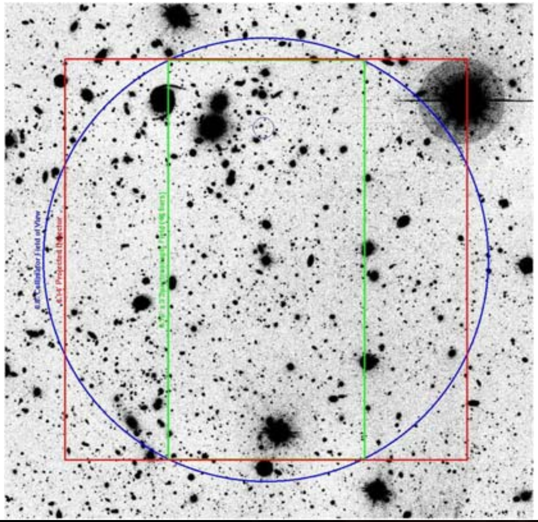

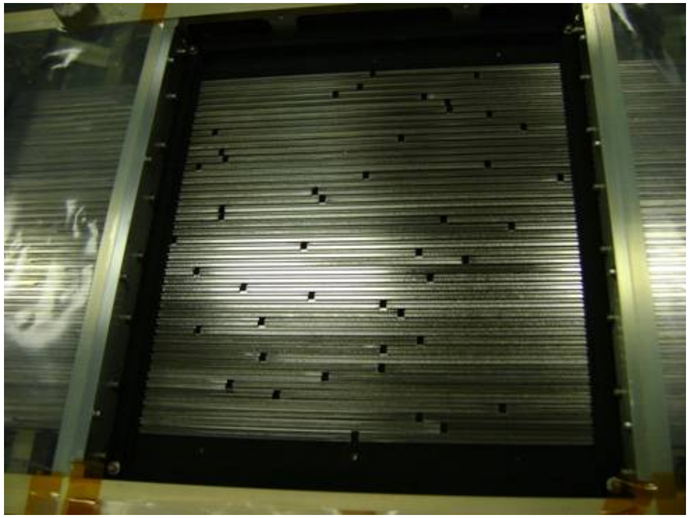

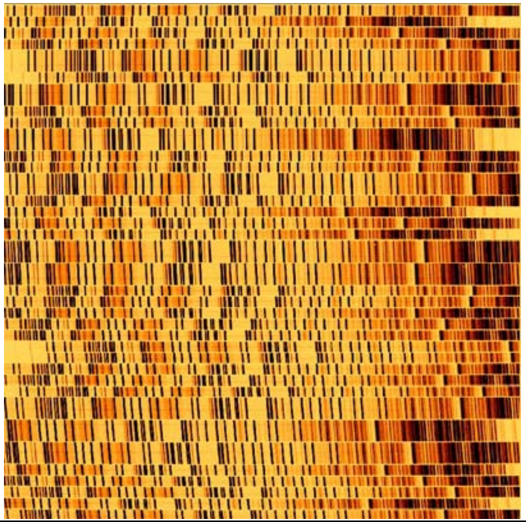

MOSFIRE

Multi-Object Spectrometer for Infra-Red Exploration

Pre-Ship Review

April 11, 2011

Version 2.0

W. M. KECK OBSERVATORY

Welcome to PSR

- **Review Board Members**
  - Tom Greene (NASA) - Chair
  - Dick Joyce (NOAO)
  - Jay Elias (NOAO)
  - Tetsuo Nishimura (Subaru)
  - George Jacoby (GMT)

- **TSIP Representatives**
  - Bob Blum & Mark Trueblood
- **WMKO Director**
  - Taft Armandroff
- Other invited guests and members of the WMKO staff

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AGENDA

08:30	Assembly/refreshments
09:00	Introduction – Sean Adkins (WMKO)
09:10	Overview – Ian McLean
09:30	Performance summaries
09:30	Overall scientific performance – Chuck Steidel
10:00	Optical, CSU and FCS – Nick Konidaris
10:20	Mechanical; shipping & handling – Bob Weber
10:40	Electronics & Systems – George Brims/Ian McLean
11:00	Software – Jason Weiss
11:30	Q & A session; working lunch – Lab visit? (12:30)
13:00	Installation plans – Mike Pollard (WMKO)
13:30	Commissioning plans – Chuck Steidel
14:15	Concluding remarks – Ian McLean
14:30	Executive session - Committee
16:30	Summary of review outcomes - Committee
17:00	Adjourn
18:30	Dinner

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OVERVIEW

Ian McLean

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What is MOSFIRE?

- **Multi-Object Spectrometer For Infra-Red Exploration (0.97-2.45 μm)**
- **It is a large vacuum-cryogenic instrument**
- **At the Cassegrain focus of Keck I, MOSFIRE will provide:**
  - Spectroscopy over a 6.12′ x 6.12′ FOV with a resolving power of R ~ 3,300 for a slit width of ~0.7″ (2.9 pixels); R~4,800 for a 0.5″ slit
  - Imaging over a FOV of 6.9′ diameter projected onto a 6.12′ x 6.12′ detector with 0.18″ per pixel sampling
  - Using one H2-RG detector with 2048 x 2048 pixels, MOSFIRE captures most or all of an atmospheric window in a single exposure for any slit placed within a 6.12′ x 3′ field; read noise <5e- rms (Fowler 16) and dark current <0.01 e-/s
  - A single diffraction grating is used in multiple orders (3, 4, 5 and 6) for K, H, J and Y respectively; two discrete grating angles are determined by fixed stops
- **MOSFIRE's multiplex advantage is achieved using a cryogenic Configurable Slit-mask Unit (CSU)**
  - Pairs of opposing bars configured under computer control are used to produce a slit mask *without* cryo-cycling of the instrument
  - Up to 46 slits (each ~7.0″ long) can be deployed; reconfiguration takes ~5 min

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Introduction

- The project began in July 2005, passed PDR in April 2006 and DDR in April 2007; these reports are on-line in public area.
- MOSFIRE is a multi-institutional project involving
  - California Institute of Technology (CIT)
  - University of California, Los Angeles (UCLA)
  - University of California, Santa Cruz, (UCSC)
  - W. M. Keck Observatory (WMKO)
  - In partnership with the Swiss Centre for Microelectronics (CSEM)
- Profs. Ian McLean and Charles Steidel are co-PIs
- Senior Co-Is are Harland Epps & Keith Matthews
- The project is managed for WMKO by Sean Adkins
- *MOSFIRE is funded by an award from TSIP and by a private donation to WMKO from Gordon & Betty Moore; we are very grateful for this generous support.*

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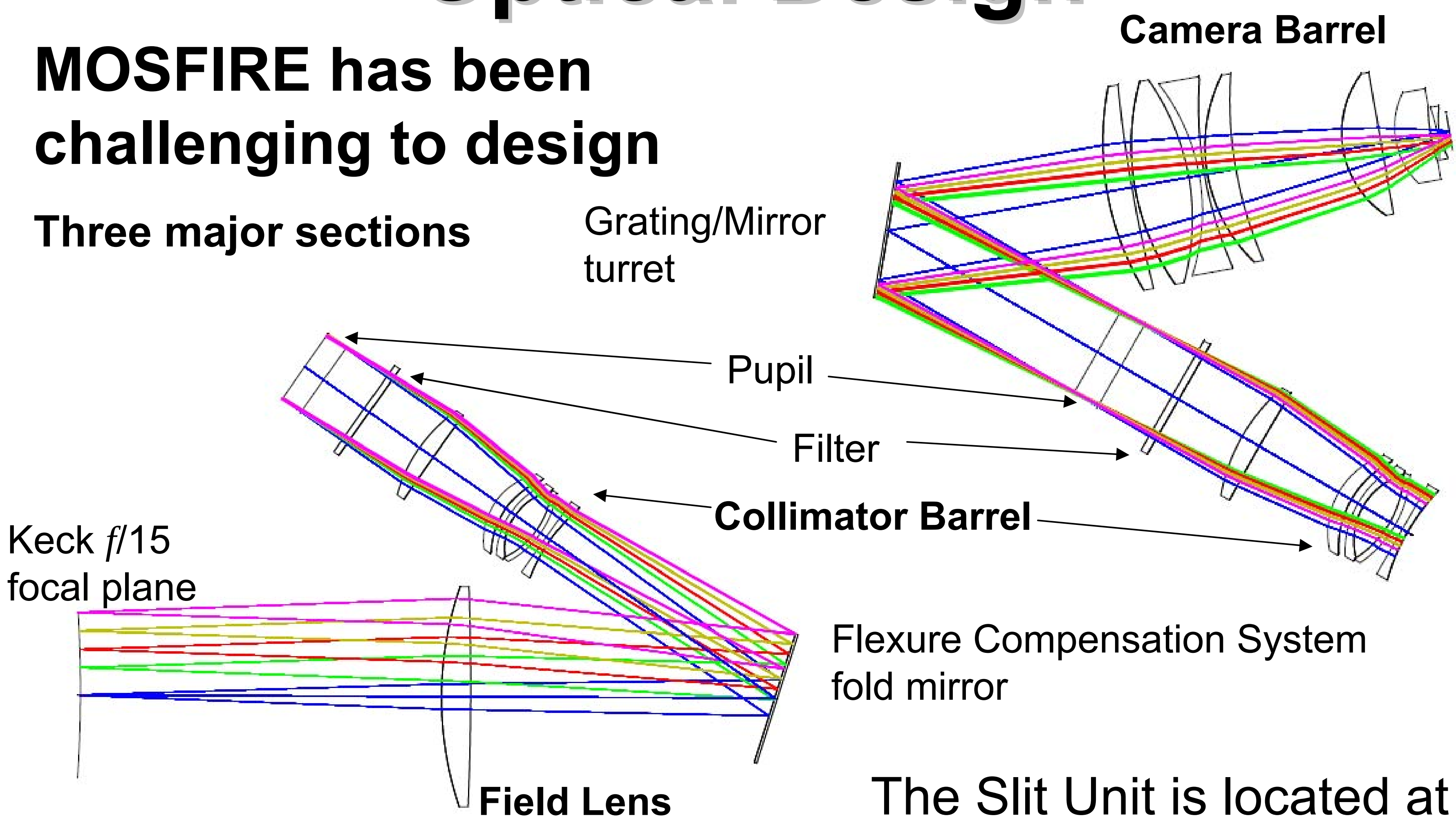
Development path

- Decisions made up-front to simplify MOSFIRE
  - *Choices consistent with KONSAG recommendations*
  - *Heritage when possible; early risk mitigation for others*
- Areas of highest risk identified and given priority
  - *Cryogenic Configurable Slit Unit (CSU)*
  - *Optical design; acquisition of optical materials, cryo indices*
  - *Mechanical flexure at Cassegrain focus*
  - *New ASIC-based detector*
- *Many problems were solved along the way*
- First light in the lab was obtained on July 1, 2010

Optical Design

MOSFIRE has been challenging to design

Three major sections



Entrance window not shown

The Slit Unit is located at the Keck *f*/15 focal plane

The following slides are from our 2010 SPIE paper

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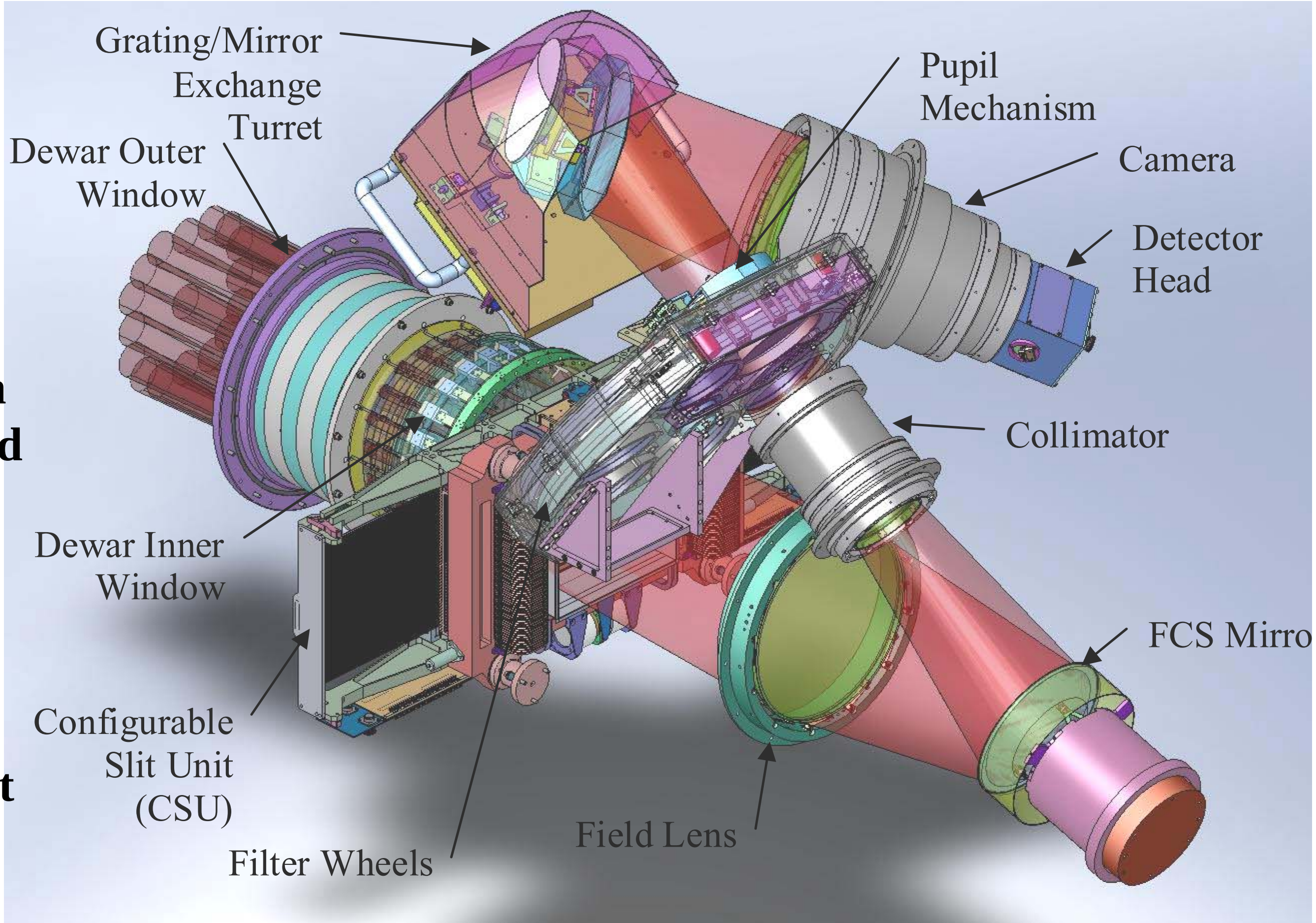
Optical layout

PHYSICAL LAYOUT:

- **Double-window**
- **Large Field Lens**
- **Flexure Compensation Mirror – Collimator fold**
- **Double Filter Wheel**
- **Rotating Pupil**
- **Grating/Mirror Turret**
- **7-element Camera**



Optical design by Harland Epps

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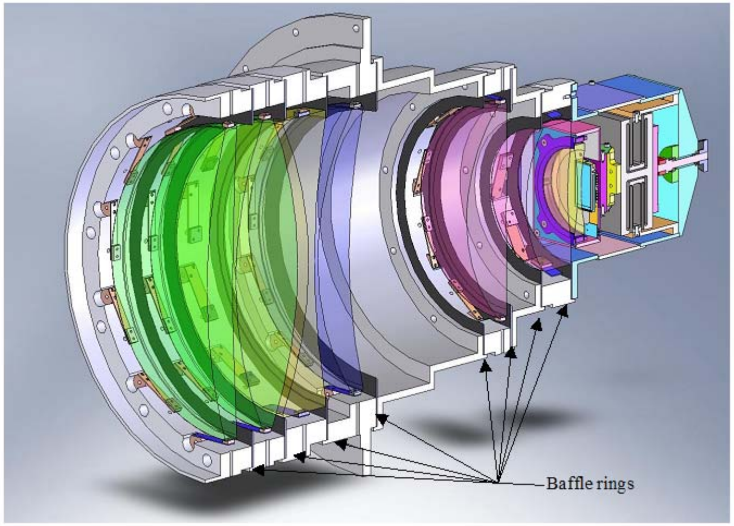
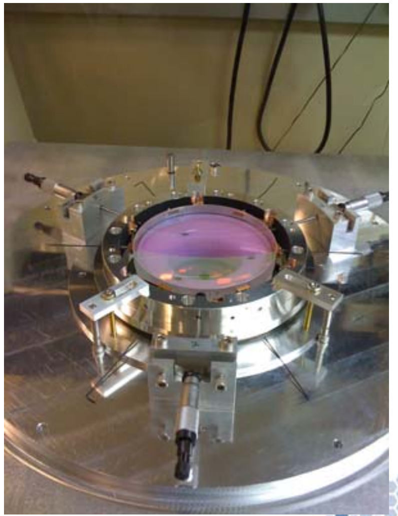
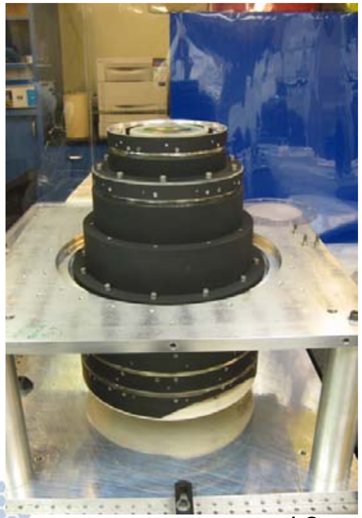
Optics fabrication and assembly

- Optimized for 120 K; fabrication dimensions calculated for 20 C
- Lenses ground and polished by Coastal Optics and coated by Evaporated Coatings Inc.
- Lenses stacked and spaced using a stationary Coordinate Measuring Machine (CMM)
- Subassemblies mounted into precise locations in MOSFIRE using a portable CMM







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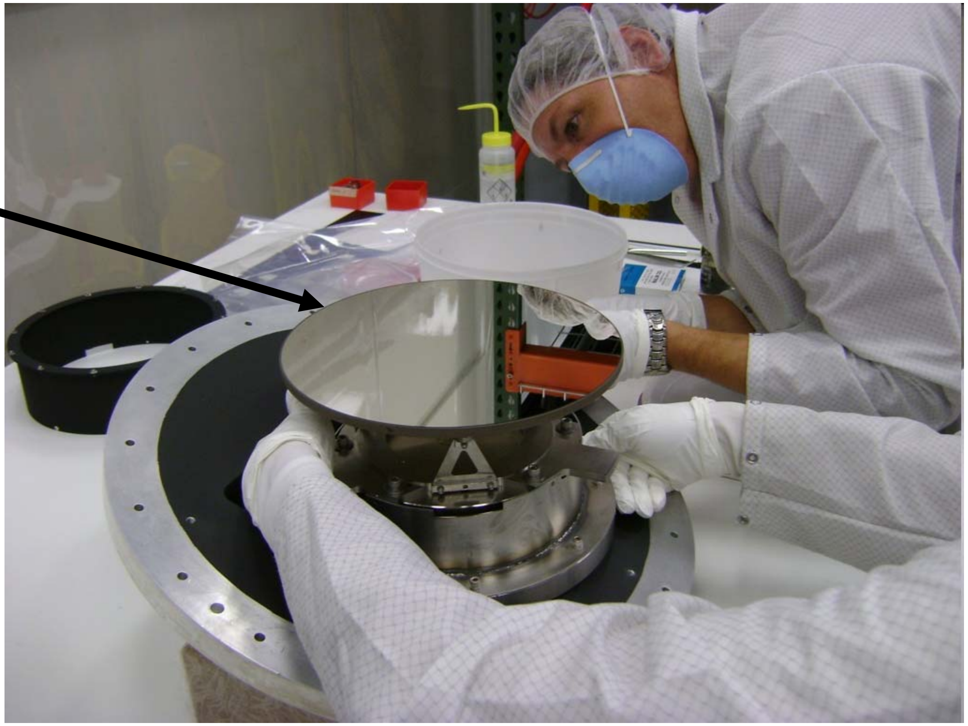
Installation of the optics

The collimator fold mirror goes onto the flexure compensation mechanism



The diffraction grating mounts back to back with the imaging mirror

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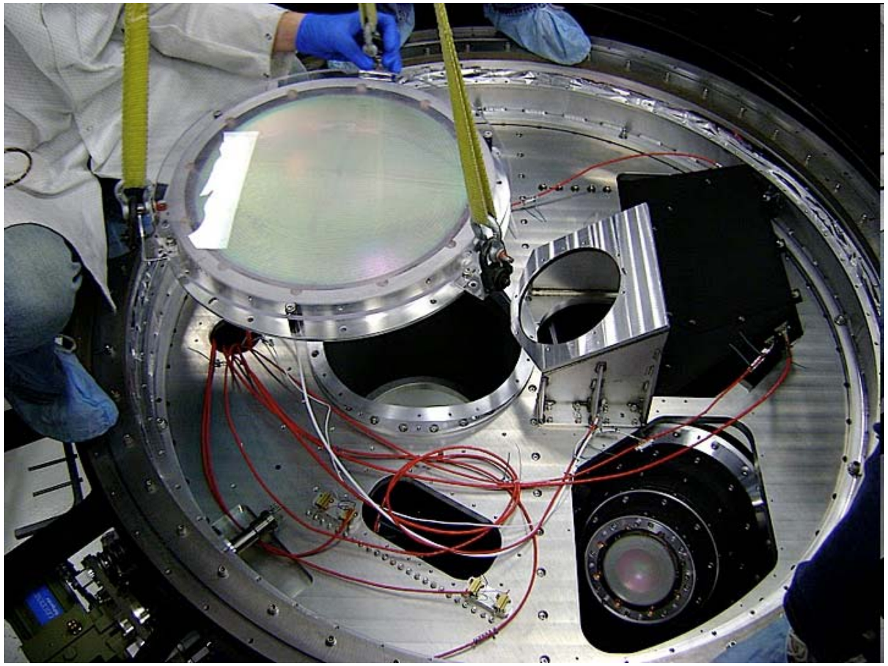
Installation of the optics

Installation of assembled Camera



Installation of Field Lens

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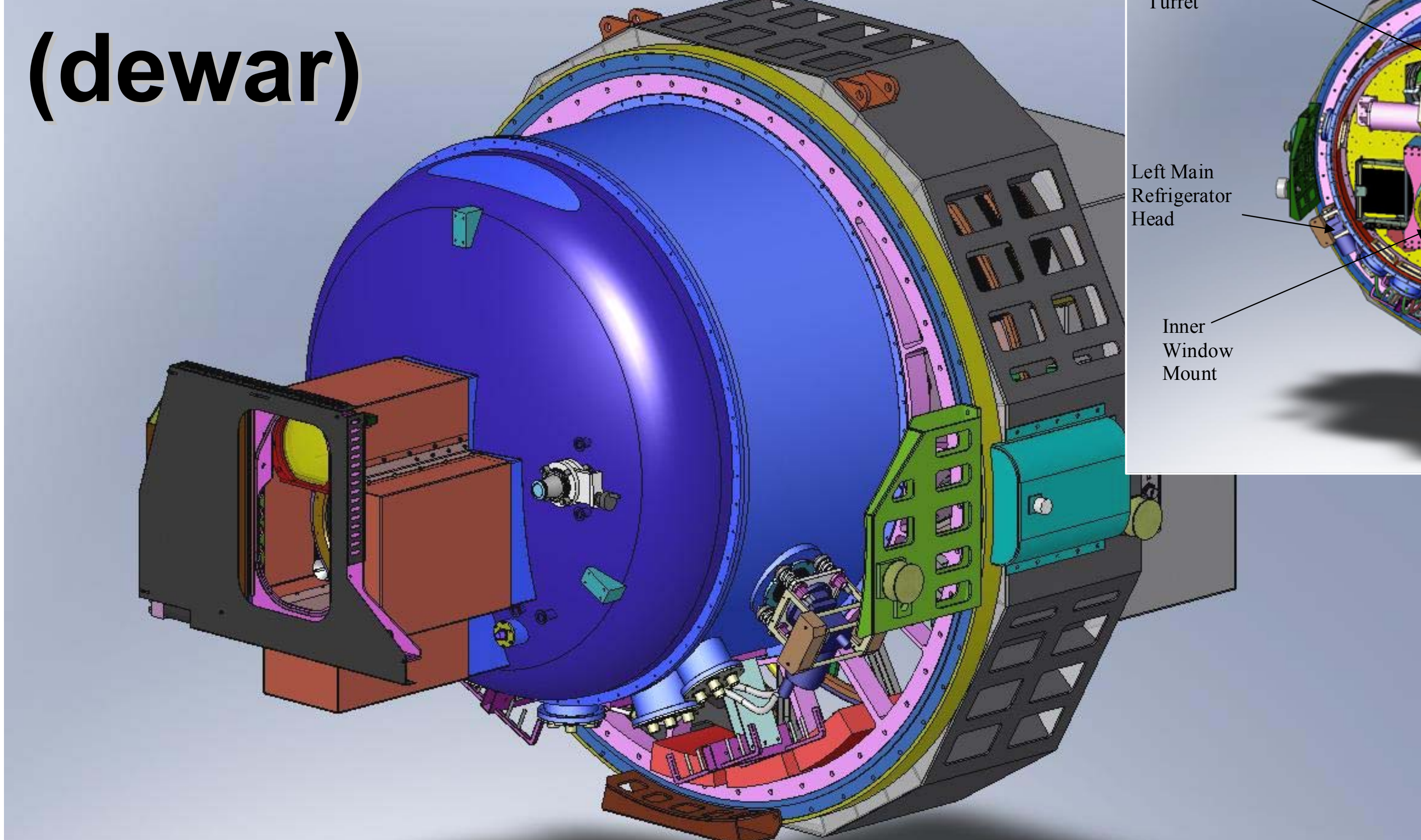
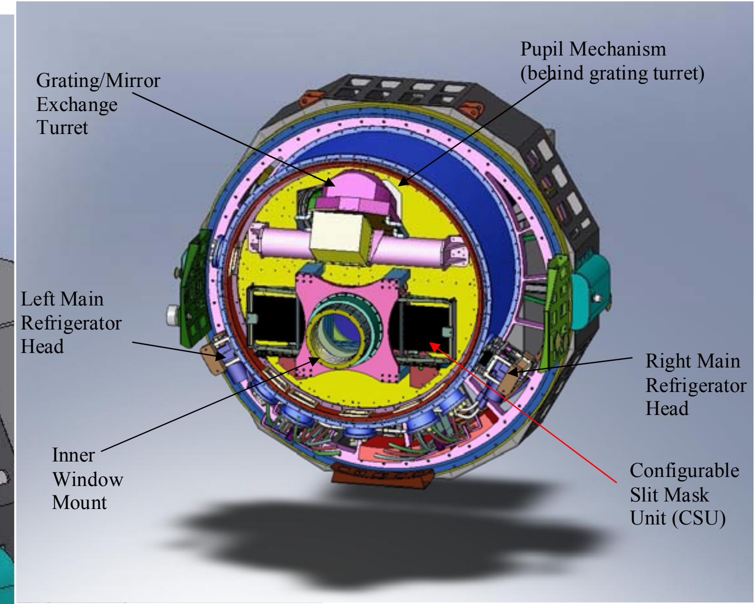
Vacuum Chamber (dewar)





Solid model drawing of the large vacuum enclosure (blue) which has a diameter ~1.5 m and fits inside the same volume as LRIS at the Cassegrain focus of Keck 1. The independent off-axis CCD guider is at the front. A cable wrap (black) and electronics cabinet (grey) are shown in the rear. MOSFIRE is cooled by three closed-cycle refrigerators. The insert shows a view with front cover removed to reveal the inner window, slit mask unit and grating/mirror exchange turret.

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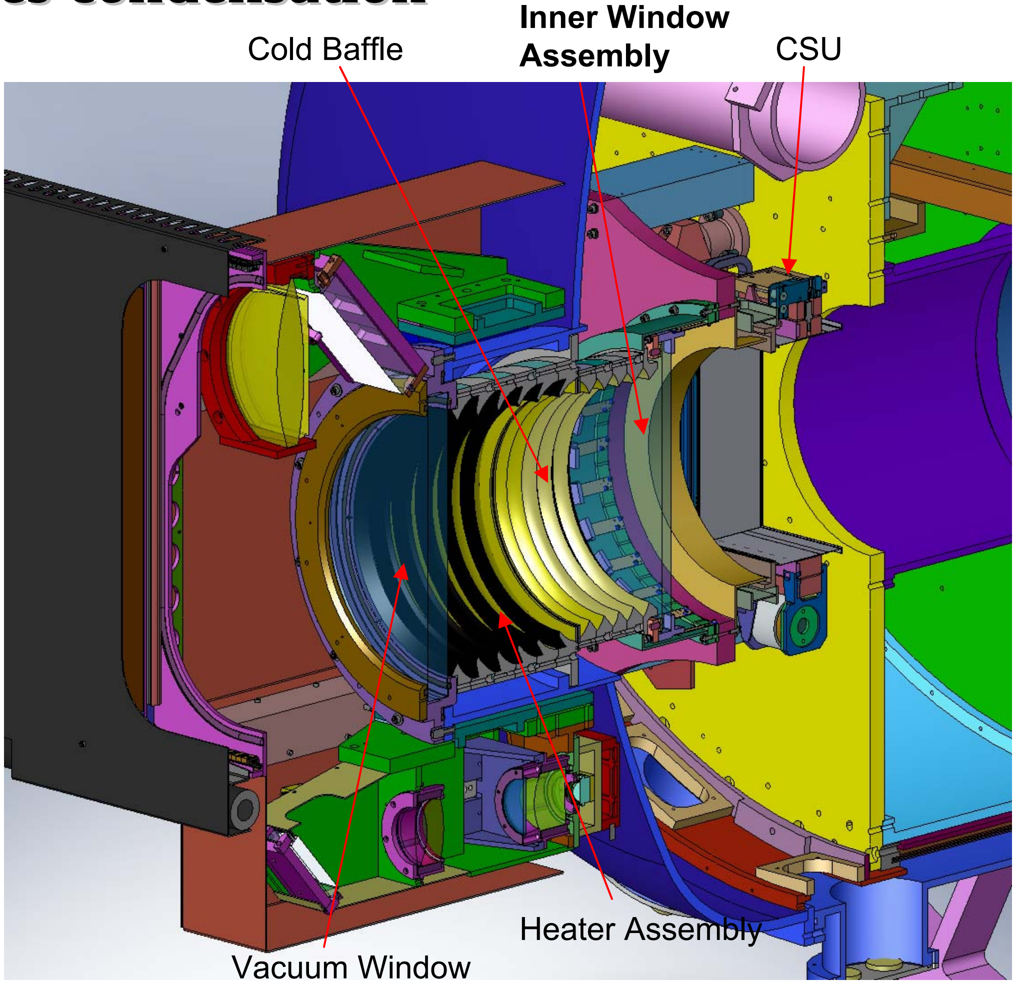
The Double Window

eliminates condensation

- A thick outer window provides the vacuum seal.
- ***A second inner window helps control thermal radiation from a heater in the snout tube.***
- Consisting of six stacked aluminum rings wrapped with resistive metal film heaters & MLI, the heater forms the inner lining of the snout tube and balances heat lost by the front window to the interior.
- A cold baffle, consisting of 5 stacked aluminum rings, lines the optical path between the heater and the inner window



Inner "window" acts as a radiation boundary

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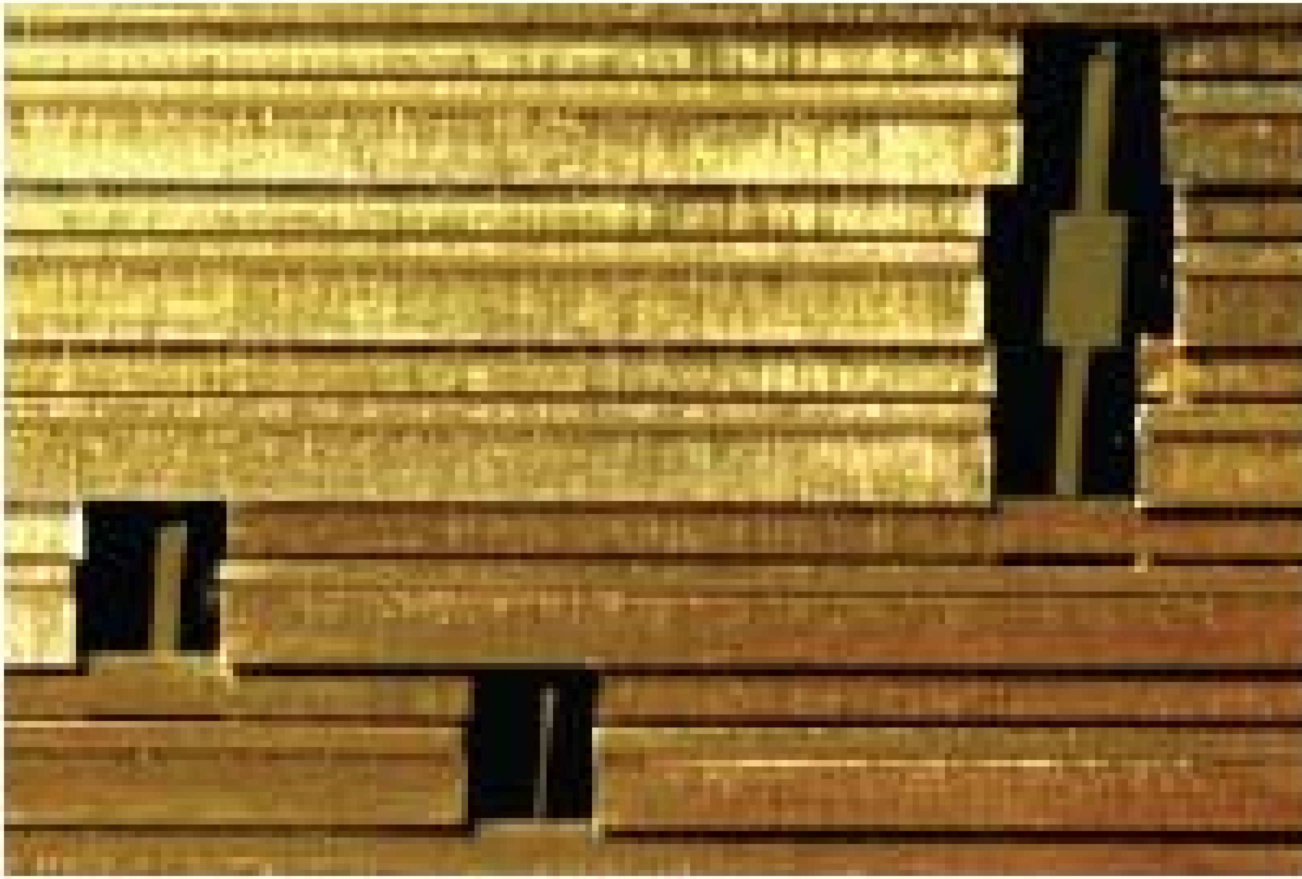
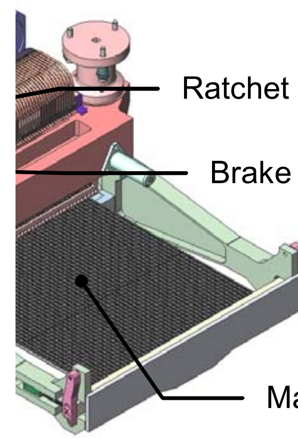
MOSFIRE’s Cryogenic Slit Mask Unit

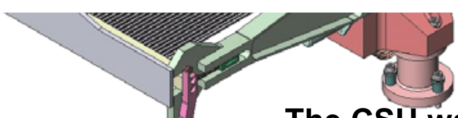
The aperture is 267 x 267 mm.





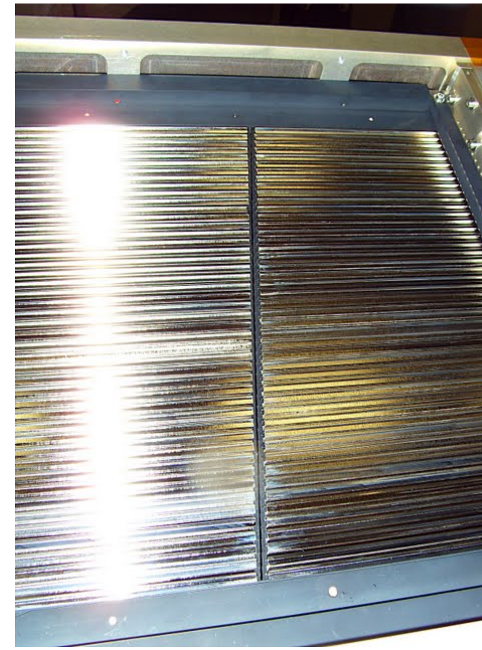
THE MOSFIRE CSU

Pairs of opposing bars configured under computer control produce a slit mask without cryo-cycling of the instrument



The CSU was developed by the Swiss Center for Electronics and Micro-technology (CSEM)

Closing on June 11, 2010



Long slit

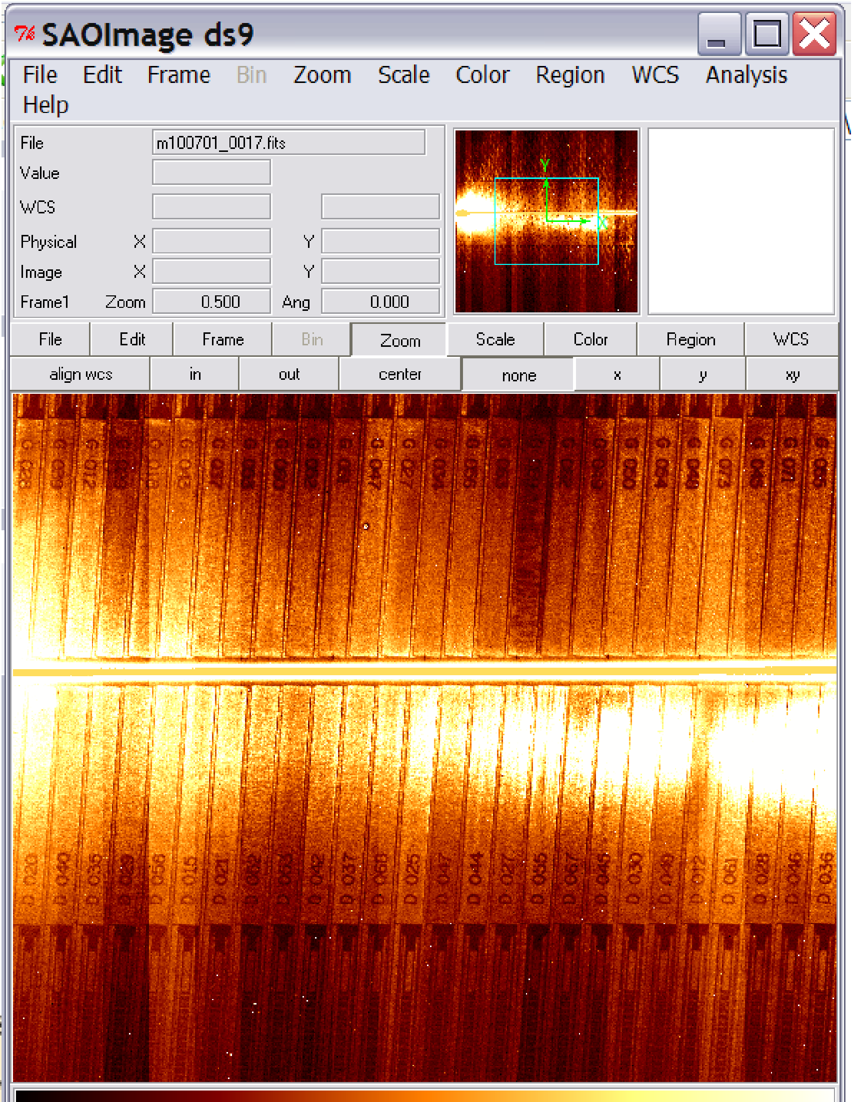
H-band filter in beam

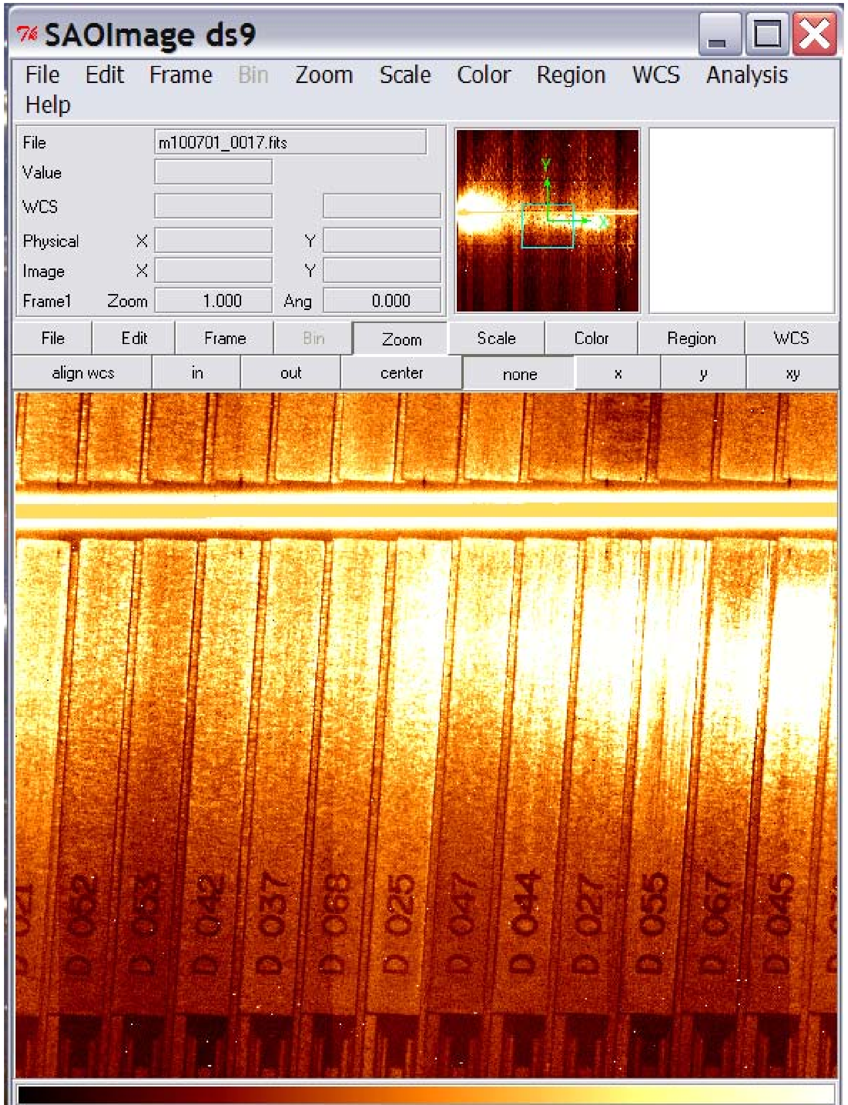
Imaging mode

Hexagonal pupil

July 1, 2010 - First Light!

Slit flooded with light. We can read slit bar numbers on the back side of the bars by scattered light. Focus looks good!





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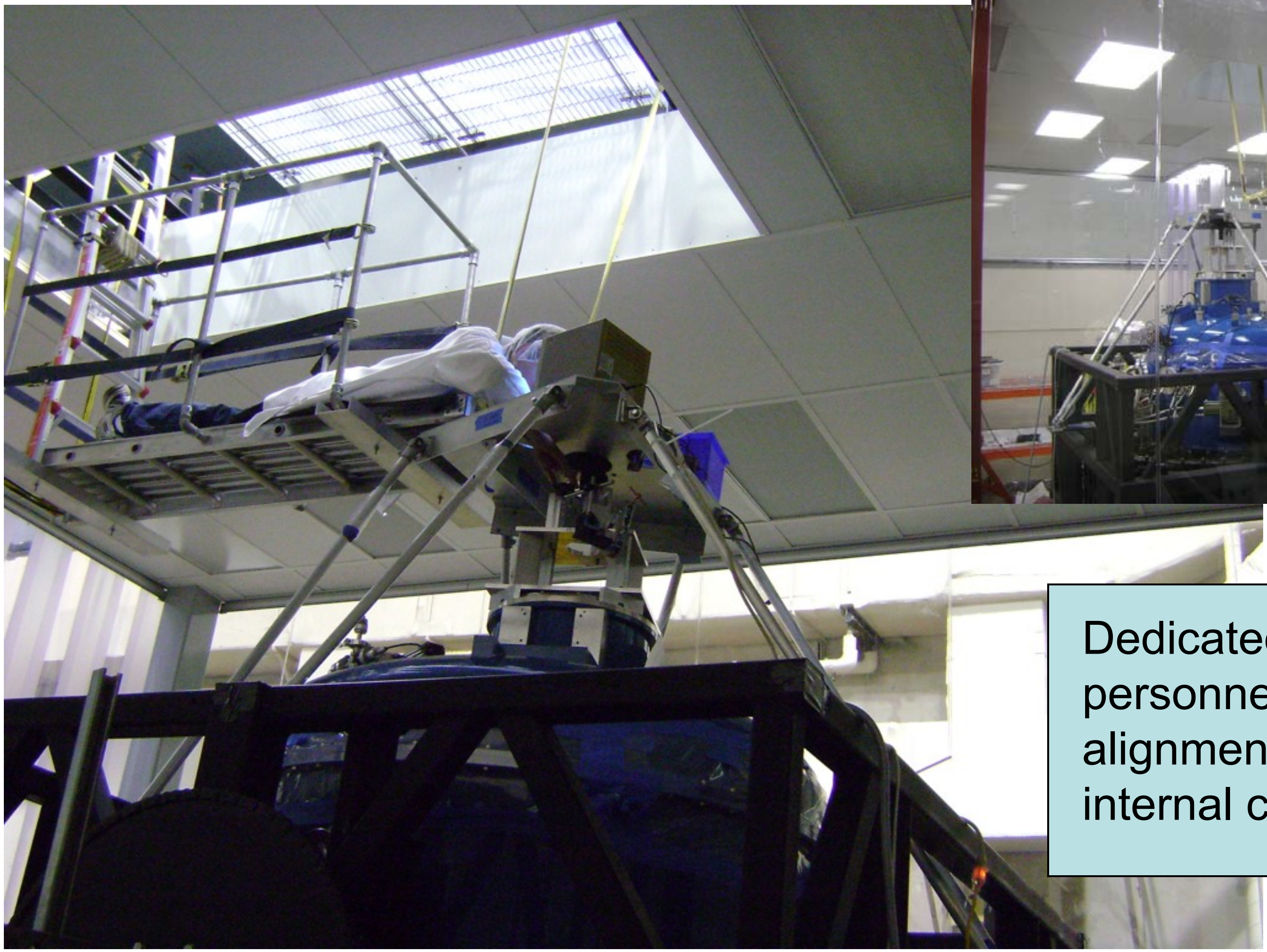
Cool Down Cycles

- **1 & 2**: thermal/vacuum performance
- **3 & 4**: first trial of CSU (no optics or detector)
  - fold-mirror alignment using cross-hairs
  - problems with masking bars and power supply in CSU controller
- **5**: first light in lab (July 2010)
  - SPIE paper presented; problem with one masking bar
- **6**: "2nd light" following remounting of field-flattening lens
  - curtailed by thermal short (fixed for next cool down)
  - still having problems with one masking bar
- **7**: discovered four light leaks (fixed for next cool down)
- **8**: CSU removed and pinhole mask inserted
  - flexure and optical performance measured; acceptance testing
  - CSU refurbished by CSEM in parallel
- **9**: CSU re-installed. **All cryogenic systems operational**

COOL DOWN #3



Dedicated and daring personnel check cold alignment of MOSFIRE's internal cross hairs.

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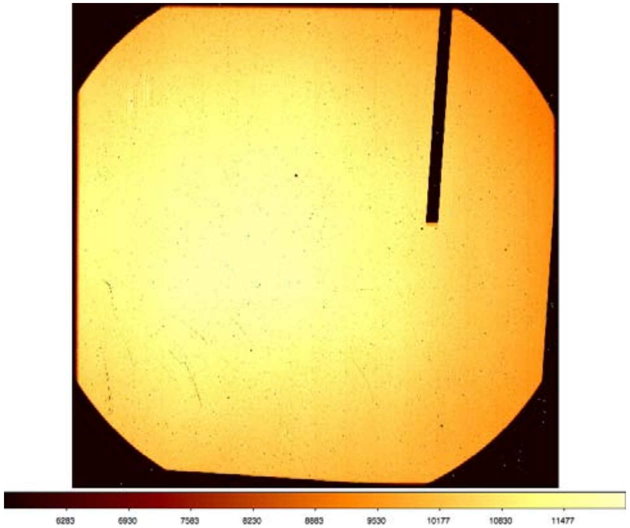
Cool Down 5

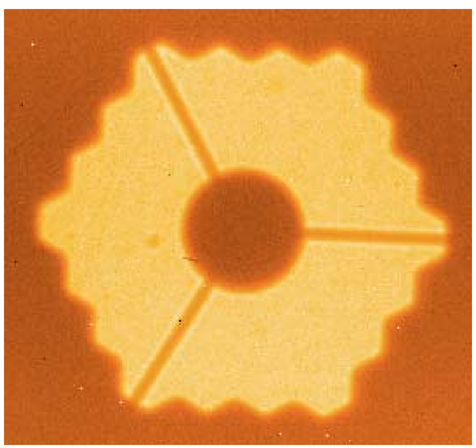
- **Highlights of testing**
  - Excellent optical performance demonstrated
  - CSU performed over 500 mask configurations, one stuck bar (#69) began working at the end of 4 week cool down
  - Charge persistence, excess dark current (or is it?)
  - Coordinate centers not quite congruent; detector rotated
  - Iris blades in pupil mask did not deploy fully
- **After cool down 5**
  - Refined alignment – grating tilted and mirror tip/tilted
  - Detector Head clocked by 4°
  - Added stronger springs to pupil mask mechanism
  - *Decided to change field-flattener lens mount in Detector Head*

CSU and Pupil issues



CSU reliability: This bar was stuck for some time but eventually moved freely again. The source of the problem is believed to be small amounts of magnetic debris sticking out from the permanent magnets in the CSU clutch and brake coils and causing friction. Debris comes from hairline cracks in the magnets caused by thermal cycling.

SSC asked for a Review – held on October 5



Pupil reliability: For optimized operation in K-band the pupil closes down to the serrated hexagon shape of the telescope aperture and tracks the pupil image as the instrument rotator compensates for field rotation. The iris blades don't close all the way down reliably due to excess friction.

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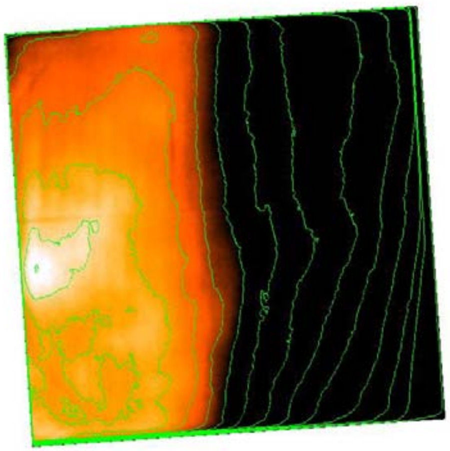
Cool Down 6

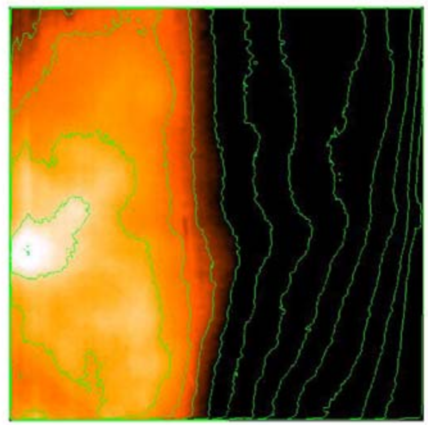
- **Highlights of testing**
  - *Terminated early because of thermal short in modified detector head*
  - When focus was backed off, the detector went to its correct temperature; images were softer but still good enough for testing
  - Confirmed grating/mirror alignment adjustments were correct
  - Confirmed detector clocked in correct direction, but overshoot 0.25°
  - CSU operated with intermittent problems from bar 75, but *not* stuck
  - Iris in pupil mask mechanism still not closing all the way
- **After cool down 6**
  - Fixed thermal short; caused by error in new lens mount design
  - Removed pupil mask mechanism; more extensive rework identified
  - Replaced pupil mask mechanism with temporary circular mask
  - Adjusted detector clocking angle by 0.25° back
  - Compared "dark" frames in cd 5 and cd6 after detector rotation …

Light Leaks!

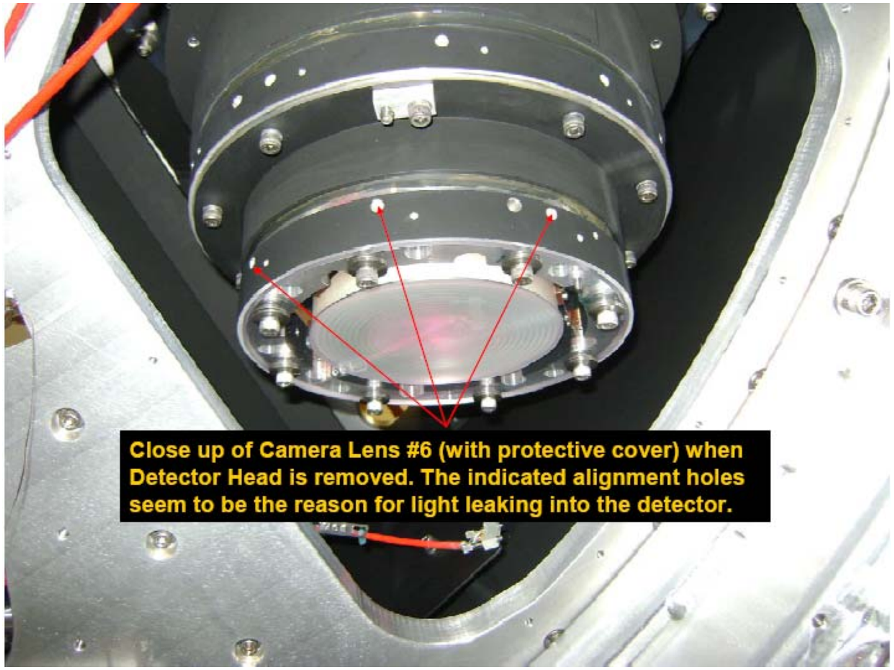
This is not a detector charge persistence issue after all



Cool down 5

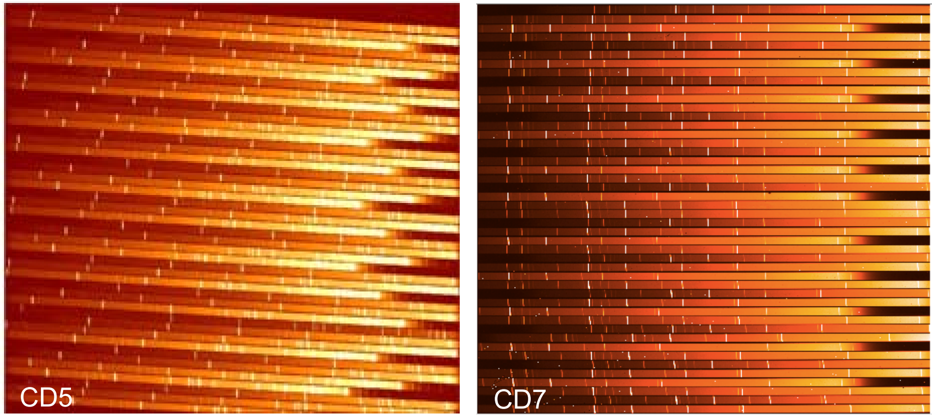


Cool down 6



Light leaks: After a rotation was applied to the detector it was noticed that a pattern seen in dark frames remained fixed as if due to light leakage from <u>before</u> the detector. The signal patterns on the detector are NOT due to charge persistence or dark current but due to stray thermal radiation. MOSFIRE is not light tight! We blocked holes in the Camera Barrel for cd7.

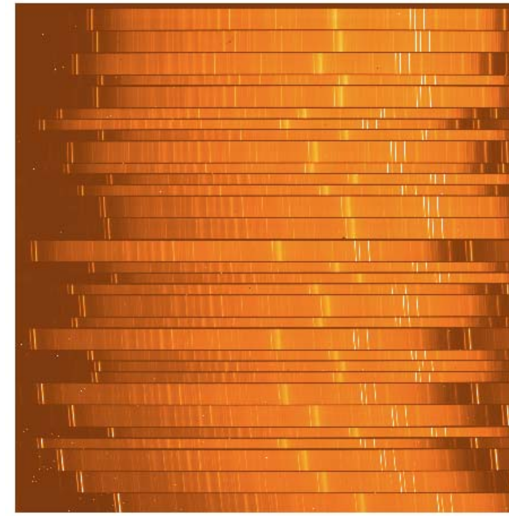
Cool Down 7

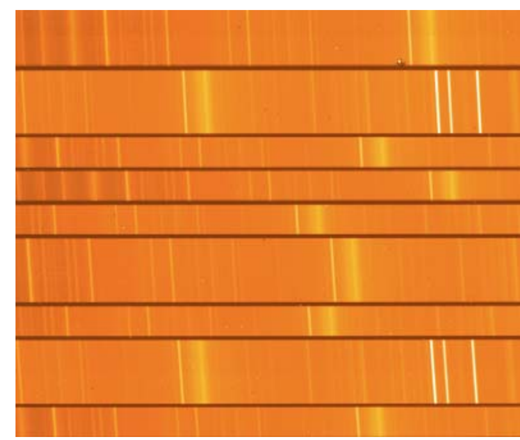


- **Highlights of testing**
  - Alignment is now excellent
  - ***One focus works for all bands and all parts of the field***
  - Blocking of holes in Camera Barrel reduced stray light by 30% only
  - Found more serious light leaks by extensive testing; heated certain parts of the instrument; leaks at front snout and at all 3 CCRs
  - CSU operated well except for bar 75 which remains unreliable
  - Completed extensive flexure testing and modeling
  - Flexure is ~20% larger than in cd5; only change was to detector head (DH) which implies some flexure is in the DH
- **After cool down 7**
  - Light shields designed for front end and for each CCR head
  - Modeled DH flexure – added stiffening
  - Removed CSU for “cleanup” and installed pinhole mask

Cool Down 8 and 9

- **Cool Down 8**
  - Pinhole mask
  - Extensive evaluation of flexure; FCS works
  - Optical testing
  - Began software acceptance testing
- **Cool down 9**
  - CSU and pupil mechanism re-installed
  - CSU re-calibrated; flexure re-checked
  - **All mechanisms reliable – no failures**
  - Filter wheel 1 moved ~1400 times
  - Filter wheel 2 moved ~270 times
  - The grating turret moved ~780 times
  - The shim moved ~170 times
  - PM executed over 200 slews & 40 hours tracking
  - CSU Formed ~500 masks
  - **Extensive acceptance testing**





Fun spectra

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Compliance Summary

- The desired wavelength range (0.97-2.45 μm), resolving power, FOV and pixel scale (0.18″) have been obtained
- Pinhole tests show that image quality <0.25″ rms diameter images over the entire field as required
- Detector performance gives 4.9 e- rms with 16 reads and dark current is <0.008 e-/s/pixel in 1800s frames as required
- Throughput using as-built parameters for the optics and detector yield >30% average over the full bandwidth which exceeds requirements
- Repeatability of grating positions is 0.1 pixels or better as desired
- Spectra are aligned to detector rows to 0.08°
- CSU provides 46 slits using 92 bars; each slit is 7.01″ long with an overlap region of 0.96″ to minimize light leakage; the slits are repeatable to <0.03″. All cryogenic mechanisms reliable.
- Flexure compensation maintains image positions to <0.1 pixels rms for elevation angles >22° as desired
- The instrument cools down in ~8 days and can withstand a 1 hour power shutdown as shown in **Figure 2** of the report

Results of 1 hour power off test

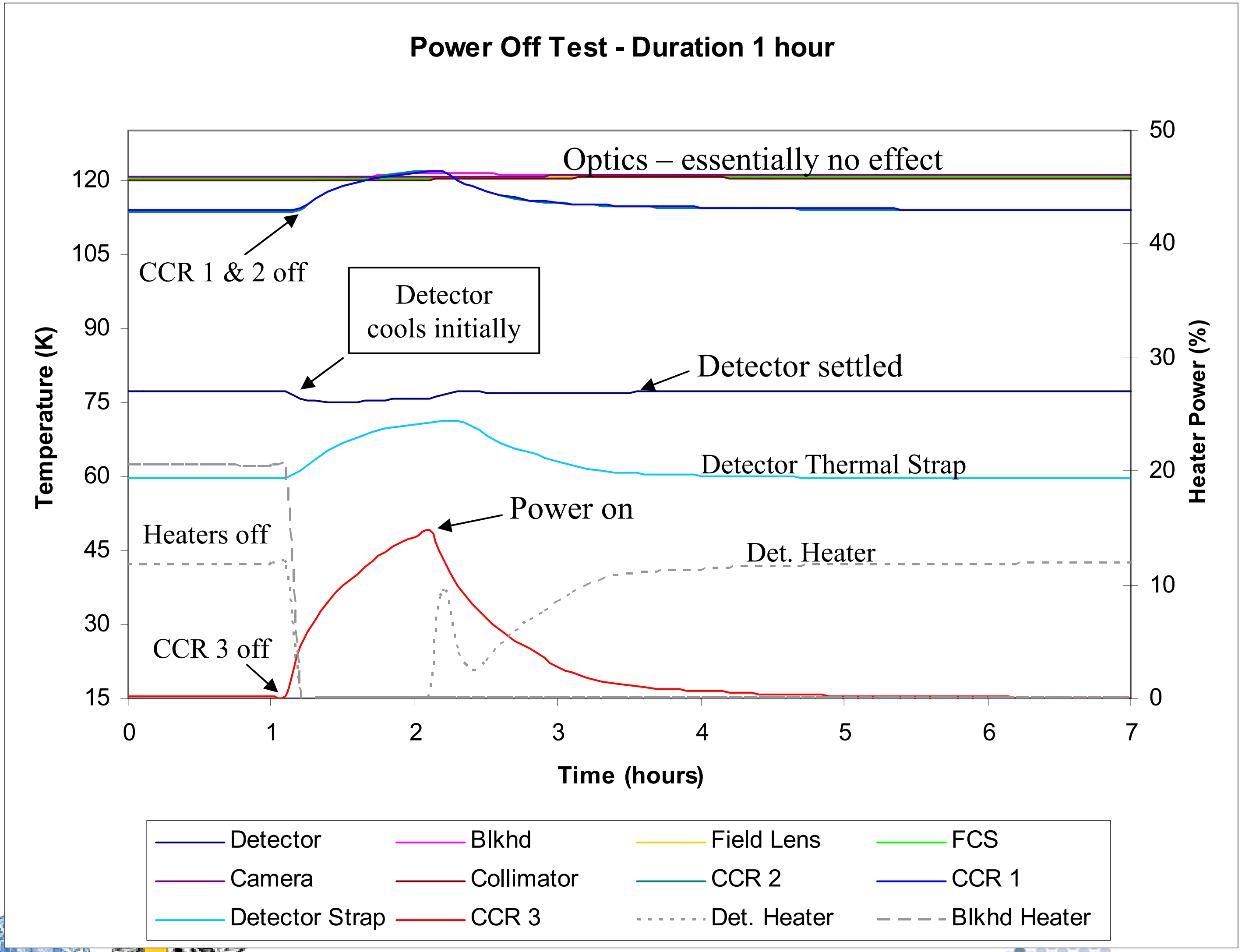

Figure 2: power off test

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Power Failure Tolerance

- **Figure 2** shows that the detector temperature changed by ~2 K, but returned to the set point temperature (77 K) within 90 minutes when power was restored.
- For the optics, the highest temperature rise was 0.7 K at the Field Lens and the smallest rise (0.46 K) was seen on the Camera Barrel.
- These variations are not sufficient to degrade the instrument's optical performance or cause a measurable increase in the background level.
  - Long dark frames taken when the Camera Barrel was at 140 K are barely different from those taken at 120 K.
- The temperature changes observed are well below the level that the design analysis indicates would result in any component damage.
- Only a small (1 K) change in the temperature of the outer window was observed during the test, as determined by an IR camera.
- Thus, Figure 2 confirms that MOSFIRE can return to normal operation within 90 minutes of being installed in the Cassegrain cage and power being restored.

STATUS OF MOSFIRE

- **All Level 1 requirements met or exceeded**
  - FOV, wavelength range, resolving power, multiplex advantage
  - Image quality and throughput are excellent in all modes
  - Detector performance is excellent; over 24,000 images taken
  - Mechanisms are reliable; CSU works
  - Thermal performance as predicted
  - Flexure correction is successful; over 2,000 measurements taken
  - Guider and Cal Unit functional
  - Stability and Repeatability excellent
  - Following cleaning & refurbishment, the CSU is 100% operational
  - Software is user friendly
- **We have come a long way**

ERVATORY

Performance Summaries

MOSFIRE Team

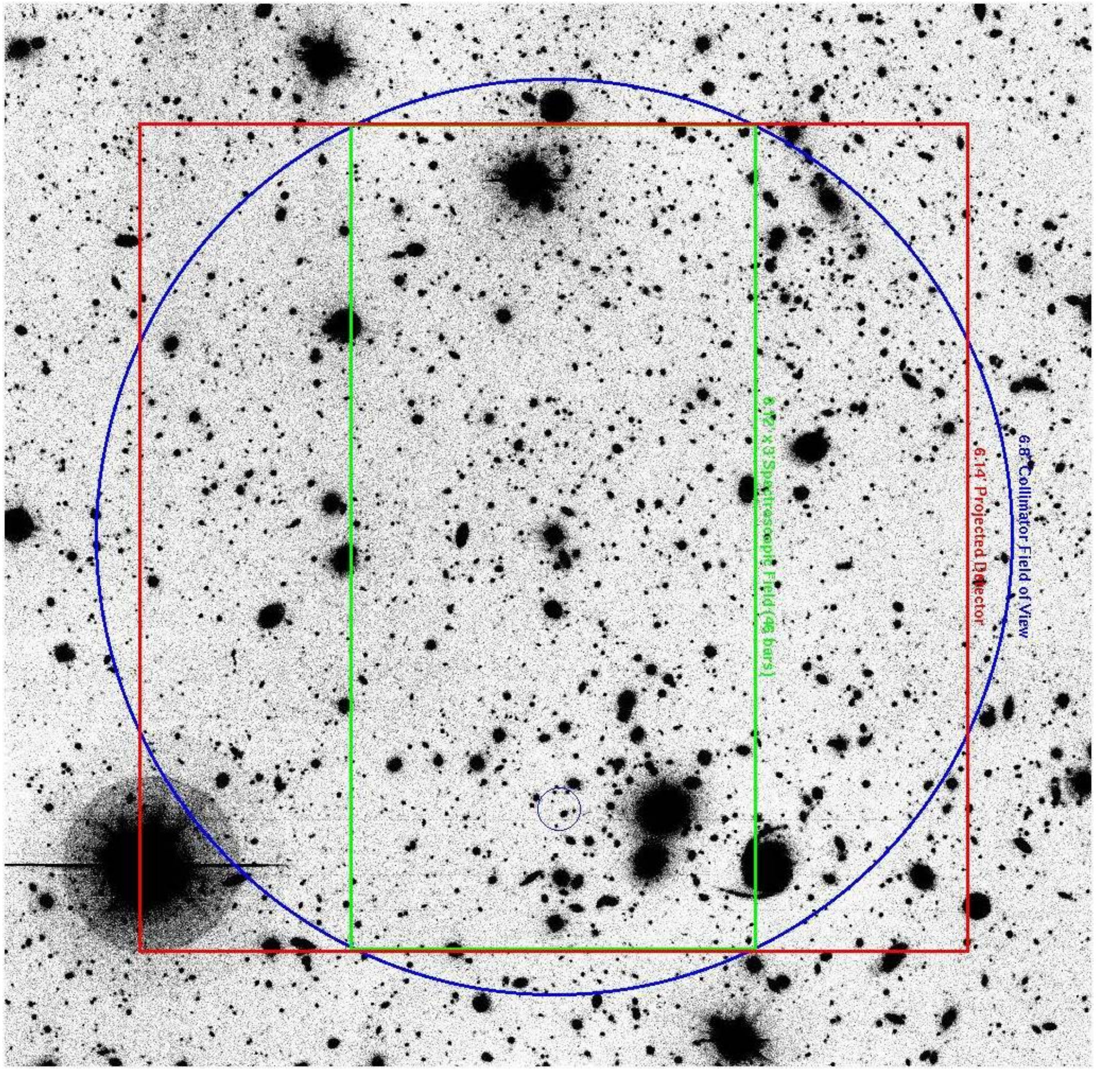
W. M. KECK OBSERVATORY

Overall performance to meet science requirements

Chuck Steidel

W. M. KECK OBSERVATORY

MOSFIRE Field Configuration



Blue: 6.8′ diameter collimator field of view

Red: 6.12′ x 6.12′ projected detector

Green: typical 6.12′ x 3′ spectroscopic field

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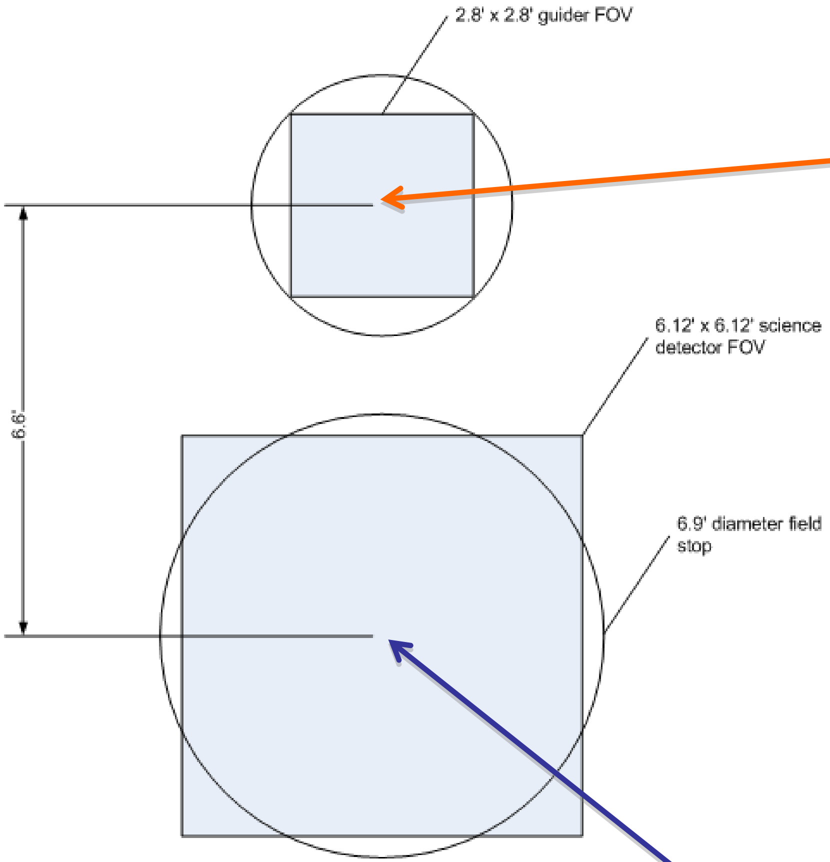
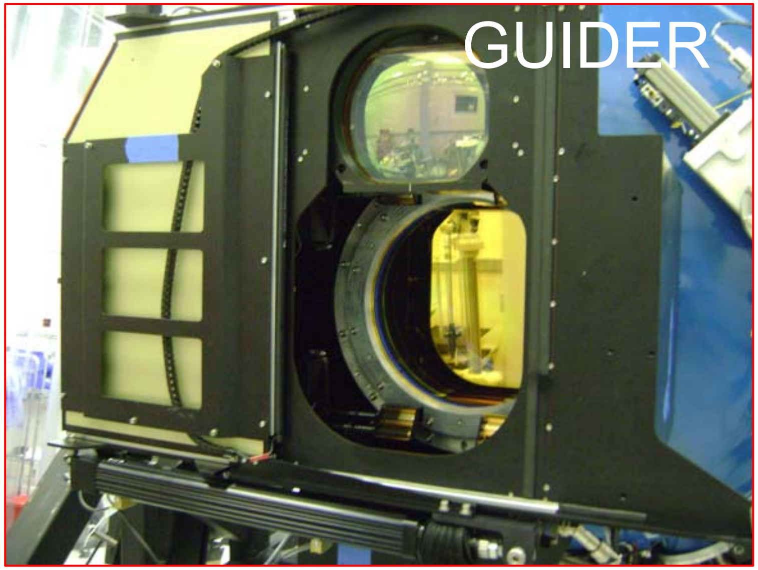
MOSFIRE Guide Field



Optical (RG780) guider field centered 6.6’ from telescope optical axis



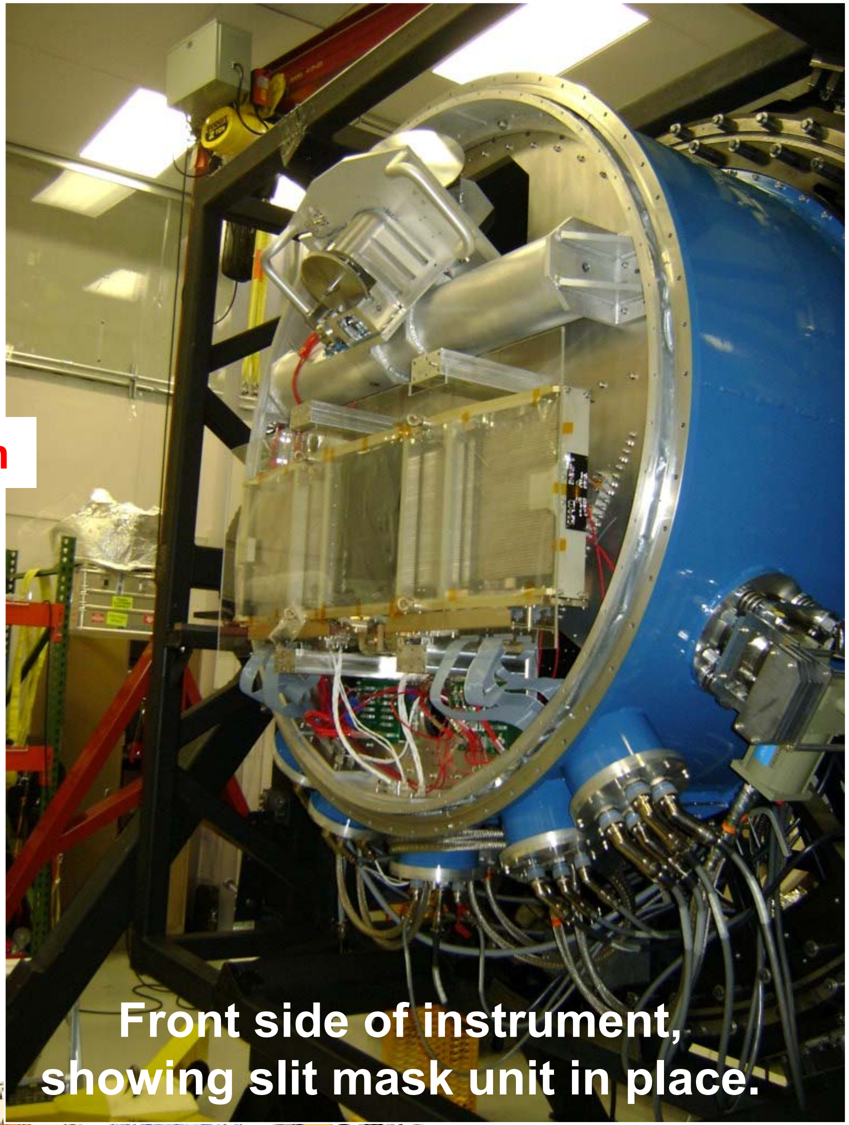
Science field centered on the telescope optical axis

MOSFIRE CSU
(Configurable Slit Unit)

Swiss Center for Microelectronics (CSEM)

CSU installation and testing

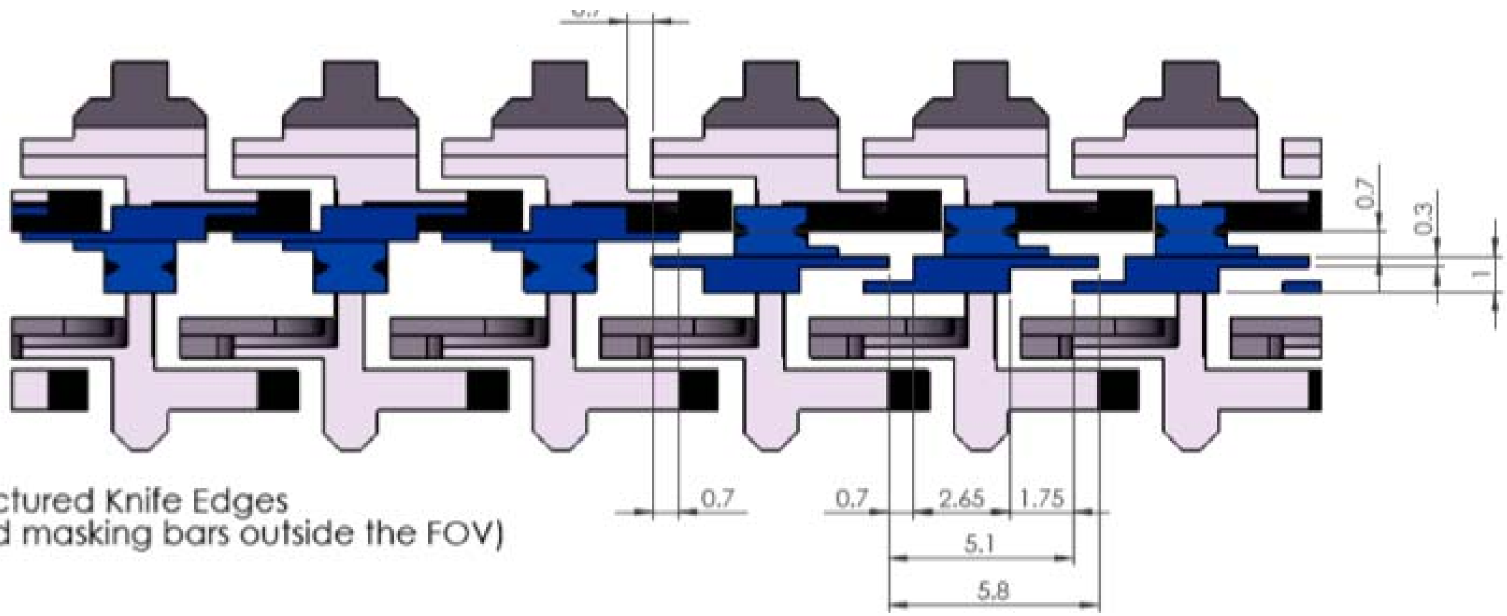
1.5m



Front side of instrument, showing slit mask unit in place.

Rear side, showing electronics cabinet (open) under test.

CSU Masking Bars



Manufactured Knife Edges
(stiffened masking bars outside the FOV)

Comparison of the main Knife Edges dimensions
MosFire CSU/PSc/18.07.08

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CSU Masking Bars

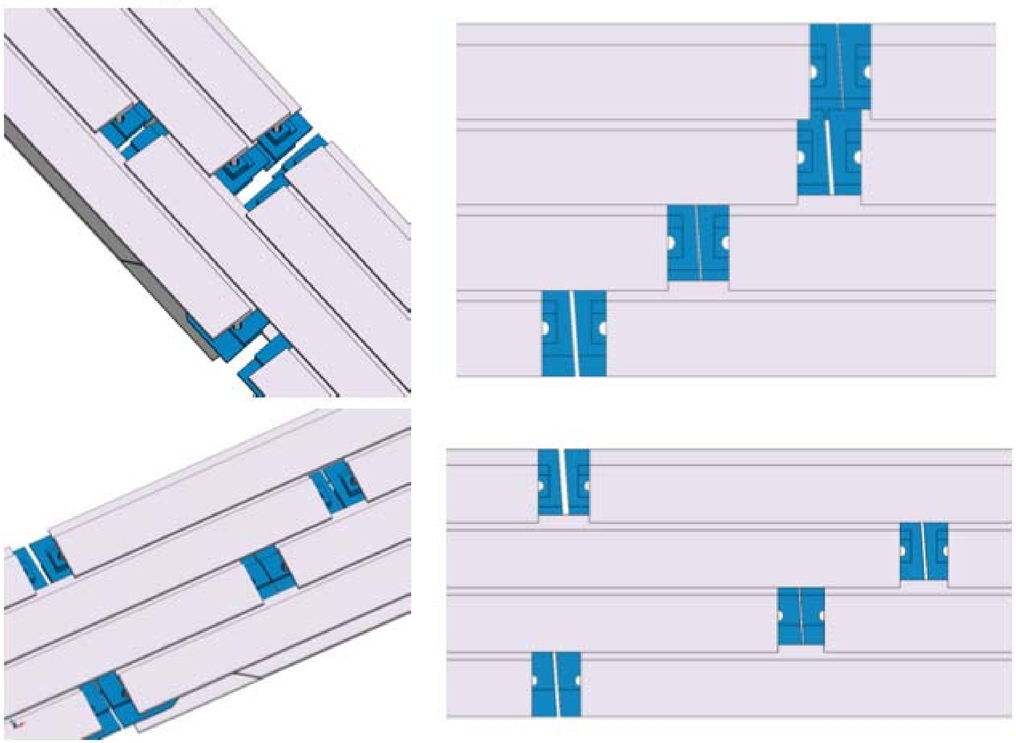
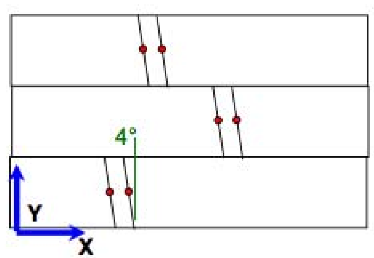


Figure 5–8 Slit creation with bars

The masking bar tips equipped with a knife edge incorporate an angle of 4° as shown below:



- Bar positioning accuracy requirement ±36μm (0.05″)
- Knife edges uniform to ~5μm rms
- Infrared black
- Four degree tilt angle

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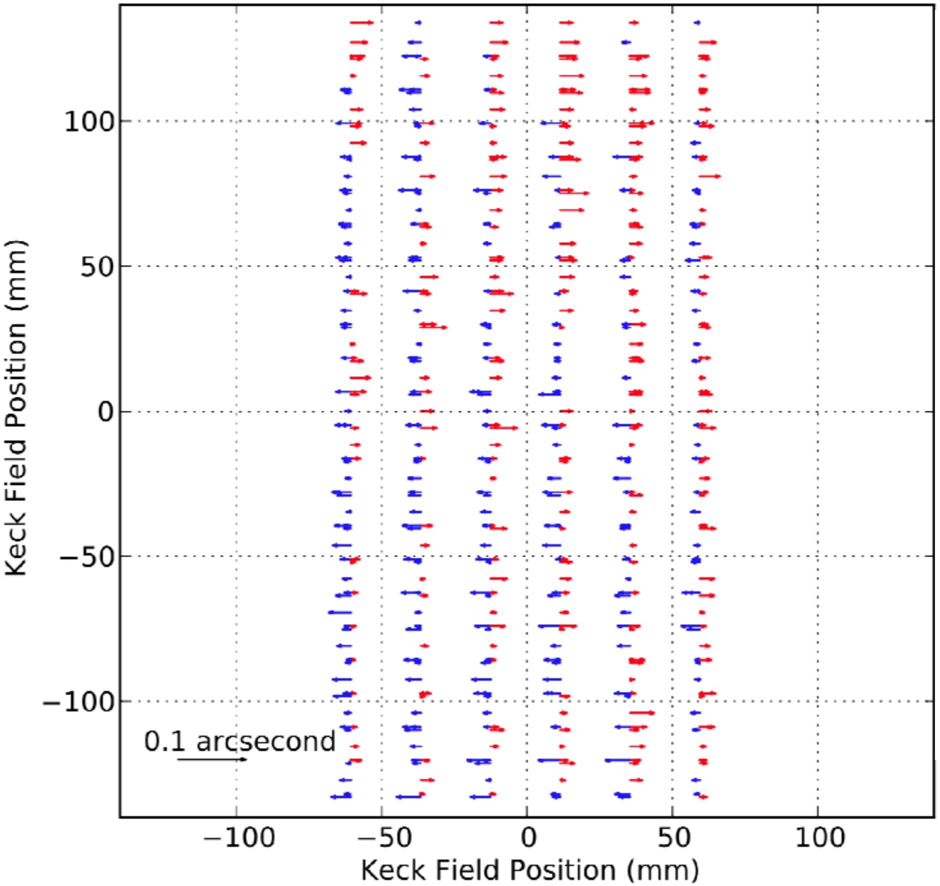
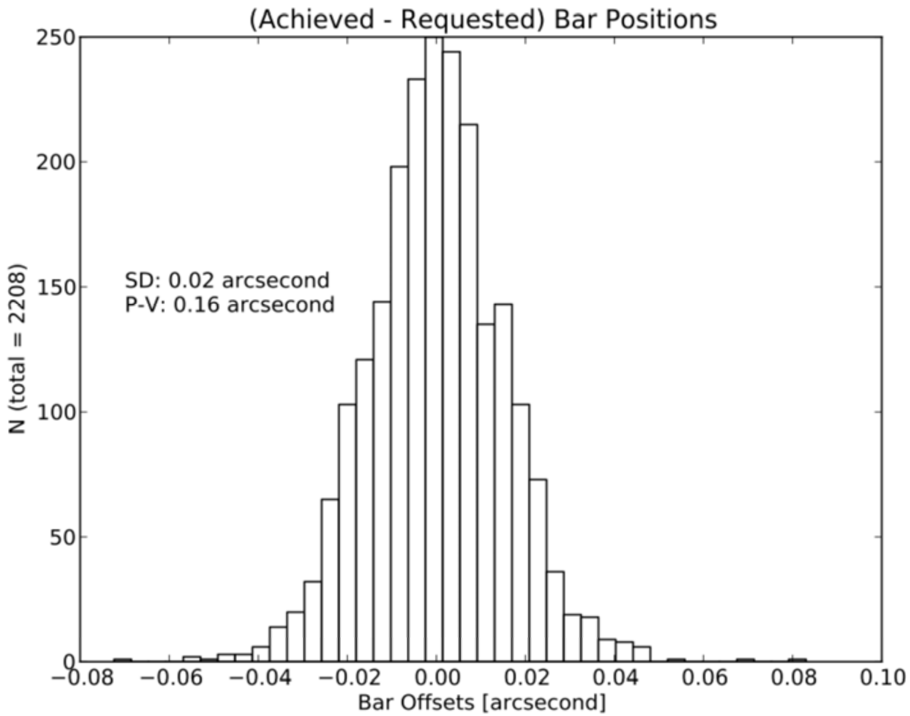
The CSU Works!

(rms~ 0.02″ precision)





This plot will be discussed again later.

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Field of View

- The angular size of the sky area imaged on the detector is limited by:
- projected detector: 2040 pixels x 0.1798"/pixel=366.8" square on the sky
- the CSU square baffle sized to match
- a circular baffle in front of the field lens just after the CSU (d = 414″ = 6.9′ ~unvignetted collimator field of view)
- Geometry of illuminated region shown here
- Slits can be placed anywhere within a rectangular 3.0′ by 6.12′ region without vignetting as illustrated in **Figure 3**.

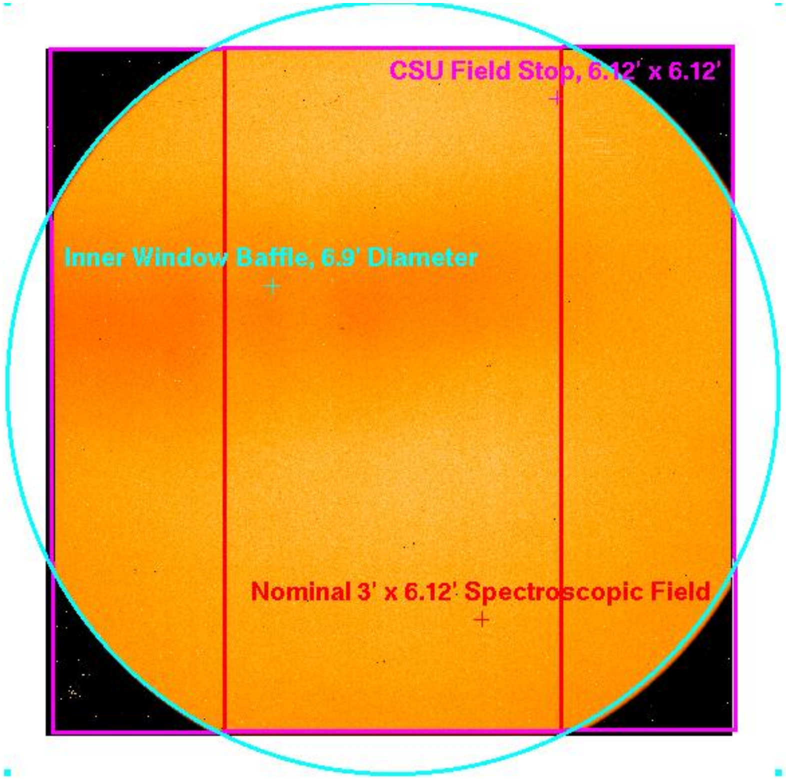

Figure 3: MOSFIRE FOV. The orange area is the illuminated region.

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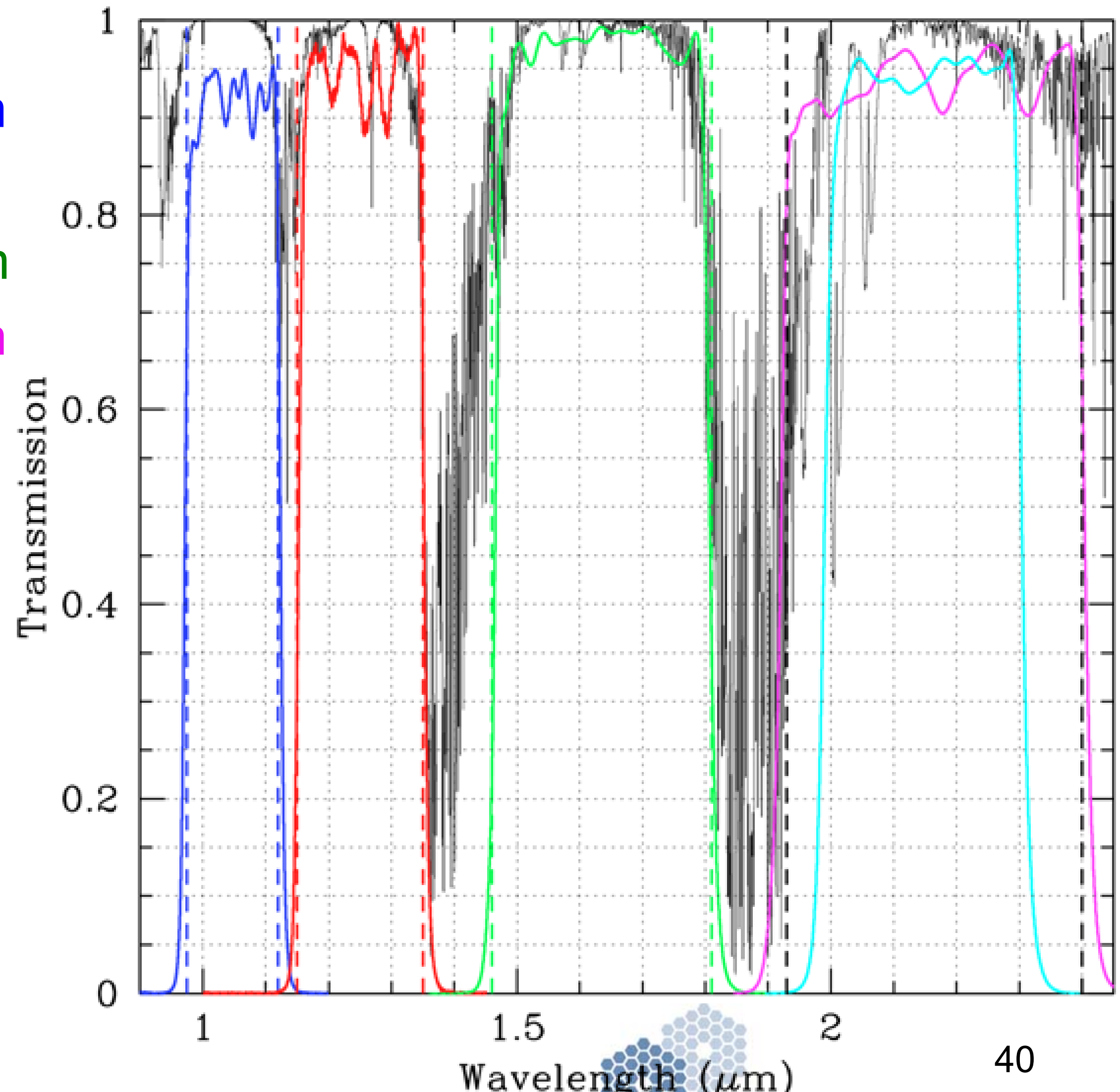
Wavelength coverage

(matches spectral orders with atmospheric bands)

- Y-band: 0.972 to 1.125 μm
- J-band: 1.153 to 1.352 μm
- H-band: 1.465 to 1.809 μm
- K-band: 1.921 to 2.406 μm



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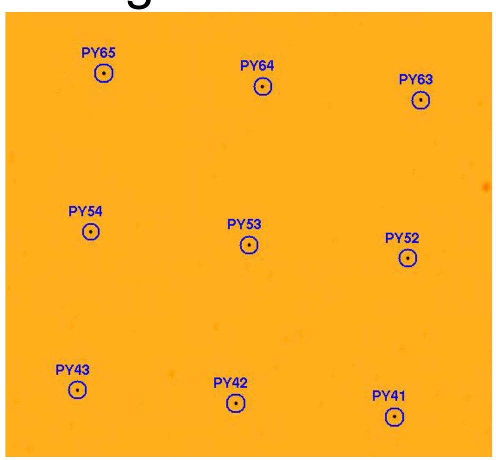
Imaging Plate Scale

- **Requirement:** to re-image the Keck Cassegrain f/13.66 focal plane (nominal 0.72516 mm/") onto the H2-RG detector (18 μm pitch) with a plate scale of 0.18"/pixel, *i.e.* a focal reduction of ~7.25 times.
- Assuming nominal Keck scale, as-built pixels are 0.1798″, linear to ~0.2%
  - measured using precision pinhole mask at telescope focus position during cool-down #8



Spectral resolution

- **Requirement: R > 3,000 with a 0.7" slit**
- **As built, averaged over wavelength band:**

Band (Order)	λ/Δλ(0.7”)	λ/ Δλ(2pix)
Y (6)	3380	4960
J (5)	3310	4930
H (4)	3660	5340
K (3)	3620	5280

±4% within each band

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Image Quality

- Evaluated using pinhole mask images, spectra
- The image quality is actually so good that it is quite difficult to measure the rms image diameter given our pixel sampling at the detector.
  - Pinholes project to only 0.75 pixels (FWHM) at the detector
- Our best estimate of the rms image diameter in imaging mode is < 0.18″ ~1 pixel (averaged over all bands, with no refocus).
  - The requirement was <0.25″.

Pinhole Mask Images

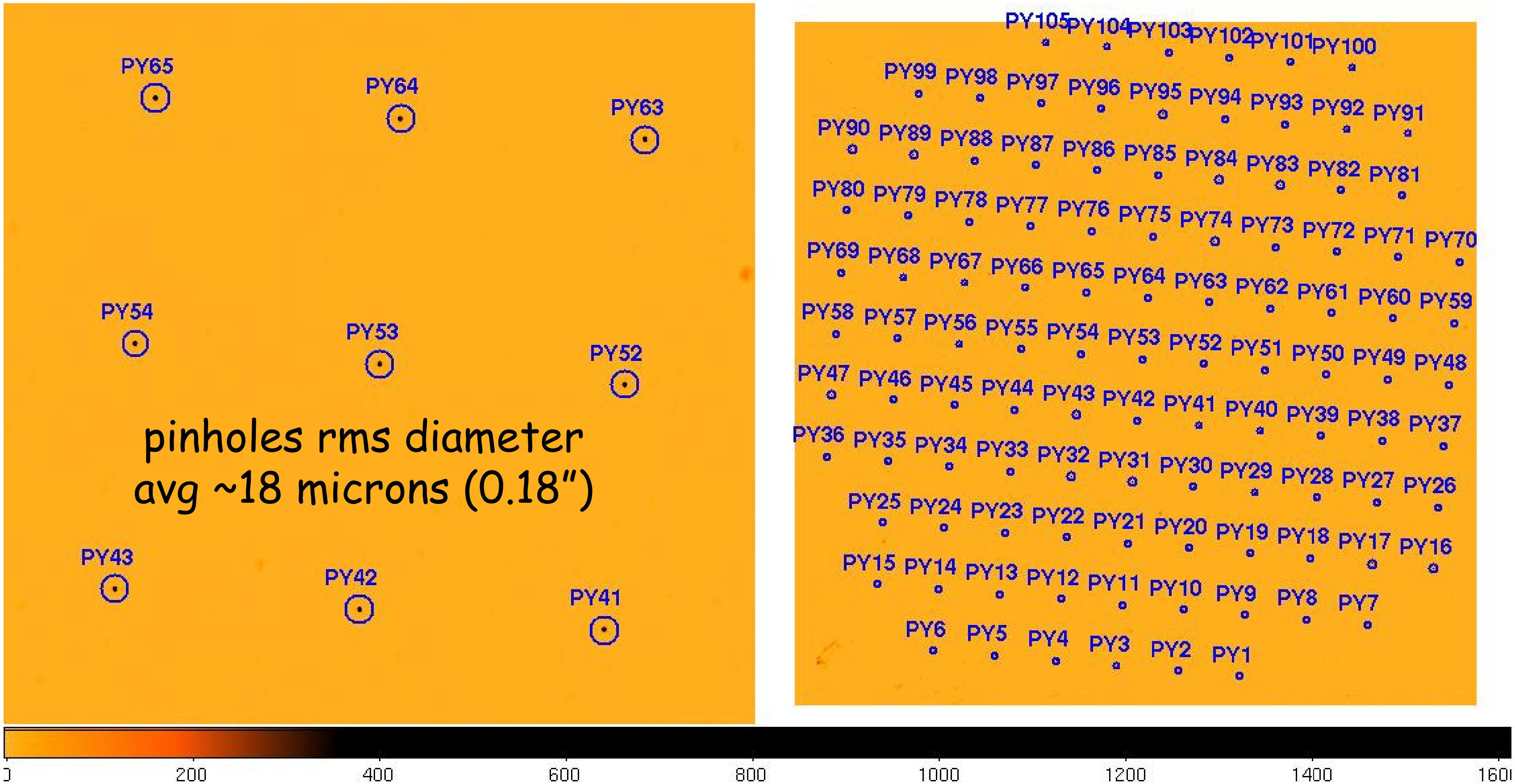

Figure 4: The left side of the figure shows a close up image of the MOSFIRE pinhole mask and the right side an overall view with identifying information for each pinhole.

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Pinhole Mask Spectra

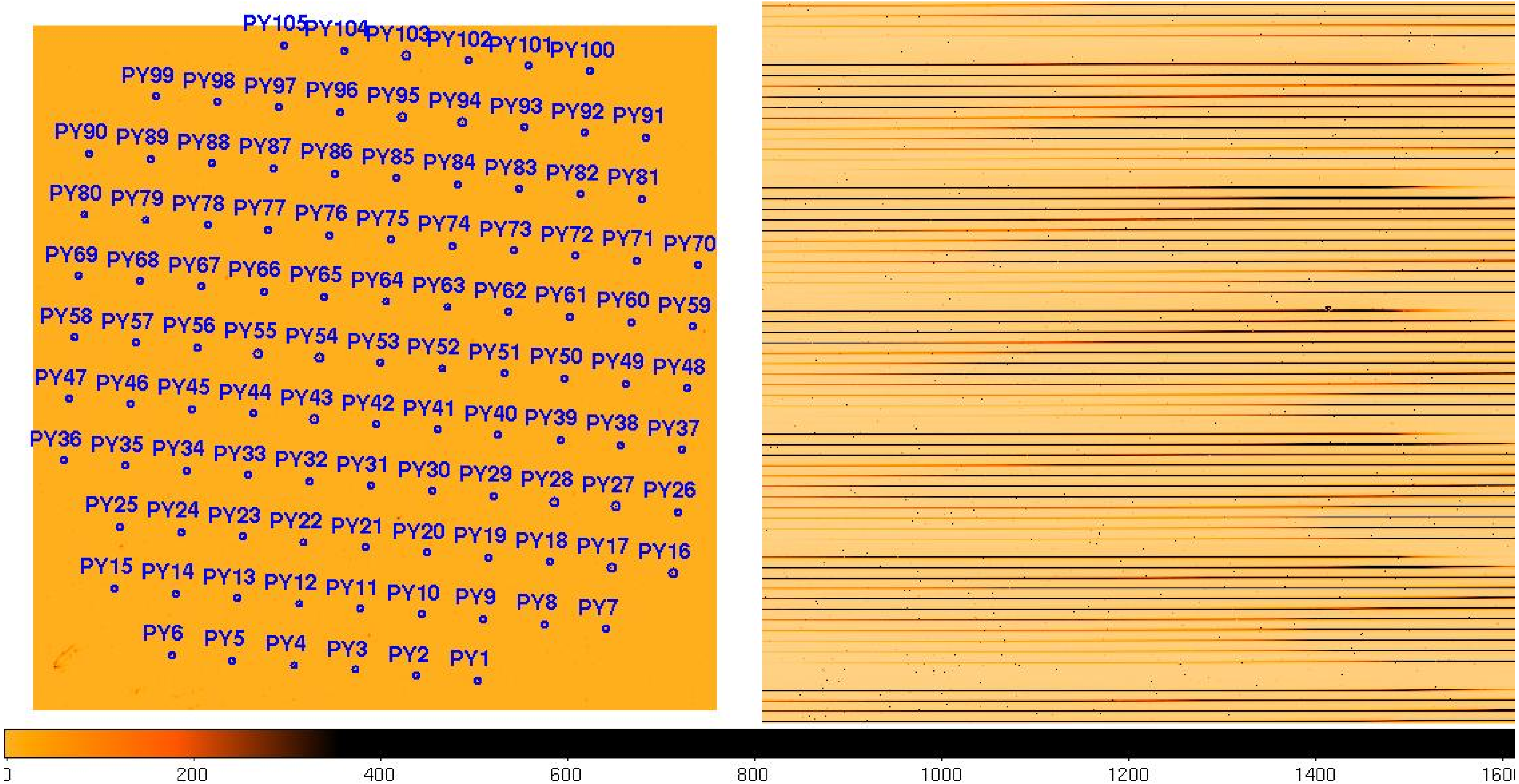


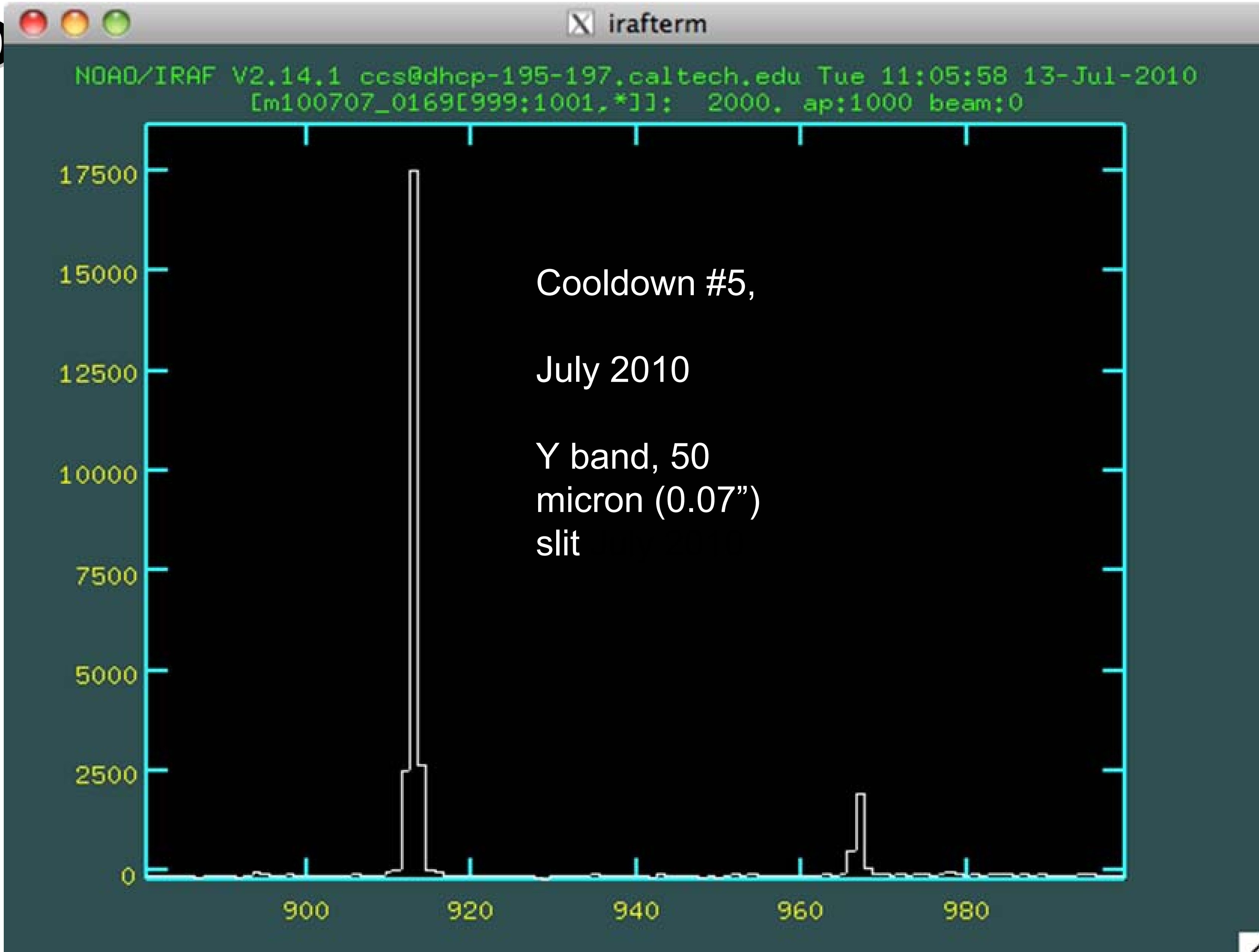
Figure 5: The left side of the figure shows an image of the MOSFIRE pinhole mask with identifying information for each pinhole. The right image shows K band arc lamp spectra. The spectra are aligned to the detector rows within 0.08º.

Figure of Merit

- In spectroscopic mode, the figure of merit is the fraction of light from an unresolved spectral line falling within a 2 x 2 pixel box, for which the requirement was > 80% ensquared energy.
- The as-built system was evaluated from the spectra of arc lamps taken through the pinhole mask as shown on the right side of Figure 5.
- As summarized in Table 14, values closer to 90% (averaged over the full field) are achieved.
- A cross cut of a pinhole mask spectrum is shown in **Figure 6**.

D ality

box)



mall

hole
on

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Throughput

- Requirement: throughput from slit to detector > 30% on order blaze in each band (orders 6, 5, 4, and 3).

- We only have estimates from as-built specifications as provided by vendors
  - for the optical coatings,
  - detector QE,
  - grating diffraction efficiency
  - filter transmission.
  - our own estimates of the internal transmission of all refractive optics, accounting for materials and thicknesses (Table 12)

Filters

- **MOSFIRE provides space for 10 filters in two six-position filter wheels (5 filters + open in each wheel).**

- **At DDR 5 filters provided:**
  - broadband Y, J, H filters doubling as photometric filters for imaging and order sorting filters for spectroscopy,
  - a wide K filter for K band spectroscopy,
  - and a Ks filter for imaging or spectroscopy.

- **During the FSD phase Alice Shapley (UCLA) purchased four additional intermediate-band filters for MOSFIRE called J2, J3, H1, and H2.**
  - envisioned primarily as imaging filters, roughly split J & H bands in half

- **The full filter complement in MOSFIRE at the time of the pre-ship review is summarized in Table 16.**

As-built MOSFIRE Filter Curves

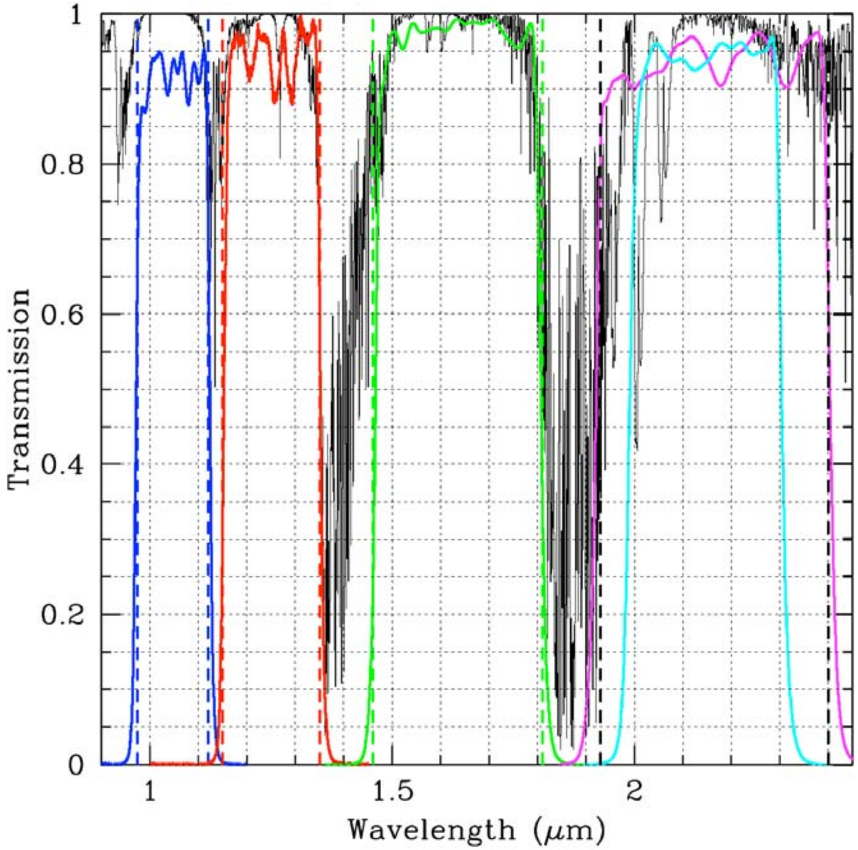

Figure 11: Y (blue curve), J (red curve), H (green curve), K (magenta curve), and Ks (cyan curve) transmission plotted with the atmosphere. Broadband filter nominal passbands are indicated by the dashed lines.

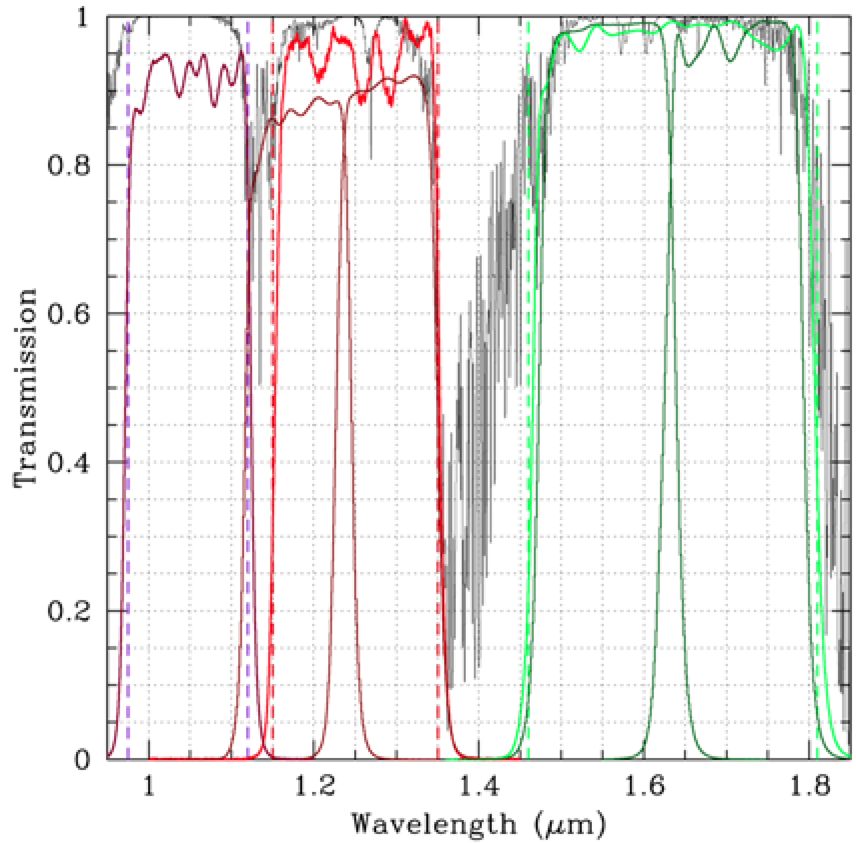

Figure 12: J2, J3 (brown curves) and H1, H2 (dark green curves) with the Y band (purple curve) and the J and H broadband filters (red & green curves) along with the atmospheric transmission. Broadband passbands are indicated by dashed lines.

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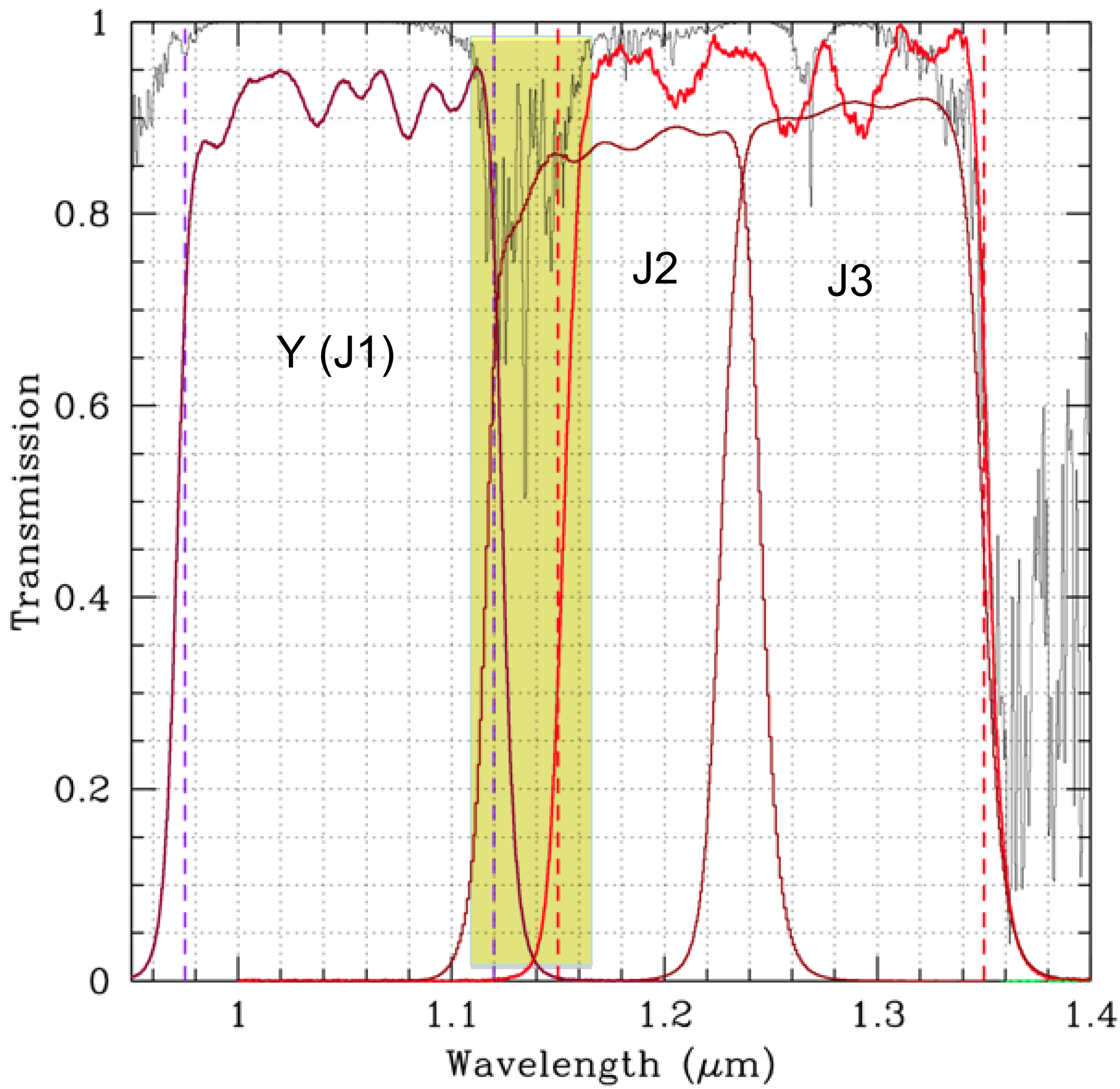

Note: J2 filter provides spectroscopic access to the only small piece of wavelength range with significant atmospheric transparency not accommodated by our order-sorting scheme!

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Spectrometer Grating

- **MOSFIRE uses a custom reflection grating that is interchangeable with a plane mirror for imaging.**
  - **110.5 lines/mm with a blaze angle of 21.93° (1st order blaze of 6.35 μm)**
  - **Gold coated**
  - **Used in orders 3, 4, 5, and 6 with a 40° included angle and angle of incidence (AOI) of 42.6° (H and K) and 41.5° (Y and J) to adjust blaze peaks toward the center of detector for central slits.**
  - **Tested at the relevant AOI by Newport/Richardson. Fig. 13 shows absolute diffraction efficiency over the wavelength range used for each order.**

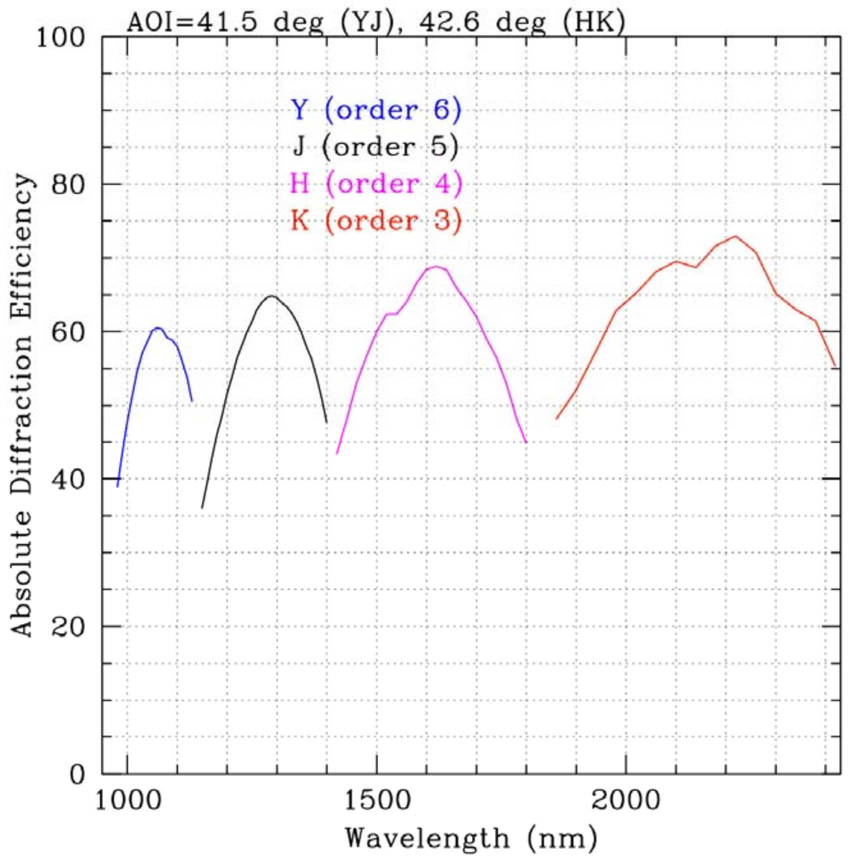

Figure 13: As-built absolute diffraction efficiency for the MOSFIRE grating with S and P polarizations averaged.

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Optical Coatings

- All anti-reflection coatings on transmitting optics, and all reflecting surfaces, except the gold-coated guider mirrors, the windows (United Lens) and the grating, were done by Evaporated Coatings, Inc.
- All of the as-built coatings passed a “tape test” for adhesion (see reference 45).
- a sub-set were cryo-cycled in a test chamber prior to optics mounting to ensure that they remained resilient after temperature cycling over a range larger than that used inside the MOSFIRE cryostat.
- All optics have been through 5 cool down and warm up cycles since being installed in the instrument, with no degradation observed thus far.

Coating performance

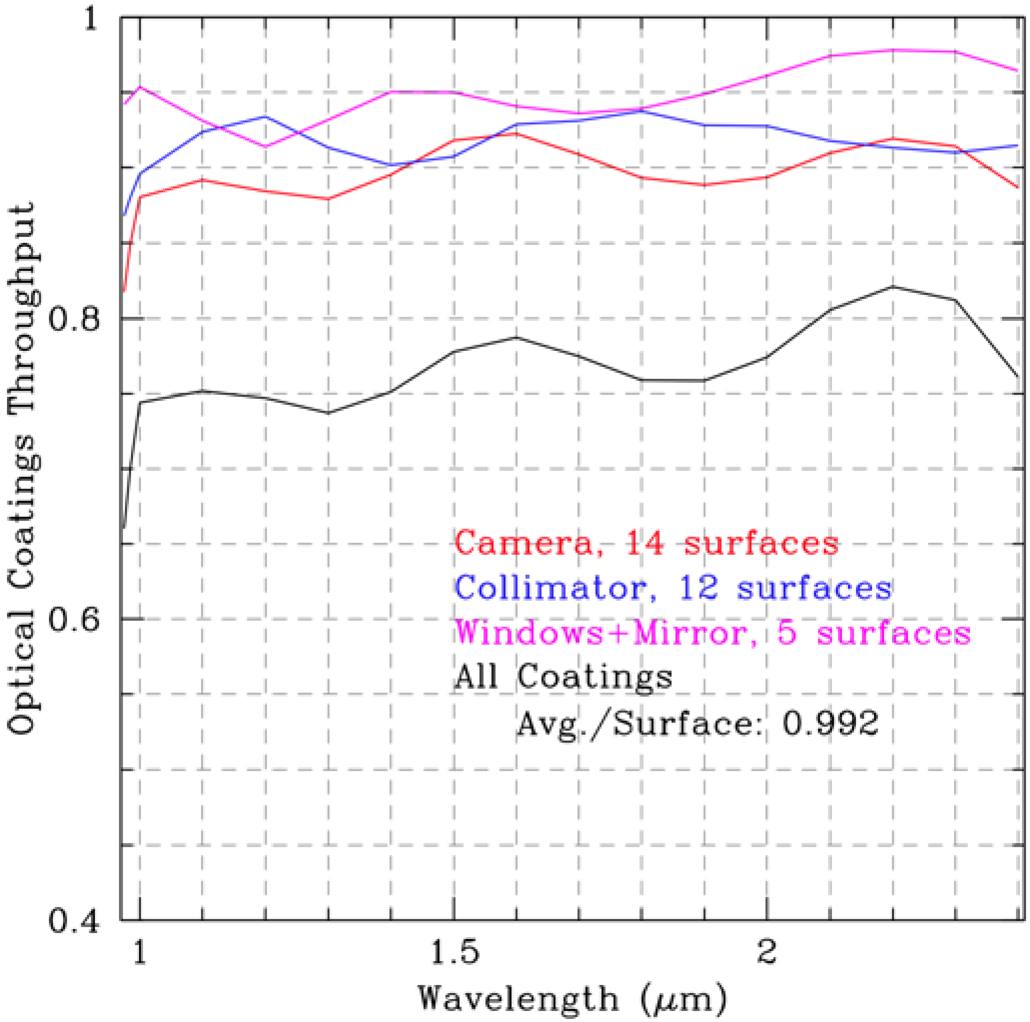

Figure 8: MOSFIRE optical coating throughputs

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Predicted Spectroscopic Throughput

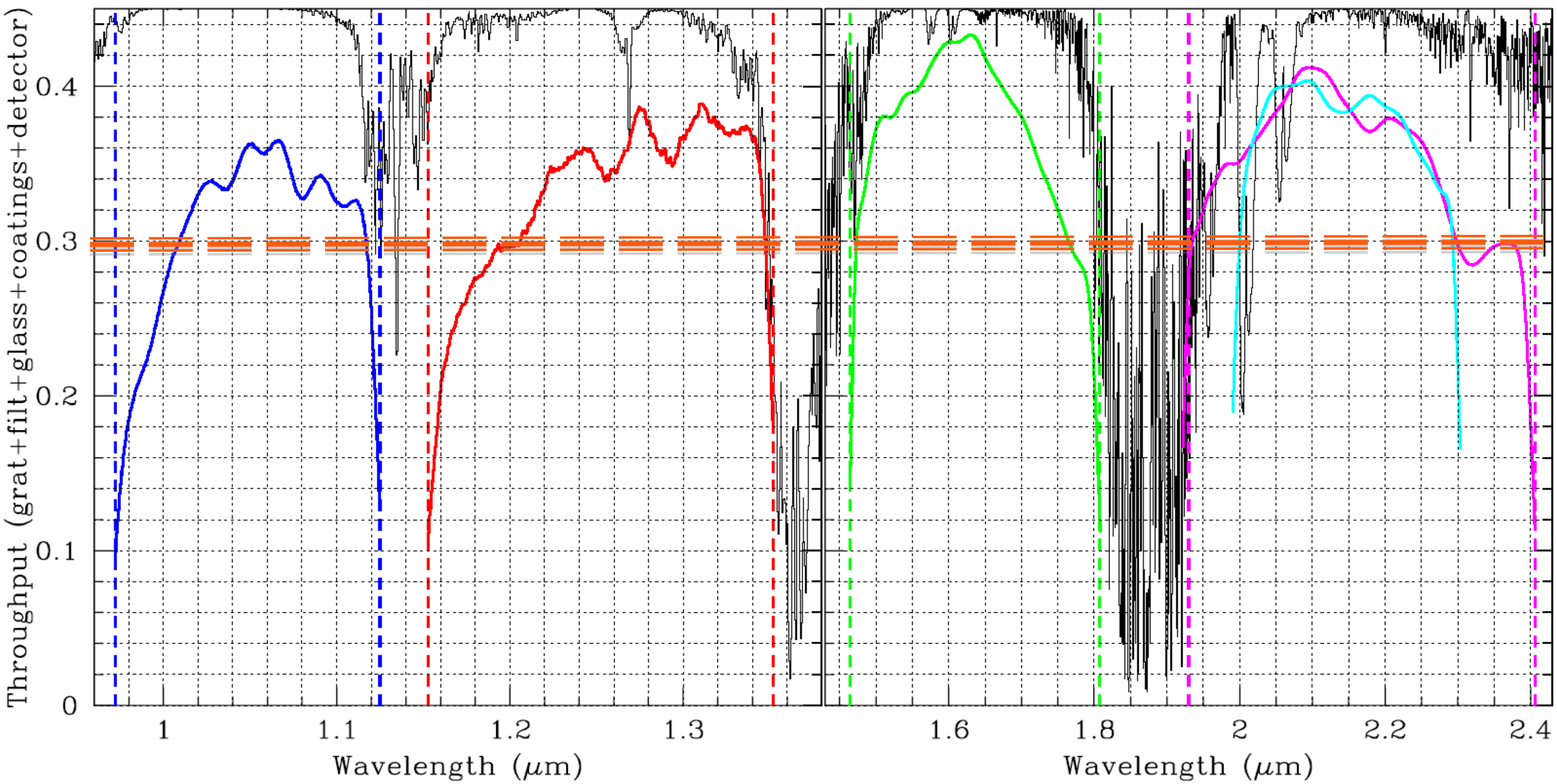

Figure 7: The half power points for each broad band filter are indicated by the dashed lines. The blue curve is the Y band, the red curve is the J band, the green curve is the H band, the magenta curve is the K band, and the cyan curve is the Ks band.

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CSU Light Blocking

- Images used to evaluate the CSU light blocking were obtained with the instrument at the horizon (bars horizontal), in imaging mode, with Y, J, H, and K filters.
- Very short integrations (0.25 s) using sub-array readout with illumination from the Ne arc lamps were made, followed by longer (120 s) integrations with the even numbered masking bars fully across the field of view.
- This orientation provides a “worst case” for masking bar “sag”, so that the measure level of light leakage should be considered an upper limit.
- An example portion of the image taken in the H band is shown in **Figure 9**.

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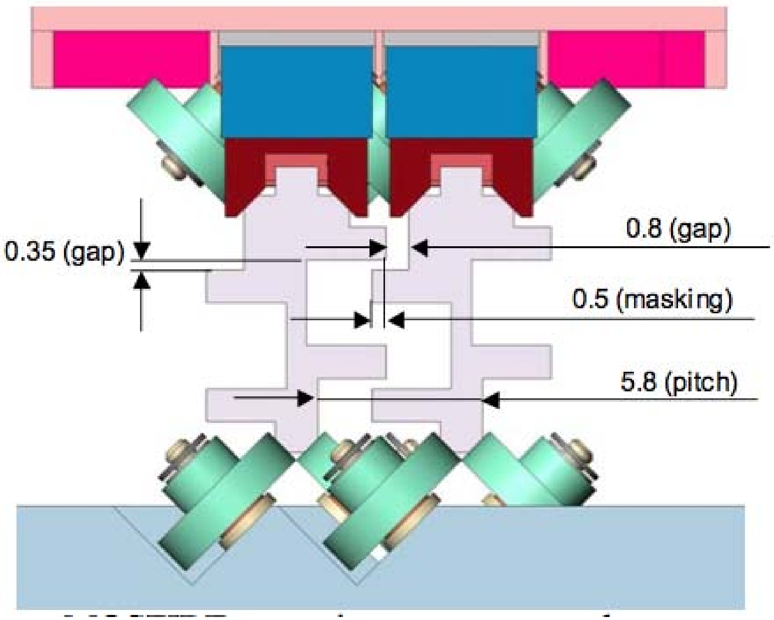
Bar Profiles and Light Blocking



@DDR

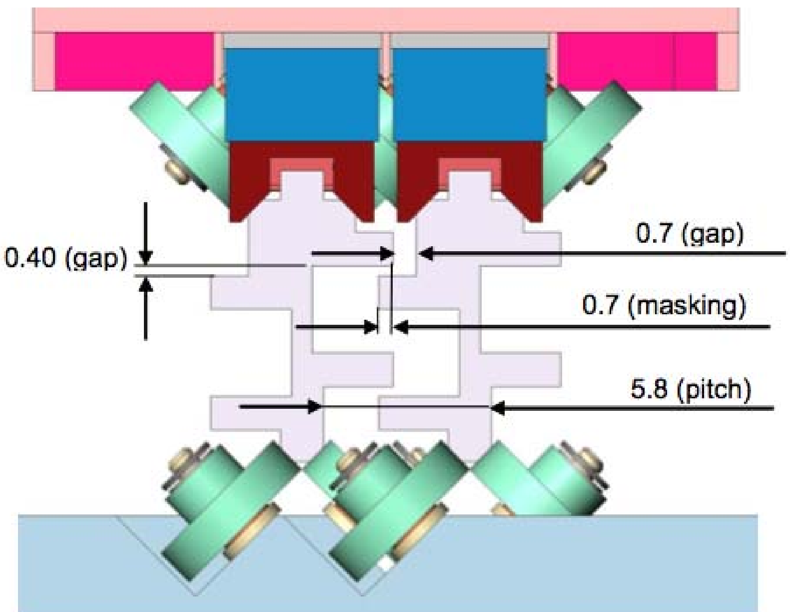


Figure 5–3 Guide wheel and bar detail

As-Built

CSU light leakage test, H-band

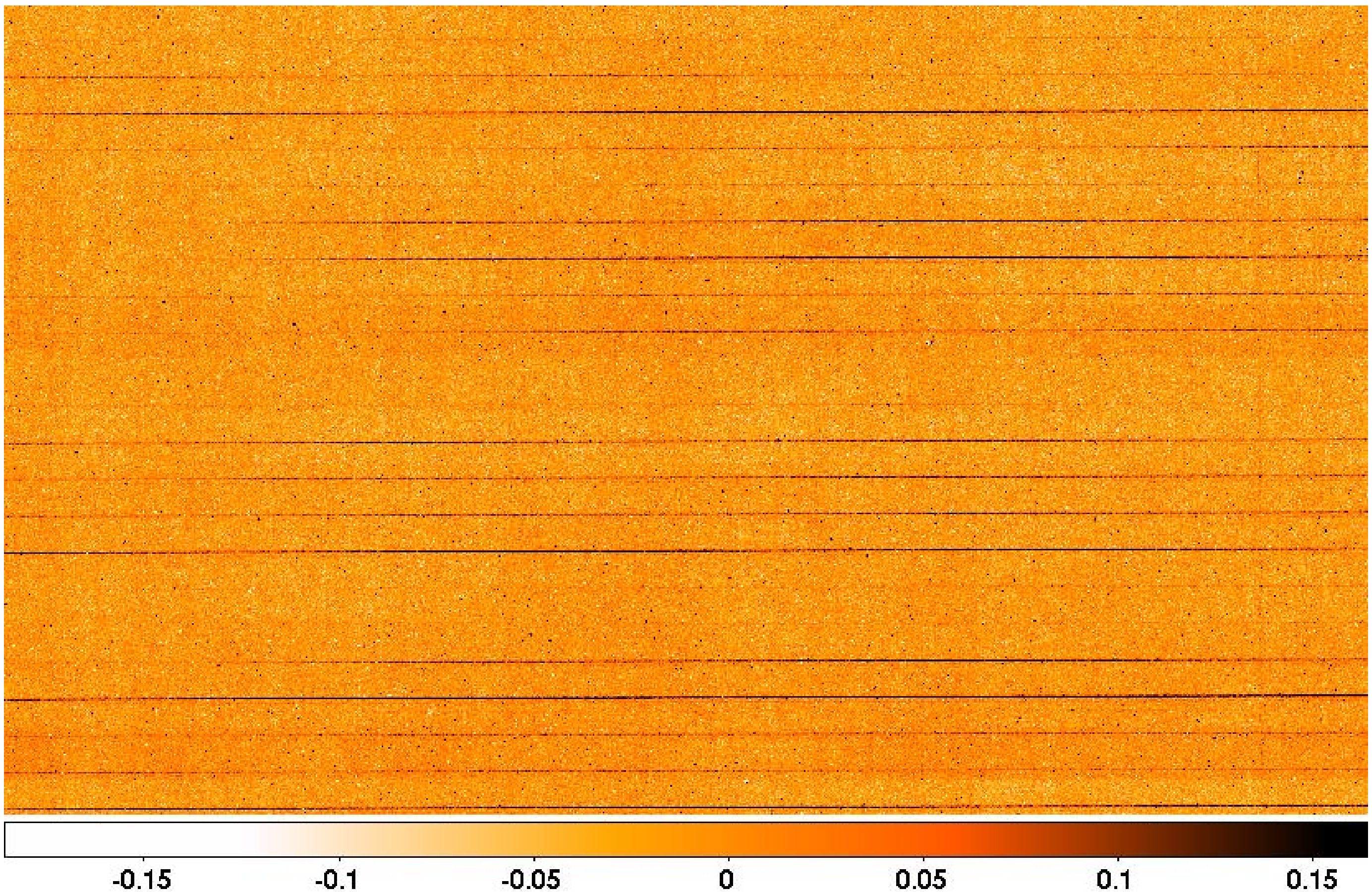


Figure 9: Horizontal lines are leaks between masking bars, with peak levels corresponding to 1.4 x 10^{-5} of the baseline signal. Between these, there is no significant signal measured.

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CSU Light Blocking Test Results

Table 13: CSU Light Blocking Test Results

Test Condition	Y band	J Band	H band	K band	K (spec)
Leak/Baseline (mean)	9.6×10^{-8}	5.0×10^{-8}	6.9×10^{-8}	1.0×10^{-6}	7.1×10^{-7}
Leak/Baseline (peak)	1.5×10^{-5}	8.0×10^{-6}	1.4×10^{-5}	5.1×10^{-5}	3.4×10^{-5}
Laboratory Measurement	-------	6.8×10^{-7}	$3\text{-}6 \times 10^{-7}$	-------	-----------

Results of the CSU light blocking tests during cool down 9 and a comparison to lab tests (reference 48) are summarized in Table 13. Note that the lab results are those for the 0.5 mm bar gap, and at DDR MOSFIRE's bar gap was increased to 0.7 mm, so that the as-built gap is 40% larger than used for the lab tests. For the entry labeled "K (spec)", the statistics are for the mean level and peak when the incoming light is dispersed, without changing the illumination source.

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Ghosting

- Extensive ghost analysis of the optical design was done using the "pre-construction design (Optics Report 10) and presented at the DDR in April 2007, and then for the final design optical design.
- *We cannot detect any ghosting in imaging mode with the as-built instrument.*
- We do see features related to **grating ghosts** in spectroscopic mode.
- Ghosts are in-focus images of dispersed spectra, reflected from the surface of the detector, re-collimated by the camera, reflected back in the 0th order of the grating, and re-focused on the detector.
- These ghosts were anticipated (see Optics Report 23) and are an unavoidable consequence of the MOSFIRE geometry, which has the grating normal only a few degrees from the optical axis of the camera, meaning that some spectra, from some slits, will appear as focused ghosts on the detector.
- Ghost intensity measured between 1.6×10^{-3} and 0.5×10^{-3} of primary signal
  - Compare our estimate of ~0.5% (5×10^{-3}) (Optics Report 23) with assumptions about detector AR coating performance and grating efficiency in 0th order.

Spectroscopic Ghost Features

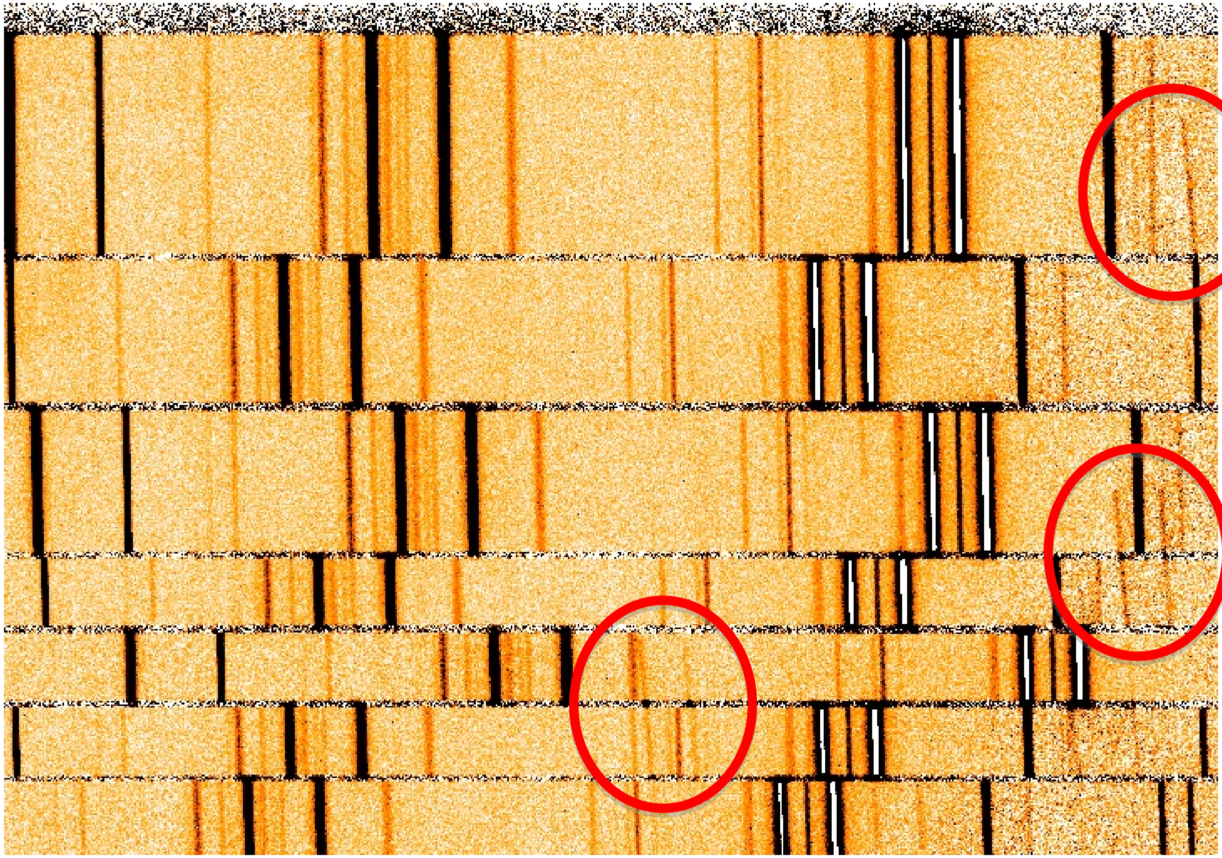

Figure 10: A small portion of a Y-band arc spectrum. This figure indicates ghost features that are 0th order back-reflections of the bright, saturated pair of lines on the right side of the image. In this case, most of the ghost lines fall at positions beyond the long-wavelength filter cutoff. The ghosts can be recognized by their tilts that are at slightly different angles compared to the primary image.

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Observing Modes

- MOSFIRE provides two observing modes as required, **direct imaging** and **multi-object spectroscopy** with a multiplex of up to 46 objects.
  - use of long slits is a variation on multi-object spectroscopy
- As specified in the requirements the slits are deployable on a nominal 5.8mm (8″) pitch.
- Gaps increased at DDR to increase margin for light leaks: **7.01″ of slit + 0.96″ gap;**
- As specified in the requirements, adjacent slit bars can be combined to form longer slits in increments of 8″. **(e.g., 2 bar slits are 7.01”+0.96+7.01” = 15”)**
- The slit widths are continuously adjustable from 50 microns (0.07″) to full-open (6.12′).

Spectral Coverage

Table 17: MOSFIRE Spectral Coverage As-built

Band	*Dispersion (Å/pixel)*	*λ center, Å (note 1)*	*Range at center, Å*	*Range at -1.5' (see note 2)*	*Range at +1.5' (see note 2)*	*Shift, Å/mm (see note 3)*
K	2.1691	21760	19540 to 23970	20340 to 24060 (82%)	19210 to 23170 (82%)	12.209
H	1.6269	16321	14680 to 18040	15280 to 18090 (82%)	14640 to 17440 (82%)	9.157
J	1.3028	12450	11530 to 13520	11650 to 13520 (94%)	11530 to 13520 (100%)	7.460
Y	1.0855	10373	9716 to 11250	(88%)	9716 to 11250 (100%)	6.216

Notes:

1. Central wavelength for a slit at the center of the field.
2. Wavelength range for slits placed at X = ±1.5' from field center. The number in parentheses is the fraction of the wavelength range for central slits covered by the spectra from slits at the extrema.
3. Shift of the central wavelength per delta (X) = 1mm at the CSU, in angstroms.

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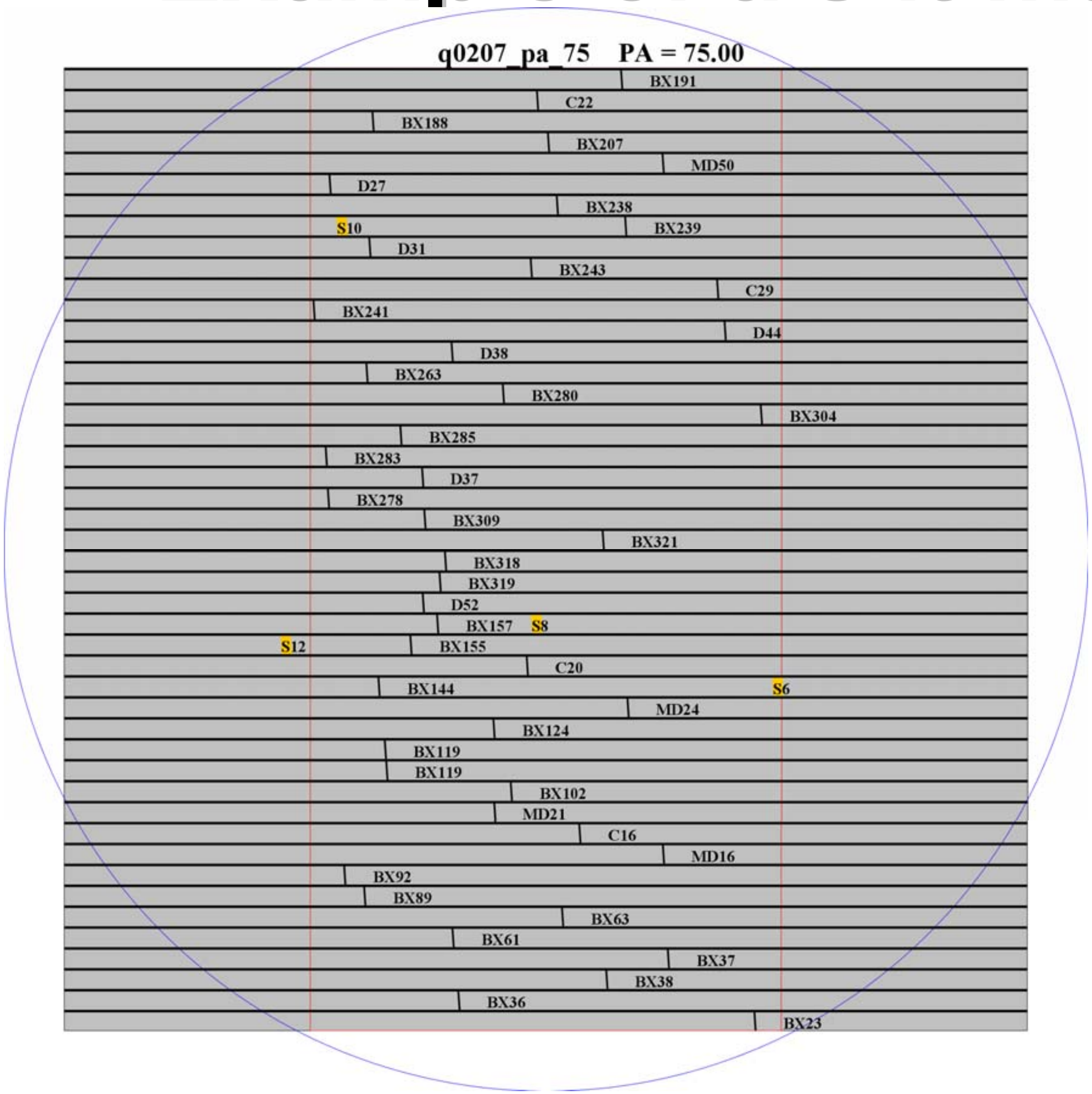
Example of a slit mask design



MASCGEN also makes predictions from slit positions in focal plane of the wavelength coverage seen by the detector (examples following)

Figure 14: Example slit mask design
This mask was created automatically using MASCGEN. Yellow boxes indicate alignment stars to be used for field acquisition.

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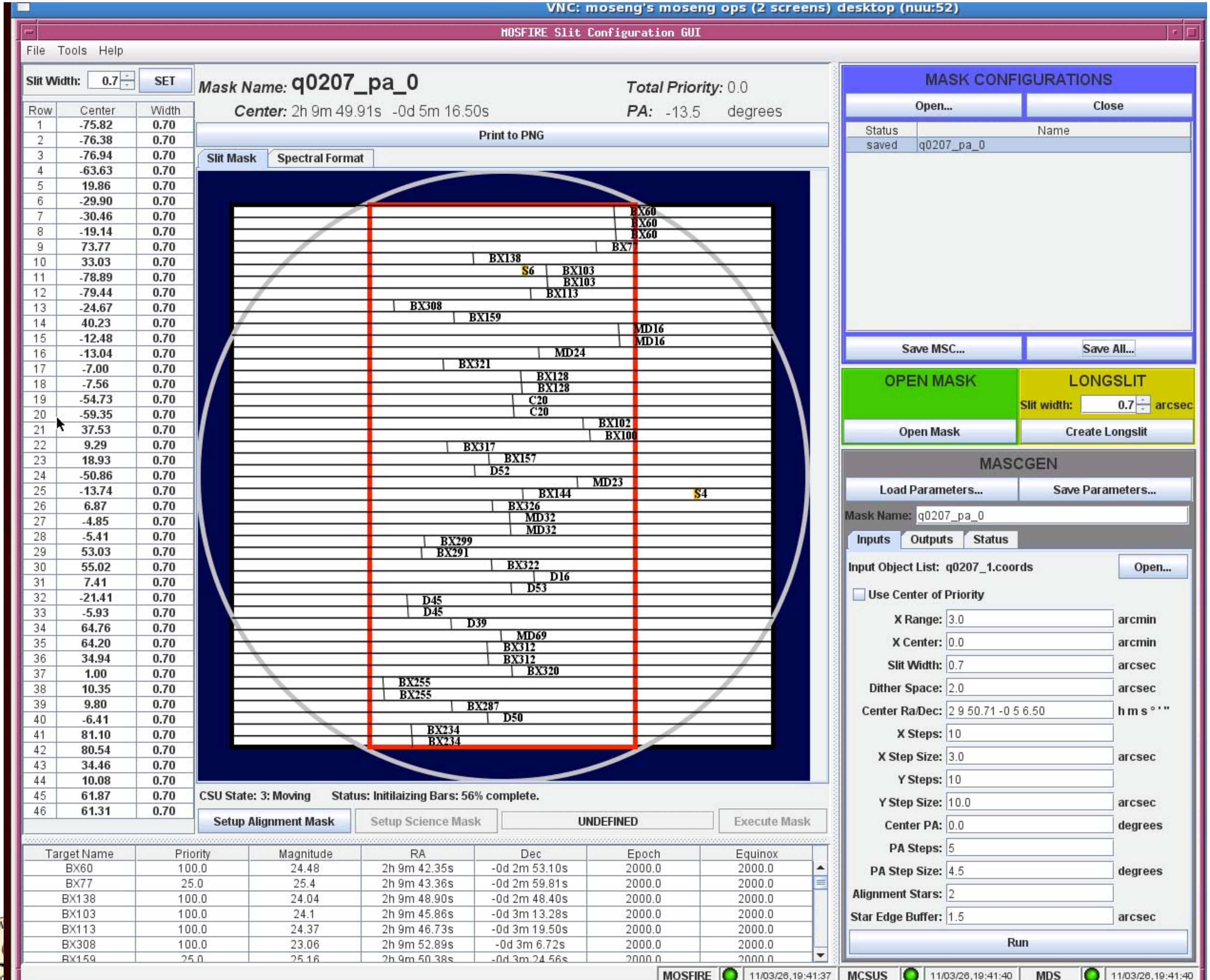

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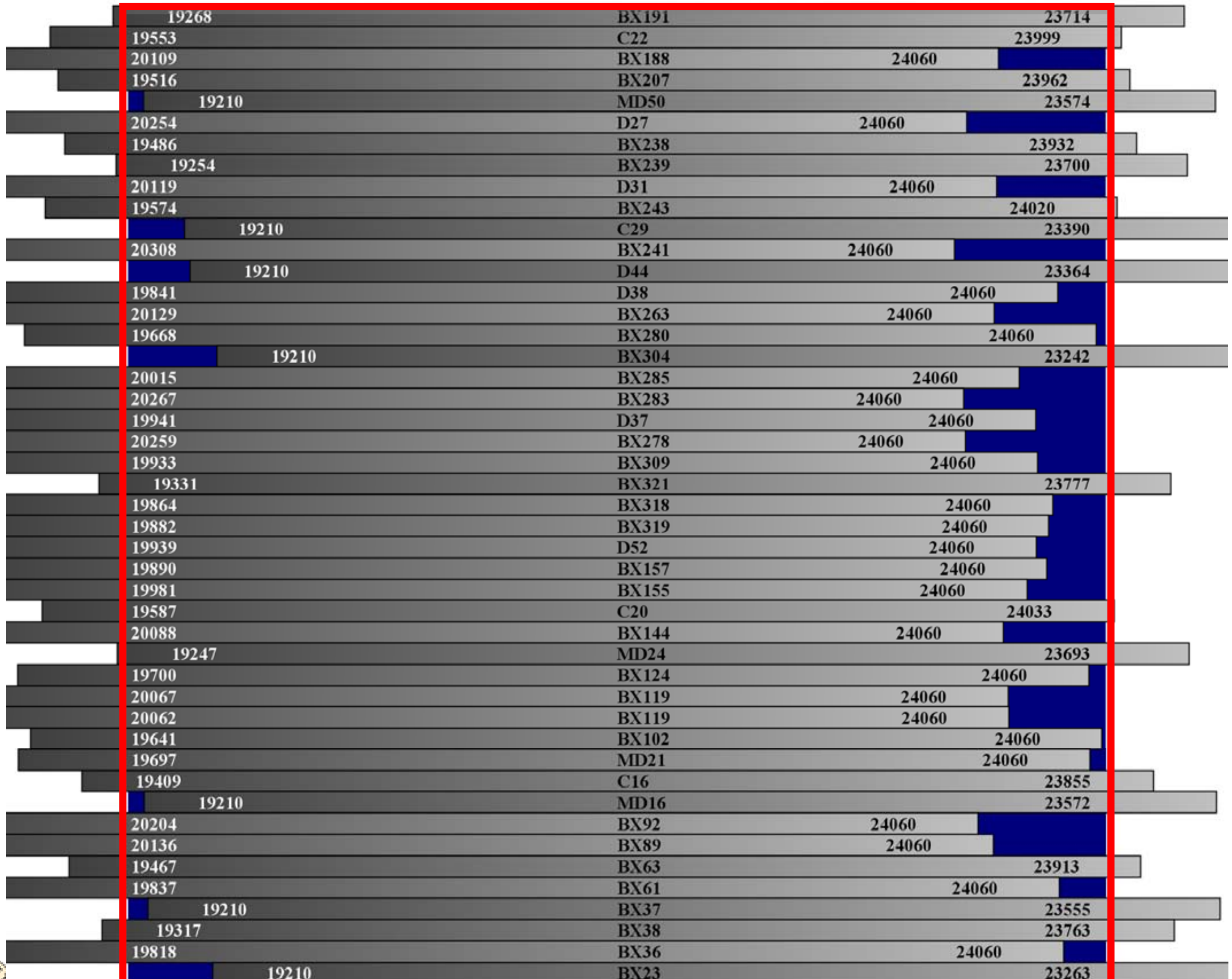
Wide K-band Spectral Map (1.921-2.406 microns)



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Spectral Maps: H, J
(for the same mask design)

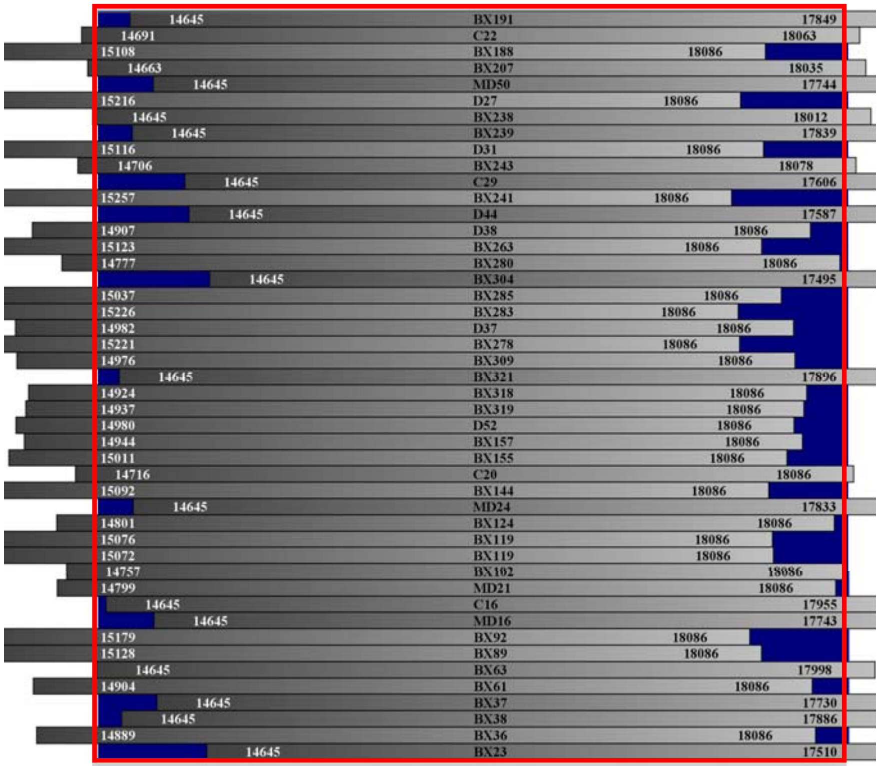

Figure 17: H band spectral map

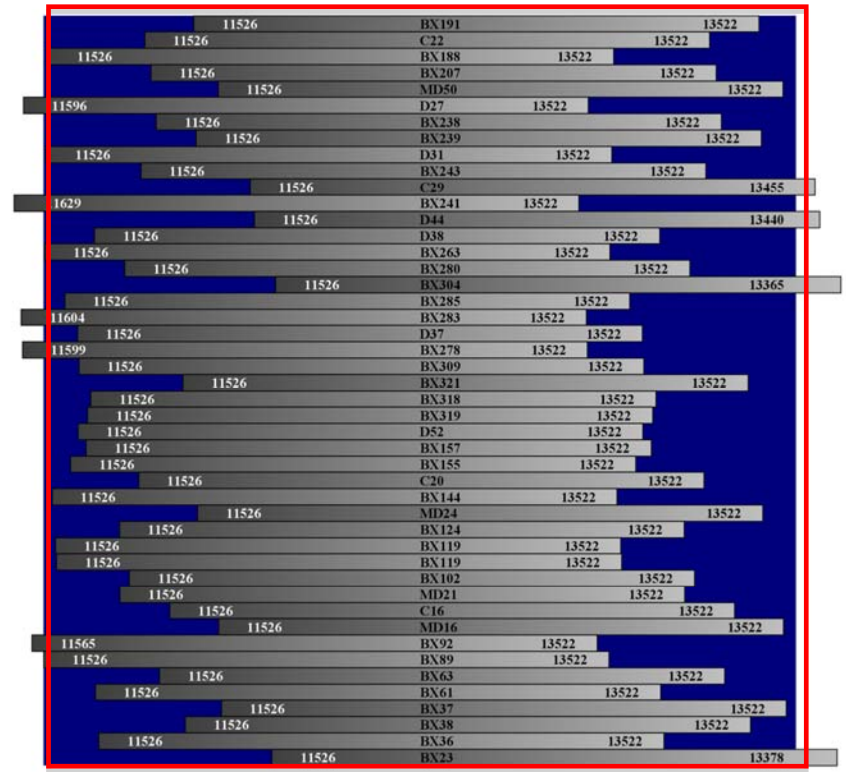

Figure 18: J band spectral map

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Spectral map on detector, Y band

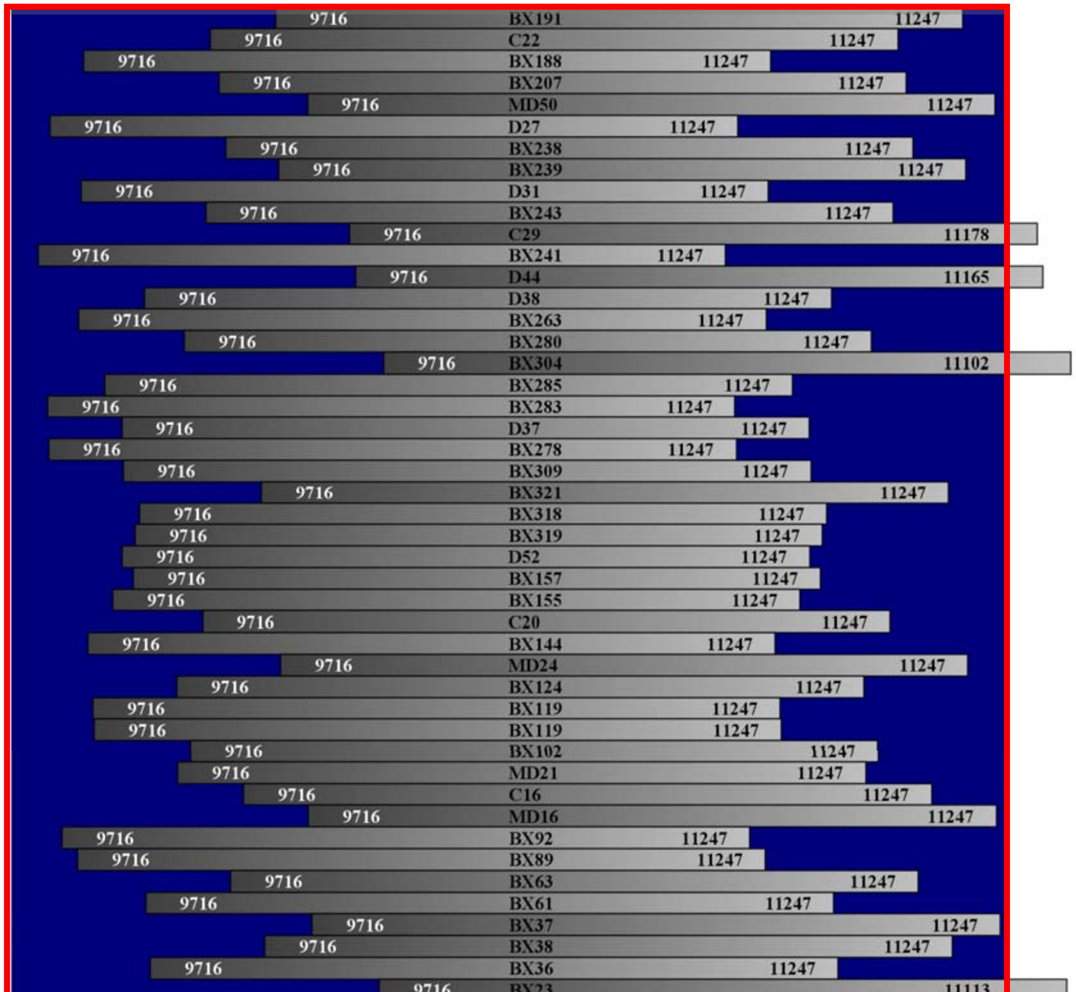

Figure 19: Y band spectral map

One focus for all bands & modes

- MOSFIRE was designed with a detector focus mechanism that was operated successfully during cool downs 5, 6, 7, and 8.
- Analysis of spectral line widths (and pinhole mask images) distributed over the nominal 3.0' x 6.12' spectroscopic field revealed that the instrument is very **close to being parfocal in all bands and all modes**
- Table 18 shows for each band, and for the average of all bands, the dispersion of best focus values over field in steps, the average line width at best focus, and the average line width for a 0.60" equivalent entrance slit at the nominal focus position of -200 steps; slits were distributed over the nominal spectroscopic field of view and over the full wavelength range covered by each slit.
- Differences from band to band are at most only marginally significant.
  - optimal focus within band as a function of field pos'n varies at the same level.
- By using a fixed focus setting, the average line widths remain very close to their bandpass optimized values (column 4 of Table 18) and we mitigate the risk of a mechanical failure in the focus stage.

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No refocus needed

Table 18: MOSFIRE Best Overall Focus

Band	*Best focus position in steps*	*Average line FWHM at best focus (pixels)*	*FWHM at -200 steps (pixels)*
K	-300 ±80	2.25 ±0.12	2.42
H	-210 ±80	2.38 ±0.12	2.39
J	-10 ±70	2.40 ±0.21	2.51
Y	-410 ±80	2.25 ±0.12	2.46
average	-230 ±170	2.35 ±0.26	2.45 ±0.18

variation in line width within a given band, averaged over field pos'n, ±5%

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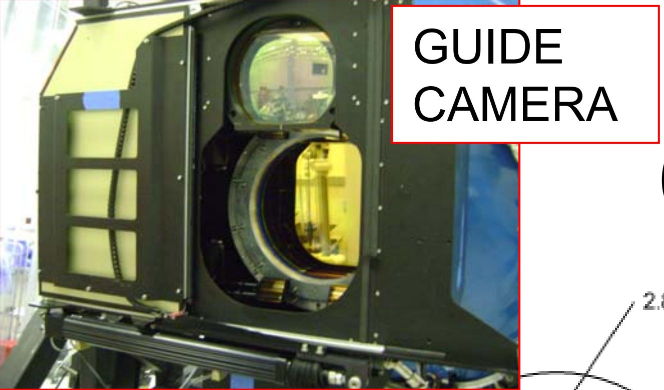
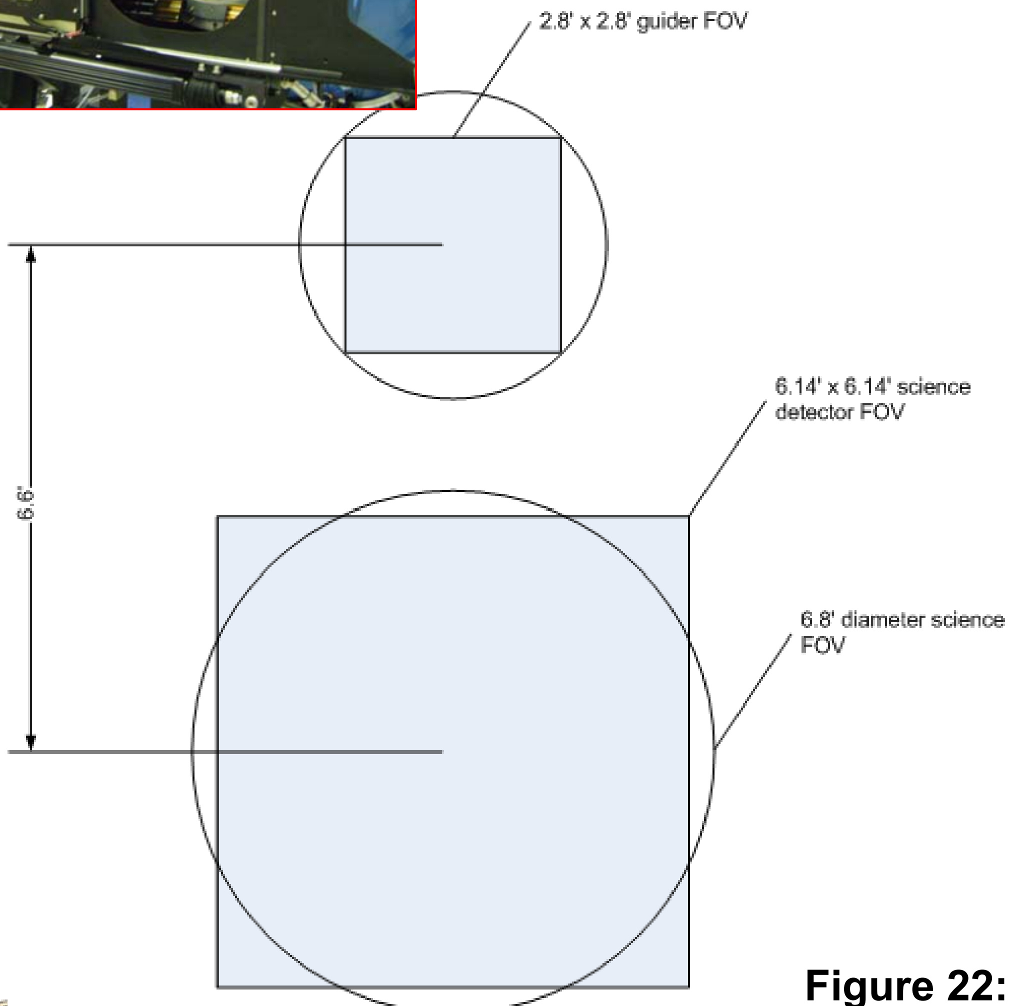


CCD Guider



- As specified in the requirements MOSFIRE is provided with an optical guider with remote focus control.
- The MOSFIRE guider provides an offset FOV adjacent to the science FOV.
- This FOV is 2.8' x 2.8' and is offset 6.6' from the center of the MOSFIRE science FOV as shown in Figure 22.
- The guider is controlled by the Observatory’s MAGIQ software.

Figure 22: MOSFIRE science and guider FOVs

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Opto-mechanical Requirements

Nick Konidaris

Optical Component Mountings

- The mounting of MOSFIRE's cryogenic optics is designed to ensure that optical alignment is maintained during cool down and warm up cycles while keeping stress on the optics within safe limits and also to maintain the alignment of the optics at all rotator angles and telescope elevations as specified in reference 1.
- An example of one of the MOSFIRE cryogenic lens mounts is shown in **Figure 23**.
- This design is based on work that began in 2003 (references 16 and 17). The basic approach is to support the lenses by their perimeter girdles with many, bonded metal flexures which are anchored into metal support rings (or cells).

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Cryogenic lens mounts

- This approach more evenly distributes the support loads of larger, heavier lenses than many alternate mounting schemes.
- All of the radial flexures assist in lifting the lens mass with some in compression and some in tension, similar to the spokes of a bicycle wheel.
- This mounting approach eliminates any potential shifting of the lens due to differential contraction of the lens mount components during temperature cycling because friction is not a factor in resisting the restoration of the lenses to their proper positions once all of the components have stabilized at the new steady state temperature.
- The mount approach also prevents the lenses from permanently shifting due to accelerations encountered by the instrument during shipping, transport, or normal operations handling which might briefly displace the lenses.

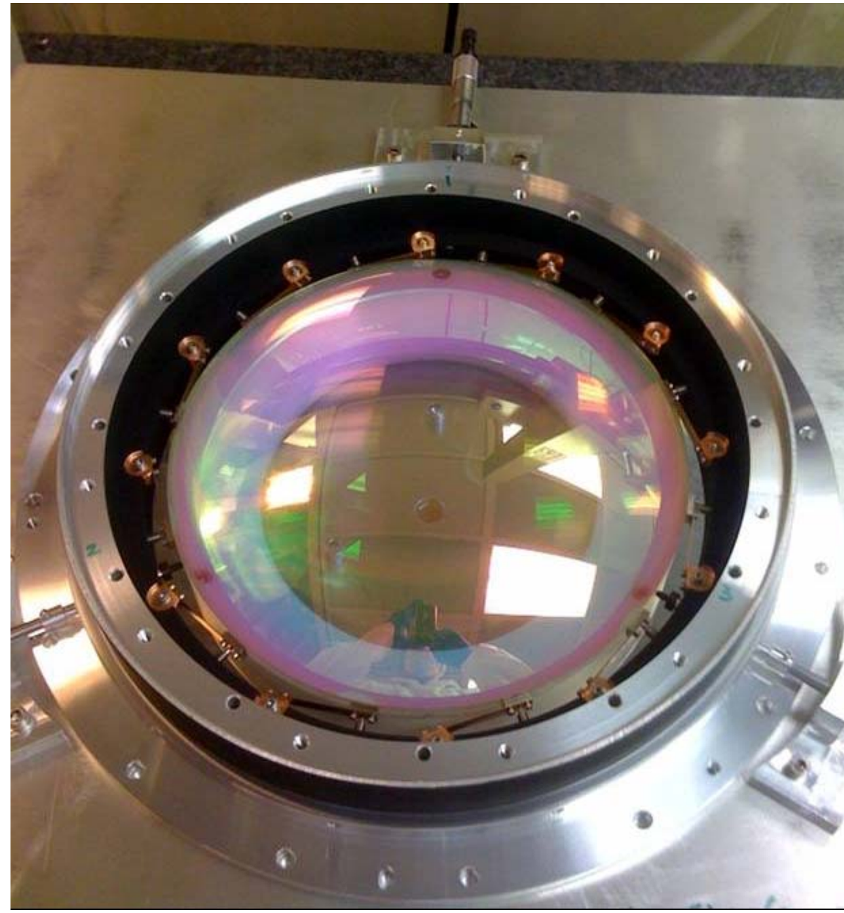
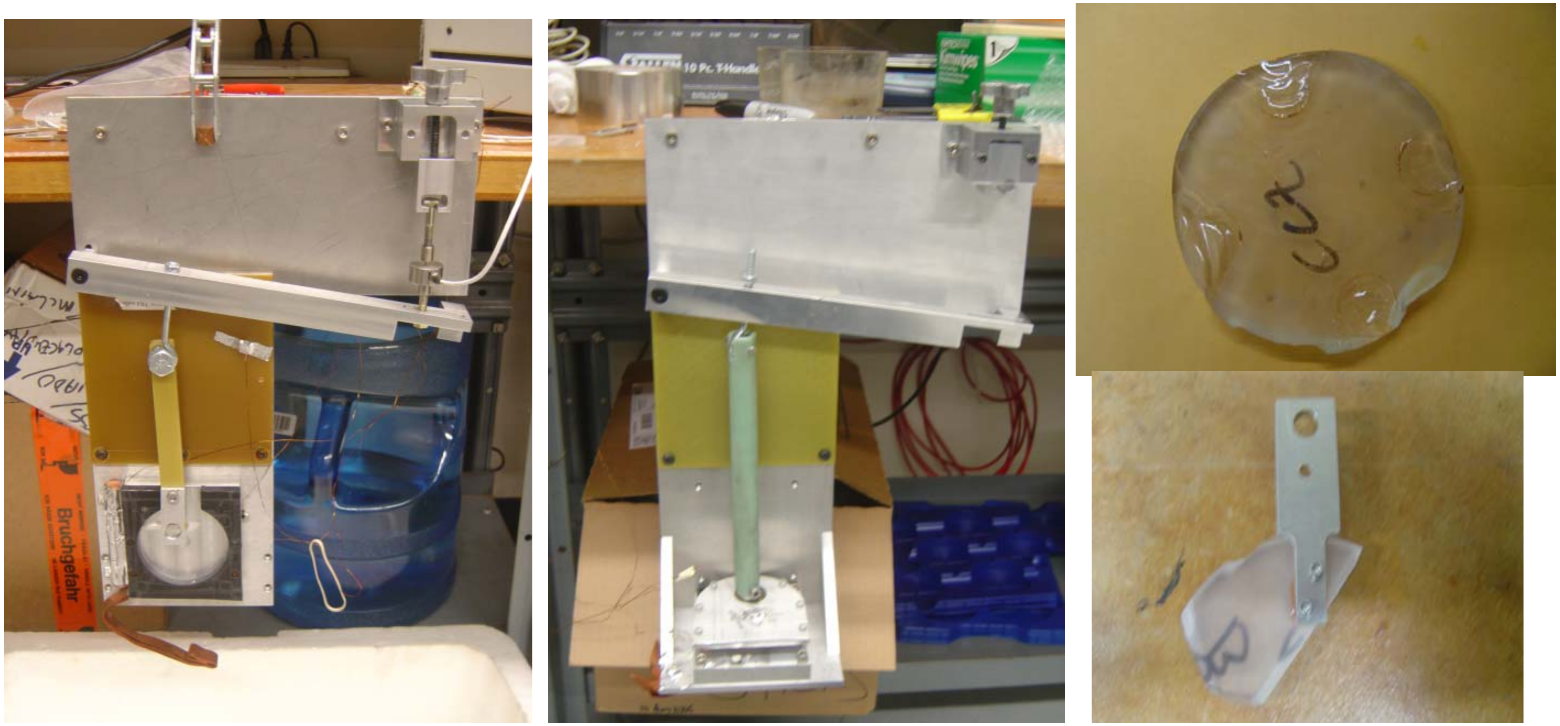


Figure 23: MOSFIRE camera lens 4 mounted its cryogenic lens cell

Adhesive Bond Pull Tests



Substrate Material	Min. Failure Force Shear (lbs.)	Max. Failure Force Shear (lbs.)	Min. Failure Force Tensile (lbs.)	Max. Failure Force Tensile (lbs.)
Clearceram-Z (for mirrors)	158	215	90	138
Calcium Flouride	110	240	95	122
Barium Flouride	92	216	78	125
S-FTM16	31	49	50	62
I-FPL51	66	93	74	92
Zinc Selenide	49	62	52	78
Fused Quartz	38	52	55	80

Table 16: ***Adhesive bond cryogenic pull test results summary.***

Figure 24: Bonded flexure pull-test fixture.
The fixture was used to test shear strength (left) and tensile strength (right) of flexure pads bonded to lens material samples.

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Bonding set-up – dummy lens

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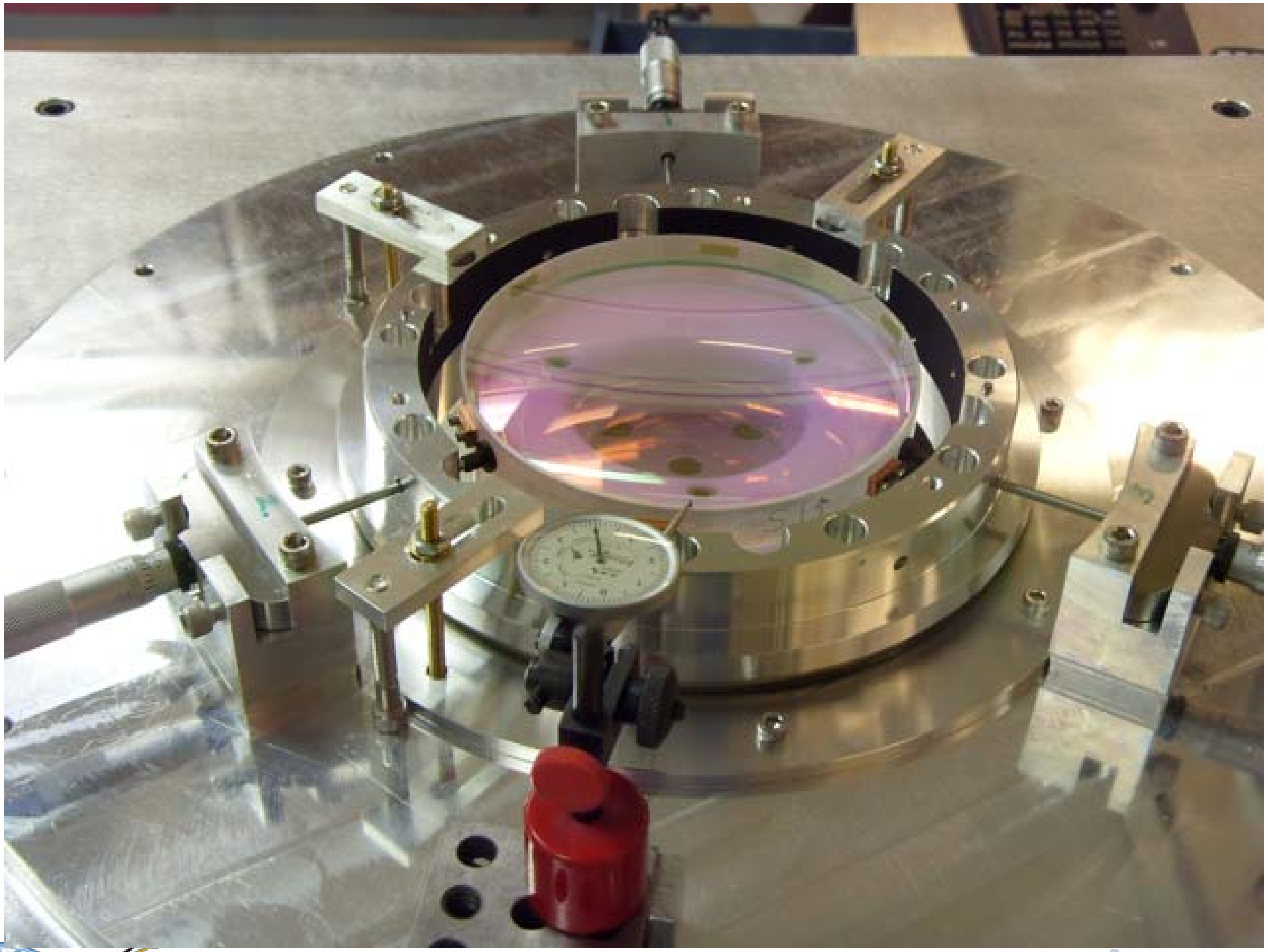
Bonding set-up – real lens



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Coordinate Measuring Machine

Aluminum copies of each of the lenses were made for use in the alignment and bonding process refinement.

Figure 25: Final alignment and bonding fixture set-up

The copies were utilized to practice alignment and bond procedures prior to actually mounting the real lens.

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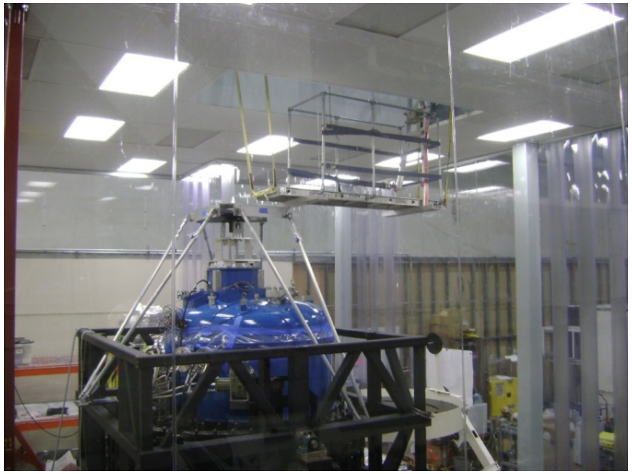
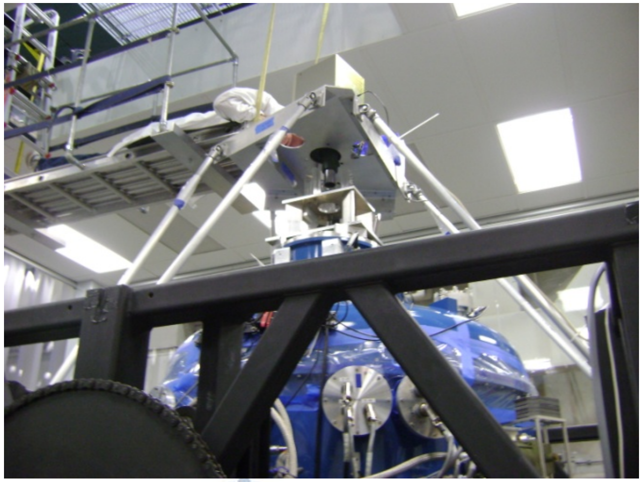
Alignment

- Extensive operating temperature measurements of the instrument's optical axis alignment confirm that the specifications are met.
- Lateral displacements are 0.1 mm in x and 1 mm in y between the instrument’s optical axis and the instrument’s axis of rotation. The requirement was < 1 mm.
- Looking at MOSFIRE from the rear when the instrument is pointed at the horizon, positive x is to the left, and positive y is vertical.
- The relative tilt between the bearing axis and the optic axis is 0.06° compared to the 0.1° specification.
- The z axis position error between the nominal telescope focus location and the actual focal plane location in MOSFIRE cannot be measured except by installing MOSFIRE in the telescope and determining the amount of secondary piston away from the best focus position to focus the telescope with MOSFIRE installed.





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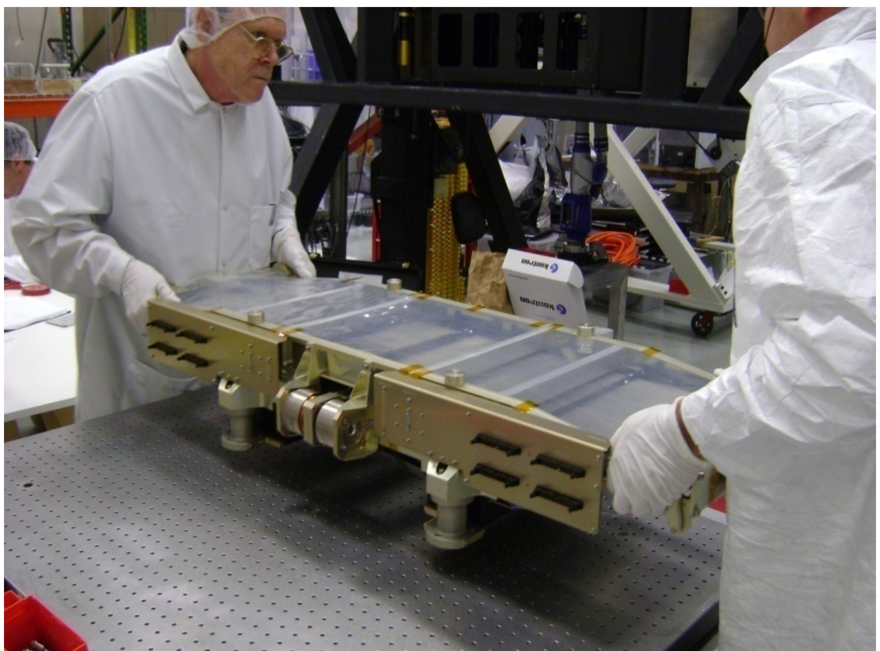
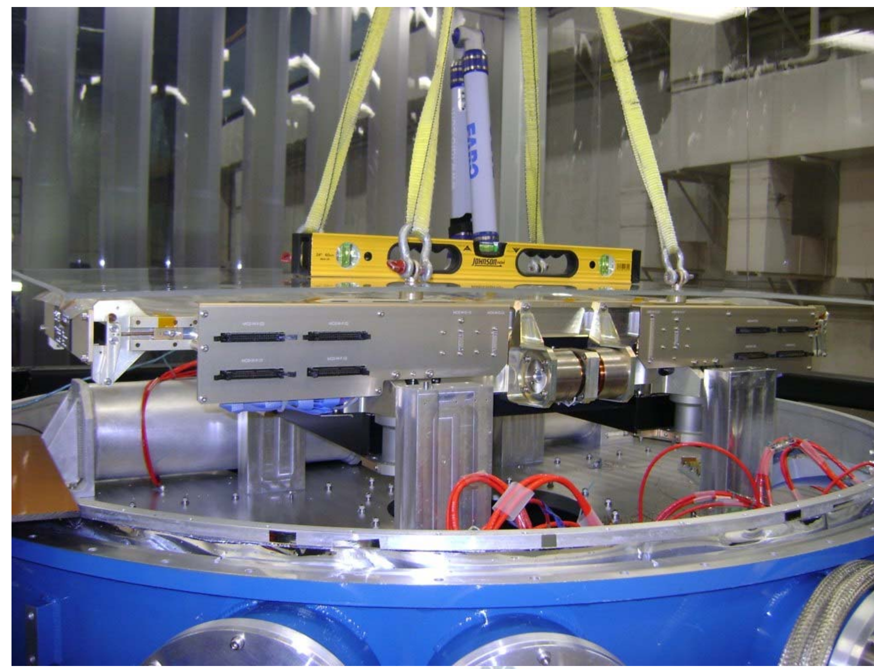
Configurable Slit Unit

- The CSU underwent extensive testing at CSEM before it was delivered to MOSFIRE, and the compliance matrix compiled by CSEM is in reference 4.
- Limited facilities were available for cryogenic testing, and only one complete cryogenic test cycle was performed prior to delivery (reference 28).
- **The CSU was first operated in MOSFIRE during cool down 3 (Nov/Dec 09)**
- Since that time over 1,000 mask configurations have been made.





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CSU cleaning

- Difficulties were encountered with reliable operation during cool downs 5 - 7 and evidence surfaced that the magnets used to actuate the CSU's slit bar ratchet clutches and brakes were cracking, creating magnet debris. One or two bars out of 92 were unreliable.
- *In all those cases we were still able to work and use MOSFIRE*
- The magnets were subjected to excessive stress due to the difference in rate of thermal expansion and contraction between the magnet and the aluminum frame of the brake or clutch in which the magnet was mounted.
- **We held an external review in October 2010 to assess the status of the CSU and recommend a course of action.**
- *The result was a recommendation to disassemble the CSU, remove the debris, and correct any damage that may have resulted.*
- This work was performed successfully by CSEM during the period of late November 2010 to mid-February 2011.
- Failure modes are given in Backup Slide 223.

CSU performance

- **Pinhole mask used to map CSU plane to detector pixels in cool down 8**
  - Transformation allowed measurement to ~6 μm accuracy of locations on that surface using measured image locations on the detector.
- During cool down 9, with the CSU re-installed, the mapping solution was used for extensive measurements of bar positions vs. requested positions.
- These measurements were used to generate newly-calibrated bar offsets and cryogenic scale corrections for each of the 92 bars.
  - these were implemented as part of the CSU server software, which allows easy re-calibration if it ever becomes necessary.
- The typical bar accuracy over the nominal 3.0' x 6.12' spectroscopic field is 10 μm in the CSU plane, **mapping to <0.02" arc seconds on the sky** and 0.07 pixels at the detector, easily exceeding the accuracy requirement and matching the laboratory measurements made by CSEM.
- The new calibration also has the advantage that it has been achieved at 120 K, rather than room temperature of the initial calibration
  - (and, no changes to low-level software needed).

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CSU performance

Results of cool down 9 testing indicate that we have completely satisfactory performance from the CSU.

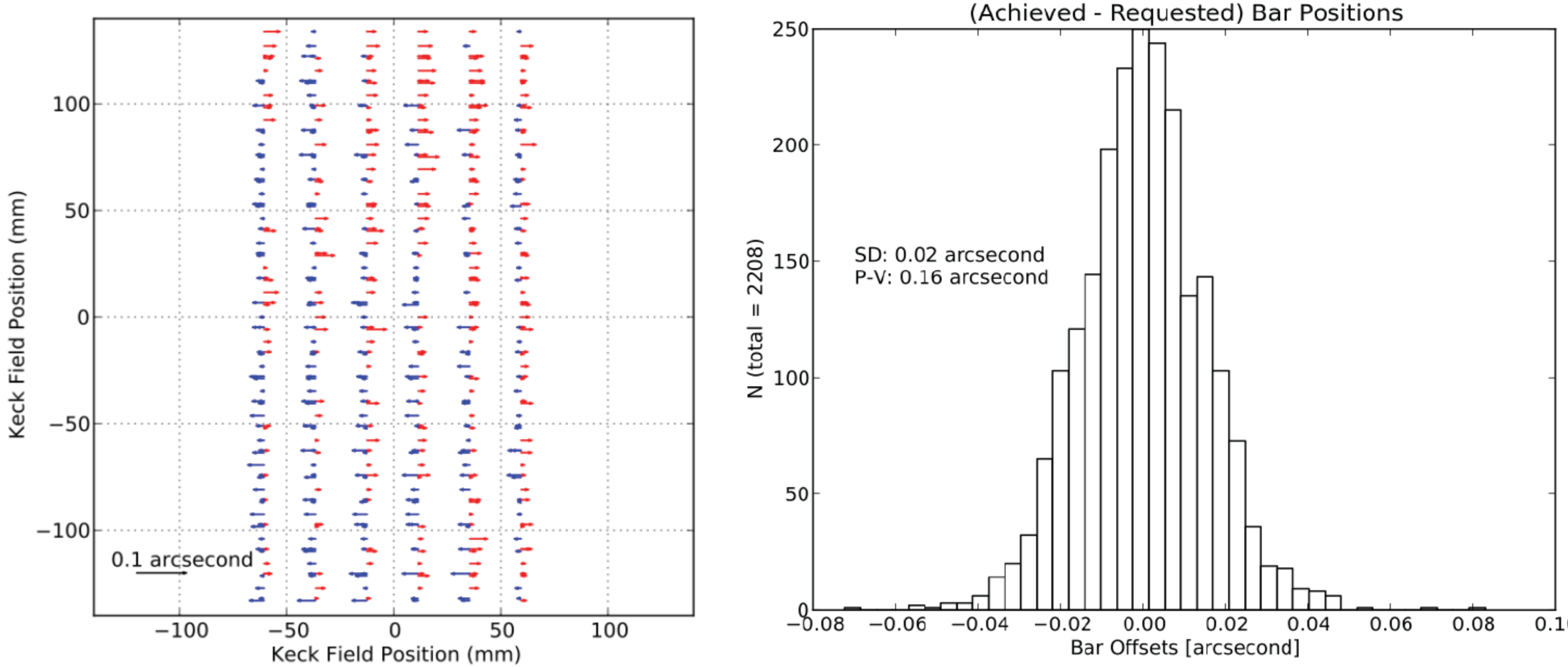

Figure 35: The left figure shows the bar positioning errors in terms of the Keck telescope focal plane for all of the CSU bars. The right figure shows a histogram of the bar positioning errors in terms of the Keck focal plane coordinates for 2208 bar positions.

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Flexure

- As indicated in Table 19 of the Report, the requirement for MOSFIRE flexure correction is that over the course of any 2-hour track on a science target, the image motion at the detector due to flexure must be smaller than 0.3 pixels.
- At the latitude of the Observatory the expected change in rotator angle in a 2 hour period is a maximum of ~60°, with elevation change < 30°.
- The *goal* requirement is for image motion to be less than 0.1 pixels at all rotator angles and all telescope elevation angles.
- It is also highly desirable that the positions of slits at the detector remain stable to sub-pixel levels to allow flat-field calibrations to be obtained for a given configuration during the afternoon or early morning.
- As built, instrument flexure in the dispersion direction (instrument X) is close to the FEA prediction (±1.2 pixels, **Figure 31**), but flexure in the Y direction (spatial, along slits in spectroscopic mode) is significantly larger than predicted (**Figure 32**).

Flexure

This figure shows measured image motion in spectroscopic mode versus rotator angle for 4 elevation angles, 60° (red), 45° (green), 30° (blue) and 0° (horizon, black). Although Y-direction motion is larger than predicted, deflections are repeatable, indicating negligible hysteresis.

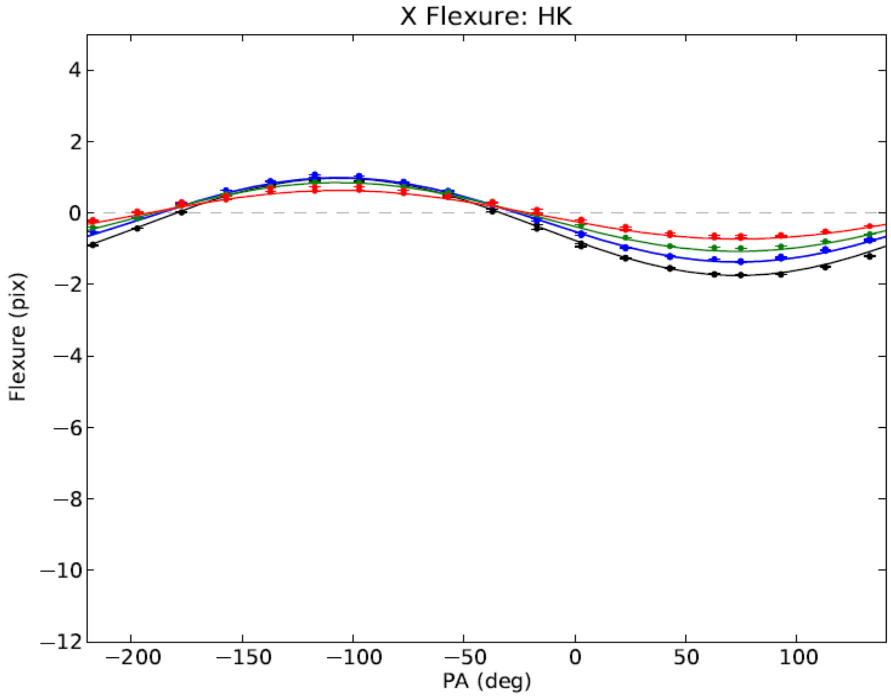

Figure 31: MOSFIRE x-axis flexure vs. rotator angle, HK spectroscopic mode

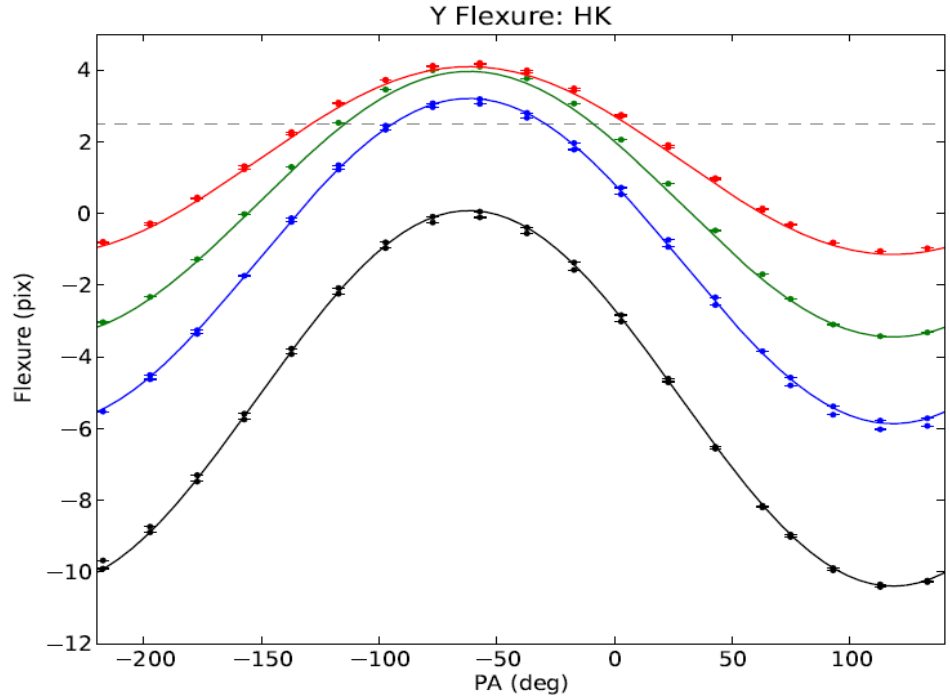

Figure 32: MOSFIRE y-axis flexure vs. position angle, HK spectroscopic mode

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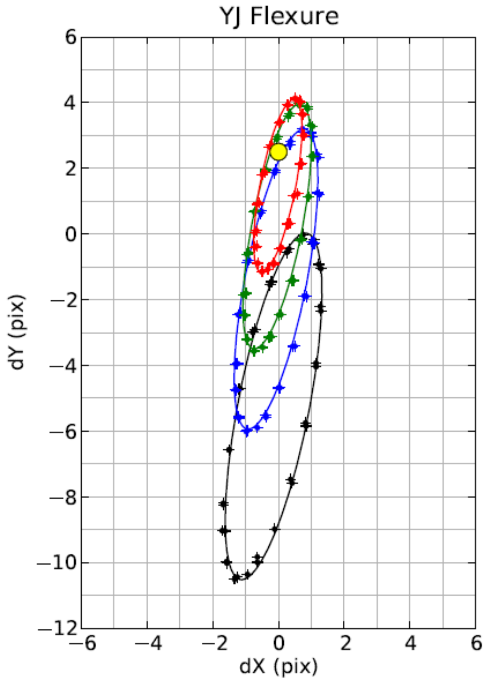
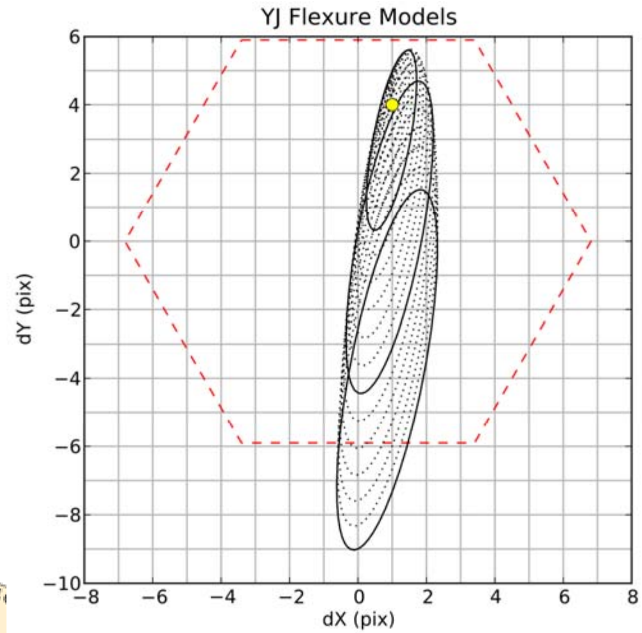
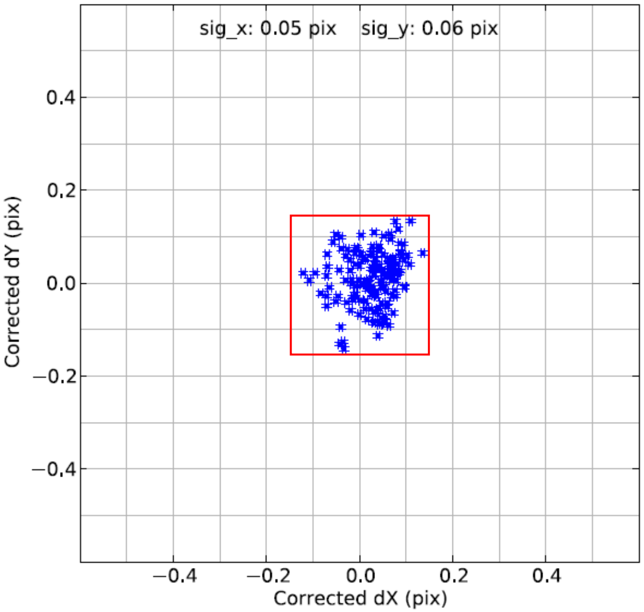


Figure 33: Image motion due to flexure in YJ spectroscopic mode, at various elevation angles

Figure 34: FCS performance
On the left side below, the FCS range is shown with a red hexagon, with flexure motion vs. elevation indicated with ellipses.
On the right side, the performance of the FCS is shown over a full 360 degree rotation at an elevation between calibration values.





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Verification of Mechanical Performance

Bob Weber

A Cross-Section of MOSFIRE

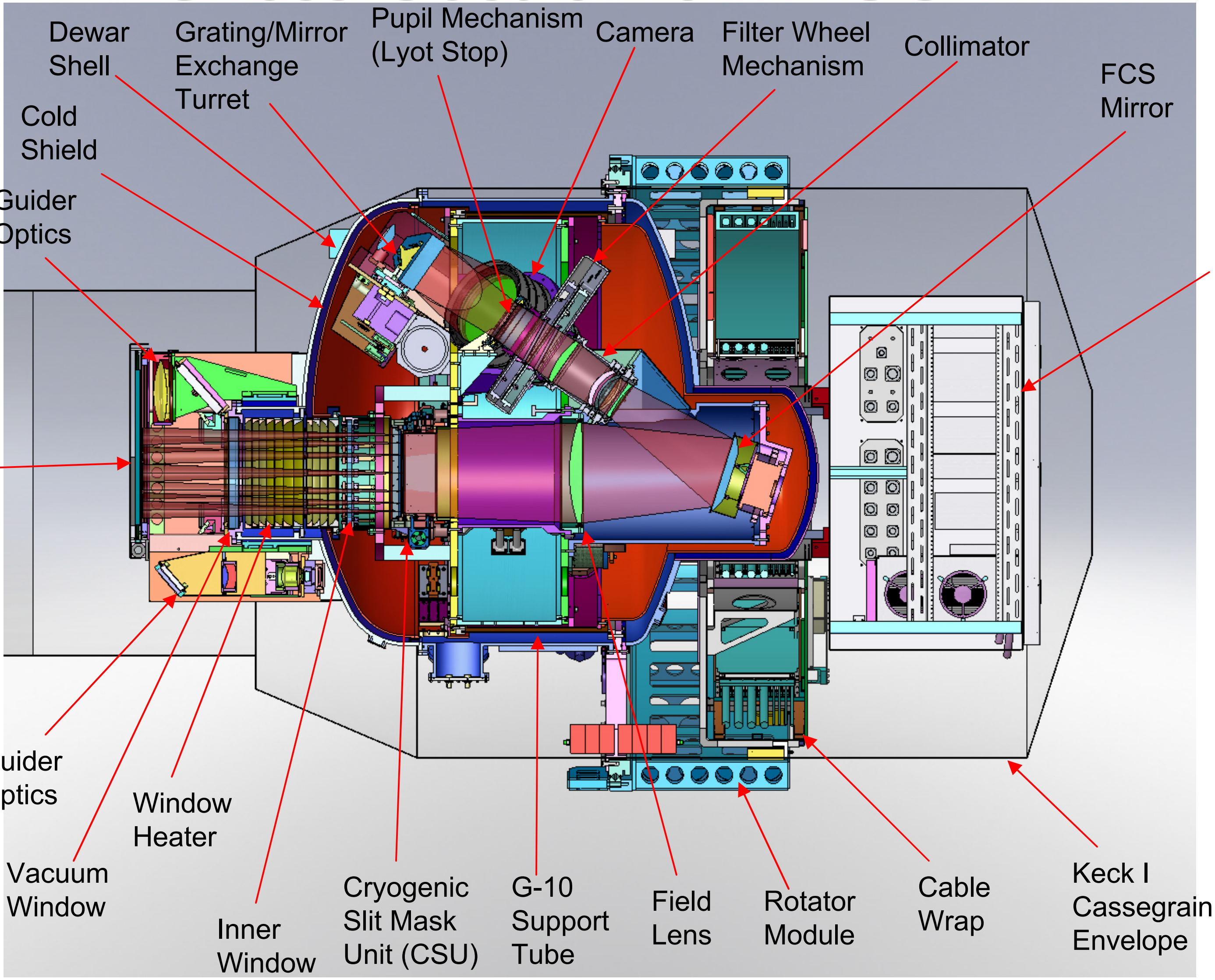

Figure 21: *Section view of as-built MOSFIRE model (Rev 63)*

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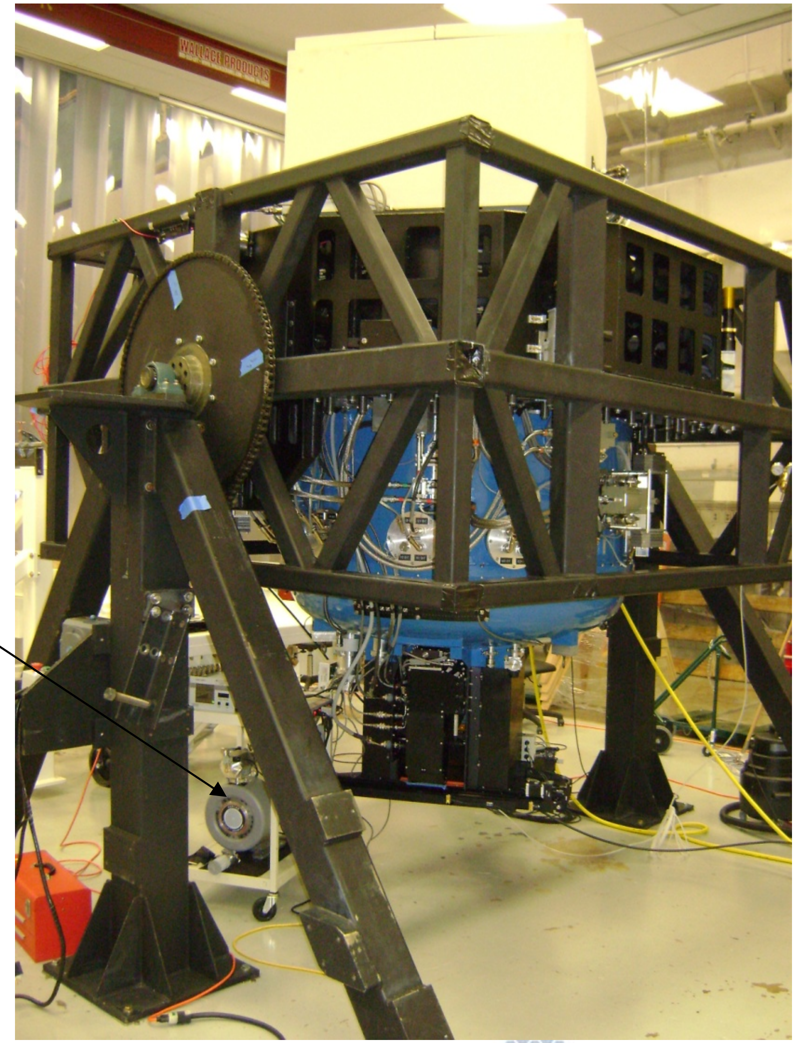
Overall Layout & Constraints

Notes for Figure 21

- A cylindrical vacuum enclosure (the dewar) is attached to a Rotator Module that is a copy of the one used for LRIS
- The Dewar encapsulates the optical design and fits the Cassegrain space
- The instrument is divided into
  - “cold” sub-systems which reside inside the dewar, and
  - “warm” sub-systems that are located outside the dewar
- Photons pass through the Double Window and then through a Cryogenic Slit Unit
- The optical path is folded in the Collimator with an articulated mirror which is utilized for Flexure Compensation
- Photons exit the collimator and pass through the Filter Wheel before reaching the Pupil Mechanism
- After the pupil, the optical path is folded again by the Grating/Mirror ExchangeTurret
- Finally, photons enter the Camera optics and arrive at the Detector Head
- Warm sub-systems include a Dust Cover, Calibration Lamps, and a CCD Guider at the front
- At the rear is a large Cable Wrap and a pair of racks in a single Electronics cabinet
- Vacuum fittings are positioned on the front cover and CCR heads are positioned around the cylindrical body
- A standard Keck Handler, similar to LRIS, is used for instrument transfers

MOSFIRE

- MOSFIRE post-cool down #9 - warming to ambient and facing down for connection to the pumping station
- The large black stand is a modified version of the stand used for the Keck ESI instrument



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Summary

- The instrument is heavier than specified by 150 kg. The excess will be balanced out by adding weight to the top end of the telescope, which in turn will require adding weight to LRIS to restore the balance to avoid top end weight changes.
- *Dimensions, flexure, thermal properties and alignment are within requirements*.
- The CSU meets mechanical requirements as delivered by CSEM.
- In earlier testing the CSU's operability was found to be compromised when magnets cracked during thermal cycling and produced debris which jammed the mechanism. After a review in October 2010, CSEM provided two engineers for almost three months who worked on-site to eliminate this problem. As of cool down 9 the CSU is 100% operable.
- Filter wheel mechanism cycle times are approximately *double* the values specified in the requirements, this will lead to a 30s delay, at most.
- Grating/mirror exchange turret repeatability is double the required 0.1 pixels for one of the modes (HK spec), but is acceptable and will not limit observing.
- Rotator range is limited to slightly less than the 530° specified, but is still acceptable and will not limit observing.
- The getter cannot be removed without disturbing the vacuum and the canister cannot be baked along with the contents. We do not believe that getter service will be frequent, and will occur only when the instrument is opened for servicing.

Weight and CG

Sub-System/Sub-Assembly	Conceptual Design Weight Estimate (lbs.)	Preliminary Design Weight Estimate (lbs.)	Detail Design Weight Estimate (lbs.)	Current Design Weight Estimate (lbs.)	Difference (lbs) {Relative to DDR}	Difference (%) {Relative To DDR}	Comments
Vacuum System	137	137	21.5	17.3	-4.2	-19.53	No onboard pumps
Cable Wrap	315	325	270	339.4	69.4	25.69	Includes hoses & cables; added as-built cable shield, plastic pads, & chain clamp
Collimator Assembly	80	61.5	40	39.8	-0.2	-0.45	Glass=11.25 lbs.
Camera Assembly	155	127	129.5	138.5	9.0	6.98	Glass=66.7 lbs.
Internal Structure Assembly	810	804	773	785.9	12.9	1.66	
Detector Mount Support Assembly	25	25	15	10.7	-4.3	-28.67	
Field Lens Assembly	35	32	32	32.0	0.0	0.00	Glass= 21.3 lbs.
Filter Wheel Assembly	95	85	93.8	90.4	-3.4	-3.62	
Optical Baffle Assemblies	30	30	7.4	8.0	0.6	8.11	
Pupil Mechanism Assembly	15	14	16	16.4	0	2.50	
FCS Assembly	32	37	37	47.3	10	27.84	Mirror= 7.3 lbs; stage= 26 lbs (invar, not aluminum)
Guider System	100	95	103	99.4	-4	-3.50	Glass= 26.5 lbs
Getter	0	0	5	15.0	10	200.00	2 cans(8 lbs.), getter & thermal bridge not in model
Thermal Strapping Assemblies	75	75	87.9	93.1	5	5.92	
CSU	77	77	90.6	92.4	2	1.99	
Calibration Lamps & Power Supplies	0	0	30	33.8	4	12.67	added after PDR,
Grating/Mirror Exchange Assembly	98	106	126.9	126.5	0	-0.32	Mechanism for second grating added after PDR
Dust Cover Assembly	25	55	65	77.5	13	19.23	Includes Guider Assembly Cover
Vacuum Chamber	1260	1295	1300	1335.4	35	2.72	Includes port covers w/ connectors
Cold Head Assemblies (3x)	80	148	287.1	200.5	-87	-30.16	Inc: cold plate extensions, mounts, and 34 lbs./ea of balance weight on main CCR's
Window Assembly	30	60	185.5	172.8	-13	-6.84	Glass= 29 lbs; includes heater & inner window mount
Electronic Cabinet & Cabling	400	469	576.5	890.0	314	54.38	measured cabinet weight is 740 lbs; plus cabling/hoses=150 lbs estimate
Shield Assemblies	125	450	369.6	380.6	11	2.98	Initial shield weight under-estimated, MLI not included
CCR plumbing	0	0	0	106.0	106		estimate from CAD model
Instrument Counterweights	0	0	326.5	301.2	-25.3	-7.75	
Total Weight	3999	4508	4989	5450	461	9.24	Goal= <4400 lbs.
Total Weight (w/out Counterweights)			4662	5149	486	10.43	
Cold Weight			2009	2049			
CG Location (relative to bearing CL):							Model weight used in CG calculation= 4946/4882 lbs.
Nominal Wrap Position :	*w/out Cweights*	*W/ Cweights*					
X Position (in)	-0.48	0.06					
Y Position (in)	2.10	0.05					
Z Position (in)	2.41	2.10					

Table 20: As-built MOSFIRE weight and CG estimate.

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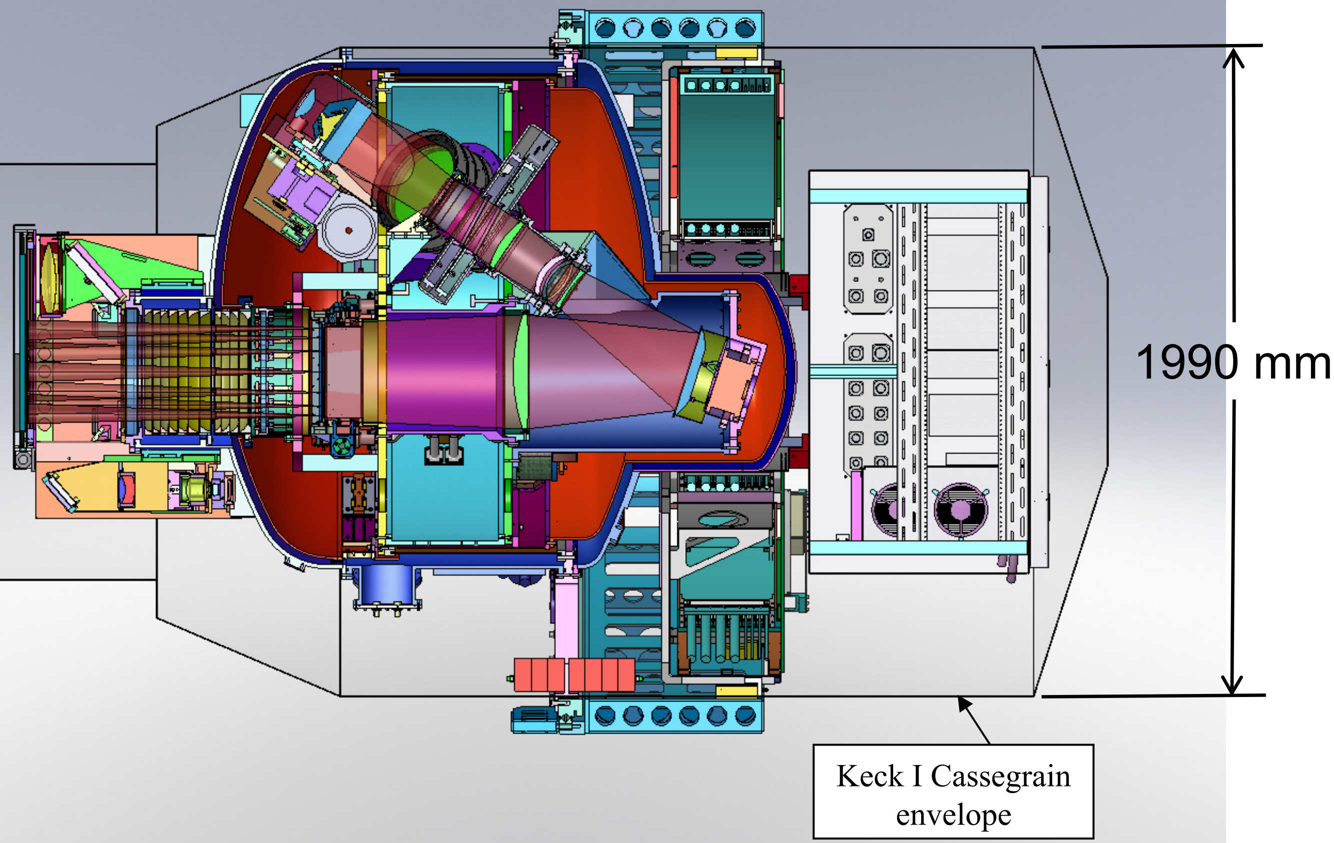
Overall Dimensions

- The overall dimension requirement for MOSFIRE is 2030 mm x 2030 mm x 3607 mm (height x width x length).
- The overall dimensions from the as-built CAD model [Rev 63], excluding the rotator, are 2002 mm x 2002 mm x 3179 mm.
- The height and width are the overall dimensions of the cable wrap, and the length is the distance from the Dust Cover to the electronics cabinet.
- Within the Cassegrain tube, the major diameter available for a rotating instrument is actually 1990 mm.
- A cross section of MOSFIRE, which includes the full Keck I Cass envelope, is shown in **Figure 26**.
- The as-built CAD model indicates that MOSFIRE will fit within the envelope.
- **The as-built dimensions of MOSFIRE were verified using a tape measure as follows:**
  - Total length (electronics cabinet to dust cover) = 125 in (3175 mm)
  - Diameter of the cable wrap = 79 in (2006 mm)
- The measurements agree with the model, given the accuracy of the method.

MOSFIRE and the Cass envelope

Figure 26: MOSFIRE with the Keck I Cassegrain envelope



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Ambient Temperature

- The MOSFIRE requirements specify an operating ambient temperature range of -15 °C to +20 °C. Environmental test facilities are not available to confirm that operation will be satisfactory over this range. During laboratory testing the ambient temperature in the test facility ranged from +20 °C to +25 °C.
- There are three external mechanisms (rotator bearing, dust cover drive and guider focus drive) and three closed cycle refrigeration (CCR) heads that are exposed to the ambient environment.
- The temperature ratings of these mechanisms are summarized in the Table below:

	Operating Temperature Range		
Mechanism	**Min.**	**Max.**	**Notes**
Rotator bearing	-10	+30	Bearing is lubricated with Kluberplex BEM 34-132 with a service temperature range of -35 °C to +140 °C
Dust cover drive	-29	+40	
Guider focus	+10	+40	Identical units in use in similar operating temperature range to MOSFIRE's requirements
CCR heads	+4.4	+43	Other identical units in use in the WMKO operating temperature environment

Implementation Requirements

- **Dewar Window**
- As specified, the dewar entrance window (also referred to as the "vacuum window") is protected against the formation of condensation or frost on the window.
- The entrance window configuration is illustrated in **Figure 20**.

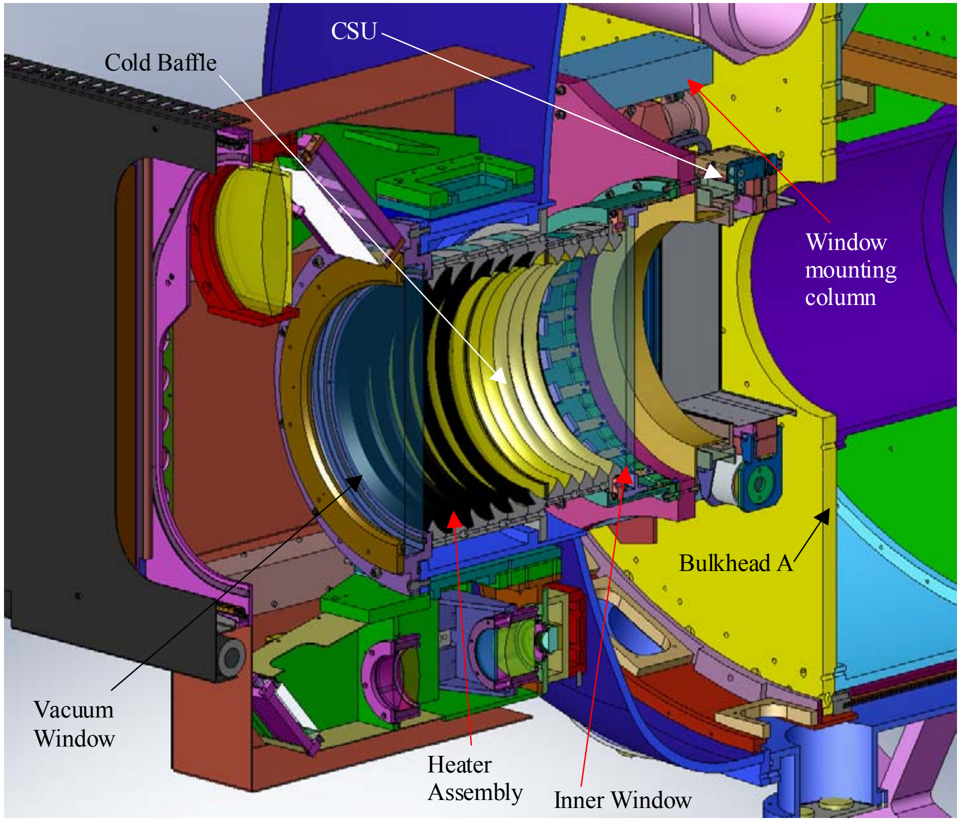


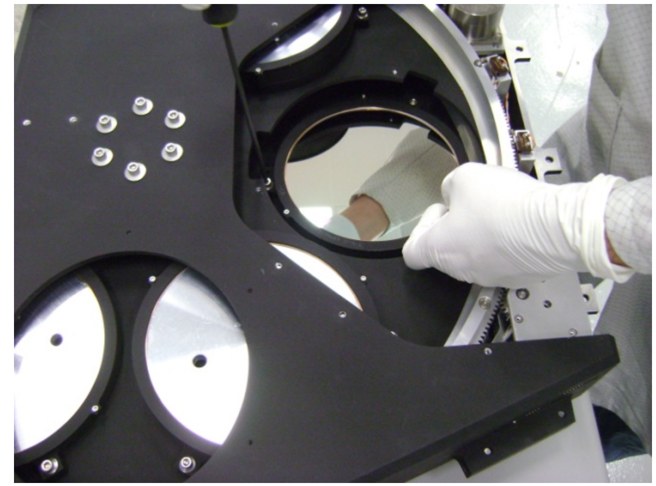
Figure 20: MOSFIRE dewar window configuration

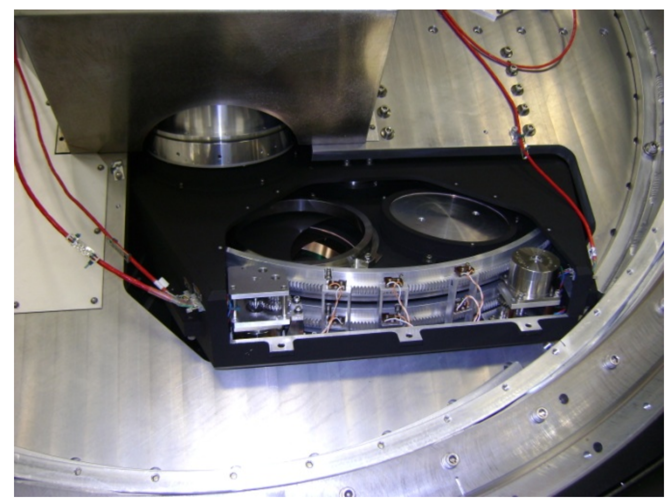
Dewar window

- The vacuum window is 34.9 mm thick and provides the vacuum seal.
- A second inner window serves to limit thermal radiation reaching CSU bars.
- A snout tube extension of the dewar aids in thermal isolation by increasing the separation between the windows and the CSU and therefore reducing the window viewing angle from the CSU.
- A heater is located between the windows within the snout tube constructed of coated aluminum rings with unique profiles to efficiently heat the window while minimizing heat directed back to the CSU.
- Surfaces facing the vacuum window are coated with black paint and surfaces facing the inner window are plated with gold.
- The heater baffle assembly consists of strip heaters attached to the outer wall and covered with MLI.
- Attachment of the heater baffle assembly to the snout is insulated to minimize heat transfer to the dewar walls, minimizing the heater power requirements as the heat is restricted to radiating to the window and snout interior rather than also trying to heat the dewar walls.
- The inner window is in vacuum and acts as a radiation boundary with an intermediate temperature between ambient and that of internal optics.
- As specified in the requirements, the two windows do not obstruct the FOV, and both are anti-reflection (AR) coated to maximize transmission in the near-IR.

Filter Wheels

- The maximum measured in-beam position variation was 0.08° (compared to the 0.10° "typical" requirement).
  - Measurements made "warm" with portable CMM
- The maximum cycle time is 57 seconds, with a typical cycle time of ~35 seconds.
- The requirement for cycle times is 30 & 15 seconds, respectively.
- The wheel detent design and, subsequently, the drive design had to be altered during I&T in order to achieve the accuracy, repeatability, and reliability requirements.
- With the upgraded drive design, the output speed had to be halved in order to meet the repeatability and reliability requirements.





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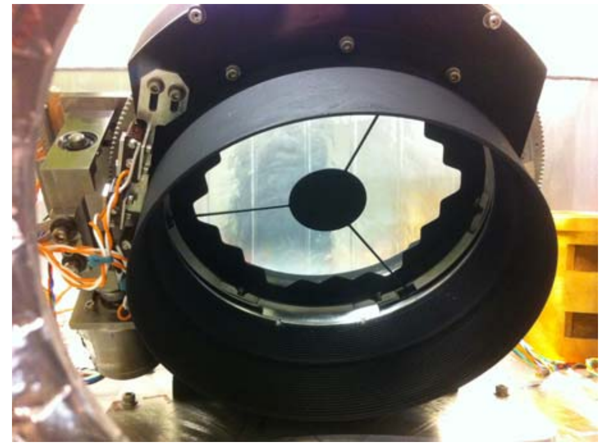
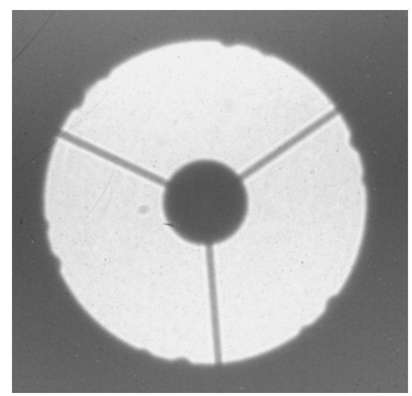
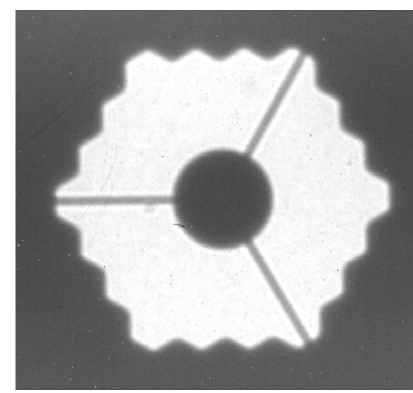
Rotating Lyot Stop

- **Multiple open/close tests of the pupil mechanism were carried out.**
- In CD #9 the open/close procedure was repeated 20 times at 3 elevation angles and 3 rotator angles.
- In all 180 open/close procedures the mechanism repeatedly opened and closed to the same location within a 0.8 milliradian uncertainty.
- **The pupil mechanism was also opened and closed successfully in rotation tests a total of 320 times.**
- Confirmation of tracking was done for three speeds (0.00218, 0.00109, and 0.0005045 radians per second) and four different zenith distances.
- Tracking scripts of 30 minutes and 5 minutes were used in each position and for each speed.







Grating/Mirror Exchange Turret

- The grating/mirror exchange turret has been operated thousands of times in its final, as-built configuration without any movement errors.
- The in beam repeatability is 0.1 pix (YJ and Mirror Pos'n) ; 0.2 pix for HK grating pos'n, compared to the requirement of 0.1 pixel.
- The maximum cycle time is <45 seconds, as required.

The Rotator- Alignment

- The rotator is a structure in which the MOSFIRE dewar, cable wrap and electronics racks are mounted and which rotates this assembly about the instrument's optical axis in order to compensate for the image rotation that occurs as the telescope follows the sidereal motion of the sky.
- The MOSFIRE Cassegrain rotator module was installed and aligned in the Keck I telescope in May 2008 prior to shipment to California.
- Operating temperature alignment of the instrument optic axis to the rotator axis was measured during MOSFIRE cool down #3 (Oct- Dec, 2009). The measurements were reviewed on the instrument alignment slide.
- The maximum combined decenter error requirement is < 1 mm; the maximum combined tilt error requirement is <0.1°; the maximum combined Z axis translation requirement is +/-1 mm.
- The as-built alignment meets the requirements, as shown below; we could not measure z axis translation in the lab.

MOSFIRE As-Completed Rotator Alignment			
Parameter	**Actual**	**Tolerance**	**Units**
Rotator decenter in x	0	+/-0.25	mm
Rotator decenter in y	-0.35	+/-0.25	mm
X axis tilt	0	+/-10	µrad
y axis tilt	145	+/-10	µrad
z axis translation	-	+/-0.1	mm

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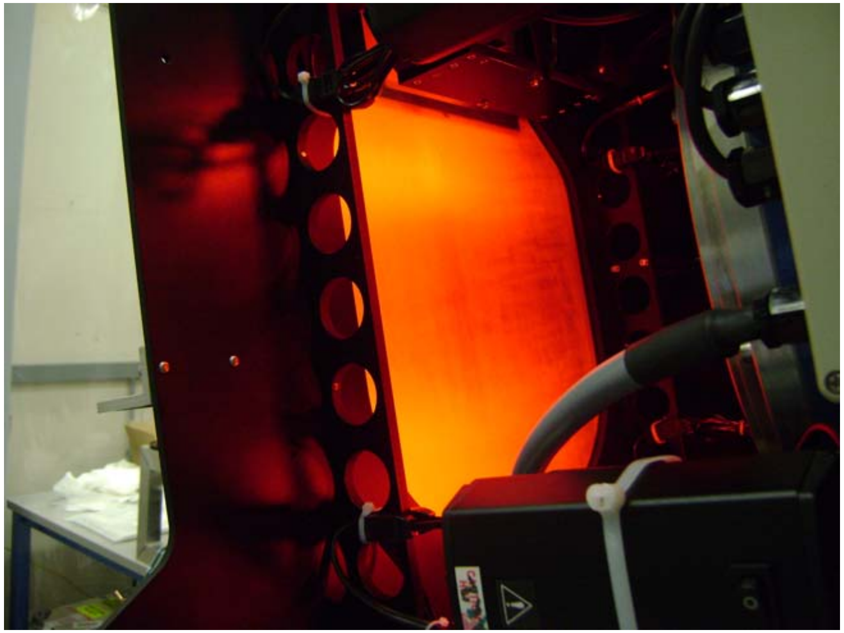
The Rotator- Performance

- The rotation range of the rotator is determined by the range of the MOSFIRE cable wrap.
- The limit hard stops in the MOSFIRE rotator module have been set to allow a maximum of 527° of rotation in the clean room environment.
- The MOSFIRE limit switches will be set at the Observatory to prevent contact with the hard stops and allow a maximum of ~520° of rotation.
- While this will be 10° less than the requirement it still allows sufficient travel to accommodate the rotation required by all of the common combinations of observing duration and declination at the worst case azimuth angles (due north and due south) while not requiring more than a 180° slewing of the rotator to achieve sufficient rotator travel to a hard limit.

- Note: At the present time were are investigating and correcting problems (binding and large drive currents) with the rotator drive system and cable wrap that were noticed on cool down 9.

Calibration Lamps

- MOSFIRE has 4 Argon and 4 Neon arc lamps mounted just outside the dewar entrance window but inside of the dust cover shroud.
- The lamps have reflectors and are aimed at the inside panel of the dust cover door.
- The lamps have been used successfully throughout the laboratory testing of MOSFIRE.



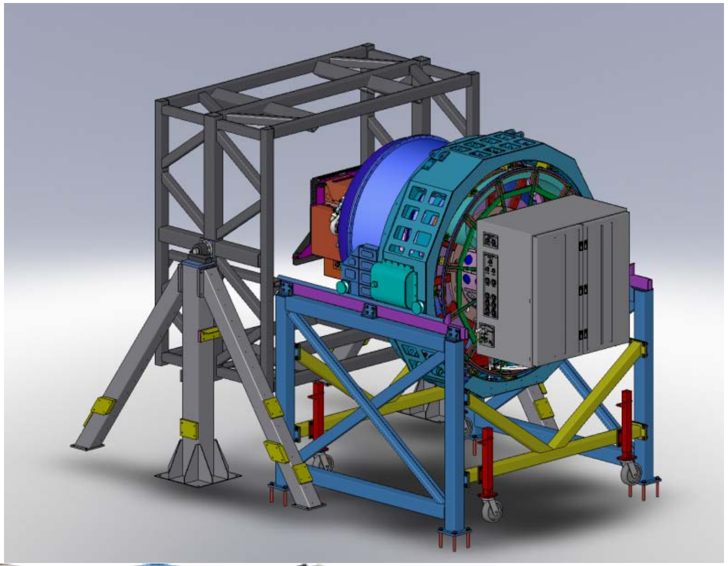
View of rear of Dust Cover with side panel removed to show illumination by arc lamps. The arc lamps are too bright unless their length is partially shielded.

MOSFIRE Shipping Preparations

Bob Weber

Removal From ESI Stand

- MOSFIRE will be de-coupled from the ESI stand defining points and lowered onto the ESI stand rails with the aid of an overhead crane.
- The as-built weight of MOSFIRE plus rotator will be determined at this time.
- A custom-built Instrument Removal Platform (IRP) will be positioned next to the ESI stand- aligned with the rails- and bolted to the floor.
- MOSFIRE will be backed onto the IRP.



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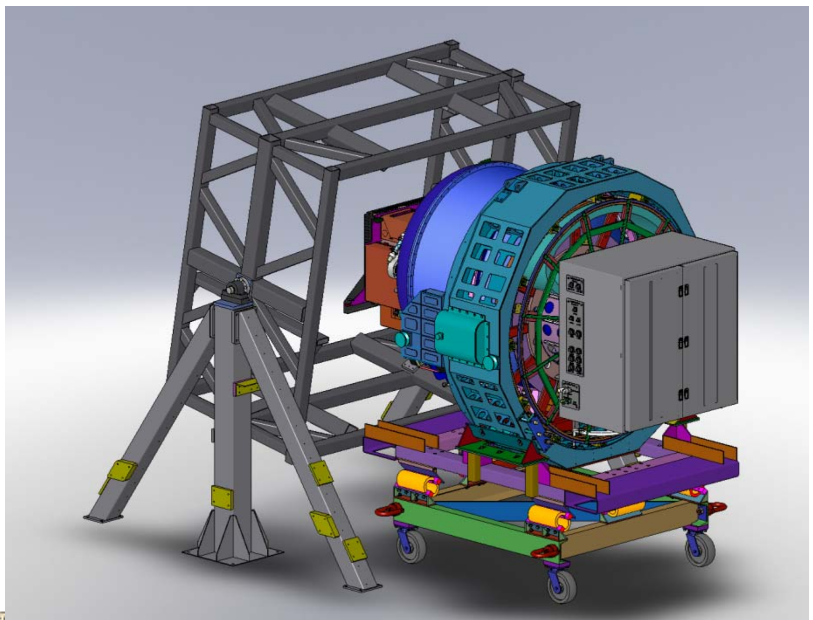
Transfer to Shock-Isolating Platform

- MOSFIRE will be lifted by the overhead crane.
- The IRP will be unbolted from the floor and rolled out of the way.
- The Shock-Isolating Platform, based on a platform design used to transport LRIS successfully, will be rolled into place under MOSFIRE.
- MOSFIRE will be lowered & secured onto the Shock-Isolating Platform.



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Moving Day

- Dunkel Bros. Machinery Moving, Inc. will be contracted to move MOSFIRE from the Clean Room to the selected port.
- They will design and fabricate a “crate” which will be assembled around MOSFIRE to protect it from damage
- The Shock-Isolating Pallet to crate interface will include the ability to vacuum-bag the entire instrument within the crate. Dunkel Bros. personnel will complete the vacuum bagging operation.
- Dunkel Bros. will provide all of the equipment to move MOSFIRE out of the clean room, position MOSFIRE in the crate, and position the crate on the trailer, which they will also provide.
- Dunkel Bros. will be responsible for transporting the crated instrument to the port with their truck/trailer.

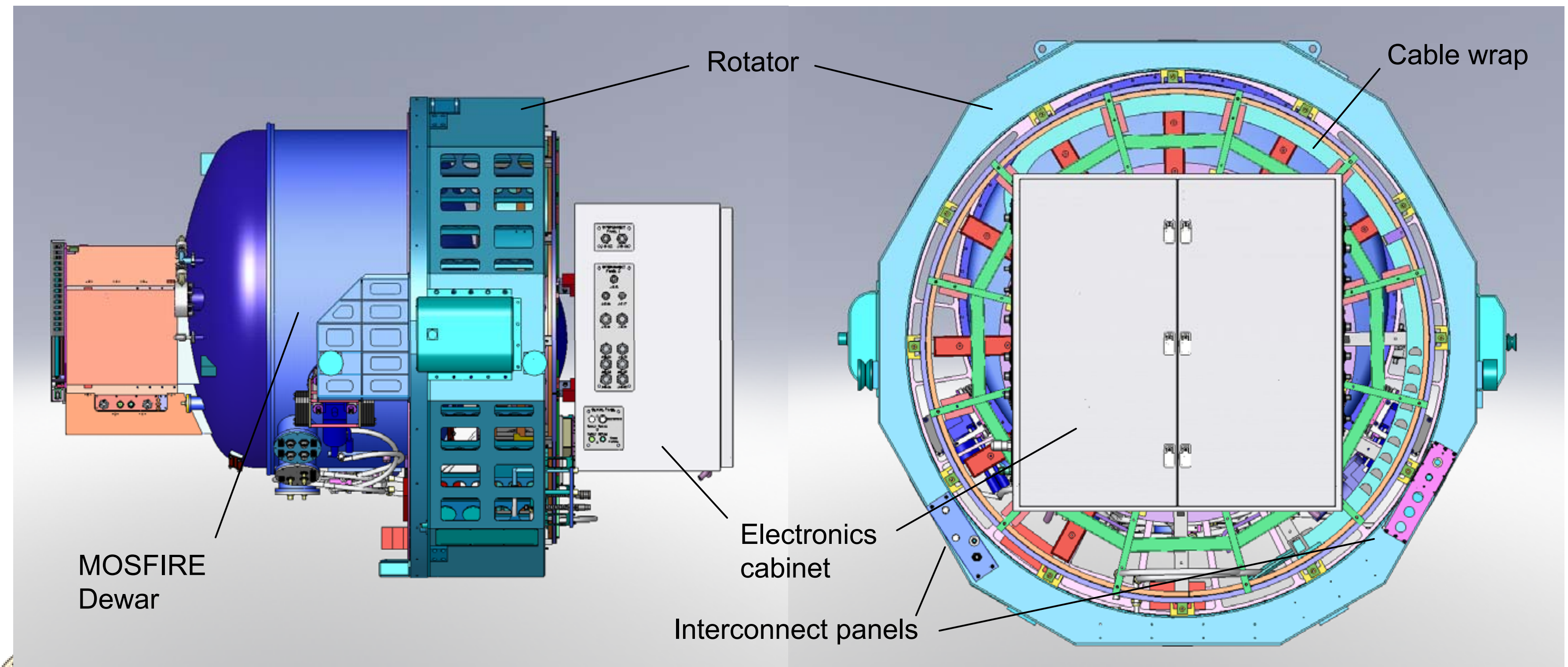
Verification of Electronics & Systems

George Brims

W. M. KECK OBSERVATORY

Electrical/Electronics Design

- **MOSFIRE electronics consists of two major component groups**
  - the instrument electronics located in the electronics racks mounted on the instrument
  - the computer rack containing the instrument host computer and data storage disks located in the Keck I computer room.
- The host communicates with the instrument via a dedicated 1000Base-SX network
- Instrument electronics are housed in two EIA 19 inch racks in a custom NEMA-4X cabinet



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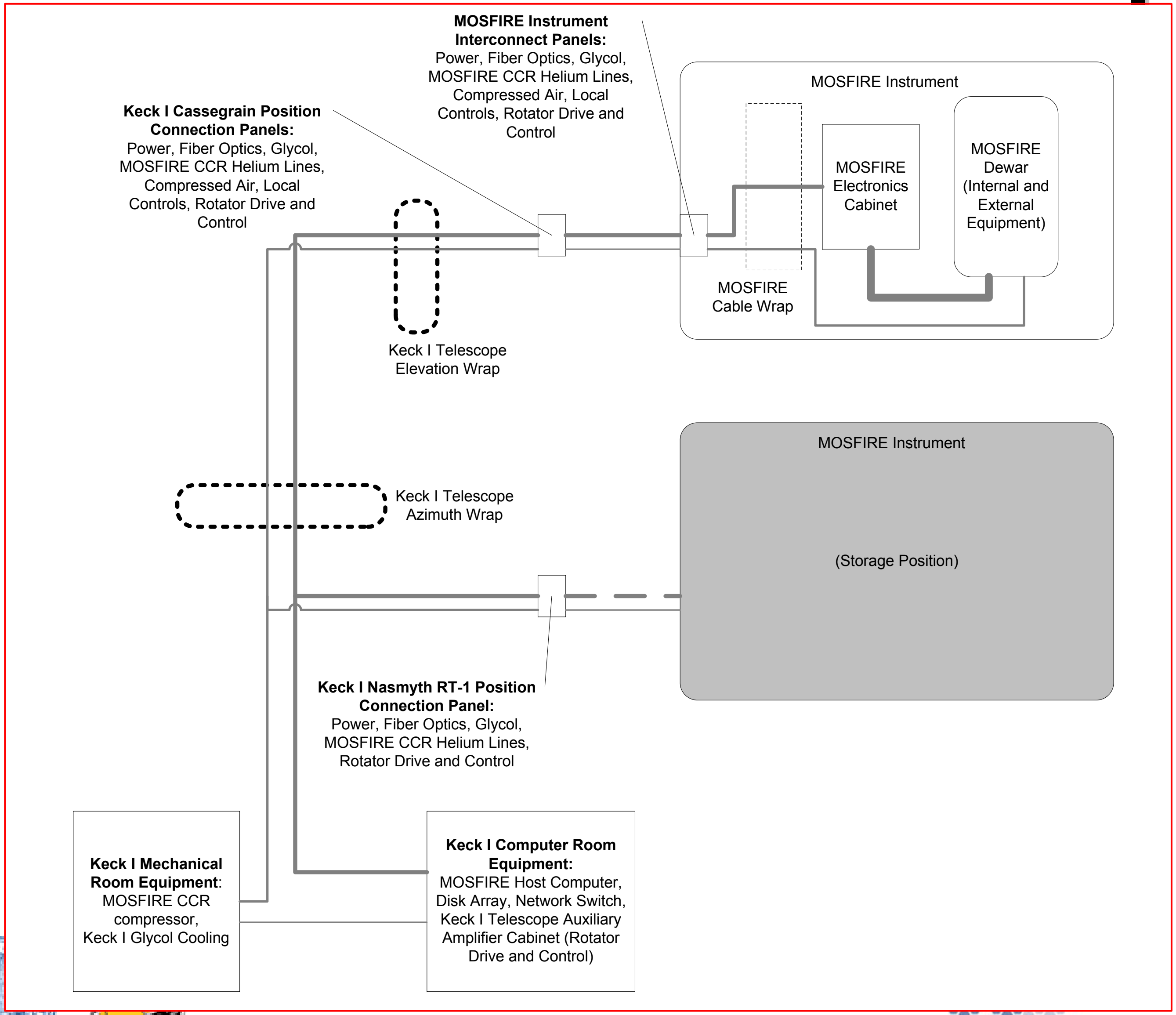
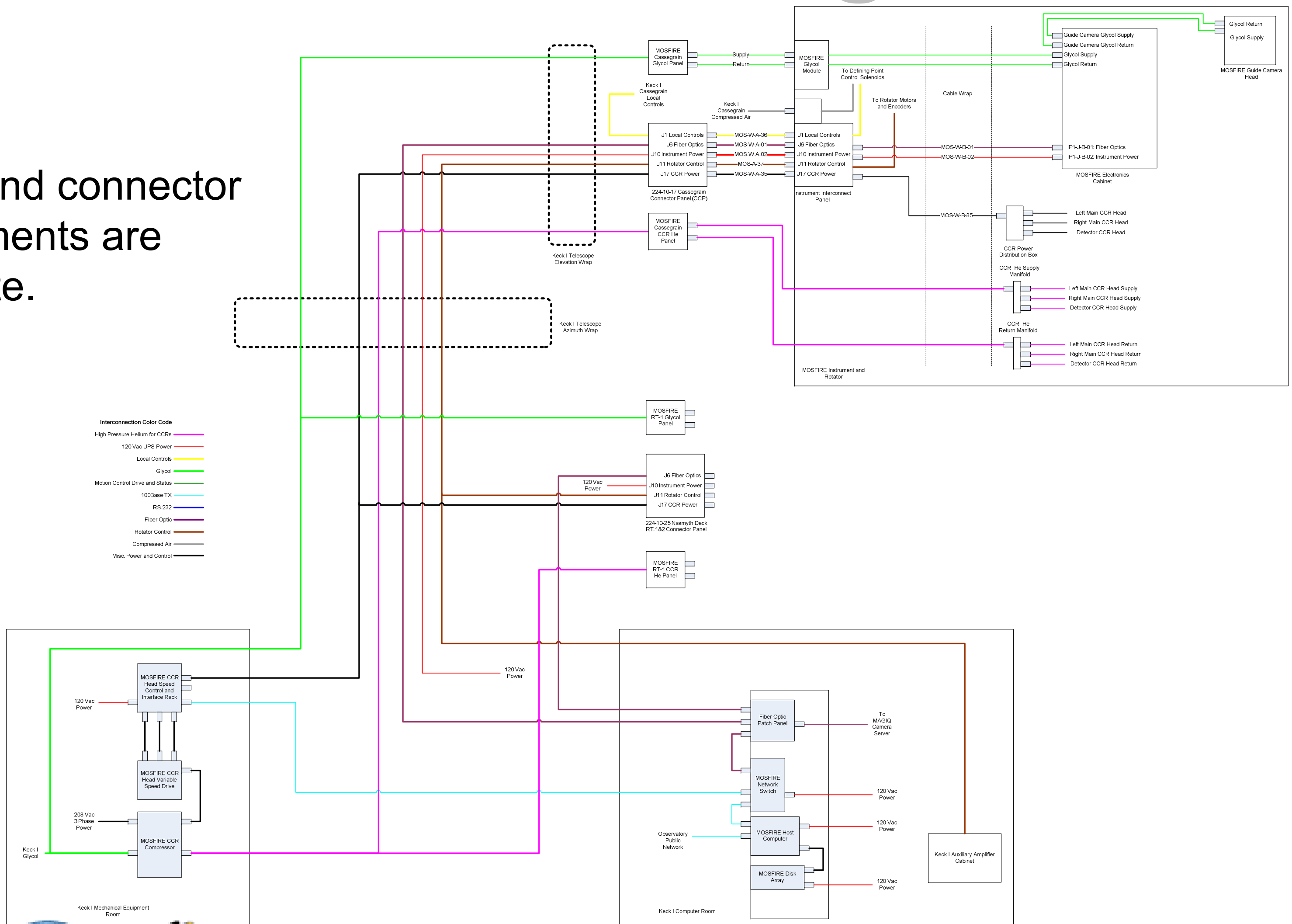
MOSFIRE at the Telescope



Interface Diagram

Cable and connector assignments are complete.



MOSFIRE One Line Diagram
10/09/09 Rev 9
SMA, edited by GB

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Components of the System

The main components of the MOSFIRE electronics are:

- The science detector system
- The motion control systems (rotary mechanisms, FCS and the CSU)
- Thermal management systems (Dewar internal structure and detector)
- Housekeeping systems (temperature monitoring, pressure monitoring, coolant flow monitoring, and power control)
- Data communications system

In subsequent slides we will outline how the delivered system meets the Requirements

W. M. KECK OBSERVATORY

Features of the System

The main features of the MOSFIRE electronics are:

• Efficient packaging of all external components in the weather-tight electronics cabinet.

• Providing efficient access to all cabinet modules components for servicing.

• All external cabling rugged and properly routed between cabinet and instrument, cabinet and observatory.

• Guide camera system and arc lamps packaged within the front dust cover enclosure.

• Detector Jade 2 electronics housed in small enclosure on dewar shell.

Temperature & Humidity

- All electronics in MOSFIRE are designed for operation in an ambient temperature range of –10° C to 30° C and a relative humidity of 95%, non-condensing, with two exceptions.
- These are the Pulizzi power controllers, which are rated for 0° C to 50° C, and the HP network switch, rated from 0° C to 55° C.
- These are located within the electronics cabinet, which will be an environment somewhat warmer than the telescope dome, so their slightly elevated lower temperature limit should not present a problem.
- Other examples of both these components are already in operation at the Observatory and work satisfactorily.
- Cables are selected for an operating temperature range of –30° C to 100° C

Host & Target Computers

- There are three computers in the computer room dedicated to MOSFIRE. One is the instrument host computer, one is the detector target dedicated to detector control and acquisition, and the third is a spare.
- They are all identical, Sun model Sunfire X4150 running Solaris.
- The *embedded* detector control computer is an Augmentix model A+R200 PC type computer located in the electronics cabinet.
- This computer is an industrial/server grade 1U, 19 inch EIA rack mount computer equipped with a flash disk as the system disk, and a second flash disk as backup.
- It runs Windows XP, a WMKO approved operating system.
- The computer is equipped with local monitor, mouse and keyboard connections for test and diagnostic purposes, but is usually accessed over the network.
- It contains a built-in CD-ROM drive, but in the event of a failure an external drive may be connected via USB when required for maintenance.

Instrument Connection Panel

- All interconnections to the MOSFIRE instrument (AC power, fiber-optics and CCR power) are made at a single location, called the Instrument Interconnect Panel (IIP), on the stationary portion of the rotator frame.
- The panel is located on the lower right portion of the frame
- This location also has the connections for the Instrument Rotator and the Local Controls for the defining points.
- A separate panel for glycol and CCR helium connections is located on the lower left of the rotator frame.
- The interconnect panel itself does not incorporate circuit breakers to protect the wiring of the MOSFIRE instrument dewar and the rotator, but the AC power inside the electronics cabinet is distributed by the Pulizzi power controllers, which incorporate protective breakers (and surge protection), and rotator power is supplied by the Observatory telescope servo system, so no on-instrument protection is required.

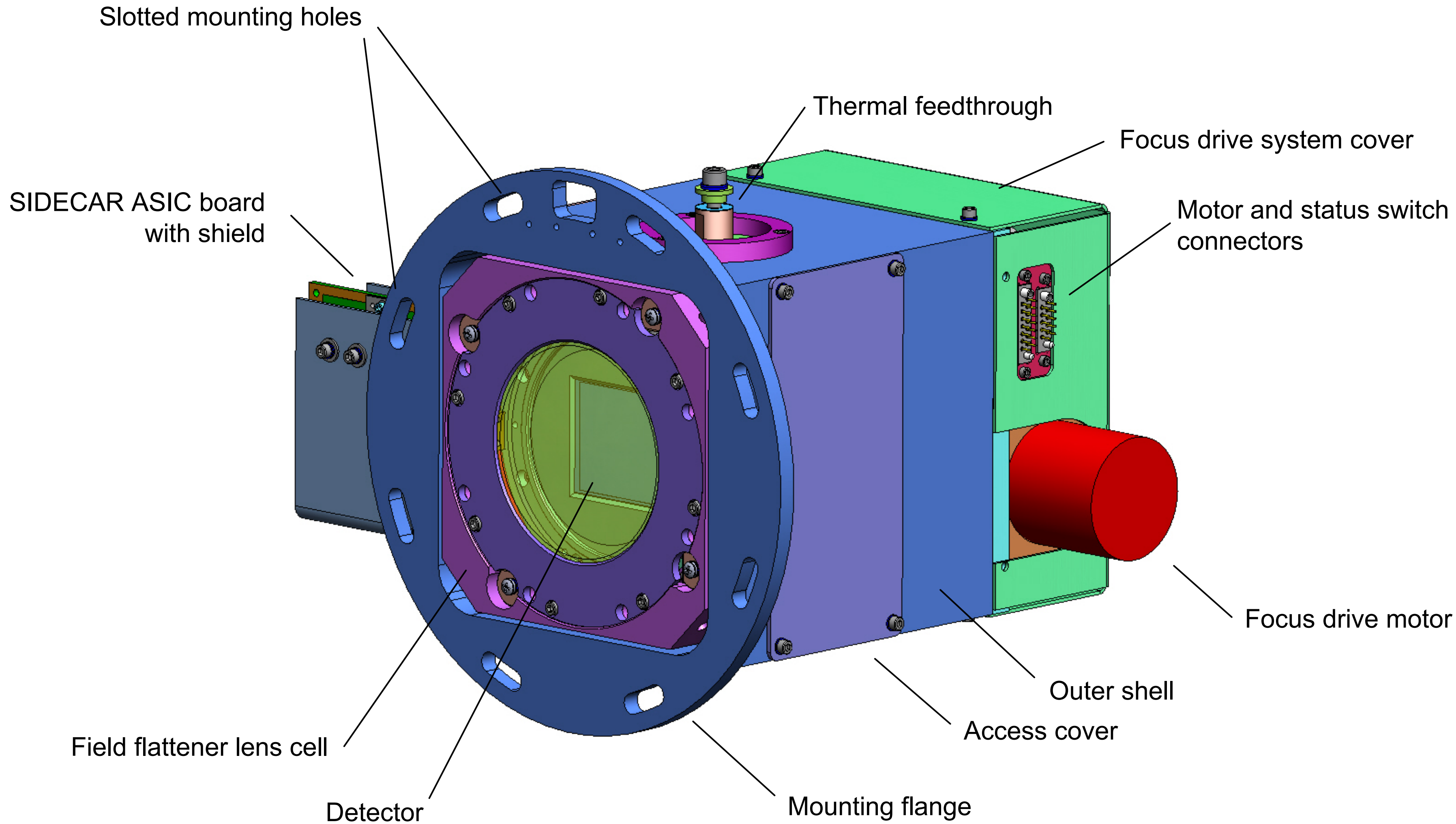
Digital Control and Status Communications

- Digital communications for control and status information between the HP Procurve network switch and subsystems and modules (Lantronix terminal server, Pulizzi power controllers and Augmentix target computer) within the electronics cabinet has been implemented using the TCP/IP protocol over a 100Base-TX Ethernet interface.
- Communication between the network switch in the cabinet and its counterpart in the computer room is over a fiber-optic 1000Base-SX connection.
- A terminal server in the cabinet provides RS232 connection to the Pacsci motor controllers, Lakeshore temperature controller, Physik Instrumente FCS controller, CSU control rack, and Varian vacuum gauge.
- The terminal server is a Lantronix EDS16PR, superseding the ETS8PS with the approval of WMKO.

Motion Control Systems

- All mechanisms except for the CSU and the FCS actuator are stepper motor driven.
- The motion controllers for all stepper motors, with the exception of the guider camera focus controller, are PacSci model PD2400D.
- The guide camera focus controller is a Newport model LTA100 supplied by WMKO.
- Control of the FCS, the only piezo device in the system, is performed by a Physik Instrumente 500 series controller.
- The CSU control and drive system was provided by CSEM

Detector Head



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Detector performance

Ian McLean

Science Detector

- The science detector is a Teledyne Hawaii-2RG HgCdTe device with a nominal format of 2048 x 2048 imaging pixels and a cut-off wavelength of 2.5 μm
- The requirements for the performance of the science detector are given in Table 30.
- All measurements are at a temperature of 77 K unless noted otherwise.
- Dark current is <0.008 e-/s/pixel (meets goal)
- Charge persistence is ~0.04% (meets spec)
- Flatness is ~ 9 μm (meets goal)
- Readout noise =17e- rms in a single CDS (meets spec)
- Readout noise = 4.9e- rms with Fowler 16 (meets goal)
- Minimum integration time = 1.455s with HxRG v. 2.30

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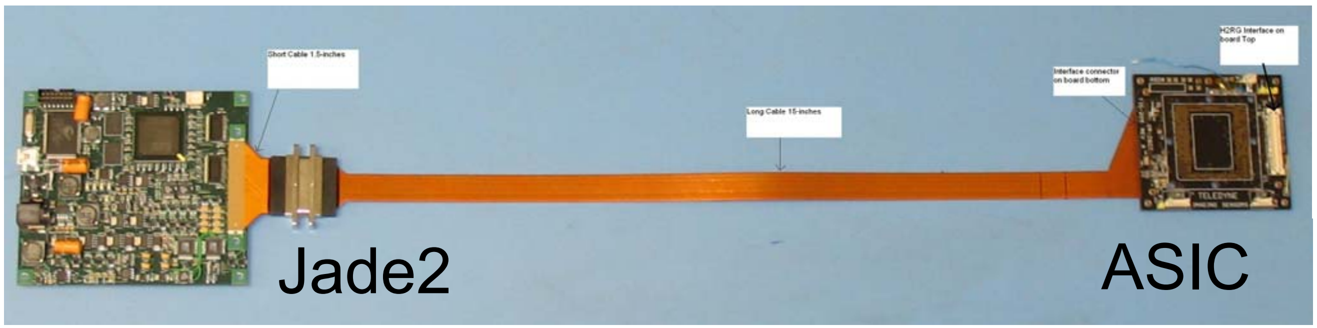
Detector Performance

- The H2-RG is operated with the SIDECAR Application Specific Integrated Circuit (ASIC) and Jade2 card interfaced over USB 2.0 to a PC



- *Five devices were examined and the final MOSFIRE detector was chosen for its low noise, low dark current, high QE, uniformity and flatness*
- Considerable in-house software development and iterative testing involving Teledyne was required, but the ASIC has been shown to provide low-noise performance equivalent to that of a standard controller

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Detector Noise

Each Fowler set uses the shortest integration time that can accommodate that number of samples. Measured noise decreases more slowly than expected for pure Fowler sampling and reaches a noise floor of about 3 e- rms. This behavior is modeled by the quadrature sum of pure Fowler, a white noise floor of 2.15 e- and a very small dark current of 0.008 e-/s/pixel.

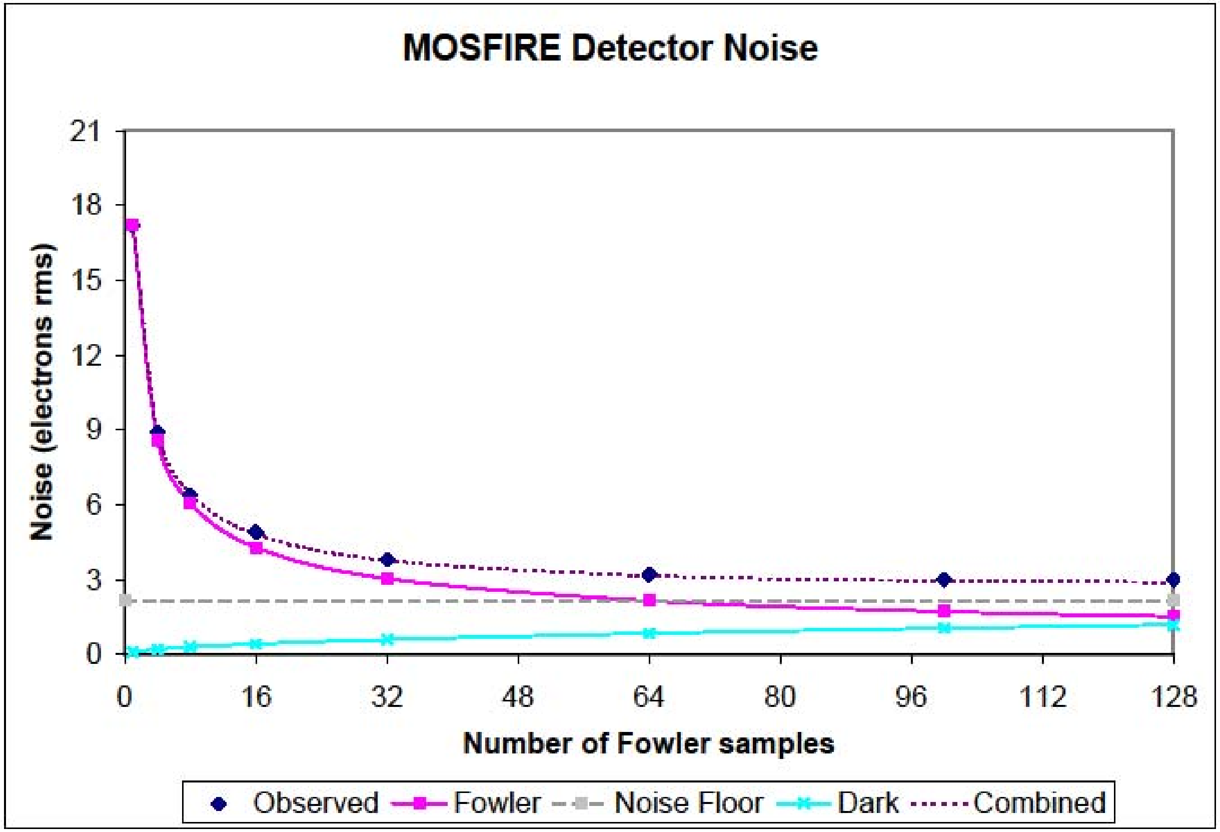

Figure 39 is a plot of the measured noise (in electrons) as a function of the number of Fowler samples.

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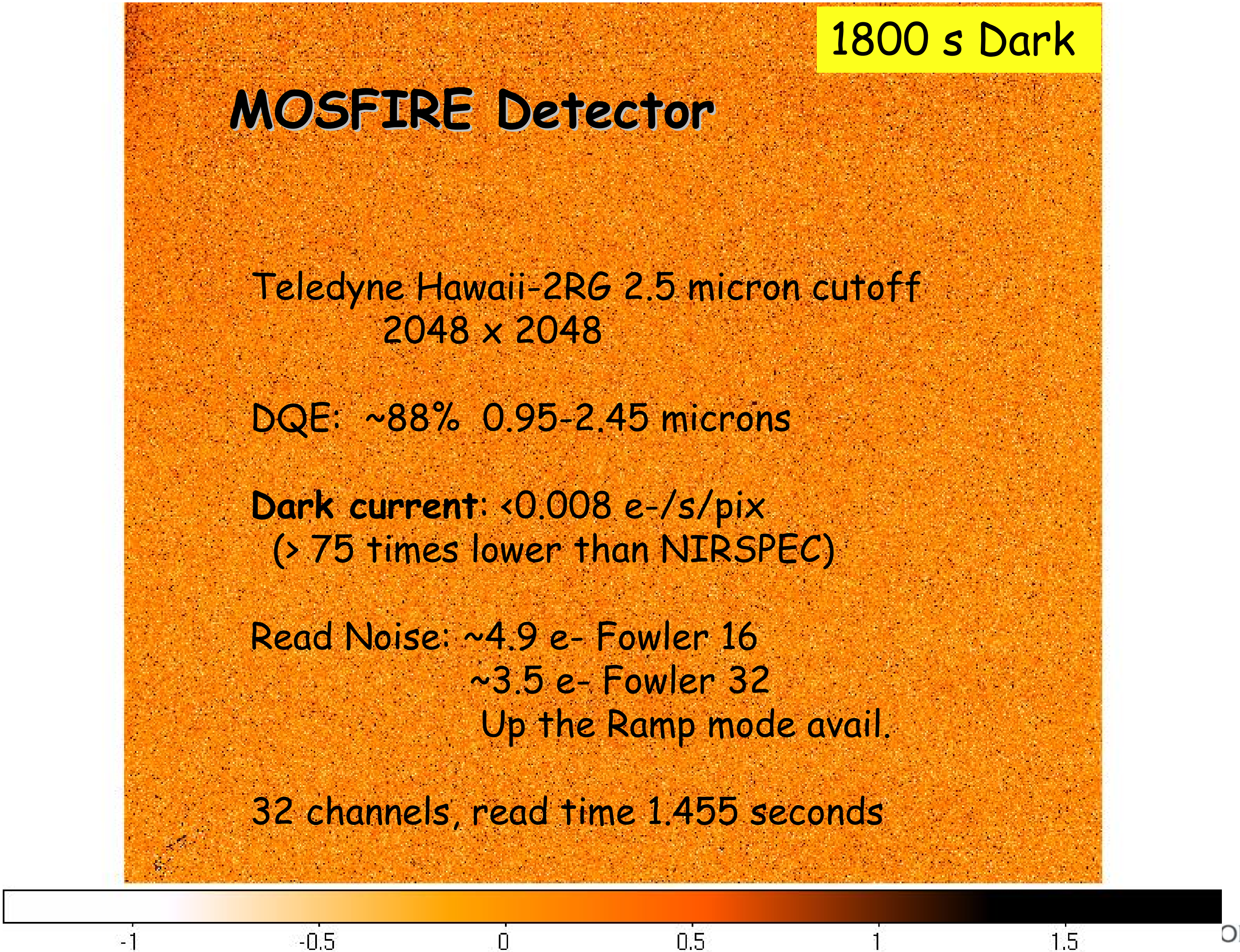


1800 s Dark

MOSFIRE Detector

Teledyne Hawaii-2RG 2.5 micron cutoff
2048 x 2048

DQE: ~88% 0.95-2.45 microns

Dark current: <0.008 e-/s/pix
(> 75 times lower than NIRSPEC)

Read Noise: ~4.9 e- Fowler 16
~3.5 e- Fowler 32
Up the Ramp mode avail.

32 channels, read time 1.455 seconds

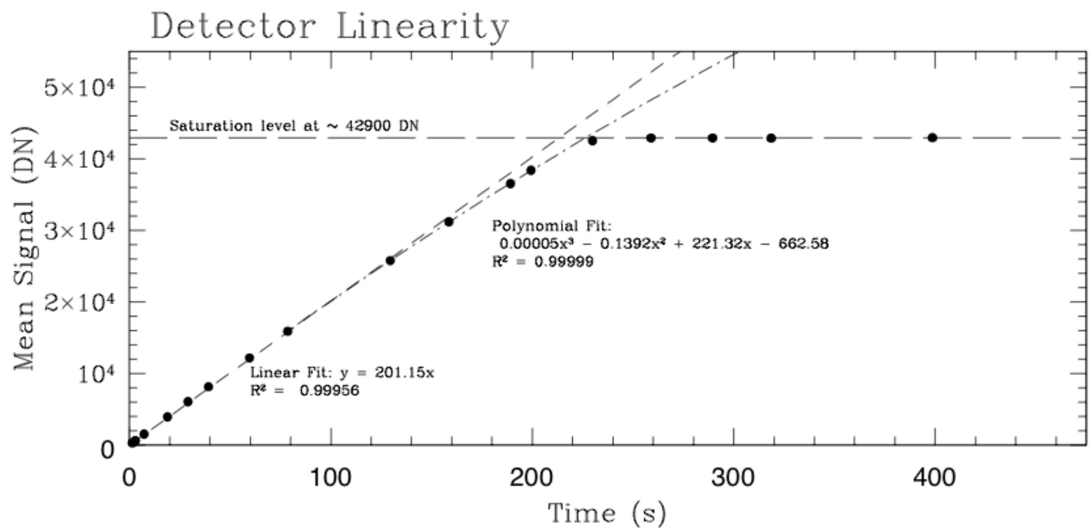
Linearity and Gain

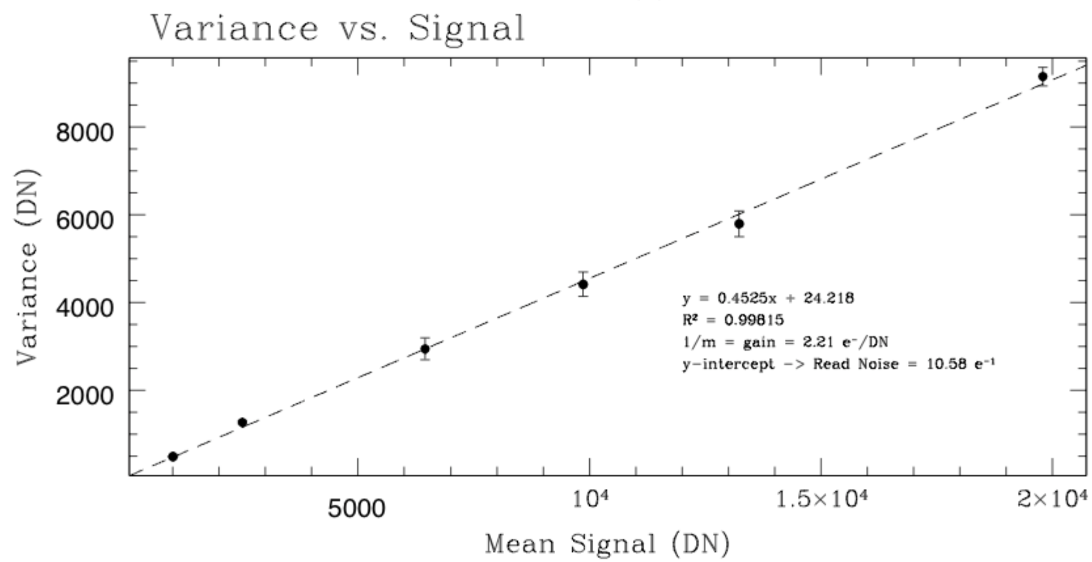
Detector Linearity

- CDS images with increasing exposure time
- Linear response (1%) up to ~60% of full well; well-behaved
- 1% @ 26,000 DN~56,000 e-
- 5% @ 37,000 DN~80,000 e-
- A/D saturation @43,000 DN ~92,500 e-

Gain Factor

- Gain = Inverse slope = 1/m
- Measured Gain = 2.21±0.05 e^-/DN
- 3% different from calculated value of 2.15 e^-/DN based on Teledyne value for capacitance
- Detector Bias = 300mV





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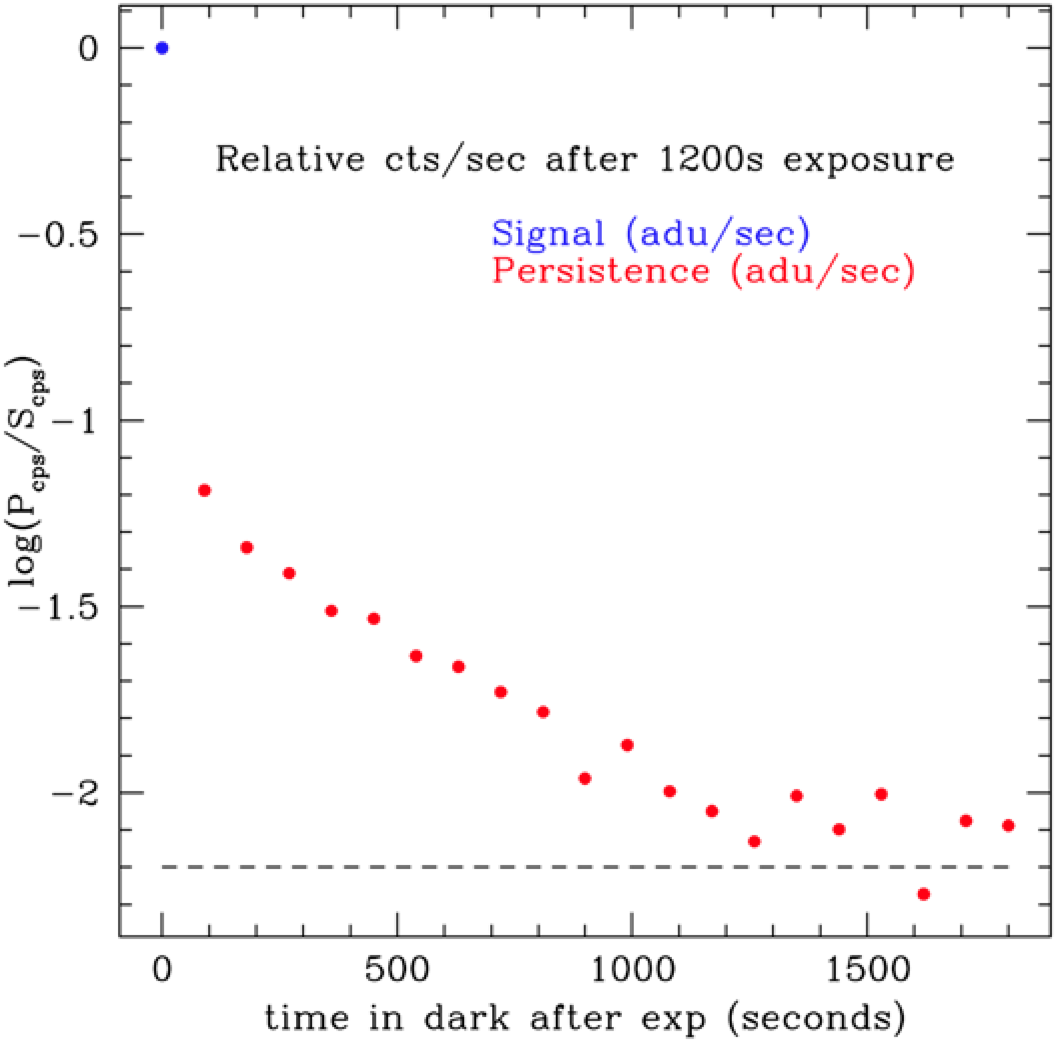
Charge persistence: it is complicated



Bottom line: ~0.4% of the stimulus signal leaks out over a long timescale

Decay time constant is long, and ~of order the timescale over which stimulus accumulated

τ~500 seconds in this case

Degradation: We are aware of degradation problems seen with JWST devices but have seen no evidence of this so far.

Thermal performance

Ian McLean

Internal Temperatures

- MOSFIRE's internal opto-mechanical components operate at the specified temperature of 120 K. MOSFIRE is equipped with a temperature control system that maintains the internal temperature at 120 K ±0.1 K.
- Temperature stability is based on statistical analysis of hundreds of measurements. For example, in one 24 hour period the standard deviation in the temperature near the Field Lens was ±0.037 K, and ±0.030 K at the Camera Barrel .
- The maximum gradient any of the sensors see while operating under temperature control is ~0.1 K/h.
- Larger gradients are encountered during cool down and warm-up.
- The detector head and field flattening lens can experience and tolerate at least 6 K/h.
- All other optics experience thermal rates of ~2 K/h or less. The typical cooling and warm-up rates are ~1 K/h or less.
- Heating is limited by resistor choice, in-line fuses, and thermal cut-out devices for both the detector block and MOSFIRE bulkhead.

Thermal Performance

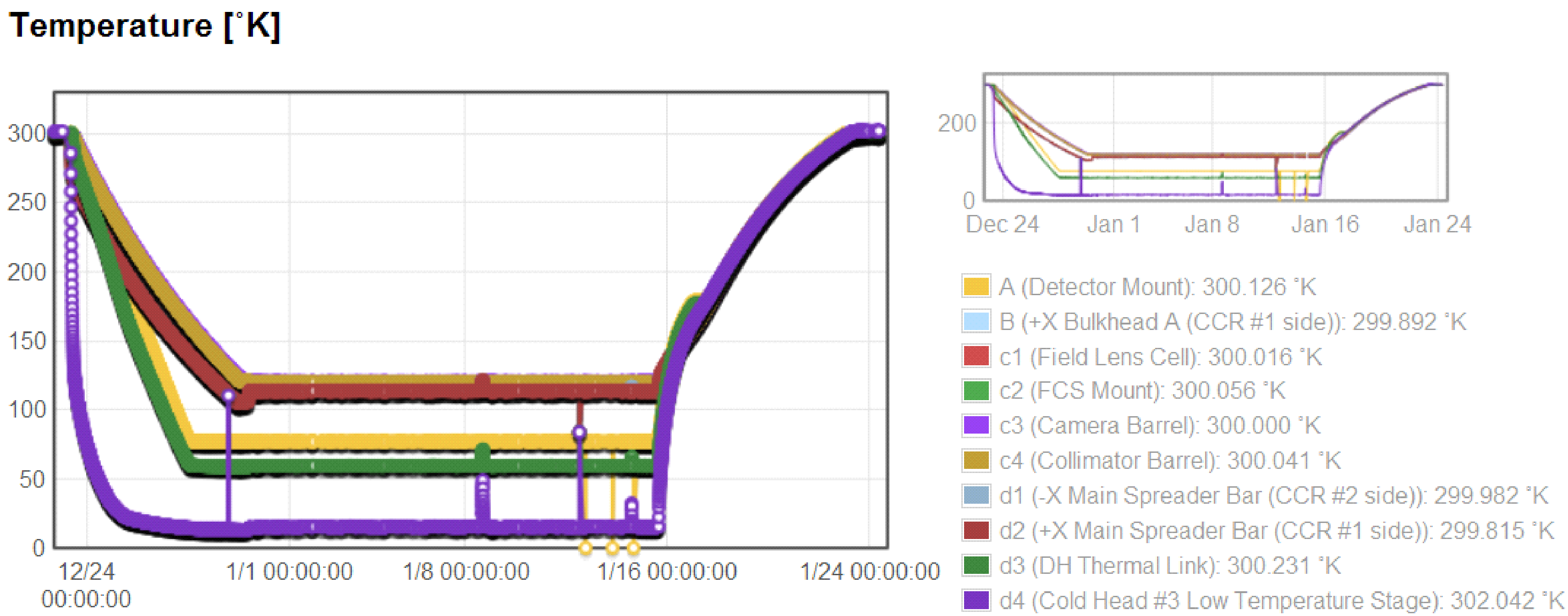


Figure 27: MOSIRE internal opto-mechanics temperature vs. time, cool down 8

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Science Detector Temperature

- MOSFIRE's science detector operates at the specified temperature of 77 K.
- MOSFIRE is equipped with a Lakeshore temperature control system that maintains the detector temperature at 77 K ± 0.02 K as shown by the graph in **Figure 28**.
- Statistical analysis over a typical 24 hour period gives a standard deviation of ±0.017 K.
- During the testing phase, stopping and starting the detector system for software development, causes small variations at the 20-30 mK level.
- We see no evidence for a change in noise or dark current behavior due to these small fluctuations.
- The choice of operating temperature is partially dictated by the optical design of the field-flattening lens which is co-mounted with the detector and therefore also at 77 K.
- The exact temperature is not critical for this lens. In fact, we have operated the detector head over the range 69 K to 100 K.
- At 77 K, dark current is negligible (<0.008 e-/s/pixel) and operation at a lower temperature could lead to problems with QE and charge persistence.

Detector stability

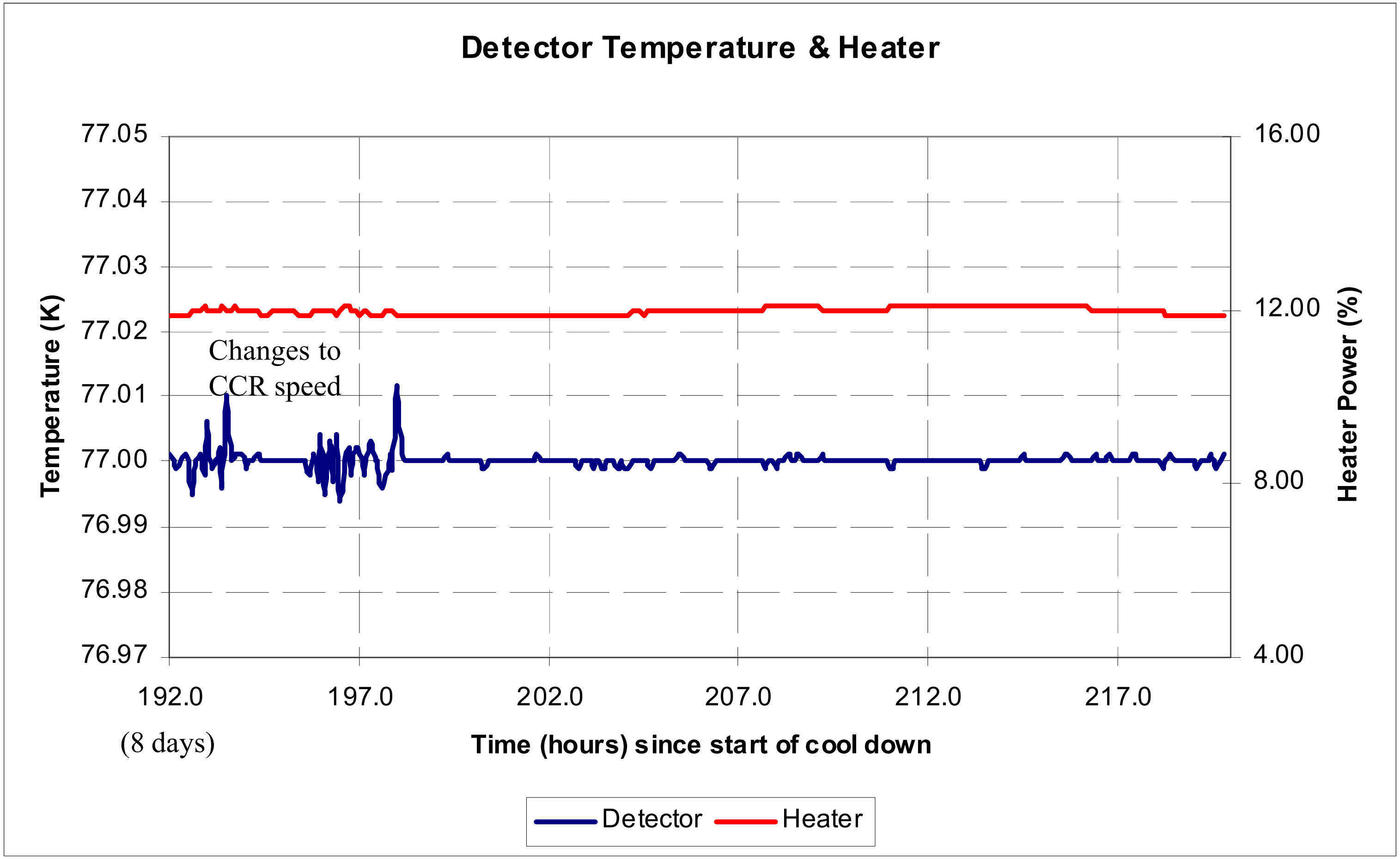

Figure 28: MOSIRE science detector temperature vs. time

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Cool down and warm up time

- The time to cool MOSFIRE down to operating temperature in the lab is 192 hours (8 days).
- The internal temperature sensors on the opto-mechanical structures reach 120 K in ~6.5 days, but it takes another day for the optics to stabilize at operating temperature.
- A graph of the temperatures during cooling for cool down 8 is shown in **Figure 29**.
- MOSFIRE's warm up time is 216 hours (9 days) in the lab.

Cool Down

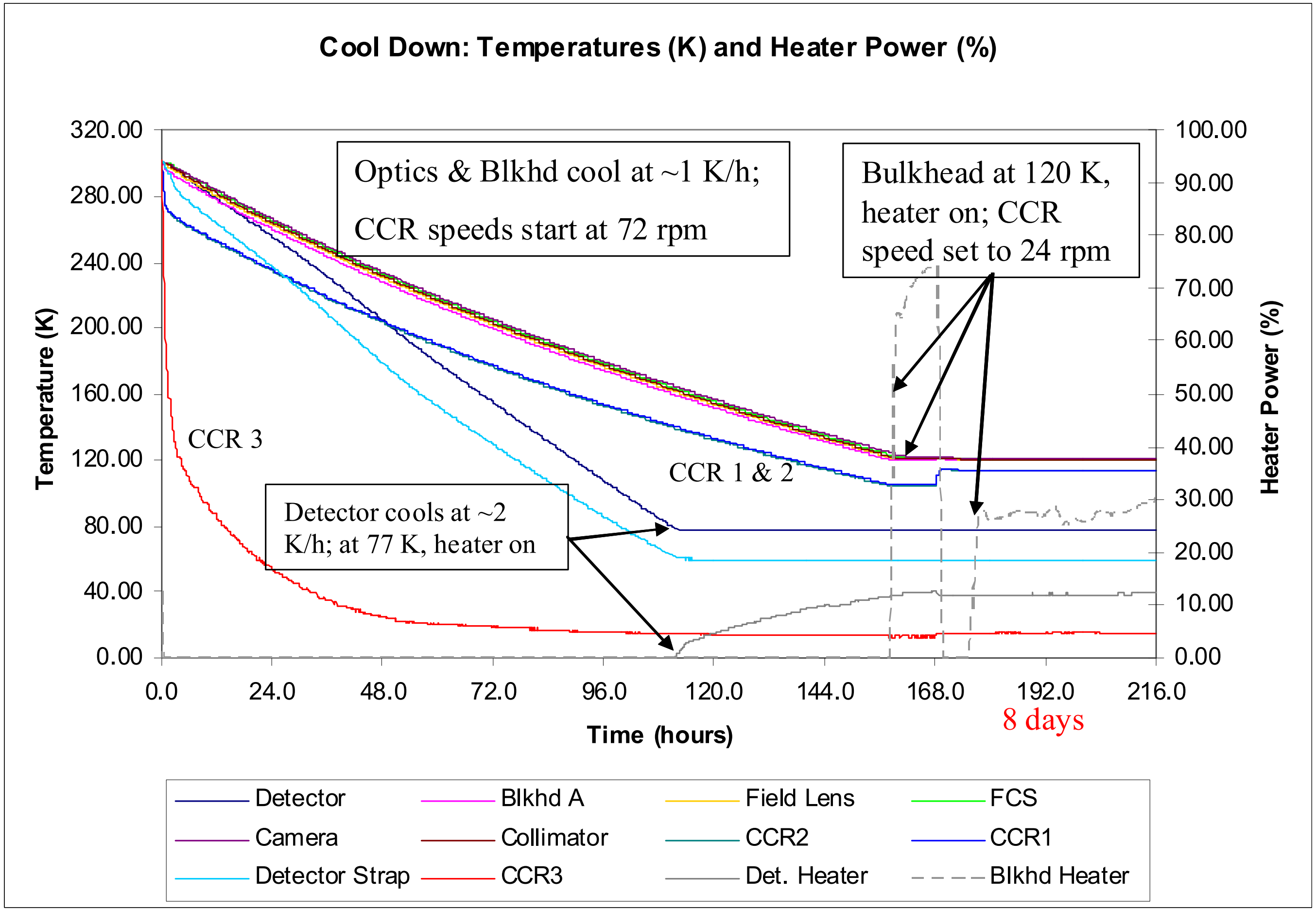

Figure 29: MOSIRE temperatures vs. time when cooling for cool down 8

Vacuum

- The typical operating pressure obtained in the MOSFIRE dewar is 1 x 10^{-7} torr once the instrument has stabilized at operating temperature.
- Based on the pressure stability observed during lab testing, MOSFIRE should be able to exceed the specified hold time, but MOSFIRE was never kept at operating temperature for more than ~4 weeks in any of the cool downs.
- **Figure 30** shows MOSFIRE pressure vs. time for cool down 9.

Pump down

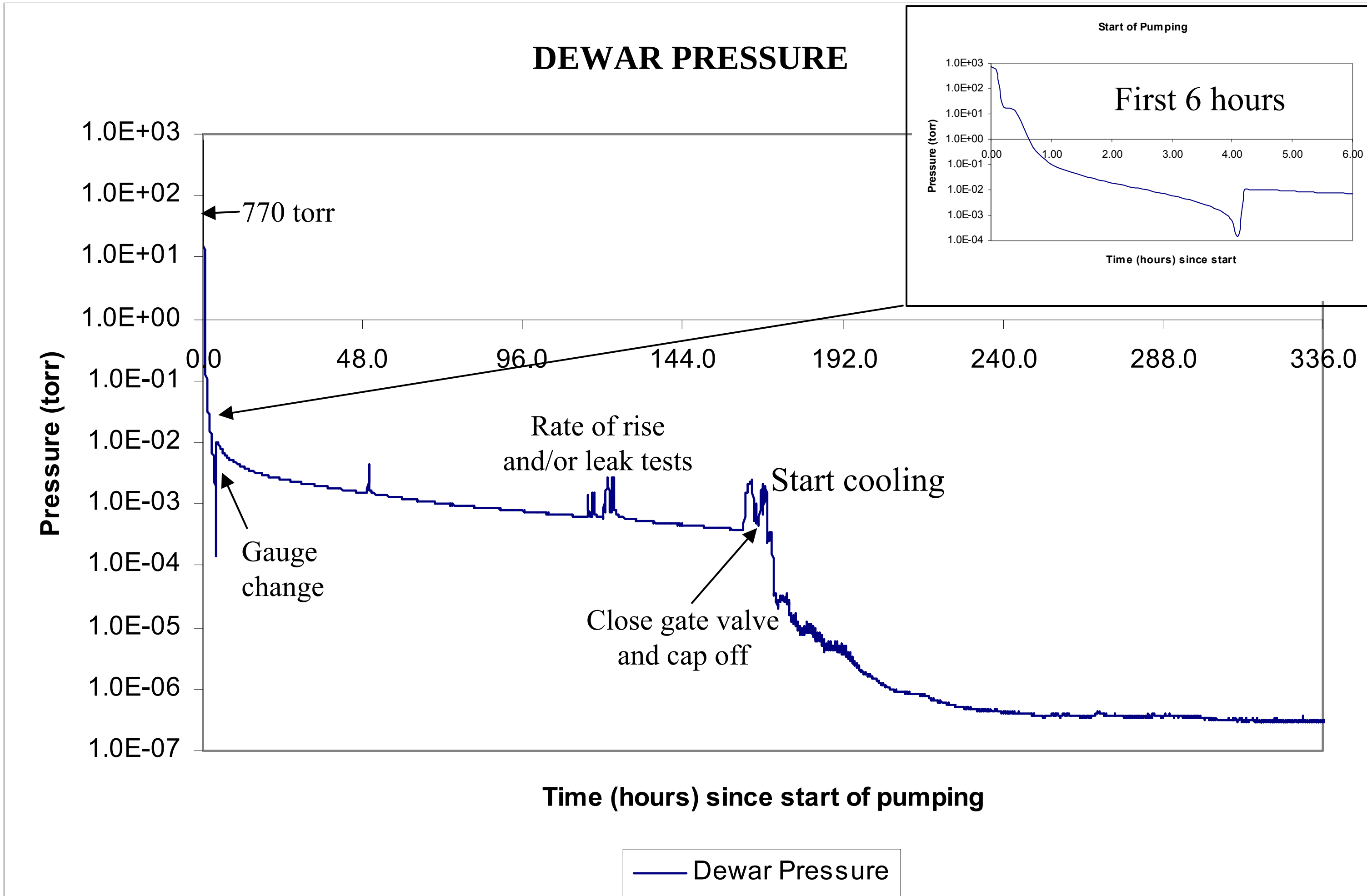

Figure 30:MOSIRE dewar pressure vs. time for cool down 9

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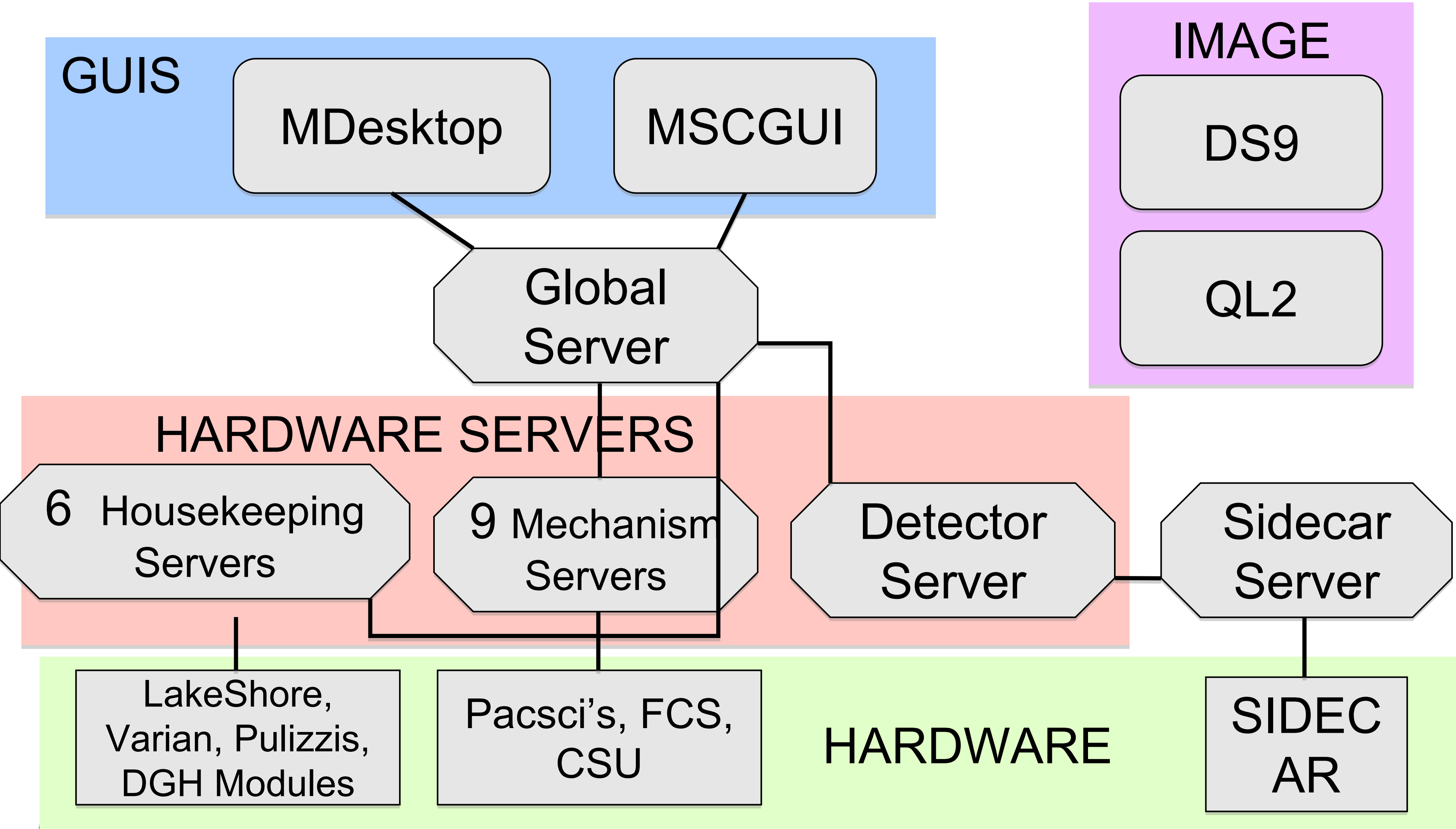
Software Verification

Jason Weiss

MOSFIRE Software Overview



Housekeeping Servers

- All Housekeeping Servers have been reliably monitoring, polling, and logging for several cool downs.
- MPAS (Pressure):
  - Small bug fix this last cool down (crash on Ethernet disconnect)
- MTCS (Temperature):
  - Recently added monitoring of Setpoint when ramping
- MDHS (Dewar/Window Heater, Cabinet monitoring):
  - No significant changes
- MPWS (Power):
  - Added “init” during next successful communication after a failed one.
  - Log power statuses whenever they change
- **No outstanding actions**

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Mechanism Servers

- Six Servers share common library base
  - Grating turret and shim, Filter wheels, Detector Focus (not used), Dust Cover
  - MRMS: set peak current when setting continuous current
- MMPRS (Pupil Rotator): Tracking
  - Implemented tracking using test chamber, tested in instrument cool down 9.
  - Uses test functions that simulate Keck DCS rotator updates
  - Extensive mechanism testing
- FCS:
  - Improvement on model
  - Lots of use due to model work
  - Added keywords for astronomer's GUI
- **No outstanding actions**

CSU Server

- Successfully made many improvements to reliability and error recovery
- Use of a state file to maintain bar positions
- Use of bar statuses to keep track of reliability of state file bar positions
- Consistent approach to error recovery
- Minimizes initializations, which are time consuming
- Many hours spent testing; the CSU formed ~500 masks in cool down 9 alone

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Detector Server

- MDS initiates exposures, SidecarServer performs
- MDS gets feedback from SidecarServer via single name-value callback
- MDS gets FITS header info from self and global server and sends to SidecarServer
- MDS-SidecarServer has taken >24,000 frames written to disk
- MDS monitors SidecarServer heartbeat to confirm connectivity
- *Minor issue: DCS Oneshots crash MDS*

Hardware Server Notes

- Systematic server keyword testing
  - All issues resolved
- Modifications completed during last cool down, now considered stable and reliable
- Performs primary functions well:
  - Housekeeping servers poll and log reliably
  - Mechanism servers home and move reliably
  - Detector server takes and aborts images reliably. FITS header collection works (except for DCS)
  - All servers survive interruptions gracefully and notify user
- **Servers exercised for hundreds of hours performing primary functions**

Global Server

- Represents subserver keywords as single point interface to GUIs
- Coordinated keywords
  - Observation Mode:
    - Moves both filter wheels, both grating mechanisms, and pupil rotator by specifying a filter-grating mode (imag/spec) combination, e.g. H-spec
    - Used by GUI → main method of moving instrument mechanisms
  - Filter:
    - Move both filter wheels only, target by name
    - Home filter wheels one at a time, open first
  - Grating:
    - Move grating turret and shim, target by name (imag or spec)
  - Abort:
    - Aborts multiple mechanisms, if moving. Needed to abort coordinated moves
  - Dust Cover:
    - Turn off lamps (if on) when opening dust cover
- **Received lots of exercise during last few cool downs**

GUIs

- MDesktop
  - **Two versions:** Astronomer and Engineering
  - Astronomer version only presents mechanism and detector control/status + CSU status
- MSCGUI
  - Tested end-to-end to create & execute masks
  - Creates FITS table extensions, appended to FITS files by MDS

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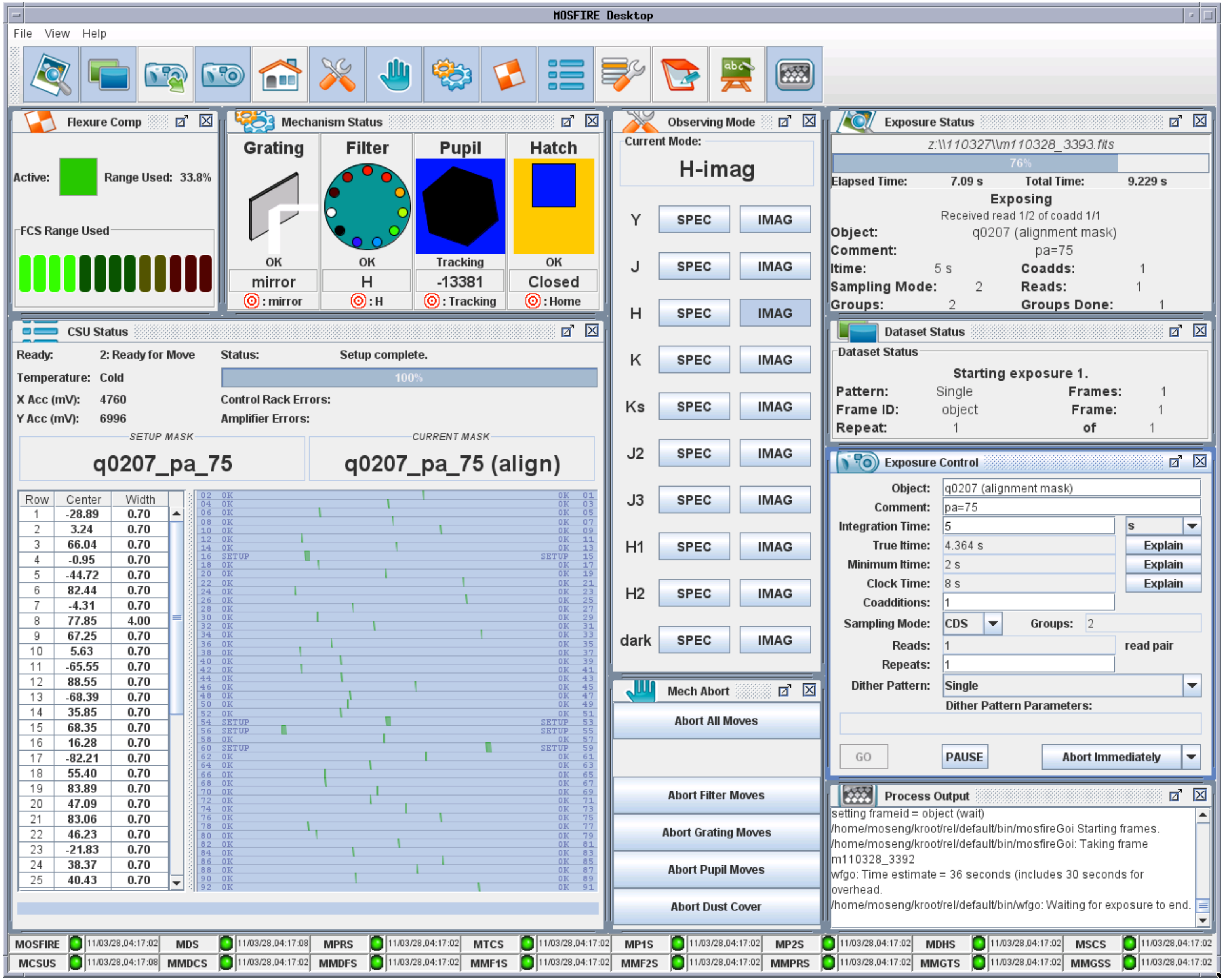

Figure 37: Astronomer MOSFIRE Desktop

Main user interface for astronomers at the telescope.

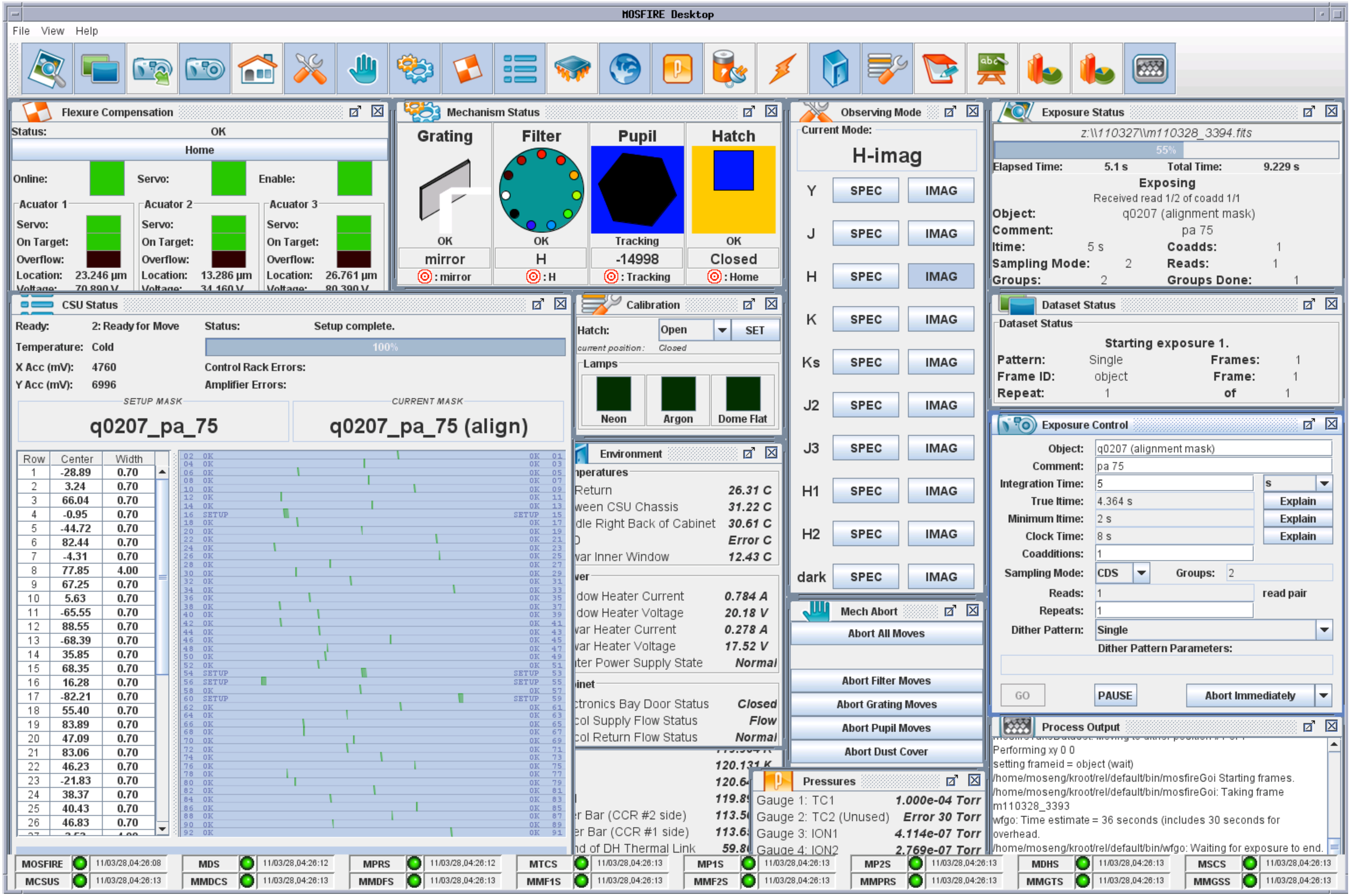

Figure 38: Engineering MOSFIRE Desktop

Support Astronomers/Engineers version with additional controls and status items.

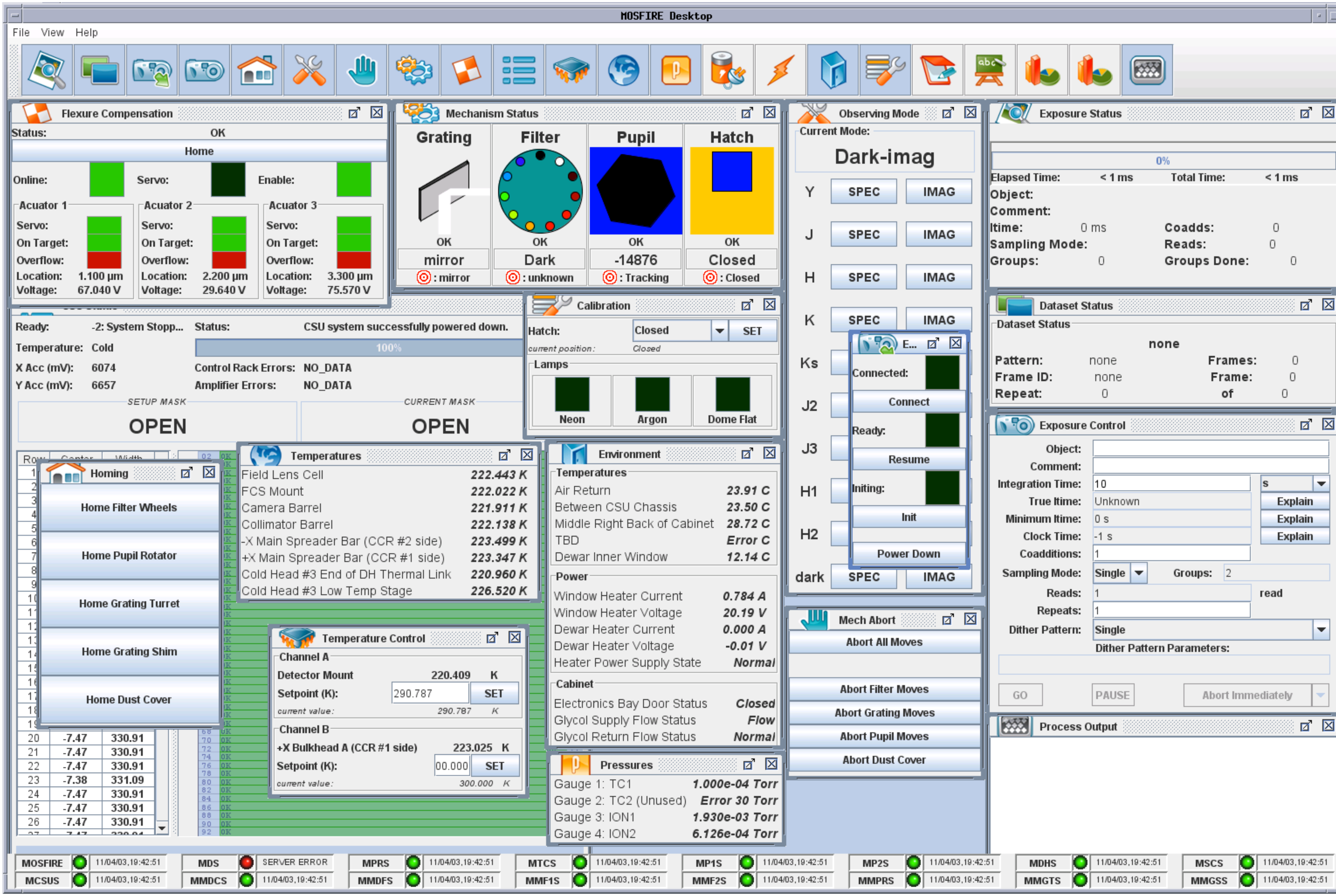

Figure 38: Engineering MOSFIRE Desktop

Showing some hidden GUIs.

MDesktop

- **Minor issues:**
  - Occasional crashes
    - Thread safety in MGS keyword table – resolved with semaphore
    - KJava error handling – improved, needs more testing
    - *Recovery just takes seconds to restart GUI*
  - Occasional show/modify failures
    - Due to MGS blocking from subserver commands with long latencies. All long latency (> 3s) commands are threaded, but perhaps *any* command with a latency > ~1s should be also.
    - *Repeating command usually works*

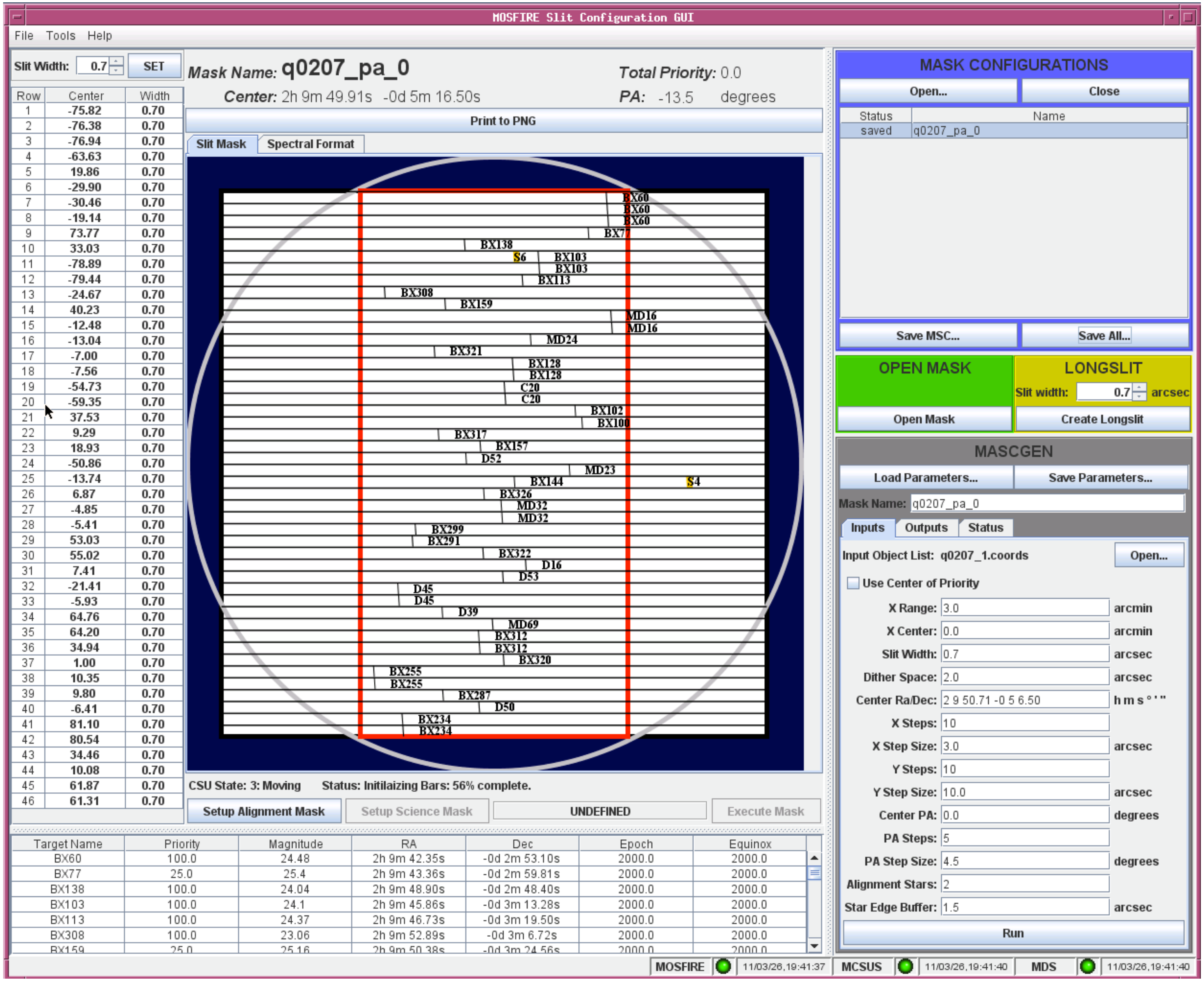

Figure 40: Screenshot of the MOSFIRE Slit Configuration (MSC) GUI

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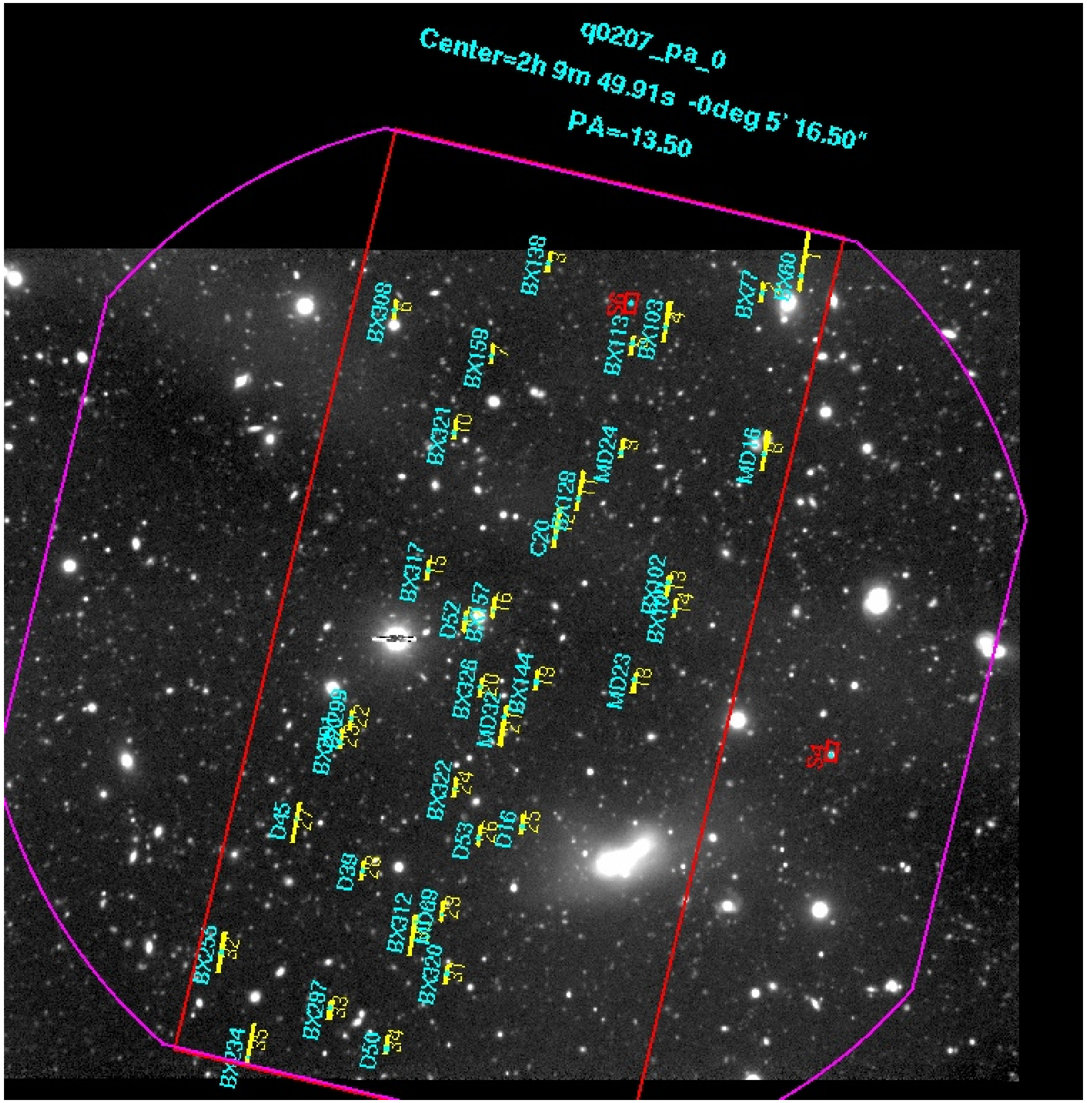
MSCGUI Data Products

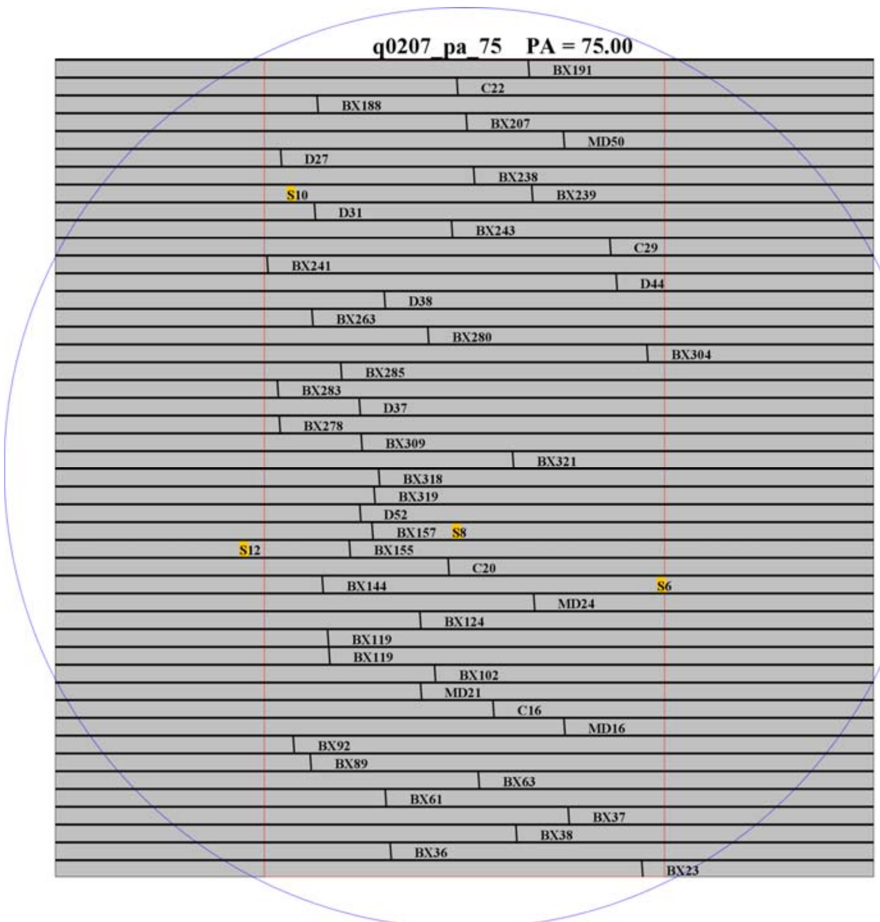
- MOSFIRE Slit Configuration (MSC). Stores all information about science and alignment masks, including pointing information, targets in mask, and MASCGEN arguments to create mask
- Target list: list of objects in mask
- Science Slit List: list of contiguous slits, giving center of slit, target info, and relation of target to center of slit
- MCSUS scripts for alignment and science masks
- Pointing information in Keck Star List format
- DS9 regions file for mask overlay
- MASCGEN arguments file
- Can optionally print images of mask from GUI, including spectral format for any of the 5 broadband filters

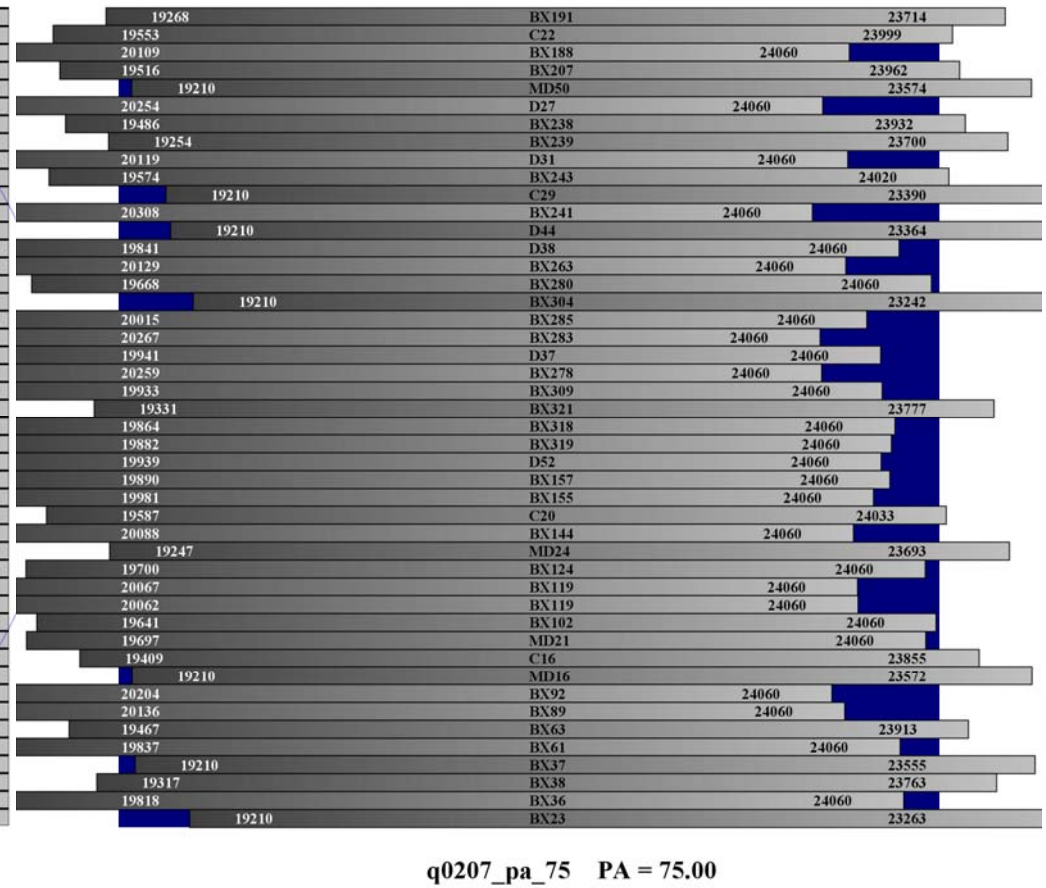


DS9 format “regions” file produced by MASCGEN/MSCGUI.

Can be overlaid on any user image that has a WCS

Mask and Spectral Images





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MSCGUI

- Excellent shape
- Remaining work:
  - Close off unused bars when switching from open to longslit
  - Allow filter selection in Spectral Calibration GUI

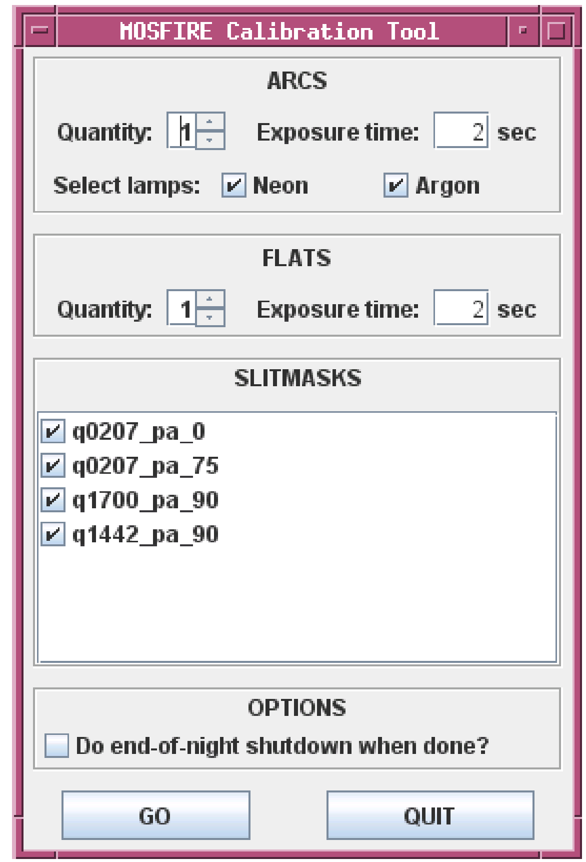

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Image Display

- DS9 used exclusively in the lab testing
- Quicklook 2 (OSIRIS) is also available
- Node locked IDL license on computer called *nuu*

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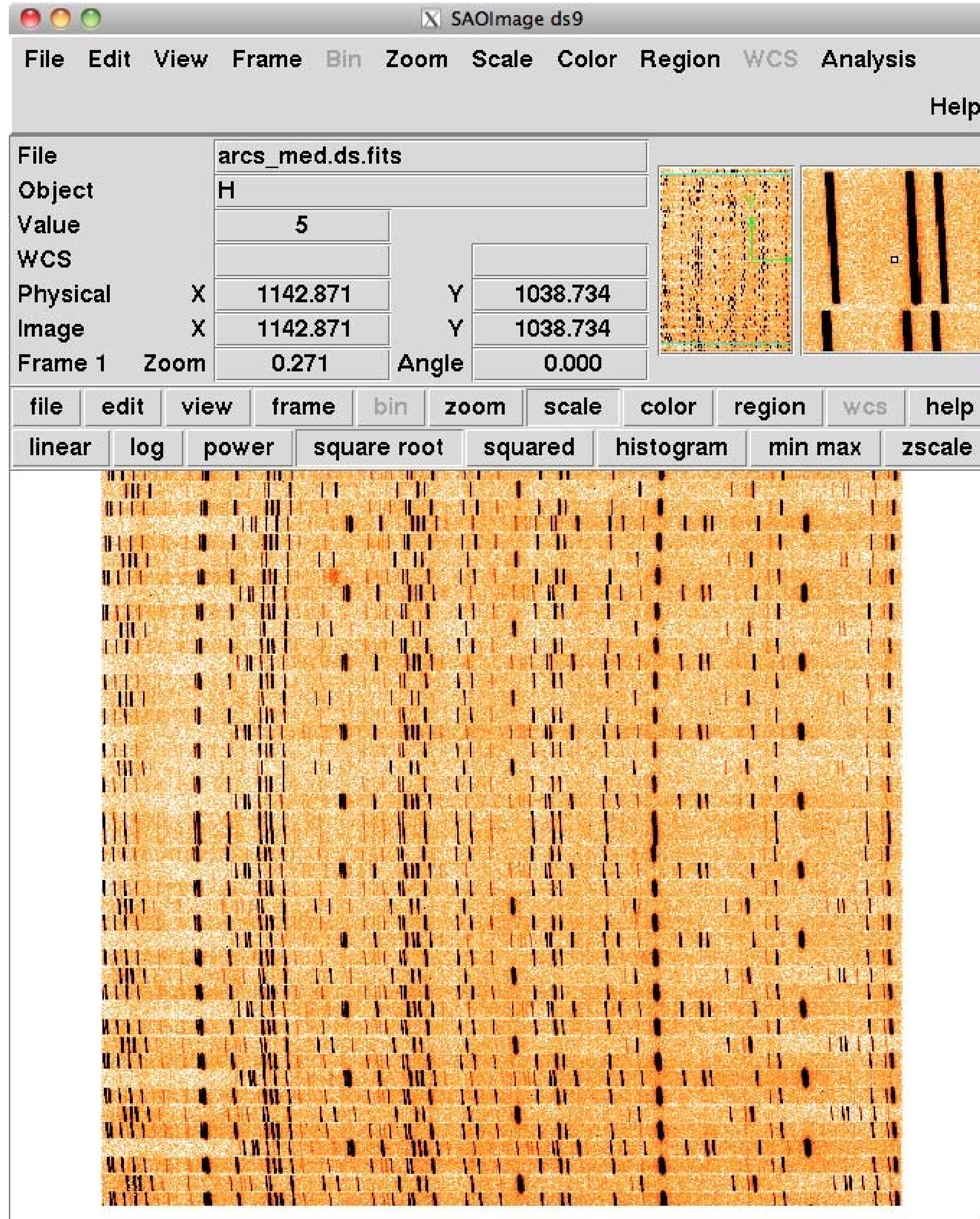
DS9

- Python script monitors MDS
- Automatically opens latest image and differences with previous image



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Quicklook 2

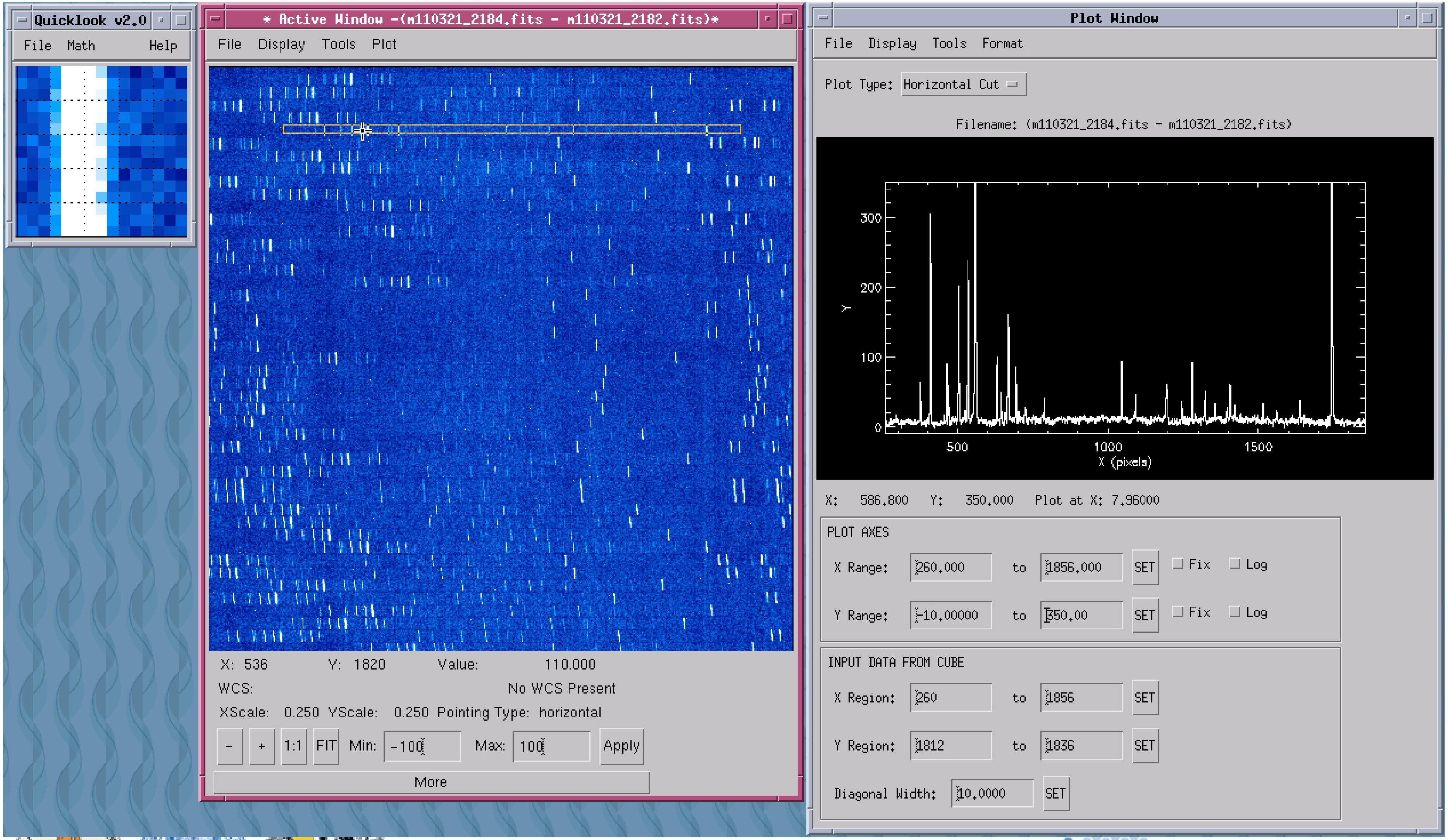

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Image Display

- QL2:
  - Minor customization for MOSFIRE
  - Add automatic display of images as taken
- Other:
  - Program to analyze images of mask, determine bar positions, and create mcsus state file

Scripts

- Custom night time scripts complete
- Start/Stop scripts complete
- A few operations scripts still needed:
  - Start Run, Start Night, End Night
- Existing Keck standard instrument and telescope scripts not installed yet
  - Add later with Support Astronomer assistance

Summary

- **The deliverable software used extensively in lab testing of MOSFIRE.**
- CSU server improved to prevent bar collisions, decrease recovery time, and reduce number of initializations. (see §11.3.1.1).
- The MSCGUI has been demonstrated to generate slit masks from a list of prioritized targets, produce a number of informational data products, and execute the mask. It also produces mask description tables in FITS extensions (automatically appended).
- The detector software is stable and reliable. It is currently unable to retrieve DCS keyword information (from DCS simulator) for the FITS header.
- The hardware servers are in very good shape. Although small modifications were made during the last cool down, the primary functions of each server have been in place for months and have been working well.
- All housekeeping servers reliably poll hardware and log readings to a comma-delimited time stamped file.
- Mechanisms servers reliably home/move mechanisms to desired position.
- The servers were systematically tested on a keyword level. The results of the testing are detailed in reference 2.
- The GUIs are now in their complete form and offer all of the desired functionality with only a few minor exceptions.

Very short list of remaining tasks

(can be discussed later if required)

- Debug occasional GUI crashes & modify errors: In progress
- Target & host computer reset tests (see §11.3.2.2.1.3): By first light
- DCS oneshots from MDS: Before first light (fallback strategy exists)
- Fix automatic image display in QL 2 (see §11.4.1.2): Before first light
- Finish operational scripts (see §11.5.1.5.4): Before/during first light.
- Add ability to specify which filters to take spectral calibration data for using the GUI (see §11.4.1.1.1.4): Before/during commissioning
- MSCGUI: close off bars in long slit mode when previously in open mask (see §11.4.1.3): During commissioning
- Improve exposure and dataset abort performance (see §11.3.2.2.2): During commissioning.
- Tool for determining positions of CSU bars from images of the slits (see §11.3.1.1): During commissioning

MOSFIRE Installation Plan

Mike Pollard

W. M. KECK OBSERVATORY

MOSFIRE Installation Plan

- Items to be shipped early
- Pre-arrival tasks
- Integration schedule
- Scheduling resources and telescope restrictions

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Items to be shipped early

- Computers
- Pneumatic pigtail for defining points gear motor
- Fiber-optic cables
- CCR speed controller equipment

Pre-arrival tasks

- Mechanical
  - Complete lift bag plumbing for MOSFIRE pneumatic control panel
  - Inventory hardware
- Electrical
  - Install computers in K1 computer room
  - Install CCR speed controllers in K1 machinery room
  - Complete fiber-optical install in K1 computer room
  - Inventory hardware
- Software
  - Set up instrument accounts

Integration schedule

- Days 1 thru 4
  - – Receive instrument
  - – Unpack and uncrate
  - – Mechanical tasks
    - Rotate gear motors and modify mounting for serviceability
  - – Prep for lift to NasDeck

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Integration Schedule

- Days 5 thru 8
  - Move instrument to NasDeck
  - Complete handler mods
  - Initial test of comms.
  - Initial Cass. fit check
  - Confirm defining point positioning (manually define)
  - Manually control and check rotation
  - Optical alignment check with K1
  - Contingency day

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Integration Schedule

- Days 9 thru 12
  - Pump down
  - Install rotator hardware
  - Install defining point plumbing
  - Install control cables for defining point panel

Integration Schedule

- Days 13 thru 20
  - Cool down
  - Rotator cable install
  - Guider hardware install
  - Test rotation and defining point controls
  - Check balance and tune rotator
  - MAGIQ software testing
  - Contingency day

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Integration Schedule

- Days 21 thru 23
  - Automatically define instrument
  - Check rotation via automated system
  - Check telescope interlock system
  - Balance telescope
  - Re-check and adjust optical axis alignment with K1 (if needed)
  - MAGIQ software testing
  - Telescope access contingency

Resources and telescope restrictions

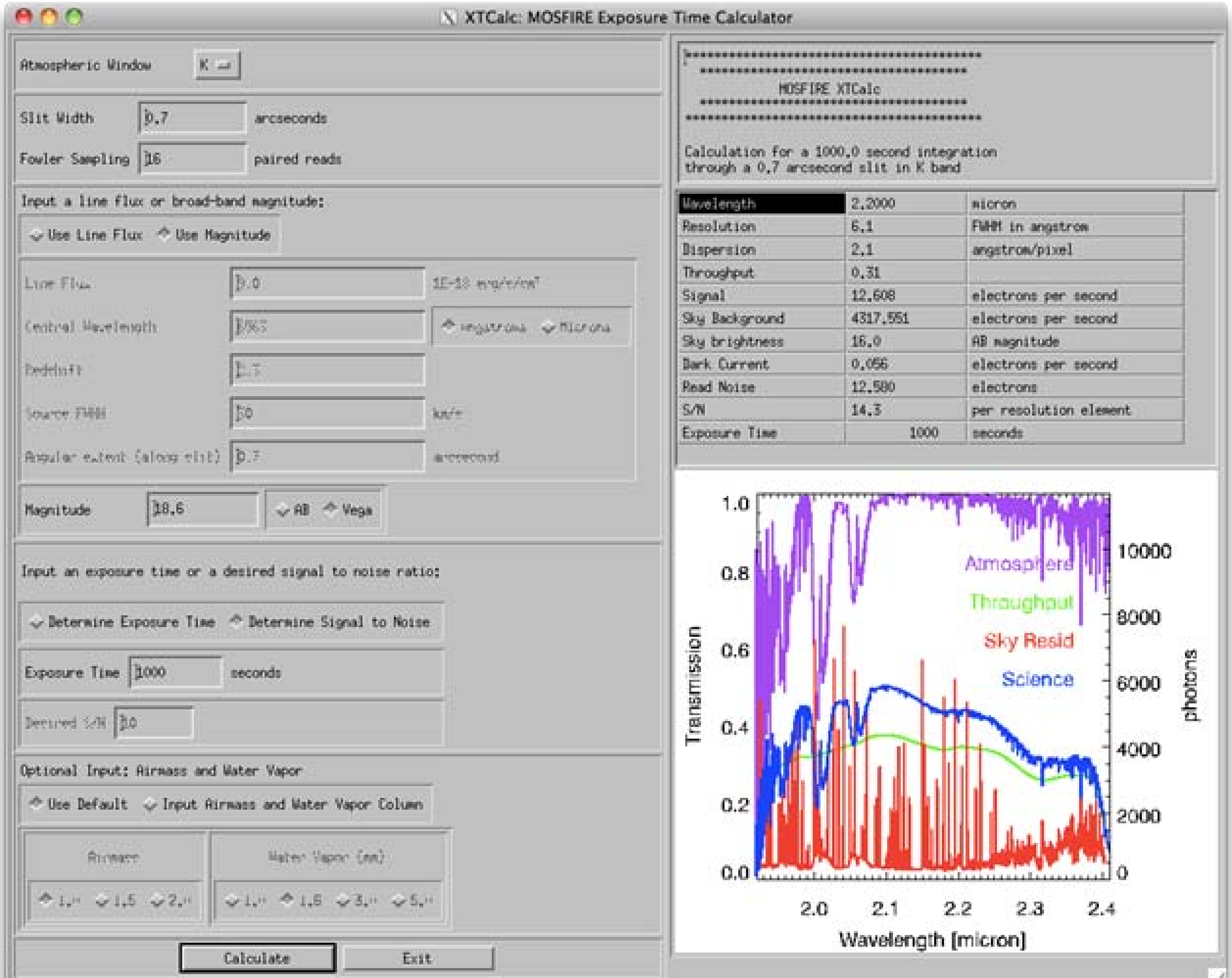
- Restrictions for telescope added to summit schedule
- Resources tentatively scheduled with summit supervisors

W. M. KECK OBSERVATORY

Commissioning Plans

Chuck Steidel

MOSFIRE Exposure Time Calculator



Gwen Rudie (Caltech)

Figure 39: Prototype MOSFIRE Exposure Time Calculator (XTcalc)

W. M. KECK OBSERVATORY

Using MOSFIRE: Overview

- Before observing run:
  - design slit masks using standalone MASCGEN/MSCGUI application, save .msc files or upload to Keck.
- In the afternoon:
  - verify mask designs using MSCGUI after moving into user directory
  - While at the horizon stow position, if desired, enable FCS and obtain lamp spectra using all mask configurations anticipated for the night
  - When pointed to el=45 deg for flats (4pm) launch script to obtain mask images and dome spectroscopic flats for each mask/bandpass combination to be used

Using MOSFIRE: Overview

Observing: (example)

- Configure CSU with "alignment" version of first mask (while slewing);(~300s)
- Slew telescope to target field, slew rotator for desired sky PA
- Select filter for alignment (if K or Ks, pupil will begin tracking with the hexagonal mask) (30-60s)
- Using Slit Alignment Tool, acquire guider image for comparison with DSS image; select star, enable telescope offset recommended by SAT (30s)
- Use SAT to obtain an image through the mask. SAT will take a "sky" image at a nodded position (stored by SAT), followed by a ~10-30 second image. (~60s)
- SAT analyzes image to measure star positions relative to alignment boxes. SAT uses header information to predict where the boxes will fall on the detector, and where the stars should be within the boxes. (~30s)
- SAT calculates needed rotation (of rotator) and offset (of telescope) to place stars at their proper positions (~30s)

Using MOSFIRE: Overview

Observing: (example)

- If desired, allow SAT to obtain another image of mask to check alignment (~60s)
- Configure CSU to science version of the mask (~20-30s)
- Configure for spectroscopy (~30-45s)
- START EXPOSURE SEQUENCE
- total alignment overhead:

~5.5 minutes (not including initial CSU configuration)

~10 minutes (if CSU not configured while slewing telescope and rotator)

W. M. KECK OBSERVATORY

MOSFIRE MASCGEN: User target list

04/07/11
10:07:34

demo.coords

BX1	25	21.87	02	09	37.47	-0	05	28.73	2000.0	2000.0	0.0	0.0
BX2	100	24.01	02	09	37.04	-0	03	55.59	2000.0	2000.0	0.0	0.0
BX3	100	24.49	02	09	37.13	-0	04	49.98	2000.0	2000.0	0.0	0.0
BX4	25	21.36	02	09	37.93	-0	03	31.31	2000.0	2000.0	0.0	0.0
BX5	100	23.04	02	09	37.52	-0	07	23.19	2000.0	2000.0	0.0	0.0
BX6	50	24.71	02	09	37.25	-0	03	48.82	2000.0	2000.0	0.0	0.0
BX7	100	24.23	02	09	37.34	-0	06	25.13	2000.0	2000.0	0.0	0.0
BX8	100	23.80	02	09	37.50	-0	04	36.50	2000.0	2000.0	0.0	0.0
BX9	25	25.50	02	09	37.33	-0	06	55.38	2000.0	2000.0	0.0	0.0
BX10	50	24.89	02	09	37.48	-0	07	19.97	2000.0	2000.0	0.0	0.0
BX11	25	25.20	02	09	37.54	-0	06	31.04	2000.0	2000.0	0.0	0.0
BX12	25	25.08	02	09	37.60	-0	04	12.51	2000.0	2000.0	0.0	0.0
BX13	100	24.25	02	09	37.77	-0	03	26.48	2000.0	2000.0	0.0	0.0
BX14	25	25.45	02	09	37.79	-0	04	51.54	2000.0	2000.0	0.0	0.0
BX15	25	25.28	02	09	37.92	-0	07	24.18	2000.0	2000.0	0.0	0.0
BX16	50	24.55	02	09	37.99	-0	03	17.41	2000.0	2000.0	0.0	0.0
BX17	100	24.39	02	09	38.05	-0	06	26.91	2000.0	2000.0	0.0	0.0
BX18	25	25.23	02	09	38.01	-0	06	52.31	2000.0	2000.0	0.0	0.0
BX19	100	24.34	02	09	38.23	-0	07	03.18	2000.0	2000.0	0.0	0.0
BX20	25	25.31	02	09	38.16	-0	06	27.31	2000.0	2000.0	0.0	0.0
BX21	100	23.07	02	09	38.62	-0	06	04.06	2000.0	2000.0	0.0	0.0
BX22	100	24.13	02	09	38.55	-0	05	30.92	2000.0	2000.0	0.0	0.0
BX23	100	24.02	02	09	38.62	-0	03	45.66	2000.0	2000.0	0.0	0.0
BX24	25	25.47	02	09	38.92	-0	06	36.68	2000.0	2000.0	0.0	0.0
BX25	25	25.31	02	09	39.10	-0	07	35.90	2000.0	2000.0	0.0	0.0
BX26	100	23.73	02	09	39.33	-0	03	39.30	2000.0	2000.0	0.0	0.0
BX27	50	24.77	02	09	39.18	-0	02	47.79	2000.0	2000.0	0.0	0.0
BX28	50	24.94	02	09	39.46	-0	03	49.19	2000.0	2000.0	0.0	0.0
BX29	25	22.13	02	09	39.94	-0	04	07.28	2000.0	2000.0	0.0	0.0
BX30	100	24.20	02	09	39.83	-0	05	13.87	2000.0	2000.0	0.0	0.0
BX31	25	25.07	02	09	39.83	-0	04	39.47	2000.0	2000.0	0.0	0.0
BX32	25	25.36	02	09	39.90	-0	03	47.00	2000.0	2000.0	0.0	0.0
BX33	50	24.95	02	09	39.96	-0	03	42.95	2000.0	2000.0	0.0	0.0
BX34	50	24.99	02	09	40.17	-0	06	06.03	2000.0	2000.0	0.0	0.0
BX35	100	22.98	02	09	40.62	-0	02	57.74	2000.0	2000.0	0.0	0.0
BX36	25	19.51	02	09	40.97	-0	05	33.15	2000.0	2000.0	0.0	0.0
BX37	100	23.57	02	09	40.65	-0	04	11.65	2000.0	2000.0	0.0	0.0
BX38	100	24.36	02	09	40.56	-0	04	36.36	2000.0	2000.0	0.0	0.0
BX39	50	24.59	02	09	40.48	-0	08	02.22	2000.0	2000.0	0.0	0.0
BX40	100	24.12	02	09	40.68	-0	03	18.96	2000.0	2000.0	0.0	0.0
BX41	25	25.43	02	09	40.71	-0	05	31.52	2000.0	2000.0	0.0	0.0
BX42	100	24.40	02	09	40.78	-0	05	34.55	2000.0	2000.0	0.0	0.0

potential targets, with user-assigned relative priority

S2	-1	19.86	2	09	40.97	-0	05	33.15	2000.0	2000.0	0.0	0.0
S4	-1	20.71	2	09	41.57	-0	06	00.20	2000.0	2000.0	0.0	0.0
S6	-1	21.95	2	09	46.76	-0	03	04.00	2000.0	2000.0	0.0	0.0
S7	-1	21.13	2	09	47.97	-0	04	53.18	2000.0	2000.0	0.0	0.0
S8	-1	21.19	2	09	49.76	-0	04	27.17	2000.0	2000.0	0.0	0.0
S9	-1	21.67	2	09	50.07	-0	04	26.46	2000.0	2000.0	0.0	0.0
S10	-1	21.51	2	10	00.91	-0	04	59.39	2000.0	2000.0	0.0	0.0
S11	-1	21.97	2	10	00.34	-0	04	40.21	2000.0	2000.0	0.0	0.0
S12	-1	21.06	2	09	50.96	-0	06	01.42	2000.0	2000.0	0.0	0.0

Potential alignment stars

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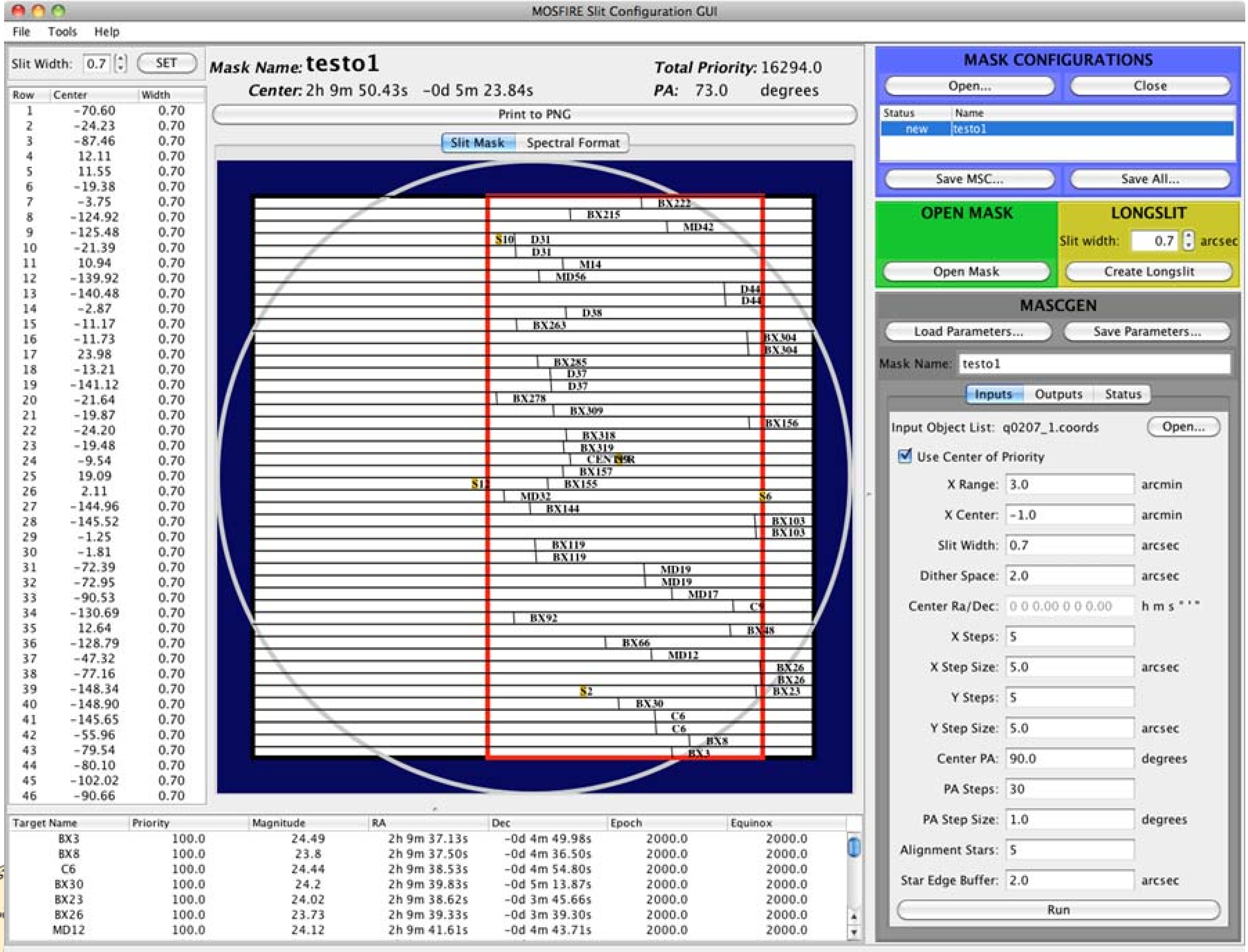
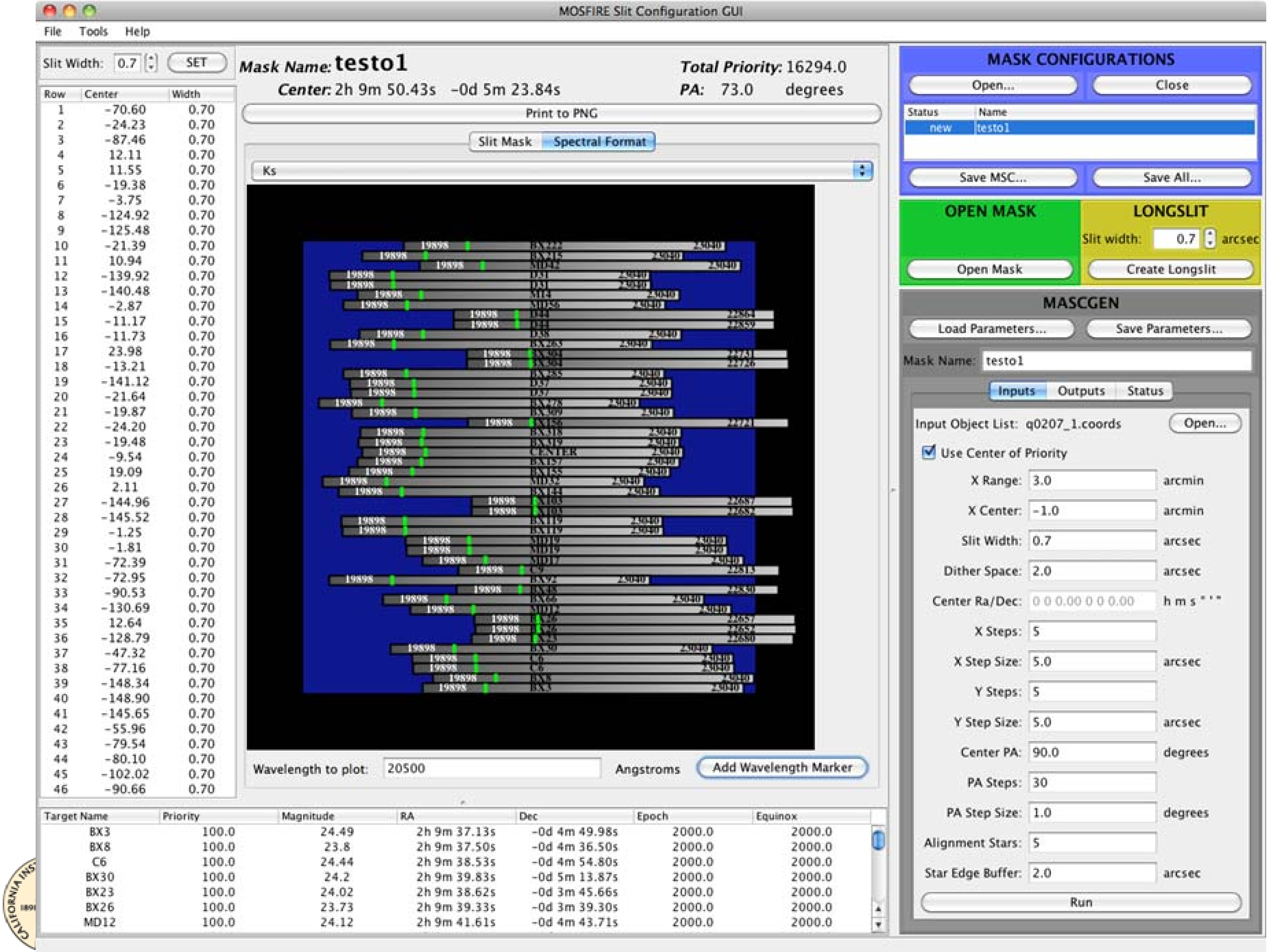
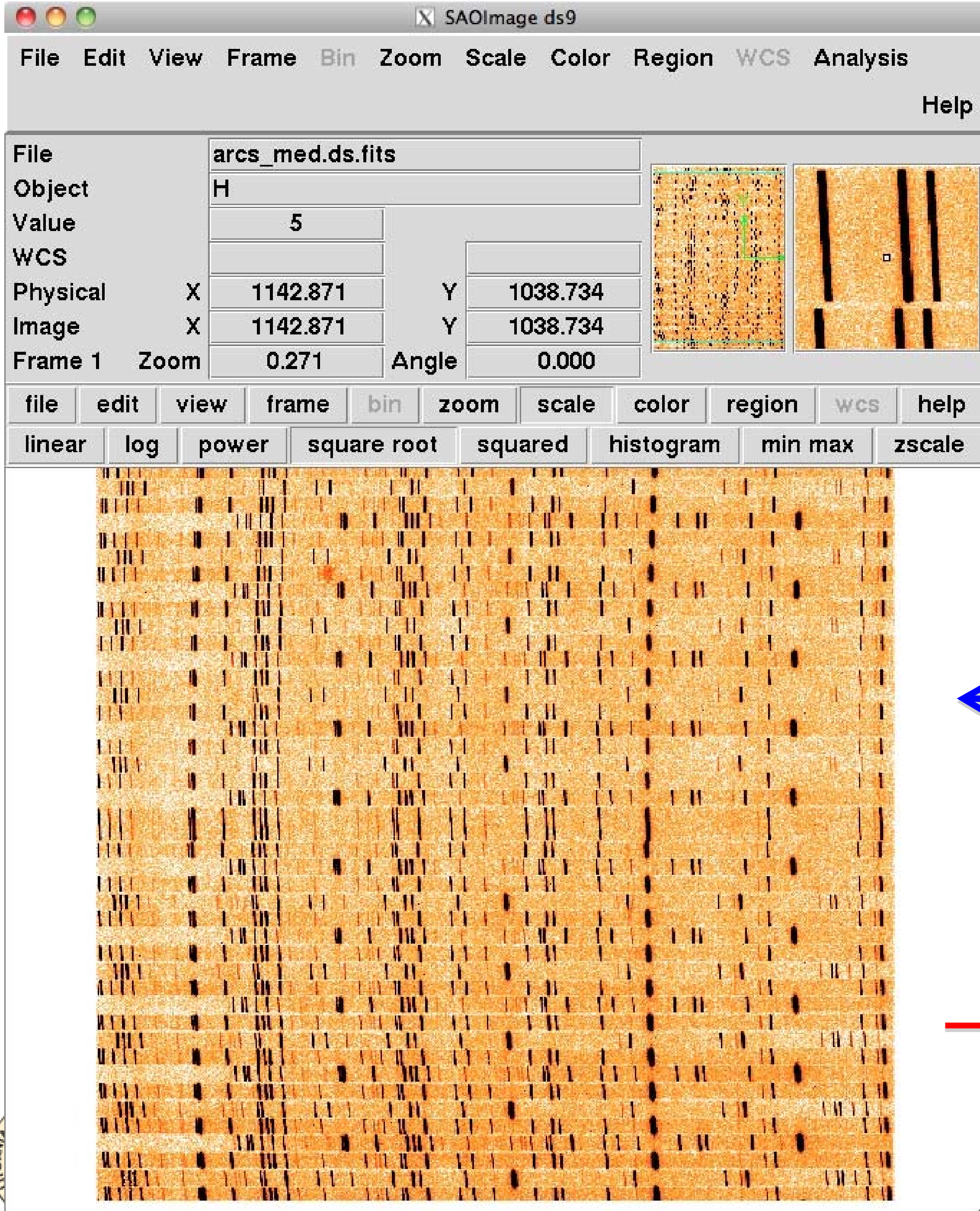
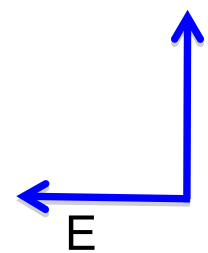


MOSFIRE Slit Configuration GUI
File
Tools
Help
Slit Width: 0.7
SET
Mask Name: testo1
Total Priority: 16294.0
Center: 2h 9m 50.43s -0d 5m 23.84s
PA: 73.0 degrees
Print to PNG
Slit Mask
Spectral Format
Row Center Width
1 -70.60 0.70
2 -24.23 0.70
3 -87.46 0.70
4 12.11 0.70
5 11.55 0.70
6 -19.38 0.70
7 -3.75 0.70
8 -124.92 0.70
9 -125.48 0.70
10 -21.39 0.70
11 10.94 0.70
12 -139.92 0.70
13 -140.48 0.70
14 -2.87 0.70
15 -11.17 0.70
16 -11.73 0.70
17 23.98 0.70
18 -13.21 0.70
19 -141.12 0.70
20 -21.64 0.70
21 -19.87 0.70
22 -24.20 0.70
23 -19.48 0.70
24 -9.54 0.70
25 19.09 0.70
26 2.11 0.70
27 -144.96 0.70
28 -145.52 0.70
29 -1.25 0.70
30 -1.81 0.70
31 -72.39 0.70
32 -72.95 0.70
33 -90.53 0.70
34 -130.69 0.70
35 12.64 0.70
36 -128.79 0.70
37 -47.32 0.70
38 -77.16 0.70
39 -148.34 0.70
40 -148.90 0.70
41 -145.65 0.70
42 -55.96 0.70
43 -79.54 0.70
44 -80.10 0.70
45 -102.02 0.70
46 -90.66 0.70
BX222
BX215
MD42
S10
D31
D31
M14
MD56
D44
D44
D38
BX263
BX304
BX304
BX285
D37
D37
BX278
BX309
BX156
BX318
BX319
BX157
BX155
MD32
S6
BX144
BX103
BX103
BX119
BX119
MD19
MD19
MD17
C9
BX92
BX48
BX66
MD12
BX26
BX26
S2
BX23
BX30
C6
C6
BX8
BX3
Target Name Priority Magnitude RA Dec Epoch Equinox
BX3 100.0 24.49 2h 9m 37.13s -0d 4m 49.98s 2000.0 2000.0
BX8 100.0 23.8 2h 9m 37.50s -0d 4m 36.50s 2000.0 2000.0
C6 100.0 24.44 2h 9m 38.53s -0d 4m 54.80s 2000.0 2000.0
BX30 100.0 24.2 2h 9m 39.83s -0d 5m 13.87s 2000.0 2000.0
BX23 100.0 24.02 2h 9m 38.62s -0d 3m 45.66s 2000.0 2000.0
BX26 100.0 23.73 2h 9m 39.33s -0d 3m 39.30s 2000.0 2000.0
MD12 100.0 24.12 2h 9m 41.61s -0d 4m 43.71s 2000.0 2000.0
MASK CONFIGURATIONS
Open...
Close
Status Name
new testo1
Save MSC...
Save All...
OPEN MASK
Open Mask
LONGSLIT
Slit width: 0.7 arcsec
Create Longslit
MASCGEN
Load Parameters...
Save Parameters...
Mask Name: testo1
Inputs
Outputs
Status
Input Object List: q0207_1.coords
Open...
Use Center of Priority
X Range: 3.0 arcmin
X Center: -1.0 arcmin
Slit Width: 0.7 arcsec
Dither Space: 2.0 arcsec
Center Ra/Dec: 0 0 0.00 0 0 0.00 h m s ° ' "
X Steps: 5
X Step Size: 5.0 arcsec
Y Steps: 5
Y Step Size: 5.0 arcsec
Center PA: 90.0 degrees
PA Steps: 30
PA Step Size: 1.0 degrees
Alignment Stars: 5
Star Edge Buffer: 2.0 arcsec
Run


MOSFIRE Slit Configuration GUI
File
Tools
Help
Slit Width: 0.7
SET
Row Center Width
1 -70.60 0.70
2 -24.23 0.70
3 -87.46 0.70
4 12.11 0.70
5 11.55 0.70
6 -19.38 0.70
7 -3.75 0.70
8 -124.92 0.70
9 -125.48 0.70
10 -21.39 0.70
11 10.94 0.70
12 -139.92 0.70
13 -140.48 0.70
14 -2.87 0.70
15 -11.17 0.70
16 -11.73 0.70
17 23.98 0.70
18 -13.21 0.70
19 -141.12 0.70
20 -21.64 0.70
21 -19.87 0.70
22 -24.20 0.70
23 -19.48 0.70
24 -9.54 0.70
25 19.09 0.70
26 2.11 0.70
27 -144.96 0.70
28 -145.52 0.70
29 -1.25 0.70
30 -1.81 0.70
31 -72.39 0.70
32 -72.95 0.70
33 -90.53 0.70
34 -130.69 0.70
35 12.64 0.70
36 -128.79 0.70
37 -47.32 0.70
38 -77.16 0.70
39 -148.34 0.70
40 -148.90 0.70
41 -145.65 0.70
42 -55.96 0.70
43 -79.54 0.70
44 -80.10 0.70
45 -102.02 0.70
46 -90.66 0.70
Mask Name: testo1
Total Priority: 16294.0
Center: 2h 9m 50.43s -0d 5m 23.84s
PA: 73.0 degrees
Print to PNG
Slit Mask
Spectral Format
Ks
Wavelength to plot: 20500
Angstroms
Add Wavelength Marker
Target Name Priority Magnitude RA Dec Epoch Equinox
BX3 100.0 24.49 2h 9m 37.13s -0d 4m 49.98s 2000.0 2000.0
BX8 100.0 23.8 2h 9m 37.50s -0d 4m 36.50s 2000.0 2000.0
C6 100.0 24.44 2h 9m 38.53s -0d 4m 54.80s 2000.0 2000.0
BX30 100.0 24.2 2h 9m 39.83s -0d 5m 13.87s 2000.0 2000.0
BX23 100.0 24.02 2h 9m 38.62s -0d 3m 45.66s 2000.0 2000.0
BX26 100.0 23.73 2h 9m 39.33s -0d 3m 39.30s 2000.0 2000.0
MD12 100.0 24.12 2h 9m 41.61s -0d 4m 43.71s 2000.0 2000.0
MASK CONFIGURATIONS
Open...
Close
Status Name
new testo1
Save MSC...
Save All...
OPEN MASK
Open Mask
LONGSLIT
Slit width: 0.7 arcsec
Create Longslit
MASCGEN
Load Parameters...
Save Parameters...
Mask Name: testo1
Inputs
Outputs
Status
Input Object List: q0207_1.coords
Open...
Use Center of Priority
X Range: 3.0 arcmin
X Center: -1.0 arcmin
Slit Width: 0.7 arcsec
Dither Space: 2.0 arcsec
Center Ra/Dec: 0 0 0.00 0 0 0.00 h m s ° ' "
X Steps: 5
X Step Size: 5.0 arcsec
Y Steps: 5
Y Step Size: 5.0 arcsec
Center PA: 90.0 degrees
PA Steps: 30
PA Step Size: 1.0 degrees
Alignment Stars: 5
Star Edge Buffer: 2.0 arcsec
Run

MOSFIRE Detector display (DS9; Right Monitor)





@PA=0

W. M. KECK OBSERVATORY

MOSFIRE Field Acquisition

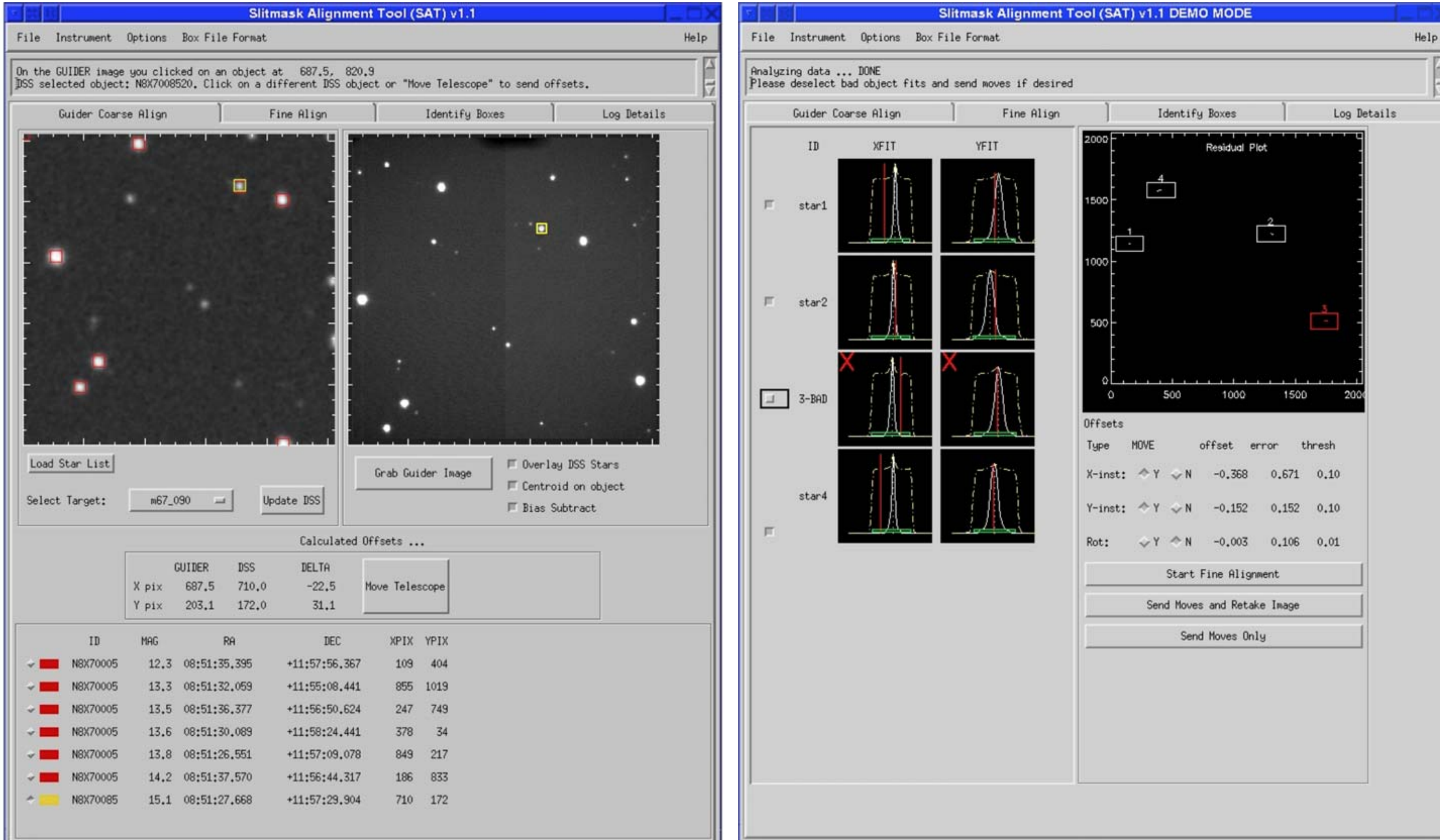
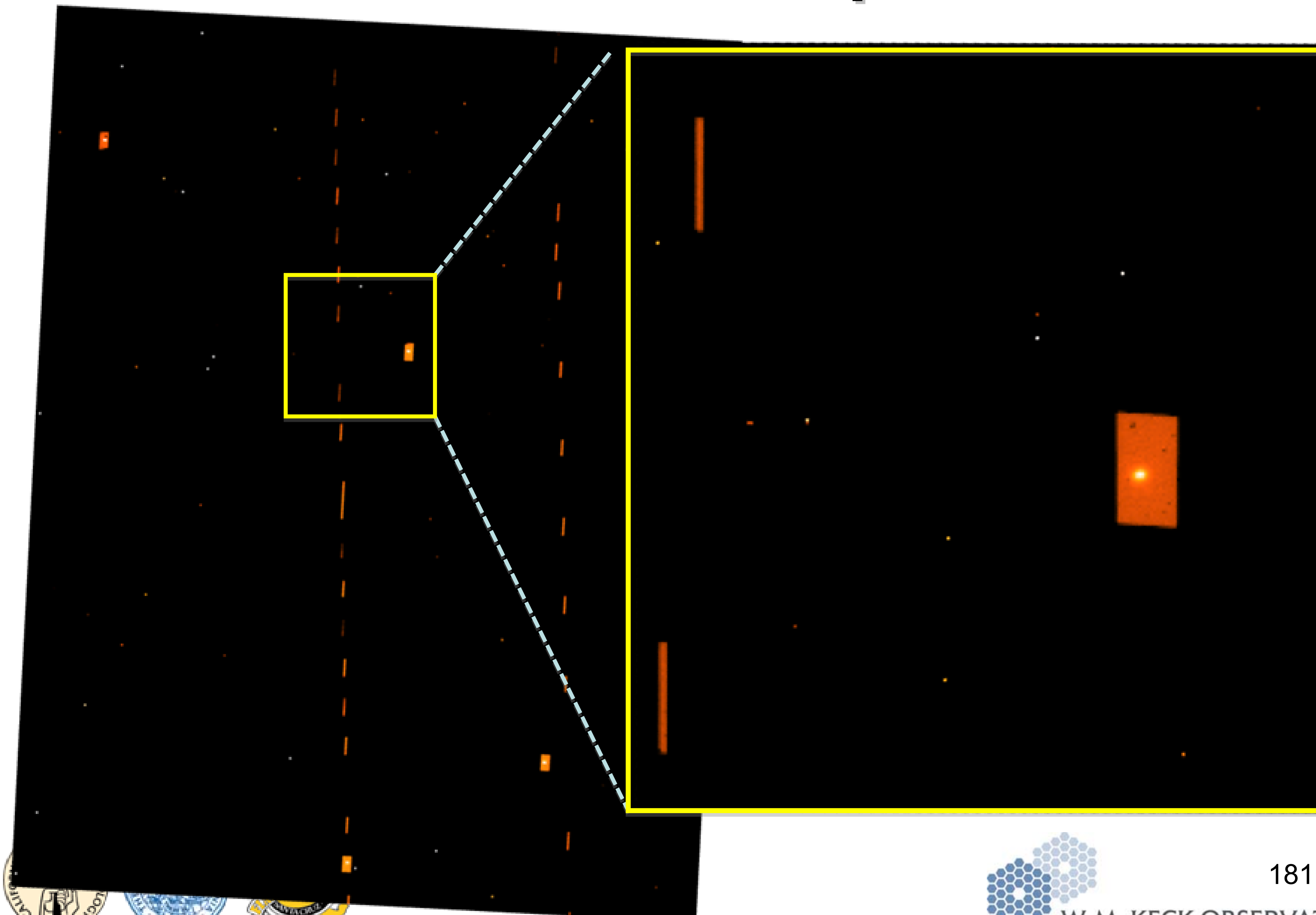


Figure 42: The MOSFIRE Slitmask Alignment Tool

MOSFIRE Field Acquisition



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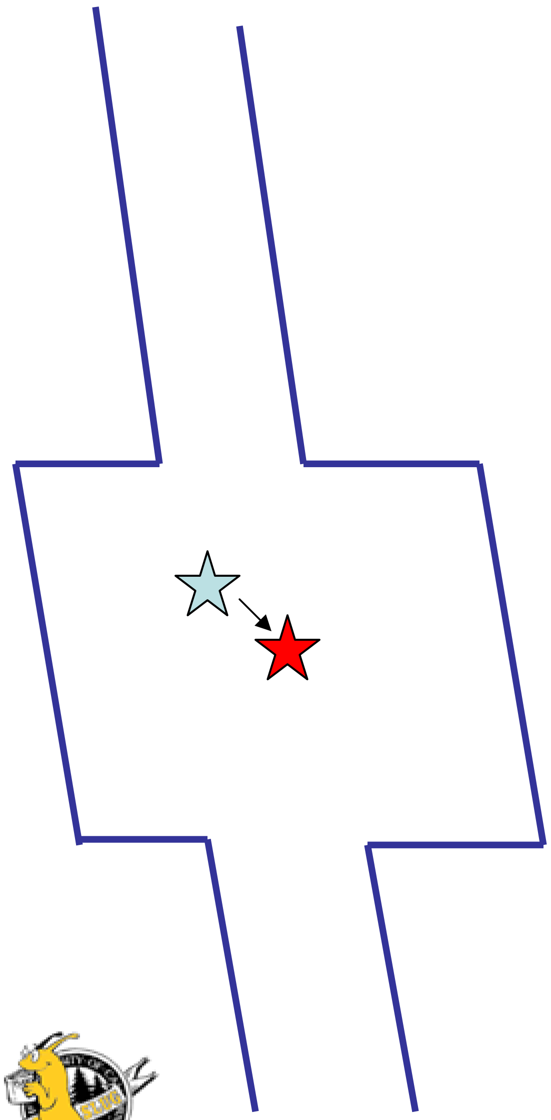
Calibration/Long-slit Acquisition



- Send middle bars to field center with desired slit width
- Open center bar to "alignment box" size
- Grating ➔ imaging mirror
- Send telescope to MOSFIRE field
- Use SAT (or interactive tweak) to center the star
- Close middle bar
- Mirror ➔ grating
- Normal dithering along slit

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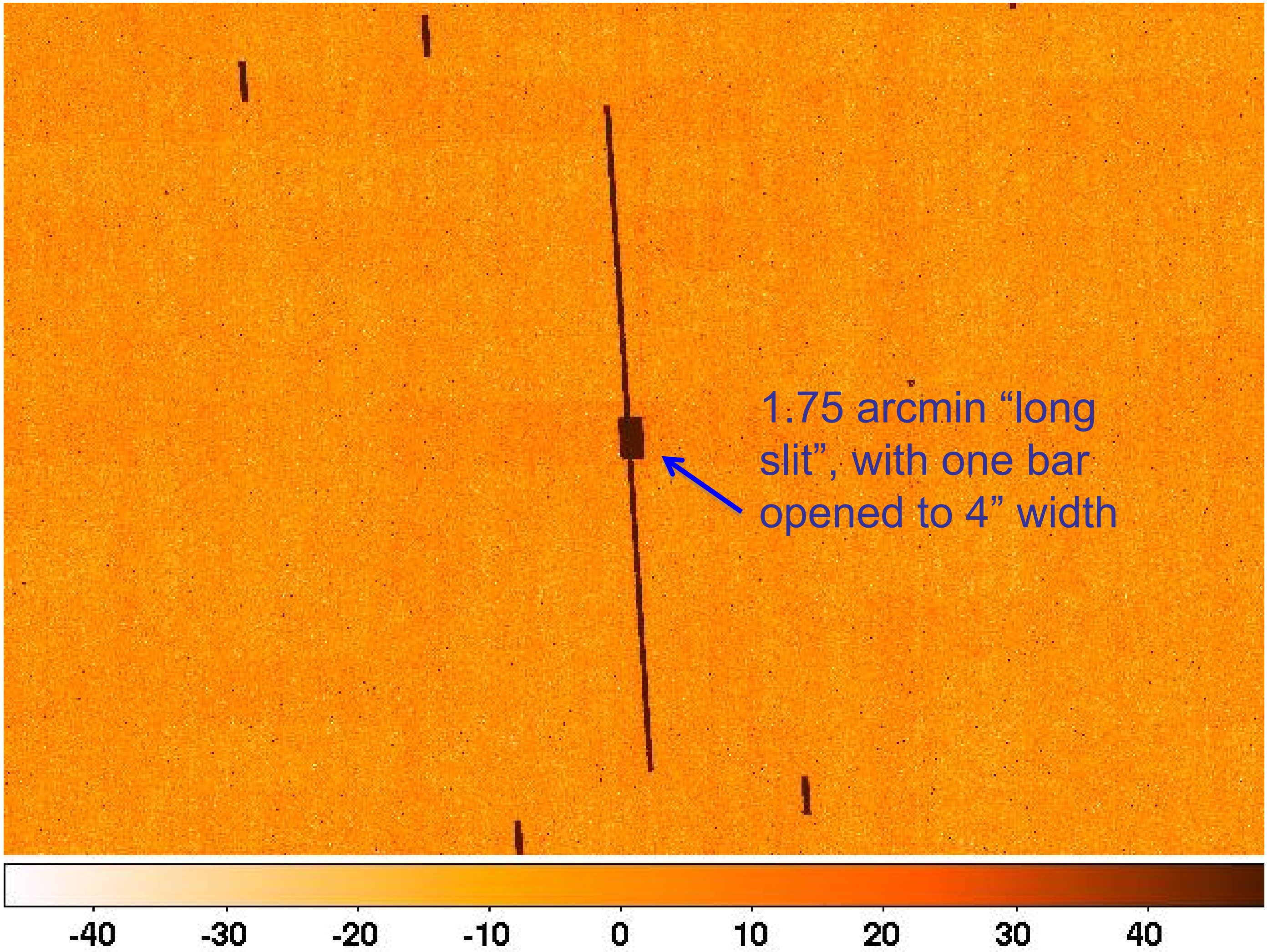
“Long-slit” Field Acquisition



W. M. KECK OBSERVATORY

MOSFIRE Observing Strategies

- **MOSFIRE provides many options for how the detector is run, and what works best will be science-dependent.**
  - **<u>Fowler sampling</u>**: no limit on #read pairs N except that exposure time must be >= N*1.45 sec

    (64 reads hits the read noise floor)
  - **<u>"Up the Ramp"</u>:** in our implementation, obtains M read groups, each of N reads. Basically, multiple Fowler samples w/o reset in between. Detector server writes out each difference image up the ramp. Can then be combined using any weighting scheme.
    - we have contemplated coordinating telescope nods with group times up the ramp
- <u>Part of commissioning plan is to investigate what cadence between reads or nods works best in what situation.</u>

DRP Status

- Programming work began during the summer of 2009 with a survey of available software tools and options for the architecture of the DRP, and while the instrument had not yet achieved first-light in the lab (and so there were no “as-built” data to experiment with), we concentrated on developing a MOSFIRE simulator, using the full ray-trace of the instrument and all other parameters that were reasonably well-known at the time.
- An example of a spectral image produced with the simulator is shown in **Figure 43**.
- The MOSFIRE DRP is intended to be usable by any astronomer without the need for python expertise.
- Plans for the distribution of the MOSFIRE DRP are currently TBD, but it is imagined that the level of support from the observatory staff will be similar to that of existing reduction packages.
- We anticipate the active participation of the WMKO community in maintaining and upgrading the software and algorithms as more experience is gained in a wide range of MOSFIRE science applications.

Data Reduction Pipeline

- At the time of the DDR in April 2007, we had planned to adapt the existing DEIMOS reduction pipeline (running under IDL) for use with MOSFIRE.
- However, several members of the MOSFIRE team are experts using Python, which is becoming increasingly popular among astronomers, is well-supported by the astronomical community, and unlike IDL is available free of charge and without the cumbersome licensing issues.
- A data reduction pipeline for MOSFIRE has been in development since the summer of 2009, at which point the decision was made to use the publicly available, well-supported, powerful (and free) Python package available from the Space Telescope Science Institute[1].
- The available code is bundled with several add-on packages including "pyraf", a Python extension that allows the use of IRAF and STSDAS tasks from within python scripts. This package is continuously under development for the HST data reduction pipeline, and will be the platform for JWST as well.

[1] http://www.stsci.edu/resources/software_hardware/pyraf/stsci_python

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Software & Hardware
•stsci_python

Download
Documentation
Installation Instructions
Release Notes
Citation

STSDAS
TABLES
PyRAF
PyFITS
pysynphot
MultiDrizzle
specview

stsci_python

stsci_python is a library of Python routines and C extensions that has been developed to provide a general astronomical data analysis infrastructure. It includes the following:

- PyRAF, an environment for running IRAF tasks without using the IRAF CL
- MultiDrizzle, a task for combining dithered STScI images
- PyFITS, used to read FITS images and tables into numpy or numarray objects and to manipulate FITS headers
- pysynphot is a synthetic photometry package (still in development) designed to replace STSDAS.SYNPHOT. It is suitable for library or interactive use.
- Numdisplay, used to visualize numpy array objects using image display tools like ds9 and ximtool

You can download the complete stsci_python package from our download page

Release Notes

Old release notes

stsci_python news

STSCI_PYTHON 2.11 released
More...

STSCI_PYTHON 2.11 Patch 1 released
More...

Contact

For further information, contact help@stsci.edu

Simulated K-band spectrum

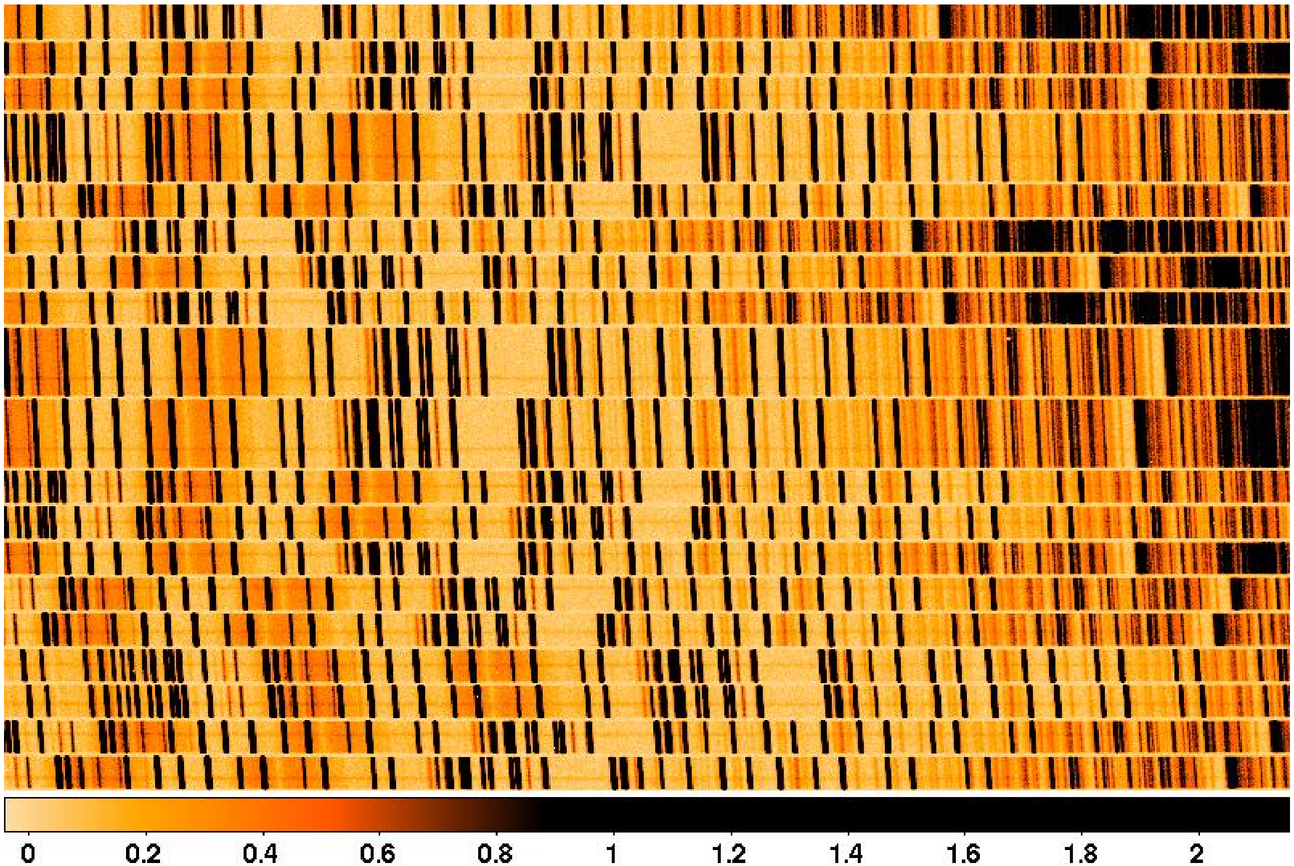


Figure 43: Portion of a simulated K-band multi-slit spectrum
(created using the MOSFIRE simulator)

W. M. KECK OBSERVATORY

Automated Line Lists and Wavelength Solutions

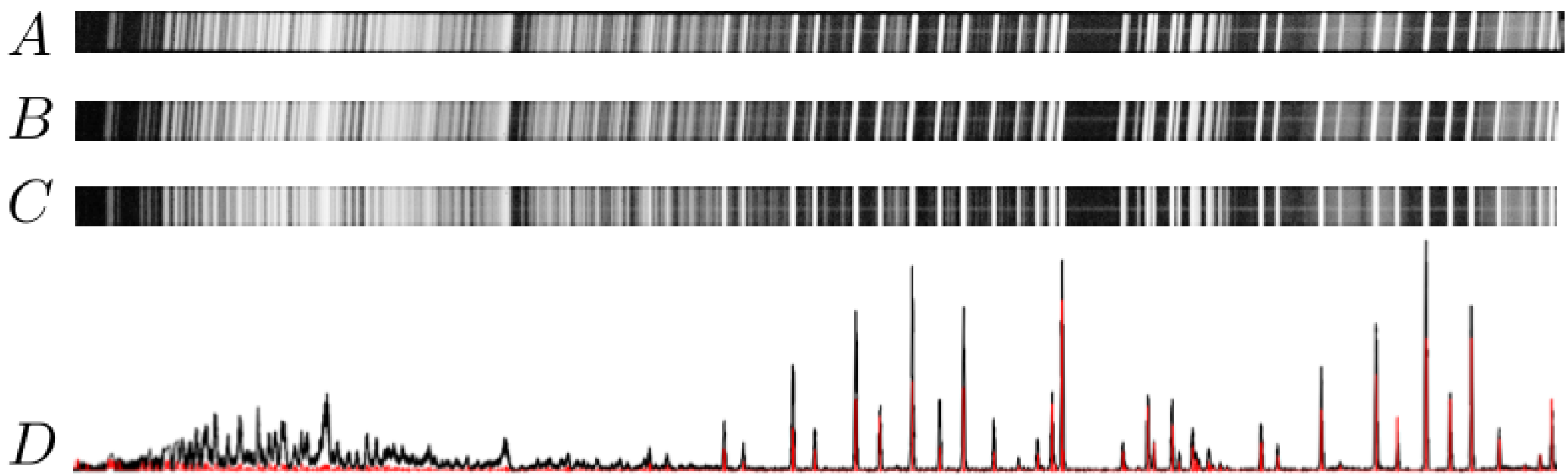
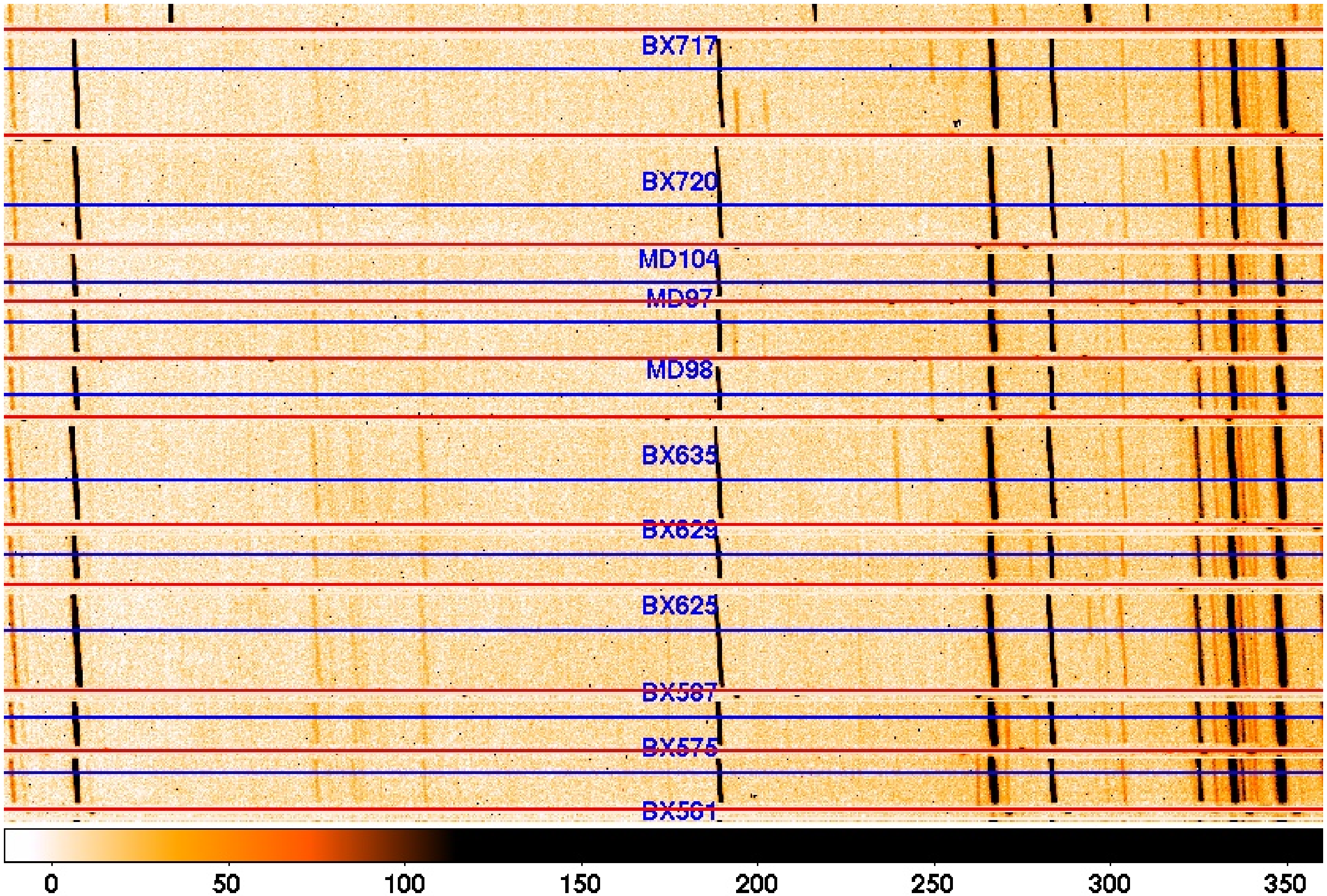


FIG. 3: Stages of calibration (where η is a strictly monotonic function of λ, with $\eta(\lambda) = p_x(\lambda, y_c)$ for y_c at the centre of the slit):
A : raw slit image in p_x, p_y (note that the top and bottom edges are slightly u-shaped)
B : resampled to p_x, y
C : resampled to $\eta(\lambda), y$
D : plot of pixel values versus $\eta(\lambda)$ (black), compared to list of theoretical OH spectral lines [4] (red).

R. Lasenby, MSDN73.01, "DRP Design and Implementation"

W. M. KECK OBSERVATORY

DRP: Slit Finding/Tracing Using Header Information



Red: Edge Trace

Blue: Predicted Object Trace

Initial wavelength solution from linear model

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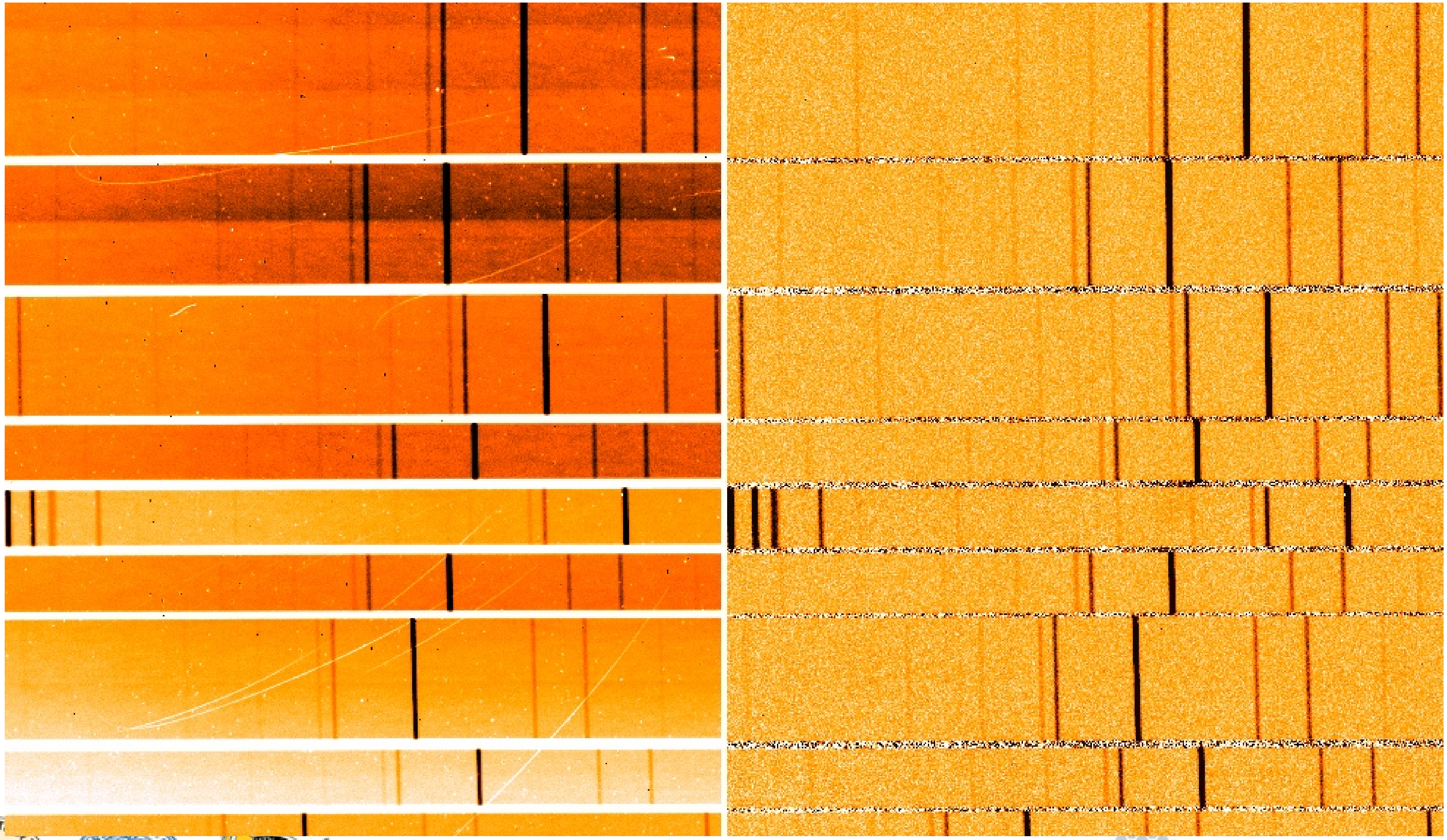
Flat Fielding Demonstration (H band arc + ambient light)



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DRP Development

- The primary use of the DRP will be to produce calibrated, 2D, background subtracted spectral images with wavelength solutions, all with minimal need for user-interaction.
- There will also be a module for imaging data reductions that will automatically assemble mosaic images into an astrometrically correct stacked image.
- All of the DRP modules will be fine-tuned during the commissioning phase using real on-sky data; with a plan to make it available to the WMKO community by the time commissioning has been completed.
- Plans for the distribution of the MOSFIRE DRP are currently TBD, but it is imagined that the level of support required from the observatory staff will be similar to that of existing reduction packages (i.e., generally minimal).
- We anticipate the active participation of the WMKO community in maintaining and upgrading the software and algorithms as more experience is gained in a wide range of MOSFIRE science applications.

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Commissioning

Chuck Steidel

MOSFIRE Issues

- **In most ways MOSFIRE bears more similarity to LRIS than to previous near-IR instruments at Keck**
  - e.g., fixed position offset guider field
  - ~6′ field of view: need to understand both the telescope and the instrument focal planes to get light through slits
  - the most commonly used mode is going to be multi-object spectroscopy
  - it is “seeing limited”
- On top of issues having to do with wide field instruments
  - there are idiosyncrasies of near-IR detectors and background that present additional challenges,
  - also opportunities to do things differently

Commissioning Tasks

- **The plan is in MOSFIRE document MGDN1403, "MOSFIRE On-sky commissioning plans"**
- This is a list of tasks that is being maintained (and added to) that must be completed in order for the astronomical community to make efficient use of observing time.
- Initial tasks are high priority items without which it would be difficult or impossible to take care of the more subtle issues.

For example:

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Example Task

Task ID / Priority	1/ H
Title:	Verify flexure model
Lead:	Konidaris
Other persons involved:	Observers: Steidel, Trainor, Kassis Data Reduce: MOSFIRE team (Trainor lead)
Sky time Requested	none
Required conditions	This is best done with closed dome, and would take 1-2 hours of time with the telescope if done in the afternoon. It should be done before going on the sky, to ensure stable image positions while establishing POs, etc

Purpose: Verify that the flexure model obtained in the lab works when the instrument is mounted on the telescope. Very that FCS can read rotator angle and elevation as supplied by the DCS, and make adjustments automatically based on observing mode in use.

Observing Plan: With lab flexure model active, take sequences of images and spectra (YJ and HK grating settings) at each of 4 elevations: 0, 30, 60, 90 over full rotator range at each, in 20 degree intervals.

Reduction Plan: Use suite of python scripts developed in lab to analyze in near-real-time. Make adjustments to the model parameters if necessary, in preparation for on-sky commissioning.

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Fundamental Tasks:

- Orientation, handedness, pointing, guiding
  1. Verify the ability to take an image, have it display, etc.
  2. Establish/confirm rough pixel scale, orientation of guider and science field images as seen on detector (we think we already know this accurately for the science field).
  3. Establish the physical rotator angle zero point (maps instrument angle to sky PA), verify
  4. Establish pointing origin (guider "REF" position and the MOSFIRE P.O., which will be near the optical axis, at the center of the field.)
  5. Demonstrate the ability to focus the telescope (using the MIRA aka MALIGN tool), and obtain consistent results vs. field position and vs. initial piston/tilt of the secondary.

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Tasks (cont'd)

6. Metrology/astrometry between guider and science field (mask alignment will rely on this being accurate to better than ~1")
7. Demonstrate guiding/tracking; test correction for differential refraction between the guider (0.78 μm) and science field (0.95-2.41 μm)
8. Mapping the focal plane of the guider so that quasi-closed-loop offsets can be made while guiding (linear pixel scale is probably not adequate assumption)
9. Verify alignment of MOSFIRE pupil with the telescope optical axis (should be well aligned by design).
10. Establish zero point offset between the pupil mechanism motor steps and the physical Cass rotator (ROTPPOSN keyword).
11. Verify that pupil is aligned and tracking at the same rate as the rotator, at a fixed sky PA.

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Orientation Tasks (cont'd)

12. Measure relative flexure between guider and science field.
13. If significant, map it and devise a way to account for it in the guider software.
14. Test motion control scripts for offsetting telescope while guiding.
15. Align a slitmask and test/modify alignment software. Do this at several different elevations and sky PAs.

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"Break it In" Tasks

(test possible failure modes, recovery procedures)

1. Reboot instrument control computers while on sky. Record steps needed for recovery.
2. Power cycle mechanism controllers (remotely) while on sky, confirm means of re-establishing positions after power is restored.
3. Verify rotator linearity, tracking, zenith angle lower limit.

Calibration Tasks:

1. Characterize effects of very bright objects in field, scattered light w/proximity to the moon, etc.
2. Precision calibration/verification of telescope focal surface seen by MOSFIRE, and the mapping to detector pixel
   - Should be at most a scale change, telescope focal surface expected linear to 0.02% over MOSFIRE FOV, MOSFIRE linear to 0.2%
   - Note that only the telescope focal plane is crucial for designing slit masks, but having accurate slit-to-detector solution makes it much more efficient to align masks(and helps the DRP).
3. Establish photometric zero points, measure throughput, for all observing modes

Calibration Tasks:

4. Obtain and test various methods of flat-fielding (twilight, dome, dark sky). Ensure that there is an acceptable solution for spectroscopic dome flats.
5. Use sky spectra taken in each MOSFIRE spectroscopic mode to build a reference OH spectrum to be used by DRP wavelength calibration; measure instrumental background (sky + instrument) vs. wavelength.
6. Test dither scripts in imaging and spectroscopic mode. Establish most effective cadence/dwell times for faint spectroscopy, vs. band.
7. Test different data acquisition schemes: #Fowler samples, individual integration times, up-the-ramp group time, in various regimes of S/N.
8. Test time efficient guiding scheme and coordination with UTR difference images.

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Calibration Tasks:

9. Test methods for telluric correction of (a) long slit data and (b) data for entire slitmasks, using a single calibration star.
   - e.g., test narrow but long slit dithered observations with spectral over-sampling; scripts to move a single star to each of N slits on a mask efficiently and accurately, etc.
10. Take spectroscopic (wide slit) data to establish baseline for throughput measurements in the future (define a reference "grid" of AOV stars to be used for logging time dependence of instrument throughput .

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Science Verification Tasks

- **Basic rationale: push the instrument to find out how best to use it. Two very different regimes:**
  - faint targets: background subtraction, controlling systematics, how best to accumulate long integrations (imaging and spectroscopy).
  - bright targets in the high S/N regime where flat fielding, telluric correction become more crucial.
- **Concentrate on how to make using MOSFIRE as efficient as possible (from the beginning) by spending a comparatively small amount of time now.**

Science Verification Tasks

- Of course, it will not hurt to get some nice publicity shots to announce MOSFIRE's arrival at WMKO!

- Specific programs for Science Verification are under discussion among the MOSFIRE team.

Concluding Remarks

Ian McLean

Schedule & Budget

- **Schedule slipped due mainly to CSU testing and subsequent rework, but many other factors too**
- **First light on Keck ~ June, 2011; commissioning through Fall**

Milestone	At DDR	November 2010	Current
Dewar integration begins	January 2008	June 2008	June 2008
First cold test	March 2008	December 2008	December 2008
Mechanism integration (not CSU)	May 2008	August 2009	August 2009
CSU integration	June 2008	September 2009	September 2009
Optics integration	September 2008	May 2010	May 2010
Acceptance testing begins	May 2009	July 2010	July 2010
Pre-ship review	June 2009	January 2011	April 2011
Installation begins on Keck I	August 2009	February 2011	May 2011
First light	September 2009	March 2011	June 2011
Commissioning completed	March 2010	October 2011	December 2011

- FYI: Original budget was $12.3M
- Cost at completion is now $13.46M, an overrun of 9.4%

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Acknowledgments

- Would like to acknowledge all of the team members past and present, WMKO staff and our industrial partners
- **The MOSFIRE Team is grateful to TSIP, WMKO and Gordon & Betty Moore for their support**
- *We especially want to thank you, our PSR committee for coming and helping us with your experience*
- **Our first Project Meeting was in July 2005!**
- This has been a challenging project–but no descopes
- **MOSFIRE is a unique instrument**
- Multi-institutional support needed–great teamwork
  - **We have a working instrument**
  - **It is time to go to the telescope**

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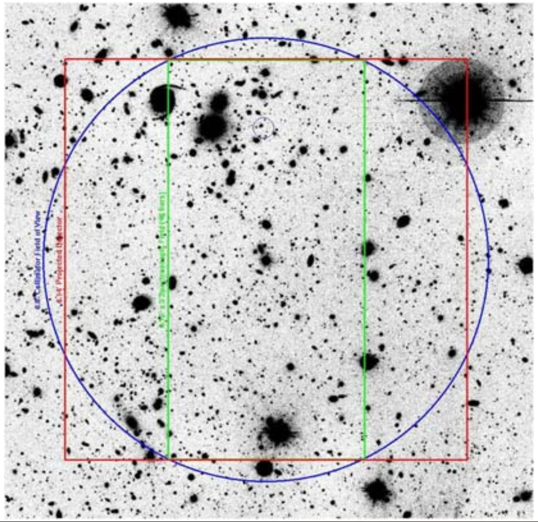

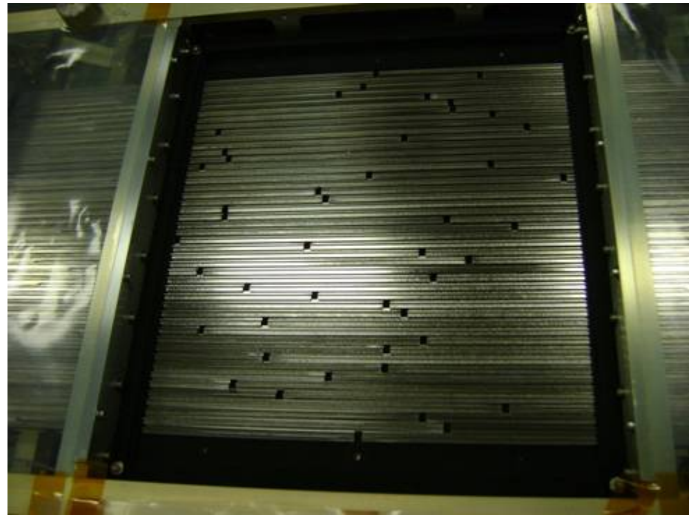

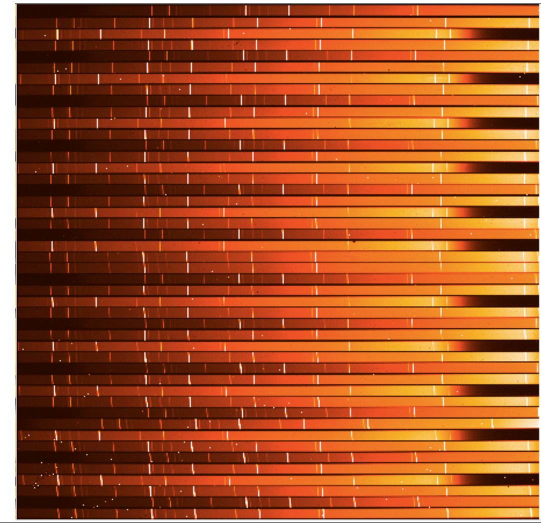

MOSFIRE

Multi-Object Spectrometer for Infra-Red Exploration

The team is highly motivated to finish the project and ship MOSFIRE to Hawaii.

We are ready and anxious for science.

Thank You

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Backup Slides

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Acceptance Testing

- Testing described in ATP Report compares the results of laboratory testing to performance requirements.
- Verification by inspection, analysis or demonstration.
- Results are compared with operational performance requirements, and with requirements for implementation and design.
- All the requirements for MOSFIRE are described in the MOSFIRE requirements document (Reference 1).
- Results described in the ATP Report are based on lab testing conducted over a period of approximately 1 year involving five cool down cycles (5 through 9).

MOSFIRE Throughput Estimates

Component	Transmission/Reflectance		
	1.0μm	1.6μm	2.2μm
Dewar Window (double)	0.95	0.95	0.95
Collimator (6 x 2 surfaces)	0.84	0.84	0.84
Fold flat (protected Ag)	0.99	0.99	0.99
Camera (7 x 2 surfaces)	0.84	0.84	0.84
Internal transmission of all glasses	0.94	0.92	0.77
Filter	0.90	0.90	0.90
Detector (Hawaii2-RG)	0.80	0.80	0.80
Lyot stop (pupil vignetting)	1.00	1.00	0.90
Net Imaging Throughput	**0.45**	**0.44**	**0.33**
Grating (on blaze)	0.65	0.75	0.83
Net Spectroscopy Throughput	**0.29**	**0.33**	**0.27**

At DDR (4/2007)

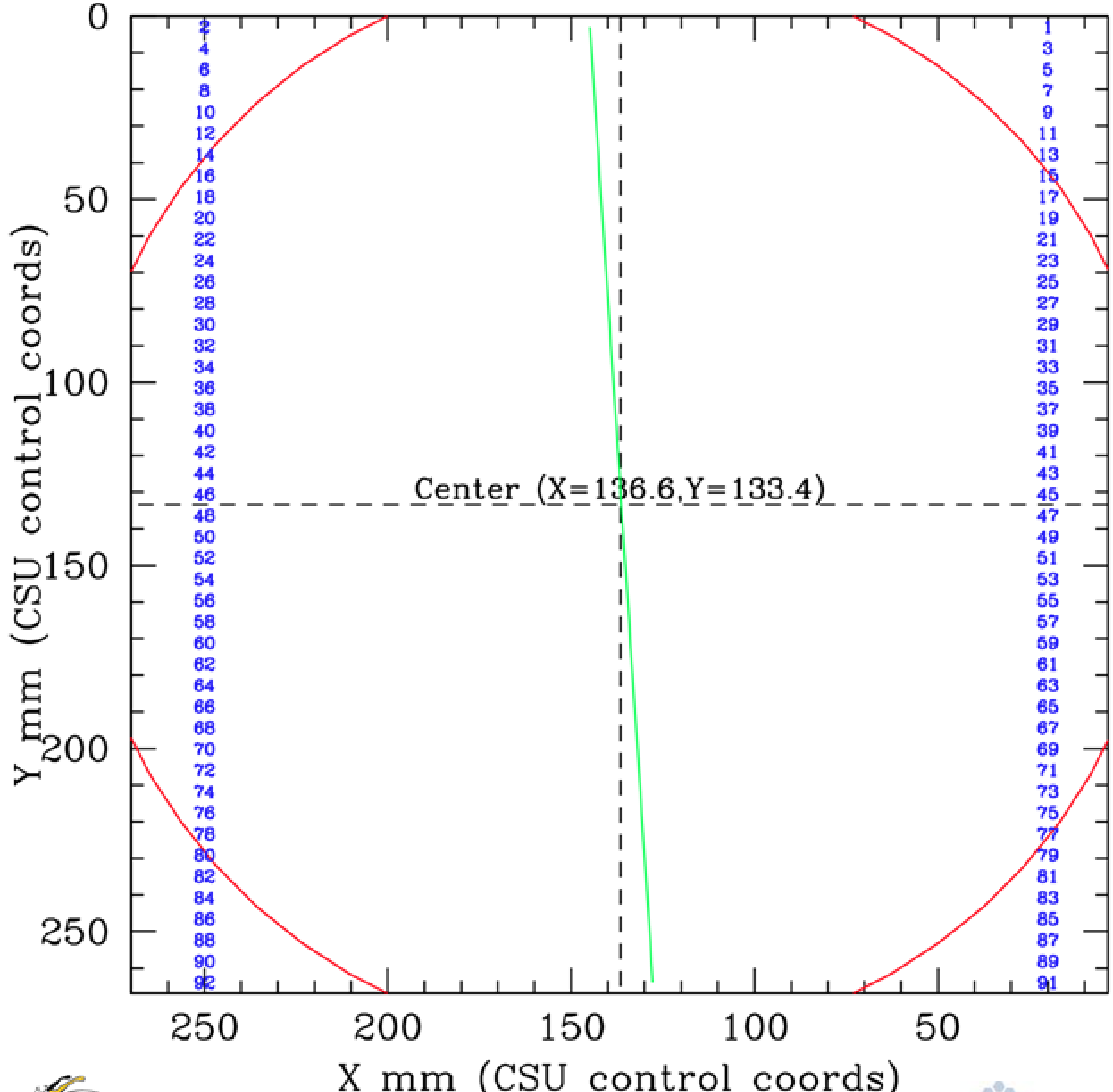
Assumptions: 1.2% reflection losses at each surface, except for ZnSe (2 surfaces @ 2.4%).

As-built MOSFIRE Throughput Estimate

- Now includes as-built numbers for filters, grating (w/actual incidence angles), glass transmission, and coatings on glass and mirrors

Band	Avg Throughput
Y (0.975-1.125 microns)	0.308±0.055
J (1.150-1.350 microns)	0.325±0.061
H (1.460-1.810 microns)	0.361±0.069
Ks (1.990-2.310 microns)	0.364±0.053
K (1.930-2.400 microns)	0.350±0.043

Averaged between nominal filter half-power points



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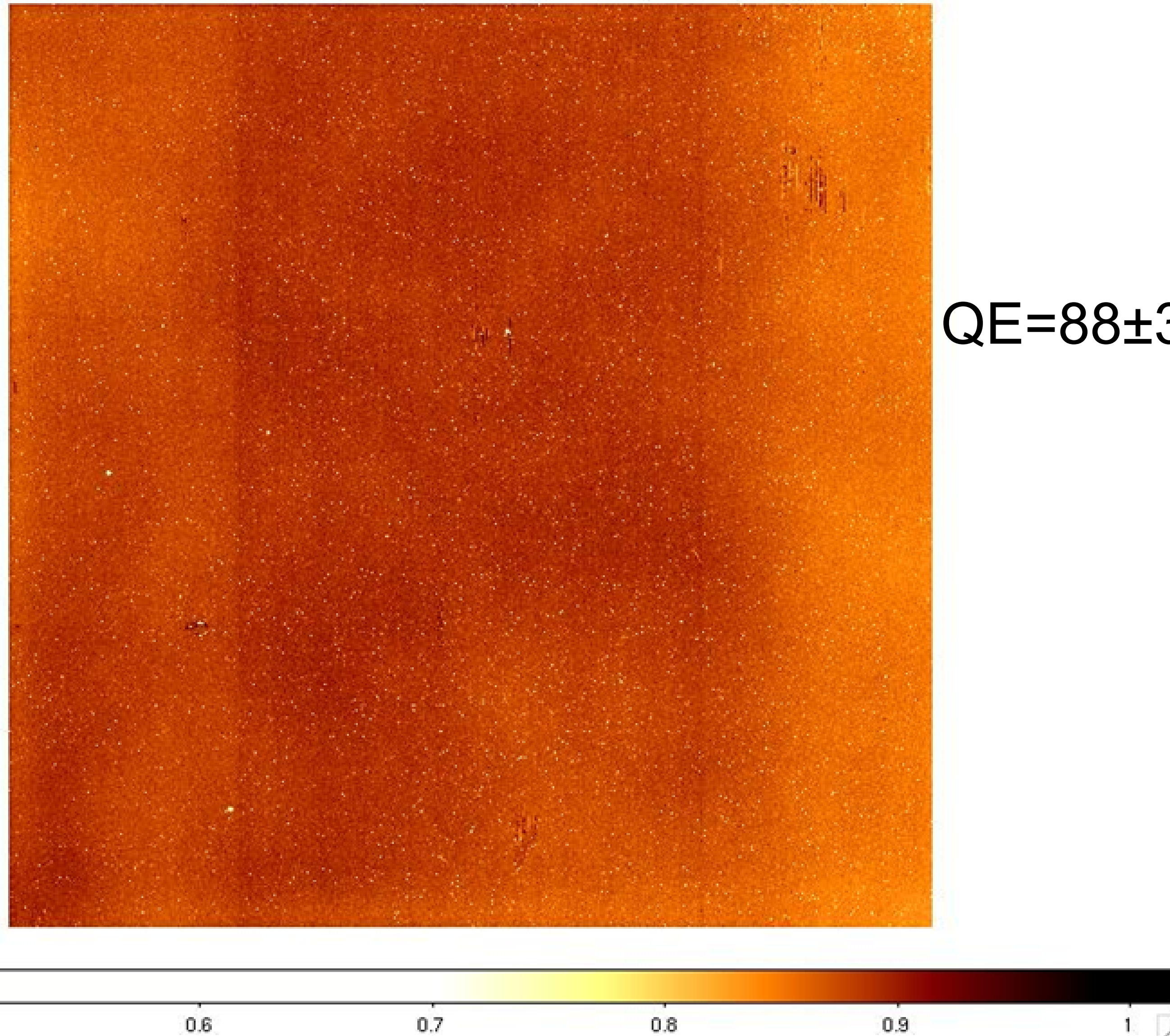
MOSFIRE-5 2μm Flat/QE map



QE=88±3%

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Comparison of Specs of Detectors offered by Teledyne

	QE	Noise:	Dark Current/Operability	Full Well	Latency	Flatness/ Planarity
Mosfire2	71% @1μm 77% @2μm	16.9e- (CDS) 6.0e- (UTR) 4.0e- (Fowler32)	0.001±0.002 99.64%	106,000e-	0.01%	9/18μm
Mosfire1	75%@1μm 86%@2μm	19.5e- (CDS) 6.6e- (UTR) 4.2e- (Fowler32)	0.002±0.003 99.85%	135,000 e-	0.05%	5/31μm
Mosfire5	83%@1μm 88%@2μm	13.6e- (CDS) 5.8e- (UTR) 3.7e- (Fowler32)	0.000±0.002 99.50%	115,000 e-	0.04%	4/9 μm

We selected Mosfire5

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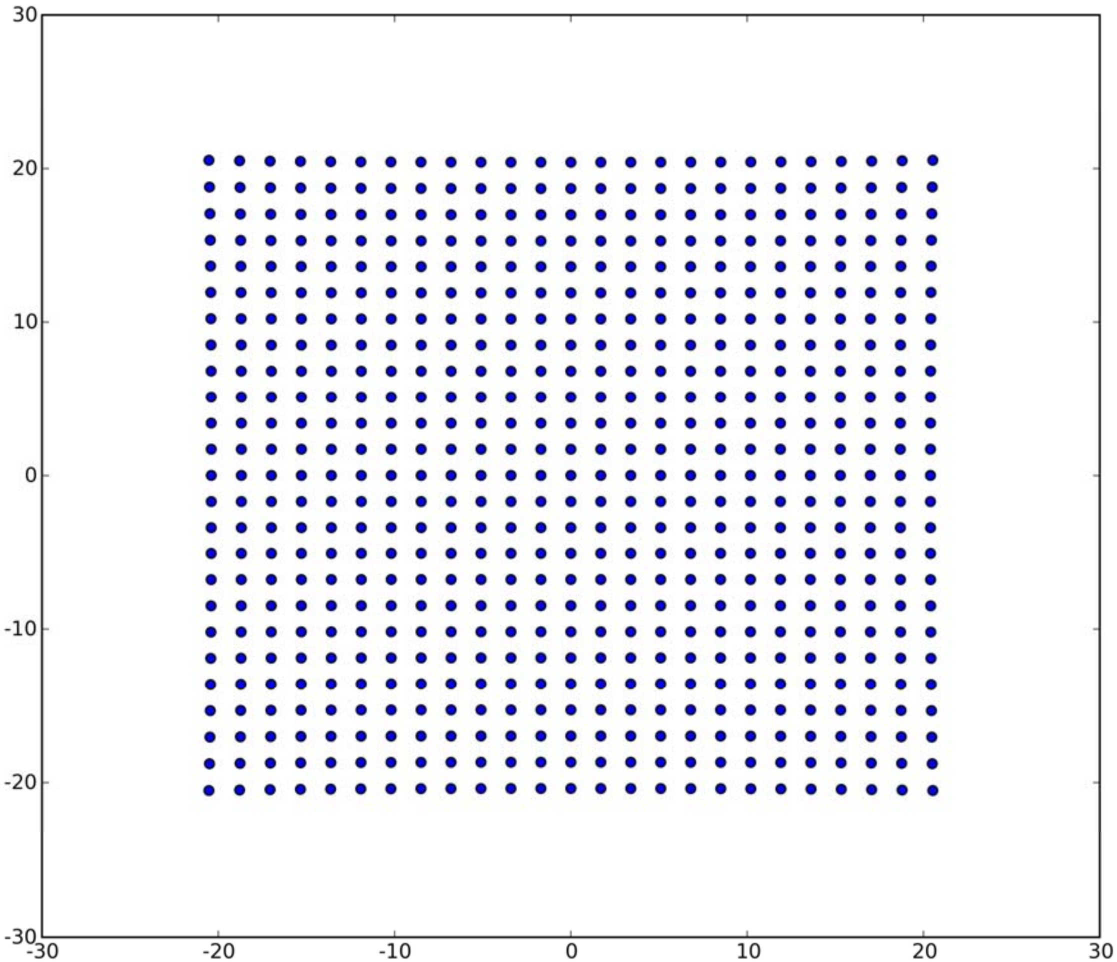
MOSFIRE Data Reduction Pipeline



Goal is to embed a first-guess astrometric solution into the header of every image, which is then tweaked up quickly for nearly-real-time full mosaic reductions.

Mapping of grid onto detector (full wavelength range)

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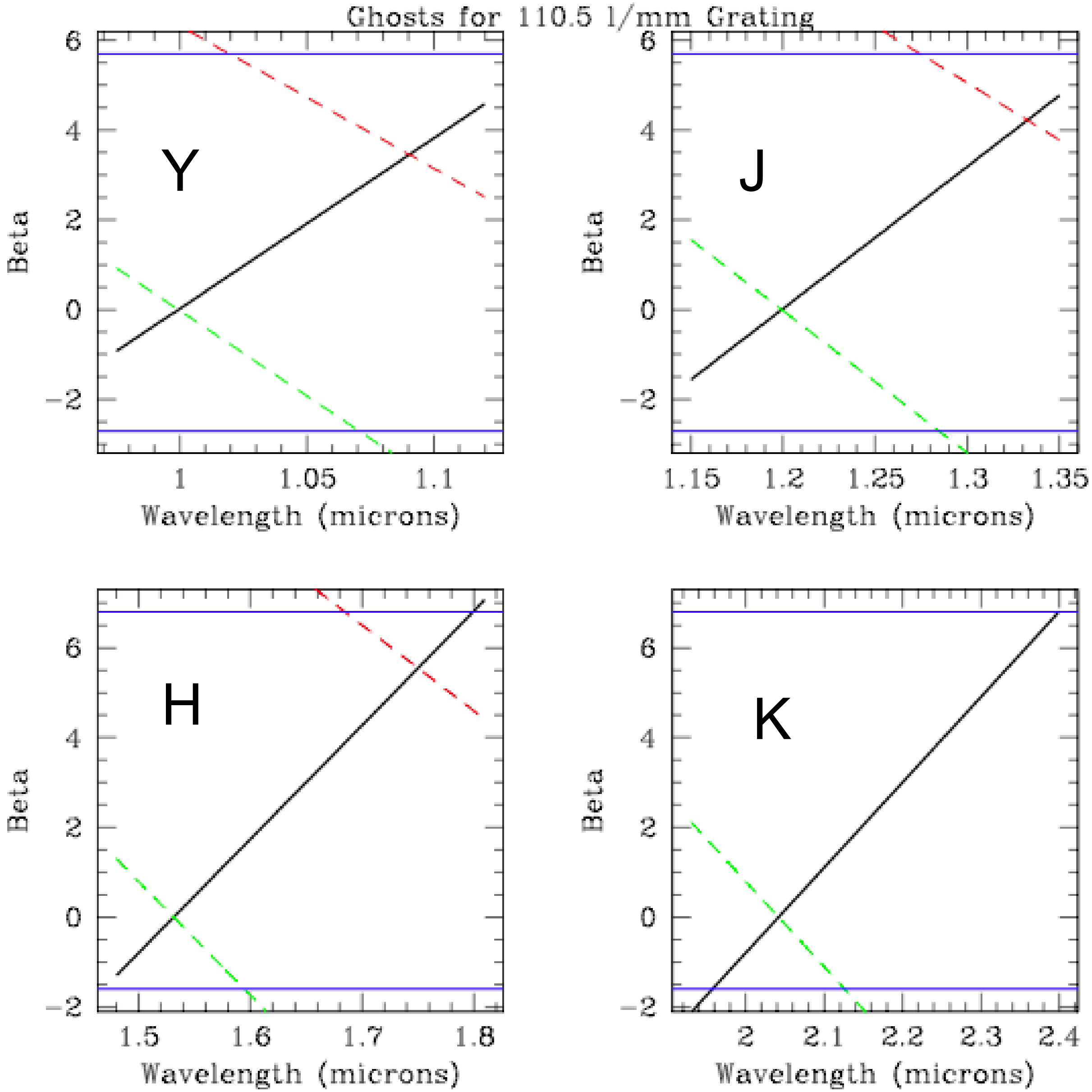
Grating Ghosts: 110.5 l/mm grating



Black: primary spectrum

Green: 0th order ghost

Red: 1st order ghost

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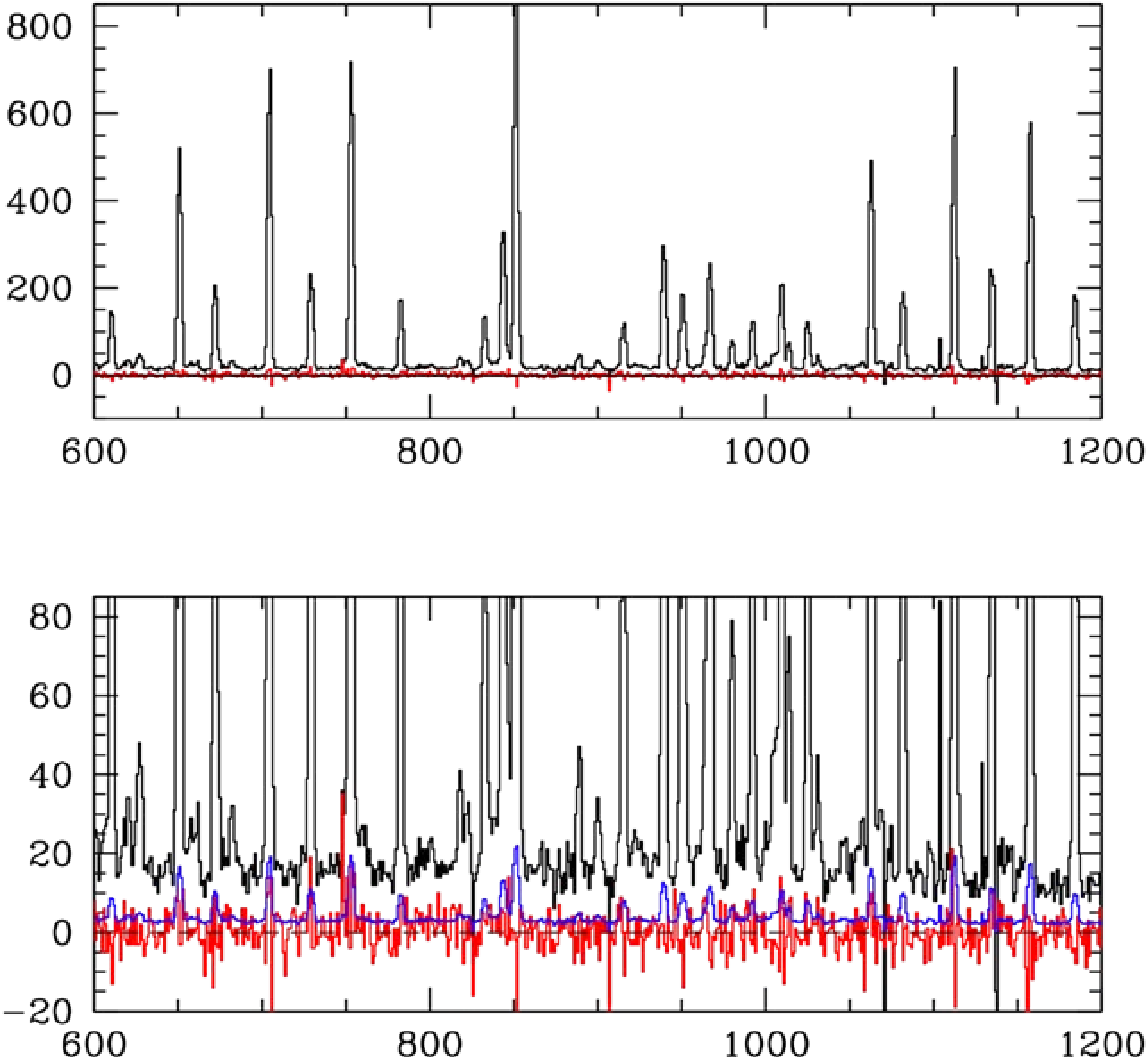

Black: H-band sky spectrum, R=2700, sum of 5x13s "interleaved"

Red: Residuals of "interleaved" sets of 5x13s (~30 s cadence)

Zoomed view; **blue** is expected 1σ from counting statistics

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Anamorphic factors

- Because of the relatively steep angles of incidence for the MOSFIRE spectroscopic modes there is significant compression in the spectral dimension of the dispersed images of slits as recorded on the detector.
- The (average) anamorphic factors are 1.357 for HK mode, and 1.335 for YJ, so that in spectroscopic mode, 1 pixel in the dispersion direction maps to 0.1798 * 1.335 = 0.240" arcsec for YJ and 0.1798 * 1.357 = 0.244" for HK.
- Thus a slit corresponding to 0.6" on the sky produces 0.6/0.240 (0.244) = 2.50 (2.46) pixel slit image at the detector (which agrees well with the line widths in Table 18).
- The nominal 0.7" slit would correspond to FWHM = 2.92 pixels for YJ spectroscopic mode and FWHM = 2.87 pixels for HK spectroscopic mode in the spectral direction.

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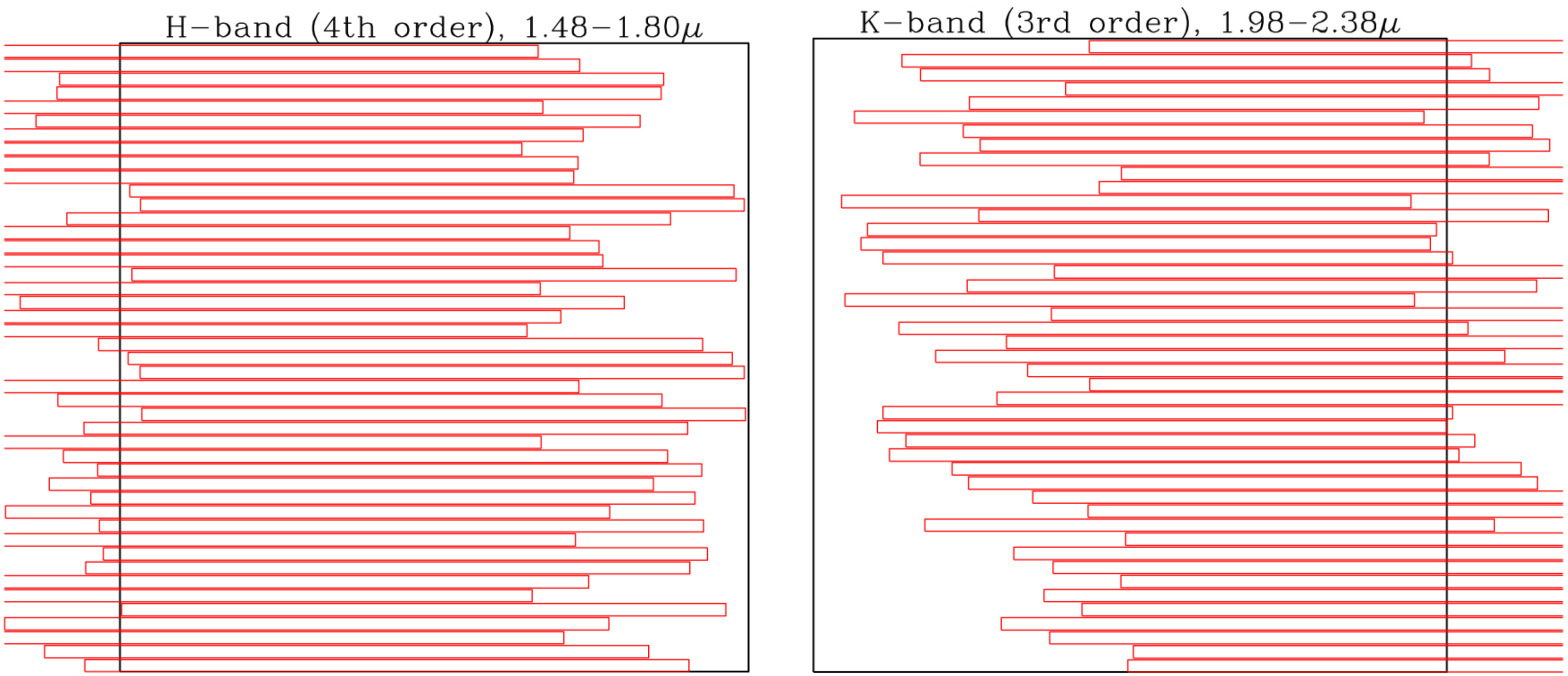
Examples of MOSFIRE Flexibility



H-band spectra, 6′ by 3′ field, shifted “left” by 1.5′

K-band spectra, 6′ by 4′ field with “YJ” grating tilt

Vacuum window

- Vacuum window stress and deflection were assessed utilizing standard formulas (reference 12) for a uniformly loaded solid circular plate.
- A conservative assumption of a simply supported edge restraint was assumed (reference 12, Table 24, Case 10a).
- For the MOSFIRE window geometry at sea level atmospheric pressure the calculations estimate a 480 psi stress at the center of the window, and 140 psi stress at the perimeter.
- Bearing stress at the window's perimeter contact with the o-ring was also estimated at 300 psi at sea level.
- The tensile strength rating of the Infrasil-302 window is 50 N/mm^2 or ~7,300 psi (reference 13).
- Based on the calculations described here the minimum safety factor is 15.2.

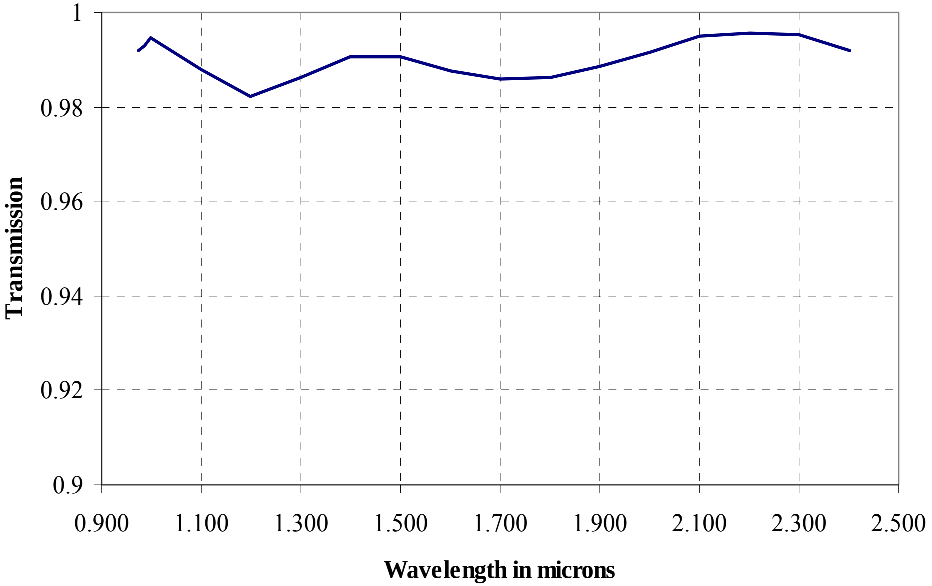


Figure 21: MOFIRE dewar window AR coating transmission vs. wavelength

The calculations predict a maximum deflection at the center of the window of 0.0011" (28 μm) at sea level. This was determined to be optically insignificant.

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CSU State Diagram

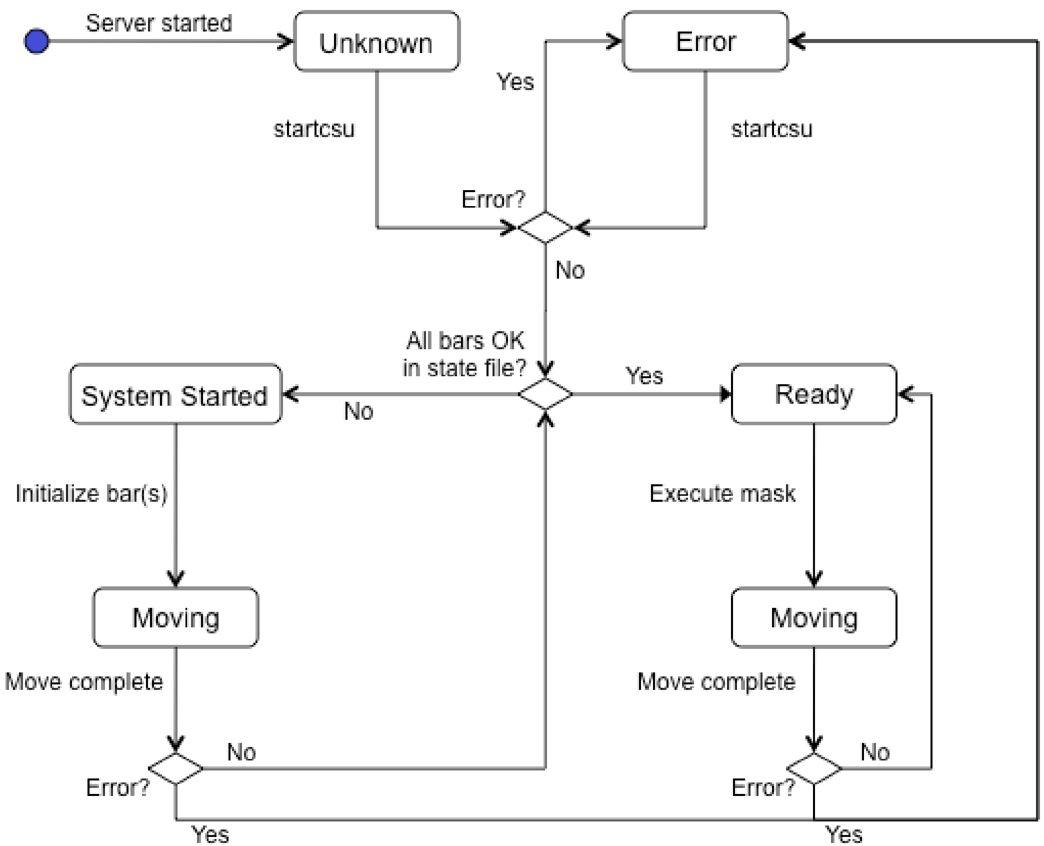

Figure 36: CSU State Diagram

Electronics Cabinet

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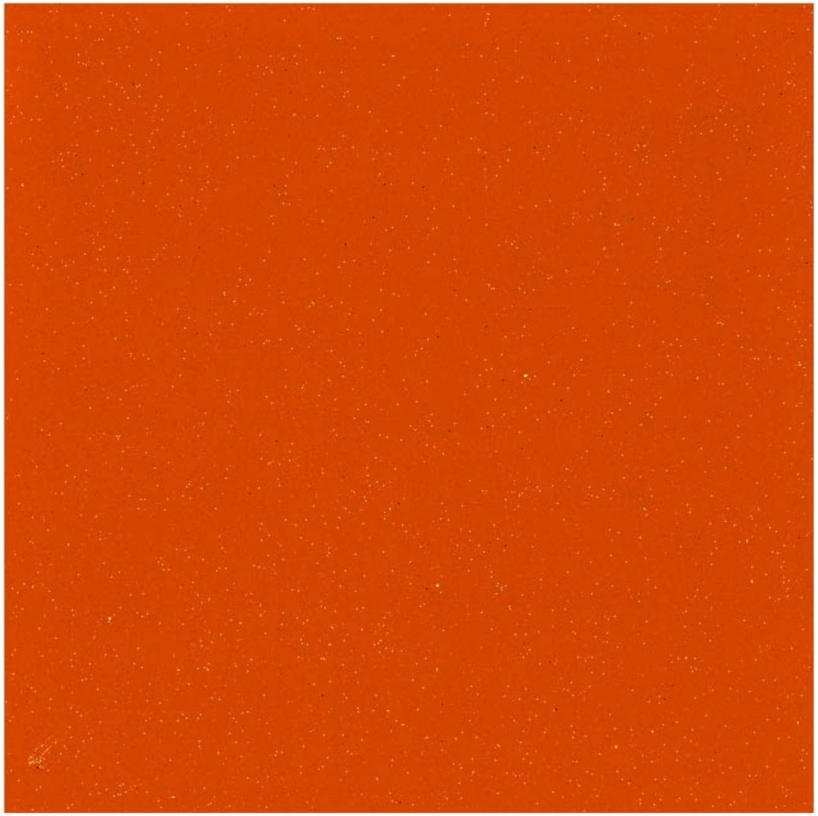
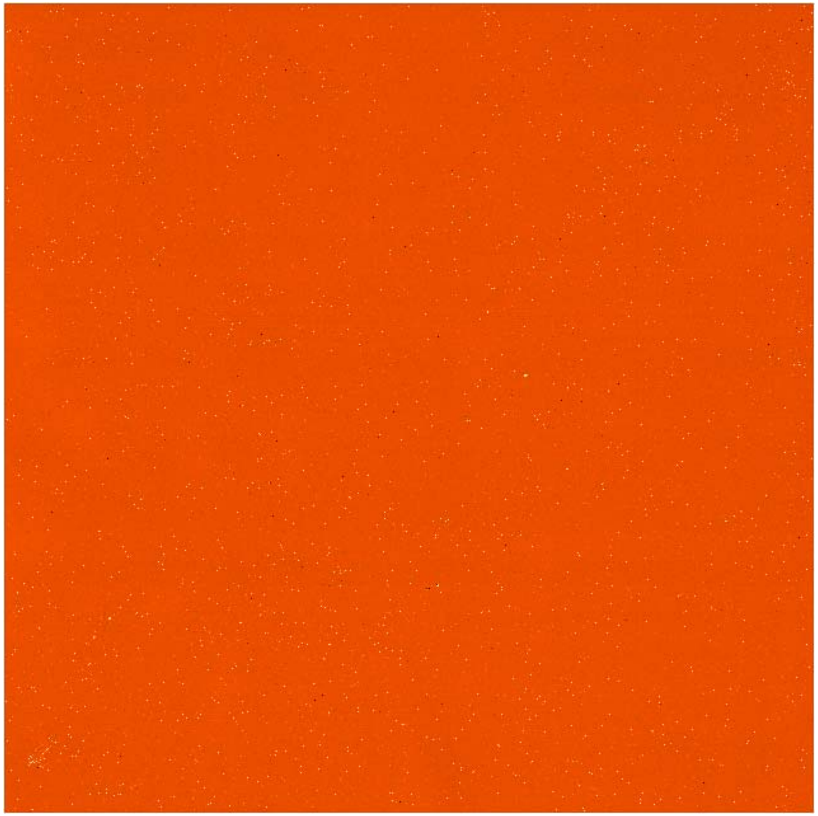
Fowler & up-the-ramp sampling



600s MCDS 16

Mean=1.77DN; Median =1.81DN;SDev=7.6DN



600s UTR 16

Mean 17.17DN; Median 17.17DN; SDev=6.45DN

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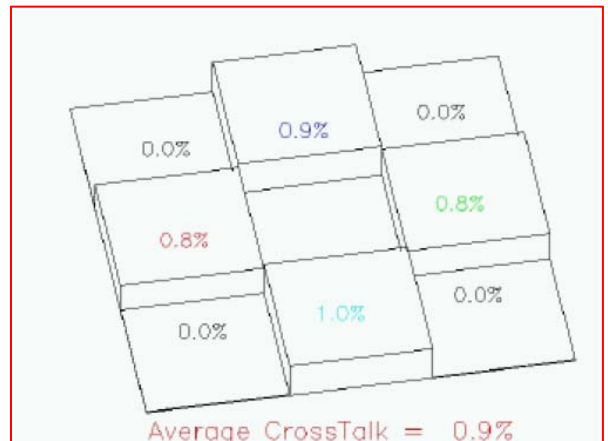
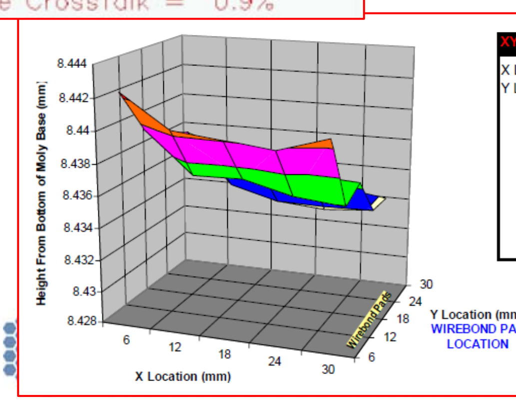
Detector properties

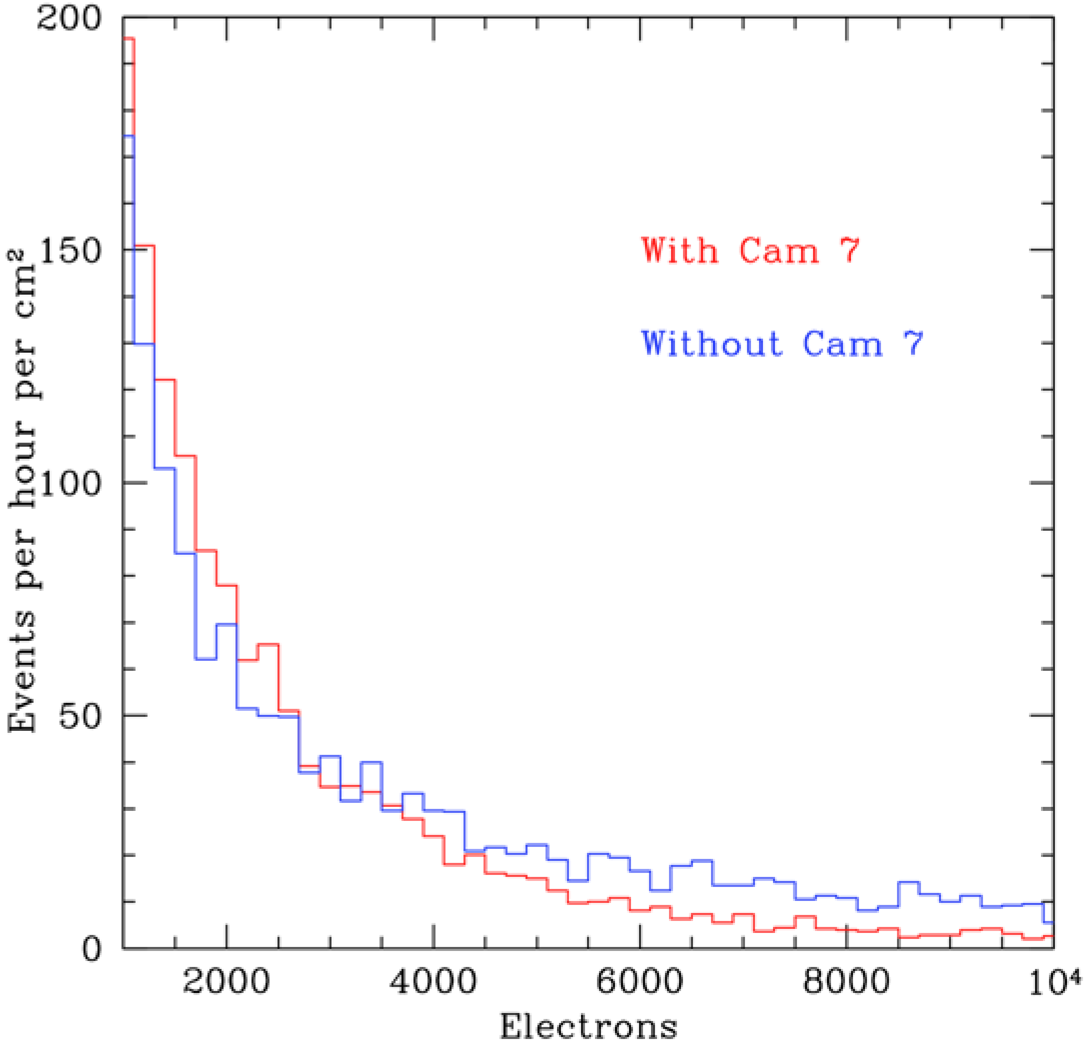
Parameter	*Goal*	*Min.*	*Max.*	*Actuals*	*Units*
Quantum Efficiency					
Y-band (0.97 to 1.1 μm)	≥ 80	60	-	**83**	%
J-band (1.10 to 1.40 μm)	≥ 80	60	-	**88**	%
H-band (1.46 to 1.8 μm)	≥ 80	65	-	**88**	%
K-band (1.9 to 2.45 μm)	≥ 80	65	-	**88**	%

DTGAINNM= 9 / Detector gain setting [0-15]
DTGAINDB= '15.05 db (low)' / Detector gain in dB
DETGAIN = 5.65685 / Detector gain factor
SYSGAIN = 2.15 / System gain in e-/ADU
VRESET = 0.3011 / Reset voltage in V, obtained from ASIC
DSUB = 0.6002 / Substrate voltage in V, obtained from ASIC
VBIASGAT= 2.0507 / Gate voltage of SCA in V, obtained from ASIC
VBIASPWR= 3.3 / Source voltage or SCA in V, obtained from ASIC
CELLDRAN= 0 / Celldrain (pix src follower) in V (from ASIC)
DRAIN = 0 / Drain (output buffer) in V, obtained from ASIC
VDDA = 3.2453 / Analog SCA supply voltage in V (from ASIC)
VDD = 3.2453 / Digital SCA power supply in V (from ASIC)
VREFMAIN= 1.001 / Ref voltage from bias block in V (from ASIC)
VPREMDRF= 1.0362 / Mid ADC ref volt from bias blk in V (from ASIC)
VPRAMRF1= 1.2512 / Ref volt 1 for internal preamp DAC in V (ASIC)
HXRGVERS= '2.3 ' / HxRG timing code version





Radioactive Optics?



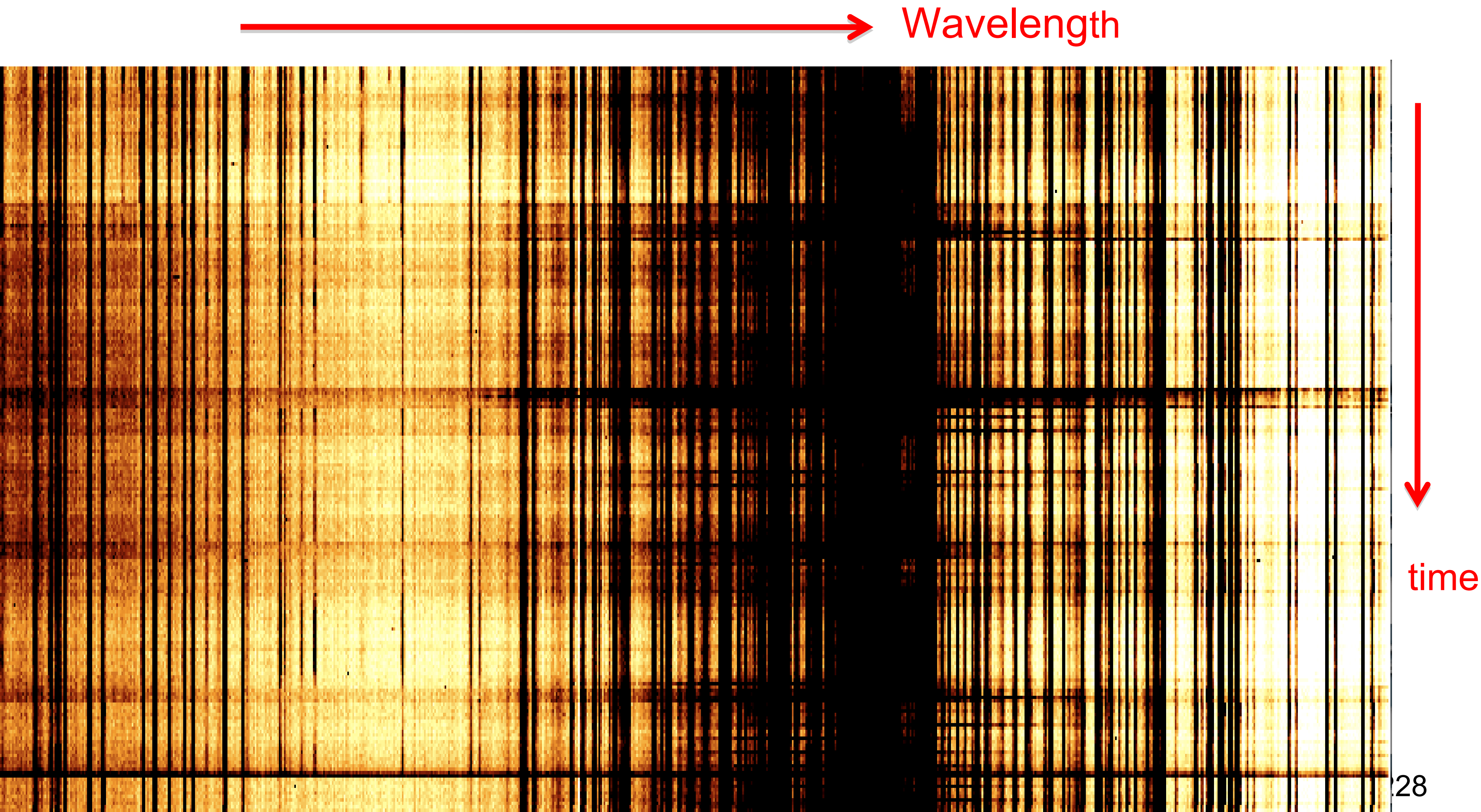
Brief scare when evidence of radioactivity of field flattener material (FTM16).

Comparison of frequency of radiation events showed at most a marginally significant difference between early detector tests w/o optics and later tests with Cam 7 in place.

For MOSFIRE at least, this is a non-problem.

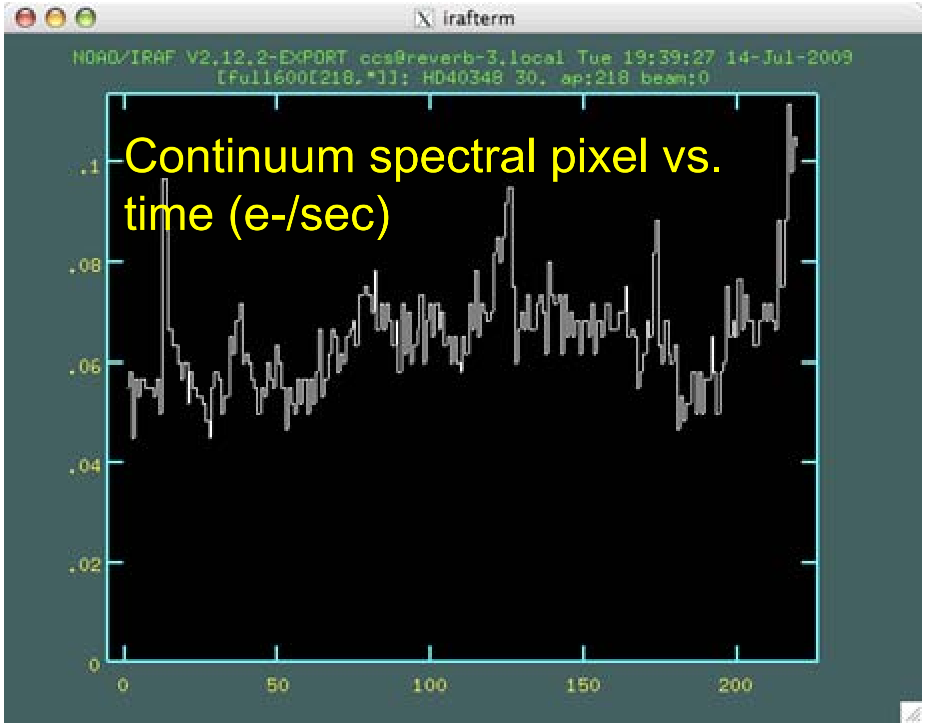
Sky Background Variation Tests

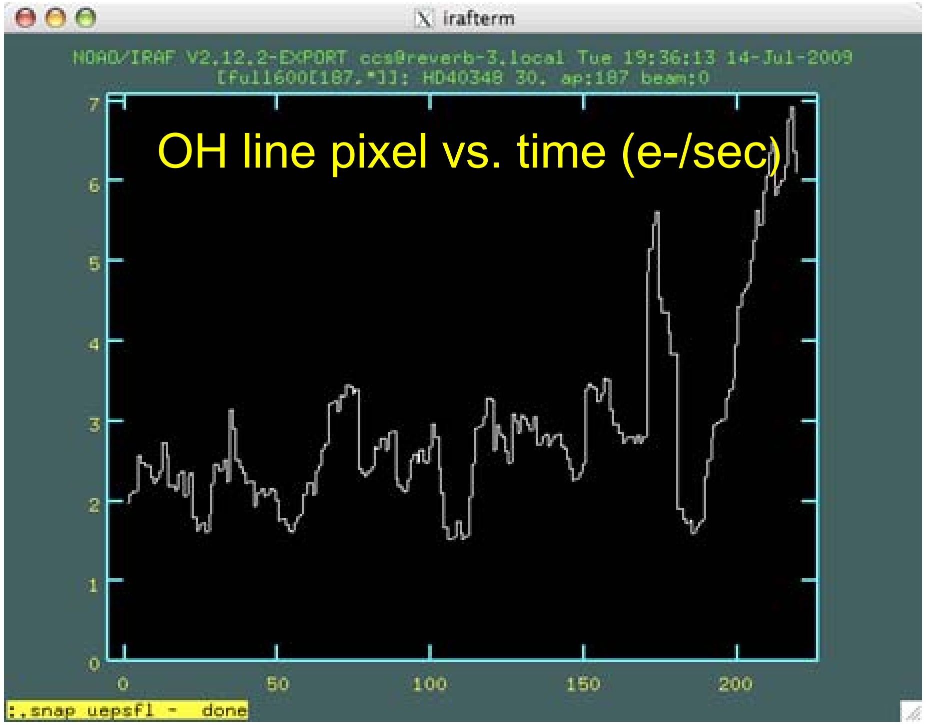
P200/Triplespec 220 x 600s (H-band shown) exposures over 5 nights in April 2009



Sky Background Variation Tests

(P200/Triplespec 220 x 600s exposures over 5 nights in April 2009)





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Background Subtraction Tests: "Interleaved" Short Exposure Sequences (Palomar, 4 Apr 09) (NPK, CCS)

"Interleaved" exposures, where red and black are combined as separate "stacks", each with 5 exposures.

1 2 3 4 5 6 7 8 9 10

Each exposure is 13s, read out w/Fowler x8. Telescope was moved slightly between two positions to mimic dither overhead (cadence ~30s between exposures)

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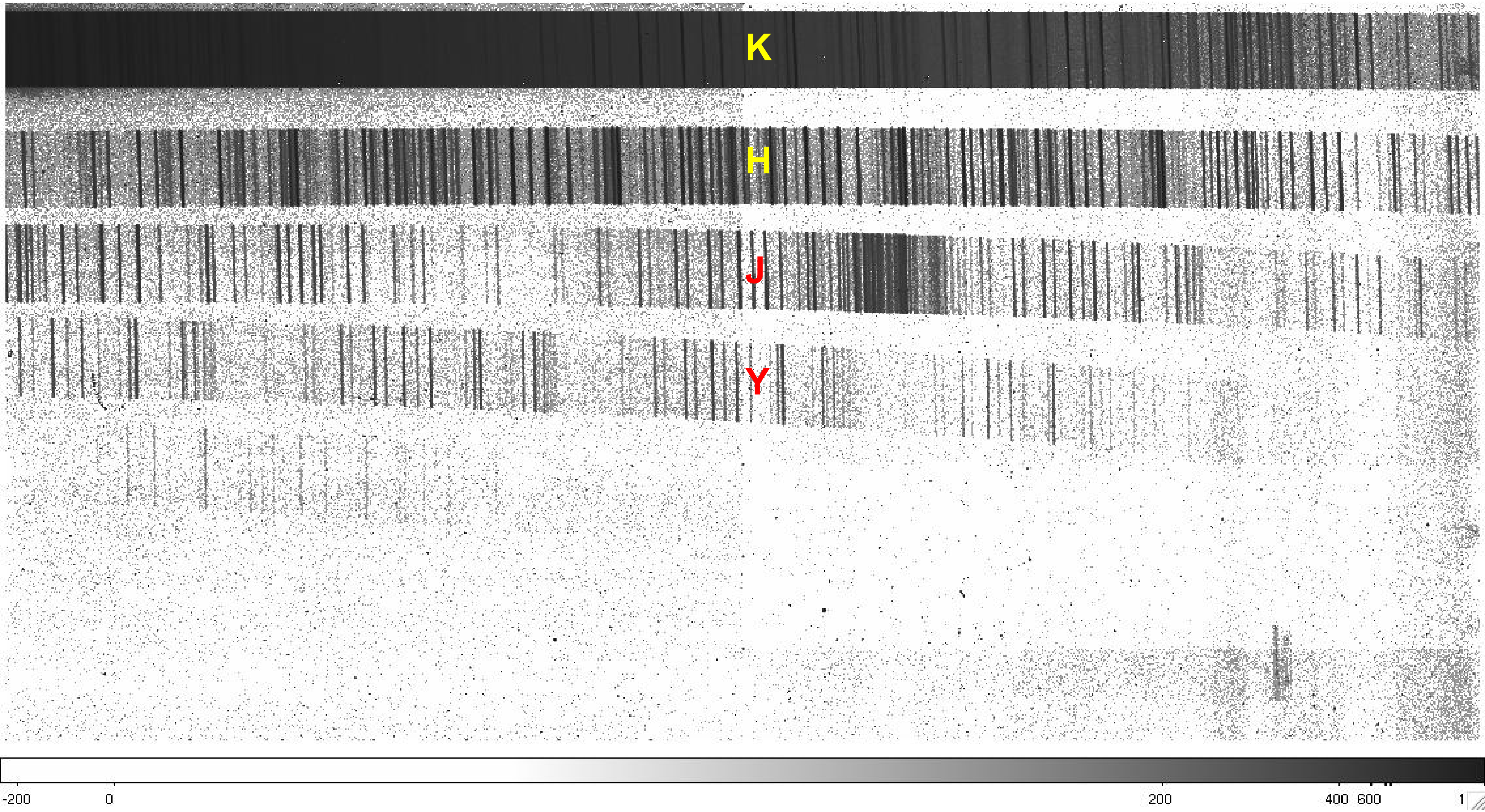
Palomar 200” TripleSpec, 5 April 2009, sum of 5x13s



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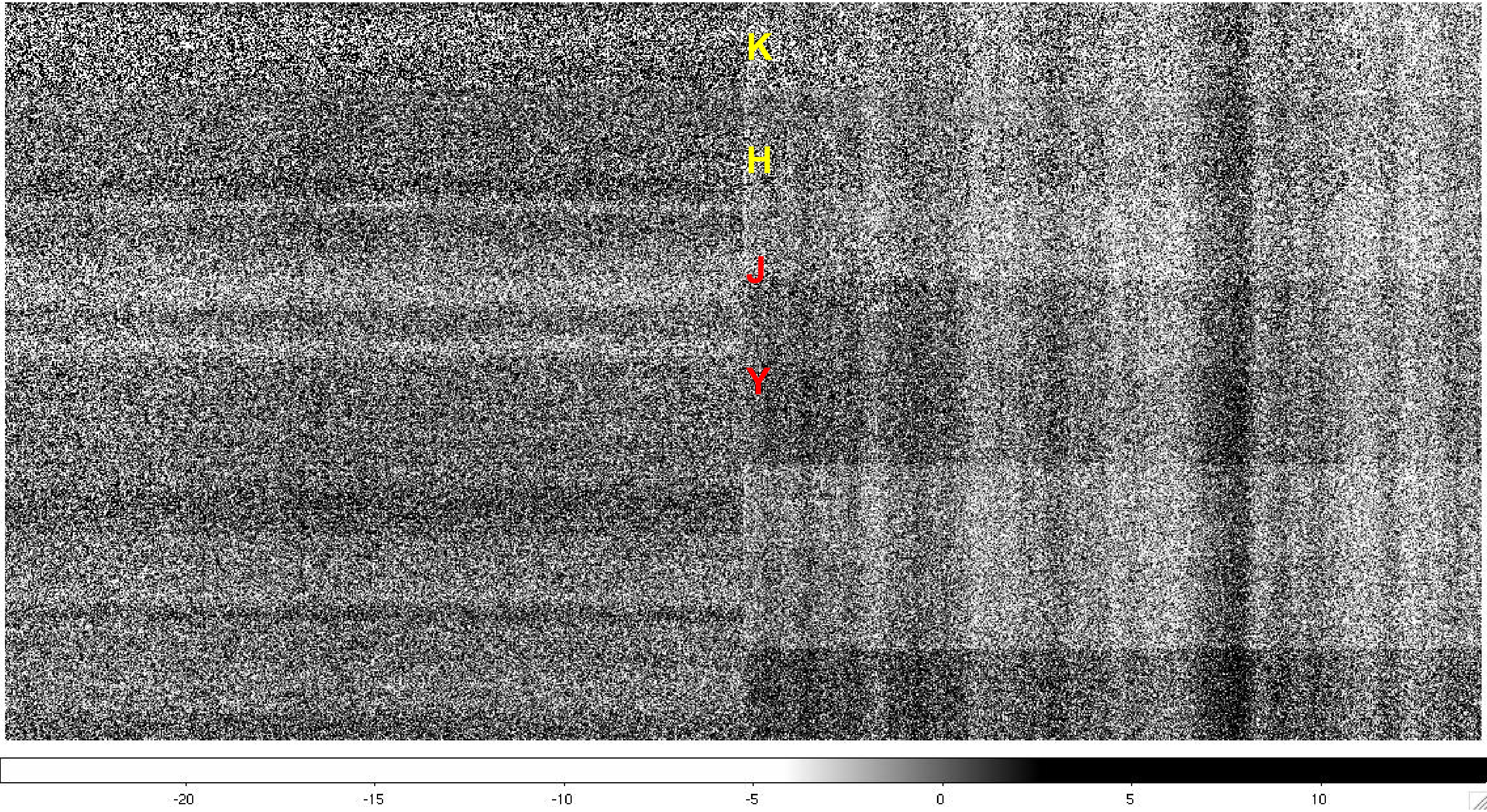
Palomar 200” TripleSpec, 5 April 09, difference of two sets of interleaved exposures, each 5x13s



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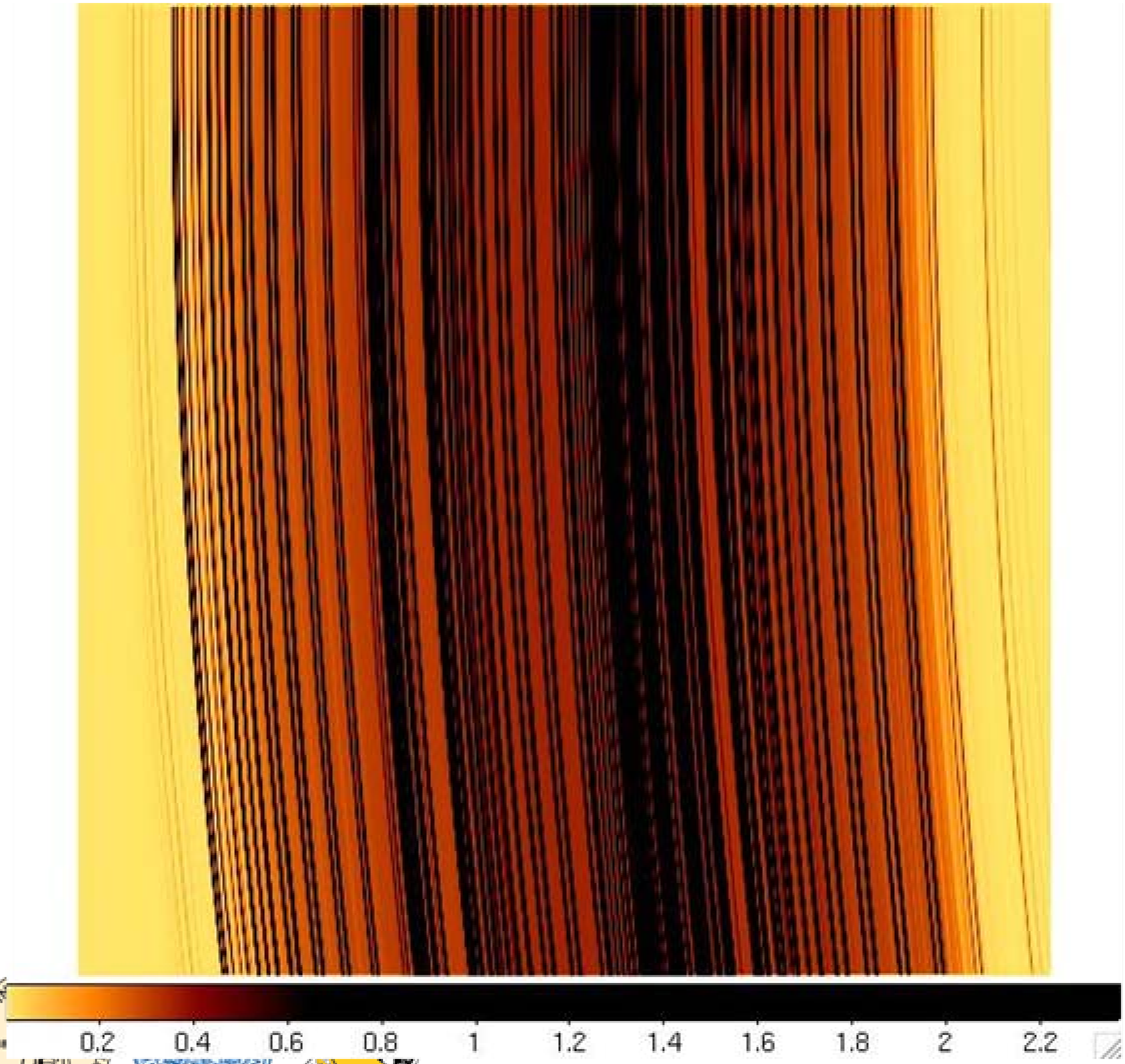
MOSFIRE Simulator



Example:

J-band super-long-slit spectral image (night sky spectrum)

CSU Failure Modes

- CSU failure modes is covered in CSEM documentation
- We have seen most failure modes which is why the CSU was refurbished!
- **Primary failures modes:**
  1. Bar fails to initialize but moves reliably: measure its current position with an image and apply required move manually
  2. Bar does not move and is stuck out of the field: no impact on imaging, move opposing bar across field for spectroscopy to close off
  3. Bar does not move and is stuck in the field; dither for imaging mode to recover occulted region, move opposing bar to close off slit in spectroscopy mode
  4. Bar moves but does not reach its commanded position reliably: tweak manually, or eliminate bar from mask set and close off that row