MODS

Instrument Manual

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Prepared by:	R.W. Pogge, The Ohio State University

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1 Introduction

1.1 Scope

This document describes the properties of the Multi-Object Double Spectrograph (MODS) and how to use it for observing on the Large Binocular Telescope. A companion manual gives the details of the MODS Observing Scripts that are the primary way to control MODS at the telescope. This early version of the manual specifically describes the MODS1 spectrograph that was delivered to the LBT in May 2010, and was commissioned between September 2010 and May 2011, going into early science operations during Semester 2011B. The MODS2 spectrograph is scheduled for delivery to LBT in autumn 2012 for a late 2012/early 2013 installation on the telescope.

The current manual describes monocular (single-MODS) properties and operations. Future versions of this manual will describe binocular MODS operation.

This document and the companion *MODS Observing Scripts* document together constitute the "user manual" for MODS.

1.2 Citing and Acknowledging MODS

The current literature citation describing the MODS instruments is

> Pogge, et al. 2010, SPIE, 7335, 9 [BibCode: 2010SPIE.7735E...9P]

All papers that use MODS data are required to cite the paper above and to include the following acknowledgement of the funding agencies that made these spectrographs possible:

> "This paper uses data taken with the MODS spectrographs built with funding from NSF grant AST-9987045 and the NSF Telescope System Instrumentation Program (TSIP), with additional funds from the Ohio Board of Regents and the Ohio State University Office of Research"

Please also send links (astro-ph, ADS, etc.) of papers using MODS data to Rick Pogge (pogge@astronomy.ohio-state.edu) so we can track the scientific use of MODS for ourselves and our funding agencies.

1.3 Online Materials

There is a large amount of supplementary online data and documentation for MODS. To avoid having many easily-broken web links scattered throughout this document, wherever we refer to the "MODS Webpage", the URL is

> www.astronomy.ohio-state.edu/MODS/

When in doubt or if there are discrepancies between this manual and the data on the MODS webpage, consider the webpage the most up-to-date and therefore definitive source.

The LBTO wiki has a section devoted to partner observing pages, including MODS:

> wiki.lbto.org/twiki/bin/view/PartnerObserving

with additional technical documents under the Instrumentation pages. All of these web pages are works in progress, so check them regularly for updates.

1.4 Acronyms and Abbreviations

ADC	Analog-to-Digital Converter (also Atmospheric Dispersion Corrector)
ADU	ADC units (aka “counts”)
AGw	Acquisition, Guide, and Wavefront sensing unit
AO	Adaptive Optics
AR	Anti-Reflection [coating]
CCD	Charge Coupled Device
DPOSS	Digitized Palomar Observatory Sky Survey
FITS	Flexible Image Transport System (image data format)
FoV	Field of View
FWHM	Full Width at Half Maximum
GCS	Guider and Collimation System (LBTO telescope subsystem)
GPS	Global Positioning System
GUI	Graphical User Interface
HA	Hour Angle
ID	Identification
IMCS	Image Motion Compensation System (MODS subsystem)
IMPv2	Instrument Messaging Protocol version 2
IR	Infrared
ISS	Instrument Support Structure (LBT focal station rotator component)
LBT	Large Binocular Telescope
LED	Light-Emitting Diode
LMS	LUCI Mask Simulator (slit mask design program)
LN_2	Liquid Nitrogen
LUCI	LBT Near-IR Imager/Spectrometer (aka LUCIFER)
MMS	MODS Mask Simulator (version of LMS for MODS)
MODS	Multi-Object Double Spectrograph
MOS	Multi-Object Spectroscopy
ND	Neutral Density
NIR	Near-Infrared, here 7000–10500Å, (aka “suboptical”)
NTP	Network Time Protocol
OSU	The Ohio State University
PA	Position Angle (measured North thru East in degrees)
PCS	Pointing Control System (LBTO telescope subsystem)
QE	Quantum Efficiency
QTH	Quartz Tungsten Halogen [lamp]
RMS	Root Mean Square
ROI	Region of Interest
SDSS	Sloan Digital Sky Survey
TCS	Telescope Control System
URIC	University Research Instrument Center, University of Arizona
UTC	Coordinated Universal Time
UV	Ultraviolet (specifically the terrestrial near-UV, ~3200-4000Å)
WFS	Wave Front Sensor

2 Instrument Characteristics

The Multi-Object Double Spectrographs (MODS) are seeing-limited low- to medium-dispersion spectrographs working in the 3200 to 10000Å range with a 6×6-arcminute field of view. MODS can be used for imaging, long-slit, and multi-object spectroscopy. Multi-object spectroscopy is accomplished with user-designed laser-machined slit masks loaded into a 24-position mask cassette. There are two identical MODS spectrographs: MODS1 is on the LBT and began science operations in September 2011; MODS2 will arrive during 2013. They are mounted at the direct Gregorian foci of the LBT as shown in Figure 1.

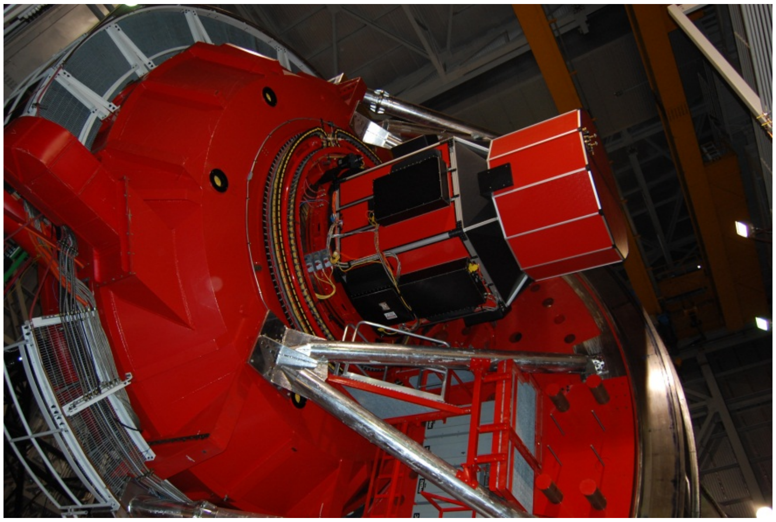


Figure 1: MODS1 on the LBT Left Direct Gregorian focal station.

After light passes through a common slit mask and field lens, a dichroic splits light into red- and blue-optimized spectrograph channels. Each channel has its own collimator, dispersers, camera, filters, field flattener (FF) lens, and detector (Figure 2). The beam selector can also direct light into the red or blue channels alone, extending wavelength coverage into the dichroic cross-over region (~5700Å) for one or other channel alone.

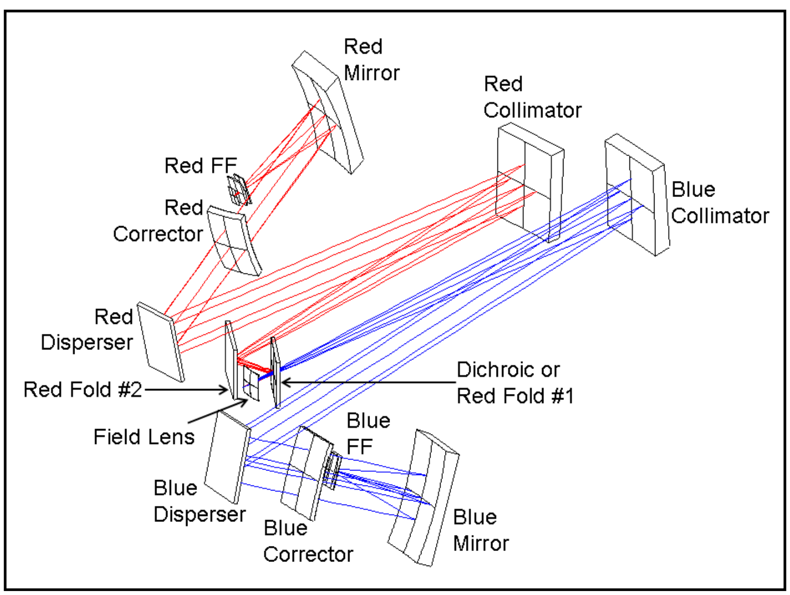


Figure 2: MODS Optical Layout

MODS was designed to deliver high throughput over a wavelength range of 3200 to 10000Å, moderate spectral resolution ($R=\lambda/\Delta\lambda\approx10^3$–$10^4$) with a 0.6″ wide slit, and imaging performance over a 4×4′ field without serious compromise of the LBT-delivered imaging performance (≤0.6″ in the original specification). At the behest of the LBT-appointed Optical Spectrograph Working Group, the available field of MODS was increased to a 6×6′ extended field with a penalty of reduced image quality outside the inner 4×4′. The primary contribution to reduced image quality outside a 5.6-arcminute diameter circle is astigmatism from the off-axis paraboloid collimator mirrors, plus any uncorrected field aberrations in the LBT f/15 direct Gregorian focal plane proper. In practical terms, the MODS "sweet spot" for imaging is the same FoV as LUCI.

The baseline configuration of MODS has large (420×320mm) reflection gratings for R≈2000 spectroscopy, and smaller (240×220mm) double-pass prisms with immersed reflection coatings for low (R=100-500) spectroscopy. A set of imaging flats rounds out the complement of dispersing optics. A fourth, unassigned disperser cell in each channel is reserved for a future large grating (e.g., for higher dispersion). The basic design of MODS should permit operation up to R≈8000 in a 0.6″ slit if such a grating can be manufactured.

Decentered fast (f/3) Maksutov-Schmidt cameras with spherical primary mirrors and aspheric corrector lenses are used to reform an image on the CCDs (Figure 3). These help provide the high throughput of MODS because there are no obscurations anywhere in the MODS beam below the slit plane. A field flattener lens doubles as the CCD dewar vacuum window. The filter wheel is located between the field flattener and the camera primary mirror.

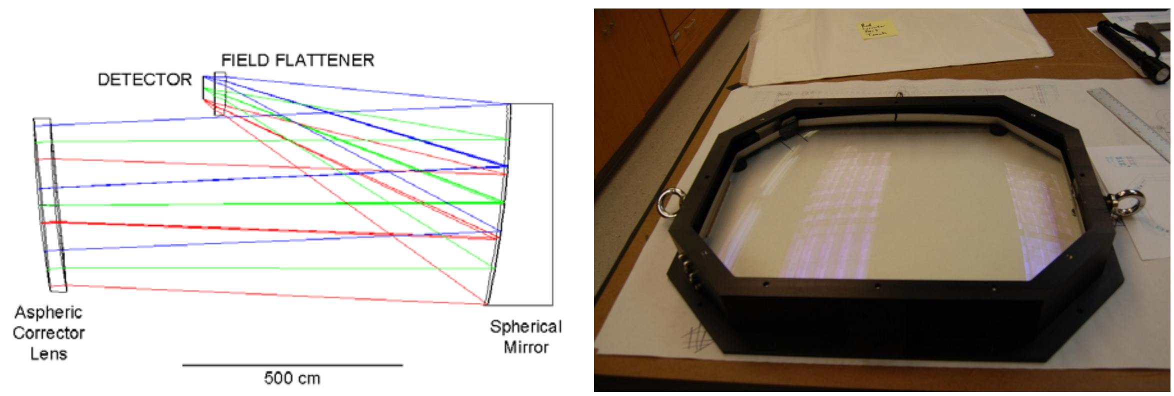


Figure 3: Left: Cross-sectional view of a MODS camera. **Right**: MODS1 red corrector lens.

The MODS science detectors are e2v CCD231-68 8K×3K monolithic CCDs with 15μm pixels. The blue CCDs are thin (16μm) backside illuminated standard silicon devices with a broadband AR coating providing excellent blue response. The red CCDs are 40μm thick deep-depletion silicon CCDs with a proprietary extended-red AR coating providing greatly improved sensitivity beyond 8000Å and much reduced fringing compared to thinned CCDs.

MODS does not have an Atmospheric Dispersion Corrector as this was prohibitively expensive to build for the full 6×6-arcmin FoV. We note that most other large-telescope optical spectrographs (GMOS, DEIMOS, ESI, and VMOS) also do not have atmospheric dispersion correctors. This means that observers wishing to work at the furthest blue wavelengths of MODS need to pay attention to effects of differential atmospheric refraction (see §3.4).

Each MODS has its own internal calibration system with an integrating sphere and pupil projector with a selection of Pen-Ray® wavelength calibration lamps and continuum lamps for spectral and imaging flat fields.

MODS has its own integrated Acquisition/Guide and Wavefront Sensor (AGw) Unit that carries the standard LBTO off-axis guide/acquire and slow (Shack-Hartmann) wavefront sensor (WFS) cameras. These are the same guide and WFS cameras as used by the AIP AGw units on other LBT focal stations, and uses the same LBTO Guide/Collimation System (GCS) software. Because the system resides inside the MODS common focal plane area, it has a different and smaller guide patrol field than LUCI.

The stability of MODS is ensured by an internal closed-loop Image Motion Compensation System (IMCS) that monitors the alignment of the optics in each channel in real time during exposures. An IR laser beam (λ=1.55μm) is launched from below the focal plane and passes through the same optics as the science light onto a Germanium quad cell mounted off-axis just above each channel's science CCD. Error signals from the quad cells are used to steer the collimator mirrors in each channel to null image motion due to gravity-induced flexure of the structure, stochastic "ticks and pops" in the structure, and any other sources of optical misalignment that occur along the beam path from the focal plane to the detectors.

Basic Parameters:

Optical Design: Seeing-limited, dichroic-split double-beam grating spectrometer
Wavelength Coverage: 3200 – 10000Å
Field of View: 6×6-arcminutes (~2900×2900 pixels)
Pixel Scales:
- **Blue**: 0.120 arcsec/pixel
- **Red**: 0.123 arcsec/pixel

Operating Modes:
- **Direct Imaging**: SDSS ugriz filters (ug in Blue, riz in Red)
- **Medium-Dispersion Grating Spectroscopy**: R≈2000 (0.6-arcsec slit)
- **Low-Dispersion Prism Spectroscopy**: R=500 – 150

Slits: Laser-cut spherical slit masks (up to 24 per MODS: 9 fixed + 15 user)
Calibration: Internal pseudo-pupil projector and integrating sphere
Pen-Ray® wavelength calibration lamps (Hg, Ne, Ar, Xe, Kr)
Quartz-Halogen and variable-intensity incandescent continuum lamps
CCD Detectors: e2v CCD231-68 3072×8192, 15μm Pixels
Flexure Compensation: Real-time closed-loop IR laser metrology system sending collimator-mirror tip/tilt corrections during exposures.
Acquisition & Guiding: 50×50-arcsec FoV CCD camera, 4 filters
Active Optics: Off-axis Shack-Hartman wavefront sensor
Dichroic: Blue-transmit/Red-reflect design, ~5700Å cross-over wavelength.
Collimators: 3450mm focal length, off-axis paraboloids. Red: Ag, Blue: Al
Cameras: f/3 decentered Maksutov-Schmidt. Red: BK7, Blue: Fused Silica
Minimum Exposure Time: 1 second
Dimensions: ~4.0×2.5 meters
Mass: 3079kg

2.1 Instrument Configurations

There are three basic operating modes: imaging, grating spectroscopy, and prism spectroscopy, summarized in Table 1. Within in each mode, MODS may be configured for dual-channel (red+blue), blue-only, and red-only operation. The instrument configuration also sets the basic CCD sub-frame region-of-interest (ROI) readout for that mode.

Table 1: MODS Instrument Configurations

Mode[1]	Channel	Filter(s)[2]	Resolution[3] (0.6″ Slit)	Wavelengths (Å)	CCD Readout[4]
Direct Imaging	Dual	B: SDSS ug R: SDSS riz	n/a	3300-10000	3088×3088
	Blue	SDSS ug	n/a	3300-6000	
	Red	SDSS riz	n/a	5000-10000	
Grating Spectrocopy[5]	Dual	B: Clear R: Clear	B: 1850 R: 2300	3200-10000	8288×3088
	Blue	Clear	1850	3200-6000	
	Red	GG495[6]	2300	5000-1000	
Prism Spectroscopy	Dual	B: Clear R: Clear	B: 420-140 R: 500-200	3200-10000	4096×3088
	Blue	Clear	420-140	3200-6000	
	Red	GG495[6]	500-200	5000-10000	

Notes:

1. Instrument configurations are requested in MODS observing scripts by specifying the channel configuration and mode name. For example, "`instconfig dual grating`" or "`instconfig red imaging`".
2. See §2.3.1 for detailed properties of the current MODS filter set.
3. See §2.5 for the detailed properties of the current complement of gratings and prisms.
4. The CCD readout region is the default size for the mode. For imaging it includes the full FoV plus imaging stop, and for the spectroscopy modes it is sized for the blue and red extremes when used with MOS masks with slits extending to the outer edges of the mask. See §2.6 for detailed properties of the CCDs.
5. The gratings are tilted to give the optimal wavelength coverage for the full spectral range of MODS. There are no immediate plans to offer other grating tilts.
6. The GG495 filter is a long-pass filter that cuts on at 4950Å, and is used to block 2nd order light from the red grating. In dual mode, the dichroic blue cutoff acts as an effective order separation filter, and so we use the Clear filter in dual-grating mode. In dual prism mode, the smaller dispersion (larger number of Angstroms per pixel) means the small blue leak is unacceptably large, especially for flat-field and comparison lamp observations, so we mandate doubling up the blocking by using the GG495 filter with the dichroic in that mode.

2.2 Instrumental Throughput

2.2.1 Imaging Throughput

Estimates of the imaging sensitivity of MODS are based on measurements of secondary photometric standard stars in the SDSS AB magnitude system. The estimated total source counts S_X in ADU for a source of brightness m_X in the SDSS X-band (X={u,g,r,i,z}) filter in AB magnitude for exposure time t_{exp} is

$$\log S_X = \log S_{X,0} - 0.4 m_X + \log t_{\exp}$$

where $S_{x,0}$, is the zero-point in ADU for $m_X=0^{mag}$. This zero point includes the combined telescope and instrumental throughput for a source observed at 1.2 airmasses. The photometric zero points for the five MODS imaging filters (see §2.3.1) are listed in Table 2.

Table 2: Imaging Zero Points

Channel	Filter	log $S_{X,0}$
Blue	SDSS u	10.25
	SDSS g	10.95
Red	SDSS r	10.90
	SDSS g	10.91
	SDSS i	10.57

As general guidance, an r=15^{mag} star will just begin saturating the central pixels on the Red CCD after 30 seconds of integration in 0.6-arcsec seeing.

2.2.2 Grating Mode Spectral Throughput

The total efficiency (instrument and telescope) of MODS in grating mode is shown in Figure 4, normalized to the efficiency at 1.2 airmasses (elevation 60°).

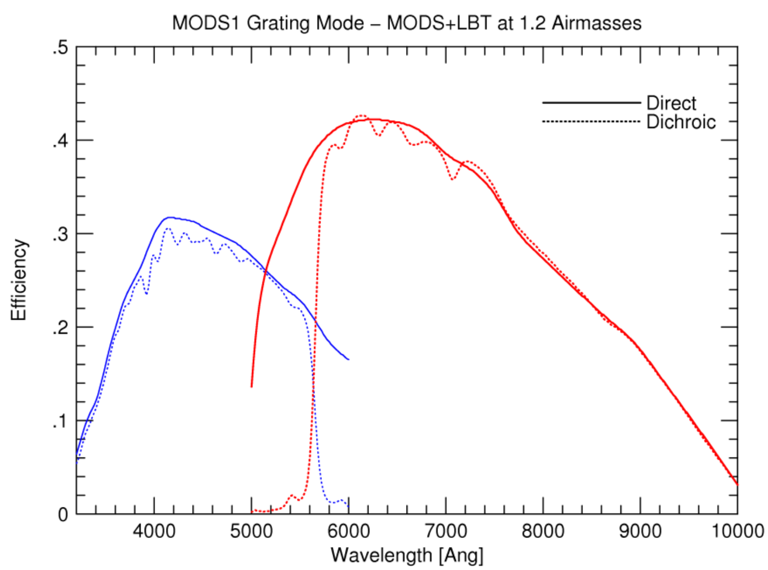


Figure 4: MODS1 Grating mode efficiencies. Solid lines are direct mode (blue- or red-only), dashed lines are dichroic (dual) mode. Efficiency includes instrument, telescope, and atmosphere at 1.2 airmasses.

These values depend on the cleanliness of the primary and secondary mirrors. The sharp cutoff around 5600Å in the dichroic mode curves is the dichroic cross-over wavelength (§2.4). The blue downturn in the red direct mode efficiency curves it the cut-off in the GG495 order blocking filter (§2.3.1).

2.2.3 Prism Mode Spectral Throughput

The total efficiency (instrument and telescope) of MODS in double-pass prism mode is shown in Figure 5, normalized to efficiency at 1.2 airmasses (elevation 60°). The efficiency curves do not include strong telluric absorption features. The wavelength coverage was artificially cutoff at 5000Å for the red, and 6000Å for the blue channel, but coverage does extend beyond those wavelengths, if at somewhat degrading efficiency. Unlike the red grating, the red prism does not require an order-blocking filter.

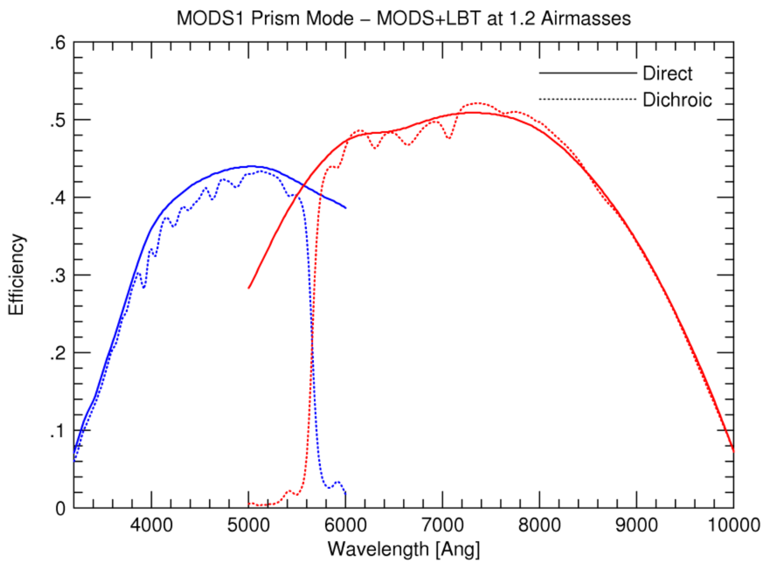


Figure 5: MODS1 Prism mode efficiencies. Solid lines are direct mode (blue- or red-only), dashed lines are dichroic (dual) mode. Efficiency includes instrument, telescope, and atmosphere at 1.2 airmasses.

The spectral efficiencies depicted in Figure 5 are linearized, following the usual reduction procedures for flux standard stars. Because the prism resolution is a strongly decreasing function of wavelength (see §2.5, Figure 12), the size of a raw spectral pixel in wavelength is larger at longer wavelengths, so the actual flux per raw spectral pixel will be larger. This is difficult to represent on plots like those shown in Figure 5, unlike the case of the grating efficiency curves.

2.3 Filters

2.3.1 Science Camera Filters

Science filters are mounted in 8-position filter wheels in the f/3 beams of the blue- and red-channel cameras. The filter is located between the camera primary mirror and field flattener lens that doubles as the CCD Dewar entrance window. Filter change times are 2 to 8sec.

The properties of the current MODS filter complement and a description of their intended use is given in Table 3, with transmission curves in Figure 6 and Figure 7. Imaging filter effective instrumental band-pass parameters are summarized in Table 4. A description of the derivation of the filter parameters is given in Appendix B.

Table 3: MODS Filters

Channel	FilterID[1]	Description	Typical/Recommended Use
Blue Camera	Clear	AR coated Fused Silica	Dual- and single-channel Spectroscopy[2]
	u_sdss	SDSS u filter	Direct Imaging
	g_sdss	SDSS g filter	Direct Imaging
	UG5	UG5 + Fused Silica	Red blocker for UV spectral flats
	ND1.5	Neutral Density 1.5	Spectral flats and comparison lamps
Red Camera	Clear	AR coated BK7	Dual-channel Spectroscopy[2]
	r_sdss	SDSS r filter	Direct Imaging
	i_sdss	SDSS i filter	Direct Imaging
	z_sdss	SDSS z filter	Direct Imaging
	GG495	Schott GG495	2nd order blocking filter[3]
	ND1.5	Neutral Density 1.5	Spectral flats and comparison lamps

Notes:

1. The FilterID is the name used to select the filter in the MODS instrument control system. For example, “"`red filter r_sdss`" or "`blue filter nd1.5`". Note that all FilterIDs are case-insensitive and have no spaces. The filter ID is stored in the `FILTNAME` keyword in the image FITS headers, along with a `FILTINFO` keyword that includes additional information (e.g., full name, manufacturer, etc.).
2. The Clear filters in each channel are designed to ensure proper camera focus balancing between unfiltered and filtered configurations. The cameras cannot be used without a filter in the beam without substantial refocusing.
3. The GG495 order blocker filter in the red channel is used primarily when configured for red-only mode. In dual-grating mode, the dichroic blue cutoff provides sufficient 2nd order blocking. There is a small blue leak in the dichroic red side that is more of an issue with the dual Prism mode, which is why we mandate using the GG495 and the dichroic together in dual Prism mode, but the Clear filter and dichroic for dual Grating mode.

Imaging filters are 86×86mm square format and may be up to 8mm thick. Spectroscopic filters are 128×86mm rectangular format (up to 8mm thick). The imaging filters were made as a set with the same optical thickness and require essentially no refocusing when changed.

There are currently no plans to support the installation of custom user filters during the initial phases of MODS1 and MODS2 deployment. Custom filters, especially medium- and narrow-band interference filters, must be designed to take into account use in a relatively fast f/3.0 beam and the thickness restrictions imposed by the filter wheel. The OSU instrument team will consider collaborations to design new filters especially for MODS.

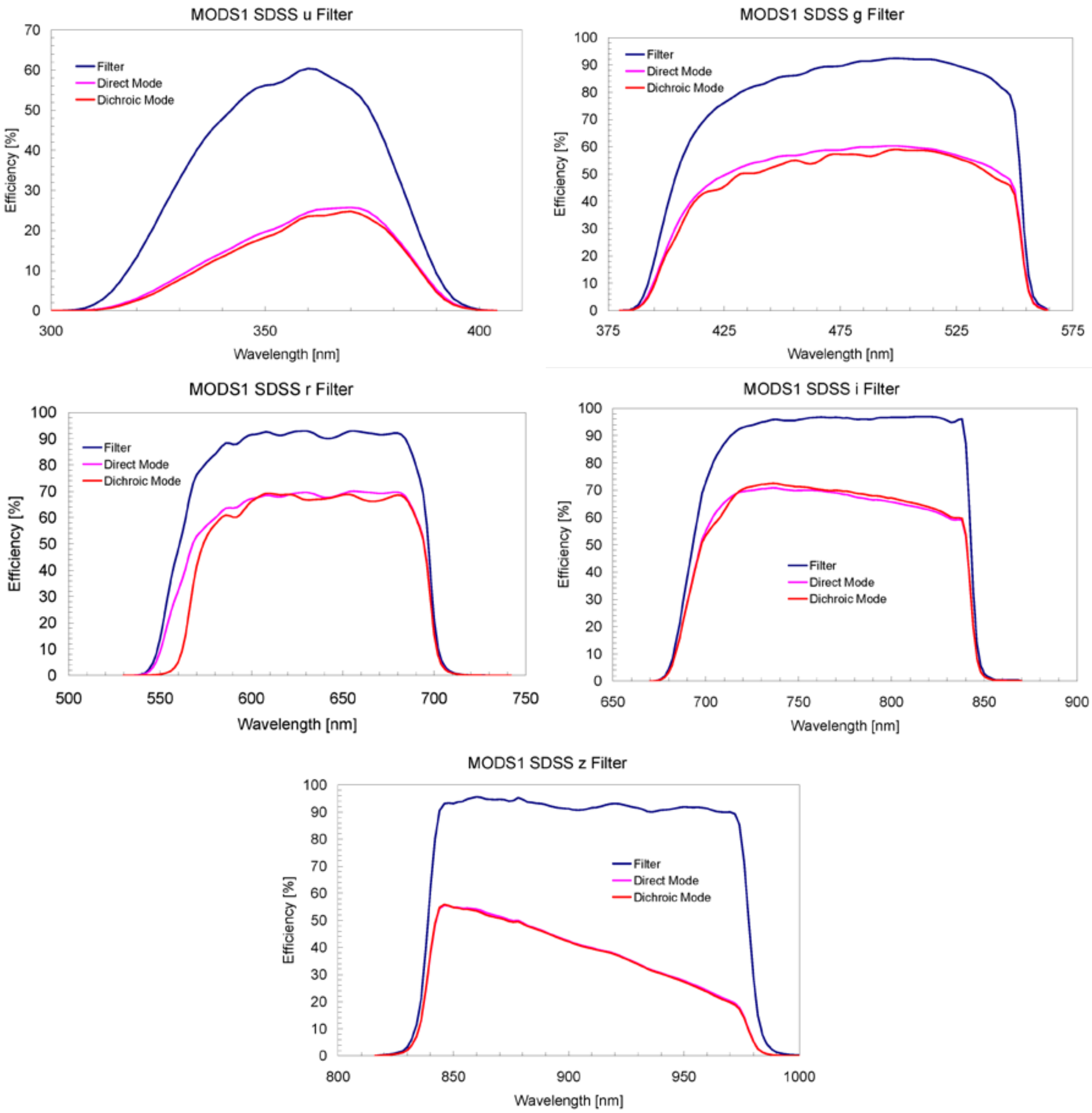


Figure 6: MODS1 Imaging Filters. Blue shows the filter-only transmission in parallel light, magenta the effective filter band including instrumental response with no dichroic (direct), and red with the dichroic.

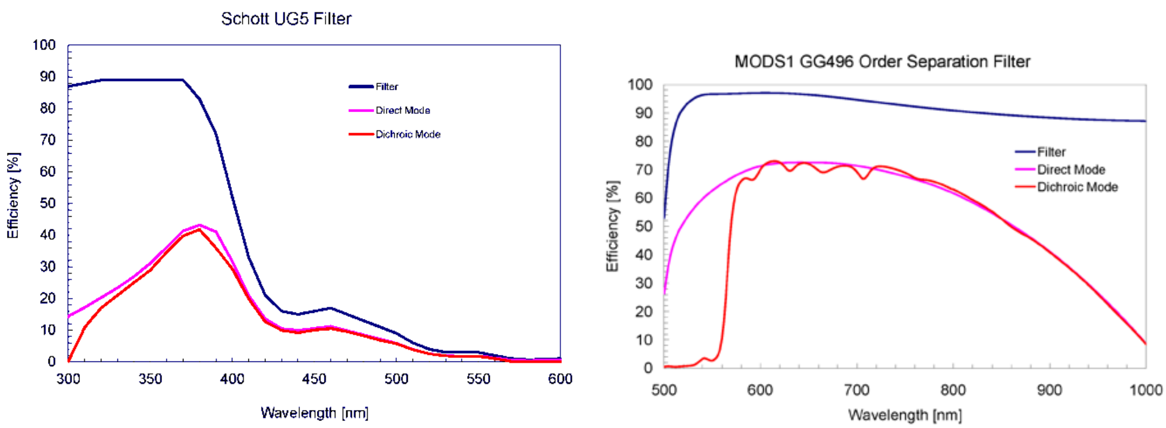


Figure 7: MODS1 blocking filters. **Left**: UG5 red blocker, **Right**: GG495 red 2nd order blocker.

Table 4: MODS Imaging Filter Parameters

Filter	Mode	Pivot Wavelength λ_P (Å)	Effective Width $\delta\lambda$ (Å)	Mean Wavelength $\bar{\lambda}$ (Å)	FWHM (Å)
SDSS u	Direct	3589.4	415.4	3580.8	480
	Dichroic	3592.9	408.8	3584.5	470
SDSS g	Direct	4767.4	1010.3	4728.7	1480
	Dichroic	4773.8	1017.3	4735.3	1460
SDSS r	Direct	6283.3	940.9	6257.8	1350
	Dichroic	6323.4	878.7	6301.3	1270
SDSS i	Direct	7646.5	1018.5	7522.0	1500
	Dichroic	7651.0	1014.4	7626.6	1500
SDSS z	Direct	8954.9	892.1	8938.7	1120
	Dichroic	8952.9	890.8	8936.7	1100

2.3.2 AGw Guide Camera Filters

The AGw unit has a 4-position filter in the guide channel (the WFS channel is unfiltered). The filter parameters are listed in Table 5, with transmission curves shown in Figure 8.

Table 5: AGw Guide Camera Filter Parameters

Filter ID	Description	λ_P (Å)	$\delta\lambda$ (Å)	$\bar{\lambda}$ (Å)	Typical/Recommended Use
Clear	Clear Fused Silica	6210	3670	5790	Default acquisition & guiding
F525LP	Red long-pass	6930	3210	6660	Moon suppression & red guiding
B_Bessel	Bessel B Filter	4310	686	4290	Deep blue guiding
ND1.0	Neutral Density 1.0	6210	3670	5790	Bright target acquisition

The filter parameters are derived from the laboratory-measured transmission curves multiplied by the measured AGw guide camera CCD quantum efficiency curves. The pivot wavelength (λ_P) is the effective wavelength of guiding for purposes of estimating the effects of differential atmospheric refraction (see Appendix B for a definition of λ_P).

The Clear filter is the default guiding filter, recommended for all dual-channel and routine observations. The effective guide wavelength is good for most applications.

For unusually blue targets in the blue-only modes (red channel idle), the B_Bessel filter may be used, but you take a 1 to 1.5 magnitude penalty for guiding at B. The F525LP filter can be used to guide in cases of unusually red sources where it is not possible to orient along the mean parallactic angle, and it can also help a little in bright moonlight.

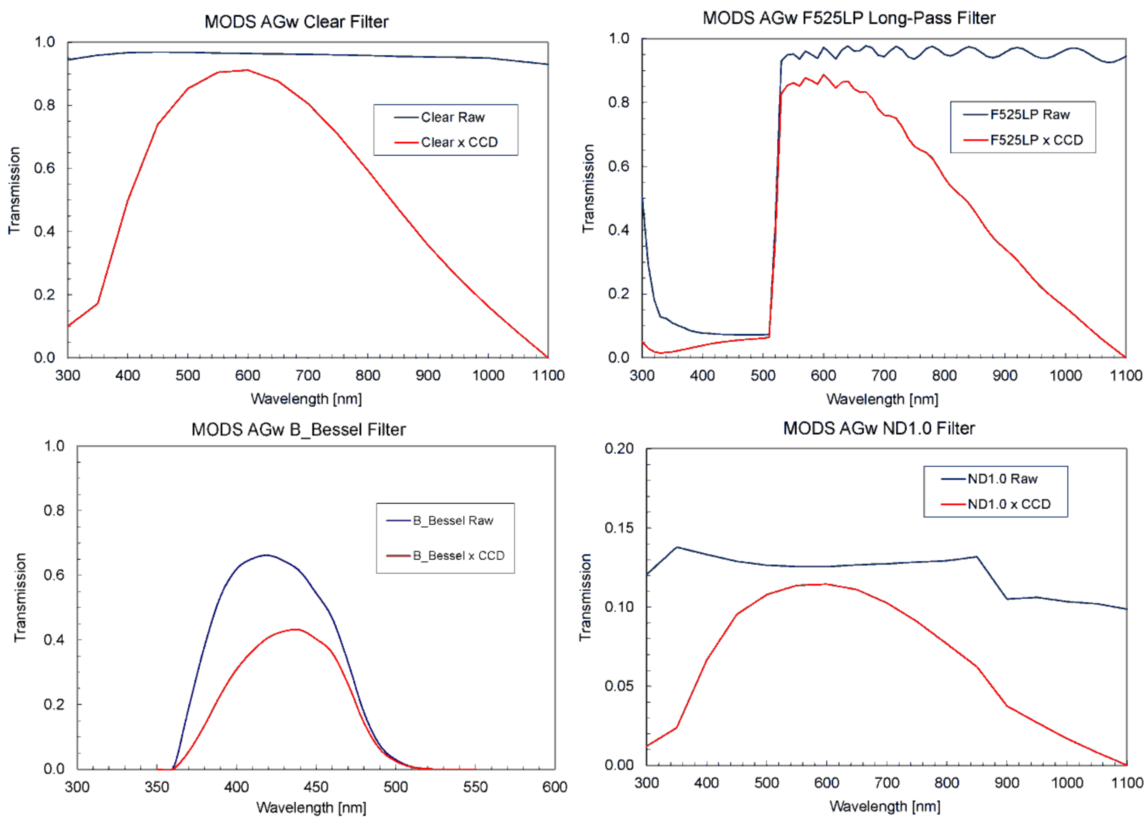


Figure 8: MODS1 AGw Camera Filters

2.4 Dichroic

The MODS dichroic is located below the slit mask and field lens, and is the last element of the common focal-plane optics. The dichroic passes blue light and reflects red light with the 50% cross-over wavelength at 5650Å. The dichroic efficiency curves for the blue (transmission) and red (reflection) channels are shown in Figure 9.

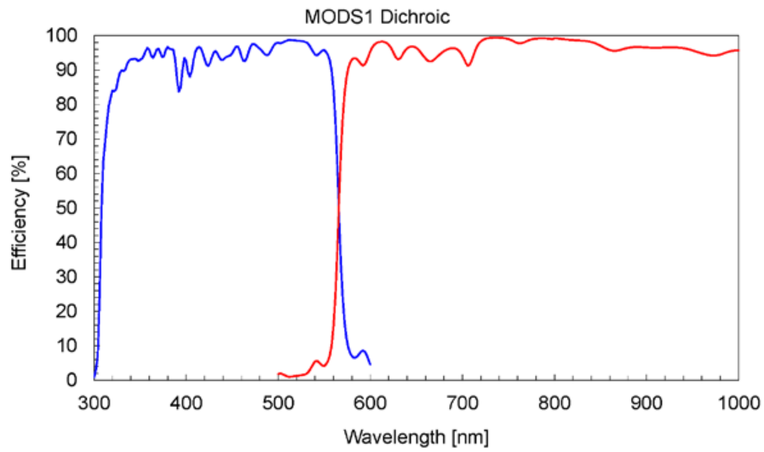


Figure 9: MODS1 Dichroic Transmission Curves

The wiggles in efficiency are real and a source of additional complication for flux calibrating MODS using flux standard stars.

2.5 Gratings and Prisms

Each channel has a grating turret containing an imaging flat mirror and up to 3 dispersers. The current complement of flats and dispersers is listed in Table 6, and their detailed properties are given in Table 7. At present there are 2 dispersers per channel with space for a future third disperser in each channel.

Table 6: MODS Imaging Flats and Dispersers

Channel	Grating ID[1]	Description	Resolution[2] (0.6″ Slit)
Blue	Flat	Imaging Flat with enhanced Al	n/a
	G400L	400 line/mm Reflection Grating	1850
	P450L	FuSi+Al Double-Pass Prism	420-140[3]
Red	Flat	Imaging Flat with Protected Ag	n/a
	G670L	250 line/mm Reflection Grating	2300
	P700L	TIH6+Ag Double-Pass Prism	500-200[3]

Notes:

1. The Grating ID is stored as `GRATNAME` in image FITS headers, along with a `GRATINFO` keyword that includes additional information (e.g., full name, manufacturer, etc.).
2. Grating resolutions quoted are measured at the reference wavelength (4000Å for Blue, 7600Å for Red) in a 0.6″ reference slit (extended-source resolution). Prism resolutions are quoted for the full range of wavelengths, blue to red
3. Prisms have variable dispersion that decreases from blue to red (see Figure 12).

Table 7: MODS1 Disperser Properties

Type	ID[1]	Lines mm^{-1}	Blaze Angle	Order	Nominal Range (Å)[2]	Linear Dispersion[3]	Spectral Pixels
Grating	G670L	250	4.3°	1	5800-10000	0.8Å/pix	5700
	G400L	400	4.4°	1	3200-5800	0.5Å/pix	5200
Prism	P700L	n/a	n/a	n/a	5800-10000	5 Å/pix	650
	P450L	n/a	n/a	n/a	3200-5800	5 Å/pix	650

Notes:

1. Disperser ID coding: G=Grating, P=Prism, ###= blaze wavelength in nm, L=Low-dispersion, M=Medium-dispersion.
2. Nominal wavelength range for dual-mode operation with the dichroic.
3. Nominal linear dispersion at the nominal central wavelength of the spectrum.

2.5.1 Reflection Gratings

MODS currently has a set of red and blue gratings giving R≈2000 (λ/δλ) in first order with a 0.6″ slit. Space is reserved in the grating turret for a future set of higher resolution gratings (up to R≈8000 with a 0.6″ slit).

The grating blaze curves (measured in Littrow configuration by Richardson Grating Lab) are shown in Figure 10 for the useful wavelength ranges in MODS. The gratings are tilted to give the optimal wavelength coverage for the full spectral range of MODS. At present we do not plan on providing alternative tilt angles.

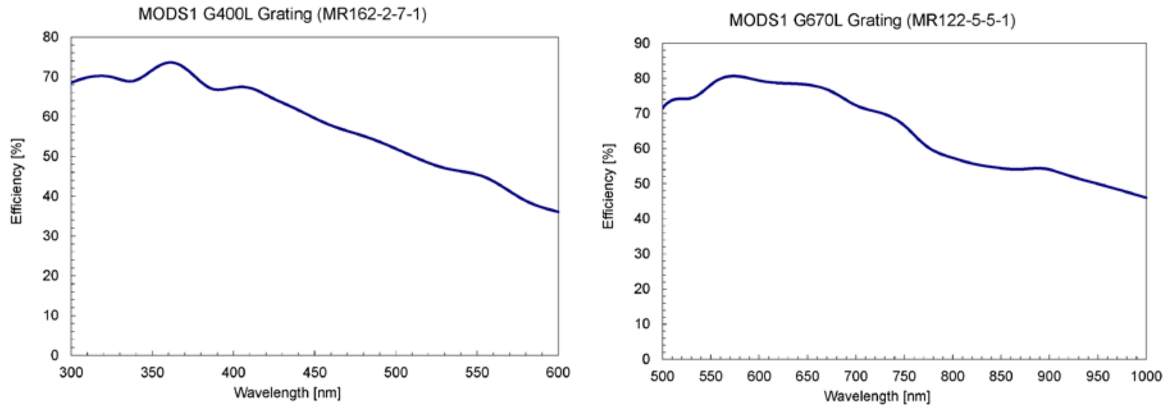


Figure 10: MODS1 Grating Blaze Functions (Left: G400L, Right: G670L)

When used in red-only mode, the red G670L grating must be used with a GG495 filter in the red camera to block light from 2nd order from contaminating the 1st order spectra. In dual-channel mode, the dichroic acts as an order blocking filter and the clear filter is used in the red camera. While this is sufficient for grating mode spectroscopy, when the prism disperser is used in dual mode, the larger spectral pixels (more Angstroms per pixel) means that the effect of the blue leak per pixel is greater, and we therefore use the GG495 filter with the dichroic to provide additional blue suppression in dual Prism mode.

2.5.2 Double-Pass Prisms

MODS has two double-pass prisms with immersed reflection coatings to provide a very low resolution (R=100-500) mode. The blue prism is made of Fused Silica glass with an immersed aluminum coating, the red prism is made of TIH6 glass with an immersed silver coating. The MODS1 red prism and the double-pass ray tracing is shown in Figure 11.

Unlike gratings, prisms have a very strong wavelength-dependent resolution. The measured resolution curves for the MODS1 prisms are shown in Figure 12. The dispersion in the prisms varies as a low-order polynomial in wavelength, higher at bluer wavelengths, lower at redder wavelengths. The nominal prism parameters listed in Table 7 were measured at the mid-point of the spectral ranges.

Also unlike the gratings, the prisms do not require order blocking filters, but future band-limiting filters for special experiments may be installed in the instrument. Because prism spectra map onto a small number of pixels in dispersion (~600 vs. ~5000 pixels for the gratings), it is in principle possible to horizontally stack slits on the multislit masks to increase the number of objects observed.

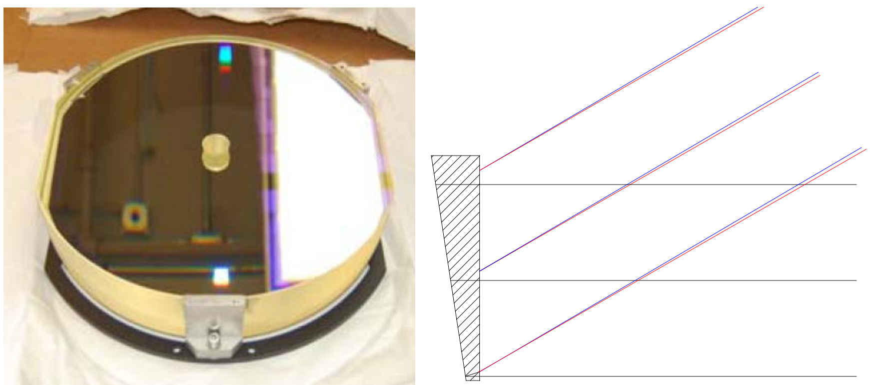


Figure 11: MODS1 red prism (left) and beam geometry (right).

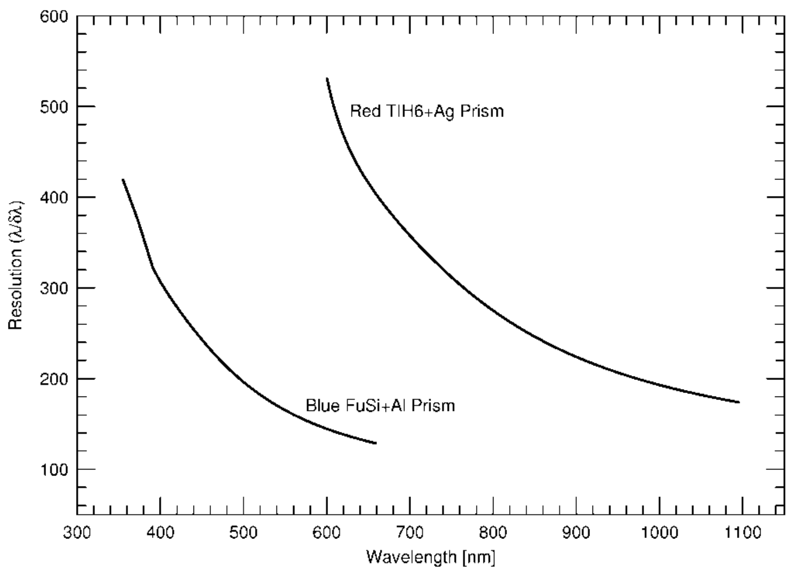


Figure 12: Measured MODS double-pass prism resolution curves

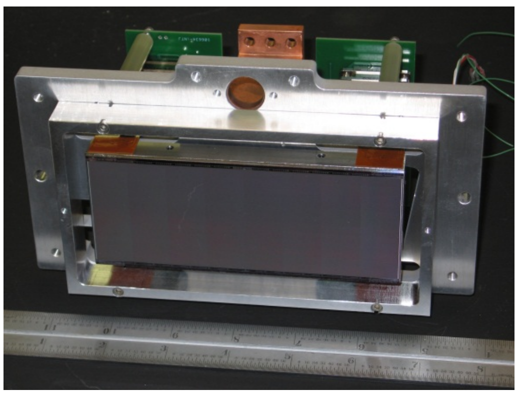
2.6 CCD Detectors

The MODS detectors are e2v Technologies, Ltd CCD231-68 monolithic backside-illuminated 8192×3088 15μm pixel CCDs operated with OSU MkIX detector controllers.

The Blue CCD is made on standard 16μm thick (100 Ω-cm) silicon coated with the e2v Astro-BB broadband coating. The Red CCD is made on 40μm thick deep-depletion (>1500 Ω-cm) silicon with the e2v Astro-ER1 extended-red coating. A photograph of one of the detector packages is shown in Figure 13 with a sketch of the readout geometry.

2.6.1 Basic Properties

The basic properties of the CCDs measured at operating temperature (-100°C) are summarized in Table 8. The conversion gain, readout noise, linearity, and dark current are average values for the four quadrants, measured on-telescope under normal operating conditions.



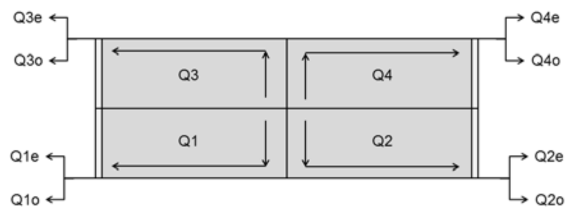


Figure 13: Left: MODS e2v 8K×3K CCD package; **Right**: Schematic of the 8-channel readout geometry.

Table 8: MODS Science CCD Properties

Property	Blue CCD	Red CCD
Pixel Full Well (e^-)	~200,000	~200,000
Typical CTE	99.9995%	99.9995%
Conversion Gain[1]	2.5 e^-/ADU	2.6 e^-/ADU
Readout Noise[1]	2.5 e^-	2.4 e^-
Linearity[1]	<1% @ 55K ADU	<1% @ 52K ADU
Dark Current (e^-/pixel/hr)[1]	0.5±0.2	0.4±0.1
Dewar Hold Time[2]	32 hours	30 hours

Notes:

1. Measured on-telescope during 2010/2011 commissioning, average of 4 quadrants
2. Measured in the LBT instrument lab at +28°C and on-telescope down to -5°C

Each quadrant is read through two output chains (even and odd), each of which have slightly different gain and DC bias levels. This makes the four quadrants distinct in raw images, and on close examination there is visible even/odd vertical striping due to the two-channel readout per quadrant. See §2.12 for more details on MODS CCD data, and §5 for the recommended calibration procedures to correct for them.

2.6.2 Exposure Overheads

Typical CCD exposure overhead times for 1×1 and 2×2 binning modes are summarized in Table 9. The measurements include all overheads associated with image acquisition: pre-exposure erase cycles, post-exposure readout time, disk-write time, and instrument/telescope telemetry queries prior to start of the exposure. Overheads should be treated as guidance-only for observing planning: variations of up to as much as 2 seconds are not unusual, mostly due to unpredictable communication latencies in the system. The constant components of the overhead that do not scale with the number of pixels readout are roughly 40 and 34 seconds for the blue and red CCDs, respectively.

Table 9: Typical CCD Exposure Overheads

	Blue CCD		Red CCD		
ROI Mode	1×1	2×2	1×1	2×2	Notes
8K×3K	104	57	99	52	Grating Spectroscopy (Full Frame)
4K×3K	76	50	71	45	Prism Spectroscopy
3K×3K	69	48	64	43	Direct Imaging
1K×1K	43	40	38	34	Long-Slit acquisition imaging
	sec	sec	sec	sec	

2.6.3 Quantum Efficiency

The measured quantum efficiencies of the blue and red CCDs for MODS1 are shown in Figure 14. These are the laboratory measurements provided by e2v.

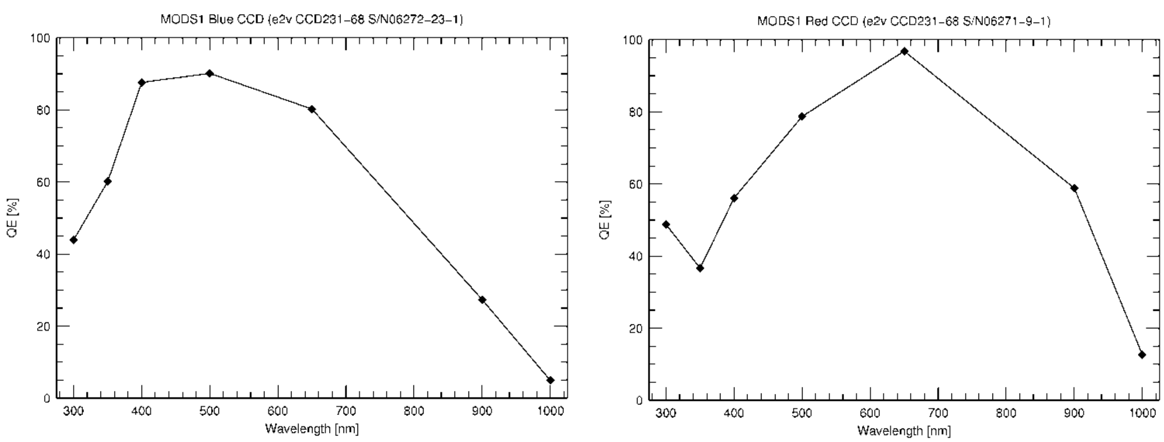


Figure 14: Measured QE of the MODS1 Blue (left) and Red (right) CCDs

2.6.4 Detector Saturation

There are two relevant saturation thresholds for the MODS CCDs:

> **ADC Saturation** when the 16-bit ADC converts run out of bits at 65535 ADU.
>
> **Full-Well Saturation** when the pixels fill with electrons at about 200,000e- (80,000ADU) and charge begins to spill into surrounding pixels.

At ADC saturation, saturated objects will have flat-topped radial profiles that "flat-line" at 65,535ADU in raw images. An example of a star with the central few pixels above ADC saturation is shown in Figure 15. Note that the "bunny ears" artifact in brightest stars is due to diffraction from the secondary mirror swing arm support (see §2.12.3).

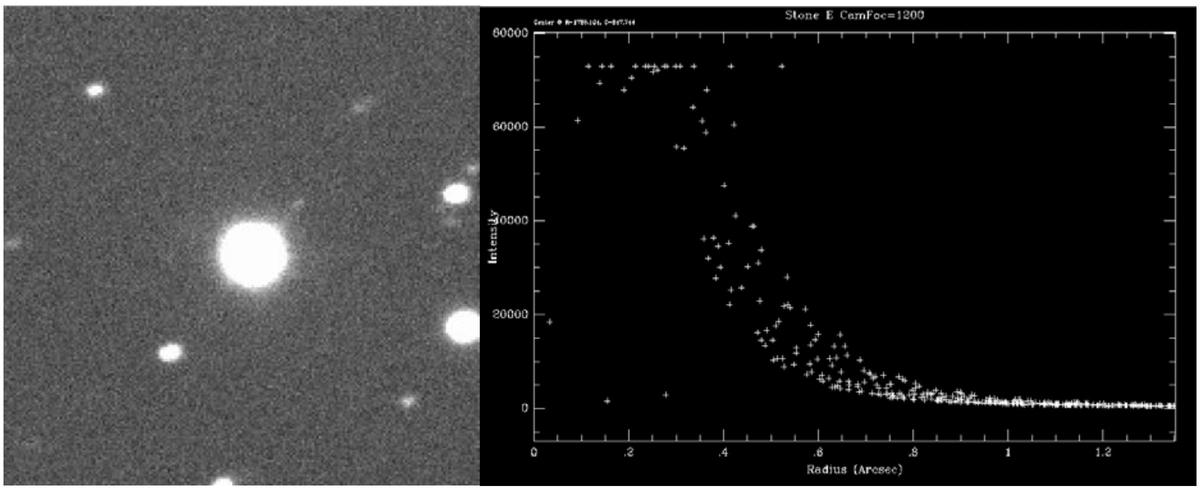


Figure 15: Star image showing ADC saturation. **Left**: image, **Right**: radial intensity profile.

Above the full-well saturation threshold, the central pixels of will begin to bleed vertically along columns as charge spills out of the affected pixels. With very saturated images, well above the full-well threshold, the excess charge begins to cause problems with the readout amplifiers, resulting in strong vertical banding and data values of 0.0 in the image pixels. Both types of full-well saturation artifacts are shown in Figure 16.

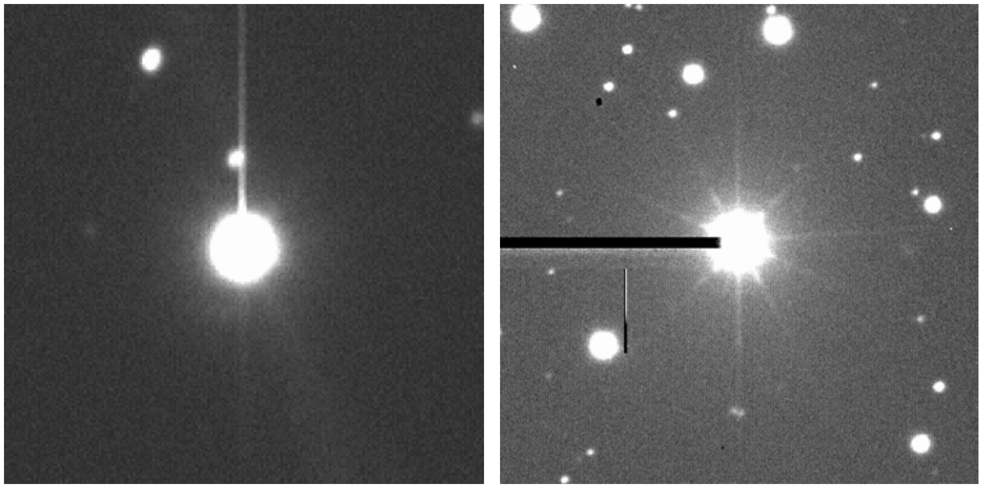


Figure 16: Images of star above full-well saturation. **Left**: Image with central pixels just above full-well showing charge "bleeding" along columns. **Right**: Severely-saturated star image near a quadrant boundary, showing charge-induced horizontal banding artifacts.

If images are very strongly saturated, far above the full-well threshold, charge-induced readout artifacts can dominate and ruin an image. An extreme example is shown in Figure 17, which shows the result of taking a 300s SDSS z filter image with an R=8.4mag star in the upper left quadrant and on the quadrant boundary.

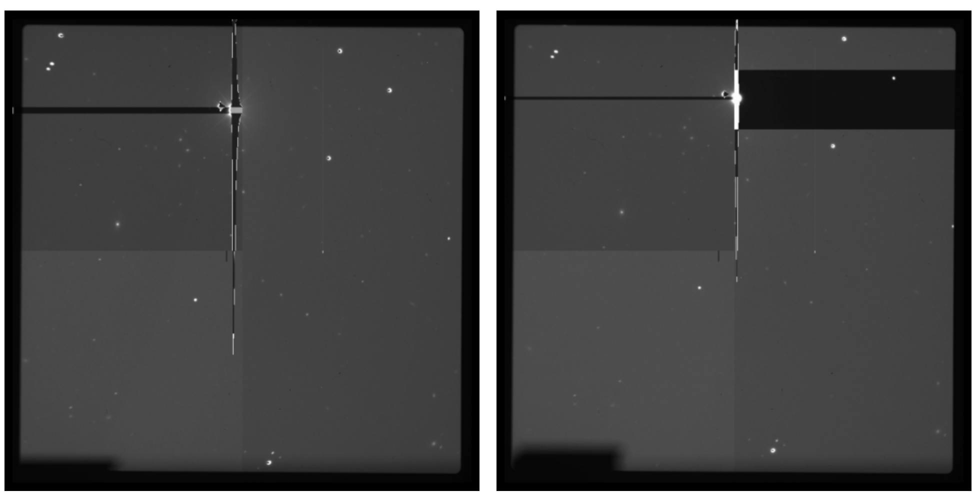


Figure 17: Extremely saturated star image showing severe bleeding and inter-quadrant readout artifacts. **Left**: The star located in 1 quadrant, **Right**: The same star on the quadrant boundary.

The general rule is that one should avoid saturating bright stars, calibration lamp lines, and bright emission-line or continuum objects. In general the effects will result in “damaged” images that cannot be recovered.

The effects do not generally persist into subsequent images in general. After very severe saturation (like in Figure 17), it is a good idea to take a couple of highly binned (e.g., 8x8) bias images to make sure any residual charge from such punishment of the CCD is cleared out.

2.6.5 Cross-Talk

There is no measurable cross-talk between the 4 quadrants of the CCDs. Representative cross-talk test images for the blue and red CCDs are shown in Figure 18.

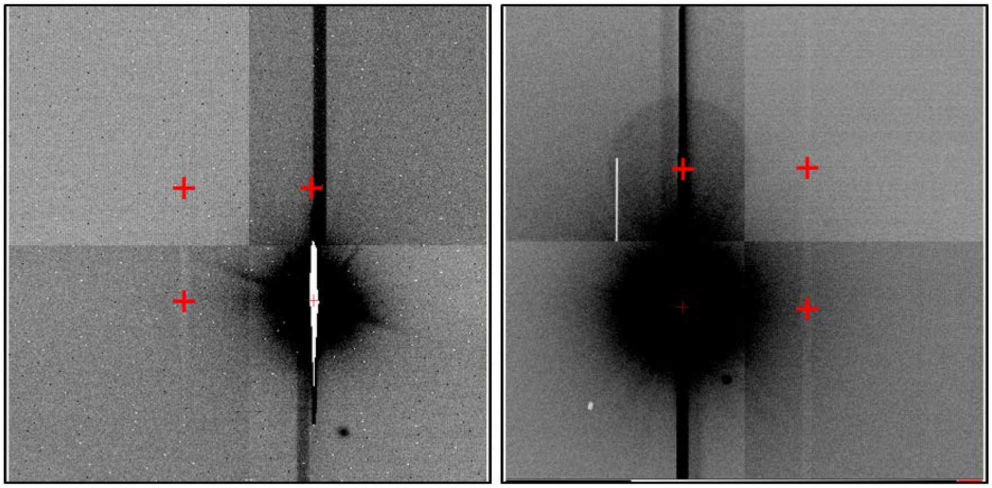


Figure 18: Cross-Talk Test images for the blue (left) and red (right) CCDs. The red crosses mark the positions where cross-talk would appear if there were cross-talk.

While there are no excess counts, there is a small *deficit* of counts at a mean level of <1 ADU in the regions of most significant charge bleeding. The level of these artifacts is at or below the detector noise when measured formally, but because the pattern is coherent over many 10s of pixels it is discernible to the eye.

2.7 Slit Masks

Each MODS has a 24-position slit mask storage cassette that can be loaded by instrument support personnel during the afternoon. The first 12 mask slots are reserved for the 9 fixed-facility long-slit masks and up to 3 test masks. The bottom 12 mask slots are reserved for user-designed masks.

There are three types of slit masks:

Permanent Facility Slit Masks

These include segmented long slits, imaging stops, and calibration masks that are always available in each MODS instrument. They are stored in the first 9 slots in the mask storage cassette and may not be removed except under unusual circumstances.

User-Designed Slit Masks

Up to 12 custom user-designed slit masks may be used per night. Observers create these masks using the MMS program and submit them a couple of weeks in advance of the observing run to LBTO for cutting and transport to the telescope.

Engineering Masks

These are masks used during instrument testing and evaluation (lab and telescope), including focus and alignment pinhole masks and ghost-image masks

2.7.1 Permanent Facility Slit Masks

The first 9 slots in each MODS slit mask cassette are reserved for the permanent set of facility slit masks. Table 10 summarizes the current set of facility slit masks.

Table 10: MODS Permanent Facility Slit Masks

MaskID[1]	Cassette Position	Description
DarkMask[2]	1	Dark Mask (closed/blind)
SieveMask	2	0.3″ 2D pinhole grid
Imaging[3]	3	Imaging Mode Field Stop
LS5x60x0.3	4	0.3″ wide 5×60″ segmented long-slit[4]
LS5x60x0.6	5	0.6″ wide 5×60″ segmented long-slit
LS5x60x0.8	6	0.8″ wide 5×60″ segmented long-slit
LS5x60x1.0	7	1″ wide 5×60″ segmented long-slit
LS5x60x1.2	8	1.2″ wide 5×60″ segmented long-slit
LS60x5	9	60×5″ spectrophotometric “fat” slit

Notes:

1. MaskID is the name used to select the mask in MODS observing scripts (e.g., "`slitmask ls5x60x0.6`"). MaskIDs are case-insensitive and have no spaces in them. It is stored in the `MASKNAME` keyword in image FITS headers, along with the `MASKINFO` keyword with additional descriptive.
2. The dark mask blocks the view out of the instrument/telescope focal plane to measure internal scattered light, and to provide protection for the post-slit field lens when the instrument is put to sleep.
3. The imaging field-stop mask ensures proper baffling at the edges of the FoV.
4. Segmented long-slit masks consist of a line of five (5) 60-arcsec long slits centered at 0, ±63, and ±126-arcsec from the field center separated by 3-arcsec wide struts. The struts are required to maintain the structural integrity of the spherical mask shells.

Figure 19 shows drawings of the LS5x60x1.0 and LS60x5 slit masks as examples of the layout of the segmented long slits and the spectrophotometric “fat” slit.

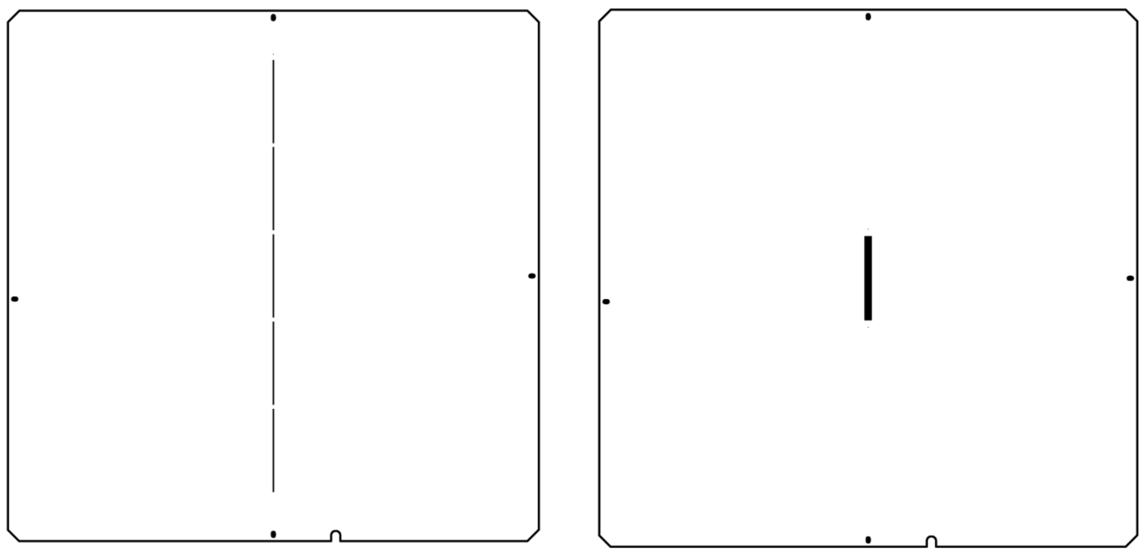


Figure 19: Examples of facility long-slit masks. **Left**: LS5x60x1.0 (note the struts), **Right**: LS60x5.

2.7.2 Custom Masks

The MODS Mask Simulator (MMS) program is provided to design custom slit masks. It is a modified version of the LMS program for LUCI, and works much the same way as LMS. The MMS webpage describes the important differences with LMS. Instructions for submitting masks for manufacture are given in the MMS manual available on the MODS webpage.

A major important difference is that MODS masks require at least two alignment star holes for aligning the mask in XY offset and rotation. These are 4×4″ square apertures centered on stars with good astrometry. We use these stars with the modsAlign program (§4.5).

Slit masks are laser machined in spherical mask blanks made of 150μm thick electroformed NiColoy®, a proprietary electro-deposited Nickel-Cobalt alloy produced by the mask blank vendor, NiCoForm, Inc. of Rochester, NY. Machining is done at URIC at the University of Arizona. The cut masks are then mounted in special handling cells and transported to the mountain where they are loaded into the mask cassette by observatory instrument support personnel before your observing run.

The slit mask insert/retract time is ~10 seconds. The maximum time to extract an old mask and select/insert a new mask is ~35 second (for the largest cassette excursion).

2.7.3 Multi-Slit Mask Field of View

MODS is designed to deliver good images inside the central 4×4′ field of view and reduced image quality in a 6×6′ "extended" science field. In practical terms, the image quality decreases rapidly outside a 5.6-arcminute diameter circle, primarily due to a combination of astigmatism from the off-axis paraboloid collimator mirrors and off-axis aberrations in the LBT f/15 direct Gregorian focal plane. For purposes of locating MOS mask slits and alignment stars, we recommend that you keep primary science target slits within a 5.6′ circle, and alignment stars within a 5.0′ circle, as shown in Figure 20. Note that the LUCI 4×4′ is inscribed inside the 5.6′ circle, so the primary science fields of MODS and LUCI are the same.

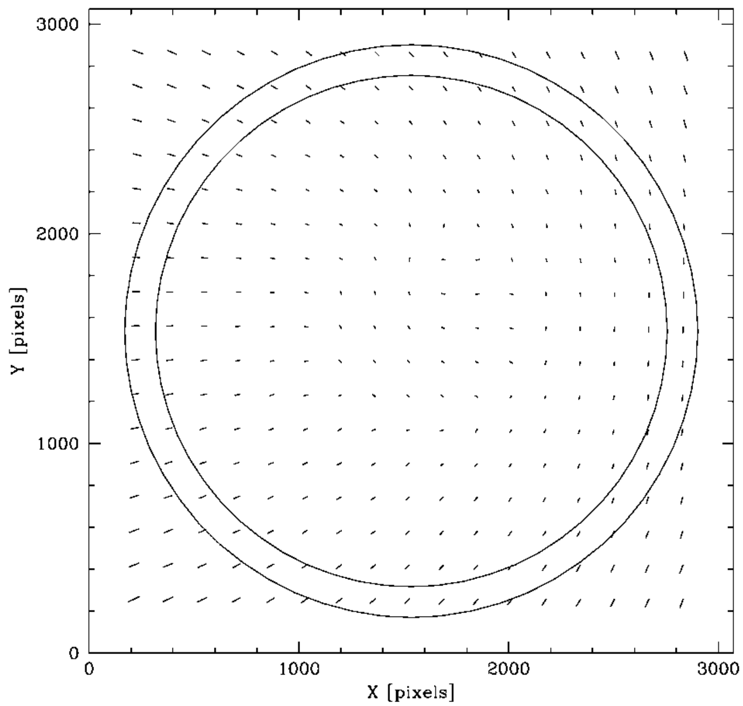


Figure 20: MODS multi-object slit mask effective field of view. The outer circle is 5.6′ in diameter, the inner circle is 5′ in diameter. The short lines show an exaggerated representation of image distortion due to astigmatisms at those field locations.

Slits may be located outside the 5.6′ circle, but with a penalty of greater image aberration resulting in reduced spectral resolution (images are smeared over more pixels). Flux and wavelength calibration precision will also be reduced in the corners of the field.

Mask alignment stars should be kept within the 5′ circle, as precise centroid measurements of alignment boxes and stars is degraded by image aberrations outside this, reducing the precision of position and rotation offsets computed. Note that this is a conservative limit, not a hard limit, and if you are taking spectra of brighter objects where the alignment with the slits will be obvious in short thru-slit acquisition images (e.g., multi-object masks of star fields or bright HII regions in galaxies), this restriction may be relaxed without penalty, except that additional mask alignment iterations may be required to fully align targets with the science slits.

2.8 Calibration Unit

Each MODS has its own internal calibration system consisting of an integrating sphere and projection optics located in a deployable calibration tower located above the slit plane. A selection of Pen-Ray® wavelength calibration lamps and continuum lamps for spectral and imaging flat fields are mounted in the integrating sphere. The lamps and their uses are summarized in Table 11. The projection optics includes a mask that will produce a representation of the telescope secondary mirror obscuration at the correct location in the MODS pupil plane for the spectrograph.

Table 11: MODS Internal Calibration Lamps

Lamp	Description	Use
Hg	Mercury(Argon) Pen-Ray® Lamp	Blue channel wavelength calibration
Ne	Neon Pen-Ray® Lamp	Red channel wavelength calibration
Ar	Argon Pen-Ray® Lamp	Dual-channel wavelength calibration
Xe	Xenon Pen-Ray® Lamp	Dual-channel wavelength calibration
Kr	Krypton Pen-Ray® Lamp	Dual-channel wavelength calibration
QTH1	10W Quartz-Tungsten Halogen Lamp	Blue spectral flat field, u imaging flats
QTH2	10W Quartz-Tungsten Halogen Lamp	Blue spectral flat field
VFlat	Variable-intensity Incandescent Lamp	Red spectral and Dual imaging flats

Spectral line finder plots and tables of identified spectral comparison lamps for the five wavelength calibration lamps are available on the MODS website. Plots of representative spectra are given in Appendix C.

The QTH lamps are used individually or together for blue/UV spectral flats.

The VFlat variable-intensity incandescent lamp is used for imaging flats in the g-z bands, and red spectral flat fields in the grating and prism modes. Its intensity can be varied over integer levels of 1 to 10 to select a brightness that won't saturate the detectors. Typical values are VFlat=2 for the SDSS r band imaging flats, and VFlat=4 for the SDSS g filter imaging flats, with greater values used for spectral calibration (VFlat=9-10 is typical of red grating flats). The brightness of the lamp is non-linear with intensity value, as shown in Figure 21, and the lamp gets slightly bluer with higher intensity (VFlat intensity is proportional to the applied voltage, and the lamp filament gets hotter with greater voltage).

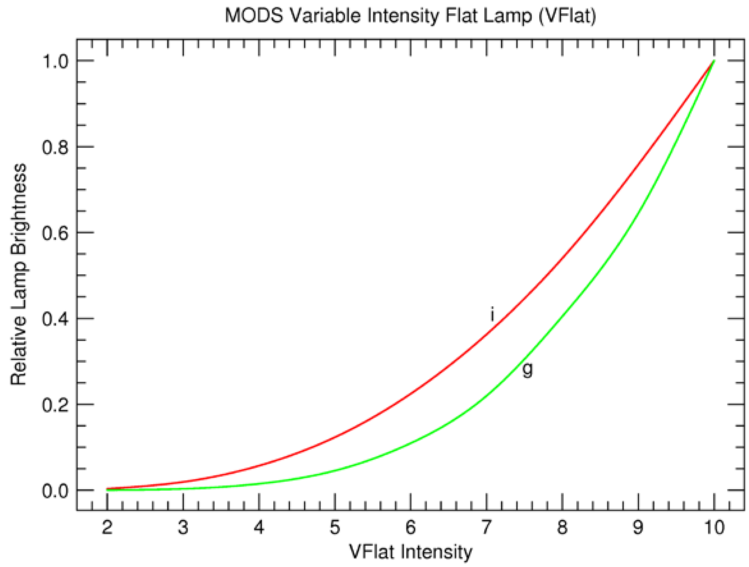


Figure 21: VFlat calibration lamp output curve. Lamp brightness is scaled to VFlat=10. The red line is the curve for the SDSS i band, the green line for the SDSS g band.

To view the calibration system the AGw guide stage has to be retracted to its home position, the instrument dark hatch closed, and the calibration optics inserted into the beam, a process that requires about 30 seconds (up to 40 seconds if the guide probe is near the science field center). Special `CALMODE` and `OBSMODE` commands are provided to configure the instrument for taking internal calibrations (`CALMODE`) or observing the sky (`OBSMODE`), taking care of the fine configuration details for you.

Good combinations of exposure times, filters, and compatible lamp combinations have been found for flat field and wavelength calibration for all modes (imaging and spectroscopic). See §5 for the recommended calibration procedures. Copies of the standard calibration template scripts are available on the MODS website as well as in public folders on the LBT control room observing workstations.

2.9 Acquisition, Guiding, & Wavefront Sensing (AGw) Unit

The front of MODS extends into the back of the LBT primary mirror cell and cannot use the facility direct Gregorian AGw unit (used, for example, by PEPSI). Instead, it has its own integrated AGw unit that uses the same guider and off-axis WFS cameras as the AIP units used by LUCI. The main differences with LUCI AGw is a larger guide/acquire camera field of view (50×50" and 2× larger pixels), an off-center WFS pickoff and guider “hotspot”, and a smaller off-axis guide star patrol field.

Overall guiding accuracy with the MODS AGw unit and the current generation LBT GCS software is measured to be ±30milliarcsec RMS, except at very low elevations (<25°) where the guide-star images are smeared out due to differential atmospheric refraction and increased astigmatism coming from the adaptive secondary mirrors.

The MODS AGw unit is tightly coupled mechanically to the MODS focal plane, sharing a mounting surface with the sensor that determines the location of the slit mask in the science field of the instrument focal plane. Measurements made during commissioning demonstrated that there is essentially no differential flexure between the guide camera and science slits after accounting for the effects of differential atmospheric refraction (§3.4).

The guide stage is very stable and repeatable. During a telescope offset, the guide probe is commanded to follow the offset. After repeated offsets (e.g., as would be done when nodding along a slit), the RMS offset repeatability was measured to be ±35milliarcseconds, independent of telescope elevation down to 30° (the final measurements were near 25°, the current lower elevation limit of the telescope). This is within the general error envelope of guiding error in the system, and roughly 10% of the width of the instrument’s 0.6-arcsecond wide design-reference slit.

2.9.1 Guide Star Patrol Field

A schematic of the MODS AGw patrol field is shown in Figure 22. This figure also shows the XY coordinate axes in the DETXY (rotator-invariant common focal plane coordinates) system. Offsets made in DETXY coordinates are used to move targets in acquisition images into the slit, and offsets along the Y axis of DETXY coordinates will dither the target along the slit.

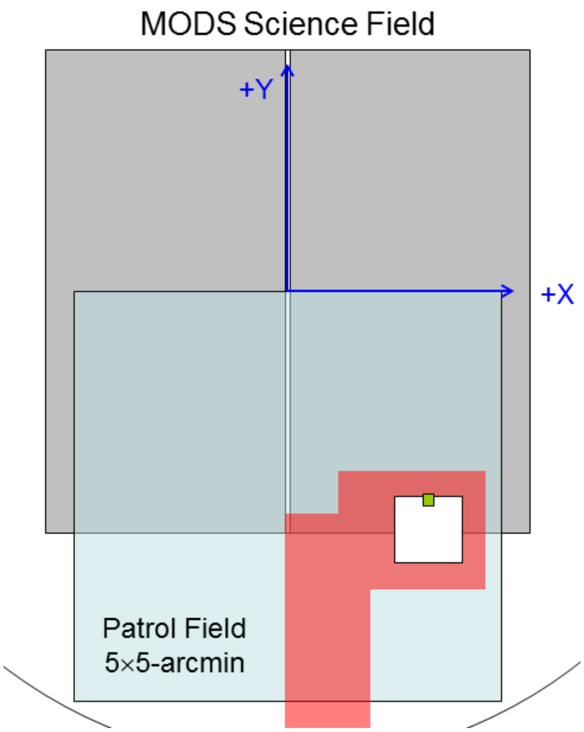


Figure 22: The MODS AGw WFS patrol field (blue) plotted on top of the 6×6-arcmin science field. The small white square is the guide probe FoV, green is the WFS pickoff FoV, and red is the shadow of the guide probe.

The `modsView` program is available to help select guide stars (see the MODS website for information on `modsView`).

Because the guide probe is located above the f/15 focal plane, its shadow is larger than the size of the guide probe itself. The detailed shadow is fairly complex as shown in Figure 23.

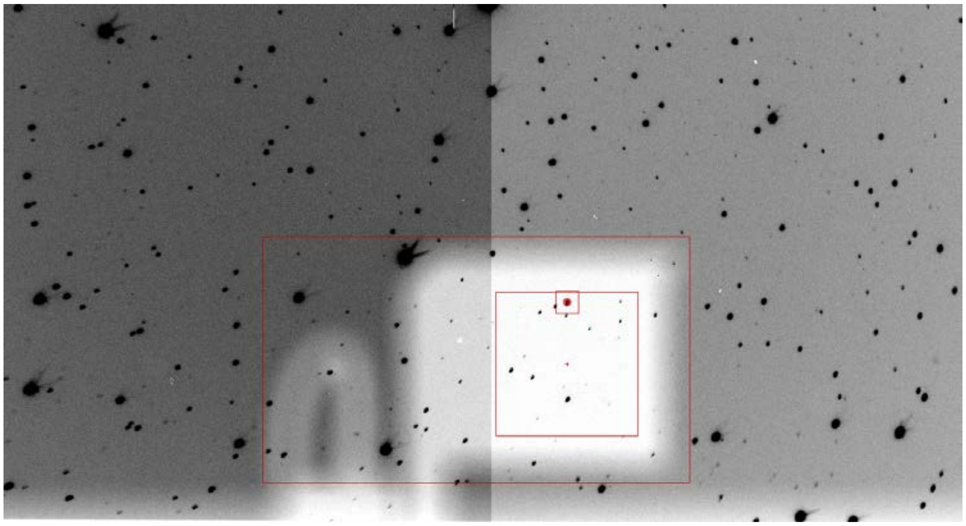


Figure 23: MODS AGw Guide Probe shadow, depicted using a sum of two images with and without the probe in the field. The red lines delimit the guider and WFS fields (Figure 22), with the large red box outlining a conservative zone of avoidance for the guide probe head and a sensor cable (loop at left). The large red box is roughly 150×86″ in size. The guide/WFS star is marked in the center of the WFS pickoff field.

In round numbers, if your guide star is located >223″ south of the science-field center at PA=0°), the guide probe will not shadow the science field. Closer to the center of the science field, a conservative zone of avoidance for PA=0° is such that you want no slits within

<23″ North
<106″ East
<44″ West

of the location of guide/WFS star. For observations of single targets roughly centered in one of the facility long-slit masks, you can utilize a fair amount of the science field to obtain guide/WFS stars so long as you keep the long slit outside the conservative boundaries above.

The `modsView` program, also available on the MODS website, can be used to examine target acquisition (.acq) scripts and check both the guide star selection and any issues with guide probe obstruction of the slit. See

www.astronomy.ohio-state.edu/MODS/ObsTools/modsView

for instructions on how to download and use `modsView`. A brief overview is in §4.6.

2.9.2 Guiding and WFS Star Brightness Limits

The MODS AGw system is as sensitive as the LUCI AGw unit, so similar recommendations on guide/WFS star brightness apply.

Bright Limit: **R≈12^{mag}**

Faint Limit: **R≈16.5^{mag}**

The limits apply for "good" seeing of 0.8" FWHM, with the Clear or F525LP filter. The bright limit is set at the point where Shack-Hartmann spots begin to saturate on the WFS camera when seeing is <0.6". The WFS limit is independent of the guide camera filter because the WFS pickoff beam is located in front of the guide camera filter wheel.

For using the B_Bessel filter to guide in blue light, the bright limit is about 1 magnitude brighter because of the lower QE of the LBTO guide camera CCDs in the blue.

In practice, guiding and WFS stars fainter than R=16.5mag are challenging to use for guide/WFS stars even in good seeing with the current GCS algorithms for guide star tracking and WFS measurement. Future work on the GCS may improve the lower limit and expand the number of available guide stars.

2.10 Image Motion Compensation System (IMCS)

MODS is a long instrument (~4m), and as it is pointed around the sky it is subject to gravity-induced flexure of the structure, stochastic "ticks and pops" in the structure's welds and bolts, "print-thru" from the instrument rotator bearing, and other sources of mechanical "flexure". There are also small thermal components of "flexure" as the ambient temperature changes. All of these factors work together to slightly misalign the optics as a function of instrument elevation angle and rotator angle, leading to undesirable motion of images across the science CCDs. Computer models and measurements at the telescope show that uncompensated image motion can be as much as 100 pixels when the instrument tracks from horizon to zenith.

To eliminate most of this image motion, MODS uses an internal closed-loop Image Motion Compensation System (IMCS; Marshall et al. 2006). The IMCS measures the alignment of the optics in each channel in real time during exposures, and then steers the collimator mirrors in tip and tilt to null the image motion. An IR laser beam (λ=1.55μm) is launched from below the focal plane and passes through the same optics as the science light onto a germanium quad cells mounted off-axis just above each channel's science CCD. A sketch of the IMCS metrology laser path for the Red channel is shown in Figure 24; the blue channel laser path is analogous.

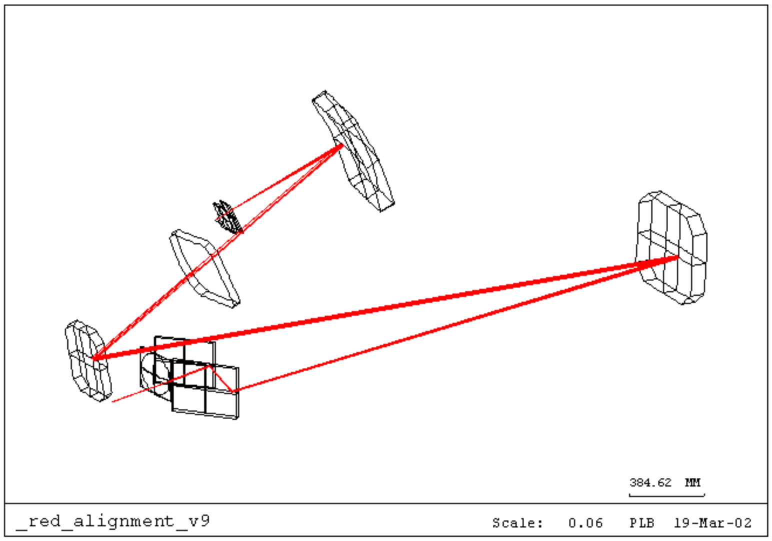


Figure 24: IMCS IR laser beam path for the MODS red channel

Error signals from the quad cells are measured every second during an exposure, with an average of three measurements used to compute the compensating tip/tilt corrections for the collimator. The red and blue channels run independently, as each has different flexure modes.

Because the IMCS IR laser beam shares the same optical path as the science beam from slit to CCD, the IMCS quad cells are only illuminated when the shutter is open, so compensation can only occur during an exposure. After a new telescope pointing and after reconfiguration of the instrument (e.g., switching from imaging to grating spectroscopy mode), the IMCS needs to be run briefly to "zero" the alignment of the optics so that the first science exposure starts in the properly aligned configuration. Because multiple measurement cycles are required to average out instrument "seeing" (the IR laser beam path is ~10 meters long), the IMCS is only engaged during open-shutter exposures of 10 seconds or longer.

On average, the IMCS nulls image motion to ±0.5 pixels rms for every 15° of elevation change while tracking (instrument elevation is the dominant term in the flexure budget). There still remains a small 1-2 pixels of residual image motion across the entire range of telescope elevation (30-90°) and instrument rotator angle (0-360°) that will show up as a field-to-field zero-point shift. Future refinements of the IMCS will be made with the goal of improving the absolute compensation. In practice, we often see <0.5 pixels of shift between spectra taken over 2+ hour integrations of continuous tracking.

When moving the telescope pointing from one position to another, the typical time for the IMCS to correct for post-pointing flexure is ~60 seconds, but it can be as long as 90 seconds if going to very low elevations (<30°). The IMCS zero points for the collimator tip/tilt/focus actuators are measured at 60° elevation with the rotator at the nominal 0° position, and stored in the instrument configuration files. These are the starting points for corrections made after either pointing the telescope or reconfiguring the instrument.

IMCS operation is automatic when using MODS in the recommended way with the scripting interface. If running MODS by hand (e.g., during technical nights), you must always follow a `PRESET` or `INSTCONFIG` command with `IMCSLOCK` to re-align the optical system.

2.11 Camera Shutter

Each camera has an integrated shutter consisting of two graphite-epoxy blades in a barn-door configuration that opens along the long-slit axis. This gives no shading along the dispersion axis and only minimal shading along the slit axis.

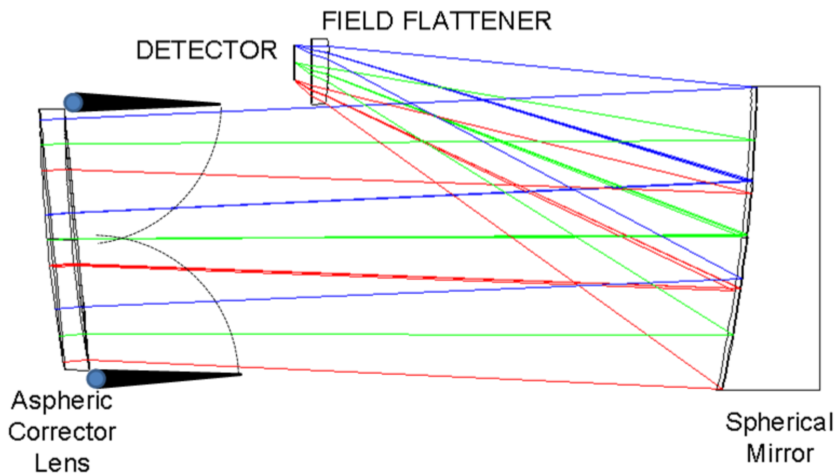


Figure 25: Schematic of the MODS camera shutter – shown in the open position

The open/close time results in a minimum exposure time of ~0.45 seconds. In general, though, we have adopted a **minimum working exposure time of 1.0 seconds**, but a 0.5 second exposure time can be requested if necessary (e.g., for a prism-mode calibration).

2.11.1 Shutter Shading Function

The finite shutter opening time, and the asymmetric geometry of the shutter behind the off-axis Maksutov-Schmidt corrector lens, means that there is a correspondingly asymmetric shutter shading function along the slit, but no shading in the dispersion (detector X) axis.

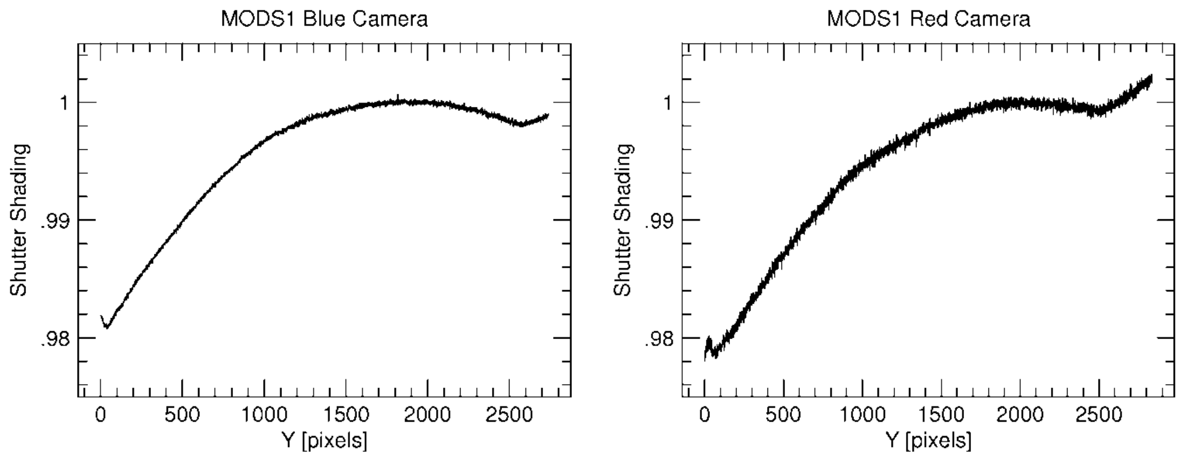


Figure 26: Mean 1-second vertical shutter shading functions for blue (left) and red (right) cameras.

At most the shutter shading function manifests as a 2% gradient from bottom to top in a 1-second integration. This gradient will decline linearly with increasing exposure time. It is sufficiently small that for typical spectroscopic exposure times, even standard stars, it may be safely ignored.

2.11.2 Shutter Lag

There is a measured time lag of **1.62±0.05 seconds** between the time recorded in the FITS header `DATE-OBS` datum and when the shutter is actually opened by the CCD controller such that

$$t_{actual} = \text{DATE-OBS} + 1.62 \text{ sec}$$

The range of shutter lag is between 1.55 to 1.68 seconds. There is no significant difference in the lags measured for the blue and red camera shutters, and no correlation with the size of the image being read out. The origin of the shutter lag is buried in the depths of the CCD controller code, and eliminating this lag time will be a goal of future CCD controller software updates.

Please keep this in mind if your observations require precision (<1 minute) timing. The rms of the measured shutter lag of ~50msec is typical of system times derived from synchronizing clocks to a local Stratum-0 GPS time server via NTP (typically 10-20msec), as is the case with the MODS computers on the LBTO mountain network.

2.12 MODS Data

MODS data are written onto the archive disk as standard FITS files. Images have names like mods1b.20111213.0001.fits. The format is “mods1b” for “MODS1, Blue CCD”, the 8-digit number is the UTC date of the observation in CCYYMMDD format, and the 4-digit number is the image sequence number during that UTC day. Raw images appear on the mountain archive disk (`/newdata`) within a few seconds after they are written to the data-taking system’s data staging disks. See §4.3 for more details. A sample FITS header is given in Appendix A.

2.12.1 Image Format

The MODS CCDs are rectangular: 8192 pixels wide by 3088 pixels high. The number of pixels readout depends on the instrument mode: 8K×3K (full-frame) for grating spectra, 4K×3K for prism spectra, 3K×3K (actually ~2900×2900) for imaging mode and MOS target acquisition, and 1K×1K for long-slit target acquisition. A graphical summary is in Figure 27.

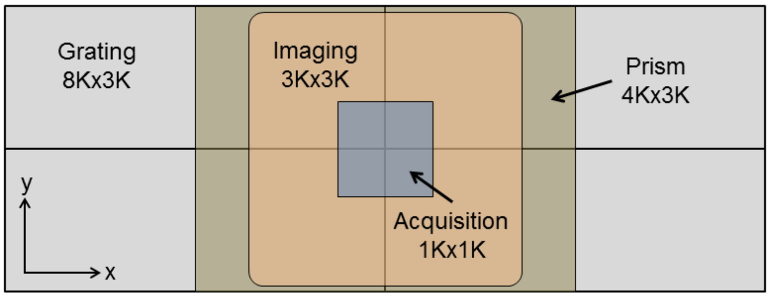


Figure 27: MODS Primary CCD readout modes

Direct images are oriented North=Up, East=Left when the instrument is rotated to PA=0°. The imaging cameras are slightly rotated with respect to the science field: -0.6° and +0.05° for the red and blue cameras, respectively. A special imaging mask acts as a field stop. Examples of raw MODS direct images are shown in Figure 28.

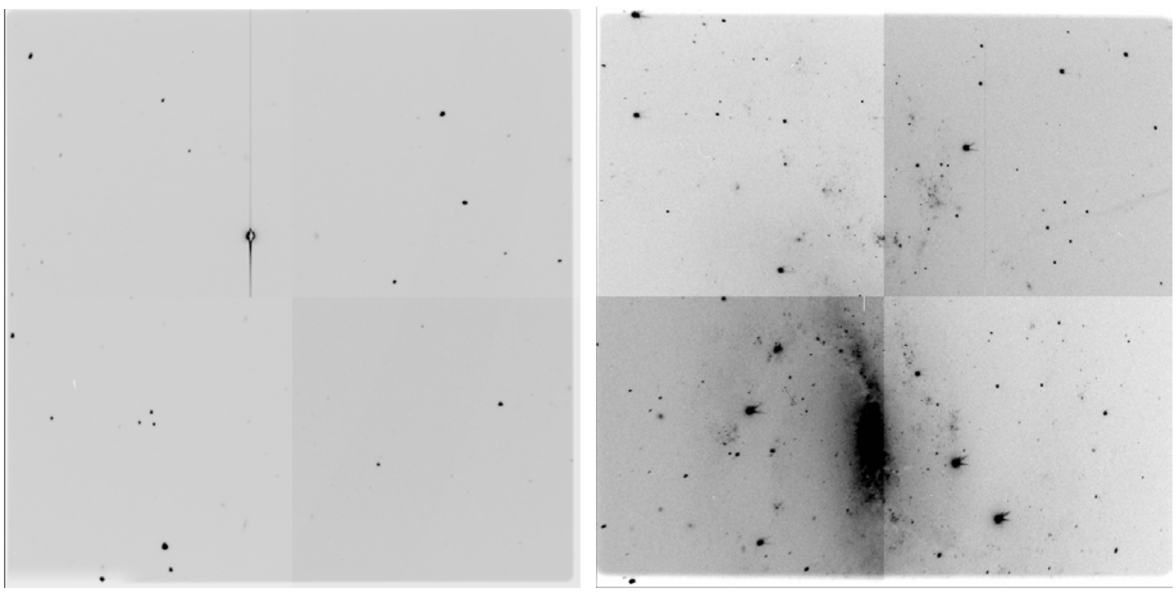


Figure 28: Raw Blue (left) and Red (right) MODS direct images.

In the spectral modes, dispersion is mapped onto the long (x) axis of the detector. Blue-channel spectra run blue-to-red from left-to-right (Figure 29), whereas red-channel spectra run red-to-blue from left-to-right (Figure 30).

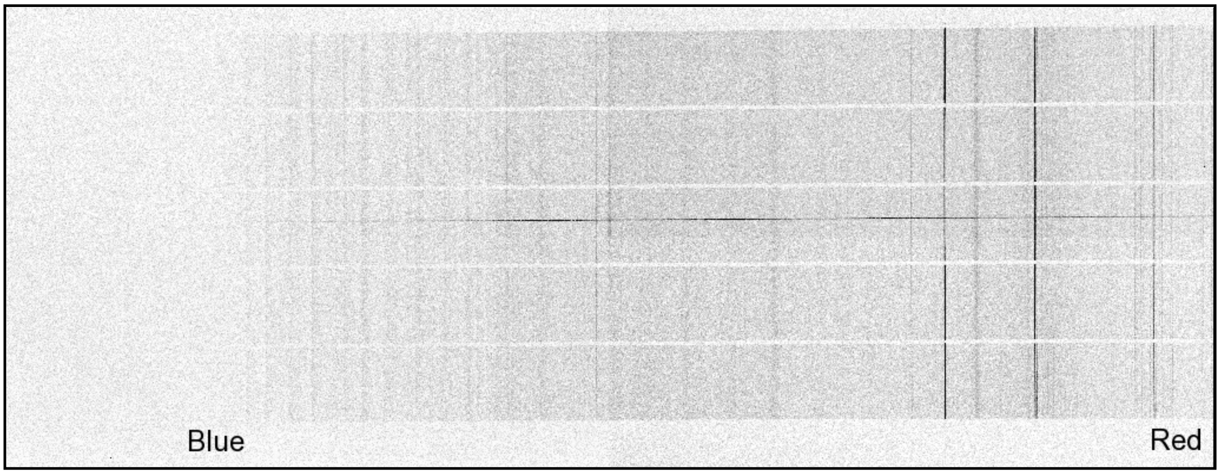


Figure 29: MODS1 Blue long-slit grating spectrum (blue-only mode). Image is bias corrected only.

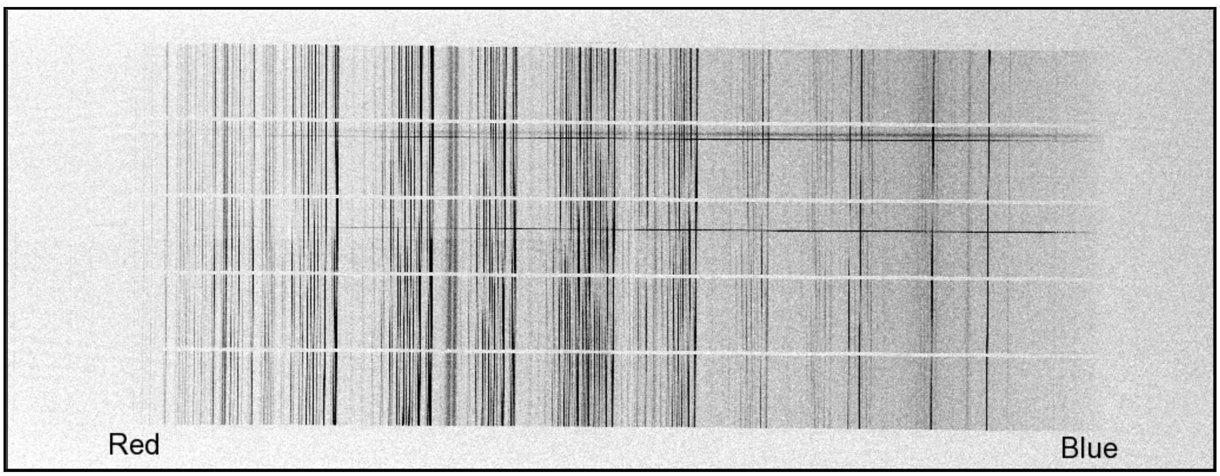


Figure 30: MODS1 Red long-slit grating spectrum (red-only mode). Image is bias corrected only. Note the strong OH Meinel bands that dominate the night-sky emission spectrum.

Raw prism spectra are oriented the same but map into only ~650 pixels. An example prism spectrum is shown in Figure 31. The short span of prism-mode spectra makes it possible to stack multi-object mask slits 3-deep horizontally.

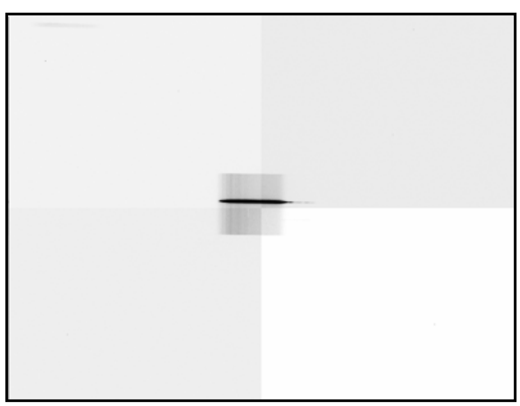


Figure 31: Raw MODS Red Prism Spectrum with the LS5x60 slit (4K×3K ROI readout mode).

2.12.2 Bias and Flat-Field Structure

The MODS CCDs are divided into 4 quadrants that are read out simultaneously. Each quadrant readout channel is further split into even and odd readout channels, for a total of 8 readout channels. The readout geometry and the clocking pattern is shown schematically in Figure 32:

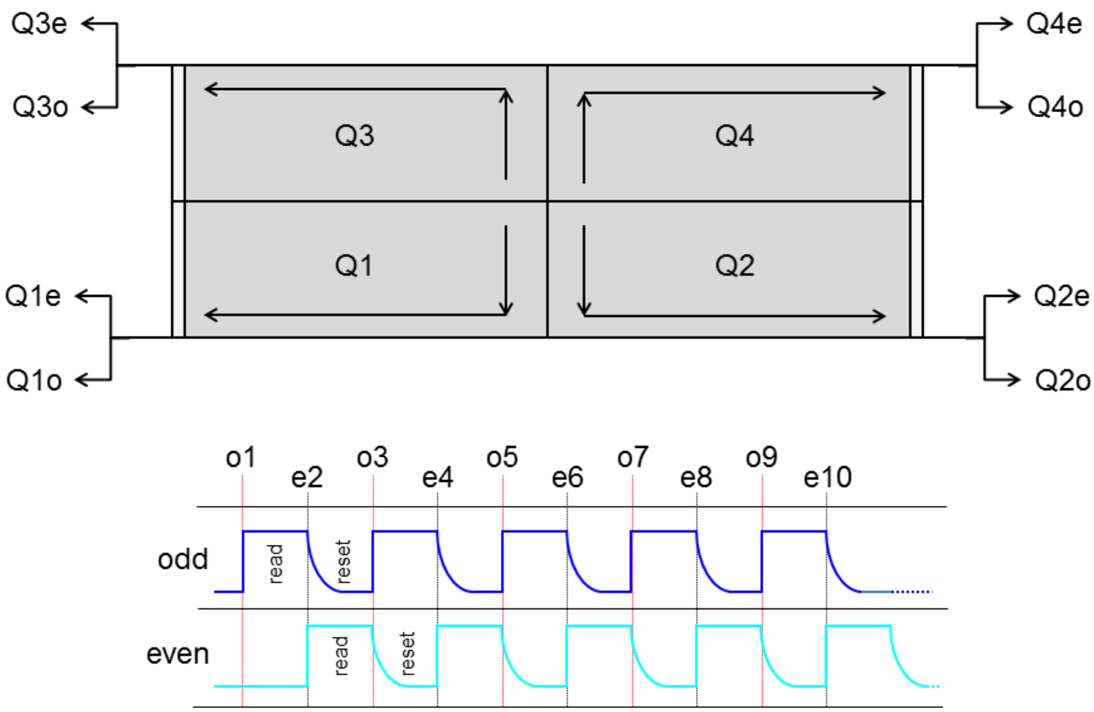


Figure 32: MODS 8K×3K CCD readout geometry (top) and the even/odd pixel readout scheme (bottom)

The readout of the even and odd pixels is staggered in time so that while one readout amplifiers is being reset, the other is reading out. This readout architecture allows us to read this large (24Mpixel) detector more rapidly than we could otherwise with a single amplifier for all pixels in a quadrant.

Each of the 8 output channels has its own readout electronics, which means there is a slightly different DC bias level and conversion gain for each channel. There are two primary effects of this on the resulting raw images. The first is that the four quadrants are distinctly visible in the raw images. Figure 33 shows an example of a red CCD bias image where the division of the detector into four quadrants is obvious. The blue CCD images look similar.

Figure 33: MODS1 Red CCD Bias image.

The effect of the staggered even/odd pixel readout scheme is that within each quadrant is to give the appearance of vertical striping when viewed zoomed in close enough to see the individual pixels. An example of this "Even/Odd Effect" is given in Figure 34 which is showing a zoom-in on the central "four corners" region at the boundary between the four quadrants of the red bias image shown full-size in Figure 33.

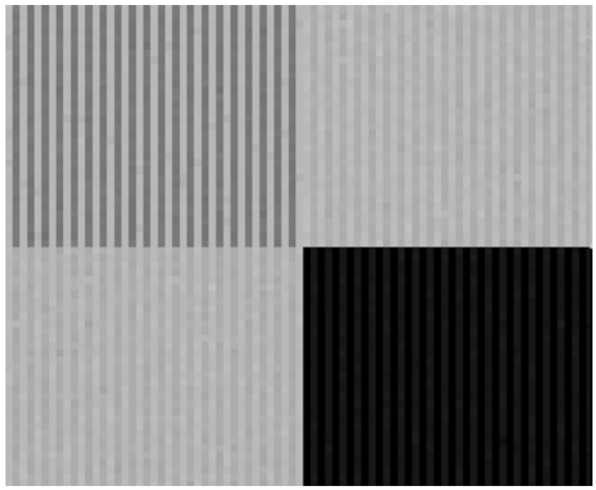


Figure 34: The Even/Odd Effect, here from the same red CCD bias frame shown in Figure 33.

The difference in the bias level between the even and odd pixel readout channels is larger than typical pixel-to-pixel variations due to readout noise. This is why the even/odd vertical striping pattern is so pronounced in raw images. In illuminated images like flat fields this "even/odd effect" is further enhanced by small (few percent) differences in the conversion gain (e^-/ADU) between the readout channels. The bias component can be removed using the overscan regions of the detector, while the conversion gain component can be corrected for using color-normalized spectra of continuum sources ("spectral pixel flats").

This readout scheme is unique to MODS, and in practical terms this means that raw MODS images cannot be bias corrected using the usual IRAF or IDL tasks, which assume that all pixels within a quadrant are read through a single output channel. Instead, we provide the modsCCDRed suite of Python programs to perform these basic 2D CCD reduction steps. These programs are available for download on the MODS webpage, and have a separate user manual.

Once you get past the particular requirements of MODS for bias and flat field correction, the 2D data are ready for use by any of the established packages for working with long-slit and multi-object spectra (e.g., IRAF `twodspec` and `onedspec` packages for long-slit spectroscopy, or adaptations of the Carnegie COSMOS package for MOS spectroscopy).

2.12.3 Image Quality

As noted in §2, MODS produces its best images inside a 4×4′ central "sweet spot", with degrading image performance into the 6′ "extended" field of view (see Figure 20). This has implications for the location of slits in MOS masks (§2.7.3), and for overall image quality at the corners of the field when the instrument is used for direct imaging.

When the seeing is very good, MODS can deliver this image quality on its science cameras, especially in the central 2′. An example of this is shown in Figure 35, where we present images taken under conditions of exceptionally good (0.36″) seeing along with the radial profile plot of one of the unsaturated stars in the image. The complex "bunny ears" artifact visible on the saturated star at about 10 o'clock in the image is due to the rigid secondary and does not appear in images taken with the later adaptive secondary mirror.

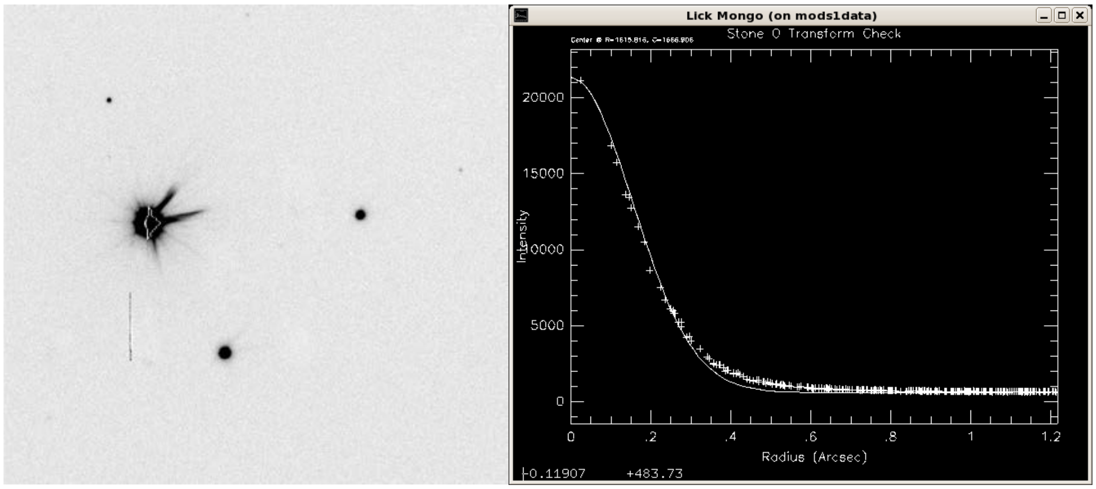


Figure 35: Example of image quality during excellent (0.36″) seeing.

Images of bright stars show faint symmetric diffraction spikes from the secondary mirror swing arm supports, and are usually only visible in relatively deep images or around saturated stars. An example is shown in Figure 36 taken with the adaptive secondary mirror (AO2) in September 2011, here in the SDSS r band taken during ~0.6″ seeing conditions.

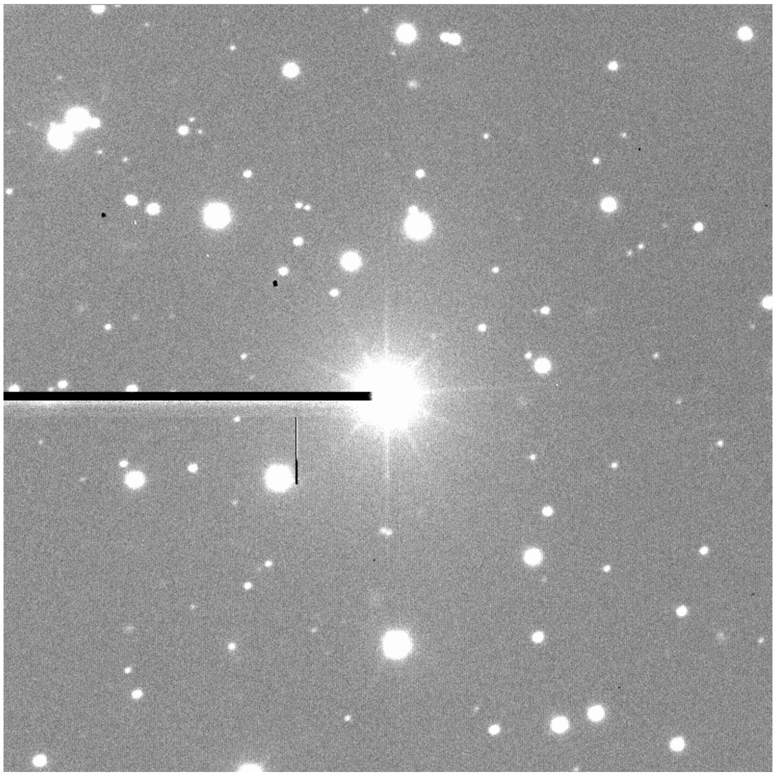


Figure 36: Image of a bright saturated star showing diffraction spikes from the AO secondary swing arm.

In the corners of the full 6×6′ field of view, however, the images degrade due to growing astigmatism from the off-axis collimator mirrors. Examples of images from the upper-right and lower-left corners taken during 0.9″ seeing are shown in Figure 37.

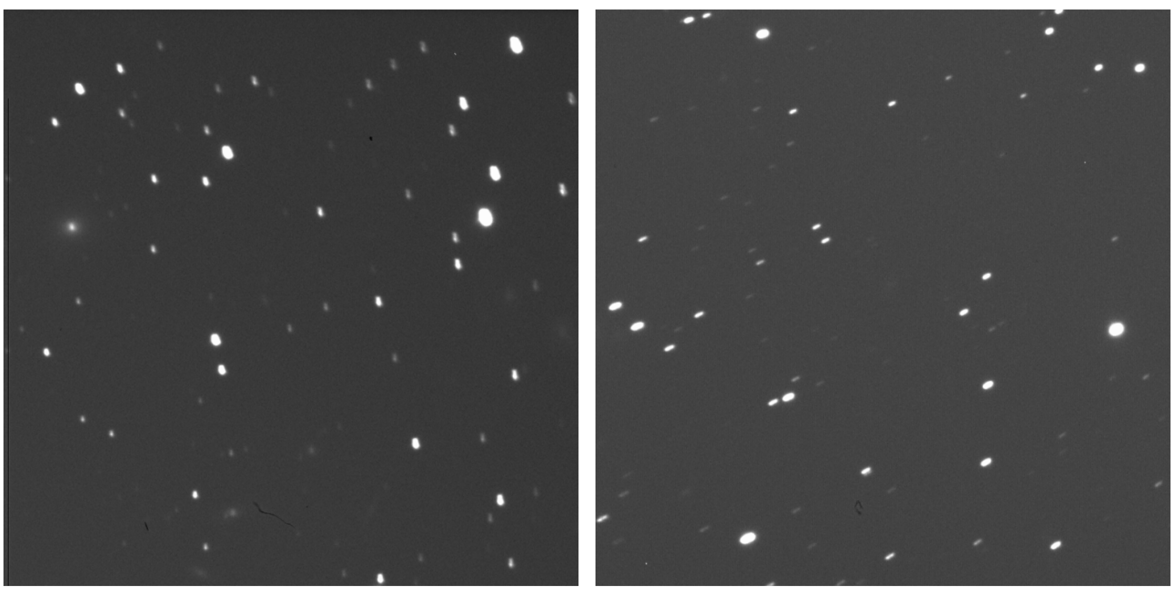


Figure 37: Images from the upper-right (left panel) and lower-left (right panel) of the MODS full field of view, showing image quality degradation due to growing astigmatism far off axis.

2.12.4 Ghost Images

The MODS optical system has two sources of ghost images: from the field lens located behind the slit and from the dichroic. All ghost images have an intensity of a few $\times 10^{-4}$ to $\sim 4\times 10^{-5}$. Field lens ghost image are present in all modes, while dichroic ghosts only appear when MODS is in dual-beam mode. Dichroic ghosts are fainter in the red channel than in blue.

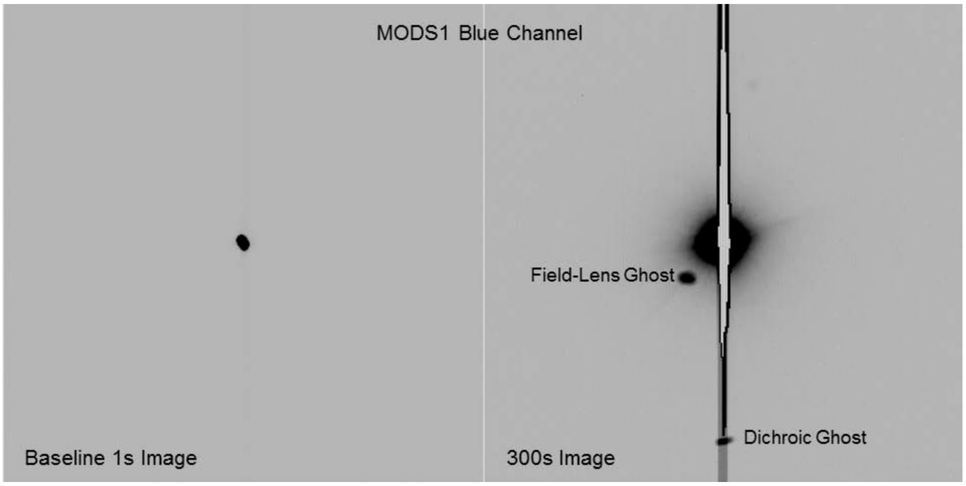


Figure 38: Example ghost images for the Blue Channel. **Left**: parent image in a 1s exposure with 37 thousand ADU in the peak pixel. Right: 300s saturation image of the same ghost mask pinhole at the same scale as left showing the field-lens and dichroic ghosts. Total counts in the peak pixel of the saturated pinhole image are ~140 million ADU.

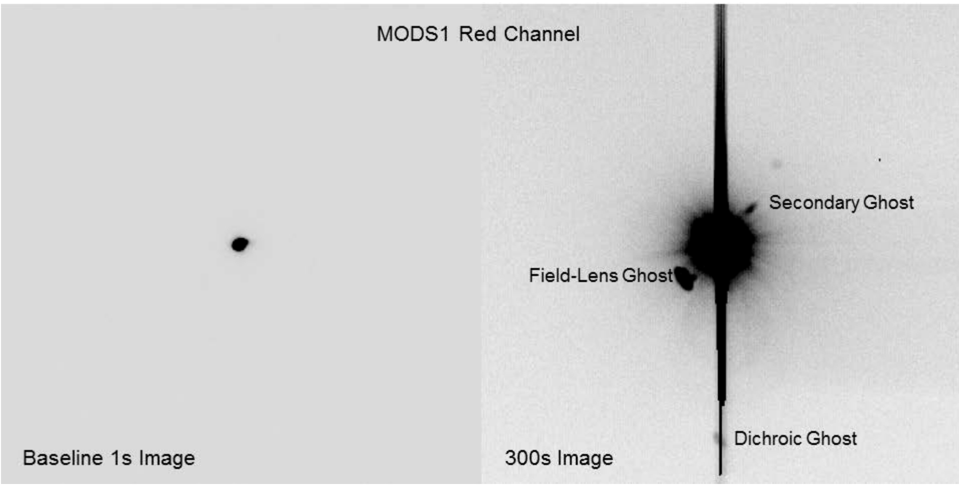


Figure 39: Red Channel ghost images. This figure uses the same aperture as in the blue-channel ghost image (**Figure** 38), but with enhanced contrast to show the much fainter red-channel dichroic ghost.

The dichroic ghost image is located immediately above the parent image of an object by ~145 pixels on the detector, as expected from the thickness of the dichroic and the 35° angle of incidence, as shown in the schematic ray trace of the dichroic ghost in the left-hand panel of Figure 40.

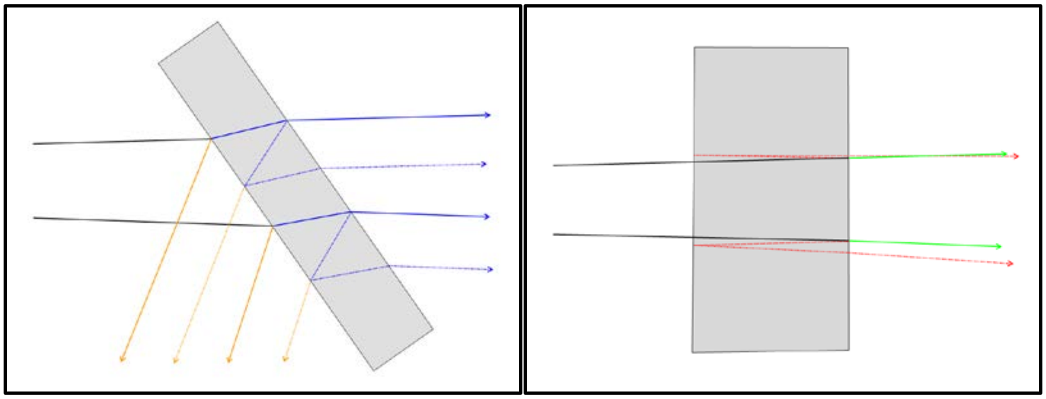


Figure 40: Ray tracings showing the origins of the dichroic ghosts (**left**) and the field-lens ghosts (**right**).

Field-lens ghost images are located along a line connecting the center of science field and the bright "parent" object. A schematic ray-tracing showing the origin of the radial field-lens ghosts is shown in Figure 40, right panel.

In general, ghost images are only visible for the very brightest stars because they are of order 10^{-4} to 10^{-5} of the brightness of the parent image. They are usually seen faintly in multi-object wavelength calibration frames for very saturated comparison lines as a faint copy of the comparison spectrum just below the original. Most people will rarely if ever see detectable ghost images in normal MODS data.

Ghost images show up most prominently is in prism mode spectra, particularly in comparison lamp spectra in which bright, saturated emission lines can leave distinct ghost images. An example is shown in Figure 41 for a blue dual-mode MOS mask prism spectrum of the Krypton comparison lamp which has bright saturated lines that lean through the dichroic.

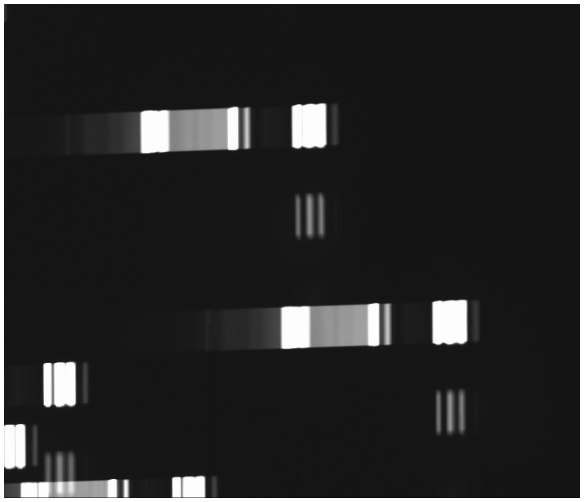


Figure 41: Blue prism Krypton MOS mask spectra, showing "red leak" lines and associated ghost image (faint 3 lines below the bright 3 in the MOS slit traces).

3 Observing in the Near-UV to Near-IR

MODS operates from 3200Å to 1.0μm, but for most practical observations the UV cutoff is around 3400Å, unless observing very bright, blue sources (e.g., most of the white dwarf and subdwarf O star spectrophotometric standards are readily detected at 3200Å).

3.1 Atmospheric Transmission

The calculated atmospheric transmittance from 3000-10500Å for airmass 1.2 (El=60°) is shown in Figure 42.

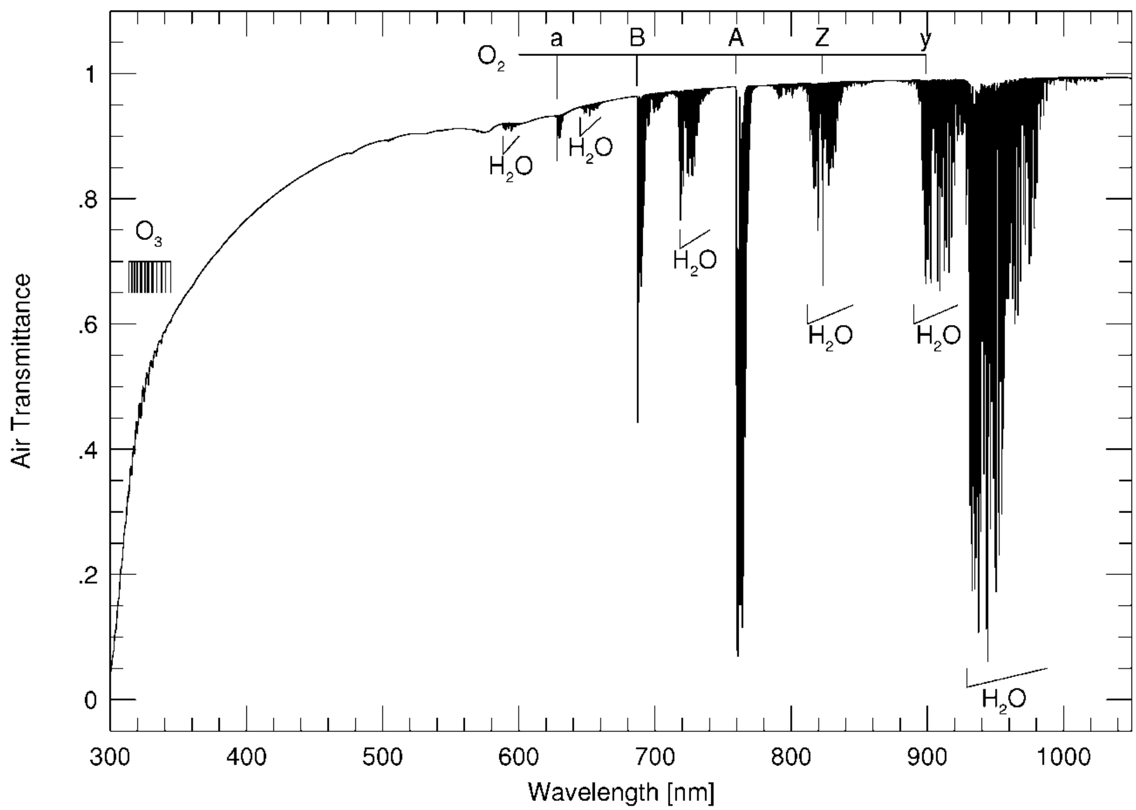


Figure 42: Model atmospheric transmittance at airmass 1.2.

At short wavelengths, transmittance is dominated by continuous Rayleigh scattering opacity from molecules and aerosols that increases towards the UV. Blue-ward of 3400Å the O_3 Huggins bands become an important source of telluric absorption features. Red-ward of 6000Å, the O_2 A and B absorption bands at 7694Å and 6867Å, respectively are the sharpest telluric features, with H_2O water vapor bands growing in importance into the near IR, especially between 9000Å and 10000Å

3.2 Atmospheric Emission

Thermal emission from the night-sky, dome, and telescope is negligible for MODS. The dominant sources of atmospheric (i.e., "background") emission will be from airglow lines arising in the upper atmosphere, light pollution from nearby population centers, and moonlight. The calculated night sky brightness during new moon for typical atmospheric conditions at airmass 1.2 (elevation 60°) is shown in Figure 43.

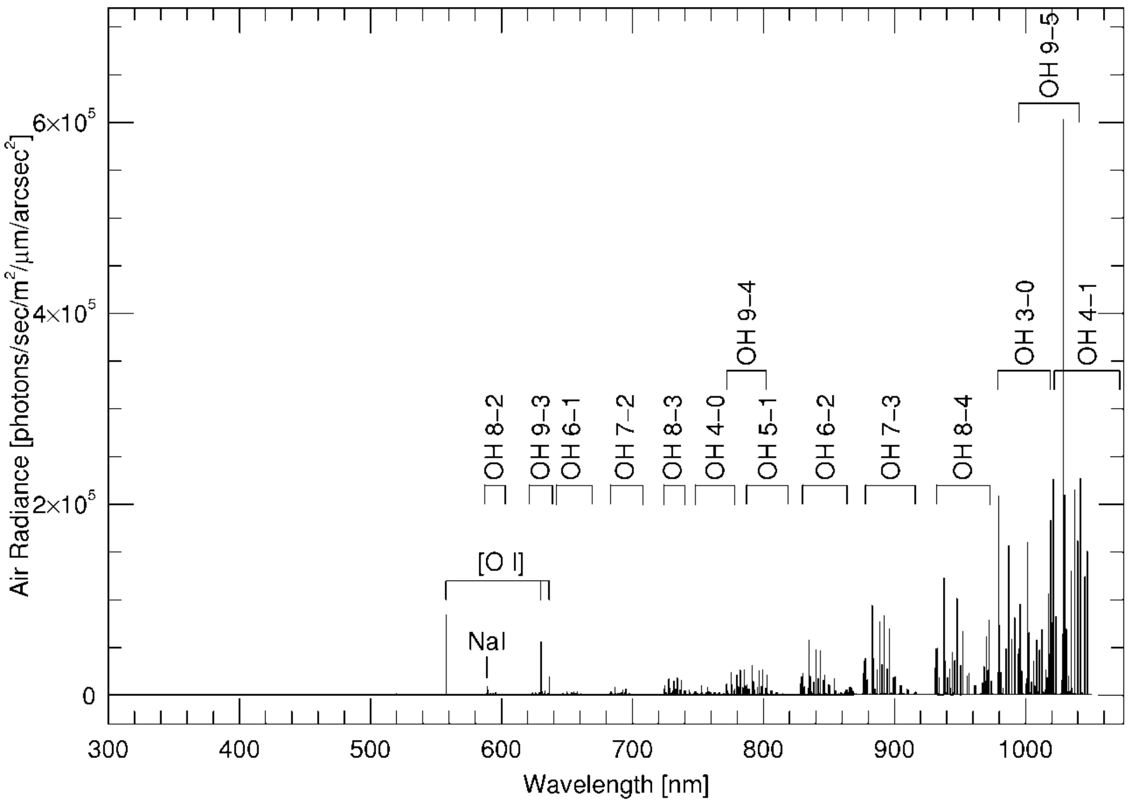


Figure 43: Model new-moon night-sky emission spectrum at airmass 1.2.

The night sky emission spectrum is dominated by the OH rotational-vibrational Meinel bands for λ≥7000Å. At bluer wavelengths, night-sky auroral lines (principally [O I] and [N I]) and upper atmosphere NaI D emission are important, augmented by emission lines and continuum from street lamps in surrounding population centers, particularly NaI D and Hg λ4358Å emission lines. Night-sky lines vary on 5-15 minute timescales throughout the night.

For very faint targets at red wavelengths (e.g., trying to observe faint high-redshift objects long-ward of 7000Å where the OH lines are important), you may wish to dither along the slit. Depending on the sizes of your objects, typical dither steps of ±10–20" along the Y-axis (along the slit) can be used with the facility segmented long-slit masks. Overheads associated with dithering are typically 5-10 seconds, dominated by waiting for the guide probe to move and the GCS to re-lock on the guide star.

OH emission lines are the dominant source of diffuse background in SDSS i and z images during dark-sky conditions. Because the MODS red CCDs are 40μm thick deep-depletion devices, they fringe less than typical thinned CCDs, and it has not been a limiting factor in taking deep images in the i and z bands.

3.3 Moonlight and Twilight Impacts

Moonlight and twilight also affect MODS performance. Both appear as a faint, blue reflected solar spectrum filling the slit. Figure 44 shows a composite of blue and red spectra taken during morning twilight of a bright supernova.

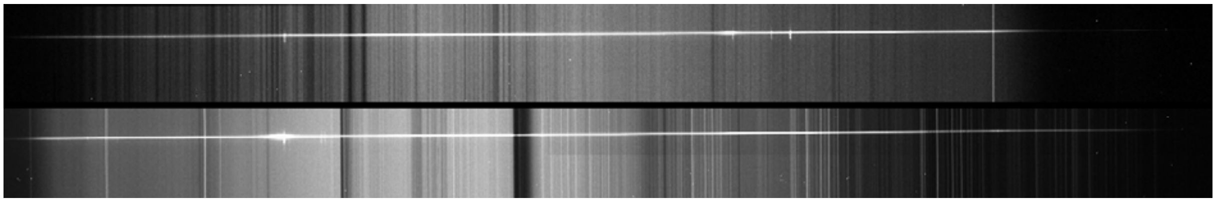


Figure 44: Spectra of SN2010jl taken during morning twilight. **Top**: Blue Channel, **Bottom**: Red Channel

Unlike the Near-IR (0.9-2.5μm), you generally cannot observe very far into astronomical twilight with MODS unless the target is very bright.

Moonlight also causes problems for the AGw unit: bright background can make it hard to find and lock-on guide stars, and can also make accurate measurement of the Shack-Hartmann spots in the WFS difficult. In general, you should avoid observing within 30° of the moon.

3.4 Differential Atmospheric Refraction

Light entering the atmosphere is refracted in the vertical direction relative to the horizon with greater refraction at bluer wavelengths. Figure 45 shows a plot of this "differential atmospheric refraction" relative to 6200Å (the guide wavelength of MODS) for Mt. Graham.

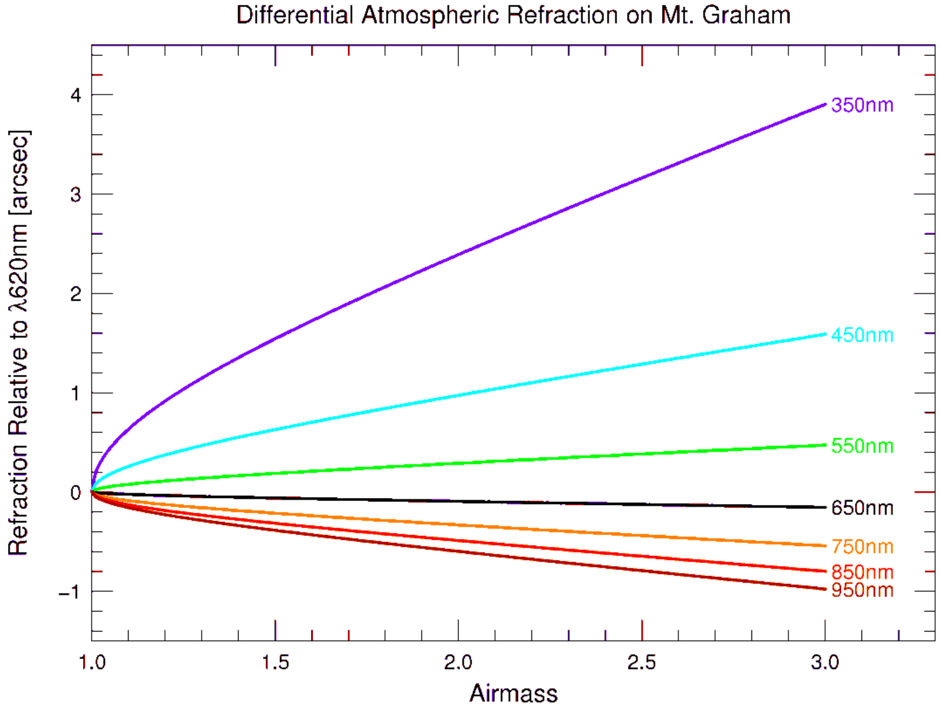


Figure 45: Differential atmospheric refraction relative to 6200Å as a function of airmass at Mt. Graham.

Different wavelengths are deflected along a great circle running from the zenith through the target. The celestial position angle of this arc is the "parallactic angle", and varies with time.

Figure 46 shows the geometry of the parallactic angle, along with plots for Mt. Graham (using the Owens 1976 atmosphere model).

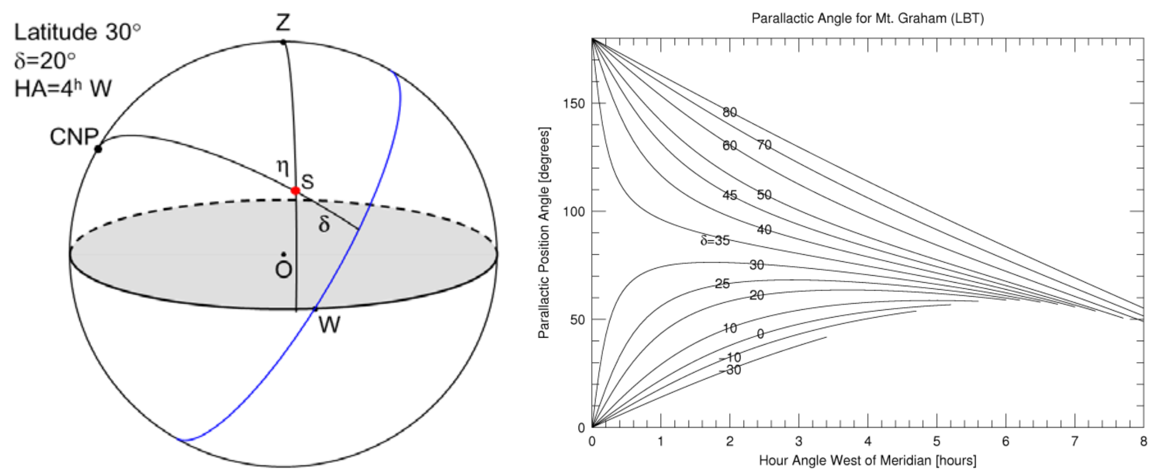


Figure 46: Left: definition of the parallactic angle (η). CNP is the Celestial North Pole, Z is the Zenith, S is the source, O is the observer, and W is the west compass point. **Right**: Parallactic angle as a function of hour angle west of the meridian for Mt. Graham for declinations δ = –30 to +80°. Curves are truncated at El=20°.

The effect on a slit spectrograph is that wavelengths near the guiding wavelength will stay at the same location in the slit as the telescope guides, but bluer (and, to a lesser extent, redder) wavelengths will deflect by different amounts along the parallactic angle. If the deflection is large enough, light will begin to fall out of the slit, particularly at blue wavelengths (see e.g., Filippenko 1982).

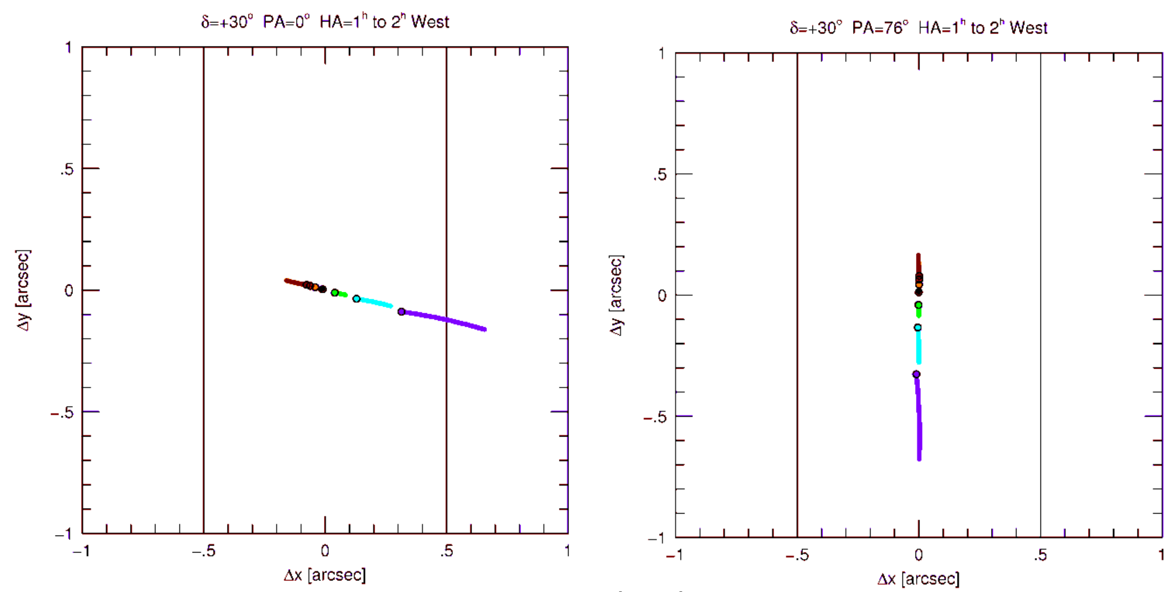


Figure 47: Differential atmospheric refraction from HA=1^h to 2^h, slit along PA=0° and PA=76° (the typical parallactic angle for this HA interval). Colors run from deep red (9500Å) to purple (3500Å) in 1000Å intervals. The circle marks the start of the tracks at HA=1^h. The guide reference wavelength is 6200Å.

Figure 47 shows calculations of differential atmospheric refraction deflection tracks relative to a 1″ slit for a source at δ=+30° observed for 1 hour from HA=1 to 2^h west of the meridian.

The first plot shows the tracks with the slit oriented along PA=0°, the second with the slit along PA=76°, the median parallactic angle during this hour angle interval.

In the case of the slit oriented along PA=0°, the bluest wavelengths (3500Å and below) start to fall out of the 1-arcsec slit about half way through the track, but in the slit aligned with the median parallactic angle for this interval (PA=76°), there will be no light lost even at the bluest wavelengths.

MODS does not have an Atmospheric Dispersion Corrector, so choosing a slit orientation that minimizes slit losses due to differential atmospheric refraction, especially at blue wavelengths, is essential.

Observing planning tools are provided on the MODS website to help determine a good slit orientation to use to minimize slit losses. Note that the "best" slit position angle is not just the parallactic angle at mid-exposure, but in long integrations it will be a combination of the refraction expected track over the integration time and the choice of slit width that determines the slit PA that minimizes slit losses. Sometimes the best slit PA can have no good guide stars available within the patrol field (this is sometimes a problem in sparse star fields at high galactic latitude). You may have to use the 180° rotated slit position reported by the planning tools. Ultimately it will require a judgment call on the part of the astronomer planning the observation, and this is why we do not offer automated ways of setting the slit PA, just tools to help you compute and visualize the effects.

Avoiding light losses due to differential refraction is why we recommend that you observe all spectrophotometric standard stars with the wide 5″ slit (LS60x5) to ensure accurate flux calibrations at the blue/UV extremes of the spectrum.

4 Observing with MODS

Basic startup and operation of MODS is performed by LBTO support astronomers. When logged into one of the observing workstations at the LBT, you will run a number of custom programs while observing with MODS, in particular

1. The MODS Control Panel GUI
2. The `modsDisp` raw image display agent and `/newdata` disk watcher
3. The MODS scripting engines: `acqMODS` and `execMODS`.
4. The `modsAlign` interactive mask alignment program (uses PyRAF and ds9)

A typical observing run requires two people: one on a workstation dedicated to operating the MODS instruments with the control panel and related programs, and a second person on a separate workstation using IRAF, IDL, or another data-analysis package to examine the incoming data, manage an observing queue, etc. The LBTO support astronomer will usually be logged into a third workstation with access to engineering programs to monitor MODS health and to take actions if there are problems.

Your LBTO support astronomer is responsible for technical instrument startup, including starting the various servers and agents needed to coordinate the activities of MODS, and for helping deal with problems. As an on-site observer, you will only run the four programs described above.

The recommended way to operate MODS for routine observing is with MODS observing scripts (§4.2). While MODS may be operated “by-hand” using the MODS control panel, this requires attention to the many details of the inner workings of the instrument and the choreography between the instrument, telescope, and IMCS that is needed for efficient observing. The MODS script engines take care of all of these details for you, as some of the steps can be quite involved and unforgiving if a crucial step is forgotten, especially late at night while suffering from the effects of high altitude and sleep deprivation.

4.1 MODS Control Panel

Most MODS functions are controlled via the MODS Control Panel, a graphical user interface (GUI) that is run on one of the observing workstations. Only one instance of the MODS GUI may be running at a time. The data taking system should stop you from launching more than one instance of the GUI, but please be aware of this restriction. Your LBTO support astronomer will show you how to start the GUI and its associated programs.

The MODS Control Panel is a multi-layered GUI with different control screens that may be selected by clicking on the icons in the GUI’s sidebar.

When launched, it starts with a small splash screen as it configures itself and builds all of the control panels, and then shows you the main “Setup” screen. The following subsections describe each of the main control panel screens. Generally, observers will only use the “Setup” and “Dashboard” screens, spending most of their time on the Dashboard.

4.1.1 Setup Screen

A screenshot of a typical MODS GUI setup screen is shown in Figure 48.

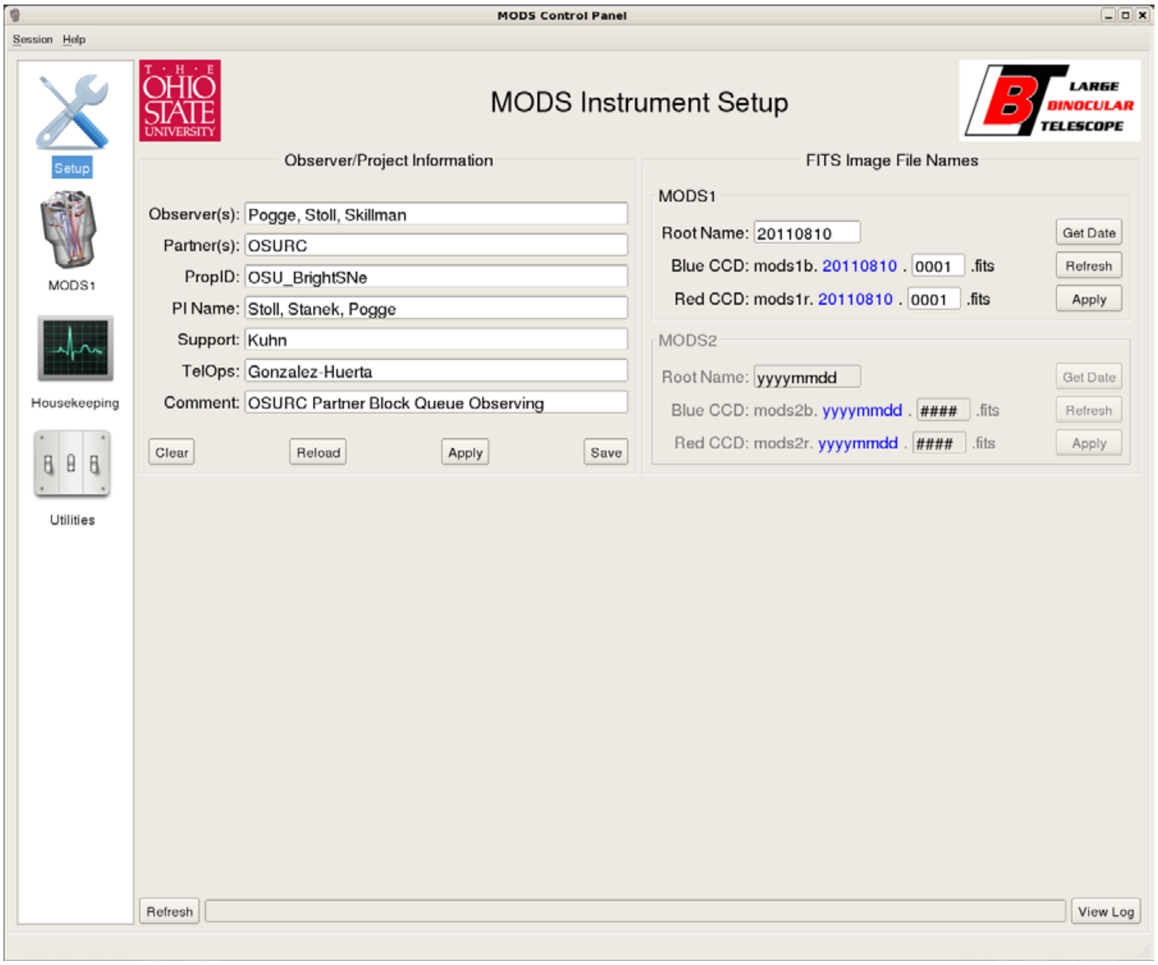


Figure 48: MODS Control Panel GUI Setup Screen

The icons for navigating the GUI are in the vertical box on the left side of the GUI. Clicking the mouse on one of these icons will take you to that control screen.

The left half of the Setup screen has entry boxes for the Observer and Project information. These set the defaults written into the FITS headers. All of the parameters in this block are saved in files owned by the individual partner observing accounts, so if LBTB observers login and start the GUI, they will see the last LBTB default.

The right half shows the filenames for the next FITS images to be written by the instrument. At present these are user-settable, with filename patterns like

```
mods1b.20110810.0001.fits
mods1r.20110810.0001.fits
```

etc. The first number, 20110810, is the UTC date in standard CCYYMMDD format. The 4-digit number is the image file counter, 0001 through 9999. At present these need to be set correctly at the start of each night, and getting them correct is the joint responsibility of the observers and LBTO support astronomers. The **Refresh** button queries the CCD controllers for the current filenames.

After changing any of the parameters in these boxes, clicking on the **Apply** button will send the changes to the CCD controllers, and clicking on the **Save** button will save the changes to the GUI restart file for your partner observing account. The **Reload** button will re-read the current GUI restart file for your partner observing account, overriding whatever values it received from the CCD controllers when the **Refresh** button is pressed (i.e., restore the most recently **Save**d values).

4.1.2 MODS Dashboard

The main control panel screen is the "Dashboard". In a full 2-MODS system there will be two dashboards, one each for MODS1 and MODS2. Figure 49 shows the MODS1 dashboard.

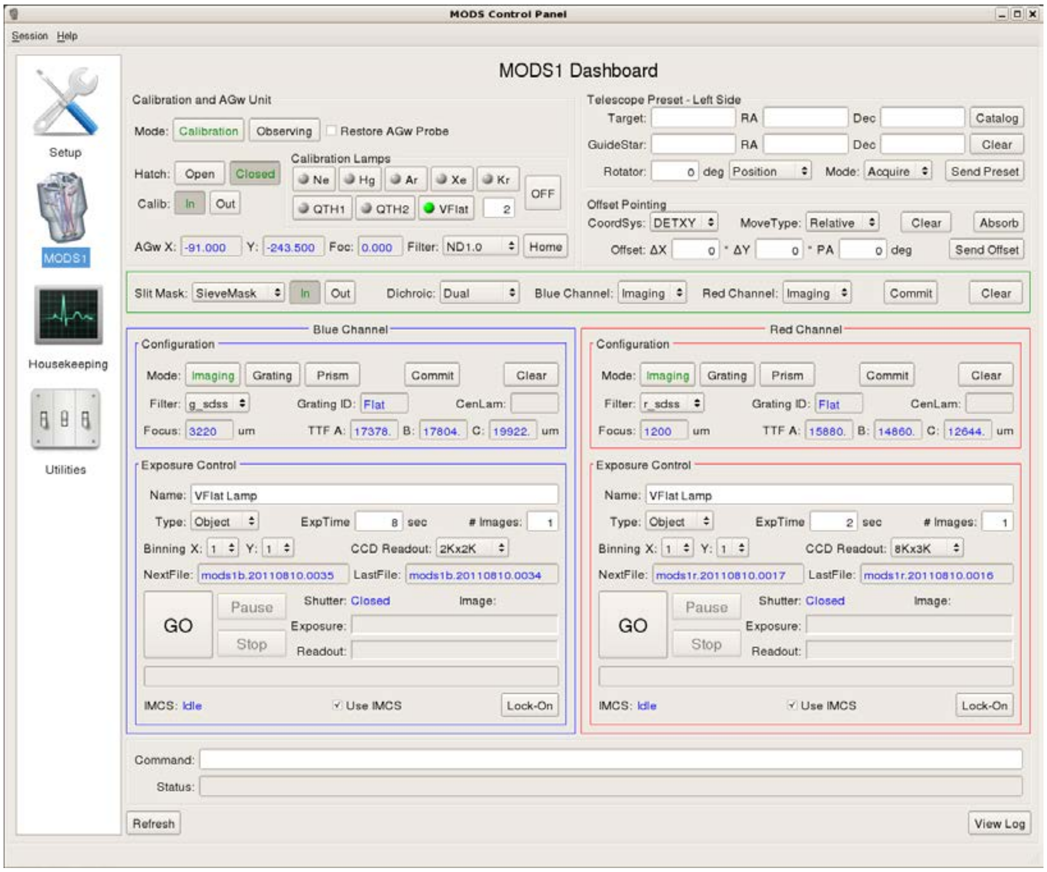


Figure 49: MODS1 dashboard screen.

The dashboard is laid out from top-to-bottom in the order that photons make their way into the instrument and through the optical system into the detectors in each channel.

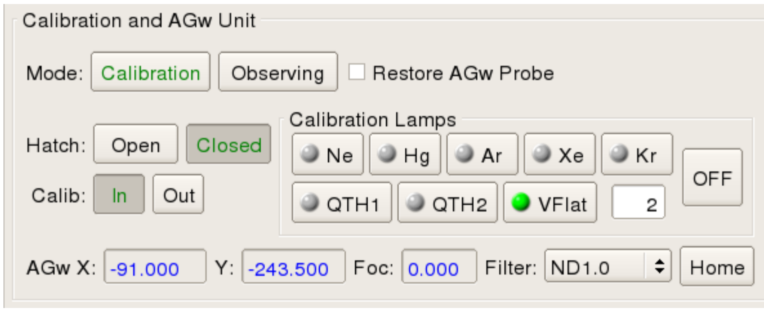
White boxes are entry boxes where you may type new parameters. When you make an entry the box background will turn pale yellow until you hit the Enter key to commit the change. Gray boxes with blue text are information displays – you cannot change these values.

When an instrument parameter is set via one of the entry widgets (text box, button, or pull-down menu), the widget will turn amber to indicate "changing state". If the requested setting is successful, the widget will revert to its normal state. If a fault occurs, the widget will turn bright red, and stay red until the fault condition has been cleared.

Occasionally, an instrument setting will be "stuck amber", meaning that the request has apparently not completed for some reason. A common cause of a stuck control is a lost completion message. **The way to clear a stuck control is to press the "Refresh" button at the lower left corner of the dashboard, and then see if the stuck control reverts to its normal state.** You may have to repeat the setting as needed.

Calibration and AGw Unit

The top left subpanel contains the controls for the common focal plane suite: the instrument dark hatch, calibration system, and AGw unit.



This lets you open the instrument to the sky (**Observing Mode**) or put in the calibration system (**Calibration Mode**):

> **Calibration Mode**: Close the instrument hatch, stow the AGw guide probe and save its location before being stowed, and then insert the calibration projector. At this point you are ready to observe internal calibration sources (flat field and comparison lamps),

> **Observing Mode**: Open the instrument hatch, retract the calibration tower, and turn off any calibration lamps that might be turned on. If the "Restore AGw Probe" box is checked, it moves the AGw guide probe back to the previously stored position.

Calibration lamps are turned on or off with the push buttons: the LED icon on the left part of the button is green when the lamp is on, the gray when the lamp is off, and red for faults

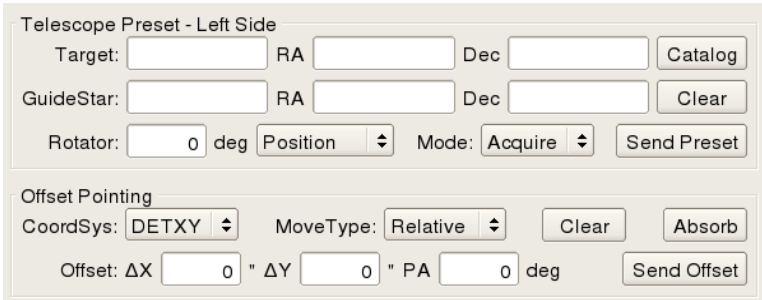
The entry box next to the "VFlat" button sets the intensity of the variable-intensity flat field lamp; 1 to 10 (see Figure 21 for the VFlat lamp intensity curves).

The "OFF" button turns off all calibration lamps.

You can also manually open/close the hatch, insert/retract the calibration projector, change the AGw guide filter, or home (stow) the AGw guide probe.

Telescope Preset Control Panel

The top right subpanel is a suite of controls for manually sending coordinates for a target and guide star to the telescope for a target preset, changing the preset mode, or sending an offset in celestial (RADEC) or slit XY-plane (DETXY) coordinates.



You can also select a target and guide star from one of the many preset catalogs of objects by pressing the "Catalog" button. This launches the catalog browser. This is most useful when using MODS during technical nights.

When MODS acquisition scripts upload targets or a script executes an offset, the parameters will appear in this window. This window does not track the current telescope parameters.

Instrument Configuration

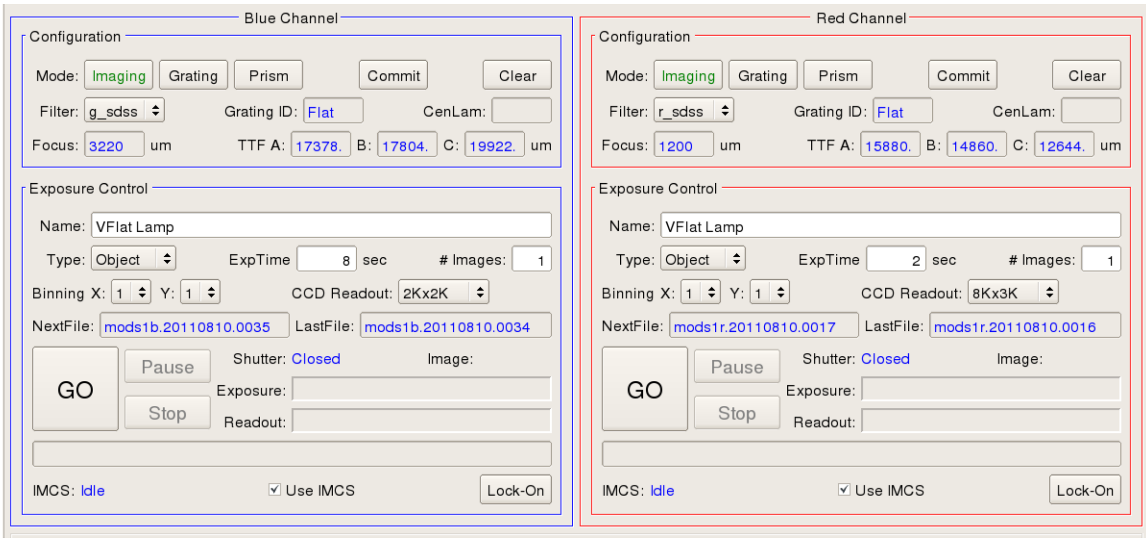
The next subpanel, outlined by the green box, provides controls for selecting the slit mask and setting the configuration of the two channels of the instrument (e.g., dual grating mode).

Slit mask selection occurs promptly: the current mask (if any) is extracted from the focal plane into the storage cassette, the storage cassette translates to the position of the requested mask, then that mask is extracted from the cassette and deployed in the focal plane. Mask insert/retract takes about 10 seconds, whereas cassette motion can take up to 15 seconds for the longest move (between positions 1 and 24).

Because configuring the instrument channels requires a lot of motions, it can take 20-40 seconds depending on the starting point. When you make a dichroic and channel selection, the "Commit" button will turn amber. You must click on the Commit button to actually send the configuration command. The "Clear" button lets you clear the selection.

Instrument Channel Control Panels

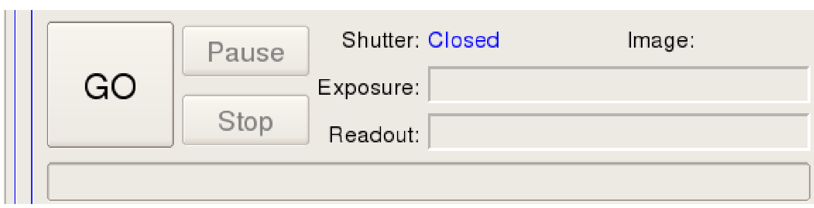
The next two subpanels, left and right, are the control panels for the blue and red spectrograph channels, outlined by the blue and red boxes, respectively.



These have controls for setting the channel configuration (disperser and filter, with informational displays about the camera focus and collimator tip/tilt/focus actuator values) and the exposure and CCD readout mode controls (image type, exposure time, number of exposures, binning, ROI, etc.). To the right of the big "GO" button are progress bars that will show exposure and readout progress graphically. Below the exposure progress bars is a status window that will display messages as exposure configuration or execution proceeds. Finally, below the status window are controls and status indicators for that channel's IMCS.

Exposure Control

The GO button starts exposures of the requested exposure time and number of exposures. During an integration, the GO button will become an Abort button, and the Stop and Pause buttons will become active.



During integrations you can take one of three actions using the labeled buttons:

1. **Abort** – Abort the integration, close the shutter if open, and discard the image.
2. **Stop** – Stop the integration, close the shutter if open, and then read out and save the image. The actual open-shutter time is recorded in the FITS header EXPTIME keyword.
3. **Pause** – Pause the integration, closing the shutter if open. The Pause button will be relabeled "Resume" and turn amber, and then wait indefinitely for one of three actions to occur:

   a. The observer clicks the **Resume** button to resume the integration. On resuming an exposure, it turns back into a gray Pause button.

b. The observer clicks the **Stop** button. This ends the exposure, reads out the CCD and writes the data to disk.

c. The observer clicks the **Abort** button, ending the exposure and discarding the data.

For exposures that have been paused for some time then resumed, the image FITS headers will record the cumulative open-shutter time in the EXPTIME keyword, and the elapsed open+closed shutter time as the DARKTIME keyword. The latter is a bit of a mis-nomer, but is useful for assessing the expected cosmic ray accumulation on an image (when the shutter is closed the "dark" CCD is still collecting charge from cosmic ray hits and the small number of hot pixels on the detectors).

While the detector is being read out, you cannot stop or abort the image acquisition, but must instead ride out the CCD read out and write-to-disk steps. If you click on **Abort** while the CCD is reading out, it should catch the abort request, and terminate subsequent exposures in the sequence (if any) after the image is readout and stored.

Aborting an imaging sequence can sometimes get messy, leaving the exposure control boxes in an apparently "stuck" state. If this happens, type "`red reset`" or "`blue reset`" in the Command Entry box (see below) to reset the state of the exposure controls.

Interactive Command Entry

Beneath the channel control panels is an entry box labeled "Command" where data-taking system commands may be entered and executed: any instrument function (including all scripting commands) may be executed by-hand with this box.

Below the command entry box is a status display that will show any command messages emitted by the data-taking system.

The interactive commands for MODS are described in the *MODS Observing Scripts* manual. Any command that can appear in a script can be typed into the Command box for execution. This is also true of a wide range of low-level engineering commands (documented elsewhere).

Other Controls

The "**Refresh**" button at the lower left of this control panel will refresh the dashboard, querying the instrument control system for updates. A full refresh takes about 10-12 seconds.

The "**View Log**" button will open a runtime communications log window showing all recent data-taking system traffic from this dashboard. This is generally only useful for engineering work.

We are reserving this space for future functions, especially for binocular MODS operation.

4.1.3 Housekeeping Screen

The housekeeping screen shows MODS engineering and housekeeping status (e.g., power state, temperature, pressures, etc.) in the system. It is primarily useful when looking at the initial state of the instrument and is generally only used by the support astronomer or telescope operator.

It also has a communication log/monitor that shows all data-taking system traffic passing through the GUI. The text in this screen is color coded: black is outgoing commands, green is command-complete messages, blue is command-in-progress status messages, amber is warning messages, red is error messages. The messages are time/date tagged, and use the instrument messaging protocol syntax employed by MODS and other OSU-built instruments. Details are discussed in the MODS engineering manuals, and should not be of general concern to observers (though they are of concern to the LBTO support astronomers and MODS instrument team members).

4.1.4 Utilities Screen

This screen shows some MODS engineering functions with locked out controls, including instrument power management controls. Regular observers should treat this console as read-only (controls are locked by default), and leave unlocking and operating instrument utilities through this screen to qualified LBTO support personnel or MODS instrument team members. You could inadvertently disable the instrument, losing valuable observing time, if you do more than just look.

4.2 MODS Observing Scripts

The most efficient way to use MODS is with its command scripting interface. MODS scripts are plain ASCII text files containing lists of instrument and telescope commands to be executed in order from the start to the end of the file. All functions of the MODS Control Panel are available via the scripting interface.

Scripts help maximize observing efficiency by automating routine observing tasks: telescope pointing, target acquisition, instrument configuration, and data acquisition. Scripts take care of the fine details of operating MODS and choreograph interactions with the LBT control systems. Properly applied, observing scripts will save observers time that might otherwise be lost to errors resulting from trying to remember all of the instrument and observing setup steps late at night or after a long hiatus from observing with the LBT.

There are five types of MODS scripts, distinguished by their filename extensions:

1. **Target Acquisition (.acq)** scripts that point the LBT to a new spectroscopic target, setup the AGw for guiding and active optics, and take through-slit and field acquisition images for alignment of the target with the slit mask.
2. **Observing (.obs)** scripts that acquire science images of a spectroscopic target once it has been aligned with the slit mask.
3. **Imaging (.img)** scripts, a hybrid of .acq and .obs scripts, for direct imaging observations that do not require alignment with a slit mask.
4. **Calibration (.cal)** scripts that acquire bias, flat field, and wavelength calibration data.
5. **Instrument Procedure (.pro)** scripts that perform instrument setup, shutdown, and housekeeping tasks.

Scripts are executed using special "script engines": programs run in Linux terminal shells that read and process the script files and then execute the script commands in a prescribed sequence. There are two script engines for MODS:

acqMODS – executes target acquisition (.acq) scripts

execMODS – executes observing (.obs and .img), calibration (.cal), and instrument setup procedure (.pro) scripts.

This division recognizes the different requirements of target and data acquisition for spectroscopy: modern active-optics telescopes require very close choreography between telescope, instrument, and guiding/active optics systems during target acquisition, but once science data acquisition begins most of the activity is centered on the instrument and consists primarily of monitoring the exposure progress.

MODS scripts are highly re-entrant: an observing script interrupted by errors or other problems can be restarted from any point within the script without editing the source file. The MODS script execution engines also feature robust error trapping and a flexible point-of-fault recovery (abort/retry/ignore) facility to notify observers of problems and provide pathways to quick resolution.

To help observers create MODS scripts, the `modsTools` suite of script preparation tools are available for observers to install on their computers. These tools create scripts that can be used as-is or as templates for crafting more sophisticated observing sequences. They ensure that observers start with syntactically correct script files as they prepare for MODS observing.

For each MODS spectral target you create two scripts: an acquisition (.acq) script to point the telescope and align the slit mask with the target, and an observing (.obs) script that acquires the science data. Imaging observations don't require detailed alignment with a slit mask, so a single hybrid imaging (.img) script is used to point the telescope and take images.

Consider a long-slit grating spectral observation of a z=6.5 QSO. You would create two scripts for this target:

1. `j1151.acq` – target acquisition script (thru-slit and field images)
2. `j1151.obs` – long-slit spectral observation script

At the telescope, you would execute the observation following these steps:

1. Point the telescope and take thru-slit and field images after locking on the guide star:
   ```
   acqMODS j1151.acq
   ```
2. When `acqMODS` pauses, use the `modsAlign` program (§4.5) to align the target with the slit using the two acquisition images in the `/newdata` directory:
   ```
   modsAlign –l mods1r.20110929.0021.fits mod1r.20110929.0022.fits
   ```
   … mark the slit and target, then accept and execute the computed offset …
3. Resume `acqMODS` from its paused state, and it will take a confirmatory thru-slit image to make sure the target is where you want it on the slit.
4. Reconfigure MODS for spectroscopy and start the science integrations:
   ```
   execMODS j1151.obs
   ```

And so on...

Both long-slit and multi-slit spectroscopy observations follow a basic 3-step sequence of actions:

1. acquire the target
2. align the targets with the slit
3. start taking science data.

If errors occur, the acquisition and observing scripting system is fully reentrant, allowing flexible resumption of observing once the problem has been corrected.

Imaging (.img) scripts are a hybrid of .acq and .obs scripts, executing target acquisition and science data taking in a single script. A pause is inserted between target acquisition and first science images to wait for the observer to confirm that the WFS collimation correction loop has converged adequately before proceeding.

See the *MODS Observing Scripts* manual for details of how to create and execute scripts, handle errors, and access the full scripting command set.

4.3 Where do the MODS data go?

Step 1: CCD Controller to MODS Data Server

A MODS CCD image is first read off the CCD into memory on the CCD control computer (e.g., M1.RC for the MODS1 Red Channel, M1.BC for the MODS1 Blue Channel). From memory it is written onto a transfer disk shared between the DOS-based CCD control computer and the MODS data server machine (a Linux workstation named `mods1data` for MODS1, and `mods2data` for MODS2).

Once on the transfer disk, a dedicated instance of the Caliban data-transfer daemon running on the data server copies it from the transfer disk and writes it onto the `/lhome/data` staging disk in FITS format. Data from the red and blue channels are written to the same data server staging disk. Once written, its FITS header is checked and augmented with additional archive and engineering keywords, its header is scanned and the running data log in `/Logs/` is updated, , and the image is ready to be copied to the LBTO data archive. The step of copying the raw image from the transfer disk onto the data server's staging disk is between 4 and 12 seconds, depending on the size of the image (this is a known bottleneck in the system we hope to improve with future hardware upgrades we will qualify first with MODS2). Post-processing of the image header and logging take less than a second.

This final transfer-and-process step is *asynchronous*: if a sequence of images is being acquired, the next image in the sequence will be started as soon as the last file is written to the inter-machine transfer disk, and the final transfer-and-process step will occur while the next image starts.

IMPORTANT NOTE:

It is at the data-transfer step between the CCD control computer and the MODS data server that the data-transfer queue can stall. The symptom is that the `LastFile` counter will fail to increment (see GUI screenshots in §4.1.2) and images will stop appearing in the `modsDisp` windows, despite the fact that the `NextFile` counter is incrementing. If the difference between `LastFile` and `NextFile` grows larger, the data-transfer queue has stalled.

If you notice that the transfer queue has stalled, type the command

```
fitsflush
```

in the Command window on the MODS dashboard GUI. This should restart ("flush") the FITS data transfer queue, and you'll start seeing the `LastImage` counter increment and images appearing on the disk.

Step 2: Data Server to the LBTO Archive Staging Disk (/newdata)

After a MODS FITS image MODS data server's staging disk has been processed for archiving, it is then copied across the network to the LBTO "new data" archive staging disk named, appropriately enough, "`/newdata`". The transfer from the MODS data server to the LBTO /newdata disk usually takes around 1 second for unbinned 8K×3K images.

Data written to `/newdata` are read-only, but may be copied onto the observing workstation disks for further analysis.

The `/newdata` disk is where new MODS images first become available to the observers on the observing workstations. This disk is where `modsDisp` (§4.4) will watch for new raw-images to display, and where `modsAlign` (§4.5) will get thru-slit and field images for mask alignment.

Step 3: /newdata to LBTO archive (/Repository and beyond)

Each image that appears on `/newdata` will be immediately ingested by the LBTO data archive software, triggering a sequence of events that typically take no more than a couple minutes to complete. These steps include (in approximately this order):

1. Image FITS header keywords are read and the archive database is updated.
2. The image is copied to `/Repository/<UTDate>` for access on subsequent days.
3. The image is gzip compressed and filed on the `/archive` disk (no user access).
4. The image copied to the Tucson archive machine.
5. The Tucson archive repeats steps 1 through 4 above.
6. The Tucson archive sends copies as needed to the Germany & Italy archives.

Within a few minutes multiple copies of each image will be distributed across a network of RAID6 data arrays in the observatory archive machines.

The images will stay on the `/newdata` disk until noon the following day when they are deleted to make room for the next night's data. Images copied to the `/Repository` disk will be available (read-only) for a month or two, stored in subdirectories organized by date. For example, data from UTC 2011 Dec 24 will be stored in `/Repository/20111224/`. Guider and WFS images taken during that same night will be stored in a GCS subdirectory of this same folder. The `/Repository` disk is kept organized by the archive software; older data are automatically deleted to make room for the newest data. Both `/newdata` and `/Repository` are available (read-only) to observers logged into the observing workstations at the LBT.

The `PARTNER`, `PROPID`, and `PI_NAME` FITS header keywords are used to assign ownership of the data, primarily by the `PARTNER` keyword. The `PARTNER` is defined by the observatory to be one or more of these reserved values:

Partner	Code
LBT Observatory Staff	**`LBTO`**
LBTB (Germany) Partner Observing	**`LBTB`**
INAF (Italy) Partner Observing	**`INAF`**
Ohio State & Research Corp Partners	**`OSURC`**
Arizona Partner Observing	**`AZ`**

for regular science operations. Additional `PARTNER` IDs (e.g., `COMMISSIONING` and `CALIBRATION`) are used for technical observing and special applications. The `PROPID` and `PI_NAME` are used differently by different partners and are user definable (or at least defined within a partner group, for example the OSURC partner block has internal conventions for how to assign `PROPID` and `PI_NAME` values for its observing queue).

If multiple partners are sharing data, `PARTNER` can be a comma-separated list, for example

```
PARTNER AZ,LBTB
```

with no spaces before or after the comma. This will allow observers from either AZ or LBTB to access the data from the archive. Note that **`CALIBRATION`** partner ID is a special flag that should be used for all calibration data (biases, flats, comparison lamps, etc.) that allows all partners access to calibration images.

4.4 modsDisp Raw Data Display

The `modsDisp` program will display the latest raw MODS images on dedicated ds9 display windows. It is run by typing

```
modsDisp
```

in an xterminal window. While multiple instances of `modsDisp` may be run on the network**, only one instance per workstation is allowed**.

The `modsDisp` program will open one dedicated ds9 window for each active MODS channel. As each new image is written to `/newdata`, `modsDisp` will open and display it in the appropriate ds9 window, and a print a brief summary of header information in the xterminal window. `modsDisp` will typically "catch" a new image on `/newdata` within 1-3 seconds.

The usual practice is to start `modsDisp` on the same workstation as you are running the MODS Control Panel GUI (I usually put the MODS GUI on the right-hand monitor with an xterm for running the scripting engines, and run `modsDisp` on the left monitor). Other instances of modsDisp are run on the second astronomer and support astronomer's workstations, respectively. This lets all users watch the progress of MODS data-taking, and is a convenient way to have the latest raw filenames available for cut-and-paste into other programs (e.g., `modsAlign`, IRAF, etc.).

A few important caveats to keep in mind as you use modsDisp and its related ds9 windows:

1. The ds9 displays are **look-only**; IRAF cannot interact with these images. This is by design: IRAF's does not like to share its image display and interaction pipes. To avoid confusing and potentially crippling resource conflicts by asking IRAF to share, if you want to run `imexamine` or other IRAF tasks on raw images, you need to open a separate IRAF session with its own ds9 display for this purpose. We recommend using a **different** workstation than the one running the MODS Control Panel GUI.
2. `modsDisp` works by watching the `/newdata` disk for new arrivals. Sometimes it gets out of sync and crashes back to the Linux prompt (with a spray of unhelpful Python error traceback). In these cases, restart `modsDisp` and start again. Note that you do not have to kill and restart the ds9 windows it originally launched. Ctrl+C typed in the `modsDisp` window will kill a hung program and let you start over.
3. While images are displayed on the ds9 windows you can pan, zoom, mess with the color map, etc., but once a new image arrives, your changes will be undone (it tries to always reset to a known default configuration). Except for the most cursory examination, open a separate IRAF/IDL/whatever instance to look at the data offline.

`modsDisp` is written in Python, and will likely be improved and extended over time.

4.5 modsAlign Interactive Mask Alignment Tool

`modsAlign` is a standalone Python program that will interactively lead you through the process of aligning targets with the slit mask. It launches a named ds9 image display tool and uses the PyRAF python interface to IRAF to compute the offset and/or instrument rotational offset needed to align the mask with the targets, and executes the offset.

`modsAlign` works with pairs of images:

An image of the target field through the slit mask ("thru-mask image").

An image of the target field with the slit mask retracted ("field image").

There are two alignment modes: **long-slit** and **multi-slit**. For long-slit mask alignment, `modsAlign` gets the identity of the facility slit mask from the image FITS header and uses that information to setup the program. For multi-slit mask alignment, you give `modsAlign` the name of the MMS file used to create the mask. This tells it where the alignment star holes (the 4×4″ holes centered on field stars) are located in the mask. All multi-object masks must have a minimum 2 alignment star holes for `modsAlign` to work, but 3-4 usually give better results.

`modsAlign` guides the user through the steps needed to align your target with the mask, computes the target offset, and then sends the offset to the telescope.

`modsAlign` can also work with a single thru-slit image if the slit is wide enough to have the star image fully within the aperture. This single-image use of modsAlign is common for acquiring spectrophotometric standard stars in the 5-arcsecond wide slit.

Detailed worked examples for both alignment modes are given in the MODS Observing Scripts manual, where it is used in the context of the `acqMODS` target acquisition script engine (the primary way that observers will interact with MODS and `modsAlign`).

4.6 modsView Target Visualization and Guide Star Selection Tool

`modsView` is a python script for visualizing the MODS target acquisition scripts (.acq or .img files) and selecting suitable guide stars. It uses [SAOImage DS9] to display a Digitized Sky Survey (DSS) image of the target field with a graphical overlay of the MODS focal plane showing the science and patrol fields, and labeling the positions of USNO NOMAD1 catalog stars in the field with their R-band magnitudes. Figure 50 shows a `modsView` screenshot.

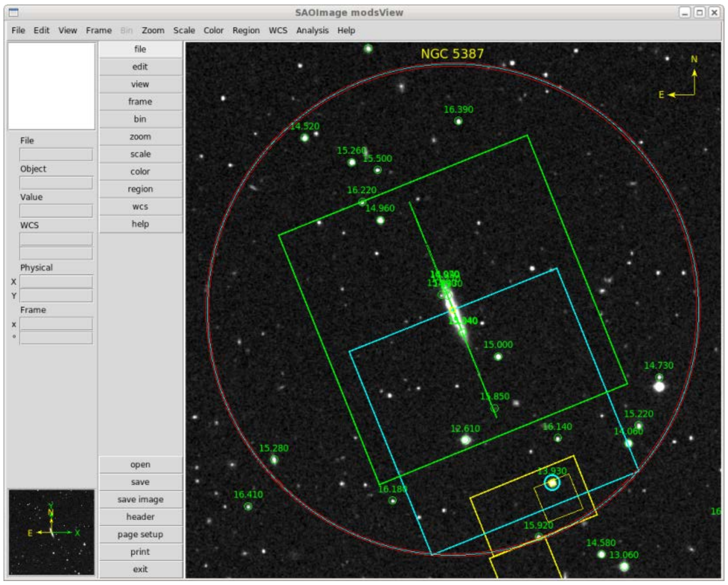


Figure 50: `modsView` display of a long-slit target acquisition script

In addition to using DSS images, you can use a FITS image of the field provided it has a valid world coordinate system (WCS) with a precise astrometric solution in its image header.

`modsView` will draw the outlines of the slits for the MODS facility long-slit masks, and it can overlay multi-object mask slit locations by loading in a valid MODS mask design (MMS) file with the `--mms` option. This latter feature is useful for helping identify multi-object fields at the telescope.

The primary use of `modsView` is to verify target acquisition scripts (.acq or .img files) created using the `modsTools` package. It will verify that the selected guide star is within the guide patrol field after the telescope preset, and after any offsets requested as part of the target acquisition (e.g., for blind offsets to a faint target). You can also display the approximate region of the guide probe's shadow to see if the choice of guide stars is occulting any of the slits. This is useful at the telescope if unexpected problems arise during a target acquisition, you can use `modsView` to see what the script is trying to do visually.

To assist in selecting guide stars, the `--find` option will print a list of candidate guide stars that satisfy the magnitude limits and patrol field constraints for the current pointing (including any offsets). At the telescope, this is useful for allowing the observers to fix acquisition scripts that have poor choices of guide stars.

Copies of `modsView` and its companion program `luciView` are installed on the LBTO mountain-top observing computers.

5 MODS Calibration

This section describes the basic calibration procedures for MODS. Standard facility scripts are provided to acquire the calibration data described below. Ask the support astronomer for the current set (also see the LBTO Wiki's `PartnerObserving` sections for the most up-to-date notes).

5.1 Calibration Plan

A summary of the basic calibration data needed to reduce MODS data is given in Table 12.

Table 12: Basic Instrument Calibration Data

Mode	Calibration	Frequency	Notes
Imaging	3K×3K Bias	nightly	5 images minimum
	Lamp Flats	once per run	5 images/filter
	Sky Flats	once per run	1-2 images/filter
Grating Spectroscopy	8K×3K Bias	nightly	5 images minimum
	Pixel Flats	nightly	5 images/configuration
	Comparison Lamps	once per run	1 spectrum/lamp/mask
	MOS Lamp Flats	once per run	3 spectra/mask
	Twilight Flats	one per run	1 spectrum/mask as needed
Prism Spectroscopy	4K×3K Bias	nightly	5 images minimum
	Spectral Flats	nightly	5 spectra/mask
	Comparison Lamps	once per run	1 spectrum/lamp/mask
	Twilight Flats	once per run	1spectrum/mask as needed

5.2 Bias ("Zero") Images

MODS science CCD biases are very stable and only need to be obtained once per night for each of the major CCD region-of-interest readout modes used during that night. Five (5) biases provide sufficient signal-to-noise for most applications when median combined.

At present, 2D Biases are not required to reduce the full-frame (8K×3K) images as the pre-scan columns remove most of the bias structure without significant residual 2D bias structure. Imaging- (3K×3K) and Prism- (4K×3K) mode images still require separate bias frames until we get overscan working for sub-frame readout on the CCDs (a stubborn bug we haven't managed to root out yet), and it remains to be seen if sub-frame readout introduces significant residual 2D bias structure in the images.

Standard scripts are provided on the mountain for acquiring bias images as part of the calibration procedure. The dome enclosure should be dark (enclosure lights off) while taking bias frames.

5.3 Dark Frames

Measured dark rates on both the red- and blue-channel CCDs are ~0.5 e^{-}/pixel/hour (see Table 8), so we have determined that taking explicit dark frames is not an indicated calibration step with MODS, and would only add noise in most cases. No scripts are provided for taking dark frames.

5.4 Flat Fields

All internal flat fields should be taken with the telescope stationary and pointed at the Zenith. They should not be taken while the telescope is moving. The instrument must be dark (closed hatch in "Calibration Mode"), and with all dome enclosure lights **turned OFF**. We still have some unresolved light leaks in the instrument near the mounting point with the instrument rotator, but our leak mitigation measures may not be suitable in all cases.

We have no indication that flats need to be taken "at position" on a target, as the combination of the general stability of the instrument and the image motion compensation system (IMCS) obviates the need for in-place flats. Slit flats can be used, with at most a small shift in wavelength, to remove fringing at the far red end of the Red Channel range for very red targets, but because the fringe amplitude is at most 2% peak-to-trough, the fringe pattern is only visible in data at very high Signal-to-Noise Ratios.

5.4.1 Imaging Flats

Imaging flats taken with the variable-intensity flat field (VFlat) lamp work well for most filters except the UV (e.g. u_sdss), where one of the QTH lamps should be used to ensure sufficient counts. However, the internal flats show a ~2% top-to-bottom gradient from scattered light internal to the calibration illumination system. Twilight sky flats can be used as illumination correction frames to correct for this gradient, and because most of the pixel-to-pixel flat fielding can be done with the internal lamp flats, only 1 or 2 well-exposed sky flats per filter are required to create the necessary illumination correction frames. This eliminates the general difficulty of obtaining twilight sky flats at the LBT.

In general, imaging flats are very stable on run timescales because the filters are way out of focus (right in front of the CCD field flattener lenses on the dewars), they are rarely removed or handled, and so are in a protected and thus relatively clean environment.

Typical flats should be exposed to deliver an average of 30,000 ADU per pixel, about the middle of the dynamic range, to ensure that the flats are always well in the linear regime of the CCD response. A minimum of 5 flats is needed in order to eliminate cosmic rays. Fixed pattern noise is more obvious in the UV imaging flats, mostly picking up annealing artifacts in the thin blue CCDs.

There are no lamp-and-filter combinations that permit simultaneous acquisition of blue and red flats, so we have found that they need to be acquired serially. A series of standard scripts are provided at the telescope to acquire basic flat field images, and we recommend acquiring imaging flats for the red- and blue-only modes without the dichroic (this also eliminates some artifacts due to low-level ghost images from the dichroic in very bright flats).

Internal lamp flats should only be taken with the telescope stationary and pointed at the Zenith, and with the imaging mask in place. The imaging mask acts as part of the fore-optics baffling for the instrument, and reduced stray light entering the system. Procedures for taking twilight flats are still being worked out, as this requires help from the telescope operator, and there are differences of opinion regarding whether the telescope should track but dither or be fixed and allowed to drift. We remain agnostic about either method, and leave that to the preferences of the observer.

5.4.2 Grating Spectroscopy Pixel Flats

The main color-free component of spectra flat field images is pixel-to-pixel variation in gain, including gain differences between the quadrants of the device and between the even and odd channels within each quadrant (the even/odd effect noted above).

The procedure that we have found works best for grating spectral flats is one we have adapted from the practice with the Keck LRIS instrument: using slit-less spectra of flat field lamps to create color-free "pixel flats". These capture enough light in the UV and far-red ends of the spectral range to get us well into the fixed-pattern noise limited regime for most of the spectral coverage of the detectors.

Blue-channel pixel flats are created using a combination of slit-less flats of the QTH lamps acquired with the clear and UG5 filters (5 each), the latter to suppress the red-end of the spectra in favor of more blue light (all flat-field lamps are intrinsically very red). Dividing by the color terms removes the wiggles from the UG5 filter. Twilight sky illumination is not recommended, as there is too much UV in the twilight sky, and we get unacceptable UV fixed-pattern artifacts in the resulting pixel flats.

Red-channel pixel flats are taken with the clear filter and the internal VFLAT lamp. While we have had success taking slit-less twilight flats in the red, they are not demonstrably better than internal lamp flats and are not worth the pain of chasing the twilight exposure times (better to use that time for slit illumination correction spectra or twilight imaging flats). We therefore do not recommend taking slit-less flats of the twilight sky in any mode.

Standard scripts for taking grating pixel flats are provided at the observatory, and on the MODS webpage.

The basic procedure is to configure the instrument for grating spectroscopy (dual-mode or either red- or blue-only mode as required), but instead of using one of the slit masks, insert the imaging mask into the focal plane. The internal calibration lamps are used for illumination. Five (5) flats are taken in each mode, with the goal of getting slit-less lamp spectra with typical peak signal levels of 30-35,000 ADU to stay well within the linear regime. Bias-subtracted frames are stacked to remove any cosmic rays, then the color term is divided out to leave just the pixel-to-pixel variations. The resulting image has a global mean value of 1.0, but each quadrant will have slightly different levels, reflecting the different conversion gains for each quadrant and the even/odd pixel differences within each quadrant.

As with imaging flats, pixel flats should be taken with the telescope stationary and pointed at the Zenith. Dome lights need to be turned OFF to avoid contaminating the spectra with light leaking into the instrument (the enclosure lights are bright metal-halide lamps). We suggest taking pixel flats at least nightly, or every-other night.

Pixel flats are used for all target spectra (objects and standard stars). Any real wavelength-dependent wiggles in the CCD wavelength response (e.g., due to the dichroic transmission) will be calibrated out later using observations of spectrophotometric standard stars.

Taking pixel flats in the prism mode is not indicated because the large spectral pixels lead to a wide range of spectral intensities and a risk of saturation at the low-dispersion red end (the continuum lamps are all very red in color). We strongly advise against taking prism pixel flats.

5.4.3 Grating Spectral Slit Flats

We recommend acquiring a few (3 each) continuum lamp spectral flats through the individual long-slits in the red for use as fringe corrector frames in the far red end of the spectrum. Blue slit flats, by contrast, are not needed for fringe correction, but can be used to capture low-level features not seen in pixel flats. Scripts to acquire useful spectral slit flats are provided at the telescope for the most commonly used facility long-slit masks. A summary of nominal exposure times for grating spectral slit flats for the four main facility long-slit masks is given in Table 13.

Table 13: Grating Spectral Slit Flat Nominal Exposure Times

Mode	Lamp	Filter	Slit Width (arcsec)			
			0.6″	0.8″	1.0″	1.2″
Blue Only	QTH	ND1.5	40	20	15	12
		UG5	17	8	6	4
Blue Dual	QTH	ND1.5	30	20	16	15
		UG5	10	8	7	6
Red Only	VFlat 10	Clear	2.5	1.5	1.0	1.0
Red Dual	VFlat 10	Clear	3.0	2.0	1.5	1.5
	QTH	ND1.5	2.5	1.5	1.0	1.0
			sec	sec	sec	sec

The exposure times are computed for 1x1 binning, and assuming that the minimum exposure time interval is 0.5 seconds, and the target is a maximum per-pixel data value of about half the full data range (30K ADU). Scaling between slits of different width is nominally linear, but we round down to be conservative with respect to saturation limits. The table above is intended as guidance only, and the standard scripts are reset annually since lamp brightness can change over time.

The MODS Red-Channel CCD is a thick (40μm) deep-depletion device, so fringing is generally small (2-3% max peak-to-trough amplitude beyond 8500Å) compared to typical CCDs, and should not constitute a major correction for most faint targets, although it will become an issue when the signal to noise is in the high 10s in that part of the spectrum.

For MOS masks, the spectral slit flats in both red and blue channels are essential for helping create high-quality traces of the slits for MOS reductions. By comparing the flat field spectra slit-to-slit, you can determine any gray-shift between the slits due to differences in the slit throughput (cut width differences, changes in image quality especially at the far edges of the field, etc.).

Because spectral slit flats, especially for the multitude of MOS masks, are not time critical (they are primarily for spectral trace finding and illumination correction), it is a good idea to execute these during cloudy nights if so unfortunate, or spread them out over your afternoon or post-handoff hours, but remember to have the telescope pointed at the **Zenith** with the enclosure lights turned off when you take them.

5.4.4 Prism Mode Spectral Slit Flats

For the Prism modes, slitless flats saturate, so we cannot use pixel flats as we do with the grating mode, and therefore spectral slit flats are needed.

Because of the low dispersion of the prisms, the standard slit flat is taken using **the narrowest 0.3-arcsec slit mask (LS5x60x0.3)**. MOS prism masks with wider slits will need to be scaled by a factor of 0.3/*w*, where *w* is the slit width in arcsec. Since this may require exposures of less than 0.5 sec duration (the minimum allowed), using wider slits will require reducing the intensity of the VFLAT lamp.

A summary of typical Prism mode flat field exposures for the 0.3″ long-slit mask is given in Table 14.

Table 14: Prism Spectral Slit Flat Nominal Exposure Times

Channel	Mode	Lamp	Filter	Exp (s)
Blue	Dual	VFLAT 5	Clear	5
		VFLAT 10	UG5	10
		QTH	UG5	1
	Blue-Only	QTH	ND1.5	1
		VFLAT 10	UG5	10
Red	Dual	VFLAT 5	GG495	1
	Red-Only	VFLAT 5	GG495	1

The dispersion of a prism is a strong function of wavelength, with lower dispersion at longer wavelengths. This means the spectral width of a pixel (in Å/pixel) is *larger* at the red end of the spectrum, and because flat field lamps are intrinsically red in color, there is a very strong spectral gradient from the blue to red end of prism spectral flats.

In short, this means that flat field calibration of Prism spectra remains very challenging, and is very strongly dependent on the particular science application. This is not a routine mode and requires black-belt level spectroscopy skills. We will continue to develop ways to flat field prism spectra, especially MOS spectra, as we gain more on-sky experience with the system.

5.4.5 Twilight Sky Flats

Twilight sky (evening or dawn) flats are often used for (1) slit illumination corrections, (2) multi-slit inter-calibration corrections, or (3) imaging-mode sky flats.

Slit Illumination Corrections:

Spectroscopic programs that need to use the entire long slit (e.g., observations of a galaxy or nebula that fills most of the science FoV) will likely require at least 1 or 2 twilight spectral flats in red and blue to help perform a high-precision illumination correction. There is a slight (2%) gradient from top-to-bottom due to the internal lamp illumination system that such twilight flats will remove. We have achieved good (<0.5%) sky subtractions in the central 1-arcminute segment of the facility long-slit masks for single targets without using twilight sky flats because the slow gradient is free of structure (the laser-cut slits are extremely clean and parallel: <1% width variations on small and large scales).

MOS Mask Inter-Calibration Corrections:

Because it is impractical (read: a waste of good telescope time) to put a standard star down the slit of every slit on an MOS mask, twilight sky flats can be used to determine inter-slit calibration corrections for a mask. Lamp flats also work well for this purpose especially if there are a lot of masks to calibrate as taking twilight spectra of all MOS masks for a run would be impractical. The flat field lamp or twilight sky observations through the MOS mask give you the relative throughput of each slit. If all slits were the same design size, this should be a small correction because of the generally high precision of the laser cutting machine provided the masks are kept clean of debris that can block the slits. The only instance in which observation of a standard star through one of the slits in an MOS mask is indicated is when accurate absolute calibrations are required for the science. If you need a good relative calibration, the regular wide-slit standard star spectra will be sufficient combined with the inter-slit "gray shift" found from the lamp or twilight spectra through the mask.

Imaging Sky Flats

Imaging programs will need to take at least one set of twilight sky flats during the course of a run, as the 2% gradient due to the internal calibration lamps will produce poor results if used without a proper twilight sky correction. Only one or at most two twilight flats are needed with signal ~10K ADU to ensure a good illumination correction (the high signal-to-noise data for good pixel-to-pixel correction comes from the internal lamp flats).

Scripts for taking these calibrations reside on the LBTO mountain computers, and are updated annually by LBTO support astronomers.

5.5 Wavelength Calibration ("Comparison Lamps")

We recommend taking wavelength calibration lamps through the 0.6-arcsec long-slit mask for grating comparison lamp spectra, and the 0.3-arcsec long-slit mask for the prism comparison lamp spectra. For the grating, 0.6-arcsec is the design-reference slit and you will have 80-100 reasonably bright and unblended lines to work with in the red, maybe 50 in the blue, which covers the range of interest. For the prism, the 0.3-arcsec slit is the smallest slit that will be imaged cleanly by the camera optics, and gives the least blended spectra (see below).

Wavelength calibrations are very stable, particularly the high-order terms that represent the details of the optical design (including optical aberrations), but you can see small, shifts of order 1-2 pixels at most due to the residual global image motion in the IMCS system (see §2.10). This small shift is readily measured and removed using night sky lines.

Only one (1) exposure per lamp or lamp combination is needed: the exposures are very short (1-5 seconds), and there are many 10s of lines, so even single CR hits are not a problem (you don't risk losing too many lines to cosmic ray hits). Short exposures plus long readout times in full-frame mode mean you could waste a lot of time taking a lot of extra comparison lamp data that doesn't give you any benefit. The MODS calibration lamp system's integrating sphere and projection optics are very efficient, and the standard scripts take comparison lamp spectra through the ND1.5 filter to avoid badly saturating the spectra.

Unlike flat fields and bias frames, it is possible to take comparison lamp spectra during the afternoon with instrument dark and full dome lights on(!), but the telescope must be stationary and pointed at the Zenith.

5.5.1 Dispersion Solutions

For the grating modes, using the IRAF `identify` task as a prototype, we recommend performing a 5th order polynomial fit to the data. This gives an excellent representation of the high-order terms in the wavelength calibration function; whereas a 4th order fit leaves significant systematic residuals and 6th order polynomial does not measurably improve the fit. In round numbers, the linear dispersion terms are 0.5Å/pixel in the blue grating, 0.8Å/pixel in the red grating for unbinned pixels.

5.5.2 Calibration Lamp Files

On the MODS webpage we provide annotated plots of MODS 1D comparison lamp spectra taken in the grating and prism modes. Lines are identified with wavelengths in units of Ångstroms. The line lists are in 2-column ASCII text format (the default format for IRAF), and only those lines positively identified in MODS comparison lamp spectra. The line wavelengths in the calibration tables are taken from the NIST Handbook of Basic Atomic Spectroscopic Data. A set of representative line plots is given in Appendix C.

5.5.3 Prism Mode Wavelength Calibration

For prism mode the lower resolutions (R=100-500) with subsequent greater line blending makes wavelength calibration very challenging. We recommend using the 0.3-arcsec slit for long-slit prism comparison lamps, and single rather than multiple lamp comparison spectra to minimize line blending.

A second effect is that with the larger spectral pixels from the prisms and the small but non-trivial leakage through the dichroic beyond the nominal dichroic cross-over, there are significant "out of band" artifacts in the comparison lamp spectra, primarily from very bright, saturated emission lines that are slightly out of focus because they are from so far out of range. This can be seen in the spectra of the Krypton lamp taken with a 0.3-arcsec pinhole slit during lab testing in Figure 51. The out-of-band red emission lines appear at the far right.

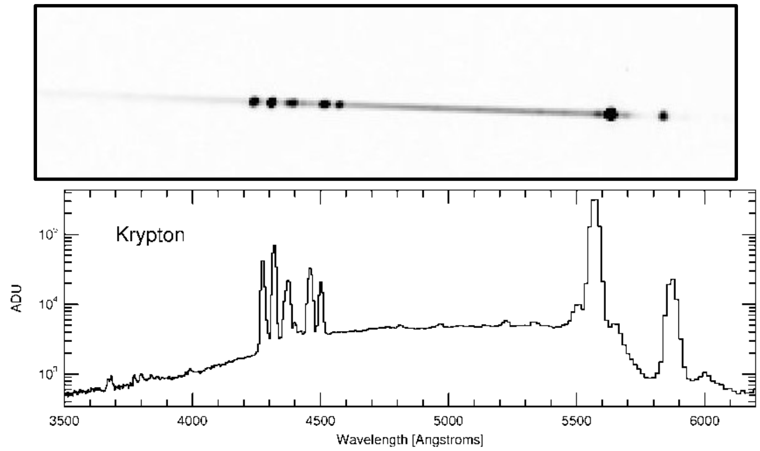


Figure 51: Prism spectra of the Krypton comparison lamp and extracted spectral scan.

There are two manifestations of this leakage in dual mode. For blue prism spectra with the dichroic, the QTH lamp spectral flats have red “banding” artifacts. An example of dichroic spectral red-leak in a blue prism flat is shown in Figure 52. Note also that ghost images are visible in this picture (e.g., as in Figure 41).

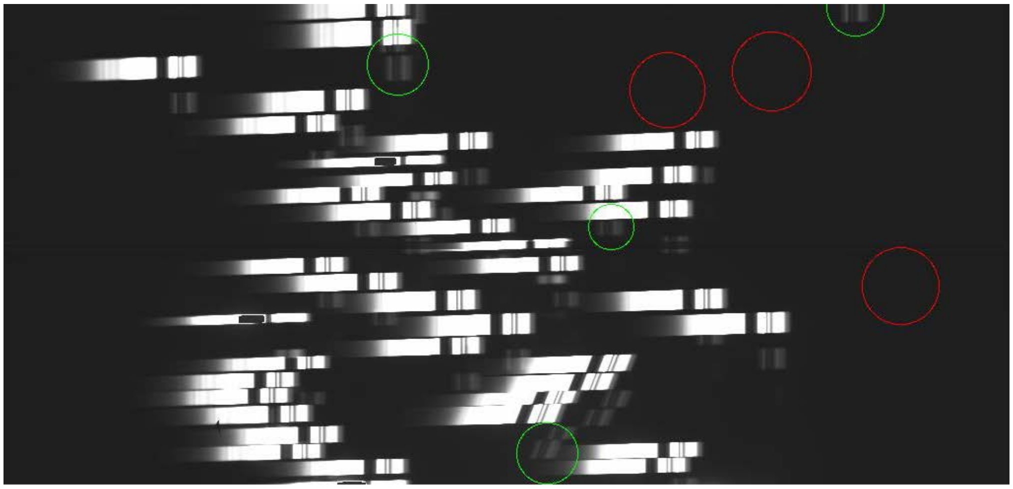


Figure 52: QTH lamp flat field through a MOS mask showing red leak and ghosts.

Notice how at the red (right) end of each spectrum there is a dark gap, then a bright band (wide/narrow/wide). Immediately below this you see a faint ghost of this pattern (circled in green; the red circles were leftover from a previous plot). The first, wide dark band moving left to right is the dichroic cutoff, and then the bright 3-part banded structure to the right of that is from small, few percent transmission wiggles in the red dichroic transmission curve (see Figure 9). They are enhanced because of the combination of the red spectrum of the QTH lamp (more light per Ångstrom) and the lower prism dispersion in the red (more Ångstroms per pixel).

A smaller but measurable “blue leak” through the blue side of the dichroic cross-over is seen in red-channel prism spectra. However, because prism spectral pixels are *smaller* in the blue, and there are fewer bright blue emission lines in the comparison lamp spectra, the effect is much less pronounced (or problematic). **Error! Reference source not found.**shows a red channel Krypton lamp prism spectrum demonstrating this effect.

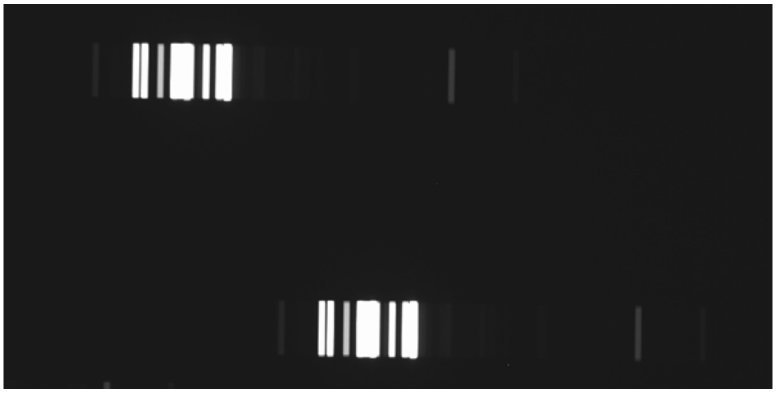


Figure 53: Red prism Krypton MOS mask spectra, showing "blue leak" lines to the right (dispersion is in the reverse direction compared to blue spectra in raw red images).

As should be clear, these artifacts are unavoidable given the properties of the prisms, lamps, and dichroic, and have implications for how you observe with multi-slit prism masks.

5.6 Spectrophotometric Standard Stars

MODS operates from 3200Å to 10000Å and we need to use standard stars with well-determined fluxes from UV to Near-IR. This section describes our preferred set of flux standard stars and our recommended spectrophotometric calibration strategy.

5.6.1 Primary Spectrophotometric Standards

The recommended MODS Primary Spectrophotometric Standard Stars are derived from the HST CALSPEC database. These are a combination of the well-observed northern-hemisphere standards from the list of Oke (1990 AJ, 99, 1621), and the four HST White Dwarf Primary spectrophotometric standards of Bohlin, Colina, & Finlay (1995 AJ, 100, 1316). These latter four stars are listed in **boldface** in Table 15.

Table 15: MODS Primary Spectrophotometric Standard Stars

Star	RA[1]	Dec[1]	Sp Type	m_{5556}	pmRA[2]	pmDec[2]
G191-B2B[3]	05:05:30.613	+52:49:51.96	DA0	11.85	+7.45	–89.54
GD 71[4]	05:52:27.614	+15:53:13.75	DA1	13.03	+85	–174
Feige 34	10:39:36.740	+43:06:09.26	sdO	11.25	+14.1	–25.0
Feige 66[5]	12:37:23.517	+25:03:59.88	sdO	10.54	+3.0	–26.0
Feige 67	12:41:51.791	+17:31:19.76	sdO	11.89	–6.2	–36.3
GD 153[6]	12:57:02.337	+22:01:52:68	DA1	13.35	–46	–204
Hz 43[7]	13:16:21.853	+29:05:55.38	DA1	12.91	–157.96	–110.23
Hz 44	13:23:35.258	+36:07:59.51	sdO	11.74	–61.6	–3.1
BD+33°2642	15:51:59.886	+32:56:54.33	B2IV	10.81	–13.6	+0.7
BD+28 4211[8]	21:51:11.021	+28:51:50.36	sdOp	10.56	–35.6	–58.7
Feige 110	23:19:58.398	–05:09:56.16	sdO	11.88	–10.7	+0.3
units	J2000	J2000		mag	mas/yr	mas/yr

Notes:

1. RA & Dec are FK5 coordinates, Equinox J2000, Epoch 2000 from Simbad
2. pmRA & pmDec are proper motions in mas/yr, FK5 Epoch 2000 from Simbad
3. G191-B2B is an HST primary white dwarf standard star. On the finder chart it is the northernmost of the two bright stars in the field.
4. GD71 is an HST primary white dwarf standard stars. The NIR extension is based on HST model spectrum.
5. Feige 66 has only relatively low-quality near-IR extension data, and should only be used in the blue or out to about 9200Å.
6. GD153 is an HST primary white dwarf star. The NIR extension is based on the HST fluxes.
7. Hz 43 is an HST primary white dwarf star. The NIR extension is based on the HST model spectrum. A faint binary M-dwarf companion, Hz43B (V=14.3), is located 3-arcsec away, so this star is not recommended in poor seeing.

8. BD+28 4211 has a faint red companion 2.8-arcsec away, and is only recommended for use in the blue channel in very good seeing.

For each primary standard star we provide flux tables with 10Å sampling on the MODS Calibration webpage, along with finding charts and template observing scripts. These tables are in IRAF-style ASCII 3-column format. Where necessary, we used HST stellar models or other HST calibration data to extend the near-IR to 10500Å. These are suitable for grating-mode calibrations. We also provide 50Å-sampling flux tables suitable for prism-mode calibrations based on the Spec50 flux tables (Massey et al. 1988 ApJ, 328, 315) with the Massey & Gronwall (1990 ApJ, 358, 344). 50Å tables are not available (or necessarily useful) for all primary standards.

The MODS flux tables have the major telluric absorption complexes censored, and we have cut out the brighter stellar absorption lines in most (but not all). Figure 54 is a regrettably crowded plot that graphically summarizes the primary standard flux table contents.

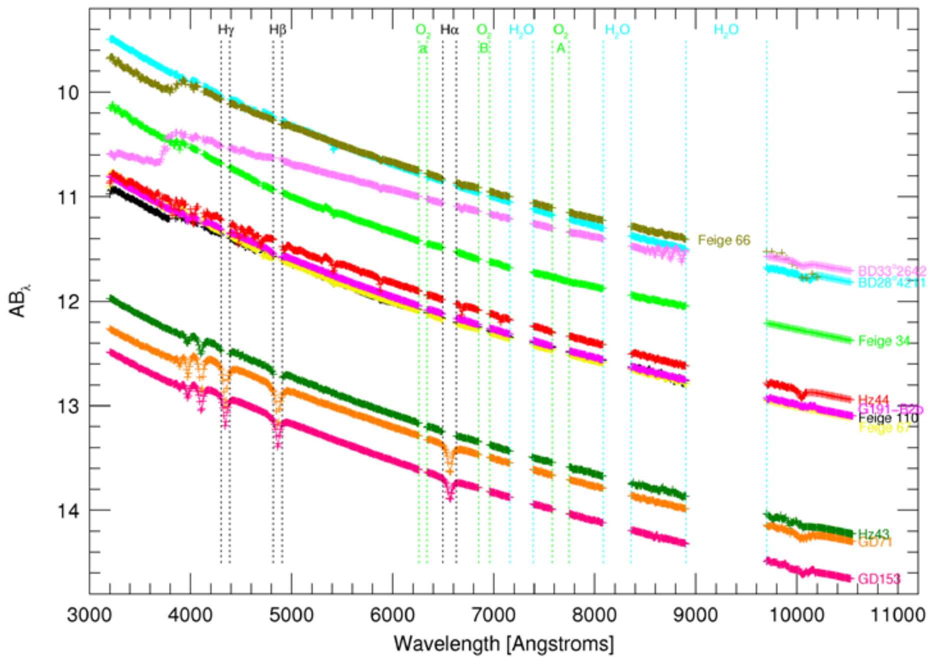


Figure 54: MODS primary spectrophotometric standard stars at 10Å sampling plotted as AB magnitudes vs. wavelength.

The original, uncensored flux tables are available from the HST CALSPEC database. Because HST CALSPEC data are for the Hubble Space Telescope, they do not contain telluric absorption features, and we must censor these spectral regions from the flux tables to avoid introducing unwanted spectral artifacts into the flux calibrations. We also censor strong absorption lines, as there is a resolution mismatch between CALSPEC and MODS spectra that can produce artifacts. At the request of observers we left the Balmer lines in the spectra of HST primary standards GD71 and GD153, but may censor these in the future. We leave this decision to individual investigators for now.

5.6.2 Secondary Spectrophotometric Standards

A set of Secondary Standard Stars is derived from the Spec50 list of Massey et al. (1988) with the Massey & Gronwall (1990) IR extensions is listed in Table 16.

Table 16: MODS Secondary Spectrophotometric Standard Stars

Star	RA	Dec	Sp Type	m_{5556}	pmRA	pmDec
Hiltner 600	06:45:13.371	+02:08:14.70	B1V	10.42	+1.2	-3.3
PG0823+546	08:26:50.4	+54:28:06	sdOC	14.36	..	..
GD 140	11:37:05.104	+29:47:58.34	DA2	12.50	-148.2	-5.3
Wolf 1346	20:34:21.883	+25:03:49.74	DA	11.59	-405.66	-564.22
units	J2000	J2000		mag	mas/yr	mas/yr

Figure 55 shows the spectra of these stars in graphical form.

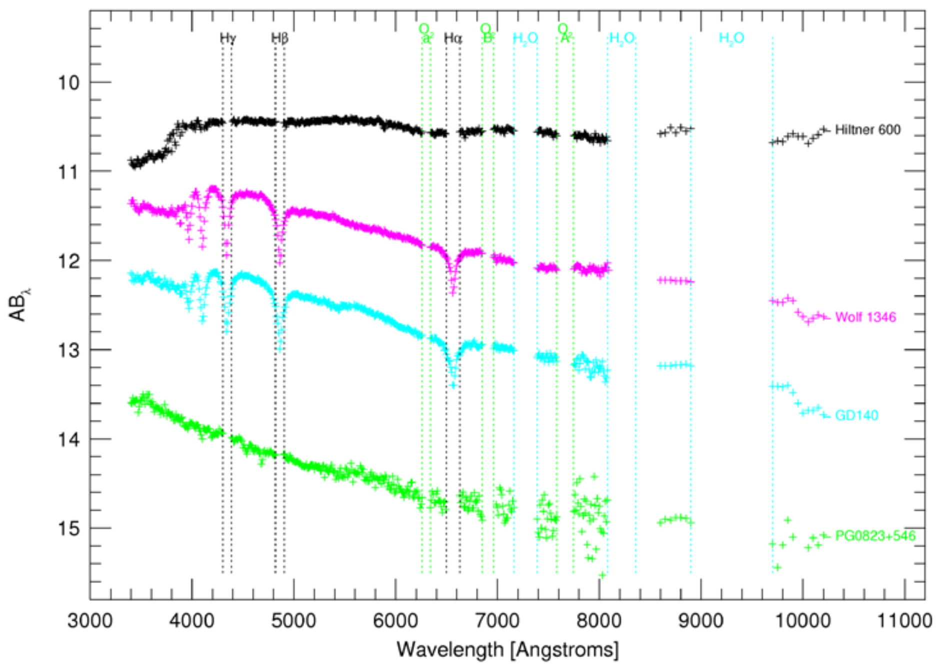


Figure 55: MODS secondary spectrophotometric standard stars at 10Å sampling plotted as AB magnitudes vs. wavelength.

The flux tables for the secondary reference stars are also posted on the MODS calibration webpage. The secondary standard star tables have been transformed into 10Å sampled versions by John Moustakas, and we also provide 50Å sampled versions for prism calibration. These stars are designated as "secondary" flux standards for our purposes because they have less broad wavelength coverage than the primary stars at the red and blue extremes, and lower-precision IR extensions than the HST standards

5.6.3 Atmospheric Extinction

At present there is no empirical atmospheric extinction curve for the Mt. Graham site. At an elevation of 3220-meters, Mt. Graham is above Kitt Peak (2100-m) and Paranal (2600-m), below Mauna Kea (4100-m), so simply adopting the published standard extinction curves for these well-characterized sites would result in significant over- and under-estimate of the approximate atmospheric extinction, especially towards bluer wavelengths.

As an interim measure until we can either obtain a good empirical extinction curve for Mt. Graham or generate an atmospheric model, we have created an approximate extinction curve for Mt. Graham using the well-measured KPNO and Cerro Paranal (ESO VLT) extinction curves scaled to an elevation of 3220m assuming an atmospheric scale height of 7000m and combined. This curve is available for download as an IRAF-style ASCII table from the MODS Calibration webpage.

The scaling we use ignores elevation-independent components of extinction like high-altitude (>5-10km) suspended aerosols, but that is a minority component and highly variable in any event (e.g., injection of particulates from volcanic eruptions, powerful sand storms, etc.). The table above also does not include time- and position-variable molecular absorption features of water-vapor, O_2, and ozone.

5.6.4 Spectrophotometric Star Observations

We recommend observing all flux standard stars with the 5-arcsec spectrophotometric slit mask (**LS60x5**). This will provide spectra across the full wavelength coverage and you will have nearly zero losses due to atmospheric dispersion and seeing. Note that resolution in the 5-arcsec slit will be seeing-dependent, but given that the flux calibrations are typically in large bins, this will have little impact on the derived response curves which have structures on much larger scales than the resolution.

Standard star spectra observed with one of the narrower slit masks will impose a substantial penalty in losses due to atmospheric dispersion at the far blue end. In part this is because a narrow slit will always have some slit losses at the blue end, exacerbated by the fact that many of the standard stars are in sparse fields that lack sufficient numbers of guide stars to always allow you to orient the slit along the parallactic angle. We do not recommend using anything but the wide slit for routine spectrophotometric standards.

We have derived good (or at least acceptable) telluric corrections from wide-slit observations of the most featureless white-dwarf primary standards. Spectral standards observed through the long-slit masks can be used to generate a telluric correction, but only if you are willing to accept significant atmospheric dispersion losses at the far blue end because many of the standard stars are in sparse fields that do not always have convenient guide stars for all position angles.

5.7 Standard Calibration Scripts

A set of standard scripts for routine calibrations like biases, flat fields, comparison lamps, and spectrophotometric standard stars are currently kept on the LBT control room observing machines in the `/home/MODSeng/modsScripts/` directory, with a parallel set of copies available on the MODS webpage.

The LBT copies of the standard scripts are read-only, but you can copy them into your partner observing account if you need to modify them. We recommend only making copies of scripts you intend to modify, as we will sometimes change key parameters in response to changes in the instrument (e.g., changes in calibration lamp brightness after replacing a burned-out lamp).

Appendix A: MODS FITS Headers

Below is a sample MODS science-image FITS header, divided into the various blocks of data. The example is drawn from various MODS1 image headers.

MODS science images are standard FITS format with single header and data units.

Basic FITS Data

FITS images are written as 16-bit integers scaled using the standard `BZERO` and `BSCALE` keywords to get all 16-bits of raw ADC data encoded.

```
SIMPLE  =                    T /
BITPIX  =                   16 /
NAXIS   =                    2 /
NAXIS1  =                 8288 /
NAXIS2  =                 3088 /
BSCALE  =                    1 / PHYSICAL=INTEGER*BSCALE+BZERO
BZERO   =                32768 /
BUNIT   = 'ADU     '           / units of physical values (LBT)
```

Detector Information

This block gives the readout configuration (binning, overscan, amplifiers, etc.) and the physical size and image scale of unbinned pixels.

```
DETECTOR= 'e2v CCD231-68 Blue CCD 1'     / Detector name
DETSIZE = '[1:8288,1:3088]'    / Unbinned size of detector full array
NAMPS   =                    4 / Number of amplifiers in the detector
GAINDL  =                    3 / Pixel integration time, in sequencer clocks
PIXITIME=            1.2000E-6 / Pixel integration time, in seconds
CCDXBIN =                    1 / CCD X-axis Binning Factor
CCDYBIN =                    1 / CCD Y-axis Binning Factor
OVERSCNX=                    0 /
OVERSCNY=                    0 /
READOUT = 'ARLBRL  '           / Amplifiers used in readout
DISPAXIS=                    1 / Spectral Dispersion Axis
PIXSCALE=                0.120 / Unbinned pixel scale [arcsec per pixel]
PIXSIZE =                 15.0 / Unbinned pixel size [microns]
```

Observatory Information

This block gives the LBT-standard information about the LBT/MGIO observing site and the telescope focal plane

```
ORIGIN  = 'MGIO-LBT'           / Location where the data was generated
OBSERVAT= 'MGIO-LBT'           / Observatory Site
TELESCOP= 'LBT-SX  '           / Telescope and Focus
FOCSCALE=                 1.67 / Focal Plane Scale [arcsec per mm]
LATITUDE=             32.70131 / Site Latitude [deg N]
LONGITUD=            109.88906 / Site Longitude [deg W]
ELEVATIO=               3221.0 / Site Elevation [meters]
```

Observer/Partner/Project Information

This block lists the observer, partner and project IDs used by the LBTO data archive, and additional information about LBTO personnel during the observing run. These data are set either by observing scripts or in the Setup screen of the MODS instrument control panel (§4.1.1).

```
OBSERVER= 'Pogge & Skillman'   / Observer(s)
```

```
PARTNER = 'OSURC   '           / LBT Project Partner(s)
PROPID  = 'OSU_HIIAbund'       / Observing Proposal ID
PI_NAME = 'Pogge   '           / Project PI Name(s)
SUPPORT = 'Pedani, Shih'       / LBT Support Scientist(s)
TELOPS  = 'Steven Allanson'    / LBT Telescope Operator(s)
```

Exposure Information

This block lists information about the exposure, including the image type, object name, exposure and dark time, and the raw filename and associated acquisition identifiers.

```
GROUP   =                    0 / Group identifier for related images
IMAGETYP= 'OBJECT  '           / Type of observation
OBJECT  = 'Dual Prism IMCS Test PA=45 El=90' / Name of object
EXPTIME =                  5.0 / Exposure time [seconds]
DARKTIME=                 7.85 / Cumulative Dark Time [seconds]
LEDFLASH=            0.0000E+0 / Time to flash lab LEDs [seconds]
FILENAME= 'mods1b.20110113.0049' / Filename assigned by the data-taking system
UNIQNAME= '110112M8.01c'       / Unique filename; if filename is invalid
ACQTAG  = 'MODS1B.20110113061700' / Unique Acquisition ID Tag
```

The `UNIQNAME` keyword is protection against accidentally overwriting image files. If an image with the same name as this file is found in the raw data directory, it writes the FITS file with UNIQNAME instead.

Instrument Configuration

This block lists the instrument (`MODS1B` = MODS1 Blue Channel), the state of the dark hatch, calibration tower, calibration lamps (the hatch is closed, the calibration tower is in, and the Krypton lamp is lit), and gives information about the slit mask, and the dichroic beam selector state.

```
INSTRUME= 'MODS1B '            / Instrument Name
HATCH   = 'CLOSED  '           / Instrument Dark Hatch
CALIB   = 'IN      '           / Calibration Tower Position
CALLAMPS= 'KR      '           / Calibration Lamps
VFLAT   =                  2.5 / Variable Intensity Flat Lamp Intensity
SLITMASK=                    6 / Slit Mask Cassette position
MASKPOS = 'IN      '           / Slit Mask Position
MASKNAME= 'LS5x60x1.0'         / Slit Mask Name
MASKINFO= '1.0 arcsec Segmented Long Slit' / Slit Mask Description
DICHROIC=                    2 / Dichroic Turret Position
DICHNAME= 'Dual    '           / Dichroic Beam Selector position ID
DICHINFO= 'CSIRO 575nm Dichroic Nr1' / Dichroic Beam Selector Description
```

This block lists the instrument configuration of the channel used (Blue) for the collimator mirror, grating, filter, and camera focus values at the start of the exposure.

```
CHANNEL = 'BLUE    '           / Channel name, Blue or Red
COLFOCUS=                18368 / Collimator Focus (A+B+C) [microns]
COLTTFA =                17086 / Collimator TTF actuator A [microns]
COLTTFB =                17925 / Collimator TTF actuator B [microns]
COLTTFC =                20092 / Collimator TTF actuator C [microns]
GRATING =                    3 / Grating Turret Position
GRATNAME= 'P450L   '           / Name of the Disperser at GRATING
GRATINFO= 'FuSi+Al Double-Pass Prism Nr1' / Description of the Disperser
GRATTILT=                19150 / Grating Tilt [microns]
GRCENLAM= '        '           / Grating nominal central wavelength [Ang]
GRORDER =                    0 / Grating order used
FILTER  =                    1 / Camera Filter Wheel Position
FILTNAME= 'Clear   '           / Camera Filter Name
FILTINFO= 'Fused Silica Clear 128x86x6mm Nr1' / Camera Filter Description
```

```
CAMFOCUS=                 3380 / Camera Primary Mirror Focus [microns]
```

Note that during an exposure the `COLTTFx` keywords will change as the IMCS steers the collimator to compensate for instrument flexure, but `COLFOCUS` will remain roughly constant (tip/tip corrections are made relative to the collimator focus vertex).

IMCS IR Laser Status

These keywords list the status of the IR laser used by the Image Motion Compensation System (IMCS).

```
IRLASER = 'ON      '           / IMCS IR Laser AC Power On or Off
IRBEAM  = 'ENABLED '           / IMCS IR Laser Beam Enabled or Disabled
IRPSET  =                  1.0 / IMCS IR Laser Beam Power Set Point [mW]
IRPOUT  =                  1.1 / IMCS IR Laser Beam Power Output [mW]
IRTEMP  =                 25.4 / IMCS IR Laser Head Temperature [deg C]
IRTSET  =                 25.5 / IMCS IR Laser Head Temp Set Point [deg C]
```

Target and Guide Star Coordinates

These keywords list the target and guide star coordinate information uploaded to the TCS by the preset used to point the telescope for this observation.

```
OBJNAME = 'M1'                 / Target Name
OBJRA   = '05:34:30.000'       / Target RA
OBJDEC  = '+22:01:00.00'       / Target DEC
OBJRADEC= 'FK5'                / Target Coordinate System
OBJEQUIN= 'J2000'              / Target Coordinate System Equinox
OBJPMRA =                 0.00 / Target RA proper motion [mas per yr]
OBJPMDEC=                 0.00 / Target Dec proper motion [mas per yr]
OBJEPOCH=              2000.00 / Target Epoch
GUINAME = 'gstar   '           / Guide Star Name
GUIRA   = '05:34:29.449'       / Guide Star RA
GUIDEC  = '+21:57:29.80'       / Guide Star DEC
GUIRADEC= 'FK5'                / Guide Star Coordinate System
GUIEQUIN= 'J2000'              / Guide Star Coord System Equinox
GUIPMRA =                 0.00 / Guide Star RA proper motion [mas per yr]
GUIPMDEC=                 0.00 / Guide Star Dec proper motion [mas per yr]
GUIEPOCH=              2000.00 / Guide Star Epoch
```

Telescope Pointing and Rotator Information

These keywords give the telescope pointing and rotator information read from the Telescope Control System (TCS) at the start of the exposure.

```
TCSLINK = 'Live    '           / TCS Communications Link Status
DATE-OBS= '2010-11-19T10:12:36.980' / UTC Date at start of obs
UTC-OBS = '10:12:36.980'       / UTC Time at start of obs
TIMESYS = 'UTC     '           / Time System
LST-OBS = '06:46:24.101'       / Local Sidereal Time at start of obs
MJD-OBS =         55519.425428 / Modified JD=JD-2400000.5 at start of obs
RADECSYS= 'FK5     '           / Coordinate System
EQUINOX =               2000.0 / Equinox of coordinates
TELRA   = '05:34:29.998'       / Telescope RA
TELDEC  = '22:00:59.963'       / Telescope DEC
POSANGLE=              0.00000 / Instrument Celestial Position Angle [deg]
TELALT  =             70.96853 / Telescope Altitude at start of obs [deg]
TELAZ   =            240.25531 / Telescope Azimuth at start of obs [deg]
PARANGLE=             52.29008 / Parallactic Angle at start of obs [deg]
ROTANGLE=           -100.34461 / Rotator Angle at start of obs [deg]
ROTMODE = 'POSITION'           / Rotator Mode
HA      = '01:12:24.101'       / Hour Angle at start of obs
ZD      =                19.03 / Zenith Distance at start of obs [deg]
```

```
AIRMASS =                 1.06 / Airmass (secZD) at start of obs
```

These parameters, except for the time, are read directly from the telescope control system. The time is the approximate time the query was received, and should be within a second or two of the actual time the shutter is opened. This “shutter lag” is measured and described in §2.11.2.

AGw Stage Configuration

These keywords list the state of the AGw (Acquisition, Guide, and Wavefront Sensing) camera stage system:

```
AGWXGP  =               -4.517 / AGW Guide Probe X focal plane position [mm]
AGWYGP  =             -138.845 / AGW Guide Probe Y focal plane position [mm]
AGWFOCUS=                0.000 / AGW Guide Probe relative focus [mm]
AGWFILT =                    2 / Guide Camera Filter Wheel position
AGWFNAME= 'F525LP  '           / Guide Camera Filter Name
AGWFINFO= 'Edmund 525nm Long-Pass Yellow 50x5mm' / Guide Camera Filter Descript
AGWXS   =               87.483 / AGW Stage X actuator position [mm]
AGWYS   =               55.837 / AGW Stage Y actuator position [mm]
AGWFS   =               47.818 / AGW Stage Focus actuator position [mm]
AGWFS0  =               38.500 / AGW Stage Focus Zero Point [mm]
```

GCS and PCS Guide Star Position Data

These keywords give data from the GCS (Guiding and Collimation System) and PCS (Pointing Control System) regarding where the GCS sent the guide probe and the measured guide star positions. These are mostly used for engineering/commissioning work.

```
GPREQ_X =                4.961 / GCS Requested guide probe PCS X [mm]
GPREQ_Y =             -138.929 / GCS Requested guide probe PCS Y [mm]
GPACT_X =                4.960 / GCS Actual guide probe PCS X [mm]
GPACT_Y =             -138.926 / GCS Actual guide probe PCX Y [mm]
GSPRED_X=                4.591 / PCS Predicted guide star X position [mm]
GSPRED_Y=             -125.829 / PCS Predicted guide star Y position [mm]
GSMEAS_X=                3.818 / GCS Measured guide star X position [mm]
GSMEAS_Y=             -124.538 / GCS Measured guide star Y position [mm]
GSDELTAX=              192.541 / GCS cumulative X guide update position [mm]
GSDELTAY=               71.543 / GCS cumulative Y guide update position [mm]
```

Instrument Environmental Monitoring Data

These keywords list the temperatures, pressures, and voltages measured in the CCD detector head electronics box at the start of the exposure.

```
DEWPRES = '9.4700E-06'         / Dewar Pressure [torr]
DEWTEMP =              -198.16 / Dewar LN2 Reservoir Temperature [deg C]
CCDTEMP =              -113.78 / CCD Mount Temperature [deg C]
HEBTEMP =                17.09 / HEB Air Temperature [deg C]
HSTEMP  =                 3.24 / HEB Post Heat Sink Air Temperature [deg C]
CTEMPIN =                 0.90 / HEB Coolant Input Temperature [deg C]
CTEMPOUT=                 2.13 / HEB Coolant Output Temperature [deg C]
TEDPOWER= 'ON      '           / HEB Thermoelectric Device Power State
LEDPOWER= 'OFF     '           / HEB External LED Power State
IGPOWER = 'ON      '           / Dewar Vacuum Ion Gauge Power State
HEB3V   =                 3.31 / HEB +3V Power Supply [VDC]
HEBFANV =                11.86 / HEB Fan Power Supply [VDC]
HEB15V  =               -15.04 / HEB -15V Power Supply [VDC]
HEB5V   =                 4.93 / HEB +5V Power Supply [VDC]
HEB24V  =                23.16 / HEB +24V Power Supply [VDC]
BOGHTRV =                 1.99 / Dewar boil-off gas heater voltage
```

Of particular interest to observers are the dewar temperature and pressure and the CCD temperature. If the LN_2 reservoir has run dry, `DEWTEMP` and `DEWPRES` will rise above the nominal values depicted above. `CCDTEMP` is the temperature of the CCD detector mount. If the detector is warming up and producing high dark counts or other warm-detector artifacts, this number will be warmer than the nominal value shown above.

Instrument Temperature Sensor Data

These keywords report the values of various instrument temperature sensors in the instrument at the start of the exposure. Sensors are located inside the instrument electronics boxes (Mechanism controller and utility boxes), on the instrument main structural truss, and sampling the air temperature inside the instrument.

```
AMBTEMP =                  0.3 / Outside Ambient Air Temperature [deg C]
TAIRTOP =                  1.6 / MODS Inside Air Temp at Top [deg C]
TAIRBOT =                  0.5 / MODS Inside Air Temp at Bottom [deg C]
TCOLLTOP=                  2.1 / Collimator Truss Tube Top Temp [deg C]
TCOLLBOT=                  0.8 / Collimator Truss Tube Bottom Temp [deg C]
IEBTEMPB=                  4.1 / Blue IEB Air Temperature [deg C]
IEBGRT_B=                  0.0 / Blue IEB Glycol Return Temperature [deg C]
IEBTEMPR=                  2.5 / Red IEB Air Temperature [deg C]
IEBGRT_R=                 -0.2 / Red IEB Glycol Return Temperature [deg C]
IUBTAIR =                  1.4 / Utility Box Air Temperature [deg C]
AGHSTEMP=                  0.0 / AGw Controller Heat Sink Temp [deg C]
```

Glycol Cooling Sensor Data

These keywords report the glycol coolant supply and return temperatures and pressures at the start of the observation.

```
GSPRES  =                 27.0 / Glycol Supply Pressure [psi-g]
GSTEMP  =                 -0.2 / Glycol Supply Temperature [deg C]
GRPRES  =                 24.7 / Glycol Return Pressure [psi-g]
GRTEMP  =                  0.0 / Glycol Return Temperature [deg C]
```

Telescope Telemetry

These keywords list the primary and secondary mirror collimation parameters at the start of the exposure.

```
M1POSX  =                0.504 / Primary Mirror X Position [mm]
M1POSY  =               -1.111 / Primary Mirror Y Position [mm]
M1POSZ  =               -0.226 / Primary Mirror Z Position [mm]
M1ROTX  =              -30.721 / Primary Mirror RX Rotation [arcsec]
M1ROTY  =                4.298 / Primary Mirror RY Rotation [arcsec]
M1ROTZ  =                0.000 / Primary Mirror RZ Rotation [arcsec]
M1CTEMP =                 4.50 / Primary Mirror Temperature [deg C]
M1ATEMP =                 0.67 / Primary Mirror Ambient Air Temp [deg C]
M2POSX  =               -4.010 / Secondary Mirror X Position [mm]
M2POSY  =               -0.317 / Secondary Mirror Y Position [mm]
M2POSZ  =                0.000 / Secondary Mirror Z Position [mm]
M2ROTX  =              148.650 / Secondary Mirror RX Rotation [arcsec]
M2ROTY  =              181.800 / Secondary Mirror RY Rotation [arcsec]
M2ROTZ  =                0.000 / Secondary Mirror RZ Rotation [arcsec]
M2CTEMP =                 4.50 / Secondary Mirror Temperature [deg C]
```

These keywords report the readings from temperature sensors located on the telescope structure. Measurements are taken at the start of the exposure. These data are important for helping track and derive the temperature corrections for the telescope collimation model, but not of much interest to observers.

```
TTEMP201=                1.614 / Channel 201 Temperature [deg C]
TTEMP202=                0.939 / Channel 202 Temperature [deg C]
TTEMP203=                0.969 / Channel 203 Temperature [deg C]
TTEMP204=                0.568 / Channel 204 Temperature [deg C]
TTEMP205=                0.731 / Channel 205 Temperature [deg C]
TTEMP206=                0.672 / Channel 206 Temperature [deg C]
TTEMP207=                0.051 / Channel 207 Temperature [deg C]
TTEMP208=                0.499 / Channel 208 Temperature [deg C]
TTEMP209=                1.072 / Channel 209 Temperature [deg C]
TTEMP210=                1.011 / Channel 210 Temperature [deg C]
TTEMP301=                0.540 / Channel 301 Temperature [deg C]
TTEMP302=                0.476 / Channel 302 Temperature [deg C]
TTEMP303=                1.351 / Channel 303 Temperature [deg C]
TTEMP304=                0.734 / Channel 304 Temperature [deg C]
TTEMP305=                1.028 / Channel 305 Temperature [deg C]
TTEMP306=                0.361 / Channel 306 Temperature [deg C]
TTEMP307=                0.282 / Channel 307 Temperature [deg C]
TTEMP308=                0.548 / Channel 308 Temperature [deg C]
TTEMP309=                1.080 / Channel 309 Temperature [deg C]
TTEMP310=                0.320 / Channel 310 Temperature [deg C]
```

LBT Weather Data

These keywords report weather conditions at the start of the exposure as read from the LBT weather station located on the roof. At present we only report ambient temperature, pressure, relative humidity, and dewpoint temperature.

```
LBTWLINK= 'Up      '           / LBT Weather Station Link State
LBTPRES =               692.70 / LBT Ambient Pressure [hPa]
LBTTEMP =                 0.20 / LBT Ambient Temperature [deg C]
LBTHUM  =                36.80 / LBT Relative Humidity [percent]
LBTDWPT =               -12.90 / LBT Dew Point [deg C]
```

Appendix B: Filter Bandpass Parameters

The MODS effective filter bandpass parameters tabulated in this manual were computed following the prescriptions of Schneider, Gunn, & Hoessel (1983). Their original formulation was in frequency units, so we adopt the reformulation of these filter parameters in wavelength units following Koornneef et al. (1986). These are the same definitions adopted by the Hubble Space Telescope and Sloan Digital Sky Survey, so they are now in broad use throughout the astronomical community (at least for ground- and space-based optical and near-IR photometry).

The filter parameters we use are formulated in terms of the **average throughput** of the filter, defined as the product of the measured filter transmission curve T_λ and the instrumental throughput Q_λ. T_λ is derived from laboratory measurements of the filter transmissions, usually provided by the filter vendors. Q_λ is estimated from the measured total transmission (including AR coatings) of the MODS lenses, the measured reflection coatings of the MODS mirrors, and the measured quantum efficiencies of the MODS CCD detectors.

For the **effective wavelength** of the filter, we adopt the **pivot wavelength**, λ_P, defined as:

$$\lambda_p = \left[\frac{\int Q_\lambda T_\lambda \lambda \, d\lambda}{\int Q_\lambda T_\lambda \frac{d\lambda}{\lambda}} \right]^{1/2}$$

The pivot wavelength has the virtue of giving an exact conversion between broadband flux densities in frequency (F_ν) and wavelength (F_λ) units:

$$\langle F_\nu \rangle = \langle F_\lambda \rangle \frac{\lambda_P^2}{c}$$

The width of a filter is poorly defined for a finite bandpass, but we will follow the successful practice of HST instruments and adopt an **effective width**, $\delta\lambda$, defined as:

$$\delta\lambda = 2\left[2\ln 2\right]^{1/2} \sigma\bar{\lambda}$$

where σ is the effective dimensionless Gaussian width of the filter

$$\sigma^2 = \left[\frac{\int Q_\lambda T_\lambda \left[\ln\left(\frac{\lambda}{\bar{\lambda}} \right) \right]^2 \frac{d\lambda}{\lambda}}{\int Q_\lambda T_\lambda \frac{d\lambda}{\lambda}} \right]$$

and $\bar{\lambda}$ is the **mean wavelength** of the bandpass defined as:

$$\bar{\lambda} = \exp\left[\frac{\int Q_\lambda T_\lambda \ln\lambda \, \frac{d\lambda}{\lambda}}{\int Q_\lambda T_\lambda \frac{d\lambda}{\lambda}} \right]$$

This unconventional definition of the mean filter wavelength in terms of the first logarithmic moment of the average throughput has the property that the corresponding mean frequency is $(c / \bar{\lambda})$, giving a value that lies between the more conventional frequency and wavelength first moments.

Finally, the **Full-Width at Half Maximum** (FWHM) of the filter is evaluated numerically by measuring the rectangular bandpass width from the average throughput curves ($Q_\lambda T_\lambda$).

When evaluating these integrals numerically for the different filters, we truncated the integration where the measured transmission fell below 0.001 at the wings of the measured transmission curves. This avoids introducing spurious shifts in the bandpass parameters because of leaks at long or short wavelengths far from the nominal filter center.

Figure 56 shows these parameters plotted for two MODS filters in direct (non-dichroic) mode: the relatively symmetric SDSS r filter and the asymmetric SDSS u filter.

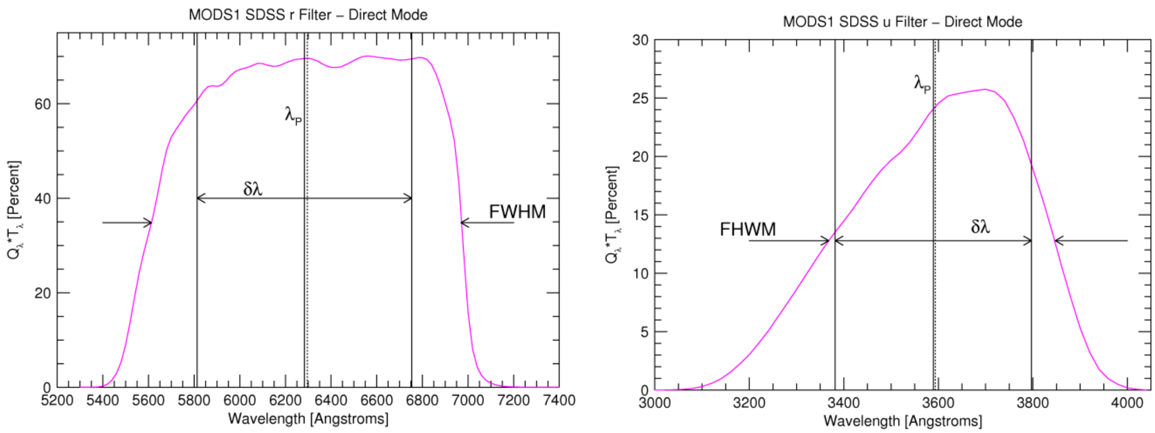


Figure 56: Filter bandpass parameters plotted for (left) SDSS r and (right) SDSS u in direct (no-dichroic) mode. The dotted vertical line near the solid line marking λ_P is the average wavelength $\bar{\lambda}$ as defined above.

Note that the effective width, $\delta\lambda$, is generally narrower than the FWHM. The effective width is used to estimate the flux in the band by multiplying the observed flux at the pivot wavelength by the effective width. The effective width is equivalent to the width of a perfectly square-sided bandpass centered on λ_P with unit transmission.

Appendix C: Wavelength Calibration Lamp Spectra

Blue GratingMode

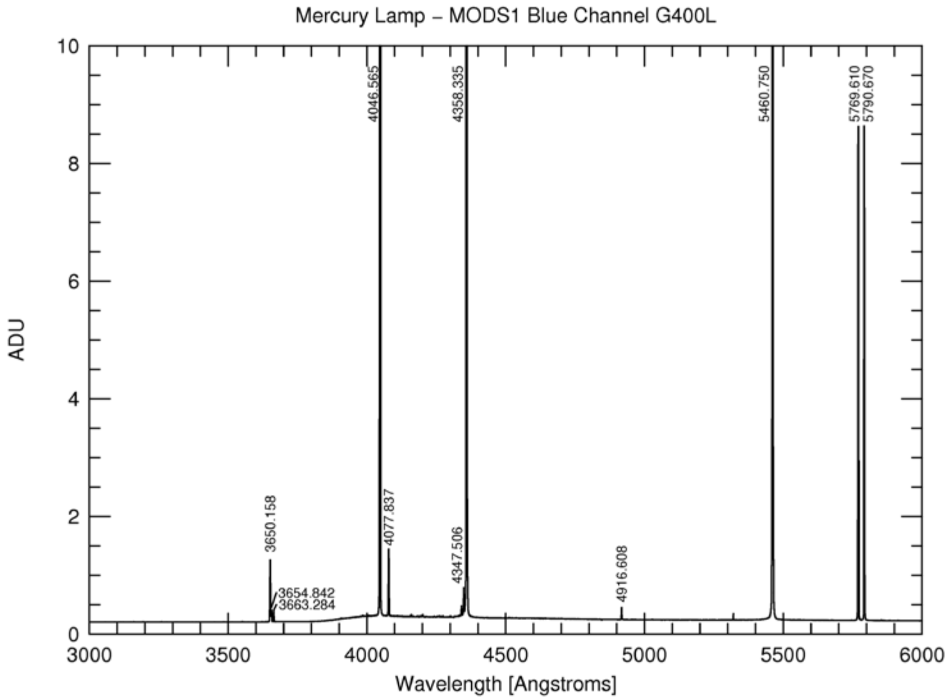


Figure 57: Hg(Ar) lamp spectrum taken with the Blue Grating (G400L)

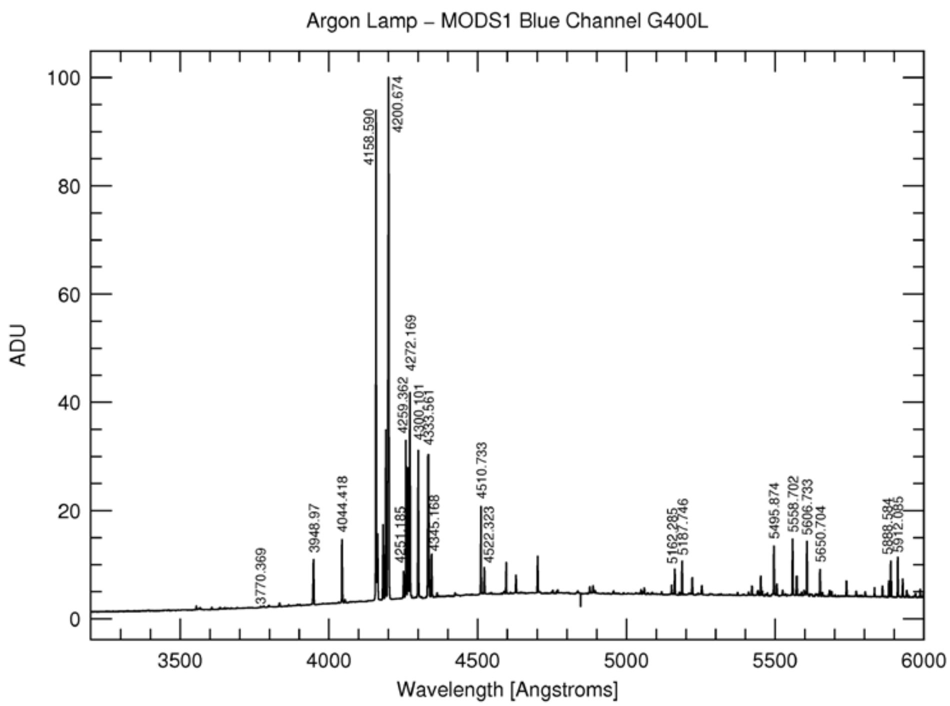


Figure 58: Argon lamp spectrum taken with the Blue Grating (G400L)

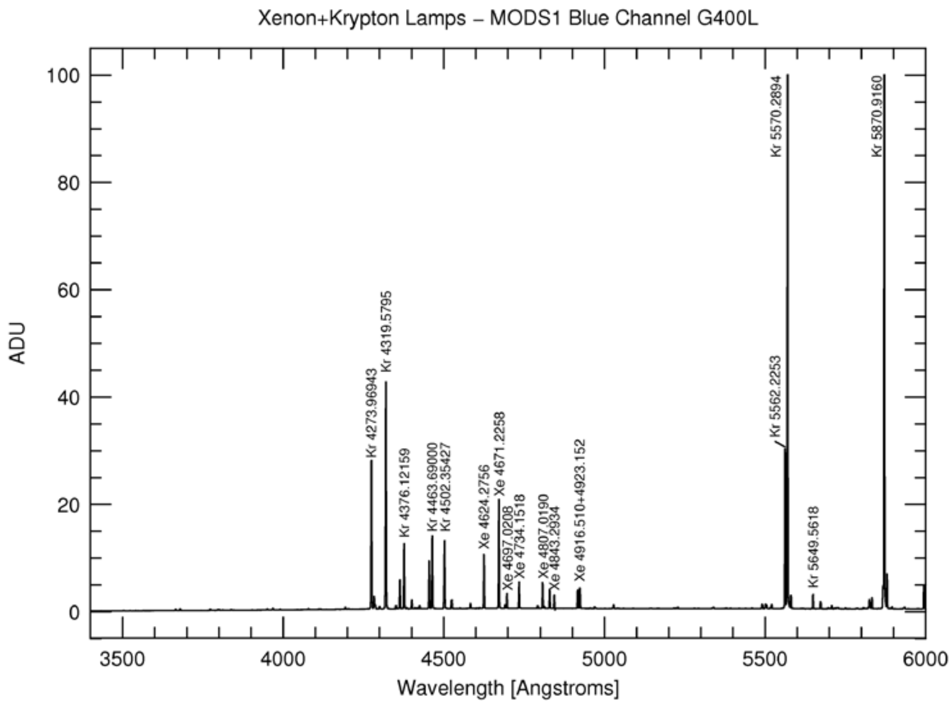


Figure 59: Xenon+Krypton lamp spectra taken with the Blue Grating (G400L)

Red GratingMode

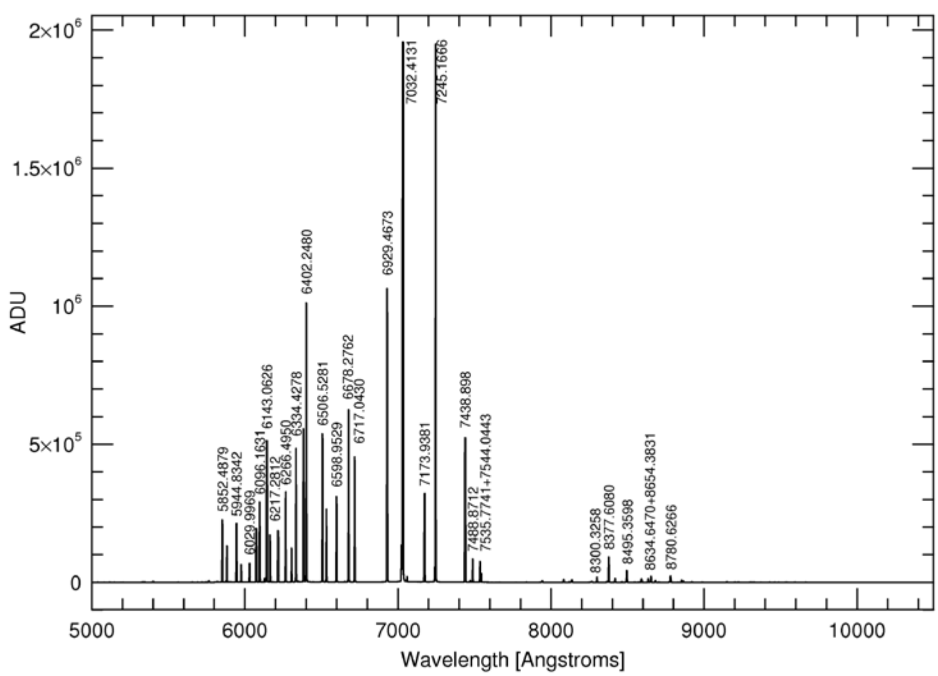


Figure 60: Neon lamp spectrum taken with the Red Grating (G670L)

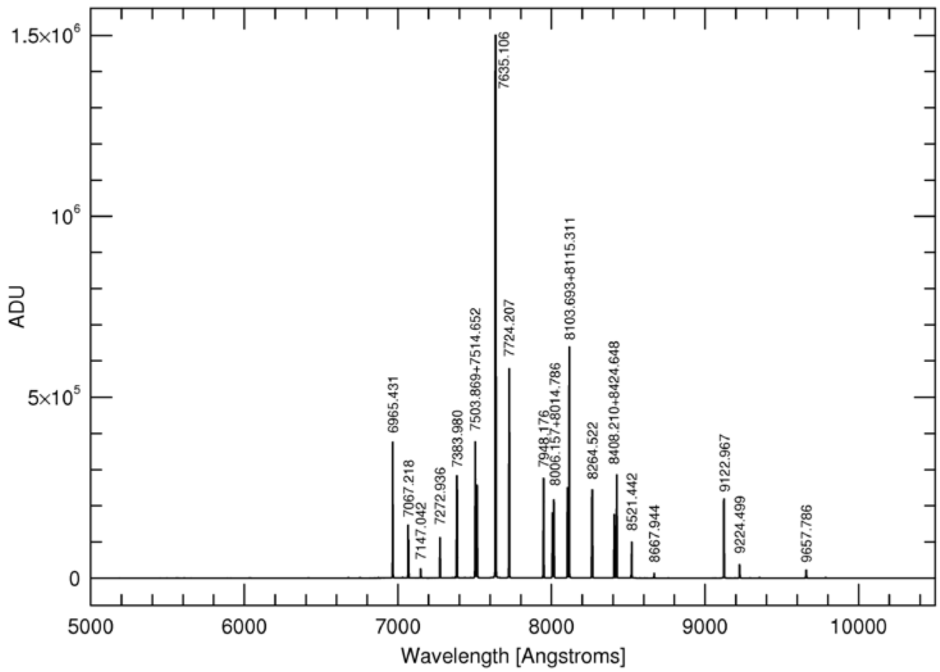


Figure 61: Argon lamp spectrum taken with the Red Grating (G670L)

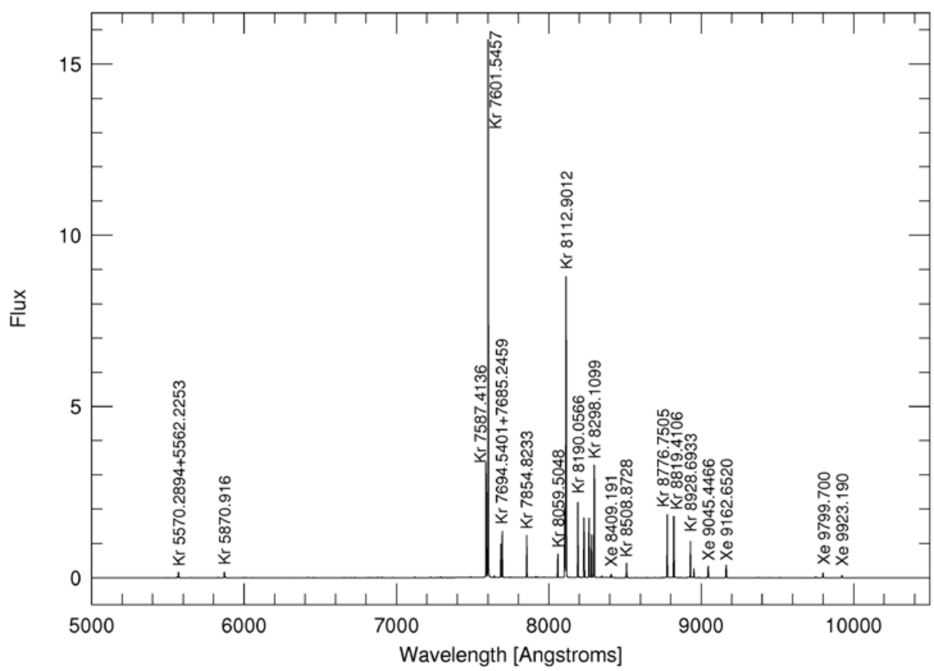


Figure 62: Xenon+Krypton lamp spectrum taken with the Red Grating (G670L)

Blue Prism Mode

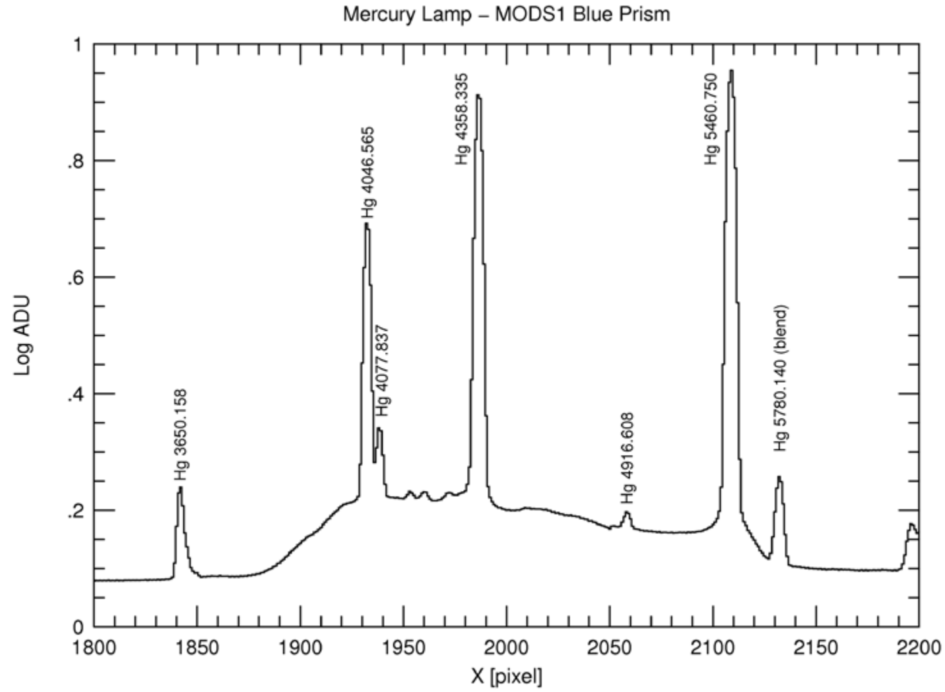


Figure 63: Hg(Ar) lamp spectrum taken with the Blue Prism (pixel space)

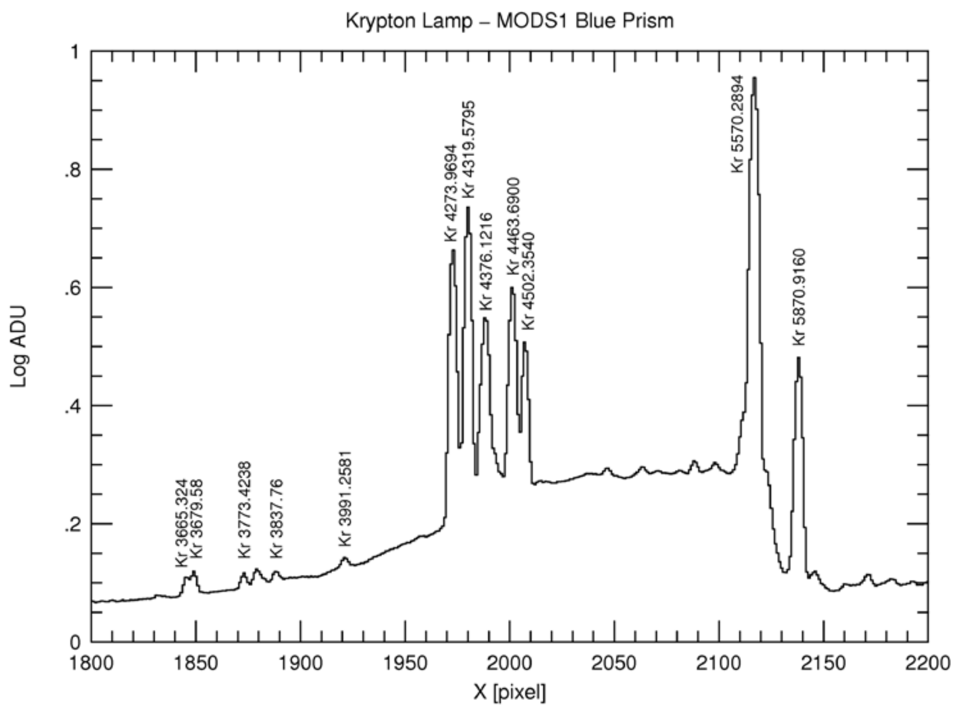


Figure 64: Krypton lamp spectrum taken with the Blue Prism (pixel space)

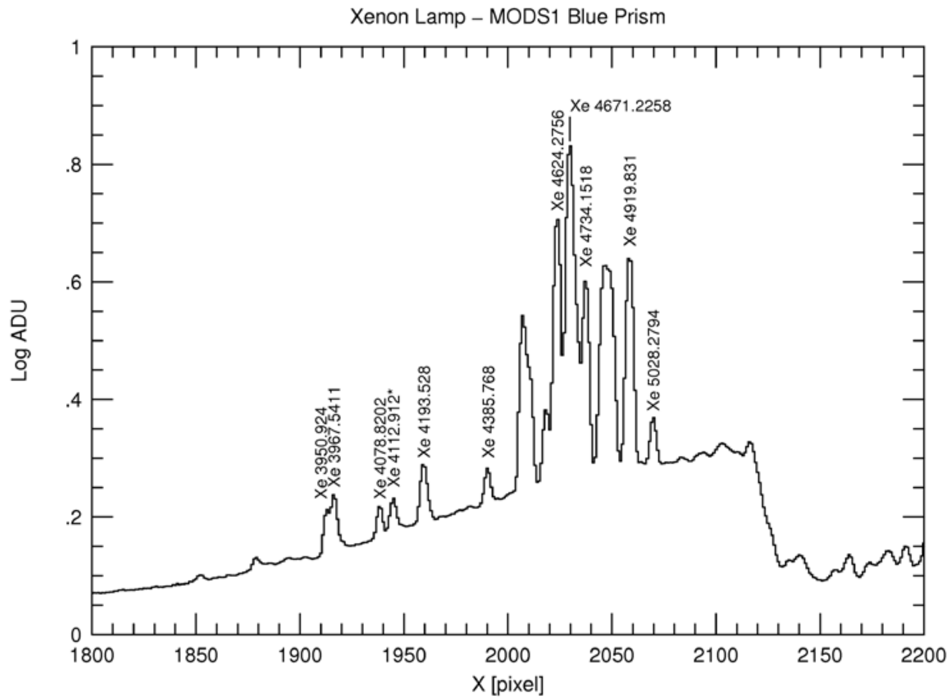


Figure 65: Xenon lamp spectrum taken with the Blue Prism (pixel space)

Red Prism Mode

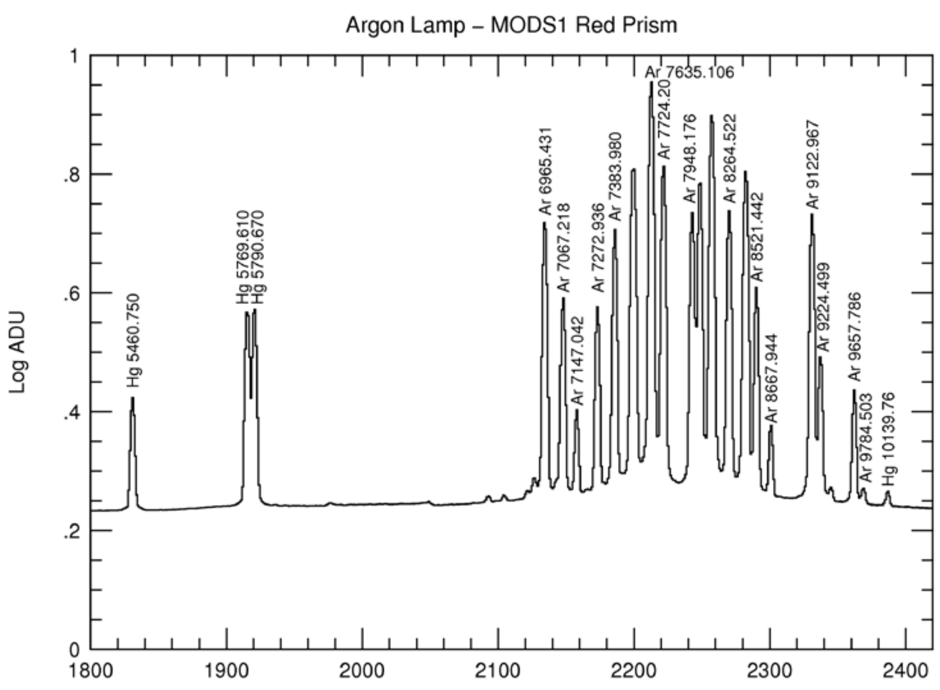


Figure 66: Argon (+HgAr) lamp spectrum taken with the Red Prism (pixel space)

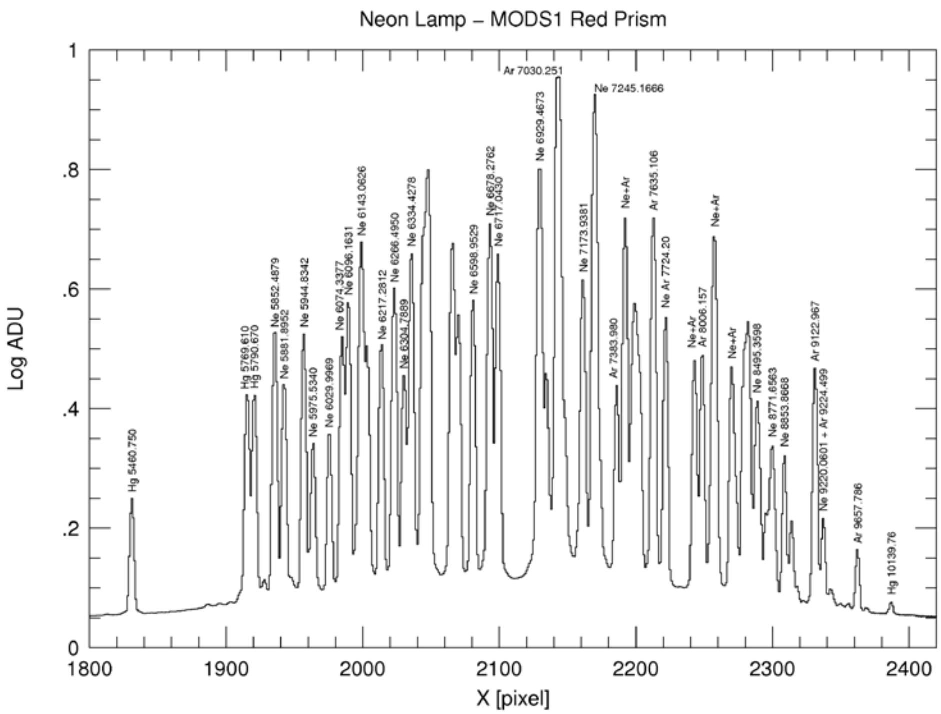


Figure 67: Neon (+HgAr) lamp spectrum taken with the Red Prism (pixel space)

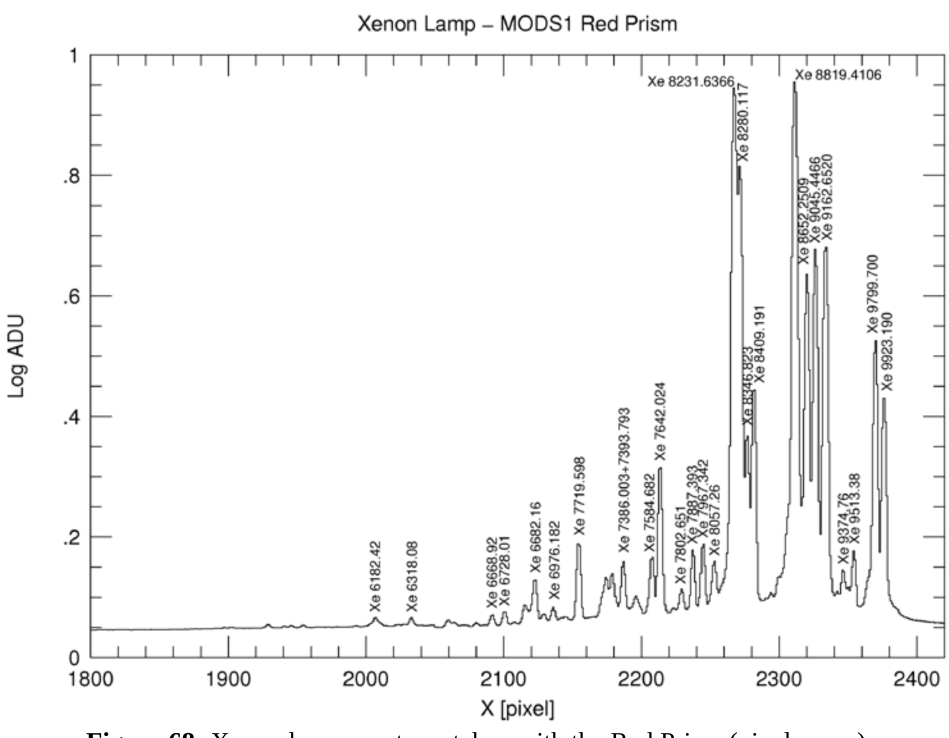


Figure 68: Xenon lamp spectrum taken with the Red Prism (pixel space)

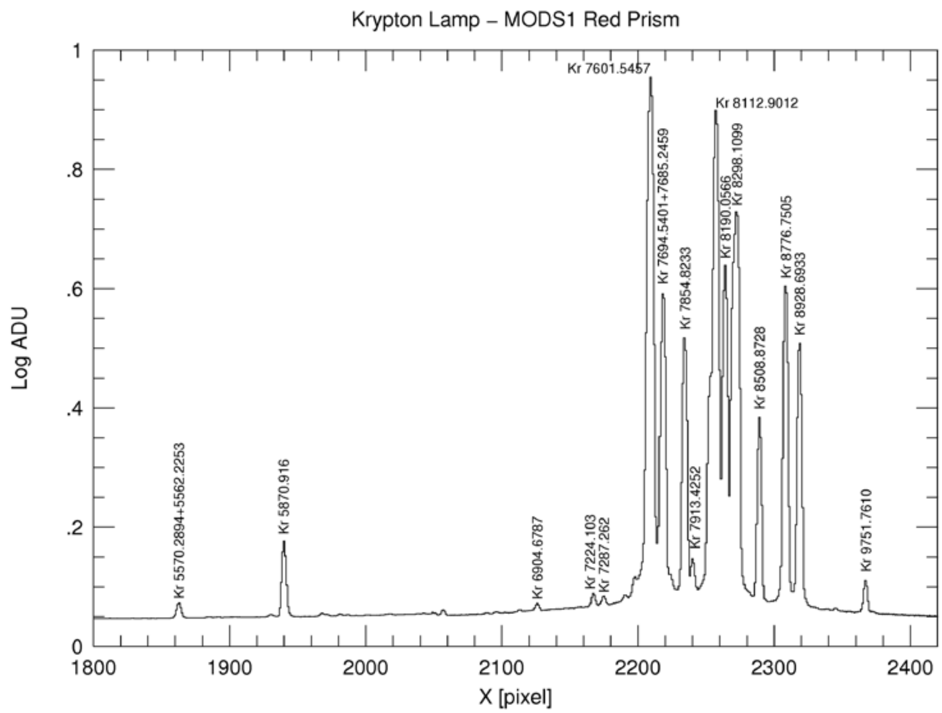


Figure 69: Krypton lamp spectrum taken with the Red Prism (pixel space)

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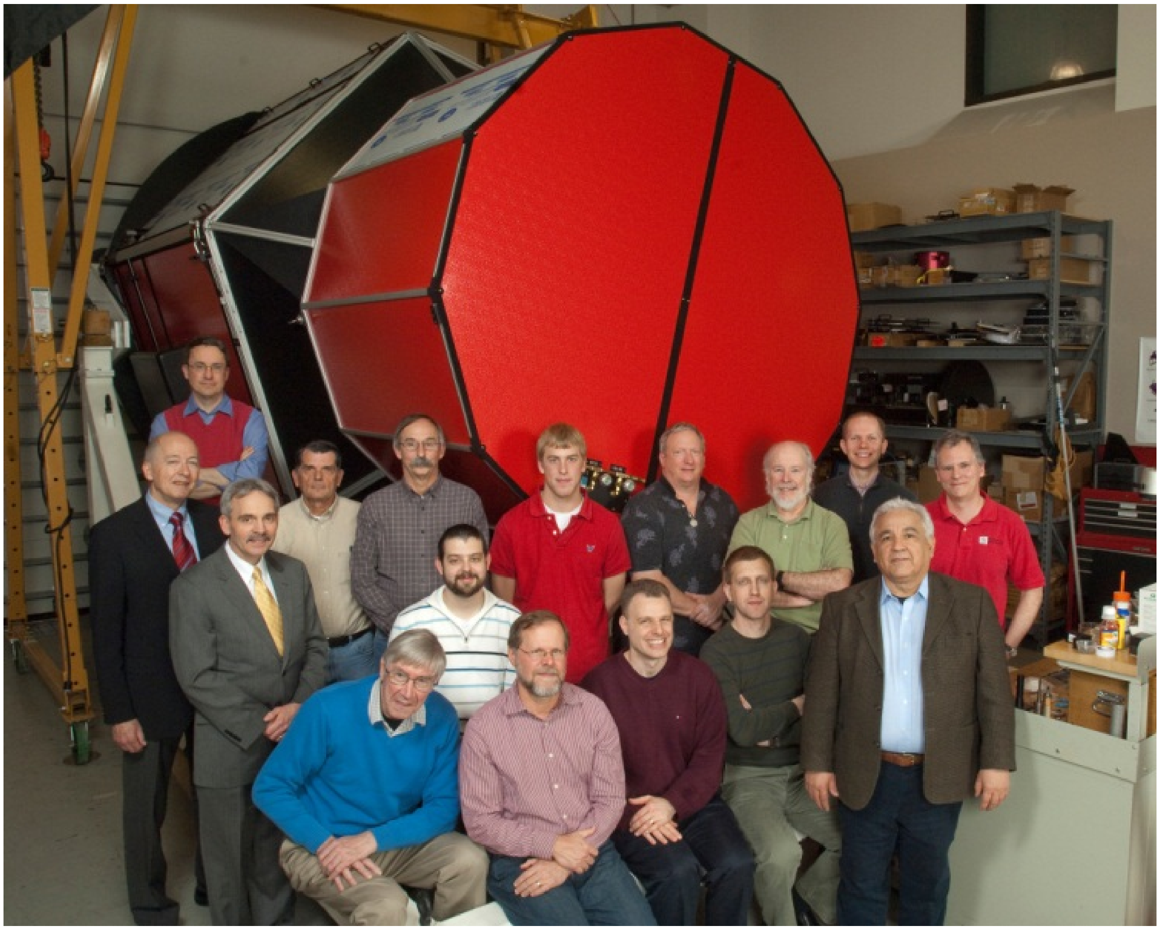
The MODS Instrument Team



The MODS instrument team with MODS1 in the high-bay instrument assembly lab on the Ohio State University main campus in Columbus, Ohio, February 2010.

Shown left to right are...

Front Row: Paul Byard (optical designer), Tom O'Brien (lead mechanical engineer), Mark Derwent (mechanical engineer), Ross Zhelem (optical engineer), Ray Gonzalez (software engineer)

Back Row: Pat Osmer (original project PI and project astronomer), Brad Peterson (Astronomy Dept. Chair), Ed Teiga (electronics technician), Dave Steinbrecher (senior instrument maker), Chris Colarosa (student engineering assistant), Josh Rosenbeck (student engineering assistant), Dave Brewer (senior instrument maker), Bruce Atwood (instrument scientist), Paul Martini (project astronomer), Jerry Mason (software engineer).

Way Back Left: Rick Pogge (project scientist and project PI).

Not Present: Dan Pappalardo (electronics engineer).

Past Team Members: Darren DePoy (project manager, astronomer, and interim PI), Philip Covington (electronics engineer), S. Ralph Belville (design engineer, retired), Brandyn Ward (student electronics assistant), Andy Krygier (student engineering assistant), Justin Randles (students engineering assistant), Jennifer Marshall (graduate student), Jason Eastman (graduate student).