Observing with Binospec
Draft of 3/14/2016
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1 Introduction to Binospec Configuration

1.1 Binospec Mask, Guider, and Wave Front Regions

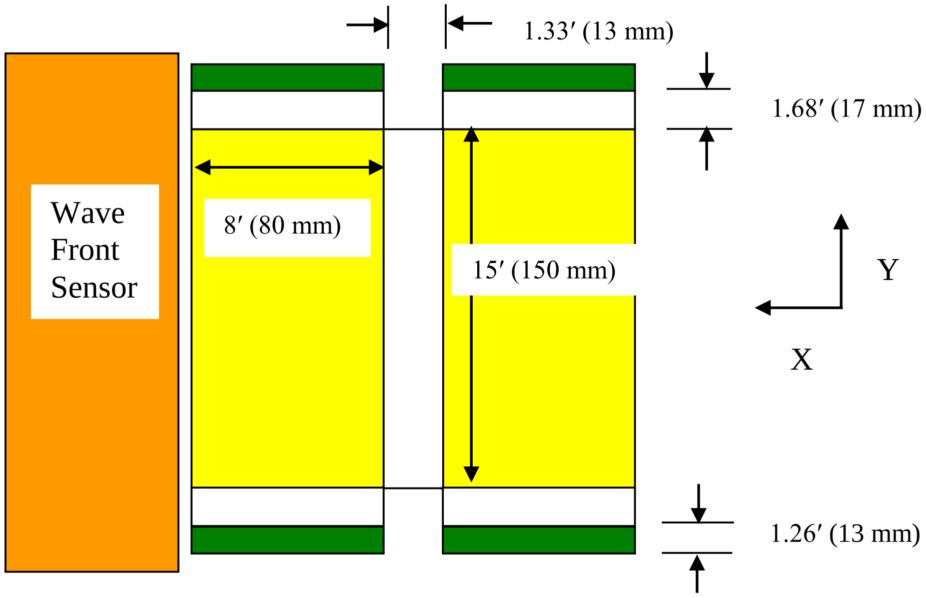

Figure 1. The layout of the two beams at the Binospec focal surface. The slits will be placed in two adjacent 8′ by 15′ regions (shown in yellow). The slit masks have a total length of ~21′ including extra field for guide stars. Two guiders, viewing through the slit masks, will each cover two adjacent guider strips at opposite ends of the slit regions (shown in green). Each guider will access a field of 26.9 sq. arcmin. At the North Galactic Pole, each guider region contains ~4.4 stars with 17 < g < 19 and ~6.4 stars with 17 < r < 19. The wave front sensor will patrol a region 7.1′ wide and 21.3′ long adjacent to the slit mask field for a total area of ~150 sq. arcmin (shown in orange).

1.1 Focusing the Spectrograph and Telescope

In order to operate properly, the spectrograph optics must be focused to produce the sharpest possible images of the slit masks. Focus is achieved by moving the science CCD with the five axis PI stage in the dewar. After initial setup, the flexure control system is used to keep the spectrograph optics in focus. Each science CCD is flanked with two flexure control CCDs, each of which detects images from a distinct pair of optical fibers mounted behind the slit mask. One fiber in each of the four pairs is placed optically ahead of the focal surface by 0.6 mm and the other fiber in the pair is placed optically behind the focal surface by 0.6 mm. When the images of both fibers in each pair are the same size, the spectrograph is in focus.

The telescope must also be focused onto the slit mask surface. The telescope is focused by moving its secondary mirror. To detect best telescope focus we will typically examine the images in the guiders mounted on the slit mask support structure below the slit mask. As part of the slit mask production, one pair of guide stars will be selected on the pair of slit masks. An aperture in the slit mask will pass the light from the guide stars to the guiders at opposite (±Y) ends of the slit masks. Each guider will be focused on the star apertures so that they are focused on the slit mask surface. Once the guiders are focused, the telescope can be focused using the guider images.

Telescope and spectrograph focus is normally verified before beginning each observation and updated about once every 30 seconds during an observation.

1.2 Focal Plane Scale

Table 1. Radial position (cylindrical coordinates) in mm versus off-axis angle with MMT f/5 corrector in spectroscopic mode. A scale correction of 1.000219 to the raytrace predictions was measured in 2003. A polynomial expression was fit to the corrected predictions and is shown for comparison. This is the default expression that has been used for over a decade with Hectospec.

$$\boldsymbol{R(mm) = 599.508197 + 7.259937 * deg^2 + 73.527900 * deg^4 - 40.535207 * deg^6}$$

Radial scale		deg	deg^2	deg^4	deg^6
Spectroscopic mode		599.508197	7.259937	73.527900	-40.535207
	Polynomial fit to the raytrace predictions			Measured scale factor	
	without linear rescale				1.000219
		Raytrace	Linear rescale	Polynomial	
arcmin	degrees	λ=5500 Å	to fit obs 2003	with scale factor	
0	0.000000	0.000	0.000	0.000	
1	0.016667	9.999	10.002	9.996	
2	0.033333	20.000	20.004	19.996	
3	0.050000	30.002	30.009	30.001	
4	0.066667	40.008	40.017	40.010	
5	0.083333	50.018	50.029	50.024	
6	0.100000	60.033	60.046	60.044	
7	0.116667	70.055	70.070	70.070	
8	0.133333	80.084	80.102	80.104	
9	0.150000	90.122	90.142	90.146	
10	0.166667	100.170	100.192	100.198	
11	0.183333	110.230	110.254	110.260	
12	0.200000	120.302	120.328	120.333	
13	0.216667	130.388	130.416	130.421	
14	0.233333	140.489	140.520	140.523	
15	0.250000	150.607	150.640	150.641	
16	0.266667	160.743	160.778	160.778	
17	0.283333	170.898	170.936	170.934	
18	0.300000	181.075	181.115	181.112	
19	0.316667	191.275	191.317	191.313	
20	0.333333	201.500	201.544	201.539	
21	0.350000	211.751	211.797	211.792	
22	0.366667	222.030	222.078	222.075	
23	0.383333	232.339	232.390	232.388	
24	0.400000	242.681	242.734	242.734	
25	0.416667	253.057	253.113	253.115	
26	0.433333	263.470	263.528	263.532	
27	0.450000	273.922	273.982	273.987	
28	0.466667	284.416	284.478	284.482	
29	0.483333	294.953	295.018	295.019	
30	0.500000	305.538	305.605	305.598	

In rough terms, neglecting distortion, the scale at the CCD will be reduced by a factor of 1097/404 = 2.72, the ratio of the collimator and camera focal lengths. At the center of the field at the telescope focus, 1′ = 10 mm, or 1″ = 0.167 mm. At the CCD, 1″ = 0.061 mm, or 4.08

science CCD pixels, or 4.52 flexure control CCD pixels. These numbers will depend on radius due to distortion in the telescope corrector optics and Binospec optics.

1.3 Imaging Configuration Parameters

To make a Binospec observation the observer must make a number of choices to properly configure the instrument. For an imaging observation, certain choices are made by default: (1) no slit mask is used, and (2) the imaging mirrors are selected instead of one of the diffraction gratings. (3) The grating stage tilts are set so that the angle between the collimator axis and the normal to the grating is 22.5°. (The angle between the grating normal and the camera axis is also 22.5° as the angle of incidence is the same as the angle of reflection.) The choices available to the user for imaging observations are the filter and desired exposure times.

1.4 Spectroscopic Configuration Parameters

To make a spectroscopic Binospec observation, the observer must in addition select: (1) a slit mask cut for the intended observation, (2) the appropriate gratings and (3) the grating tilt that places the desired wavelength on the central pixel in the dispersion direction.

1.5 Flexure Control

Tilts and shifts of the spectrograph optics can result in unwanted image motion at the detector plane. The flexure control system is used to correct this image motion. Image motion is detected by sensing shifts of the images of the flexure control system optical fibers in the flexure control CCDs. The shifts are corrected by moving the five axis PI stages in the dewars, with the goal of maintaining the images in a constant position. Both the science CCDs and the flexure control CCDs are mounted on the PI stages. The flexure control and focus update will have a cadence of about 30 seconds.

1.6 Guiding

For spectroscopic observations with a slit mask in place, guiding consists of centering the two guides in their reference apertures. For imaging observations, the guiding will be to centroid pixels in the guide camera rather than with reference to a slit mask aperture.

Occasionally, we will use a special single object slit mask with a mirror that returns light to the single object guider. In this case, guiding can be done manually with spilled light on either side of the slit or closed loop with a star image in the field of view.

1.7 Wave Front Sensing

Like MMIRS, Binospec will use continuous wave front sensing. The pre-observation preparations will include identifying an appropriate wave front sensing star accessible in the wave front sensor's field of view. The wave front sensor will be driven to the correct position as part of instrument setup. The update cadence will be about 30 seconds to average wave front errors due to seeing and not the optics. Appropriate WFS stars will have V magnitudes in the range 11-14.

2 Setting Up the Flexure Control System and Setting the Central Wavelength

2.1 Introduction

The long direction of the slit masks runs along Binospec's Y axis and the narrow direction runs along the X axis. For imaging observations, the flexure control system will attempt to drive the images of the optical fibers (X,Y) as close as possible to predetermined reference pixels in each flexure control camera. For spectroscopic observations, the Y position will be preset for each diffraction grating as small grating tips (perpendicular to the actuated tilt) may be present. The X position will be calculated from the desired central wavelength and the line wavelength appropriate for each grating.

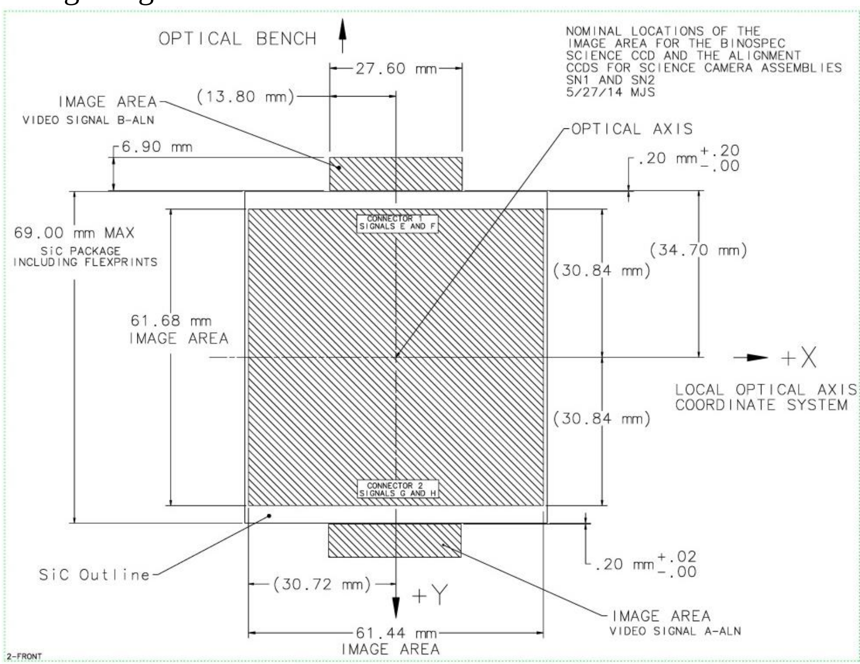

Figure 2. Binospec detector focal plane layout. A pair of fiber images will appear in each flexure control CCD.

The layout of the science CCDs and the flexure control CCDs is shown in Figure 1. Table 2 summarizes the grating characteristics and Table 3 lists the available flexure control wavelengths. The science CCDs have 15 µm pixels, and the flexure control CCDs have 13.5 µm pixels so the Å/pixel scales will differ by a factor of 1.11.

Table 2. Initial Binospec Grating Options. The angle of incidence options for the 600 lpm grating are not exhaustive.

Grating Ruling Lines/mm	Grating Blaze	Angle of Incidence	Ana. Mag.	Spectral Coverage (Å)	Central λ (Å)	Flexure Line λ (Å)	Å/ pixel	Pixels for 1″ slit	R for 1″ slit
270	5.5º	28.0º	1.08	3900-9240	6559	6506.5	1.30	3.75	1340
600	16.0°	33.2º	1.17	4500-6960	5718	5944.8	0.60	3.47	2740
600	16.0°	36.1º	1.22	6000-8480	7241	6965.4	0.61	3.32	3590
600	16.0°	38.5º	1.27	7255-9750	8489	8424.6	0.61	3.20	4360
1000	13.75	37.1°	1.24	3900-5400	4658	4358.4	0.36	3.27	3900

Table 3. Available Flexure Control Wavelengths

	Light Source Wavelength	Penray Lamp
1	435.84	Hg
2	546.07	Hg
3	594.48	Ne
4	650.65	Ne
5	696.54	Ar
6	763.51	Ar
7	794.82	Ar
8	842.46	Ar
9	912.30	Ar
10	965.79	Ar

2.2 Central Wavelength Equations

The grating equation (see e.g. Schroeder's Astronomical Optics) using my sign convention is:

$$m\lambda = \sigma(sin\alpha - sin\beta)$$

Here, *m* is the order of diffraction (an integer, typically 1 for Binospec), λ is the central wavelength, σ is the spacing between grating grooves in μm (or $\frac{1000}{lpm}$), α is the incidence angle (angle between the collimated beam and the grating normal), and β is the diffracted angle. For the central wavelength in Binospec α+β = δ=45˚ by construction. Using a trigonometric identity:

$$(sin\alpha - sin\beta) = 2\sin\frac{1}{2}(\alpha - \beta)\,cos\frac{1}{2}(\alpha + \beta)$$

We can rewrite the grating equation for the central wavelength as:

$$\lambda = \frac{2000}{m * lpm}\sin\left(\alpha - \frac{\delta}{2}\right)\cos(\frac{\delta}{2})$$

To implement the central wavelength preset, we will need to calibrate the angle for each grating tilt setting where α = 0, and measure δ precisely, although we will set it very close to 45˚. Being able to repeat the central wavelength exactly is important; calibration to better than an Å or so accuracy is not. For reference, with the 270 lpm grating at 28˚ angle of incidence and δ=45˚, the central wavelength is 6559.25 Å.

2.3 Grating Dispersion

We will also need to know where to find the other wavelengths on the flexure control or science CCDs. For this we can also use the grating equation, differentiating to get $\frac{d\beta}{d\lambda}$.

$$\frac{d\beta}{d\lambda} = \frac{m}{\sigma cos\beta}$$

To translate this into a focal plane scale in mm, we need to multiply by the focal length of the camera in mm (404 mm):

$$\frac{dx}{d\lambda} = \frac{m * 404000\mu m}{\frac{1000}{lpm} cos\beta} = \frac{m * 404 * lpm}{cos\beta}$$

To find the change in position for each Å (10^{-4} µm) we have:

$$\Delta x(\mu m) = \frac{m * 0.0404 * lpm}{cos\beta}$$

At the center of the field with the 270 lpm grating with β=17˚, 1 Å difference in wavelength corresponds to a position change of 11.4 µm, and one 15 µm pixel corresponds to 1.32 Å. With the flexure control CCD with 13.5 µm pixels, 1 pixel corresponds to 1.18 Å. Table 2 shows average dispersions for various grating setups.

2.4 Calibrating Offsets Between Flexure and Science CCDs

The science camera has 4096 pixels, so we will define pixel 2048 as the center for purposes of setting the central wavelength. The flexure control CCDs have 2028 pixels, so the nominal central pixel is 1024. We will need to measure and compensate for the offset in pixels between the physical center of the flexure control CCDs and their associated science camera. We will do this by wavelength calibrating the science CCD with the HeNeAr lamp in the UUCA, and by wavelength calibrating the flexure control CCDs with the lamps in the FCCA, and operating with the FCCA filter slots open. We will need to implement wavelength calibration code to accomplish this.

2.5 Range of Flexure Control Stages

The ranges of the flexure control stages are given in Table 4. The tip/tilt range of ±2 mrad corresponds to a Z change of ±0.123 mm across the 61.68 mm width of the science CCD. This should be useful for final alignment of the CCD perpendicular to the optical axis and possibly extending the range of acceptable focus slightly into the blue.

Table 4. Range of PI Flexure Control Stages

Motion	Range
X	±500 µm
Y	±500 µm
Z	±500 µm
tip	±2 mrad
tilt	±2 mrad

2.6 Flexure Control Images

The flexure control images are separated by 1 mm in the Y direction at the focal plane of the telescope, or 0.367 mm (27 pixels) at the flexure control CCD. The fiber pairs are separated by 2 mm in the Z direction, and the output beam will be restricted to f/8 so that the images will not vignette at the fold mirrors. The defocus of each fiber will then be 1/8 mm or 125 µm. The fiber core size is 100 µm, so the defocused image will be ~160 µm in diameter at the telescope scale or ~59 µm (4.4 pixels) in diameter at the flexure CCD.

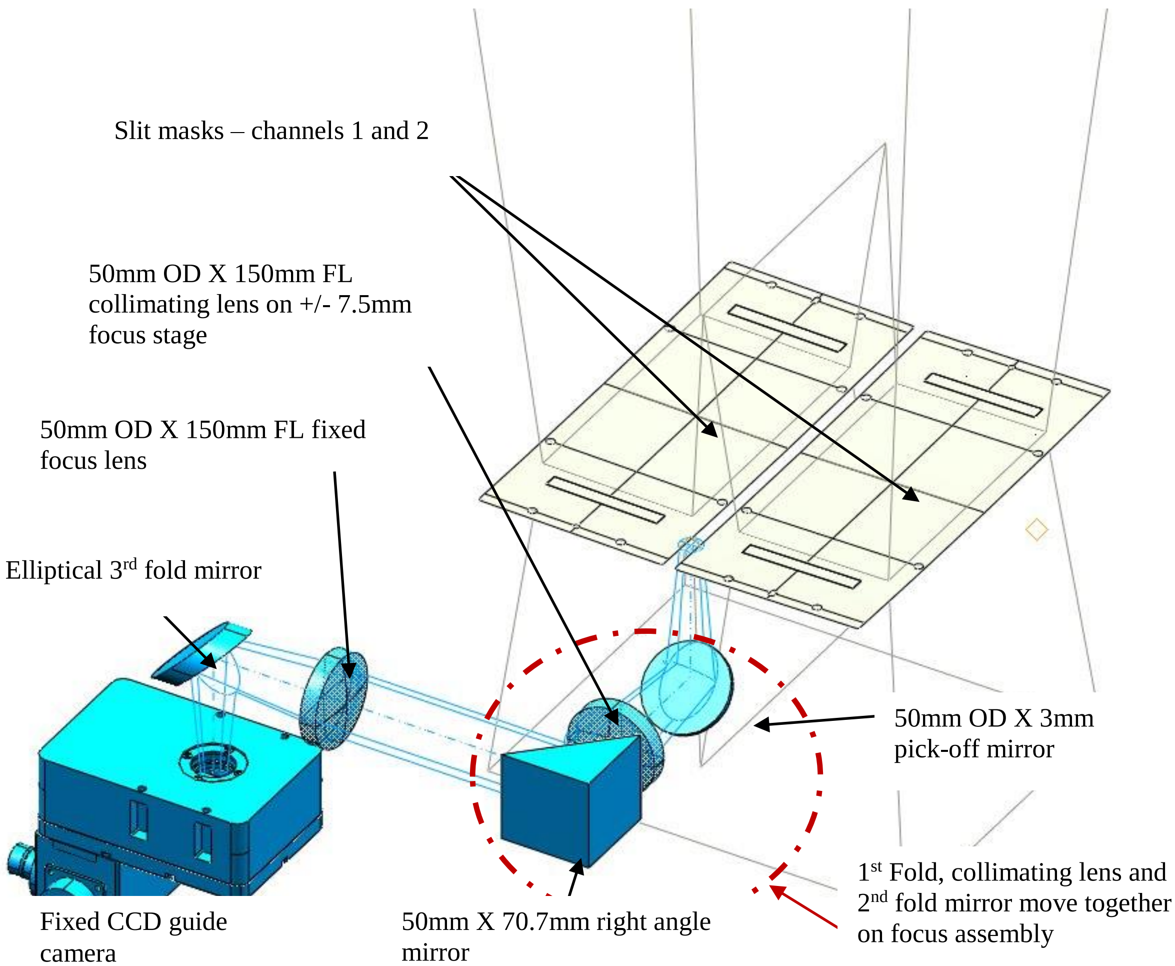

Figure 3. Guider optics. Two 150 mm focal length lenses relay the guide star image onto the CCD guide camera at the original scale of the MMT, 0.167 mm arcsec^{-1}.

3 Guider Optics

The CCD in the guider/WFS cameras is the E2V CCD47-20, a 2048 by 1024 CCD with 13 µm pixels, arranged in a 1024 by 1024 frame transfer geometry. Each 13 µm pixel subtends 0.078″. Note that the science CCDs, the flexure control CCDs, and the guider CCDs all have different sized pixels! The active area of the device is 13.3 by 13.3 mm. At the focal plane scale of the MMT, 0.167 mm $arcsec^{-1}$, this format corresponds to 80″ by 80″. The guider optics are shown in Figure 3.

4 Wave Front Sensor Optics

The WFS lenslet pitch of 0.6 mm gives a pattern of 13 by 13 spots with the 8 mm pupil provided by the 40 mm collimator operating at f/5. The Adaptive Optics Associates 0600-40-S array is identical to the one used in the existing f/5 wave front sensor. Both the lenslet and collimator lens have focal lengths of 40 mm, so the original scale of the MMT is preserved. Each 13 µm pixel subtends 0.078 arcseconds. The wave front sensor is equipped with a pneumatic stage that holds two apertures, one larger than the field of view, and the second 0.5 mm (3″) in diameter.

A Shack Hartmann wave front sensor works as shown in Figure 4. A collimating lens (not shown) collimates the light from the telescope, forming an image of the primary mirror on lenslet array. Deviations from the desired flat wave front show up as wave front tilts, which are transformed into image shifts by the individual lenslets. Each lenslet measures the wave front on a different portion of the primary mirror.

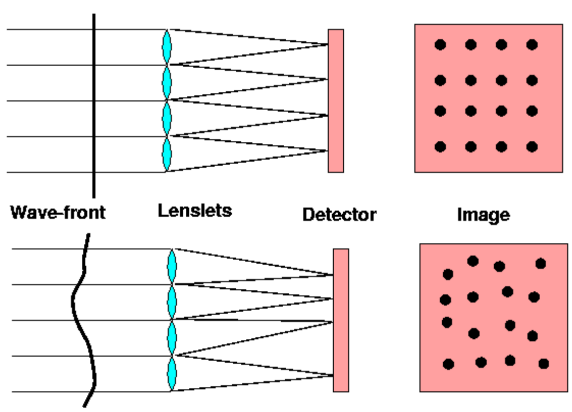

Figure 4. Principle of a Shack Hartmann wave front sensor

5 Single Object Guider

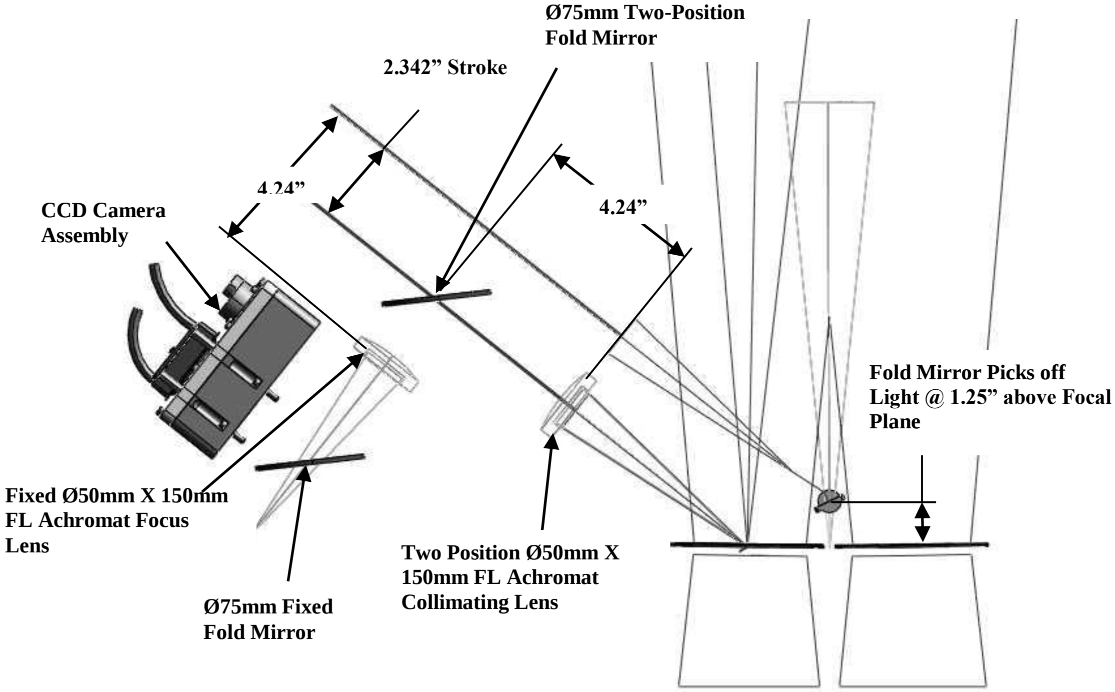

Figure 5. Single Object Guider (SOG). The SOG can be used to locate a star at the center of the field of view or to look a spilled light long slit on a special slit mask frame. The fold mirror at the center of the field of view is 20 mm in diameter and is placed at an angle of 27.5° to bend the light path by 55°. The mirror has a projected width of 17.7 mm. The 13.3 mm field of the CCD would require a 19.3 mm diameter mirror, so the edges of the image will be vignetted.

6 Calibration System and Procedures

6.1 Introduction

The Upper Unit Calibration Assembly (UUCA) contains two light sources mounted on an integrating sphere that illuminates a deployable rear projection screen. The UUCA is mounted above Binospec as shown in Figure 6.

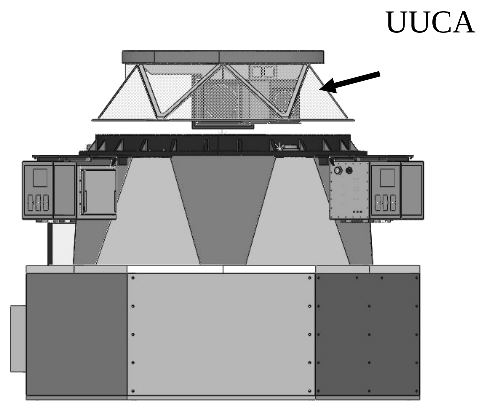

Figure 6. UUCA mounted above Binospec

The two light sources are 1) a HeNeAr hollow cathode lamp producing discrete emission lines for wavelength calibration and 2) a continuum incandescent lamp for flat fielding. The UUCA lamp can be used to illuminate Binospec at any time during the night, but it will be scientifically advantageous to do as much calibration during the day as possible to reduce loss of valuable observing time.

The HeNeAR lamp will only be used for spectroscopic observations but the flat lamp will be useful for flat fielding imaging data with one of the (**g**, **r**, **i**, or **z**) imaging filters.

6.2 Parameters Required to Specify Calibration

Table 5 lists the parameters required to specify a calibration exposure. The central wavelength will be set and maintained with the flexure control system for all spectroscopic calibrations. The flexure control system stages can be set to a nominal position for imaging observations.

Table 5. Parameters required to specify a calibration

Specification	Comments
Mask	None for imaging
Grating	
Filter	Usually long pass for spectroscopy
Central wavelength	
UUCA lamp	HeNeAr or incandescent
Exposure time	
Number of exposures	

6.3 Calibration Sequence

- Read in calibration parameters from database
- Turn on appropriate UUCA lamp and move UUCA stage to calibrate position
- Select and load mask if spectroscopic calibration
- Select appropriate grating and filter
- Verify identity of mask halves (if spectroscopic) using binary pattern engraved on the mask viewed by the guide CCDs
- Activate flexure control system and set central wavelength if spectroscopic calibration
- Take required number of exposures