Binospec: a dual-beam, wide-field optical spectrograph for the converted MMT

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ABSTRACT

Binospec is a wide-field, multi-object optical spectrograph to be used at the f/5 focus of the converted 6.5 m Multiple Mirror Telescope. Its dual beams will address adjacent $8' \times 15'$ fields of view, yielding a total slit length of $30'$. Binospec will offer ∼1–6 Å resolution at wavelengths between 0.39 and 1.0 μm with a 200 mm collimated beam diameter. Although it is difficult to design an f/5 wide-field collimator, f/5 optics are compact, allowing a small and stiff instrument structure. Binospec uses refractive optics throughout; the collimator contains three lens groups and the camera contains four lens groups. Three aspheric surfaces are used: two in the collimator and one in the camera. A pair of 2048 by 4608 pixel CCD detectors are used for each beam, yielding a sampling of $0.22''$ per pixel. Binospec's innovative optical design allows excellent image quality. Including the contribution of the MMT optics with the f/5 wide-field corrector, the RMS image diameter at Binospec's focal plane is 18 μm (1.3 pixels) averaged over field angles and colors.

Keywords: Optical and multi-object spectroscopy

1. INTRODUCTION

Binospec is a wide-field optical spectrograph currently under design for use at the f/5 Cassegrain focus of the converted Multiple Mirror Telescope (MMT). Binospec provides a total slit length of $30'$ in two beams, and will typically be used for simultaneous multi-object spectroscopy of ∼150 faint galaxies using slitlet masks. The layout of a slitlet mask is shown in Fig. 1. Binospec will offer resolutions, R, ($\equiv \frac{\lambda}{\Delta\lambda}$) of 1,000–15,000 at wavelengths between 0.39 and 1 μm.

The conversion of the MMT to use a single 6.5 m primary mirror is underway, and is scheduled for completion by mid 1999. The converted MMT is unusual among the new generation of large telescopes in that it provides a fast (f/5) wide-field focus optimized for direct imaging and optical-fiber spectroscopy. This wide-field focus requires a large secondary mirror[1] and large refractive corrector,[2] but it has enabled us to design a diverse group of powerful instruments. Several years ago we would not have predicted that an instrument like Binospec could be included in this group because we believed that it would be impossible to design an f/5 collimator to address a wide field. Clearly, we changed our minds.

Binospec began as an tentative exploration of how to provide wide-field direct spectroscopy (*without* optical fibers) for the converted MMT. Direct spectroscopy is of considerable importance for many scientific investigations. Although fiber-fed spectrscopy can address a much larger field, direct spectroscopy reaches 3 or more magnitudes deeper than fiber-fed spectroscopy due to the more accurate sky subtraction possible with slits. Our exploration was tentative because while the converted MMT's 1° field for spectroscopy

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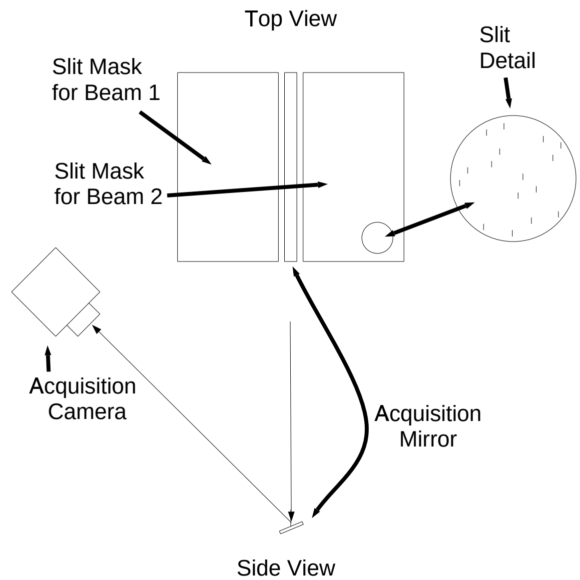

Figure 1. The layout of the Binospec slit masks. Each beam uses an independent mask registered to a common frame. Each mask is bent into a section of cylinder with its axis parallel to the short axis of the mask. The total sag is ∼0.7 mm.

with optical fibers is curently unique for a telescope of its aperture, wide-field (slit length >15′) direct spectroscopy on large telescopes is a competitive field. Several ambitious instruments for 6.5 to 10 m telescopes are underway, including DEIMOS at Keck II,[3] IMACS at Magellan[4] and VIRMOS at the VLT.[5]

Keck, Magellan 1 and the VLT have slow final Cassegrain focal ratios, f/11 to f/15, that ease the design of a wide-field collimator. No collimators addressing a very wide field at f/5 had ever been designed, but it was worthwhile to try because neither of the other foci at the converted MMT, f/9 or f/15, allows a very large field of view. Furthermore: (1) the converted MMT's wide-field corrector has atmospheric dispersion compensation (ADC) prisms that minimize light loss with narrow slits and (2) a short f/5 collimator allows a large collimated beam diameter to be fit into a compact (low-flexure) Cassegrain instrument. It was clear to us that a refractive collimator design was going to be necessary, so we began collimator design studies in 1994, and camera design studies soon thereafter. Some three years and many computer CPU cycles later, the design reached its present level of performance.

In Sect. 2, we describe the optical layout as used in Binospec, including the fold mirrors required for mechanical packaging. We summarize Binospec's optical performance in Sect. 3 and Sect. 4, and describe its mechanical features in Sect. 5 and Sect. 6. We note that in another paper at this conference, Epps describes a number of his most noteworthy recent lens designs for astronomy, including the Binospec optics.[6]

2. OPTICAL DESIGN

The advantages of a large collimated beam diameter are well known: a larger collimated beam generally allows a more favorable combination of spectral coverage, energy resolution, camera optical performance and utilization of detector format. The disadvantages are also well known: larger instrument size, higher

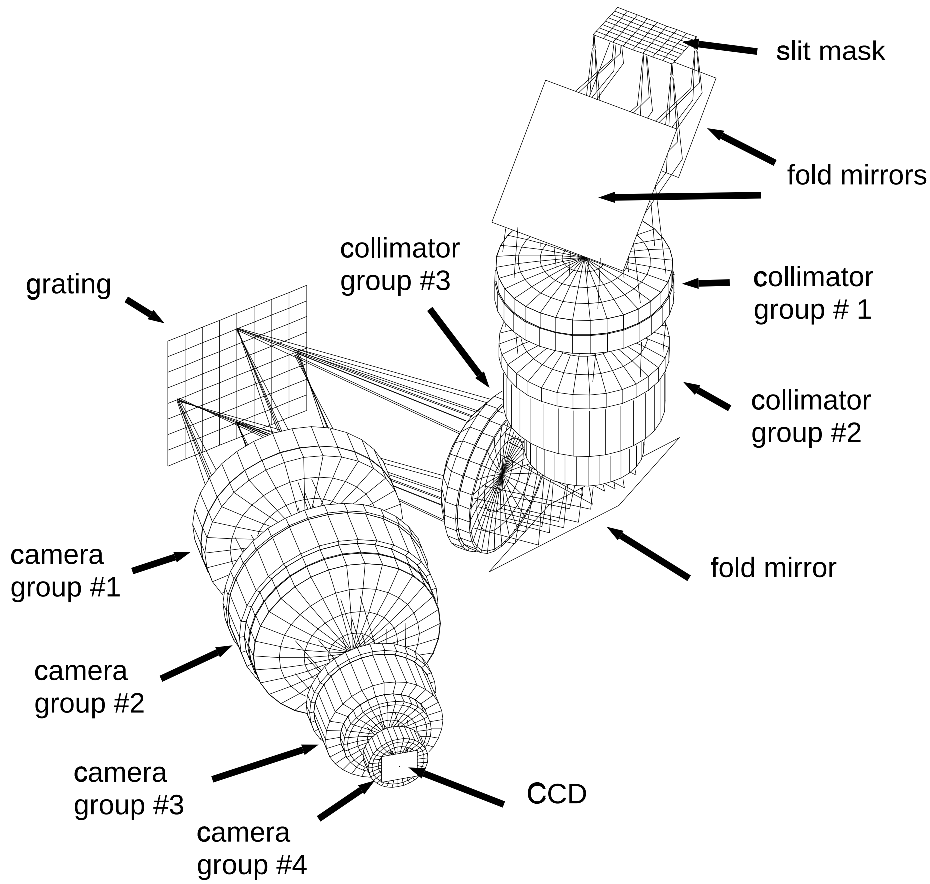

Figure 2. The overall optical layout of one of Binospec's two beams.

costs and uncertain availablity of large gratings. Given that Binospec must compete with instruments on larger telescopes, we felt that ambition was in order, and we designed Binospec to have a ∼200 mm collimated beam diameter. We elected to build a dual-beam instrument from the outset for the same reason, and here we acknowledge the influence of the ambitious DEIMOS design.[3] The camera focal length, ∼400mm, was adjusted to allow imaging a $15'$ slit length onto 4096 CCD pixels. (The standard CCDs for MMT instruments are expected to be 2048×4608 EEV devices with 13.5 μm pixels; we use a pair of these in each Binospec beam.)

The overall layout of one of Binospec's two beams is shown in Fig. 2. The collimator includes three fold mirrors. The first two fold mirrors following the slit mask separate the two beams to avoid interference between the collimator optics of the two beams. The third collimator fold mirror is used to shorten the instrument axial length. Although fold mirrors cost light, dielectrically enhanced silver coatings are very efficient across the Binospec's bandpass.[7]

The optical layouts of the collimator (without the first two fold mirrors) and camera are shown in Fig. 3 and Fig. 4, respectively. The Epps paper at this conference includes the optical prescriptions for the these optics.[6] To minimize axial and lateral color, the collimator uses two CaF_2 elements and the camera uses

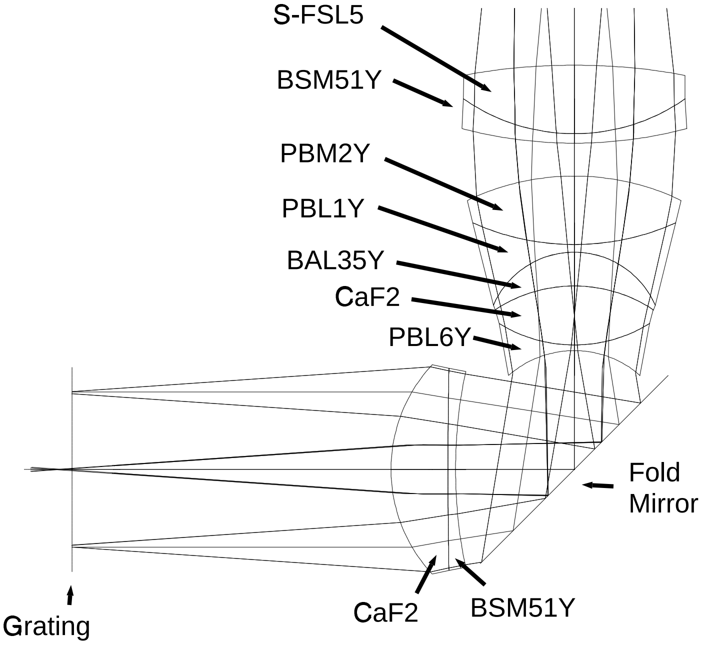

Figure 3. The Binospec collimator with a focal length of 1097 mm, producing a 206 mm diameter collimated beam.

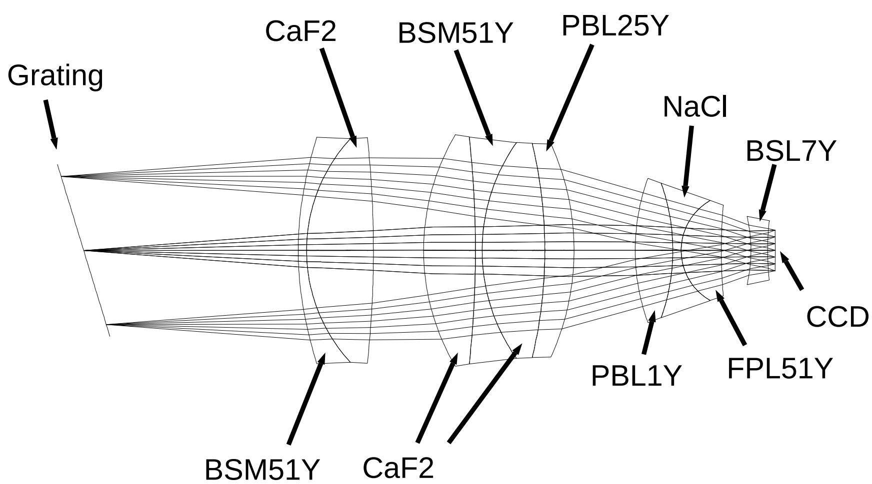

Figure 4. The Binospec camera with a focal length of 404 mm and an entrance aperture of 344 mm.

three. In addition, the camera includes a NaCl element that proved an important tool for reducing axial color. The use of NaCl always raises eyebrows, but the single NaCl lens is the central element in a triplet, and is therefore well protected from moisture damage. In addition, the collimator contains two aspheric elements with aspheric deviations of ∼0.3 mm and the camera contains a single aspheric surface with an aspheric deviation of ∼0.8 mm. Our approach to mounting these lenses is discussed in a companion paper.[8]

3. OPERATING CONFIGURATIONS AND IMAGE QUALITY

Binospec's vital statistics are summarized in Tab. 1. The camera was designed for a maximum anamorphic magnification of ∼1.32, meaning that it will maintain high image quality and will not vignette when fed with an elliptical monochromatic input beam ∼207×273 mm. Gratings with a higher anamorphic magnification can be used, but must be masked to maintain a maximum 207×273 mm monochromatic beam if image quality is to be preserved.

Table 1. Binospec spectrograph optical configuration

Collimated beam diameter	207 mm
Camera focal length	404 mm
Reduction (spatial)	2.72
CCD format	4608×4096 pixels
CCD pixel size	13.5μm
Spatial scale	0.22″/pixel
Slit length per beam	15′
Max. mono. beam to camera	207×273 mm
Camera field radius	5.9°
Camera-collimator angle	45°
Camera-grating distance	326 mm
Camera entrance aperture	344 mm

Several grating configurations are summarized in Tab. 2. The spectral resolution with a 1″ wide slit is listed in column 3, including a correction for the average RMS image quality added in quadrature. The RMS image diameter for each configuration, averaged over field angle and wavelength, is listed in column 8. These ray trace results neglect construction errors and seeing, and have been calculated for the MMT-corrector-Binospec system without a slit. The worst images, again neglecting seeing and without a slit, typically have RMS image diameters of 2 pixels (27 μm) at the spectral extremes and at the field corners. The blue 1200 gpm configuration is an exception; here the worst images have an RMS image diameter of 2.6 pixels (35 μm).

Table 2. Possible Binospec grating configurations

Ruling Density (grooves/mm)	Spectral Coverage Å	Spectral Resolut. Å	Ana. Mag.	Angle of Incidence (degrees)	Angle of Diffract. (degrees)	Vign. Loss	Ave. RMS Image Dia. (pixels)
270	3900-9312	5.1	1.08	28.01	16.99	none	1.1
650	3900-6196	2.1	1.16	32.71	12.29	none	1.5
1200	3900-5167	1.1	1.29	39.62	5.38	none	1.7
650	7656-10000	1.8	1.31	40.59	4.41	none	1.0
1200	8771-10000	0.7	1.94	60.08	-15.08	28%	1.4

Binospec can be used as a focal reducing camera if the grating is replaced with a mirror. Far better image quality and a larger field will be available with Megacam[9] at the converted MMT, but an instrument change might not always be warranted for a short observation. The performance in this mode is limited by residual lateral color at red wavelengths, amounting to 36 μm ($0.6''$) across the I band at the edge of the field. The monochromatic RMS image diameter in imaging mode, averaged over field angles and colors (0.39 to 1.0 μm) is 16 μm or $0.15''$. Lateral color is much less severe at shorter wavelengths: 21 μm ($0.34''$) across the B band, negligible in the V band and 18 μm ($0.30''$) across the R band.

4. THROUGHPUT

Although the total path length through the Binospec lenses is large, care was taken to include only materials with excellent transmission to the lower wavelength of interest, 3900 Å. These include Ohara I-line glasses, CaF_2 and NaCl. All the multiplet elements will be oil coupled. There are three lens groups in the collimator and four in the camera, leading a minimum of 14 glass-air boundaries, although we have included 4 additional boundaries for a filter and dust window. All external surfaces are Sol-gel coated (see the paper by Bohn[10] in this proceedings) and the three folding mirrors in the collimator are coated with dielectrically enhanced silver.[7]

Table 3. Binospec throughput with grating blazed at 5200 Å

Wavelength	Collimator	Camera	CCD	Grating	Final
3900	0.73	0.85	0.76	0.46	0.22
4000	0.79	0.87	0.80	0.49	0.27
5000	0.90	0.97	0.85	0.66	0.49
6000	0.90	0.97	0.80	0.63	0.44
7000	0.90	0.94	0.75	0.55	0.35
8000	0.86	0.90	0.60	0.45	0.21
9000	0.82	0.87	0.30	0.37	0.08

5. STRUCTURAL DESIGN

There are approximately 350 kg of lenses in the collimator and camera to be accurately supported by the instrument structure. The structure includes four major elements: (1) a mounting flange, (2) an optical bench that supports most of the spectrograph components, (3) struts connecting the optical bench and mounting flange and (4) a platform extending above the optical bench to support the slit mask handling equipment. Fig. 5 outlines these structural elements. The optical bench will be of a steel honeycomb construction, quite similar to laboratory optical benches. We will likely have a regular pattern of mounting holes drilled into both sides of the bench for convenience. To keep the instrument weight manageable while maintaining high stiffness, the struts connecting the bench to the steel mounting flange will be made from graphite-epoxy. This layout offers excellent access to almost every component and allows modular exchange of optics should we wish to extend Binospec's reach to the near-IR in the future.

Our goal is to keep the total instrument mass below 1400 kg, while maintaining image motion at the CCD below 1 pixel (13.5 μm) as the instrument is rotated from zenith to horizon. This flexure specification includes two terms: the deflections of the overall structure and the deflection within subassemblies (grating mounts, lens mounts and etc.) We have built a finite element model of the instrument, representing major

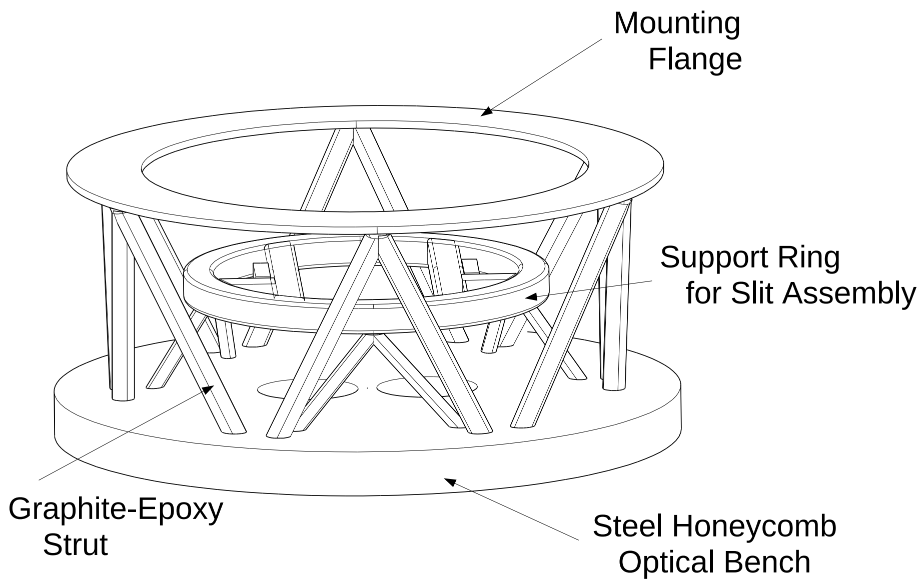

Figure 5. A conceptual drawing of the Binospec structure.

subassemblies as lump masses with the appropriate attachment to the structure. At the moment, we meet the mass budget and are within striking distance of meeting the flexure specification, but further finite element modeling of the subassemblies is required. The lowest mode at present is a 70 Hz lateral translation of the optical bench with respect to the mounting flange. The lowest mode that affects the relative alignment of the optics is a 94 Hz axial “drumming” deformation of the optical bench.

6. MECHANICAL LAYOUT

Binospec, even with its dual beams, is pleasingly compact. It will fit within a cylinder 2.5 m in diameter and 1.5 m long. We show Binospec’s mechanical layout in two figures: Fig. 6 is an isometric drawing looking down on the instrument from above the mounting flange, and Fig. 7 is an isometric drawing looking up from below.

The slit masks will be kept in a cassette that holds 9 masks in a vertical stack. The slit-mask cassette will be mounted on an linear stage that can move the cassette parallel to the optical axis of the telescope to allow selection of the desired mask. An arm mounted on another linear stage will move across the focal surface to pull the selected mask into position.

Guiding will be carried out with two coherent guide bundles that move in arcs centered on the optical axis of the telescope. This is similar in concept to the guiding arrangement developed for Hectospec.[11] We use arcs because this avoids the necessity of refocussing as the guide probe is moved; the focal surface is slightly curved. Field acquisition cameras mounted on a platform above the focal surface can be used in several modes: viewing a small mirror mounted between the masks used for the two beams, viewing a slit when the instrument is used in long slit mode, or viewing a larger field when a special reflective mask is inserted.

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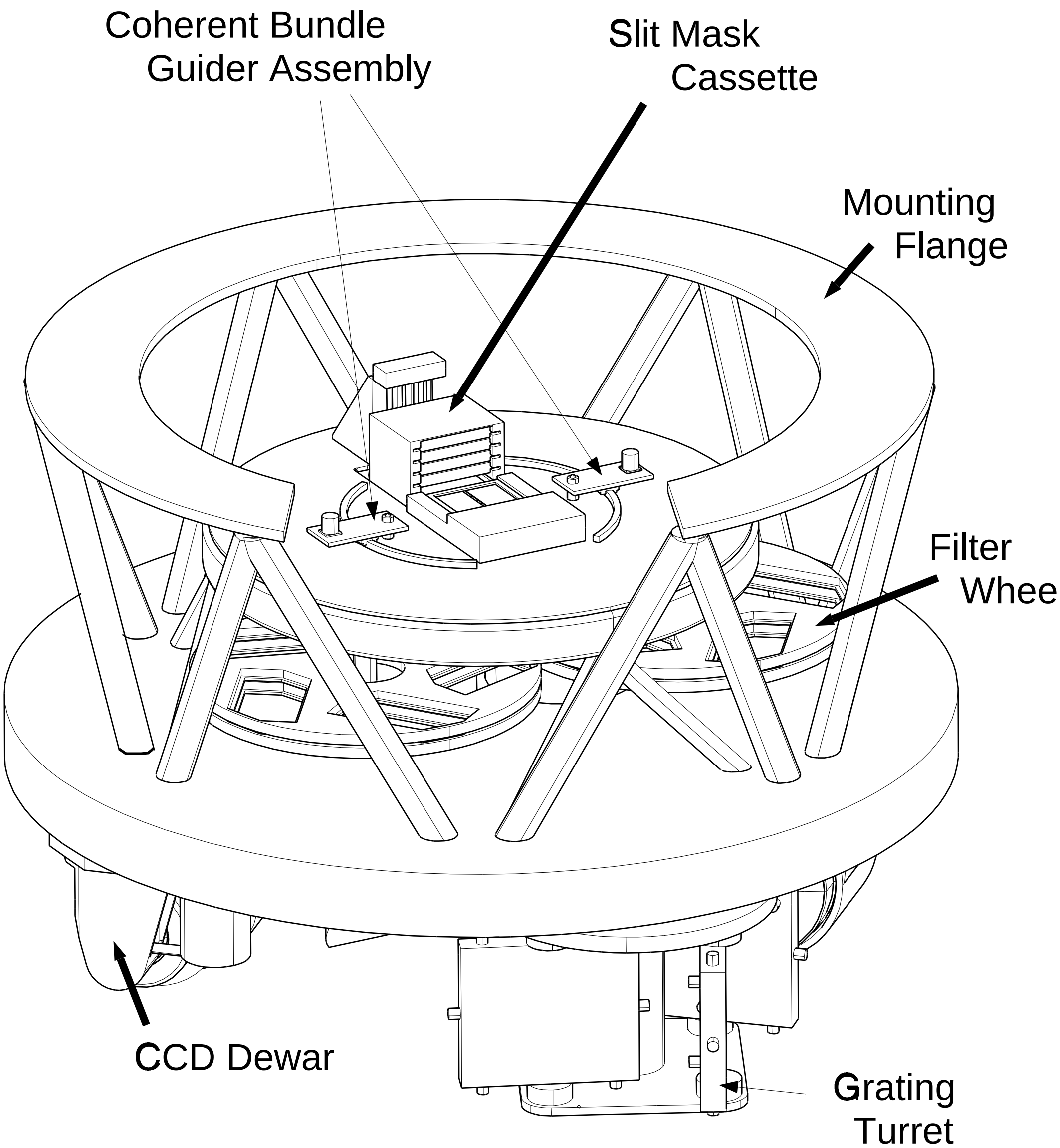

Figure 6. The Binospec mechanical layout - top view

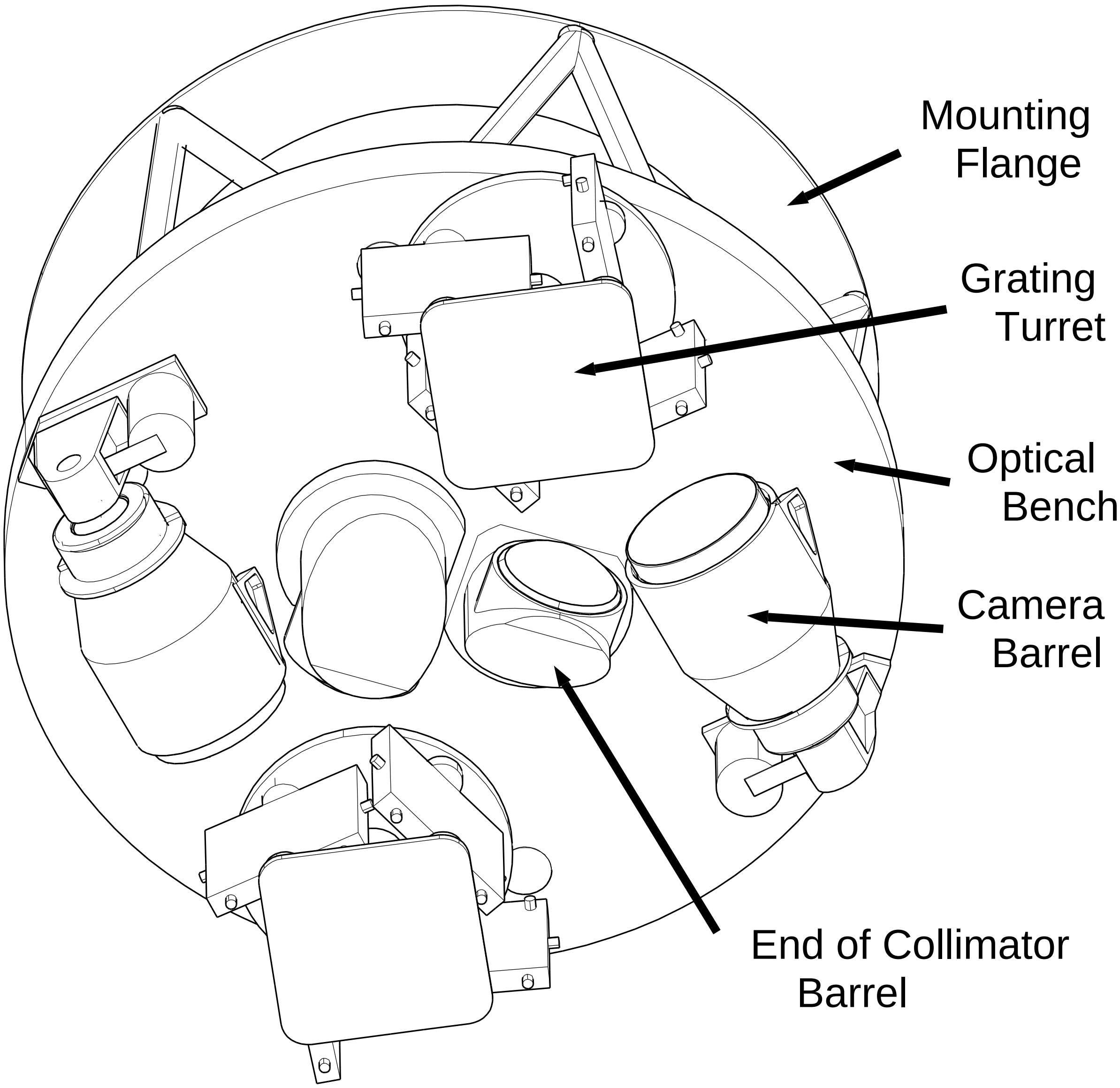

Figure 7. The Binospec mechanical layout - bottom view

throughput study.

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