1 TECHNICAL DESCRIPTION

1.1 INSTRUMENT OVERVIEW

MMIRS is a JHK imager and multislit spectrograph based on a 2048 by 2048 pixel Hawaii-2 detector that will be used at the f/5 Cassegrain foci of the MMT and Magellan-2 telescopes. MMIRS incorporates a two element CaF_2 coma corrector that replaces the large fused silica coma corrector used at optical wavelengths. If a coma corrector is not used, the images are unacceptably soft at the MMIRS slit plane. The fused silica used in the optical coma corrector has an OH content of ~1000 ppm, and would offer low throughput in the K-band.

MMIRS will be constructed in two sections. The first section will contain the coma corrector lenses, the slit mask and aperture selection wheels, the guider assembly, and a gate valve which can be closed to separate the first section from the second. The lead coma corrector lens will serve as the dewar window. The slit mask and aperture selection wheels will be cooled to LN_2 temperature by an independent dewar, but the rest of the first section will be operated at ambient temperature. To exchange slit masks, the gate valve between the two sections will be closed and the slit mask and aperture selection wheels will be warmed up. The exchange cycle can be accomplished during the daytime to prepare for nighttime observing. The second section of MMIRS contains the collimator optics, the grism and filter wheels, the camera optics, and the Hawaii-2 array. These will all be operated at LN_2 temperature to minimize the thermal background.

The Hawaii-2 detector will be operated with a modified version of the array controller we have developed for Megacam's 36 CCD arrays. This choice will help us control design, software development and maintenance costs.

1.2 SCIENTIFIC GOALS AND MMIRS DESIGN

Perhaps the strongest scientific imperative for MMIRS is timeliness: there is currently no wide-field near-infrared (NIR) imager or spectrograph available (excepting FLAMINGOS 1's occasional visits to the MMT) at the MMT or Magellan. This lack of NIR capability results in a serious lack of scientific opportunity at two large observatories. This situation drives a good deal of our thinking about the MMIRS design: in order to complete MMIRS as quickly as possible we wish to minimize risk and unnecessary development wherever possible.

The broader requirements, that we amplify below, are minimizing scattered light and thermal background to allow sensitive spectroscopy, achieving as high throughput as possible, and offering the option of high spectral resolution to resolve out sky lines. There is a range of opinion in the IR community as to the minimum resolution required to work between the sky lines, but almost all agree that R~3000 is sufficient. There is a fortunate convergence here that R~3000 is the maximum resolution possible while still covering an entire J, H or K-band with a multislit spectrograph and a 2048 pixel array. A 2048 pixel array offers 1024 two-pixel resolution elements; at R=3000 at 2.2 μm, each resolution element corresponds to ~7 Å. The total spectral coverage is therefore ~0.7 μm, allowing slits to be displaced 1′ in the spectral direction and still cover the full 0.5 μm wide K-band. Yet another fortunate convergence is that R~3000 is near the maximum resolution that can be attained with high efficiency from conventional grisms.

The pixel sampling that we have chosen, 0.2″ per pixel, is a tradeoff between field of view and sampling. At both the MMT and Magellan, 0.4″ FWHM images have been routinely obtained in

the H and K bands, suggesting that choosing sampling cruder than 0.2″ per pixel would be a mistake. Many of the imaging and spectroscopic observations anticipated with MMIRS could use as large a field of view as possible, suggesting that we operate near critical sampling.

MMIRS offers a large gain in spectroscopic performance as compared with FLAMINGOS 1. With its short focal length camera, FLAMINGOS 1 can achieve a maximum (two pixel) resolution of R~1500 with efficient conventional grisms, compromising its ability to work between the sky lines. MMIRS's large collimated beam also eases the optical design of the camera by reducing the required acceptance angles, resulting in better overall image quality.

Comparison of MMIRS to FLAMINGOS 1 and 2

	MMIRS	FLAMINGOS 1	FLAMINGOS 2
Telescope focal ratio	f/5.3	for f/9 at MMT	f/16 (Gemini)
Collimated beam diameter	100 mm	40 mm	100 mm
Collimator focal length	530 mm	350 mm	1600 mm
Camera focal length	285 mm	135 mm	260 mm
Pixel scale	0.20″	0.17″	0.18″

1.3 ESTIMATED MMIRS SENSITIVITY

We have used the observed count rates with FLAMINGOS 1 at the MMT to estimate the sensitivity of MMIRS for unresolved sources with either the MMT or Magellan telescopes.

S/N per resolution element at R=3000

Exposure Time (hrs)	Magnitude	J	H	K	J_{dark}	H_{dark}
1	15	118	142	109	125	165
2	15	166	201	155	177	233
4	15	236	285	219	251	329
1	17	35	36	22	46	61
2	17	50	51	31	66	86
4	17	71	72	44	93	122
1	19	7	7	4	13	18
2	19	10	9	5	19	25
4	19	15	13	7	27	35

The J, H, and K columns use the background levels averaged across the band. The J_{dark} and H_{dark} columns assume a background 20 times lower than the average level, appropriate for the regions between the OH airglow lines. At R=3000 approximately 40% of the spectrum will meet the low background condition (Martini & Depoy, 2000, SPIE, 4008, 695).

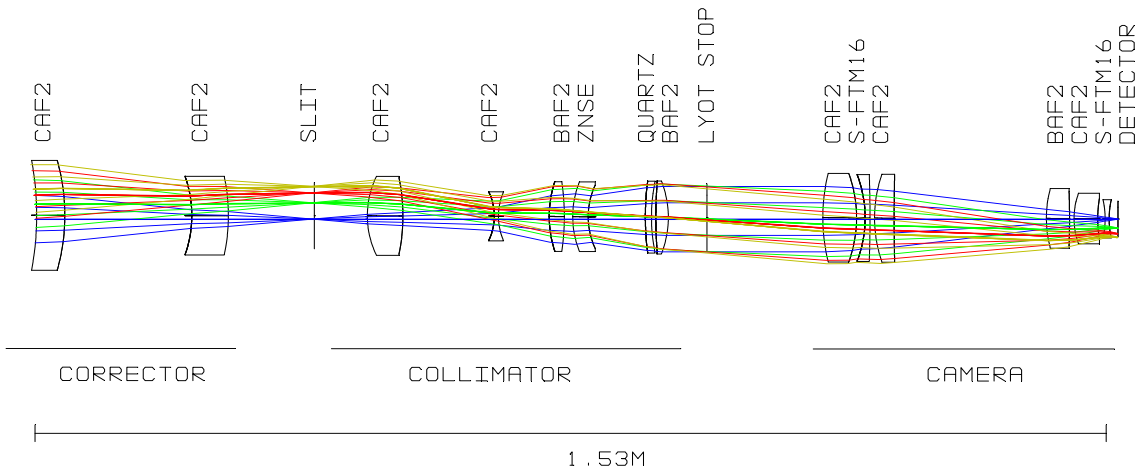


Figure 1. MMIRS Optical Design

1.4 OPTICAL DESIGN

The MMIRS optics consist of 14 all-spherical singlets: a two element coma corrector, a six element collimator and a six element camera (Figure 6). The optics were designed by H. Epps with contributions by D. Fabricant. The design includes seven CaF_2 lenses, two BaF_2 lenses, two S-FTM16 lenses (an IR-transmitting Ohara glass), one ZnSe lens, and one IR-grade fused quartz lens. All of the optical materials are readily available in the necessary diameters and thicknesses and we have verified material availability with suppliers. The largest elements in the MMIRS coma corrector, collimator, and camera have clear apertures of 168 mm, 120 mm, and 153 mm, respectively.

We have made arrangements with James Palmer (Optical Sciences, University of Arizona) to measure the cryogenic refractive indices of S-FTM16. The cryogenic refractive indices of the other materials have been measured, but we will review these measurements, and make additional measurements as necessary.

The impossibility of coupling lenses to form multiplets at cryogenic temperatures is a severe optical design constraint. However, ambitious wide-field optical spectrographs have a comparable optical complexity. For example, the IMACS instrument about to be delivered to the Magellan telescope has 12 lens groups counting the ADC/coma corrector, the collimator and the wide-field camera. For either optical or IR spectrographs effective antireflection coatings are essential for high performance.

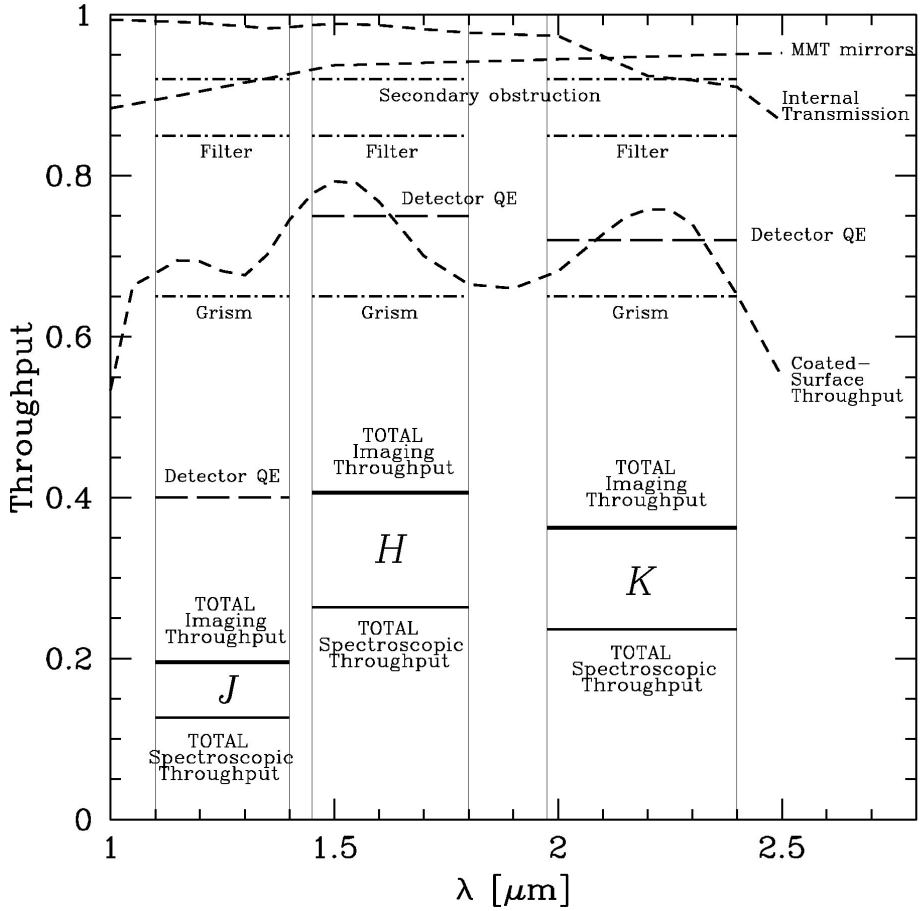


Figure 2. Throughput of MMIRS with the MMT/Magellan telescopes. The short-dashed lines show the reflectivity of the MMT/Magellan mirrors, the f/5 secondary obstruction, the internal transmission of the optics, and the coated-surface throughput of the optics. The horizontal lines show the throughput of the filters, the grisms, and the Hawaii-2 detector in the J, H, and K bands. The solid lines show the total throughput in imaging and spectroscopic modes for light incident on the telescope.

All of the optical materials used in MMIRS transmit well in the J, H, K bands, and as a result, the MMIRS optical throughput is dominated largely by surface reflection losses. The internal transmission of the MMIRS optics, the throughput of the antireflection coated surfaces of all 14 lenses, and the total throughput of MMIRS excluding slit losses is shown in Figure 7.

The coma corrector provides excellent images (0.1″ RMS diameter) on a flat focal surface, allowing high transmission through narrow slits when the seeing is at its best. At the detector, the image quality is also superb with RMS image diameters of ~ one pixel (0.2″) and 90% encircled energy image diameters of ~ two pixels (0.4″) as shown in Figure 8.

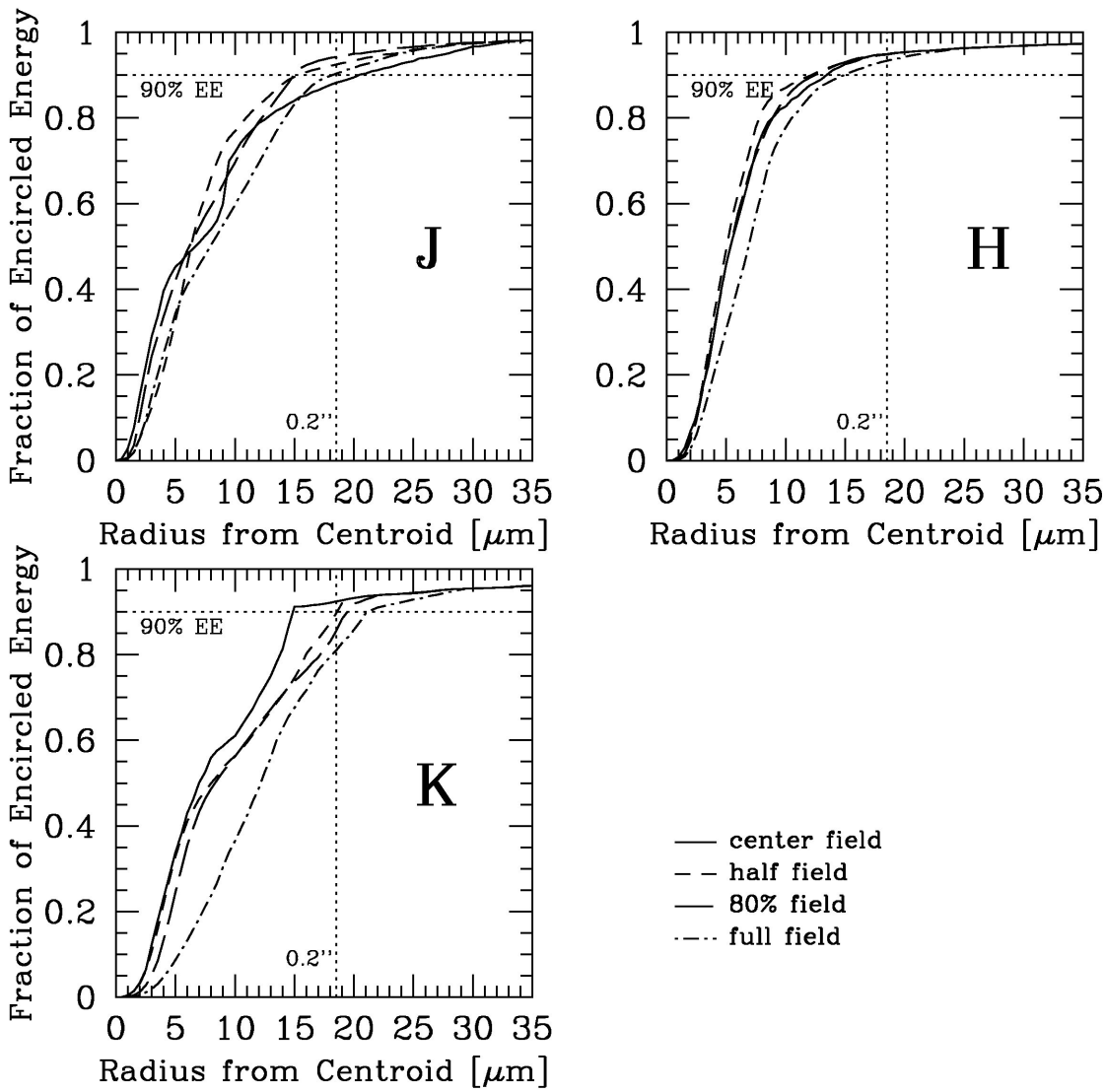


Figure 3. Encircled energy diagrams for J, H, and K band images. All 3 bands are shown at the same focus position. Half the light is contained within one pixel diameter; 90% is contained within a two pixel diameter.

We plan a suite of 5 grisms: 2 low resolution grisms covering the JH and HK bands, and 3 higher resolution grisms covering the individual J, H and K bands each at a resolution of approximately 3000 with a 2 pixel (0.4″) slit. The spectrum covers 1400 of the 2048 pixels which allows a 2′ wide field for multiobject spectroscopy with full wavelength overage. Larger fields can be covered with reduced wavelength coverage. Approximate grism parameters are shown in the table below. Theoretical grating efficiencies are determined using PCGrate software. In the design phase we will refine the grism parameters and will order custom rulings if necessary to achieve the highest practical throughput. Our budget allows for 3 custom rulings.

Grism	Wavelength Range	Grooves/mm	Prism Angle	Facet Angle	Resolution (2 pixel slit)	Theoretical Efficiency across band
J	1.11-1.39	230	41°	32°	3000	64-70%
H	1.45-1.82	175	41°	32°	3000	64-70%
K	1.95-2.45	130	41°	32°	3000	64-70%
JH	0.95-1.82	94	18°	14°	1300	55-80%
HK	1.45-2.45	80	21°	17°	1300	55-80%

1.5 MECHANICAL DESIGN

The MMIRS mechanical design makes heavy use of the successful heritage of the FLAMINGOS design. MMIRS will incorporate proven assemblies, such as the detector mount and wheel mechanisms, from the FLAMINGOS design. Modifications will be made to the dewar design, cryogenic system, and telescope interface to accommodate our telescopes and goals. The mechanical layout of MMIRS is shown in Figure 9.

1.5.1 Dewar Design

The two dewar sections will be constructed from 7075-T6 aluminum. The LN_2 tanks will be welded to the work surfaces; all welds will be rough machined, heat treated to relieve stress, and finally fine machined. The work surface and LN_2 tank assembly in each dewar will be suspended from very stiff G10 rings. Kapton heater pads epoxied on the LN_2 tanks will allow rapid thermal cycling of the dewars.

1.5.1.1 Cryogenics

The bulk of the MMIRS thermal mass, the optics, filters, grisms, and detector, is housed in the collimator/camera dewar. LN_2 cooling will provide excellent temperature stability and will minimize thermal gradients on the optical bench. The collimator/camera dewar will not be thermally cycled often, and so we plan to use a cryo-cooler to cool a radiation shield surrounding the optical bench and to heat-sink the G-10 support ring. This will increase LN_2 hold times to 2 weeks. The second stage of the cryo-cooler will be tied to a large carbon getter and will serve as a cryo-pump to provide long term vacuum stability.

In order to avoid dumping cryogen as FLAMINGOS-2 is rotated at Gemini's folded Cassegrain port, the FLAMINGOS-2 design has evolved to eliminate LN_2 except for precooling; cryo-coolers are used instead. Thermal models for FLAMINGOS-2 suggest that a high level of thermal homogeneity and stability can be achieved with cryo-coolers. In the early design stages of MMIRS, we will consider the merits of this approach, although operations at the MMT and Magellan do not require this change.

1.5.1.2 Wheels

We use a common wheel design for all the MMIRS mechanisms. This is the same wheel design used in FLAMINGOS and TRECS. Wheel positions are defined by mechanical detents, while the home position is defined by a mechanical micro-switch. We expect wheel positions to be

repeatable to within 10 µm. The wheels are driven by Portescap size 23 stepper motors. These motors have been used extensively in cryogenic instruments for a decade with excellent reliability. The wheel drive gear/worm placement is designed for proper engagement at cryogenic temperatures.

The collimator/camera dewar will have two filter wheels and one grism wheel, located in the collimated beam adjacent to the Lyot stop. Each filter wheel will carry 5 filters with one open slot. Filters with thicknesses of up to 10 mm will be accommodated. A minimum complement of filters will include the standard J, H, and K filters, the spectroscopic JH and HK blocking filters, and a dark blocker. The grisms will be carried in a wheel nearly identical to the filter wheels. We use grisms as the primary disperser for MMIRS because of their high efficiency, simple mounting, and the compact instrument design they allow. The Lyot pupil stop will be fixed.

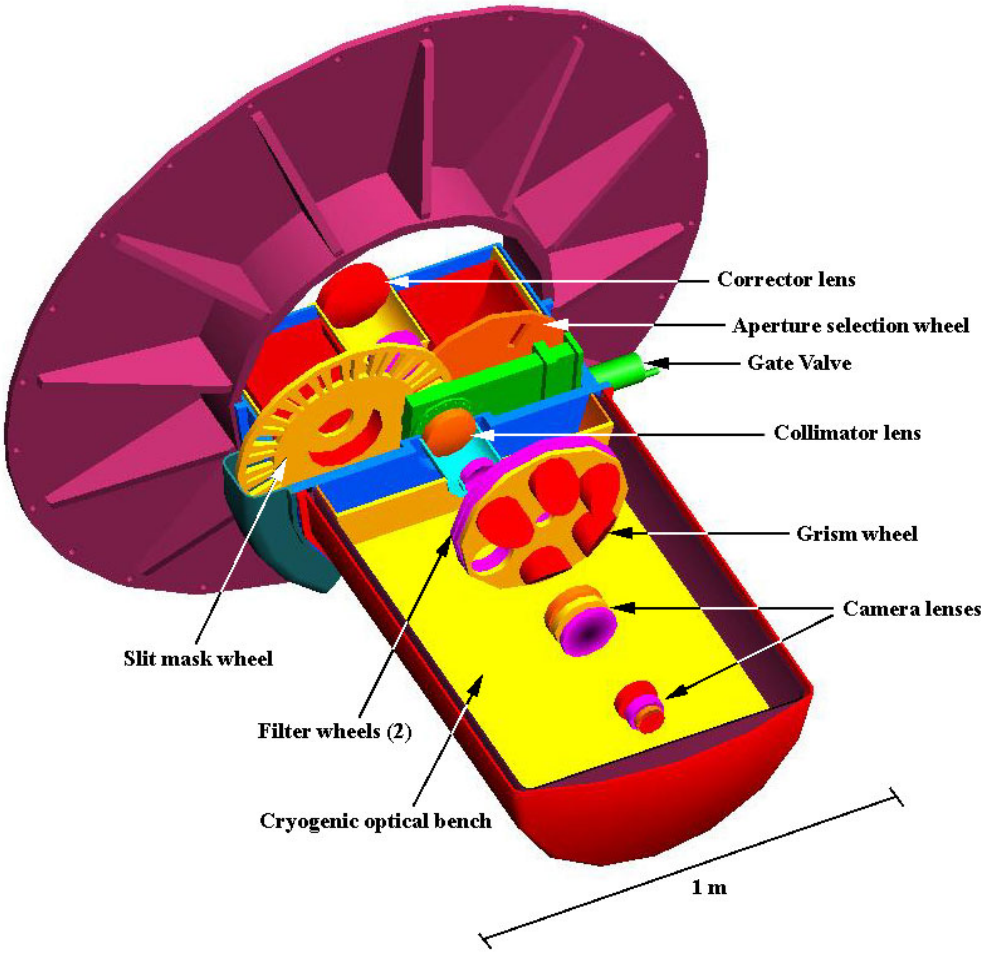
1.5.1.3 Optic Mounts

We intend to depart from the FLAMINGOS designs for the MMIRS optical mounts. The FLAMINGOS optics are mounted into tubes with precision machined brass spacers that are mechanically loaded to provide thermal compensation and mechanical self-centering. However, we are concerned about the mechanical stress imposed on the optics with this mount design.

Furthermore, MMIRS will travel between the MMT and Magellan telescopes, and we wish to guarantee the survival of the optics under rough handling. The SAO instrument team has considerable experience designing precise athermal mounts for large and small optics and the MMIRS team will draw upon this experience to evaluate mounting techniques for the MMIRS optics. Athermal optical mounts are used in the f/5 corrector, Hectospec and Hectochelle bench spectrographs, the f/5 wave front sensor and Binospec. The SAO team has provided advice on optical mounting techniques to the UofA adaptive optics group, as well as to the IMACS and DEIMOS instrument teams.

1.5.1.4 Detector Mount.

The mount for the Hawaii-2 array in MMIRS will follow the design used in FLAMINGOS. Electrical connections are made with a multilayer fan-out board. The biases, clock, and signals from the amplifiers are brought out using separate wiring harnesses to help reduce system noise and cross talk. The Hawaii-2 array is cooled by way of 267 pins in the chip carrier. The pins are coupled to two copper layers in the fan-out board, which in turn are thermally clamped to the dewar. Because the Hawaii-2 zero insertion force socket does not allow location against a defining surface, alignment will be accomplished using spring loaded screw assemblies and predefined mechanical surfaces. The array must be held flat and located relative to the final element of the camera to roughly 10 µm. Once alignment is complete, machined blocks will be clamped into the spaces in the array mount and the mount will be pinned to the work surface. This procedure will allow disassembly and assembly without having to realign the detector.



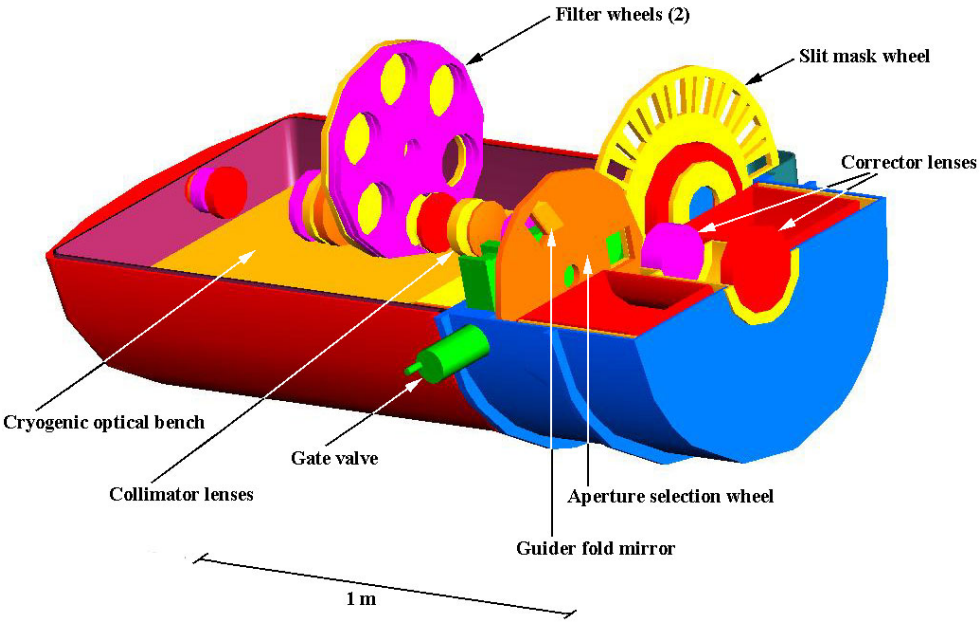


Figure 4. MMIRS Layout.

1.5.2 Slit Mask Dewar

The slit mask dewar accommodates the interchange of slit masks for multiobject spectroscopic observations. The entrance window of the slit mask dewar is the first of the two elements in the coma corrector. The second element of the coma corrector is housed inside the slit mask dewar but will be operated near ambient temperture. Early in the design phase we will determine if the added emissivity from this lens is significant; if so, we will consider how to cool this lens. (The cost impact of cooling this lens is expected to be less than $50K.) An advantage of operating this lens near the ambient temperature is that it will prevent the dewar window from cooling radiatively and condensing water from the air. The slit mask dewar can be thermally cycled during the daytime independently of the camera/collimator dewar that carries the optics.

1.5.2.1 Gate Valve

The slit mask dewar is isolated from the collimator/camera dewar with a gate valve. The gate valve allows us to keep the collimator and camera optics at cryogenic temperatures when thermally cycling the slit mask dewar, and eliminates the need for a warm window below the slit mask.

1.5.2.2 Rapid Thermal Cycling

MMIRS slit masks must be replaced during the daytime between consecutive nights at the telescope. One of the greatest challenges in achieving rapid thermal cycling is providing efficient heat transfer to the slit mask wheel. We will follow the FLAMINGOS design and use sapphire bearings in a gold-plated bearing race to maximize thermal conductivity to the wheels. The multislit masks must be cooled to less than 140 K to keep the mask thermal background below the detector dark current (0.1 e^- sec^{-1}). The thermal mass of the slit wheels and mechanisms is approximately 35 kg, which will require a cooling power of 400 W for 2-3 hours. Simple cyro-cooler systems can provide cooling powers up to about 100 W, thus we use LN_2 to pre-cool the slit mask dewar. After LN_2 pre-cooling, we will cool the cryogenic structures using a CTI-350 two stage cyro-cooler. Kapton heater pads (Figure 10) on the LN_2 tank and cold plate will allow a warm-up time of 2 hours.

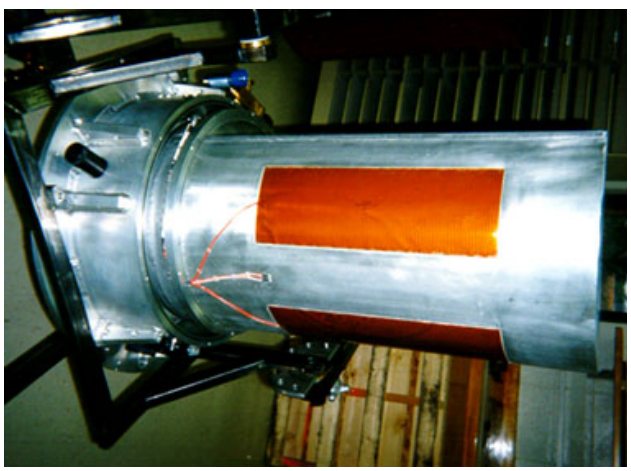


Figure 5. The FLAMINGOS dewar with Kapton heater pads used for thermal cycling.

1.5.2.3 Slit Masks

The mask wheel will hold 20 multislit plates, 6 fixed long slits, and a full-field imaging aperture. To make efficient use of the area on the slit mask wheel the slit masks must be tightly spaced. An aperture selection wheel will precede the slit mask wheel to define the appropriate field of view and ensure that light passes through only a single slit mask or long slit. The coma corrector provides a flat focal plane well suited to multislit masks. Thin sheet metal masks offer high thermal conductivity and low front face emissivity to allow the masks to reach an equilibrium temperature of 140 K. At the MMT, the slits will be cut with the Nd-YAG laser machining system that we will purchase for the multislit Binospec optical spectrograph. At Magellan, a

similar laser machining system has already been purchased for IMACS. A two pixel wide slit at the detector scale is 60 μm wide at the telescope focal plane scale. The slit edges should be uniform to 0.6 μm RMS so that slit transmission variations are kept below 1%. This uniformity will facilitate flat-fielding and sky subtraction. The laser slit mask cutting systems have advertised repeatabilities of 0.1 μm and accuracies of 0.25 μm, meeting this requirement.

1.5.3 Mechanical Flexure

The MMIRS dewars must be mechanically stiff to prevent differential flexure between the optics, slit masks, and the detector. Such flexure would blur long-exposure images and spectra. Typical exposure times in the NIR are 600-1000 sec; longer exposures would saturate near strong night sky lines and would suffer from poor sky subtraction.

A worst-case gravitational deflection of the instrument corresponds to a 15 degree tilt over 1 hour. Finite element analysis of the FLAMINGOS-2 design predicts 1.3 μm deflection of the dewar vaccum vessel and a 0.1 μm deflection of the multislit wheel relative to the dewar. This 1.4 μm per hour deflection corresponds to 2% of a 2 pixel-wide slit per hour on MMIRS, a very acceptable deflection. Because the MMIRS shares a similar dewar design and identical mechanisms with FLAMINGOS-2, we believe that this finite element analysis provides a reasonable estimate of the MMIRS mechanical flexure. We intend, however, to perform an independent finite element study of the MMIRS dewar.

A finite element analysis of the FLAMINGOS-2 vacuum vessel under vacuum indicates that stresses are very low. The MMIRS 170-mm diameter, 40-mm thick entrance element will experience peak stresses below 350 PSI and peak deflections less than 15 μm, reflecting conservative design principles.

1.5.4 Mechanical Interface to the Telescope

The MMIRS dewars will be bolted to a mounting structure. This structure will provide a convenient means of handling MMIRS, and it will be compatible with both the MMT and Magellan telescopes. The mounting structure will also support thermally isolated enclosures for the system electronics.

1.5.5 Electronics

We have developed a CCD controller capable of driving the 36 CCDs (72 channels) in the Megacam mosaic camera. This controller has been extensively tested on the Minicam camera, as well as on the Hectospec and Hectochelle bench spectrographs. We will use this controller with some modifications to drive and read out the MMIRS Hawaii-2 array. The Megacam controller consists of five basic board types. 1) The I/O board provides communications with a host computer via an EDT PCI/RCI fiber optic interface. This interface is used to transmit commands to the controller (including clock waveform patterns) and to transmit 16-bit data back to the computer. 2) The timing board generates the digital clock signals to drive the focal plane array. The clock waveforms are downloaded from the computer and stored in RAM on the timing board. 3) The driver board is responsible for converting the clock signals from digital to analog signal levels and for generating DC bias voltages. Each driver board is capable of driving three CCDs. The Megacam controller requires 12 of these boards; MMIRS will require only one. 4) The A/D video processing boards for the Megacam CCDs will not be suitable for MMIRS. We will design new signal processing boards suitable for the Hawaii-2 array. With four channels per board we have 18 boards in Megacam. This number will be reduced to eight in MMIRS. We will be consulting with other groups with experience running Hawaii-2 arrays as we develop our signal

processing board. 5) The boards in the Megacam controller are connected via a custom 6-U format backplane.

SAO has already invested in a Hawaii-2 multiplexer, an engineering-grade array, and a science-grade array for MMIRS. The multiplexer and the engineering grade array have been delivered; the science grade array is expected in the next few months. We will begin developing the modifications to the controller as soon as funding is available. Because we have large parts of the controller fully designed and debugged and because the MMIRS controller is a smaller system than the Megacam controller, we do not anticipate that controller development will be a critical path task.

1.5.6 Guiding and Wavefront Sensing

Wavefront sensing will be accomplished using the facility f/5 wavefront sensor at both the MMT and Magellan. Between observations, this instrument rapidly deploys a pick-off mirror to the center of the field to measure the wave front aberrations from the primary mirror support and collimation errors. These measurements are used to adjust the primary support actuators and the secondary hexapod (for collimation).

Guiding will be accomplished using a pickoff mirror attached to the aperture selection wheel that deflects light to a guide camera. The guide field will be reimaged onto either a cooled CCD or an intensified camera. The guider will be designed to monitor and correct the telescope focus, which can change on the time scale of an observation.

1.5.7 Software

1.5.7.1 Existing software

We have already developed most of the software required to operate MMIRS. Most of this has been tested with the Minicam at the MMT. The detector electronics will be based on the controller developed for Megacam, thus the software required to acquire data will be largely identical. The Hectospec and Hectochelle spectrographs both make extensive use of stepper motors; we have developed libraries of routines for low-level control and have built a client/server architecture for interfacing to a higher control level. In addition, we have developed an exposure queueing system that allows for automatic sequencing of observations to allow efficient observing. The exposure control system controls the dithering of the telescope, guide star acquisition, filter changing, and detector control. The flexibility of this system will allow operation of IR instruments such as MMIRS.

1.5.7.2 Additional software for MMIRS

The following new software will be required for MMIRS:

- Hawaii-2 pixel reordering. The Hawaii-2 has 32 output amplifiers that are read out in parallel. The pixels from each amplifier must be inserted into the correct place in the output image.
- Multiple sampling. To reduce the effects of read noise, we will implement a multiple sampling mechanism similar to the MULTIACCUM mode used in NICMOS. In this mode, the detector is read out non-destructively several times during the exposure. For each pixel, a list of counts versus time is constructed. The slope of this line gives the count rate. This mode also has the advantage of allowing one to reject cosmic rays by searching for

discontinuities in the ramp-up of counts. Furthermore, the dynamic range is also increased for long exposures because the bright stars are measured before they saturate.

- Stepper motor integration. Although we already have developed all the stepper motor modules, each instrument has a unique configuration. The software must be configured to match MMIRS.