ZnSe. The ZnSe window has good transmission from the near-IR to approximately 18 µm. The KrS5 window transmits from the near-IR to beyond the 20 µm atmospheric window. The transmission through each of these windows is shown in Appendix 2.

The pupil stop slide is a set of pupil stops that are sized for the telescopes on which the MIRAC may be used. Table 1.2 shows the hole dimensions and the appropriate telescope.

Table 1.2 Pupil stop positions

Pos. #	Hole Dia. (cm)	f/number	Telescope
blank	...	...	...
2	.167	45	SO 1.5, 2.3 m
3	.196	36	IRTF
4	.237	30	CTIO 4-m
5	.420	17	KAO
6	.470	15	MMT Upgrade

1.2.3 Electric wiring, connections

There are four electrical connectors at the top of the dewar, illustrated in Figure 1.1b. One provides the necessary bias and clock voltages to the detector. The second contains output lines from the detector to the external preamplifier electronics. The third connector is the temperature sensor and the heater connections. The fourth connector is attached to the home switches for control of the filter wheels. These connectors are mounted on the top of the dewar, pointed horizontally away from the center. The two detector connectors are each mounted on their own block, and the temperature sensor/heater and the switch connector are mounted on a common block. The detector signal output block, at the top in Figure 1.1b, is as close as possible to the electronics, to minimize the length of the coaxial analog cables from the dewar to the preamp.

A number of steps were taken to insure minimal pickup of the digital signals on the detector and the analog output lines. First, there are three separate shielded cables in the dewar for the detector connections, one each for the clocked row addresses and reset, bias voltages, and analog outputs. The analog signals are segregated on their own connector at the top of the dewar, and at a separate connector at the circuit board where the detector is mounted. At the circuit board near the detector, filter capacitors were mounted on all the bias lines to reduce potential digital pickup. The connection to the detector is made by two 31-pin miniature connectors on the circuit board on the detector mount.

The cables used were made at the Naval Research Laboratory specifically for cryogenic applications using detectors of this type. The cable is a ribbon consisting of alternate strands of insulated Constantin wire separated by nylon insulator. The flat cable is then wrapped in superinsulation which provides shielding and protection of the conductors. The beneficial characteristics of this cable are that it is very compact and flexible, has relatively low capacitance, and low thermal conduction. The capacitance of the cables was measured as installed in the dewar (approximately 30 inches) to be 130 pf for each conductor to ground, and 30 pf from one conductor to the next. The cables are taped to the LN_2 reservoir, pass under a slot in the radiation shield, and then are taped to the liquid helium reservoir. This insures that the wires do not provide a source of heat inside the helium shield. There is a 10 cm loop in each cable from the connector to the LN_2 shield to reduce heat input.

An additional 6-pin connector is used to connect the temperature monitor and heater resistor located on the detector slide. There is enough free length in the cables between the mounting slide and the point where the cables are fastened to the cold plate so that there is not excessive strain on the cables when switching from high to low magnification.

1.2.4 Actuators, Filter Motors and Control

There are four mechanisms that are controlled by external actuators which enter the dewar from the base: the pupil stop slide, the detector mounting slide, and two filter wheels. The filter wheels are driven by stepper motors that drive the wheels through a series of linkages and gears. The other two actuators are kept pulled out of the dewar into a recess in the dewar case, except when the slides are being changed. Their location is shown on the bottom plate of the dewar in Figure 1.1c.

Each filter wheel is rotated by an Anaheim Automation Co. #23D108S stepper motor and SMC20BC controller system. The motors are mounted on the base of the dewar, shown in Figures 1.1a and 1.1c. The shafts of the motor are connected through an adapter to a ferrofluidic feedthrough that transmits the rotation to the vacuum of the dewar. This feedthrough device is model #SB-250-A-N-086, part #50C103237, manufactured by Ferrofluidics Corporation. The vacuum seal consists of a permanent magnet, pole pieces, a magnetically permeable shaft and a magnetic fluid, or ferrofluid. The structure of the magnets creates a field which is concentrated between the stationary magnet and the shaft. The ferrofluid is trapped in this region, and forms a "liquid O-ring" seal between the shaft and the stationary housing. There are several stages of ferrofluid seals in the feedthrough, separated by air gaps. Each stage can sustain a pressure difference of 0.2 atmospheres, and the stages act in series to provide the total pressure capability of the seal. The feedthrough is designed to sustain a total pressure differential of >2 atmospheres, providing a safety margin.

The feedthrough shaft extends through the vacuum inside the dewar to a nylon bushing that is captured in the nitrogen shield. The nylon bushing provides thermal insulation from the warm shaft to the nitrogen temperature shield. From the nitrogen shield, a shaft extends into a nylon bushing connected to the helium temperature gear which turns the motor. This provides thermal isolation between the nitrogen and helium shields.

The motors drive the wheels from the edge using a smaller gear with a

(32/3):1 reduction. The motor controller accepts ASCII command strings from the PC via a RS-232 interface. The motors can be stepped any number of steps in either direction, at the user selected speed. The stepper motors have 400 steps per revolution, which gives 4267 steps for one revolution of the filter wheel. This corresponds to a positioning accuracy of .007 μm in wavelength for the CVF filter.

Mounted on top of the filter wheel right at the edge is a small block which defines the initial reference, or "home" position. Two microswitches are mounted on a stand on the cold plate so that they are positioned just above the wheels. To move the wheels to the home position, the controller rotates each wheel until the block mounted on the wheel comes in contact with its home switch. This position is centered on one of the filters. To move to other filter positions, the motors are stepped the appropriate number of steps, determined by the filter spacing.

The normal position of the other actuators is fully withdrawn outside the dewar into a cylindrical recess in the dewar case. When the pupil stop slide or detector mount needs to be moved, the actuator is pushed into the dewar. The end of the shaft enters the nitrogen shield through a hole which is covered by flexible aluminized mylar that is slotted in an "X" pattern to allow the actuator to pass through. The actuator is pushed into a flexible nylon coupling that is connected to the mechanism. For the pupil stop slide, the actuator is rotated and a rack and pinon gear causes the slide to move. A spring loaded ball bearing presses against the slide and falls into a detent at each slide position. The slide positions are described above, in Table 1.2.

The array mount slide is engaged by pushing the actuator in until it enters the coupling, shown in Figure 1.1b, and then twisting to lock it in. Then the array position is changed by pushing or pulling it to the other position. Two spring-loaded balls on either side of the mount fall into detents which define the correct position, similar to the pupil stop mechanism.

The center of the chip socket has been cut out and a copper finger extends through to provide the surface where the detector chip carrier is mounted. A 2.29 cm square of .254 mm thick indium foil is placed between the chip and the copper to insure good strain-free thermal contact. The detector is held in place in the socket by a copper bracket that presses the chip from the front side into the socket, shown in Figure 1.1b. The bracket also acts as a radiation baffle; the top side and the cavity on the side facing the detector is painted black, and the opening is just large enough to expose the sensitive area of the array. The copper mount is thermally isolated from the slide by a block of G-10. The mounting bracket that connects to the cold plate has two stainless steel shafts on which the detector mounting assembly slides, pulled or pushed up or down by a third rod connected to an external actuator. Thermal contact between the detector mount and the cold plate is made by a flexible copper foil strap which has been optimized to provide sufficient cooling so that when the detector is running with no heater the temperature of the array is 6.5 K.

1.3 Detector

This section describes the detector array currently used in MIRAC. We received much assistance from Grant Albright, Skip Augustine, and Stone Klengler of Hughes from their comments and suggestions on electronics design and in the initial testing phase of the detector in the MIRAC dewar.

1.3.1 General description

The detector used in the MIRAC is a arsenic-doped silicon (Si:As) Impurity Band Conduction (IBC) 20x64 pixel array, bonded to a capacitive transimpedance amplifier (CTIA) readout, designated CRC 444A, serial number AR6. This detector was developed by Hughes Aircraft Co. of Carlsbad, CA. The relevant parameters are summarized in Table 1.3.

Fowler and Joyce (1990) provide a general description of the Hughes Si:As IBC arrays. The array is a hybrid device consisting of a readout circuit that is "bump-bonded" to the detector array using indium "bumps". Figure 1.3 shows the IBC detector cross section. It consists of a high resistivity substrate, a transparent contact, the heavily doped IR active layer, a lightly doped blocking layer, and aluminum contacts on the top, with an indium bump for connection to the readout.

Table 1.3 Hughes IBC Detector Characteristics

Material	Si:As
Operating Wavelength (μm)	2-26
Number of Pixels	20x64
Pixel size (μm)	95x95
Pixel spacing (μm)	100
Readout Mode	Parallel
(# of lines)	(20)
Peak QE[1]	0.4
Well Size (e^-)[2]	1×10^5
Read Noise (e^-)[3]	80

[1]Hughes test report data
[2]MIRAC measurement 2/9/91
[3]MIRAC measurement 2/9/91

Stetson *et. al* (1986) give a description of the operating principle of this detector type. In the heavily doped IR detecting layer, acceptor impurities exist which are ionized. The negative charges associated with acceptor sites are fixed, but the positive donor sites "D+" are mobile, and can migrate through the crystal when the acceptor sites are sufficiently close. When a positive bias is applied to the top Al contact, a field is created which drives the pre-existing D+ sites toward the substrate. The undoped blocking layer prevents the injection of additional D+ charges, so a region depleted of D+ charges is created near the top contact. A negative space-charge is left in the depleted region, since the negative charges are immobile. When an incident IR photon is absorbed, it creates a mobile D+ charge and a conduction band electron. The applied field sweeps the electron out through the blocking layer where it is collected by the top contact. The D+ change travels in the opposite direction and enters the undepleted region of the detecting layer.

This design has advantages over a standard photoconductor in reducing the noise due to the detector. In the depleted region there are almost no empty states below the conduction band to trap electrons, so the collection efficiency is extremely high. Also, the conduction band electron concentration under these conditions is virtually zero, making the D+ charge collection efficiency high. The high collection efficiency of the charge carriers minimizes noise due to carrier recombination. Since the detecting layer is highly doped, it can be made thin while keeping the quantum efficiency high. The thin detecting layer lowers the sensitivity to incident charged particles.

1.3.2 Array Format and Packaging

The detectors are arranged as two sub-arrays of 10x64 pixels, separated by one pixel in the short direction and offset by half a pixel in the long dimension. This is illustrated in Figure 1.4. The spectral response of the detector material is shown in Figure 1.5. The full range is from approximately 2 μm to 26 μm, peaking at a quantum efficiency of approximately 0.4 at 22 μm. Much of this range, however, is limited for ground-based astronomy by atmospheric absorption.

The wire bonding diagram is shown in Figure 1.6. The detector itself is bonded to a ceramic "chip carrier", which has 68 contacts on the four sides. Pin 1 of the carrier is an "L"-shaped pad shown in the upper left of the diagram, and the numbering proceeds counterclockwise as viewed from above the detector, 17 contacts to a side. The metalization of the outer pads wraps around from the top to the sides of the carrier, allowing electrical contact to be made from the edge as well as from the top. The numbers marked on the chip carrier contacts on the edge are the numbers of the pads of the detector that they are connected to.

1.3.3 The CRC-444A Readout

The CRC 444A decoder is shown in Figure 1.7. This uses 8 address bits to specify 64 pixels. The addresses are coded such that four bits are always 1 and four bits are always zero. The detector and readout use negative logic, with "0" = 0 V and "1" = -4 V. Also, consecutive addresses differ by two bits, and require changing one address line from a zero to a one, and another address line from one to zero. One advantage of this scheme is that the address clocking is very uniform, and cases where all the bits toggle simultaneously are avoided, preventing possible noise pickup problems. The code is shown in Appendix 3, Table A3.1. For each pixel, four of the address lines are connected as shown in Figure 1.7 to enable the reset and the output for that pixel.

The CRC 444A unit cell is shown in Figure 1.8. The RESET CLOCK and ENABLE CLOCK are from the decoder in Figure 1.7. The bias voltages are labeled with a capital V and the current supplies are labeled with a capital I. The values used for each of these are shown in Table 1.4. The currents are consistent with the sum of the currents approximately equal to zero.

Table 1.4 MIRAC Bias Voltages

Bias Name	Volts	Current[1] (μAmp)
V_{SUB}	9.00	.36
I_{SS1}	5.00	172
V_{SS0}	3.00	260
V_{DD3}	0.00	3248
V_{SSC}	0.00	<.02
I_{SS3}	0.00	-11.7
V_{CL}	0.00	<.02
V_{SSD}	-1.00	36.8
V_{CAS}	-2.00	<.2
V_{DD2}	-2.00	-249
V_{DET}	-2.60	<.02
V_{DD1}	-3.00	-3651
V_{RST}	-4.00	-2.0
V_{EN}	-4.00	-40.0
V_{ADJ}	-6.00	-2765

[1]Current measured on 7/19/90, at 7.5 MHz clock rate, reading out 32 of 64 rows, 8.8 μm, 20% ND looking at room temperature radiation, detector temperature = 12.4°K. The current was calculated from measurements of the voltage drop across series resistors.

The detector pixel and readout unit cell consists of the circuit from the left edge of the diagram to the point where the ENABLE CLOCK is connected. This circuit exists for every pixel. The part of the unit cell labeled "Current mirror/output driver" is part of the column readout circuit, and there is one for every 64-pixel column. The point labeled V_{OUT} is the output of the detector chip, and the "typical output load circuit" is implemented on the MIRAC Preamp board.

The readout circuit is a Capacitive TransImpedance Amplifier (CTIA) whose output voltage is proportional to the integral of the input current flowing into the feedback capacitor from the detector. The transimpedance of the amplifier, defined as the ratio of the output voltage to the charge on the input capacitor, in Volts/Coulomb, is equal to the reciprocal of the feedback capacitance, assuming negligible parasitic capacitance and gate leakage current. For the remainder of this dissertation, I will use units of millivolts/electron for the transimpedance. The overall transimpedance for the array is the output source follower gain divided by the CTIA feedback capacitance.

There are two advantages of using the CTIA circuit. First, the bias on the detector is held constant during charging of the feedback capacitor, resulting in detector linearity. The second advantage is that the input voltage gain at the source follower effectively suppresses noise introduced after the amplifier input. The input voltage gain is the ratio of the detector and parasitic capacitance to the feedback capacitance, which for this array is approximately 4.

The reset pulse dissipates the charge which has built up in the capacitor, allowing for another integration. The difference in voltage output levels between the "before reset" and the "after reset" is proportional to the flux incident on the detector during the integration time. This linear relation holds until the charge building up on the capacitor exceeds the "well size" value given in Table 1.3 above. At this point the pixel saturates, or the response curve flattens out and eventually does not rise with increasing flux. Therefore, as the flux level increases, to keep the detector from exceeding the well size each pixel must be reset more often.

The peak of a 300K blackbody curve is near 10 μm, so the ambient temperature telescope radiates strongly in the mid-IR. The atmosphere also radiates in the mid-IR. The combination of the thermal telescope and sky emissivity result in backgrounds that are often larger than the source signal by a factor of 10^6. For the backgrounds present in the mid-IR from ground-based telescopes using 10% bandwidth filters, typically a rate of 10 KHz is required to operate the detector in its linear range.

1.4 Electronics

The MIRAC electronics were designed to perform the necessary tasks to operate the detector properly, sample the analog signals synchronously and convert them to digital values, store these values as pixels in a frame, coadd multiple frames, and transfer the stored coimages to the computer. These functions had to be accomplished within the design goals of low noise, multiple sampling modes and options, subject to size and cost constraints. In addition to the electronics associated with the detector array, a temperature controller and monitor were necessary to maintain a constant detector temperature, and an interface was necessary to transfer the images from the camera electronics to the computer.

The electronics were designed by William Hoffmann, Larry Coyle, and John Geary and constructed and initially tested at Smithsonian Astrophysical Observatory Central Engineering. Peter Crawford of SAO assembled the signal processor boards and the power supply. A block diagram of the MIRAC system is shown in Figure 1.9. The Figure is divided into three main sections, the cryostat, the electronics at the camera, and the equipment in the telescope control room. There are six main components of the electronics: the bias voltage supply, the preamplifiers, the signal processors (20 channels total, one for each column of the array), the digital controller, the temperature monitor and controller, and the filter wheel controller and motors.

1.4.1 Detector Bias Supplies

There are 14 separate bias supplies necessary to run the detector and its readout. The operating bias voltages are listed above in Table 1.4. These voltages are generated on a separate bias voltage board, which is enclosed in its own shielded box to separate it from the other electronics components. The voltages are derived from regulated ±10 and ±15 volt supplies on the bias board.

Figure 1.10 shows a representative bias voltage circuit. In series between 10 and -10 V are a fixed resistor R1, a 1K 10-turn potentiometer (pot), and a second fixed resistor R3. The resistance values R1 and R3 are chosen so that when the 1K pot is set to the middle of its range, the voltage is at the nominal value, with a total range of ±1 V about this value. The voltage from the adjustable pin of the pot then goes to a buffer amplifier of unity gain. The output of the amplifier goes to a small series resistor, and then directly to the detector via a shielded cable to the top of the dewar and then through the dewar wiring. The points labeled T1 and T2 are test points that are wired to a connector on the side of the bias box, where a breakout board can be plugged in to monitor voltages. There are bypass capacitors in a small box in the cable leading to the dewar, as well as on the circuit board with the detector chip socket in the dewar. These are to eliminate noise due to digital pickup on these lines.

Two of the "bias" supplies (I_{SS1} and I_{SS3}) are actually current sources. These supplies have an additional series resistors of 38.3 kΩ and 51.1 kΩ, respectively, at the point labeled (R5). The detector bias V_{DET} is also equipped with an additional series resistor of 24.3 kΩ, to provide protection against high currents through the detector. V_{ADJ} does not go to the detector itself, but provides the voltage for the output MOSFET source follower amplifiers' source resistors which are located on the preamp board.

1.4.2 Preamp

The preamp acts as a buffer and an amplifier of the signal coming from the detector. Twenty separate signals come from the detector to the top of the dewar, and are connected to the preamp inputs via a short coaxial shielded cable. The preamp electronics are housed in a separate shielded box near the top of the electronics enclosure, with separate power regulators inside, to prevent extraneous noise pickup from other parts of the MIRAC electronics.

The preamp circuit is illustrated in Figure 1.11. Two inputs for every channel enter the preamp: the signal, which is the source of the array output MOSFET source follower, and signal reference. The signal reference is connected to analog ground in the preamp for every channel. The signal is connected to a unity gain buffer amplifier, and through a 30.1K source follower resistor to V_{ADJ}. The output of the unity gain amplifier is connected to a second amplifier with a gain of -4. An offset bias of +3.2 V is also added at this stage. This bias, along with the preamp gain and gain on the signal processor, were selected to match the array output, which has a range of approximately -1.2 to -.2 V, to the A/D input range of ±2.5 V.

The "+" input of the second op amp (gain -4) is connected through a 4.99 kΩ series resistor to the detector return, which are the coaxial shield of the signal cables and are all tied together at the preamp board. This point is then connected to analog ground on the board. The output of this stage is connected through coaxial shielded cable to the input of the signal processor board.

1.4.3 Digital Controller

The main functions of the digital controller are indicated in the MIRAC block diagram, Figure 1.9. A more detailed block diagram of the controller is shown in Figure 1.12. The serial interface receives commands and parameters from the PC, and it sends the data from the "first in first out" (FIFO) memory on the signal processors to the PC. A number of camera parameter registers exist where the current values are stored. These parameters control the operation of the timing on the controller and signal processor. Two programmable array logic (PAL) chips (denoted as "PAL1,2 Timing Generator" in the diagram) create the reset pulse and the control signals for sampling the data. Other counters and timing signals keep track of the number of frames in the coimage, the transfer of the coimages to the FIFO memory, and clearing the frame memory on the signal processor between coimages.

1.4.3.1 Timing, addressing

There are a total of nine clocked signals driving the array readout: eight address lines and a reset pulse. The row address is generated by a counter that starts at zero and counts up to the maximum row (n-1). It is then reset to zero to start the next cycle. This row address is used to specify the address of the coadder memory, as well as to clock the array. The 6-bit row address is converted to the 8-bit array address using an electronically erasable programmable memory (EEPROM) chip, and then is sent through optical isolators to the dewar.

All timing on the controller is specified by the master clock, which is derived from a 30 MHz crystal oscillator. This is divided by two for a maximum clock rate of 15 MHz, which can be further divided by factors of two, based on the value in the clock rate register. A single pixel select time is divided up into 24 master clock cycles. At the clock frequency of 15 MHz, this is 67 nsec per clock cycle or 1.6 µsec per pixel. This corresponds to .1 msec for a full 64 row frame and .05 msec for half frame. The rate at which the detector is read out is command selectable to 16 different rates. The frame rate is derived from counting down the master clock by powers of 2 to obtain the desired value. This gives a range of frequencies of 15 MHz down to 457 Hz.

The controller has several different modes of clocking the detector. The usual mode is selecting each pixel from 1 to 64 in sequence and resetting each one. When number 64 has been reset, the controller begins again at 1, with no pause in between. Another possible mode is to clock through half the addresses, 1 to 32, before starting again at 1. This mode has been used exclusively since June 1990, when it was discovered that one of the address lines was malfunctioning, and only half the array could be read out correctly. It was decided not to attempt to repair this device since no replacement array was available at that time.

Another possible readout mode is a "burst" mode, where the pixels are read out quickly in succession, but there is a delay time between frames. The delay can be set to be an integer number of pixel readout times. This mode is useful in low background conditions, when a longer integration time is possible. It also synchronizes the integration periods of each pixel, making them closer to simultaneous. The range of delay values is 0 to 65536, making the readout rate range .05 msec to 3.3 sec at 15 MHz clock frequency, or much larger frame times for lower clock frequencies.

The controller directs the data sampling synchronously with the clocking of the detector. There are four different modes possible: single sample, with the sample taken during the pixel select just before the reset; delta reset - taking a sample before and after the reset, finding the difference between the two, and sending the difference to the computer; double sample - taking two samples as in delta reset, but sending both to the computer; and triple sample, where samples are taken before, during, and after the reset, and all three samples are sent to the computer. See the signal processor section below for a more detailed description of these modes.

1.4.3.2 Controller and processor timing

There are two PAL chips on the controller. The PAL timing diagrams are shown in Figure 1.13. The first PAL device, called PAL1 here, has as input the master clock (referred to as BITCLK), a control line called PIXWAIT which can be used to stop the clocking of the array, and SMODE00 and SMODE01, two bits which control the sample mode. The outputs of the PAL1 are the detector reset pulse DRST/, the CVRT/ pulse which causes the A/D's to take a sample, PIXCLK2/ that signals the start of a new pixel on the downward transition, and five control lines CT0-CT4 which are inputs to the second PAL (PAL2). The slash "/" after the names above indicates that it is negative logic, e.g., for the DRST/ pulse, the reset occurs when the signal in the timing diagram goes low. These control lines are used by the second PAL to generate control signals for the coadding of data.

The control line PIXWAIT is used to turn the detector reset pulse off, along with the other coadder logic. This is used when the camera is being operated in the burst mode, when the detector clocking is suspended for a number of pixel read times after each frame. Otherwise, the detector is continuously reset and clocked whenever the electronics power is on, even when not imaging. This insures a steady state in the detector and eliminates noise due to detector temperature drift which would result if the readout was not constant. The DRST/ and CVRT/ outputs are different for the various sample modes, due to the different number of A/D samples necessary.

Four separate diagrams are shown in Figure 1.13b-e for PAL2, one for each of the different sample modes. The DRST/ and CVRT/ signals are not inputs to PAL2, they are shown for reference. The outputs perform the following functions. COADST is the signal that latches the coadder memory row address for a particular pixel. COADDA is the signal that causes a "coaddition" to be latched in preparation for storing the value to memory. There are two coadditions necessary per sample, one each for channel A and B on the signal processor. COA8A is the signal that selects between channel A and B on the signal processor. COA7A and COA6A are the highest bits of the coadder memory address. For a particular row address, there can be up to three samples stored for triple sample, and these are stored in different areas of memory based on the value of COA6A, COA7A and COA8A. This is shown in the coadder memory map diagram in Figure 1.14.

ADDSUBA is used to control whether the coadders are adding or subtracting the numbers. For the Δ reset mode, this is used to subtract the post-reset sample from the pre-reset sample, and only the difference is stored and transferred to the PC. OFFBLKA and OFFBLKB are address bits for the fast offset function of the signal processors, which has not been implemented.

1.4.3.3 Controller logic

The controller uses the signals generated by the PALs to control the processes of sampling the data on the signal processors and storing the coimages in coadder and FIFO memory. The timing is based on the following user-selected parameters: the clock frequency, the number of frames per coimage, and the number of rows per frame, or the portion of the array being read out.

The control of the data taking and coimage generation is accomplished using the PAL signals described above, along with a number of other signals derived from these on the controller. Some of these are described below:

FIRSTROW - This is true during the first pixel read of a frame, or when the row address = 1.

LASTFRAME - This is true when the last frame of the coimage is being coadded by the signal processor. If there is only one frame per coimage, this is true all of the time.

TOFIFO - This is the result of LASTFRAME AND COADDA/. This is used to direct the data to the FIFO memory during the last frame of the coimage. During this period, the coadder memory is filled with zeros. If there is only one frame per coimage, then the image always goes to the FIFO and the coadder memory is not used to store the frame.

A typical integration would proceed as follows: first, the controller receives the START COIMAGE command from the PC. As soon as the row address reaches the maximum value and toggles back to 1, the flag IMAGING is set. This enables the coadder timing and starts the data taking process. Also, the frame counter is initialized to the number of frames per coimage. Based on the selected sample mode, each pixel row is read out by the signal processors under the direction of the controller, and the frame stored in the coadder memory. After all of the rows have been read, the row address is reset to 1, the frame counter is decremented, and the next frame proceeds in the same way, with the current frame being coadded to the previous result in coadder memory. This proceeds until the frame counter reaches zero. When this occurs, LASTFRAME is set and the image is transferred to the FIFO memory by writing the result of the coadder to the FIFO instead of the coadder memory. The coadder memory is simultaneously loaded with zeros, to prepare for the next integration. After the last frame is completed, the IMAGE READY flag is set, the frame counter is initialized and the next integration begins.

If a STOP COIMAGE command has been sent during a coimage, the data taking process continues until the last frame has completed and the IMAGE

READY flag is set. At this point, the IMAGING flag is turned off and the data taking stops until the next START COIMAGE command is received. The imaging process will stop only after the last frame has been completed, so to take a single frame, START and STOP COIMAGE commands must be sent consecutively before the frame has completed.

1.4.4 Signal Processor (SP)

The function of the SP board is to sample the analog waveform from the detector at one or more places per pixel to determine the voltage due to flux on the detector. This information must be converted to a digital value and stored in memory. Successive frames are coadded, according to the observing mode selected, and saved in memory. The data is transferred as requested to the controller board when the PC directs the transfer of images. A block diagram of the signal processor is shown in Figure 1.15. There are five main sections to the SP board: the analog section, the A/D sampling, the fast coadder, the coadder memory, and the FIFO memory.

1.4.4.1 Analog Section

The analog portion of the SP consists of an amplifier stage and a voltage over-range protection circuit. The amplifier stage includes a unity gain buffer with programmable bandwidth, and a second amplifier with unity gain. The bandwidth selection allows the maximum bandwidth in the sampling to be set to the optimum value, based on the operating frequency. The available bandwidths are given in Appendix 4, in Table A4.2. Noise can be filtered out in this way without loss of signal, decreasing the read noise, hence increasing the dynamic range for background noise limited operation.

The voltage over-range circuit is to protect the A/D converters from unintentional inputs that exceed the safe operating range of the converters. The maximum input range for conversion is ±2.5 V, and the maximum safe voltage is ±3.5 V. The voltage protector circuit clips the voltage at 3.0 V so that the safe range of the converters is not exceeded. The output of this stage is connected to the input of the track and hold device, which is controlled by the A/D converter.

1.4.4.2 A/D Sample Modes

The analog-to-digital conversion is directed by signals from the controller board and is synchronized with the addressing of the detector to insure the samples are taken at the appropriate time. The output voltage level from the detector is proportional to the amount of flux incident on the detector, so to measure the flux, the output level must be measured accurately. After the analog signal is sampled and converted to digital numbers, these numbers must be added (or subtracted) and stored until read out by the computer. When the CONVERT pulse arrives from the controller, the A / D converter commands the track and hold chip to hold the current input value, and then converts the input voltage to a digital value, which it transfers to its output bus. The data word from the 12-bit A / D chip goes through a latch to an input to the coadder chips.

Figure 1.16 illustrates a typical column output signal and the relevant timing. Three pixel reads are shown in this figure, the middle pixel being illuminated by a point source and the two pixels to either side illuminated by a faint background. When the pixel output is selected, the output rises to the signal level. The reset pulse causes a spike to appear in the output. The output level then falls to the reset level. The signal is then the difference between the signal level and the reset level.

There are several sampling options available. The simplest mode available is "single sample", where one sample is taken before the reset pulse. This mode generates one data word per pixel. This mode cannot be used effectively for taking data in most cases, since it depends on the absolute stability of the output level from frame to frame, which is subject to drift.

A second type of sampling available is "double sample", where two samples are taken per pixel, one immediately before and one after the pixel reset. The first sample measures the pixel output after the integration, and the second sample measures the output level after resetting the pixel. The difference between these two levels is the signal due to flux on the detector. There are actually two modes available for this, one named "delta reset" and the other "double sample". The delta reset timing is shown in Figure 1.17. Both take samples in the same way, but in the delta reset mode, the two samples are subtracted immediately in the fast coadder and stored as a difference. The advantage to this mode is that the number of data words that must be transferred to the computer is cut in half, making fast frame rates possible. The delta reset mode is the one used most often on the telescope when using the mid-infrared 10% bandpass filters.

Another available mode is "triple sample", where three samples are taken per pixel reset, one just before, one during, and one after the reset. The sample taken during reset is clamped to a constant reference voltage. This mode is potentially useful for relatively long integrations for near infrared observations and for high spectral resolution mid-infrared observations with a Fabry-Perot interferometer (see section 1.8.2).

1.4.4.3 Fast Coadder

The coadder adds successive frames and stores the result in the coadder memory. The SP block diagram in Figure 1.15 shows the general path of the data. The 12-bit data from the current row being read out is added to the 24-

bit coimage currently in the memory (the memory values are zero if this is the first frame). The result of this operation is then stored back in the coadder memory, overwriting the previous result. During the last frame of the coimage, the result is transferred to the FIFO memory, and the coadder memory is loaded with zeros from the second set of tri-state buffers which are connected to ground (digital zero).

The 24-bit coadder memory can store a coimage with as many as 4096 frames (12-bit per pixel) without overflowing. This means that a much slower image transfer rate between the camera and the computer can be used. For example, if the camera is operating at the maximum full frame rate of 9766 Hz, the transfer rate to the PC can be as slow as 2.4 Hz if performing the maximum number of coadds. Usually, the number of frames per coimage and the transfer rate is determined by the time for a telescope secondary half "chop" cycle, typically .05 seconds.

1.4.4.4 FIFO Memory

The FIFO memory is where the image is stored until the PC reads the data. The use of separate coadder and FIFO memory gives the camera the capability of taking a second image while preserving the first image. The read and write operations to the FIFO can be asynchronous and can be done simultaneously. The camera can therefore be continuously taking data, with no "dead time" between images. No conflict will arise if the second image is completed before the first image is completely read out.

The implementation of the FIFO memory on the SP uses the Cypress Semiconductor CY7C421, a 512x9 bit FIFO memory. Three are used per channel, or six per SP board. 24 bits out of the total of 28 are used for data, and two bits are loaded with the current area of coadder memory, based on the sample mode. This gives a total of 26 bits of valid input. The MSB input is set to GND. There are two flag outputs of the FIFOs, a FIFO full flag and a FIFO empty. The first flag is set when a WRITE TO FIFO operation is attempted when the memory is full, and the second flag is set when a READ FROM FIFO operation is attempted when the memory is empty. These two flags are appended to the output word from the FIFOs when being read out, to make a total of 28 bits that are transferred to the PC.

1.4.5 Command and Data Link to PC

The MIRAC controller is linked to the array processor board (APB) in the PC by a serial transmission line using the "Manchester" data encoding format at 1.25 Mbit/sec. This is accomplished using two 1551 encoder/decoder chips manufactured by Harris. One chip is in an interface box connected via two 16-bit I/O cables to the APB, and the other is on the controller. One Manchester-encoded word is 32 bits long. All of the operating parameters of the camera are set by the computer sending commands through this interface, and all data are received from the camera through this interface in the opposite direction. Appendix 4 gives a list of the commands used.

The APB sends commands to the controller through its parallel I/O bus to the interface box. The command to be sent is written by the APB as two 16-bit words, which are latched to a 32-bit bus in the interface box. The useable size of a transmitted word is 28 bits, the other bits are used in the Manchester encoding format for synchronization bits and parity. The 1551 chip then reads the data in through a parallel to serial shift register, encodes the data word, and sends it to the 1551 chip on the controller in the MIRAC electronics. Command words are accepted asynchronously by the 1551 chip on the controller and are decoded and output as a serial stream consisting of the original word sent. The data enter a serial-to-parallel shift register and are clocked in a set of latches.

The command segment of the word is sent to a decoder chip which determines which command is being sent. Based on this, the data, if any, can be sent to the appropriate latches to store the parameter just sent. For example, if the command being sent is to set the number of frames per coimage, the upper 5 bytes that carry the command will be decoded to select the frames per coimage command, and the lower 12 out of 23 bits will contain the number of frames/coimages to use. These data are latched into a register in the controller, which is used to determine when the coimage is finished by being compared to the "number of frames completed" counter. Other commands, such as the

FIFO reset, do not require any data bits in the command.

There are two types of commands that can be sent to the electronics controller from the computer, "Group 1" or data functions and "Group 2" or parameter setup functions. See Appendix 4 for a summary of the commands available. The first group of commands are always active (i.e., the controller will respond regardless of its state). These commands include the RESET commands for the controller and the SP FIFO memory, and commands to control the image recording and transferring to the computer. The second group can only be set when the camera is not "imaging", or currently sampling and storing data. This is to prevent the parameters from inadvertently being changed during an observation.

The transmission of data from the camera to the APB proceeds in a similar way, except it is initiated by a command from the APB requesting a number of words based on the current data sampling mode (1 word per pixel for single sample and delta reset, 2 for double sample and 3 for triple sample). The camera then sends the requested number of words to the APB, which places the data in memory to be used by the PC. Data words are sent in a similar way as from the APB, with the data first loaded into a shift register, clocked into the 1551 chip serially, and then transmitted to the 1551 chip on the interface, where they are decoded and sent to the computer. The image data words are 24 bits long, with the upper 4 bits used for transmitting the area of coadder memory used and the FIFO full and FIFO empty flags. These latter flags can be used to monitor the condition of the memory to insure that images are not being overwritten.

The serial encoding chips now in use have a 1.25 Mbit transmission rate. The data words sent are 32 bits long (with 28 bits valid data), so an entire frame of 20 columns and 64 rows can be transmitted in .033 sec, or a rate of 30 Hz. For single sample or Δ reset mode, this gives a maximum chop frequency of 15 Hz (2 frames per chop cycle) when reading out the entire array.

1.4.6 Temperature Controller

The detector sensitivity and uniformity are functions of the detector operating temperature, so in order to calibrate the observations properly and to reduce noise due to drifts, the detector temperature must be maintained constant. There are four factors which affect the detector temperature: the detector self-heating, the power dissipated by the heater resistor, radiative and conductive cooling to the helium temperature cold plate, and the flux incident on the detector.

The direct connection of the detector mounting block to the cold plate is through a flexible copper heat strap attached to the base of the mounting block. The block is attached to the slide of the mounting bracket via a block of G-10 which acts as an insulator. This is done to thermally isolate the detector stage from the cold plate so that the detector can be operated near 10K, and to insure that the dominant cooling is through the heat strap and therefore can be easily controlled by changing the size of the strap. The thermal connection can be adjusted in this way to insure that the minimum amount of extra heating is required to maintain the temperature at the proper value, minimizing the amount of helium boil-off and heat dissipation inside the dewar.

The temperature controller monitors the temperature at the detector by measuring the voltage across a calibrated diode (Lakeshore Cryogenics DT-470-SD-12) which is attached to the detector block on the sliding mount. The heater resistor is also attached to the same block. The diode calibration is valid for a 10 µAmp current, which when at a temperature of 10K results in approximately 1.2 V across the diode. The MIRAC program, described below, continuously monitors the temperature sensor and displays the current detector temperature in real time.

The controller has two modes, a "manual" mode where the heater voltage is set directly without feedback, and the "auto" mode where the controller sets the heater voltage to maintain a selected temperature. The controller can control the temperature in the range of about 8K to 16K with a stability of .003°K rms. The controller was designed by William Hoffmann and Barry McLendon and assembled in the Steward electronics shop.

1.4.6.1 Temperature Controller Operation and Test Results

Figure 1.18 shows the cool-down of the dewar from room temperature, first after the pre-cool using LN_2, and then after filling with helium. The time required to cool from room to LN_2 temperature is approximately 4 hours, and the time for cooling from nitrogen to helium temperature is approximately 75 minutes. Since the detector block presumably has the weakest connection to the helium reservoir, the detector temperature should be a good indicator of the complete cooldown of the system.

Figure 1.19 shows the effect of the controller being turned on and set to reach a desired temperature, and the effect when changing temperatures. Initially the heater turns full on, to heat the detector block from LHe temperature to the goal of near 8.5 K. The controller increases the heater power initially to a value greater than necessary to maintain the desired temperature, to reduce the time necessary to reach it. As the detector heats and gets near the goal, the heater power is reduced until the temperature settles on the desired value. Similarly, if reducing the temperature, the heater will reduce its power input to a value below what is required to maintain the goal temperature, in order to minimize the time necessary to reach the new temperature. If the new temperature value is drastically different from the current one, there may be some overshoot in the temperature, but it will still reach the new temperature much faster than if the heater had simply been set to the equilibrium value.

When increasing the temperature slightly, as was done from seconds 320-500 in Figure 1.19, the overshoot is less severe and the temperature stabilizes quickly. When reducing the temperature slightly, from 700-900 seconds, the heater turns off completely and the cooling time is dominated by conduction through the copper strap attached to the detector block.

The flux incident on the detector has an effect on the heating, although not a direct one. When the output level of the detector changes, it changes the amount of power being dissipated in the output MOSFET source follower. When the detector is operating under low flux conditions and the output signal is low, the voltage drop across the source follower is high, dissipating more power on the detector readout. Therefore, less heater power is required to maintain the temperature. When the detector is operating under high flux, less power is dissipated by the output source follower, so more heater power is required. This has the curious effect that when going from blanked off to fully illuminated, the heater power has to be increased, which is the opposite one would expect if the detector was being significantly heated by external radiation.

This effect is illustrated in Figure 1.20, where the detector temperature and heater power are plotted as the filters are changed between the 8.8, 9.8, and 11.7 μm filters. As the filters are changed, the detector is momentarily blanked off, the self-heating increases, and the detector temperature rises. The controller tries to compensate to this by dropping the heater power. When the new filter is in place, the self-heating returns to close to its previous value, and the heater power rises again. The net effect of this is that about 150 seconds are necessary for the detector to stabilize between filter changes, or any other changes that increase the output level of the detector, such as changing the delay or frame rate. It should be noted that this test was performed before the temperature controller was properly optimized, so this is perhaps a worst case.

Since these tests were done, several changes were made in the thermal connections of the detector stage. The heat strap was making poor contact with the cold plate because of loose connections, so the strap was tightened and had to be significantly reduced in size. Also, the detector cover was not properly tightened, so parts of the detector stage were not thermally connected. When these changes were completed, the heat transfer properties were measured by monitoring the temperature in the 8-12 K range under changing heater power inputs. The thermal conductivity to the LHe cold plate from all paths was determined to be 5.7 mW/K. The contribution to the conductivity from the heat strap was determined from measuring the total conductivity as the width of the strap was reduced. The conductivity of the strap currently being used is 3.6 mW/K. The heat capacity of the detector block is 2.77 J/K, for a time constant of 485 sec.

1.4.6.2 Temperature Controller Performance

The temperature controller circuit was optimized for the MIRAC dewar before the most recent observing run from June 1-3, 1991. The relevant parameters of the dewar are the heat capacity of the detector block and the cooling power of the copper strap in the temperature range near 10K. The strap had recently been modified so that the self-heating of the array would bring the temperature to 8.5 K for a V_{ADJ} of -5 V, so that the extra heater power required would not be excessive yet allow good control of the temperature near 10K.

The temperature of the detector and the heater power at the time of each observation are recorded in the observation file header. Several hundred observations are taken on a night with good weather. From these data, a record of these parameters can be compiled for the entire night. This was done for the night of June 3, 1991, and the results are displayed in Figure 1.21. The first graph shows the temperature of the detector, and the second graph shows the heater power. Except for a few short spikes, the temperature for each observation can be seen to be within a total range of about .005°K. Excluding the first 50 minutes of the night, the average temperature is 10.022°K, with a standard deviation of .003°K. The largest variations can be understood as changing flux levels incident on the detector. During the first 40 minutes of the night, flat field integrations were being taken, which involves obtaining images at many different filter positions and two different sky positions. During the rest of the night, the variations can be caused by filter changes, or when the telescope is pointed at a different source. When the pointing of the telescope is changed to a new object, the telescope can momentarily point at the dome, which saturates the detector.

1.4.7 Power Supply and Grounding

Each subsystem of the MIRAC electronics is separated, in most cases into its own shielded enclosure, to prevent additional noise on the detector signal. Each of these separate systems has its own power supplies, in order to isolate it further from the other subsystems. In total, eight separate supplies are necessary. For the portablility requirement for MIRAC, the supplies were designed to be easily portable and convenient to set up. The power supply was designed by Frank Laccata and assembled by Peter Crawford at SAO.

1.4.7.1 Power Supply

The DC power supplies for the controller, signal processor, preamp, bias supply, and temperature controller electronics are housed in a single suitcase style aluminum case, approximately 43 x 53 x 19 cm. The power supplies are from Power One, Inc., and are summarized in Table 1.5. The voltage of each supply is higher than what is necessary for the components on the board, allowing for a voltage drop in the power cable and on-board voltage regulators.

Table 1.5 MIRAC Power Supplies

Electronics Subsystem	Power One Model #	Output Volts	Voltage On Board	Amp Rating
Preamp	HAA24-0.6-A	±24	±15	.6
Bias	HAA24-0.6-A	±24	±15,±10	.6
Camera Clock	HB12-1.7-A	-12	-4	1.7
A/D Converters	HB12-1.7-A	-12	-5.2	1.7
Analog Processor	HN24-3.6-A	24	15	3.6
Analog Processor	HN24-3.6-A	-24	-15	3.6
A/D and Fast Coadd Logic	HE12-10.2-A	12	5	10.2
Detector Heater	HAD15-0.4-A	±15	±12	.4

All of these supplies are mounted to the panel in the lower half of the power supply case. There is an ELCO connector on the front panel for the power cable, a number of power supply status LED indicators, a multiple-pole switch and two test points where currents can be monitored, power switches for electronics and temperature monitor and heater power, and a standard 3-prong A/C power cord.

An interlock circuit prevents the power supply from providing power to the camera electronics if the power cable is not plugged in properly, or if the detector is above the maximum safe operating temperature. This prevents accidental damage of the detector if the dewar has for some reason warmed up. This circuit also provides a short time delay after the A/C power to the supplies is turned on, to allow them to stablilize to their proper output values and to prevent any voltage spikes from propagating to the camera electronics.

As mentioned above, there are on-board voltage regulators that provide a stable, low noise voltage of the proper value. This provides isolation of the electronics from noise pickup on the long power cable, as well as isolation between the various systems on the same board. This is especially important on the controller and signal processor boards. The clock signals necessary to run the detector are generated on the controller, and separate voltage regulators and optical isolators prevent pickup from the digital signals on the controller. On the signal processor, the analog section and the A/D converters use a separate voltage regulator from the digital logic of the fast coadder and FIFO. This prevents noise from being introduced before the A/D conversion takes place.

An additional benefit of separate supplies and regulators on the boards is that when problems occur, they are relatively isolated and can be located easily. For example, there were a few bypass capacitors that failed on the signal processor boards after several hours of use. The output at the computer quickly shows which signal processor boards are not working. There was no short when tested with an ohm meter, but when power was turned on, the voltage drop across the regulator indicated that the current had reached the regulator's maximum rating.

1.4.7.2 Grounding

The grounding within the MIRAC electronics has been carefully designed to prevent noise and ground current loops within the system. The camera and electronics are isolated and all electrical connections to the telescope control room are through the power cable. The dewar is isolated from its mounting plate and the telescope through G-10 spacers and nylon washers. The camera is isolated from the computer through optical isolators on the serial transmission line.

All of the power supply returns are brought out to the electronics separately in the power cable. Earth ground is also brought out on a separate line and connected to the electronics backplane. The power supply returns (except for the biases, isolated clock drivers, and preamp), earth ground, and the electronics chassis are connected together at the electronics backplane. The dewar case is connected to the electronics chassis via its mechanical mounting. The returns for the bias supplies and isolated clocks are connected to the dewar case at the top of the dewar near the connector. The return from the detector is also connected to the dewar at this point. The preamp return is connected to the electronics chassis. On the SP boards, the analog and digital returns are also tied together at the A/D converter.

1.5 MIRAC Computer and Interface

1.5.1 Data and Command Interface/Local Controller

The interface between the MIRAC electronics and the APB discussed above also serves as a "local controller" that enables commands to be sent without the computer. The interface detects whether it is connected to the PC. If not, the encoder switches to local mode, where the commands are entered using a set of thumbwheel switches and a push button to send the command. All the commands may be sent in this way to initialize the camera to the desired operating parameters.

1.5.2 Array Processor Board (APB)

All communication to the MIRAC electronics as well as control of data transfer and chopping is done through an AT-compatible coprocessor board called the SKY 321-PC array processor, made by Sky Computers, Inc. This board utilizes the Texas Instruments TMS 32010 digital signal processor, a 25-MHz fixed-point 16-bit processor, with a 32-bit accumulator, 16x16 bit hardware multiply instruction, 4K program memory and 144 bytes of on-chip RAM. A block diagram of the SKY board is given in Figure 1.22. It has several registers that can be assigned to I/O ports on the PC, and 64K of data RAM which is memory-mapped onto the PC address space. This results in increased speed and flexibility, since no explicit data transfer is necessary between the SKY board and the PC -- the data are just read and written directly to memory by both the PC and SKY board. The SKY board is also equipped with two 16-bit auxiliary ports for input and output, based on an extension of the DT-Connect format, a protocol designed by the Data Translation Corp. for use with their A/D and frame processing boards. These ports are used to communicate with the camera through the local controller/interface. There are a few additional I/O bits that provide control of the data I/O to the interface and from the camera, and four digital outputs, one of which controls the chopping of the telescope. Programs for the SKY board are written in TMS 32010 assembly language and are compiled on the PC. The object code is then written to the program memory on the board directly by the PC.

The operation of the SKY APB program is shown in Figure 1.23a. There are three main functions of the APB program: to receive command words from the PC to send to the camera electronics, to coadd images and alert the PC when the image is finished, and to receive commands from the PC to set parameters within the APB program. After initialization, the APB enters a main "polling" loop where it checks the status of registers and takes the appropriate action. In the first function, the APB enters into a mode where it transfers all data received from the PC to the camera, until the mode is terminated by the PC. Control of this transfer is through the STCREG, or status and control register, and the data are transferred through the COMREG register. The camera initialization and operating parameters are set in this mode, as well as sending the BEGIN and END COADD. Depending on the observing mode, the PC also sets variables in the APB program. These include whether to chop or not, how many coimages in the image, how many coimages per chop cycle, the chop wait time, etc. These are set by writing the parameters to the shared data memory, then commanding the APB processor to read these parameters into its on-chip memory.

Figure 1.23b illustrates the operation of the image transfer and coadd routine. There are two basic data taking modes which the APB controls, the "Grab" mode and the "Chop" mode. (For wobbling the telescope, the PC does a series of GRAB or CHOP images.) In the grab mode, the APB constructs a single image from the coimages sent from the camera. When the required number of coimages has been recorded, the camera is sent the STOP command. In the chop mode, two separate images are constructed at the same time, one for each chop beam. In between each chop phase, the camera is stopped, the chop beam changed, time is allowed for the chopper to settle, and the START COIMAGE command must be sent. This procedure is repeated until the desired integration time on source is reached. In both modes, when the number of coadds has been taken, the APB halts the camera and notifies the PC that the image is ready. When the PC is done storing the data, it signals the APB to continue observing, or to wait for the next command.

Figure 1.23c shows the procedure on the APB and on the PC for transferring command words from the PC to the APB. Three flag bits and one

8-bit data port is used to transfer the 16-bit command words. The routine to send commands to the electronics from the PC is similar. When the data word is received from the PC, the APB calls the subroutine to send the word to the electronics, then returns to this procedure to accept the next word from the PC.

1.5.3 MIRAC PC Control Program

The main tasks of the PC control program are to send the operating parameters to the APB and the camera, to initiate the data taking and store the images, and to display the images and provide simple data analysis functions. Also, since image accumulation times are often several minutes, it is desirable to be able to perform display and analysis functions while the camera is taking data. An additional goal was to make the program relatively simple to operate, so that it could be used by new observers with minimum instruction and possibility for user-generated errors.

These designs were implemented in the control program called MIRAC, written in Turbo Pascal v. 5.0 for an MS-DOS computer. The program will run in any IBM-compatible PC running DOS v. 3.3 or above, with 640K RAM and an available 8-bit slot for the APB and available address space between 640K and 1 MB. The program can be run on any PC without the APB to use the data analysis and display functions on previously obtained data. A hard drive is recommended for fast storage and retrieval of data. If a math coprocessor is in the system, the program will use it to increase the speed of calculations. The program uses overlays to swap out parts of the program that are not currently being used, allowing the program and data space to be larger than 640K. The unused code is stored in expanded memory and swapped as needed. If the PC has no expanded memory, the overlays are swapped to the disk. The overlay operation is completely automatic and transparent to the user. The computer now used is a Gateway 2000, a 25-MHz 386 IBM PC-compatible, with 4 MB of RAM, 150 MB hard drive, 80387 math coprocessor, and a monochrome VGA display.

1.5.3.1 MIRAC Program Structure

The user interface structure in the MIRAC program consists of a command line menu across the top of the screen, with pull-down menus for each general heading. See Figure 1.24 for an illustration of the program's main screen. There are several command line menus, each containing pull-down menus and entries to move between the command lines. There are four command lines: OBS (Observe), DISP (Display), PRN (Printer), and UTIL (Utilities). The OBS menu controls the camera operating parameters and observing modes. The filter can be selected, general features of the program set up (i.e., the directory where images are stored, initializing the APB, etc.), and the user can start the process of taking data. The DISP menu includes choices of how the observations are displayed, including using a gain matrix and / or flat field automatically. Simple data reduction can be done, such as flat fielding and adding images together using offsets to construct a mosaic image. Previously stored images can be read in and displayed. The PRN menu controls the hardcopy functions, usually to a grayscale image printed on a HP laser printer. Figure 1.25 shows an example of this printout. All of the relevant header parameter values are printed at the top of the output. Below that are various statistics on the image, including the total source counts and background RMS. The UTIL menu provides access to DOS functions, file output utilities, macro definitions, and system information.

The current camera and program operating parameters are stored in a default file on the PC. All of these are collectively called the "header", since this information is written to the beginning of every image file stored. The header information may also be stored to other files and read in from the program by name, making it possible to keep default files for different telescopes or observing conditions.

The most common display mode used is one that displays the most recent image taken, shown in Figure 1.24. At the top of the screen, below the command line, are some of the current camera parameters. The temperature of the detector is measured and displayed once a second, to allow for monitoring. The image is displayed in the center of the screen with a 16-level grayscale that can be autoscaled or the limits fixed to user-supplied values. For chopped images and nod sets, the off-source images are automatically subtracted. If a gain matrix or flat field has been chosen, it is applied to the image before being displayed. A summary of statistics of the image is given below, including the average and RMS for the whole map, as well as for any source in the image and the background. This gives a quick indication of the signal to noise of each image. If a source is detected in the image, a gaussian profile is fit to the source in both directions, and the source position and FWHM are displayed. The numbers labeled "SKY FLUX" are the level of one of the off-source images in the chop pair or nod set, and that number compared to the last several images. This gives an indication of the absolute sky flux, and can be used to indicate when the sky is varying rapidly.

At the bottom of the display screen are two status lines. The first displays the time, date, and the current object name. The camera status is also displayed. The status can be "DATA" for taking an image, "IDLE" for no activity, "STORE" for writing an image to disk, "WAIT" for pausing during an observation. If observations are being taken, the time left in the current observation is displayed compared to the total time, and the current observation number compared to the total number to be taken. The second line displays information on the current data being displayed: the time and date of the displayed observation, and the source and file name.

1.5.3.2 MIRAC Data Files

The images from the camera can be viewed only, viewed and saved, or only saved. The data file names are chosen automatically, in a format which includes the date and image number, for example, "C910528A.001", which is the first data file saved on May 28, 1991. The image files all start with the letter "C", followed by the last two digits of the current year, two digits each for the month and day, and an index letter that starts at "A". The file extension is a number that begins at "001" and increments automatically until 999. At this point, the index letter is incremented from "A" to "B" and the numbers go to zero. The file is therefore fully specified by the date, index letter, and number. The "header" of the data file includes all the information on camera parameters, program operating modes, and source information. The data are stored without change directly from the APB. For example, if the camera is being operated in double sample mode, both the "before reset" and "after reset" values are stored for each pixel in the image. In addition, if the image is taken in the chop or nod mode, all the images in that set are stored in the same file. When the picture is retrieved from disk, all the necessary arithmetic, such as subtracting off-source images and multiplying by a gain matrix, is done automatically, according to the information in the file header. This can also be overridden, and each individual frame in the file displayed separately.

While observing, a log file can also be kept automatically by the program. This is a text file that keeps track of the images taken during a night of observing. The file begins with a listing of the current header parameters. After this information, one line is written for every observation, with the following information: File number, date, time, wavelength, integration time, object name, and offsets. This file can be viewed from within MIRAC, in case one needs to double check the observations that have been performed during that particular session. If the program is terminated, when the program is started again the new observations are appended to the old list for that session, unless a new file is started. A new file is automatically started for a new night of observing.

1.5.3.3 Telescope Control

The MIRAC program has a number of options to control the operation of the telescope. The chop signal is generated by the APB and the output is located on the local controller / interface box. This is a 0 to 5 V logic level, with 0 specifying the first chop beam and 5 V the second chop beam. The "on-source" beam is software selectable.

There are a number of different options for controlling the telescope wobble motion. One option is to output a logic level to specify the beam. This can be used on the SO 2.3 and 1.5 m telescopes, which have a wobble interface that accepts a logic level input. This output is provided on the A / D breakout box (the same box that connects to the dewar temperature monitor). Another possibility is to trigger the telescope wobble using a logic pulse. This is necessary for the IRTF telescope control. Either a positive (0 - 5 - 0 V) or negative-going (5 - 0 - 5 V) pulse can be selected.

On the SO 2.3 and 1.5 m telescopes, the telescope can also be controlled by sending ASCII commands via a RS232 interface to the mount micro. In addition to the wobble beam control, other telescope parameters and commands can be sent, such as setting the guide and drift rates, RA and Dec bias rates, setting offset and wobble vectors, and various telescope motion commands.

The MIRAC PC program has the ability to control the telescope offsetting for a series of observations, in order to construct a mosaic image. The offsets may be entered in an "absolute" mode, where a zero point is defined and all offsets are relative to that initial position, or a "relative" offset, where the offsets are relative to the previous observation. All offsets can be entered in units of pixels or arcsec RA and DEC, and the program, using the plate scale of the telescope and the camera magnification, calculates the offset in RA seconds of time and Dec arcsec. Before each observation, the observer has a chance to enter the desired offsets, and the PC then sends the offsets, moves the telescope, and after an appropriate delay starts the observation. These offset values are saved to the image file header, so when the images are combined these offsets can be used to align the images.

1.5.3.4 Image Display and Processing

There are a number of built-in display capabilities in the MIRAC program. These include contour images, grayscale maps, and "cuts", or a plot of a single row or column. The current image can be displayed, or previous images read from disk files. These displays can be printed, and there are additional printout options, such as printing out the values in a map, or doing statistics on the rows or columns. Figure 1.25 shows a typical printout of an image. All the camera parameters and observing conditions are displayed in the top section of the output. Some statistics of the image are displayed, similar to the observing screen. The grayscale image is printed at the bottom.

The MIRAC program has the capability to perform simple image processing tasks. Gain matrices and/or flat fields can be applied to an image, an image can be smoothed, and images can be added, subtracted, multiplied, or divided by constants or other images. A mosaic utility also exists, where the images can be combined using offsets from a number of sources. If the telescope was being controlled by the PC, the offsets stored in the file header can be used. The user may also type in offsets, or select to have them read in from a file. The offsets can also be calculated by the mosaic routine, by aligning the peak values, calculating the centroid, or a cross-correlation calculation. The images are shifted and averaged.

For additional processing, a utility exists within the MIRAC program to convert the image files to FITS format, and can be read directly by IRAF or another image processing program. The utility program reads in the image file and performs the subtractions and gain matrix arithmetic, and can also expand the map into subpixels for more accurate registration of the images. The images are written to FITS files on the PC, which can be transferred to other computers by copying to disks or using ethernet, if available.

1.6 Guider Box

The Guider box has two main functions: to provide the mechanical connection from the dewar and TV monitor to the telescope, and to bring the telescope beam into these instruments. Figure 1.26 illustrates the basic design of the guider box. It is a rectangular, anodized aluminum box, with a round flange on the top for mounting to the telescope. The beam exits the telescope at the Cassegrain focus and enters the guider box through a hole in the top. There is a large mirror that can be rotated into the beam near the midpoint of the guider box. This mirror can be used with an eyepiece attached at the viewport, but is usually in the stow position, out of the field of view of the camera. The telescope beam first encounters a beamsplitter, which reflects the IR radiation to the side where the MIRAC is mounted. Some of the optical light passes through the beamsplitter and is reflected by other mirrors into the TV guider. This design allows for simultaneous viewing of the source for guiding while the IR image is being taken. The guider box design was modified and fabricated by Tom Tysenn, and the coupling between the dewar and guider box was designed by Dick Young.

1.6.1 Optics - Dichroic, Optical Flats

The beamsplitter and mirrors in the guider box are shown in Figure 1.26, along with the two telescope focus positions for the MIRAC high and low magnification settings. In order for the TV guider to be in focus at each of the positions, two folding flats are used to provide additional optical path length, and the third flat changes positions to add or remove these mirrors from the path. When the rotating flat is in position shown in Figure 1.26a, the telescope beam is reflected directly from the rotating flat into the TV guider relay optics. For the high magnification case, the mirror is rotated into the position shown in Figure 1.26b, and the telescope beam is reflected from the lower two mirrors first before being reflected by the rotating mirror into the TV guider optics, thereby adding 12.54 cm to the path length to allow the TV to remain in focus. The moving mirror rotates on a shaft mounted in bearings pressed into the side of the guider box, and each position is defined by a hard stop. The position of this hard stop is adjustable using a screw mechanism attached to a knob outside of the guider box.

The dichroic mirror is mounted in a cell in which the tilt of the mirror is adjustable using a spring-loaded "floating" mirror holding bracket. This cell moves above a fixed plate that is connected to the outer walls of the box. This is illustrated in Figure 1.27. One corner of the mirror holder rests on a steel ball on which it can pivot. There are recesses in the plates where the ball sits, and the two plates are pulled together by three springs. In the two corners next to the corner with the ball, springs pull the mounting plate against adjustment screws that are linked to knobs outside the guider box. Turning the knobs causes that corner of the mirror to rise or fall, resulting in an almost pure E-W and N-S adjustment of the beam.

1.6.2 Mechanical Coupling of Dewar and Box to Telescope

The guider box is connected to the telescope by at least three 5/8" bolts that connect the mounting flange to the Cassegrain mount of the telescope. The dewar is connected to the guider box via the interface illustrated in Figure 1.28. A mounting plate is bolted to the dewar using G-10 spacers and nylon sleeves around the bolts to achieve electrical isolation from the telescope. The surface of the mounting plate that attaches to the telescope has a slot in the center and a stainless steel tooling ball mounted near the top. Two captive bolts on either side of the slot are mounted in the plate. The guider box has a steel block near the top with a hemisphere recess in the top to accept the ball on the dewar mounting plate. About midway down the guider box there is a block with a ridge which fits into the slot on the mounting plate, and two threaded holes in which the captive bolts on the plate attach.

This design makes it easy to mount the dewar on the telescope. To attach the dewar, the dewar is lifted to the guider box, tipping the top forward slightly. The ball is inserted into the hole and the slot is aligned with the ridge, and the dewar is slowly lowered to lock it into place. At this point the dewar is held to the box, and the two captive attachment screws can be tightened to secure the camera.

1.6.3 TV Guider Port

The TV camera mounts on the guider box on the opposite side from the dewar. The camera bolts to a tube that extends out from the face of the box. This tube contains reimaging optics to focus the image of the star on the TV, accounting for the longer optical path and the focus of the TV camera. The TV camera focus is almost even with the plane of the front surface of the mounting flange, and the telescope is focused for MIRAC, which has its focus at 13.72 cm in front of the dewar window for low magnification, or 1.176 cm for high magnification. This puts the telescope focus in front of the dichroic for low magnification, and a few centimeters past the dichroic for high magnification.

1.7 MIRAC Test Results and Performance Evaluation

1.7.1 Initial Tests, Corrections to Reduce Noise

Before the current electronics system was built, the detector was operated with a prototype controller and bias board, with one completed preamp board and no digital processing. The detector output was monitored at the output of the dewar and preamp, using a frame "synch" pulse generated on the controller board which could be used to determine the pixel address that was being reset.

There were a few initial problems with the electronics that had to be overcome before the detector could be successfully operated. One problem was that V_{CSD}, a detector test point, had to be left floating for the detector to operate properly, whereas it was at first set to 0 V initially with its own bias power supply amplifier. The other problem was that the detector reset pulse was the wrong polarity. To reset properly it must be held at logic 1 (-4 V) throughout the integration and pulsed to logic 0 (-1 V) during reset. Initially, the electronics were designed to do the opposite.

A number of noise problems were observed in these tests. First, digital pickup on the bias supply circuit at the controller board was measured to be on the order of 300 mV. This noise signal was present on all power supplies, ground planes, and bias supply outputs. There was no single digital chip or line that was causing the noise. When we attempted to determine the source of the noise by removing the digital chips one by one and measuring the noise at each stage, the noise was reduced by approximately an equal amount for every chip removed. No amount of filter capacitors or rerouting of digital lines could reduce the noise significantly. Filter capacitors built into the bias supply cable leading to the dewar also did not eliminate the noise. It was because of this result that the decision was made to place the detector bias supplies in a separate box that was shielded completely from the digital electronics.

Even when shielded in this way, the detector bias supply voltages and the clock signals come in close proximity, since they share a connector on the top of the dewar and a connector at the detector mount in the dewar. As a precaution, the filter capacitors in the bias cable were left in place, and as recommended by Hughes, additional bypass capacitors were installed on the connector board inside the dewar. The capacitors installed were Vitramon #VJ2321A223 GFA, type NPO. These low temperature coefficient capacitors have a value of .022 μF (± 2%) and were supplied by Hughes. With the permanent controller board and self-contained bias supply currently in use, carried out with the grounding protocols described above, the bias line noise problems did not occur.

Several detector parameters were measured during these tests. These measurements should be considered to be preliminary and approximate. The mean transimpedance of the array was determined by measuring the voltage across a current sensing resistor in the V_{DET} line for the pupil blanked off and for the pupil open to f/45, 8.8 µm, and the 20% neutral density filter. This is a measure of the total detector current for the 1280 pixels. The results are summarized in Table 1.6.

Table 1.6 Transimpedance Determination

Current sensing resistor	R = 24.3 KΩ		
	Blanked	Open	
Resistor voltage	.045	2.55	mV
Total array current	.0019	.105	µA
Number of pixels	1280		
Total current difference per pixel	.0805	namps	
Integration time	100	µsec	
Integrated charge per pixel	$8.05x10^{-15}$	coulomb	
	$5.03x10^{4}$	electron	
Detector output voltage difference (for a "typical" pixel)	.31	V	
Transimpedance (V/Q)	1/.026	pf^{-1}	
	$6.2x10^{-6}$	Volts/electron	

The saturation voltage difference for a typical pixel (column 6 row 34) was measured to be .9 V, with a linear range of .75 V. In terms of electrons, the full well is $1.45x10^5$ and the linear range is $1.25x10^5$ electrons.

The responsivity of the detector in amp/watt and e-/photon at the four mid-infrared filter wavelengths was determined from the measurement of the output of a "typical" pixel (column 6 row 34) with the calculated photon flux and the flux calibration performed with the Hughes calibrated detector. The solid angle was estimated from the design pupil size and pupil-to-detector spacing at low magnification. The area of the pixel was taken to be (.95 µm)^2. The result of this calculation is shown in Table 1.7. The measurements of signal correspond to the signal difference between a 319K blackbody and the chopper blade at a temperature of 295K. The calculated QE agrees reasonably well with the expected value of approximately .23 at 10 µm. The significance of Table 1.7 is not so much a determination of detector properties as a check on the consistency of the values used for filter transmission, camera solid angle, optics efficiency, etc. The reference detector mentioned is the Hughes calibrated reference detector.

Table 1.7 Responsivity Determination

Integration time	t = 100 μsec			
Solid angle at detector	$\Omega = 4.6 \cdot 10^{-3}$ ster			
Area of pixel	$A = 9.03^{-5}$ cm^2			
Window Transmission	t_W = .8			
Optics Reflectivity	t_O = .9			
Attenuator	t_A = .20			
	Filter wavelength (μm)			
	8.8	9.8	11.7	12.5
Output (volts)	.34	.6	.54	.7
Output (10^4 e–/pix-read)	5.5	9.7	8.7	11
Output (10^{-9}amp/pixel)	.088	.16	.14	.18
Filter bandwidth (μm)	.82	.93	1.03	1.07
Peak transmission	.83	.81	.81	.71
Planck power (10^{-11} W/pixel)	3.6	4.2	4.3	3.7
Planck photon rate (10^5 photons/pixel-read)	1.6	2.2	2.7	2.4
Response (amp/watt)	2.4	3.8	3.2	4.9
Response (e-/photon)	.33	.45	.32	.47
Detector electron gain = 1.4				
Calculated QE	.23	.32	.23	.34
Reference detector calibration				
Output (10^{-9}amp/mm)	3.2	6.2	7.6	7.8
Output (10^{-11}amp/pixel)	3.2	6.2	7.6	7.8
Ratio of array to reference detector	2.8	2.6	1.8	2.3

These calculations do not take into account the detailed shape of the filter transmission curve and the detector response. Also, the emission of the dewar window, and the known undersize of the f/45 pupil add some uncertainty to the calculations.

1.7.2 Background Measurements Using Calibrated Detector

The background level in the dewar was checked independently by using a calibrated detector loaned to us by Hughes. At the time of this test, the gold plated surfaces inside the optics housing, the filter wheels, and detector section of the helium-shielded area had not yet been painted black, and not all baffles were in place. The measured background with both filter wheels and the pupil blanked off was $1.5 \cdot 10^{9}$ photons cm^{-2} sec^{-1}. This is compared to $1.2 \cdot 10^{15}$ photons cm^{-2} sec^{-1} for a 77K source, or $1.4 \cdot 10^{18}$ photons cm^{-2} sec^{-1} for a 295K source (π ster). These photon fluxes are for the full bandwidth of the Si:As detector which peaks at 22 µm and has a cutoff at 25 µm.

Other measurements were made with various attenuator and filter combinations. It was found that the ND attenuators did not reduce the flux by the expected amounts, and it was consistent with approximately 2% of the flux that passes through the first filter wheel bypassing the second wheel. This was attributed to radiation reflected from the gold coated surfaces and reaching the detector. All surfaces have since been painted black, so the background is likely to be lower than reported here, with less radiation bypassing the filters.

1.7.3 Optimization of MIRAC Detector

An optimization of the detector was performed by first choosing a method to measure signal to noise, and then varying each of the parameters independently from their canonical values and measuring the effect on signal to noise (S/N). The parameters could of course be interrelated in some complex way and would require changing several parameters simultaneously. However, one would hope that testing each one individually would identify the critical parameters on which to concentrate.

The test setup is illustrated in Figure 1.29. The blackbody source was positioned behind a plate with a hole. A chopper which is controlled by the observing program is placed in front of the hole. The signal measured was the difference between the blackbody and the room temperature chopper blade. Chopping was done at .585 Hz. The camera was operated at 7.5 MHz clock frequency, Half Array mode, 6400 coadds per chop phase, and a detector temperature of 11.52K. The signal was measured at .5 Hz, and the noise measurements were done at 12.2 Hz, 7600 coadds per chop phase. The data were obtained in the following way: at a particular parameter setting, three chop sets were done. In each of these chop sets, the off-source (chopper blade) frame was subtracted from the on-source (blackbody) frame and the result was multiplied by a gain matrix. The average of the resultant maps gave the "signal" used in the S/N calculations. The noise was measured by turning off the mechanical chopper, increasing the chop frequency to 12.2 Hz, and taking six images staring at the blackbody. The RMS of all pixels in the flat-fielded chop difference was calculated for each of the six measurements, and the average was taken to be the "noise" in the S/N calculations. The detector was tested at 8.8 µm, with the 20% neutral density attenuator, a blackbody temperature of 310K, chopper temperature of 295K, and a frame rate of 9765 frames/sec. This background closely approximated the expected background at the telescope, and the chopping frequency was chosen to be close to the 9-12 Hz rates used on the telescope.

Table 1.8 lists the results of the optimization test. For each of the bias voltages, the S/N was measured for the "nominal" case, equal to the bias values recommended by Hughes. The S/N was also measured at the two other voltages given on that line, which are a small amount above (+) and below (-) the nominal value. The voltages are all given in the three columns marked "Settings", for the "-", "nominal", and "+" case. The second set of three columns give the S/N for each of the settings. The middle column S/N ratios were all measured at the same nominal settings, so it gives an indication of the scatter in the S/N values. The average nominal S/N is 3990, with a standard deviation of 85 (2%), so S/N ratio differences of a few percent are not significant. In the "-" and "+" columns, the S/N measured is given, along with the percentage change from the nominal S/N in that row.

Table 1.8 MIRAC Optimization Data

Parameter	SETTINGS -	SETTINGS Nominal	SETTINGS +	S/N at -	S/N at Nominal	S/N at +
V_{SUB}	8.89	9.0	9.29	4147 (+.39%)	3992	4021 (-1.7%)
I_{SS1}	4.85	5.05	5.25	3953 (-1.7%)	4021	4094 (+1.8%)
V_{SS0}	2.832	3.032	3.232	4176 (+6.6%)	3918	4176 (+6.4%)
V_{DD2}	0.319	0.518	.717	3804 (-4.0%)	3962	4045 (+2.1%)
V_{SS3}	-.102	0	.100	4064 (+2.2%)	3975	4030 (+1.4%)
V_{SSD}	-1.229	-1.029	-.829	5111 (+28.6%)	3973	4142 (+4.3%)
V_{CAS}	-2.216	-2.016	-1.816	3942 (-0.7%)	3971	3835 (-3.4%)
V_{DD2}	-2.217	-2.017	-1.817	3926 (+0.4%)	3911	4008 (+2.4%)
V_{DD1}	-3.222	-3.022	-2.822	4000 (+3.9%)	3851	4008 (+4.1%)
V_{DET}	-2.820	-2.620	-2.420	4077 (+2.7%)	3969	4055 (+2.2%)
V_{RST}	-4.22	-4.02	-3.82	4042 (-1.8%)	4115	4034 (-2.0%)
V_{EN}	-4.19	-3.99	-3.79	4070 (-3.0%)	4199	4052 (-3.5%)
V_{ADJ}	-7.02	-6.02	-5.02	3917 (-2.6%)	4023	4188 (+4.1%)

Other parameters:

Bandwidth (relative to 1400 KHz)

(KHz)	175	350	700	1400
S/N	3899	4072	4082	3812
% change	+2.3	+6.8	+7.1	...

Temperature (relative to 11.52K)

°K	10.23	10.54	11.52	12.51
S/N	4097	4008	3938	3755
% change	+3.9%	+1.8%	...	-4.6%

The tests confirmed that the system parameter settings used were close to optimum, and in most cases there were no indications that changes were necessary. One exception seems to be V_{SSD} where an increase of 28% is shown, but it was discovered that the readout was saturating at the high background position, so that the noise was not being sampled properly. There is evidence for a trend towards higher S/N at lower temperatures, so a new operating temperature of 10.0K was chosen. This temperature was chosen since it was a canonical value used by Hughes. The behavior of the array was well understood at this temperature and it would be easier to compare our tests with previous results.

Additional tests were performed on V_{ADJ} and V_{DET}, illustrated in Figure 1.30. The S/N measured for the V_{DET} values shown in Figure 1.30a seemed to be fairly flat across a range from −2.8 V to -2.2 V, and then dropped sharply down outside this range. The slight peak at -2.2 V is inside the scatter seen at -2.6 V where several measurements were taken, so is not considered a significant S/N peak. We concluded that V_{DET} could be left at -2.6 V. Similarly, the response of S/N to V_{ADJ} shown in Figure 1.30b seems to be flat across the range tested, all points within the scatter at -6.0 V. Two other factors affect our choice of V_{ADJ}. Making V_{ADJ} more negative dissipates more power in the detector, increasing the self-heating. Making V_{ADJ} more positive lowers the voltage across the output MOSFET source follower and reduces the bandwidth of the readout. It was decided to reduce V_{ADJ} to -5.0 V, to reduce the detector self-heating. This also allows the temperature controller to regulate the temperature more effectively. Reducing this any further would begin to limit severely the bandwidth and reduce our ability to run at high frame rates.

1.7.4 Performance Results: Noise, Sensitivity

During the evaluation and testing of the electronics with the final version of the controller board and the new multilayer printed circuit signal processor boards, much effort was put into reducing the extraneous noise sources in an attempt to keep the noise without the array to less than one least significant bit (LSB) of the A / D converter. The main sources of noise were determined to be "pickup" in the analog section of the signal processor of the digital signals present on the same board.

The noise in the analog section was occurring even though the analog circuit had been segregated into the front corners of the board with a separated ground plane. The magnitude of the pickup was extremely sensitive to the distance the analog component was from the nearest digital line. Several digital data printed circuit traces were incorrectly located under the analog section of the board. When these were re-routed with wires above the board and the original traces connected to analog ground, the noise was greatly reduced. In addition, there was one particular node (connected to the summing input of the second amplifier stage on the SP board) which exhibited extra noise that could not be reduced. This node had to be bypassed, mounting the components above the circuit board. After these modifications, our noise goals were met, with a typical single sample noise of .35 LSB rms (.11 mV rms at the preamp input) with a 1 MHz signal bandwidth.

Additional testing was conducted to demonstrate the background-limited noise performance of the array. Measurements were made in the lab of the noise as a function of flux, using different filters and neutral density attenuators to achieve a variety of flux levels. The noise was determined for each pixel and then averaged over all pixels in the column. The noise was defined as the standard deviation of the value of a pixel in 100 consecutive coimages, each coimage formed from an average of 1500 consecutive frames. The standard deviation was then multiplied by the square root of 1500 to obtain the standard deviation expected from a single frame. The array was operated at a 0.1 msec frame rate and 3.2 µsec pixel sample interval. Images were combined in a "pseudo-chop" mode at 32 Hz, where consecutive 16 msec long coimages were alternately added and subtracted. This was to suppress any drift in the background or electronics during the integration.

The results of these measurements are shown in Figure 1.31. The measurements are of two quantities, the background voltage and the noise voltage. The transimpedance of the array (g) is known from the measurements presented above. Noise results in the signal from the random nature of the conversion of photons to electrons and the motion of charge carriers through the detector. Assuming Poisson statistics, the number of noise electrons n_e is a function of the number of signal electrons N_e:

$$n_e^2 = N_e \tag{1}$$

The photons are converted to electrons at a ratio given by the quantum efficiency of the detector. The detector has an electron gain, represented by G, which gives the rate at which photoelectrons are multiplied within the detector. The current due to these electrons is amplified by the CTIA of the readout and is measured as a voltage at the output, V. The following equation gives the relation between the detector properties and the output voltage:

$$V = N_e G g \tag{2}$$

The noise electrons n_e are amplified by the same processes that the signal electrons are, so the output noise voltage v is given by

$$v = n_e G g \tag{3}$$

Using the above relations, a relation for the noise voltage as a function of the measured parameters can be written:

$$v^2 = VgG \tag{4}$$

This relation is strictly true only for each individual pixel. The difficulty in measuring these quantities is that g and G cannot be measured for each individual pixel. In the detector array, each pixel will have a slightly different value, and the measurement will yield the average of these over the array, $\bar{g}$ and $\bar{G}$. When the average values are used, the right side of equation 4 contains a "dispersion" term of the form $\left(\overline{g^2}\ \overline{G^2}/(\bar{g}\ \bar{G})^2 \right)$. If the variances of these quantities are small, the dispersion term will have a value near 1. The array is relatively uniform and so it is assumed here that this dispersion term is unity.

In addition to this electron noise term, there is a read noise term n_R that is independent of the signal level. Therefore, the total measured output noise n_T is given by

$$n_T = \sqrt{n_R^2 + VgG} \quad \textbf{(5)}$$

The dashed curve in Figure 1.31 is a best fit of equation 5 for the data, excluding the two highest background points where saturation is occurring. This fit was done assuming a transimpedance g = .0063 mv/electron. The fit gives a fixed readout noise n_R = .65 mV, and detector electron gain G = 1.41. These data were taken at a detector temperature of 10.52K, V_{DET} = -2.6 V, V_{ADJ} = -5 V, in delta reset mode. The readout noise n_R measured at the preamp input corresponds to a read noise of 188 µV at the detector for double sample, or 133 µV per sample. This implies a broad band noise of 133 nV $Hz^{-1/2}$ at the detector.

1.7.5 Standard Star Observations, Calibration

Several stars of known magnitude were observed with MIRAC to determine flux calibration and sensitivity through the available filters at the telescope. The total counts in the image due to the source were added, and the background noise was estimated by calculating the RMS of a nod set taken off the source. The star β And was observed on December 8, 1990 at the SO 1.5 m telescope at 8.8, 9.8, 11.7, and 12.5 microns. Table 1.9 gives the results of these measurements. The on-source integration time was different for each wavelength, ranging from 15 to 60 seconds, so the sensitivity values presented in Table 1.9 have been scaled to 1 second and 900 seconds on-source by multiplying by the square root of the ratio of 1 and 900 seconds to the actual on-source observing time.

Table 1.9 MIRAC Sensitivity Calibration
Steward Observatory 1.5 m Telescope[1]

Air Mass = 1

Wavelength (μm)	Background (Jy/arcsec^2)	NEFD (Jy/arcsec^2) (1 sec on-source, 4 sec total)	NEFD (Jy/arcsec^2) (900 sec on-source, 1 hour total)
8.8	2600	.28	.009
9.8	7338	.49	.016
11.7	4657	.31	.010
12.5	4665	.31	.010

[1]Measurements made 12/6/90, -4°C outside temp., humidity 24%.

The second column labeled "Background" is the flux from the "blank sky". The flux at 9.8 µm is high because of high atmospheric emissivity at that wavelength.

During the design of MIRAC we calculated a sensitivity based on measurements or estimates of the detector quantum efficiency, camera optics transmission, filter transmission and bandwidth, telescope transmission and emissivity, and sky emissivity. For the 1.5 m telescope, 900 seconds on source, 1 hour total time chopping and nodding, this calculation gave a noise equivalent flux density (NEFD) of .012 Jy / arcsec^2 at 8.5 µm and .013 Jy / arcsec^2 at 12.5 µm. These predictions agree with the observed sensitivity of .010 Jy / arcsec^2 at 12.5 µm, within the uncertainty of the calculations.

Similar observations were performed at the Steward Observatory 2.3 m telescope, using α Boo as the calibration source. Table 1.10 lists the results of these observations. There were high cirrus clouds during these observations, in addition to the relatively high humidity measured at the telescope, so these achieved sensitivities are likely to be poorer than what can be achieved under better conditions.

Table 1.10 MIRAC Sensitivity Calibration
Steward Observatory 2.3 m Telescope[1]

Air Mass = 1

		NEFD (Jy/arcsec^2)	
Wavelength (μm)	Background (Jy/arcsec^2)	(1 sec on-source, 4 sec total)	(900 sec on-source, 1 hour total)
8.8	2166	.21	.007
11.7	3417	.21	.007
12.5	5580	.38	.013

[1]Measurements made 6/2/91, 11°C outside temp., humidity 40%.

These sensitivity values can be compared with those attained with other instruments. Several other instruments exist which can obtain images in the 8-13 μm range. Since sensitivity values, if they are reported, are often in different units and different wavelengths, bandpasses, integration times, and telescopes, it is hard to make an absolute comparison. Other parameters, such as conditions of the site and the weather will have an influence on the results. Despite these difficulties, it is meaningful to make a comparison, since the measured sensitivities reveal the total effectiveness of the instrument, including all the transmission losses, emissivities, sources of extra noise, and other non-optimal behavior of the system. In this way it is more realistic than a theoretical calculation of the performance of an instrument, and demonstrates what can actually be achieved.

The instruments described were chosen to be representative of past or current array cameras that were designed for broad spectral band, high spatial resolution mid-IR imaging. The instruments were used on different telescopes under a variety of atmospheric conditions. Therefore, the sensitivity is compared here in terms of surface area brightness in Jy/arcsec^2, rather than source flux density in Jy. The surface area brightness value is more directly related to the camera performance, while the source flux density is dependent on image quality, which can be adversely affected by the telescope image quality, telescope tracking, and atmospheric seeing.

Table 1.11 gives the sensitivities of a number of instruments, from values reported in the literature. The reference given for each instrument is where the observational result was reported. First, the reported sensitivity value is given, along with the details of the observation, including on-source and total time, pixel scale, wavelength, bandpass, and telescope. In the second half of this table, an attempt is made to "normalize" the values to compare the instruments. The assumption made for the normalization is that the instrument is background noise limited, that is the noise is dominated by statistical fluctuations in the photon conversion to electrons. If an instrument is system noise limited, then this normalization would not be correct.

Four normalizations are performed successively, as appropriate. First, the value is divided by the reported number of sigma and multiplied by the square root of the integration time in seconds to normalize the result to 1 second. The value is also multiplied by the square root of two times the ratio of the on-source time to the total time in order to normalize to a total time equal to twice the on-source time. Then the value is divided by the pixel scale to normalize to 1 square arcsec. The value is then multiplied by the square root of the ratio of the surface areas of the telescope used to the IRTF, to normalize the result to the IRTF. No attempt is made to allow for differences in the telescope and site IR properties. Finally, the result is multiplied by the square root of the bandpass in μm, to normalize the result to a 1 μm bandpass. If the value is already in the proper time, scale, or telescope units, no normalization is applied at that step.

Table 1.11 Comparison of Instrument Sensitivities

Instrument (pixels)‡	Reported Sensitivity	On-Source Int. Time	Total Time	"/pix	λ(μm)	$\Delta\lambda$(μm)	Telescope
1. MIRAC (20x64)	.31 Jy/$('')^2$	1 s	4 s	1.0	11.7	1.1	SO 1.5 m
2. GSFC AMCID Camera (16x16)	.15 Jy/pix	60 s	240 s	.79	11.2	.9	IRTF
3. Berkeley Mid-IR Camera (10x64)	.8 Jy/$('')^2$	32 s	64 s	.39	12	1.2	SO 2.3 m
4. NASA-MSFC Bolometer Array (5x4)	3.1 mJy/pix**	2.95 hr	5.9 hr	4.2x4.3	10.8	5.3	IRTF
5. GSFC 5-17 μm Camera† (58x62)	10 mJy/pix	60 s	120 s	.26	10.0	1	IRTF
6. Berkeley Mid-IR Camera* (10x8)	15 mJy min$^{-1/2}('')^{-1/2}$	23 min	46 min	.39	10.6	5	IRTF
7. NRL IR Camera (10x50)	.5 Jy/pix	5 min	10 min	1.65	10	1	WIRO††
8. UCSD Golden-Gopher (20x64)	5 mJy hr$^{-1/2}('')^{-1/2}$	30 min	60 min	.93	8.5	1	Mt.Lemmon 1.5 m

Table 1.11 (cont.)
Comparison of Instrument Sensitivities

Instrument	Sensitivity Normalization			Final (Jy / ('')^2)
	Int. Time to 1 sec‡‡	Scale to 1 ('')^2	Telescope to 3 m	Bandpass to 1 μm
1. MIRAC	.22 Jy / ('')^2	.22 Jy / ('')^2	.11 Jy / ('')^2	.11
2. GSFC AMCID Camera	.82 Jy / pix	1.04 Jy / ('')^2	1.04 Jy / ('')^2	.99
3. Berkeley Mid-IR Camera	4.5 Jy / ('')^2	4.5 Jy / ('')^2	3.5 Jy / ('')^2	3.8
4. NASA-MSFC Bol. Array	.32 Jy / pix	.075 Jy / ('')^2	.075 Jy / ('')^2	.17
5. GSFC 5-17 μm Camera	.077 Jy / pix	.30 Jy / ('')^2	.30 Jy / ('')^2	.30
6. Berkeley Mid-IR Camera	.12 Jy / ('')^2	.12 Jy / ('')^2	.12 Jy / ('')^2	.27
7. NRL IR Camera	8.7 Jy / pix	5.3 Jy / ('')^2	4.0 Jy / ('')^2	4.0
8. UCSD Golden-Gopher	.3 Jy / ('')^2	.3 Jy / ('')^2	.15 Jy / ('')^2	.15

Notes to Table 1.11:

The sensitivities reported are the value given in the reference for the Noise Equivalent Flux Density (NEFD), or the RMS noise in the image background. This comparison does not consider point source sensitivity, which may give quite different results because of image resolution and smearing due to atmospheric seeing and instrumental effects.

There are two entries for the Berkeley camera for different observations reported, one a 1 µm bandpass observation on the SO 2.3 m telescope, and the other a 5 µm bandpass observation on the IRTF.

† Camera described in Gezari *et al.* 1988.
‡ Pixels given are portion of the array being read out.
* Camera described in Keto *et al.* 1991b.
** Sensitivity achieved for reported observations, although 1-2 mJy for 6 hrs integration time claimed typical.
‡‡ Normalized to 1 sigma, 1 second on source, 2 seconds total time.
†† Wyoming Infrared Observatory 2.3 m telescope

References for Table 1.11:
2. Hoffmann *et al.* 1987
3. Bally *et al.* 1987
4. Telesco *et al.* 1990
5. Gezari *et. al* 1991
6. Keto *et al.* 1991a
7. Odenwald, Shivanandan, and Thronson 1991
8. Puetter, Jones, and Pina 1990

It can be seen from the above comparison that the MIRAC is a vast improvement over the performance of the GSFC AMCID array camera, and is competitive with other systems currently in operation.

1.7.6 Sky Noise and Chop Frequency

A test was also carried out on the 1.5 m telescope at 12.5 µm to determine the chopper frequency required to keep 1/f sky noise below the background photon shot noise. The total noise for an observation will be the sum in quadrature of these two noise sources. If the constant A represents the photon shot noise and B/f the "1/f" component of sky noise, the total noise observed n(f) at a given sky background will be given by

$$n(f)=\sqrt{A^2+\left(\frac{B}{f}\right)^2}$$

where A and B are constants, and f is the chop frequency. In our observational test, the noise was determined from a time sequence of 50 1-second chopped images, and was taken to be the average of the standard deviations of each pixel over the 50 images. The results of these observations are shown in Figure 1.32. The dashed line through the data is a fit to the data of the above function n(f) in units of mV. The best fit parameter values for A and B are 2.1 mV and 3.3 mV, respectively. Converted to Janskys and scaled to the chop-nod mode, 1 sec on source (4 seconds total), these parameters are .34 and .52 Jy/arcsec^2. From these data it was concluded that a frequency of 10 Hz was sufficient to avoid sky 1/f noise, at least for the filters at wavelengths where the atmosphere is relatively transparent. It is preferable to run the chopper at the slowest speed necessary to avoid sky 1/f noise, in order to maintain good image quality in the chopped beam, and to decrease the amount of "dead time" as a result of waiting for the chopper to settle. These parameters will be very dependent on local sky conditions, but it appears there will always be times when background limited performance can be achieved at high chopper speed

(~10 Hz) and not at lower rates.

1.7.7 Optics Alignment and Evaluation

The optics were first aligned at IR labs when they were installed in the dewar, before the array was installed. The elements were placed in their holders and moved to the design spacing. It was confirmed that a pinhole light source at the focus in front of the dewar was imaged on the center of the array holder in the dewar. The focus and scale were evaluated by placing an illuminated reticle at the position of the array in the dewar, and measuring the size and quality of the image at the focus outside the dewar using a comparator with reticle.

To position the optics correctly, first the ellipsoid was adjusted to focus the pupil at the distance of the secondary. To do this, the position of the array in the dewar was illuminated, and the image of the back-illuminated pupil was viewed with an eyepiece in the darkened room. The ellipsoid was positioned so that the pupil was in good focus at the distance of the IRTF secondary, 884 cm. The focus was also evaluated using a "chop" technique. The central 1/3 of the mask on the optics housing was covered, leaving 1/3 of the area uncovered on either side. Then the pupil image was again viewed at the desired focus position, while a card was used to alternately block one side or the other of the baffle. At the correct focus position, the pupil image should not move as it is chopped. If not at the correct position, the pupil will move side to side as the mask is chopped. When the ellipsoid was set properly, the image was steady as the mask was chopped when viewed from the distance of the IRTF secondary.

The direction of the beam was then adjusted so it is normal to the dewar window. A white card with a crosshair was placed at the position of the array, and the card was illuminated from the side. A crosshair was also placed on the baffle on the outside of the optics housing. A mirror was attached to the front face of the optics housing. A telescope was used at a distance of approximately 10 feet, looking at the dewar and into the optics. The telescope was positioned so that its reflection was visible in the mirror, on center with the outer baffle. Then the ellipsoid was tilted slightly so that the two sets of crosshairs were aligned as viewed through the telescope.

The image quality was documented by photographically recording the image sharpness. An eyepiece reticle with a .1 mm spaced ruling was placed at the low magnification array position, and illuminated from behind. A mask of 4x8 mm was placed over the reticle to show the approximate size of the array. Then a camera (with the lens removed) was placed at the focus, determined from the sharpest image in the camera. A photograph from this test is shown in Figure 1.33. Several photos were taken at small displacements from this position, but this was the position with the best focus over the field.

The optics quality was also evaluated by observations with the detector on March 12-15, 1991. The tests were done using a "pinhole" source positioned at the optics focus outside the dewar. A 150 µm diameter pinhole was used for all measurements except with the 20 µm filter, where a 300 µm pinhole was used. The pinhole was mounted on a XYZ micrometer stage, which allowed for accurate positioning and measurement. The pinhole was illuminated from behind by a 40W high intensity bulb painted black. A chopper was placed between the source and the pinhole. Images were taken with the MIRAC program and normalized with a gain matrix.

Some results of these measurements are shown in Figure 1.34 which shows the observed pinhole profiles at three different wavelengths. The pinhole was adjusted to attempt to center it on the pixel in row 14, column 1. The profiles have been normalized so that the peak value is 1. The image size increases with wavelength due to diffraction. In the 2.2 µm profile, almost all of the energy is contained in the peak pixel, with some spillover into the neighboring pixels. These profiles show the optics are close to the calculated performance, showing no signs of unexpected scattering or image spread.

The measured optics distortion is shown in Figure 1.35. This was obtained by moving the pinhole source to center it on different pixel positions and then measuring the displacements on the positioning micrometers. The scale was measured by assuming no distortion between pixels 31 and 24 (where the distortion effects will be the smallest) and positioning pixels 2, 9, and 16 based on this scale. All of these pixels are in column 11 of the array. In this figure, the dotted lines are the pixel edges, so the data square is in the center of the square on the plot if it is not distorted. Pixels 24 and 31 are perfectly centered in the plot because of the assumption of no distortion between these pixels. The largest distortion is for pixel 2, which is shifted to the left and downward of a perfectly linear displacement, as expected. To the accuracy of this measurement, the optics distortion is consistent with the calculated distortion from the optics design.

The optics distortion is removed in the data processing by calculating a new image from the original data using the measured distortion. Typically, the new image has 16 "subpixels" for each instrumental pixel. Each subpixel is assigned a value taking into account the distortion to produce an undistorted image. These images can then be simply shifted and added together to produce the final image.

The efficiency of the MIRAC optics will be high, since the optics consists of gold-coated reflective elements. In the calculations of MIRAC performance, the reflectivity of each element has been assumed to be 98%. The performance observed was almost identical to the calculations (described above), so this assumption for the reflectivity is consistent with the performance achieved with MIRAC.

1.8 Future Directions

The MIRAC system has been designed to be easily adaptable to keep pace with advances in detector technology and instrumentation. Three possible areas of future improvements and additions are in improved detectors, addition of a Fabry-Perot interferometer for high spectral resolution imaging, and fast shift and coadding of images to achieve diffraction-limited performance.

1.8.1 Future Detectors

The MIRAC dewar and electronics were designed for the Hughes detector and readout currently being used. This unit is no longer being produced, and there are no available spares, so in order to replace the current detector the current system must be modified. There are several reasons why it would be advantageous to replace the current detector. First, since the address line failure occurred as described above, only a 20x32 pixel segment of the array can be read out. Changing to a different detector would enable us to use the full 20x64 format. Secondly, the current array is not anti-reflection coated, which results in a degradation of quantum efficiency. Finally, advances are continually being made in detector quality, including increased quantum efficiency, lower read noise, increased well size, and more pixels. An improved detector would provide higher sensitivity and allow the MIRAC to be used more efficiently on the telescope.

For future arrays using a similar 20x64 format, the hardware changes in the dewar would be minimal. There are a few spare wires available if the detector required additional bias or address lines. The routing of bias and address lines to the chip carrier would most likely be different. Changes could be implemented by using a new circuit board on the detector stage, or by rewiring the cable connections at the digital controller and bias supplies. Both of these are wire-wrapped, so changes are easy to implement. The PAL timing generators and EEPROM address converter can be replaced with reprogrammed chips for the new device.

Larger format arrays would require changing the baffle shape from the current rectangular form to one matching the new detector shape. Also, significant changes in the controller and signal processors might be necessary for different numbers of detector outputs.

1.8.2 High Spectral Resolution Imaging

A Fabry-Perot spectrometer (FPS) is currently being prepared for use with the MIRAC. This spectrometer was originally developed by Nishimura, Low, and Shivanandan (1984, 1985). The FPS is capable of achieving resolutions ($\lambda/\Delta\lambda$) of ~1000-10000, and is well suited for use with MIRAC because of its low background levels when cooled to LHe temperatures.

The FPS uses superconducting actuators that control the alignment and tuning of the actuators at LHe temperatures, dissipating little power within the instrument. The mechanism consists of two main assemblies, the xy-unit and z-unit. The xy-unit controls the relative tilt between the etalons, and the z-unit controls the tuning by displacing the second etalon along the optical axis. Both units are driven by superconducting Nb:Ti wire coils in magnetic fields produced by rare-earth cobalt magnets. This mechanism is housed in its own helium temperature dewar, which can be connected to the MIRAC dewar at the window port.

The FPS has previously been used with the 10 µm AMCID camera on the SO 2.3 m telescope. The FPS and camera dewar were mated, sharing a common vacuum, and the common instrument was used to observe several standard stars. Later tests done in the lab showed that the FPS could be tuned successfully for a single wavelength over the entire array when scanning over a small wavelength range. The system is now being prepared for use with the MIRAC. The coil current source and control electronics have been rebuilt, and a second spectrometer is being prepared for inclusion in the spectrometer dewar. The MIRAC LHe and LN_2 radiation shields have been equipped with threaded apertures to enable baffle tubes to be attached that will mate with the Fabry dewar.

1.8.3 Fast Shift and Coadd

Another possible direction is to improve the camera efficiency and sensitivity by using a different method of observing. One problem with the current observing technique is that during an integration lasting several seconds to minutes, there are drifts in the telescope position as well as the seeing motion which combine to spread the image out on the array into several pixels. This decreases the maximum resolution that can be achieved on the telescope, and also effectively degrades the sensitivity of the camera, since the source flux is spread out over more pixels and is more difficult to detect for a given NEFD. A possible solution to this problem is to determine the offsets introduced by these effects, so that the data can be corrected and the performance improved.

One possible method for determining the offsets is to measure the position of the source on the array and then to determine the offset needed to align it with some reference image of the same object. This is essentially what is done now with IR-bright sources ($S/N>10$) that are visible in a single MIRAC observation. The separate observations are aligned using the centroid, or by a cross-correlation algorithm, and the observations are shifted before coadding to form the final image. This usually yields more accurate offsets than those derived from the record of the offsets sent to the telescope. The problem with the current method is that it still does not remove the effects of telescope drift on short timescales, and does not treat the seeing broadening of the image.

Also, the source must be detectable in a single observation.

One possible method of improving this for the brightest IR sources would be to perform this centroid and shift operation as the frames are stored in the array processor board. Each coimage transferred from the camera would have the offsets corrected in real time as the integration is taking place. This could be performed at the chopping rate of 10 Hz, and would remove the effects of telescope drift and seeing. The major drawback of this method is that it would work for only the brightest sources, clearly detectable in a single coimage of 1/20 sec.

An alternative to using the IR image as the reference image is to use the optical image of a source in the TV guider. The source could be the same as the IR source, or another nearby star could be used, if the field of view is wide enough and the TV camera sensitive enough. The centroid would be calculated for the optical source, and assuming that the IR and optical centroids are the same, the offsets would be used to align the IR images. This could be utilized with the present method of observing, for those IR sources that are not detectable in a single observation. A more powerful method would be to use the optical image of a guide star to determine offsets for the individual coimages as they are being coadded in the array processor. This has the potential of achieving diffraction-limited images for any IR source as long as a star can be found in the field to provide the offsets.