

# Design and development of MOSFIRE, the Multi-Object Spectrometer For Infra-Red Exploration at the Keck Observatory

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## ABSTRACT

MOSFIRE is a unique multi-object spectrometer and imager for the Cassegrain focus of the 10 m Keck 1 telescope. A refractive optical design provides near-IR (0.97 to 2.45  $\mu\text{m}$ ) multi-object spectroscopy over a 6.14' x 6.14' field of view with a resolving power of  $R \sim 3,270$  for a 0.7" slit width (2.9 pixels in the dispersion direction), or imaging over a field of view of 6.8' diameter with 0.18" per pixel sampling. A single diffraction grating can be set at two fixed angles, and order-sorting filters provide spectra that cover the K, H, J or Y bands by selecting 3rd, 4<sup>th</sup>, 5<sup>th</sup> or 6<sup>th</sup> order respectively. A folding flat following the field lens is equipped with piezo transducers to provide tip/tilt control for flexure compensation at the 0.1 pixel level. A special feature of MOSFIRE is that its multiplex advantage of up to 46 slits is achieved using a cryogenic Configurable Slit Unit or CSU developed in collaboration with the Swiss Centre for Electronics and Micro Technology (CSEM). The CSU is reconfigurable under remote control in less than 5 minutes without any thermal cycling of the instrument. Slits are formed by moving opposable bars from both sides of the focal plane. An individual slit has a length of 7.1" but bar positions can be aligned to make longer slits. When masking bars are removed to their full extent and the grating is changed to a mirror, MOSFIRE becomes a wide-field imager. Using a single, ASIC-driven, 2K x 2K H2-RG HgCdTe array from Teledyne Imaging Sensors with exceptionally low dark current and low noise, MOSFIRE will be extremely sensitive and ideal for a wide range of science applications. This paper describes the design and testing of the instrument prior to delivery later in 2010.

**Keywords:** spectrometer, near-infrared, multi-object, Configurable Slit Unit, MOSFIRE, Keck Observatory

## 1. INTRODUCTION

Developed as part of the third generation instrument program at the W. M. Keck Observatory (WMKO)<sup>1</sup>, MOSFIRE is a near-infrared (0.97 to 2.45  $\mu\text{m}$ ) multi-object spectrograph and wide-field camera for the Cassegrain focus of Keck I. A special feature of MOSFIRE is that its multiplex advantage of up to 46 slits is achieved using a cryogenic Configurable Slit Unit (CSU) that is reconfigurable under remote control in less than 5 minutes without any thermal cycling of the instrument. When the bars are removed to their full extent and the grating is changed to a mirror, MOSFIRE becomes a wide-field imager. The instrument is being developed by the University of California, Los Angeles (UCLA), the California Institute of Technology (CIT) and the University of California, Santa Cruz, (UCSC). The Co-Principal Investigators are Ian McLean of UCLA and Charles Steidel (CIT), with other leading roles in optics and instrumentation being played by Harland Epps (UCSC) and Keith Matthews (CIT). The project is managed by WMKO Instrument Program Manager, Sean Adkins. MOSFIRE is funded in part by the Telescope System Instrumentation Program (TSIP), operated by AURA and funded by the National Science Foundation and by a private donation to WMKO by Gordon and Betty Moore. In this paper we update the instrument design<sup>2</sup> and describe its implementation through construction prior to telescope commissioning.

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## 2. DESIGN REQUIREMENTS

Top level science requirements for MOSFIRE were established in large part by an ad hoc group (Keck Observatory Next Spectrograph Advisory Group, or “KONSAG”) that considered the minimum scientific requirements of a cost-capped near-IR imaging spectrometer for WMKO. The key MOSFIRE design choices are summarized in Table 1. A more detailed set of requirements can be found in the MOSFIRE Requirements Document on the MOSFIRE web site at <http://irlab.astro.ucla.edu/mosfire/>.

Table 1: Summary of the MOSFIRE design parameters

|                                      |   |
|--------------------------------------|---|
| <b>Wavelength coverage</b>           | 0.975 to 2.40 $\mu\text{m}$ ; 110.5 line/mm grating used in orders 6,5,4,3 (Y, J, H, K), with choice of two grating tilts optimized for H, K or Y, J.                                 |
| <b>Spectral Resolution</b>           | $R_0=2290 \Rightarrow R=3270$ w/0.7" slit, (2.9 pixels)   |
| <b>Simultaneous Wavelength Range</b> | Coverage is 0.45 $\mu\text{m}$ (21%) in K band; 1.97 to 2.42 $\mu\text{m}$ for a slit at the center of the field; H band coverage 1.48 to 1.81 $\mu\text{m}$ for the same slit        |
| <b>Pixel Scale</b>                   | 0.18" in imaging mode   |
| <b>Field Size</b>                    | 6.12' slit length, 6.14' field for imaging; slits can be placed anywhere within the imaging field of view.  |
| <b>Multiplex</b>                     | Cryogenic Configurable Slit Unit (CSU): 46 remotely configurable slits each 7.1" long; configurable as a smaller number of longer slits. Each slit width can be adjusted arbitrarily. |
| <b>Image Quality</b>                 | Design gives $< 0.25''$ rms diameter images over 0.97 to 2.40 $\mu\text{m}$ with no re-focus.   |
| <b>Stability</b>                     | $< 0.3$ pixel residual image motion at detector over a 2 hr observation. Open-loop flexure compensation using tip/tilt mirror, look-up table.   |
| <b>Guiding</b>                       | Optical CCD guider, offset by 6.6' from the center of the MOSFIRE field, with a field of view of 2.8' square on a 1024 x 1024 detector with 0.164" sampling.                          |
| <b>Throughput: spectroscopy</b>      | $> 30\%$ not including telescope, on order blaze  |
| <b>Mask configuration time</b>       | $< 5$ minutes for full re-configuration; goal $< 2.5$ minutes   |
| <b>Filters</b>                       | Minimum complement is order sorting filters for K, H, J, Y; additional Ks photometric filter for imaging. Goal: up to 5 additional photometric broad or narrow-band filters.          |
| <b>Lyot stop</b>                     | Two position tracking pupil mask [circumscribed or slightly under-sized, matching hexagonal shape of pupil image (for H, K bands)]  |
| <b>Detector</b>                      | 2048 x 2048 Teledyne H2-RG and ASIC; 18 $\mu\text{m}$ pixels, long-wavelength cutoff @ 2.5 $\mu\text{m}$ ; low charge persistence; highest QE   |

Several additional choices flow down from the science requirements. For example, the optical design is achromatic but focus adjustment is possible during initial integration and testing. Space for additional filters is accomplished with a double filter wheel. Two grating positions give the optimum arrangement for the four spectral regions covered by MOSFIRE and this option has been included without compromising repeatability. As this is a Cassegrain focus instrument, a means for compensating for flexure has been added. For MOSFIRE’s wavelength range it is not necessary to cool the large thermal mass all the way to 77 K. Only the detector is cooled to 77 K, the remainder of the instrument is stabilized at 120 K using speed-controlled, closed-cycle refrigerators. Cooling takes about 8 days. Finally, the instrument has a guide camera and a calibration unit.

## 3. DESCRIPTION OF THE INSTRUMENT

### 3.1 Optical Design

Underlying the MOSFIRE optical design was the guideline to keep it mechanically compact and as simple as possible to fabricate. A folded, all-spherical design was adopted as the basis of our original proposal for those reasons. The optical design splits naturally into three sections: the field lens, the Collimator Barrel and the Camera Barrel. Figure 1 illustrates

the optical layout in two parts, with the Collimator Barrel repeated twice. The slit unit is located at the nominal f/15 focus of the Keck telescope. Not shown is the entrance window to the vacuum-cryogenic enclosure or “dewar”.

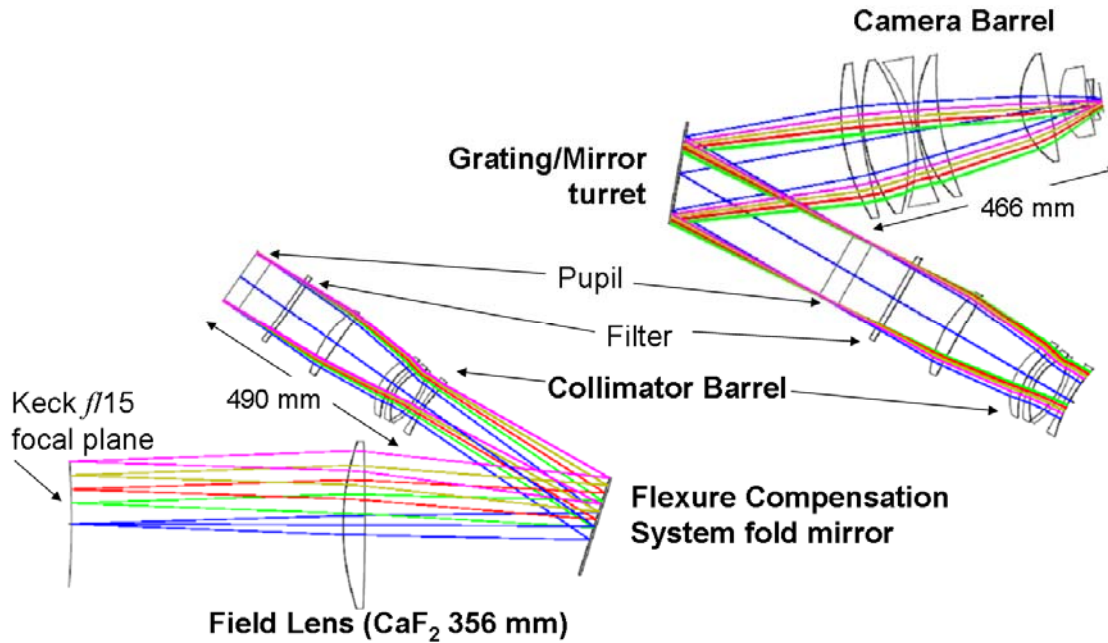


Figure 1: MOSFIRE Optical design, the double entrance window is not shown

A large (388 mm full diameter) entrance window is required to accommodate the 6.8' diameter field of view. This window is located in a tube or snout at the front of the dewar. In order to withstand the pressure differential under vacuum, while keeping the maximum stress within the “glass” below  $\sim 500$  psi, an Infrasil-302 window  $\sim 34.9$  mm thick is required. To prevent condensation from forming as the center of this large window cools by radiation, a second, thinner (17 mm) Infrasil-302 window is located 228.6 mm away in the vacuum. An aluminum tube and baffles between the windows are resistively heated as described in the mechanical section to provide radiation to maintain the outer window above the average Observatory dome temperature.

The telescope's effective focal length is 149.572 m as it is used with MOSFIRE, such that the effective f/ratio is f/14.50. Thus the collimator's focal length must be 1813.0 mm so as to produce a (stipulated) 125.0-mm beam diameter. The collimator is a critical optical component. It must capture a physically large, 6.8' diameter field of view and it must also produce a sharply focused, accessible pupil image so that a cold Lyot stop (mask) can be inserted to eliminate stray thermal radiation.

The six-element collimator contains a large  $\text{CaF}_2$  field lens separated from a second lens group. The second group contains elements made from  $\text{CaF}_2$ , ZnSe, FQtz,  $\text{BaF}_2$  and  $\text{CaF}_2$  in that order. A folding flat is placed between these groups. Note the curved Keck focal surface. This curvature ( $\sim 2.124$  m radius) is taken into account in the CSU design. The 125 mm pupil image is stationary over all field angles to  $\sim 2.5\%$  in the K-band and to  $\sim 3.6\%$  in the H-band. A Lyot stop is located at the pupil. The MOSFIRE filters, made by Barr Associates (Westford, MA) are 170 mm in diameter and tilted 6.0 degrees with respect to the optical axis to avoid ghost images.

The large (327.5 mm) distance from the Lyot stop to the grating, combined with the (300 mm) distance from the grating to the camera causes convoluted, anamorphic, wavelength and field-angle dependent compound-pupil presentations, which complicate the design. The resulting camera requires a 250 mm focal length and a 270 mm entrance aperture such that it operates at f/0.93 (under-filled), which is unprecedented for a cryogenic  $0.975\ \mu\text{m}$  to  $2.40\ \mu\text{m}$  infrared camera of these dimensions. Its field radius is 6.0 degrees to cover the corners of the H2-RG array. Harland Epps produced a 7-element all-spherical camera design that satisfies all the goals for MOSFIRE, including the need to provide for direct imaging in the K, H, J, and Y passbands as well as spectral coverage in those passbands for any object located within a rectangle at the telescope focal surface whose dimensions are  $\pm 3.06'$  along the slits and  $\pm 1.50'$  perpendicular to the slits.

The camera is composed of two elements of CaF<sub>2</sub>, followed by lenses of S-FTM16, S-FPL51, two elements of BaF<sub>2</sub> and a field-flattener of S-FTM16. The latter is mounted with the detector and cooled to 77 K.

Figure 2 shows how the optical train is laid out and folded in three dimensions. The fold mirror in the collimator section is articulated with piezoelectric actuators to provide a tip/tilt flexure control system (FCS) and the diffraction grating is mounted back-to-back with a plane mirror on a turret to enable the instrument to be switched from spectroscopic to imaging mode. Using fixed stops, only two positions of the grating are allowed in order to ensure repeatability.

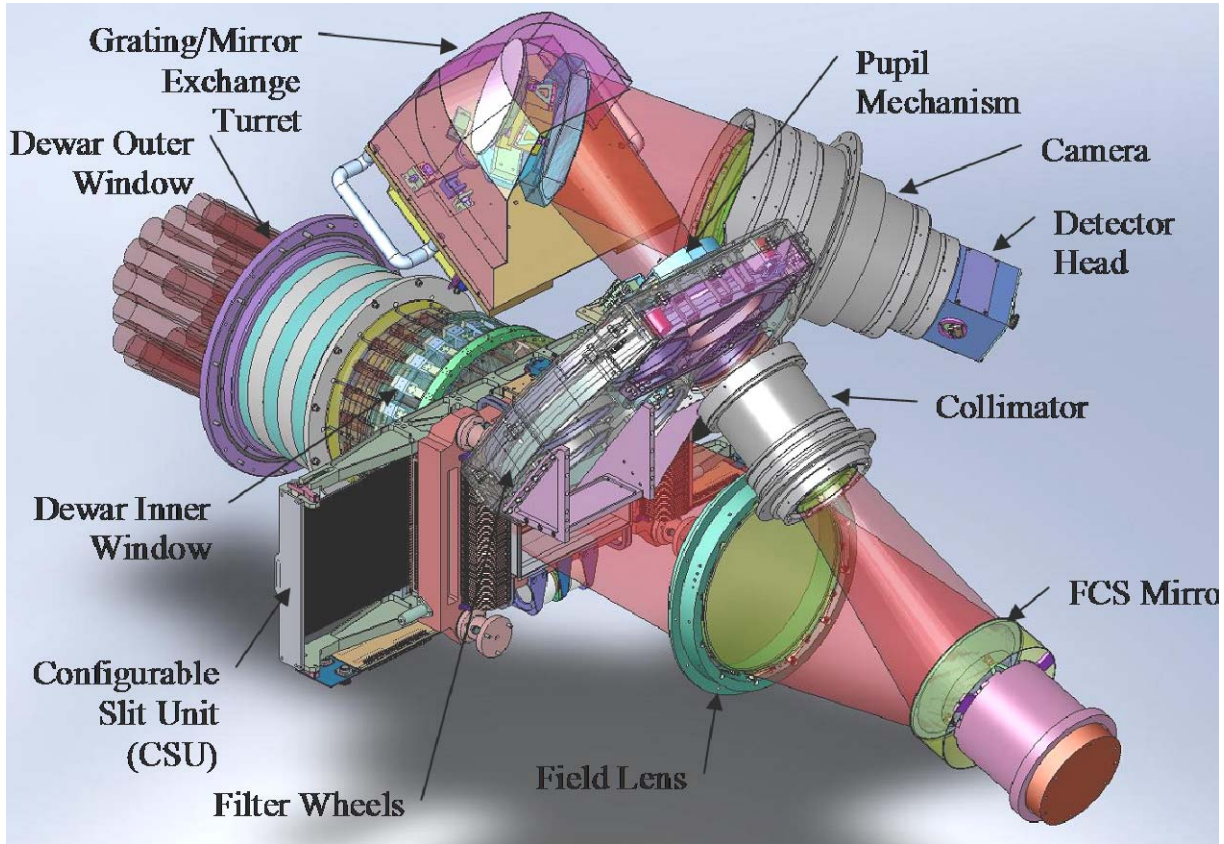


Figure 2: MOSFIRE physical layout. All components in the optical path, including the CSU, are shown.

As shown in Figure 3, the end-to-end direct-imaging performance of the telescope, collimator and camera combination is expected to be excellent. Polychromatic spot diagrams show a “wide-open” passband, which includes 20 wavelengths from 0.975  $\mu\text{m}$  to 2.40  $\mu\text{m}$  plotted simultaneously without refocus, for field angles that are 0.0, 30%, 50%, 70%, 80%, 90% and 100% of the full 6.8' field of view available for direct imaging. The area-weighted average rms image diameters are only  $0.23'' \pm 0.06''$  and all of the light falls within 3-pixel (0.54'') boxes.

Image quality in spectroscopic mode is harder to illustrate because of the many possible combinations of object locations and passbands. We adopted a spectroscopic image-quality goal for MOSFIRE that seeks to put 80% or more of the light in any given image into a (2 x 2)-pixel Nyquist sampling box, centered on the image centroid. A representative sample of *worst-case* spectroscopic images was calculated without refocus for three extreme objects placed 3.06' off-axis (at the top end of the slit), with offsets of -1.5', 0.0' and +1.5'. Our 110.5 groove/mm grating, supplied by Newport Corporation Richardson Gratings (Rochester, NY), was set to a 42.614-degree angle for K and H, so as to put 2.18  $\mu\text{m}$  light at the field center in 3<sup>rd</sup> order and 1.635  $\mu\text{m}$  light at field center in 4<sup>th</sup> order. The grating was set to a 41.524-degree angle for J and Y, so as to put 1.248  $\mu\text{m}$  light at field center in 5<sup>th</sup> order and 1.04  $\mu\text{m}$  light at field center in 6<sup>th</sup> order. To determine whether or not a given image would be counted in the analysis, the criteria adopted were that it must fall on the detector and it must fall within the following wavelength ranges: 3rd-order K (1.93  $\mu\text{m}$  to 2.40  $\mu\text{m}$ ); 4th-order H (1.46  $\mu\text{m}$  to 1.81  $\mu\text{m}$ ); 5th-order J (1.15  $\mu\text{m}$  to 1.35  $\mu\text{m}$ ); and 6th-order Y (0.975  $\mu\text{m}$  to 1.12  $\mu\text{m}$ ). The resulting spectral-image ensquared

energy concentrations, as percentages in a (2 x 2)-pixel Nyquist box averaged over all objects and wavelengths, exceeded 90% for all bands.

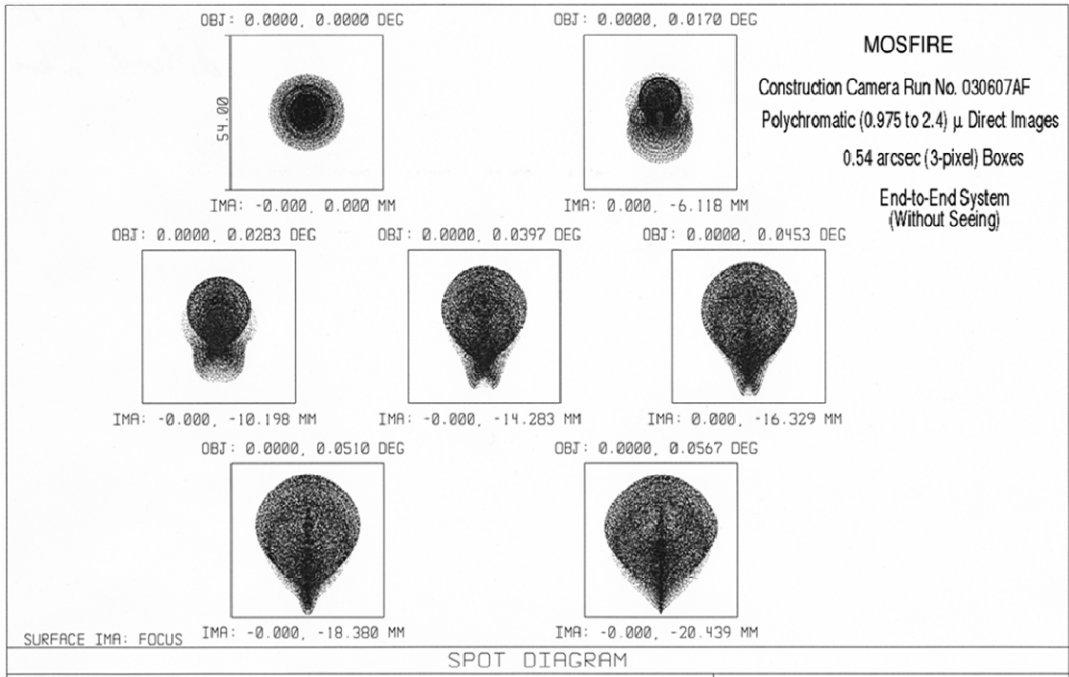


Figure 3: Expected end-to-end spot diagrams for the MOSFIRE optics in imaging mode

Construction of the optics was challenging. Using refractive indices obtained for each lens material at 120 K, the design was optimized for 120 K operation and fabrication dimensions were calculated for 20 C. Blanks were obtained from several vendors and supplied to Coastal Optical Systems (Jupiter, FL; now Jenoptik) for polishing. Anti-reflection coatings were provided by Evaporated Coatings Inc. (Willow Grove, PA). Each lens is supported in a stiff but thermally-compliant mount using flexures bonded to the lens with adhesive via thermally-matched metallic alloy pads. Pull tests (tensile and shear) at cryogenic temperatures on samples of every glass established the reliability of the bonds. Figure 4 shows the solid model of the camera barrel and one of the lenses during the bonding process.

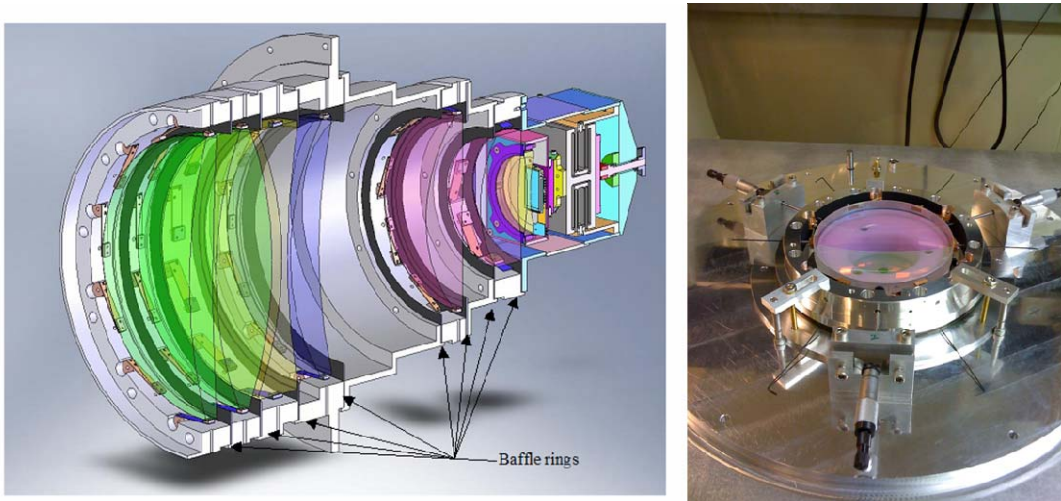


Figure 4: Cross sectional view of the Camera Barrel with Detector Head and focus mechanism attached

Full-sized aluminum dummy lenses with the correct as-built dimensions and curvatures were fabricated in order to practice the bonding and alignment technique. Each lens was bonded and mounted into its precision aluminum cell using a stationary coordinate measuring machine (CMM), and lens cells were stacked and spaced to create the collimator and camera barrels using the CMM. Each optical sub-assembly was mounted into a precise location inside MOSFIRE using a portable (Faro) CMM. Dummy barrels and cross-hairs were used to align the internal interface points. Figure 5 shows the optics being installed into the instrument.



Figure 5: Left, installation of the completed camera barrel. Right, installation of the large CaF<sub>2</sub> field lens.

### 3.2 Mechanical Design

The mechanical design was constrained by the requirement that MOSFIRE must occupy the same space envelope and have essentially the same weight as the existing LRIS optical spectrograph on Keck 1. Figure 6 shows a solid model drawing of the large vacuum enclosure which has a diameter of ~1.5 m. The cylindrical dewar can be opened from either end by removing the tori-spherical end-caps. An independent off-axis CCD guider is mounted off the front cover (facing left in Figure 6), and a cable wrap and electronics cabinet are mounted on the rear cover.

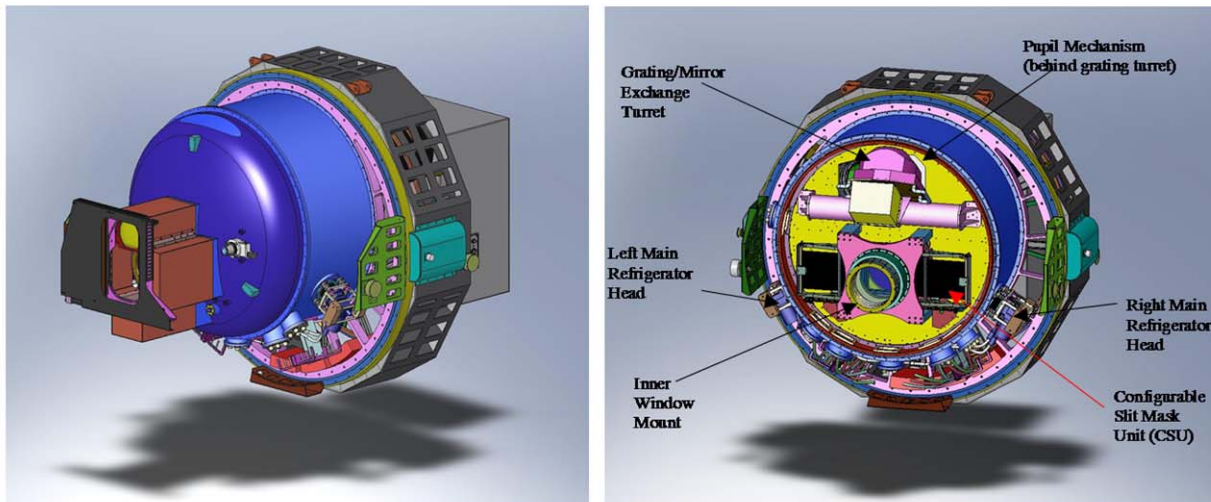


Figure 6: Left, the cylindrical overall mechanical construction of MOSFIRE. Right, a view with front cover removed showing the location of the inner window and slit mask, and the grating turret.

The intent of the design is to make all of the mechanisms accessible for servicing after removal of either the front or the rear cap. As the vacuum shell must safely resist the atmospheric pressure load in combination with the loads of external components, and also have sufficient stiffness to keep the relative motion between internal components within acceptable limits, a tubular vacuum shell was chosen based on its efficiency in meeting these requirements. The dewar was fabricated by Martinez and Turek (Rialto, CA). Figure 6 also shows a view of the front optical bench or cryogenic bulkhead that supports the grating turret, the slit mask unit and the inner window assembly. As mentioned in the optics section, a thick outer window provides the vacuum seal. A second “inner” window, which has no role in supporting the vacuum seal, helps to control thermal radiation from a heater located in the snout tube of the dewar. Consisting of six stacked aluminum rings wrapped with resistive metal film heaters and multi-layer-insulation (MLI), the heater forms the inner lining of the snout tube and balances heat lost by the front window to the interior. This arrangement effectively eliminates any tendency for the front window to accumulate condensation. A cold baffle, consisting of five stacked aluminum rings, lines the optical path between the heater and the inner window. The inner window remains cold and acts as a radiation boundary, reducing considerably the radiation load on the configurable slit unit (CSU). The system works well and was tested during the first two cool downs of the instrument before the CSU and optics were installed.

Because MOSFIRE is a Cassegrain instrument, it will experience a varying gravity vector during operation. Thus, to minimize flexure, all of MOSFIRE’s internal components are mounted on two optical benches connected by an inner and outer tubular support structure. To make this internal structure, two 1500 mm diameter circular plates (or optical benches) of aluminum were joined by a pair of nested, short tubes. This “stubby drum” is suspended inside the cylindrical vacuum chamber by a concentric cylinder made from a material similar to G-10 fiberglass (Reinhold Industries, Santa Fe Spring, CA). Each optical assembly and mechanism is attached to one or other of these benches. The small length to diameter ratio of the structure results in relatively small radial displacements. Finite element analysis was used to estimate the stability of the structure under varying orientations relative to gravity. These models predicted a worst case flexure, before correction, of about 3 pixels from zenith to horizon and about half this amount over any two hour period. Using the completed instrument in its rotation bearing on a large stiff mounting frame that can move in elevation angle, flexure values of order double this estimate have been seen in certain configurations. However, the flexure appears perfectly elastic and repeatable, and the flexure compensation mechanism is capable of accommodating this range.

Space Dynamics Labs (North Logan, UT) was contracted to perform a thermal analysis of MOSFIRE. The analysis was iterated to find the power needed to maintain temperatures of  $< 130$  K throughout the structure. Using specially-constructed blankets of MLI, it is found that two refrigerators removing  $\sim 28.5$  W each are required for steady-state operation. The CTI (Brooks Automation) 1050 heads selected are capable of much more power. Speed controllers are used with both heads and a bank of resistors added to the optical benches provides temperature stabilization. The estimated gradient among all of the optics is  $\sim 2$  K and the maximum gradient in an individual lens is  $\sim 0.1$  K. Radiant power incident on the CSU masking bars is  $< 0.3$  W and the cool down time is about 8 days.

MOSFIRE contains several cryogenic mechanisms (see Figure 2). These mechanisms are the CSU (discussed in section 3.3), the flexure control system, the double filter wheel, the pupil tracking mechanism, the grating/mirror turret and grating position mechanisms, and finally the detector focus mechanism. Bearings and motors prepared for cryogenic operation are used throughout these mechanisms. With the exception of the CSU, each mechanism was built in-house and tested extensively in smaller cryogenic chambers before being installed into the MOSFIRE dewar. In this way we were able to limit the number of lengthy cool downs of the large MOSFIRE dewar while still ensuring that the mechanism was fully de-bugged and received lifetime testing. The flexure compensation system is based on a custom version of a piezoelectric tip/tilt platform designed and manufactured by PI (Physik Instrumente).

### **3.3 The Configurable Slit Unit**

One of the major goals of the MOSFIRE design was to find a way of creating slit masks while the instrument remained cold and stable at cryogenic temperatures. The MOSFIRE cryogenic Configurable Slit Unit (CSU) is based on a prototype built for the European Space Agency (ESA) by the Swiss Centre for Electronics and Micro Technology (CSEM) as a candidate for the slit mask on NIRSpec, an instrument for the James Webb Space Telescope (JWST). Our requirements called for a significantly larger field of view (FOV) of 267 mm square and of course operation under all gravity orientations. The CSU is designed to simultaneously displace masking bars across the FOV to mask unwanted light. A slit is formed at a designated position within the FOV by positioning two opposing bars so as to create a rectangular slit. The end of each bar carries a slit jaw or knife-edge whose height is set to approximate the curvature of the Keck Telescope focal plane. A set of 46 bar pairs is used to form the MOSFIRE focal plane mask. The sides of the

bars are black and convoluted so that light is prevented from passing between adjacent bars. Bars that form one side of the slit can be moved independently of those that form the other side. Thus, any width of slit can be formed up to a completely open imaging field when the bars are fully retracted. Also, bars on one side form an identical assembly to those on the other.

The CSU consists of two major subassemblies, the indexing stage and the support frame. It is the indexing stage that provides the mechanism for positioning the bars. Masking bars are displaced across the FOV using incremental steps (inchworm principle) where a number of oscillating steps are required to displace the masking bars. A voice-coil actuator on an indexing stage provides the motion to move the bars from opposite sides simultaneously. A common position sensor (LVDT) keeps track of all relative movement of bars with respect to the fixed reference frame. All bars can be displaced at the same time or individually, as is the case when final slit position is to be achieved. There are two mechanisms associated with each bar: a brake which holds the bar's position by friction and a mover (called the ratchet clutch) which inserts a sapphire claw between the two teeth nearest it on the bar's edge. A coil of wire moving in a magnetic field actuates each of these mechanisms. By energizing a bar's brake coil, the brake for that particular bar can be released, and by energizing a bar's mover coil, the mover claw for that bar is inserted. Ratchet and brake clutch actuators are used to engage and block the masking bars during the incremental movement of the indexing stage. Clutches are assembled in a side-by-side array to create a sub-assembly capable of addressing all bars in parallel or individually. The masking bars are held within the support frame and are guided using rollers on bushings. The rollers ride on a pair of angled surfaces machined along the top and bottom lengths of each bar. On the upper surface, the bars are machined to provide a tooth profile that engages with the ratchet clutch to provide motion. The tooth pitch is 1.2 mm.

Figure 7 shows the completed and delivered CSU undergoing warm testing in the MOSFIRE dewar. A random mask configuration is shown in the left image and the close-up on the right reveals the infrared black knife-edges at the end of each bar. The picture also shows that masking bars can be aligned to create longer slits.

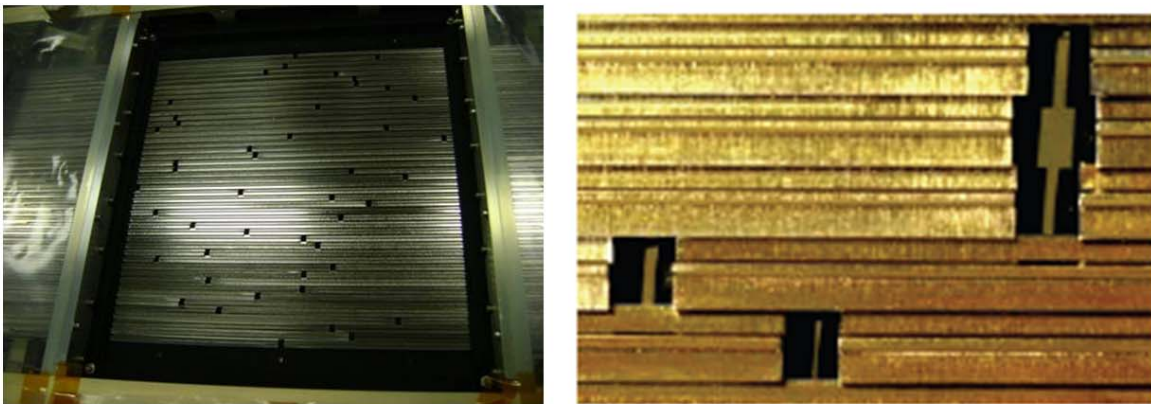


Figure 7: Left: a picture of the CSU showing a mask configuration. Right: a close-up showing the black knife-edge slits.

The CSU has been bench-tested extensively and has been operated cryogenically on three separate occasions at the time of writing. During each cool down, one masking bar failed to operate correctly. These problems have been traced to debris from cracks in the permanent magnets associated with the ratchet coils. Apart from this issue, the mechanism has worked remarkably well and hundreds of cryogenic masks have been formed.

### 3.4 Electronics and Detector Design

Most of the electronics consist of commercial off the shelf (COTS) equipment with the required interconnections. There is a limited amount of custom equipment including, the CSU control system, the interface board for the science detector application specific integrated circuit (ASIC) and a few printed circuit boards used to simplify various high pin count interconnections. The MOSFIRE electronics consists of three major component groups, the MOSFIRE instrument electronics located in the electronics cabinet mounted on the rear end-cap of the vacuum enclosure behind the cable wrap, the MOSFIRE CCR compressor and controls located in the Keck I mechanical equipment room, and the MOSFIRE computer rack containing the instrument host computer and data storage disks located in the Keck I computer room.

Choosing the SIDECAR ASIC drive system for the H2-RG 2k x 2k HgCdTe array from Teledyne Imaging Sensors (formerly Rockwell Scientific) simplified much of the electronics. The ASIC provides clocks and bias voltages to the detector and digitizes the detector outputs. As shown in the lower left of Figure 8, the SIDECAR ASIC is packaged separately on a small board that is located inside the dewar next to the detector head. Just outside the dewar wall is another board, the Jade2, which provides the interface between the ASIC and USB 2.0. Figure 8 also shows the field-flattener lens at the front of the detector module. This entire unit bolts directly to the camera barrel but the detector has a separate cooling path using a CTI 350 refrigerator which also cools the two large getter canisters. Detector temperature is controlled using a standard Lake Shore Cryotronics 340 temperature controller.

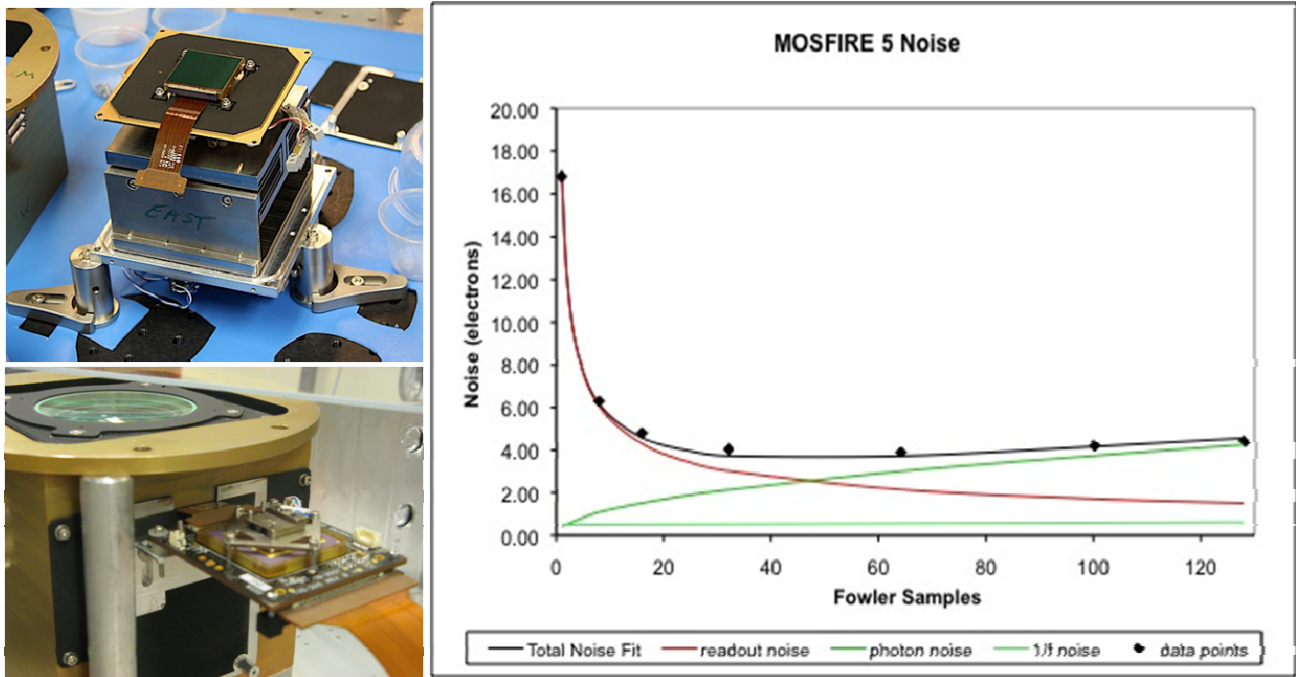


Figure 8: Part of the MOSFIRE detector module is shown at left. Upper left, the detector block and the titanium flexure focus stage are shown. Lower left, is the assembled module with built-in field flattener lens (top) and SIDECAR ASIC board. Right, a plot of noise (electrons) versus the number of Fowler samples used. The exposure time is just long enough to accommodate each sample. The data are fit by the Fowler noise reduction and a small light leak of  $\sim 0.1$  e/s/pixel.

MOSFIRE’s science grade detector and ASIC board have functioned well. Dark current at 77 K is extremely low ( $< 0.01$  e/s/pixel) and the noise performance of the ASIC has met our goal of 4 electrons rms using 32 Fowler pairs. The graph on the right side of Figure 8 shows the noise data as a function of Fowler samples using exposures of different durations, each just long enough to accommodate the set of multiple reads. Poisson noise on any constant-level photon leakage during these exposures will increase as shown in the green curve, whereas multiple reads should decrease the noise according to the red curve. The data are fit by the quadrature sum of these two noise sources.

### 3.5 Software Design

A primary goal of the MOSFIRE software design was to make use of heritage code from existing Keck instruments, such as OSIRIS and DEIMOS. The MOSFIRE computer architecture consists of three main computers and two switches: an instrument host computer, a detector target computer, and a detector control computer. The detector control computer’s responsibility is to run the MOSFIRE ASIC Server and SIDECAR ASIC control software. This system runs Windows XP Professional and resides in the instrument electronics cabinet. The detector target computer runs the detector server program and connects to a data storage array. The instrument host computer runs everything else. These latter two systems run Solaris and reside in the Keck I telescope’s computer room. All network devices are connected through two private network switches: one at the instrument, one in the Keck I computer room.

MOSFIRE employs a client-server architecture which facilitates distributed processing and remote observing. This framework, which began with NIRSPEC and NIRC2, was refined in the implementation of the OSIRIS instrument software. The server architecture offers many features that have become standard practice for infrared instruments at WMKO. Each instrument server is compliant with the Keck Task Library (KTL), which uses remote-procedure calls (RPCs) in a WMKO standard framework for network communications. Standard WMKO keywords are used as the main applications programming interface (API), and simple clients, such as “show” and “modify” facilitate easy access and scripting. By using existing KTL interfaces to other popular languages such as Java, IDL and Tcl, a diverse range of user interfaces can be implemented.

At the time of writing, all of the MOSFIRE servers are complete and in use to support integration and testing. Work is under way to complete the required “global server” and further develop the mask-generation software in tandem with a data reduction pipeline.

#### 4. PERFORMANCE

MOSFIRE is currently in the integration and testing phase. All of the optics and mechanisms, and in fact everything internal to the dewar has been installed. Only final assembly of the Guide Camera and Dust Cover mechanism must be completed at the time of writing. Many problems have been solved to reach this point. Figure 9 shows the completed instrument under test.

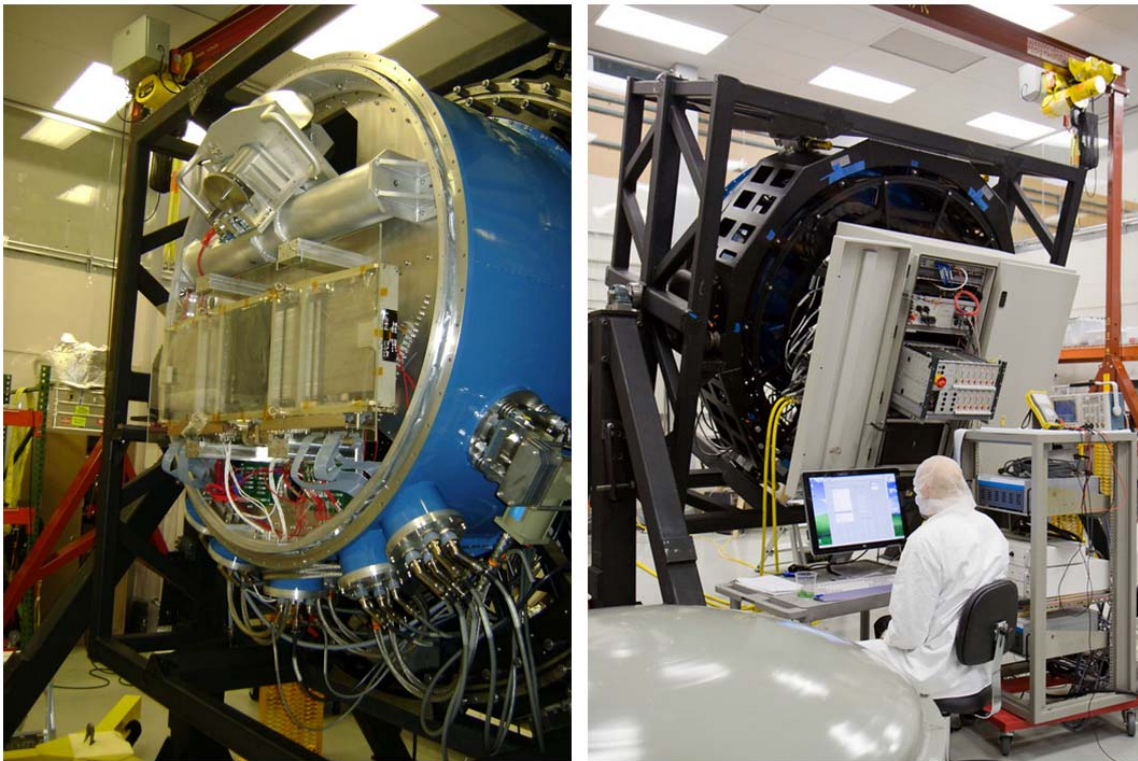


Figure 9: Left, the front end of the instrument is shown open. The upper structure is the grating turret mechanism and the lower module is the CSU. Right, a view showing the rear of the instrument with the electronics cabinet open and the CSU electronics pulled forward and under test.

On July 1, 2010 in the middle of this conference, we obtained “first light in the lab” with MOSFIRE. The instrument was cooled down in a known configuration ready to take an image. All of the masking bars were moved to create a single long slit, the pupil mask was stopped down to the hexagonal shape, the grating turret was set to the mirror for imaging mode and the H-band filter was in position. Figure 10 shows our “first light” image. A flashlight was shone into the window to illuminate one end of the long slit (to identify the axes) and a short exposure image was taken. Of course, the detector was completely saturated along the slit. However, enough light was reflected back from the field lens and

scattered behind the CSU that we could read the engraved serial numbers on the back side of the masking bars. We were sharply in focus all across the field. Needless to say, this was a very gratifying moment. Extensive testing of the instrument is under way as this paper goes to press.

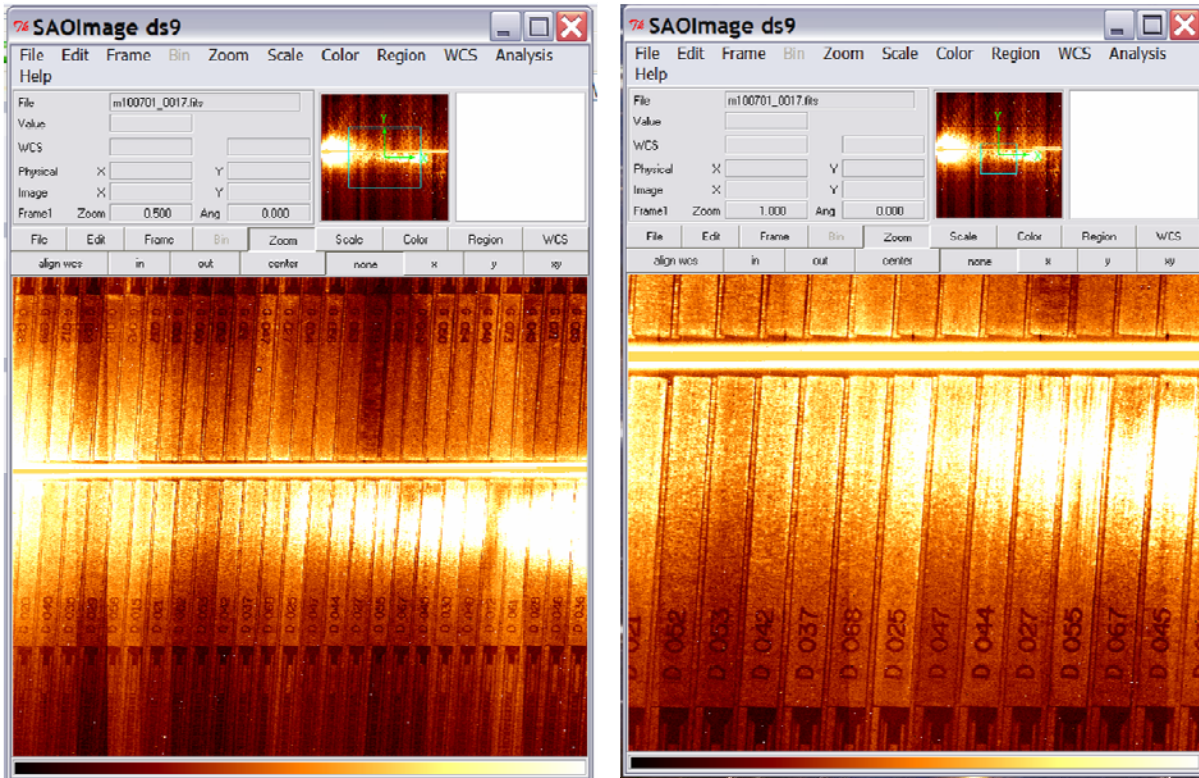


Figure 10: An image of the long (horizontal) slit configuration was obtained in H-band on July 1 (left picture). A bright illumination source at the left end of the long slit completely saturates the detector along the length of the slit. However, scattered light illuminates the back surface of the masking bars. Zooming in (right picture) reveals that the focus is sharp enough to read the serial numbers engraved on the bars.

The left side of Figure 11 shows the layout of the MOSFIRE field of view on the sky. The MOSFIRE detector footprint of 6.14' x 6.14' is shown against a 15' x 15' image of a field. In imaging mode, the field of view is vignetted slightly by the field lens in the corners of the detector, but in spectroscopic mode there is essentially no vignetting of the spectra for slits placed within an area 6' x 4' field of view. Also shown in Figure 11 is the relative location of the Guider's field of view which is 2.9' square, and centered 6.6' off-axis. There are 144 potential targets in this field and 20 potential alignment stars. Software automatically generates a new mask configuration for any selected field center and position angle based on a user-supplied target ranking. A fraction of the slits will use two bars to provide a length of 15.0".

We have also estimated the instrument throughput by carefully calculating the transmission losses through every element and combining this with the vendor-supplied test data on the anti-reflection coatings, the silvered fold mirrors, the diffraction grating and the H2-RG detector. The right side of Figure 11 is a plot of the expected throughput as a function of wavelength. It is clear that we have met our goal of 30% across almost all of each band, Y, J, H and K. Based on these data, and the performance of the science grade detector, we can predict the on-telescope sensitivity. For example, in imaging mode we expect to obtain a signal-to-noise ratio of 10 in 1000s for objects having Vega (or AB) magnitudes of 24.4 (25.0), 23.7 (24.6), 22.5 (23.9) and 21.7 (23.6) in Y, J, H and K respectively. In spectroscopic mode with a 0.7" slit giving a resolving power of  $R = 3270$ , the limiting magnitudes become 20.9 (21.5), 20.4 (21.3), 20.1 (21.5) and 18.6 (20.5). To derive these numbers we assumed 0.05 e/s dark current and a read noise of ~4 e/pixel. We also assumed a background for spectral regions between OH lines. Sensitivity is evaluated over a 3-pixel resolution element assuming a 0.5 arcsecond square extraction aperture. Imaging limits assume 3 x 3 pixel (0.54") aperture for a point source under good seeing.

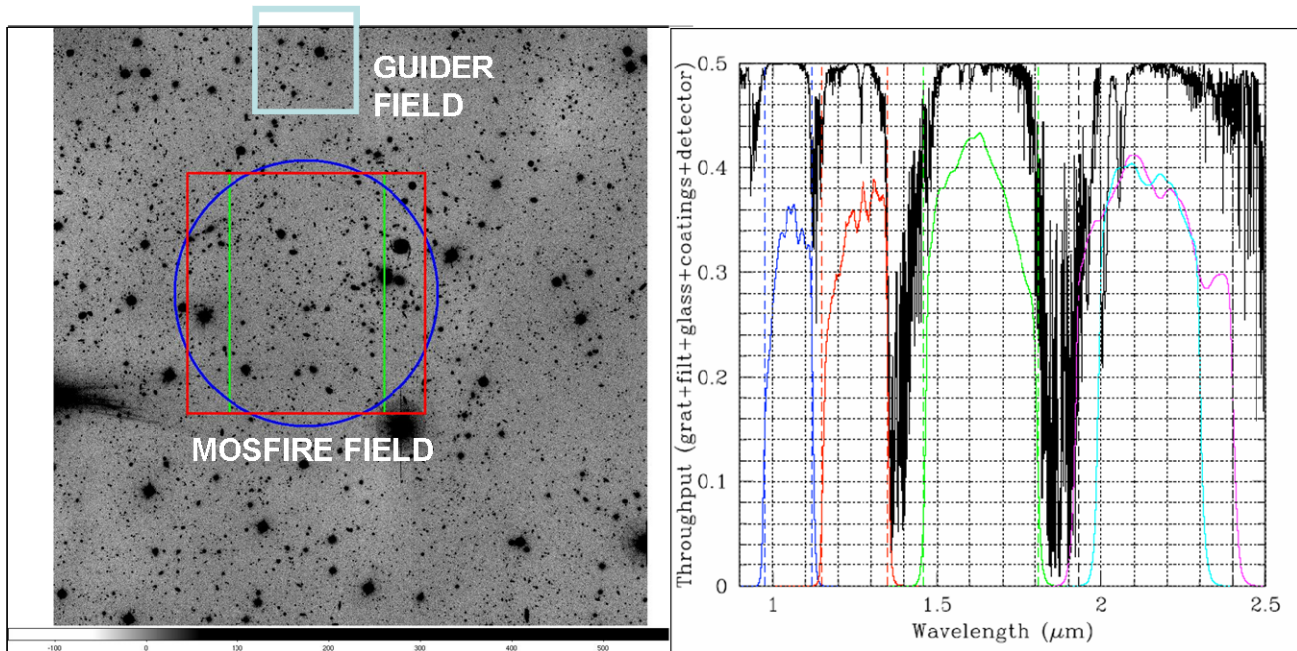


Figure 11: Left, the imaging and spectroscopic fields of view, and the guider field of view on the sky for MOSFIRE. Right, is a plot of the calculated throughput using as-built data for the lenses, mirrors, grating and detector.

## 5. CONCLUSIONS

MOSFIRE is one of the most challenging cryogenic infrared spectrographs ever attempted. The sheer size, mass and complexity have strained our attempts to create a build-to-cost project. High risk areas such as the CSU, the large optics and the bonding technique for mounting lenses were mitigated by attacking these areas early in the project. Cost was also contained by taking advantage of heritage from previous instruments designed for WMKO. Large test chambers were used to test and evaluate individual mechanisms before they were installed into MOSFIRE. In this way the number of cool downs of the large MOSFIRE dewar was kept to a minimum. MOSFIRE is almost fully assembled and detailed acceptance testing is under way.

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