MODS: Optical Design for a Multi-Object Dual Spectrograph

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ABSTRACT

The paper describes the optical design for the Multi Object Dual Spectrograph (MODS) for the Large Binocular Telescope (LBT). MODS is designed to cover the entire spectrum accessible to silicon CCDs from a ground-based telescopes with the highest possible throughput. Multi-object capability is available using 0.6 arc-second slit masks covering a high quality field of 4 arc-minutes in diameter with an extended field of up to 6 arc-minutes in diameter with reduced image quality. Under the very best seeing conditions and with the LBT adaptive optics in operation, slit widths of 0.3 arc-seconds can be used to enhance the resolving power and/or reduce the background.

The optical path is divided into blue and red channels by a dichroic beam splitter following the slit or slit masks. The blue channel covers a wavelength range from the atmospheric cut-off at ~320 nm to ~ 550 nm while the red channel covers the range from ~550 nm to the limit of useful sensitivity of silicon CCDs (~1000 nm). This approach allows the optimization of transmissive and reflective coatings to provide the very highest throughput for each channel.

The design is conventional in the use of reflective parabolic collimators. However, the cameras are designed as *decentered* Schmidt/Maksutovs with large aspheric coefficients for the inner surfaces of the correctors. This approach enables the field flattener and detector to be positioned outside the beam entering the camera where it will not vignette. Figures are presented showing image quality for imaging and spectrographic modes.

Keywords: spectrographs, dual-beam, decentered optics, Schmidt camera

1. INTRODUCTION

The Multi Object Double-Spectrograph (MODS) is one element of an initial instrument complement for the Large Binocular Telescope (LBT). The LBT is a consortium of the University of Arizona, the Italian astronomical community, the German astronomical community, The Ohio State University, and the Research Corporation to build the world's largest telescope on a single mount. MODS will be built at The Ohio State University as part of our commitment to the project. The primary science driver for the instrument is a set of observational programs designed to address key research topics related to the evolution of galaxies and structure in the universe (see Osmer in these proceedings)

2. SPECTROGRAPH SPECIFICATIONS

The basic input specifications defined by the projected research program with the spectrograph are as follows.

- Very high throughput at all wavelengths.
- Spectral range 320 nm – 1000 nm from the atmospheric cut-off to the practical limit of CCDs in the red.
- Moderate resolutions 10^3 to 10^4 over the entire spectral range
- Imaging, long slit and multi-slit spectrographic capability with a 4 X 4 arc-minute field in good seeing conditions (~0.6″) and an extended field up to 6 X 6 arc-minutes with poorer atmospheric seeing.

3. DESIGN APPROACH

We opt for a double-spectrograph design with reflective collimators and cameras with gratings that maximize the throughput in the blue and red regions of the spectrum. There are several reasons for this:

- The number of surfaces is a minimum for reflective designs.
- The effectiveness of anti-reflection and reflective coatings can be individually optimized for separate red and blue channels.
- Grating spectra cover a spectral range of only one octave without the confusion of overlapping orders, and grating blaze functions are too narrow to provide high throughput over a wavelength range from 320 nm – 1000 nm.
- The double design allows the use of different optical materials and optimization in each wavelength range.

4. DESIGN DESCRIPTION

The following section is a description of the optical path through the MODS design.

4.1 ADC

An atmospheric dispersion compensation (ADC) assembly ahead of the LBT f/15 focus will be used while observing away from the zenith.

4.2 Telescope focal surface

The focal surface of the gregorian LBT is convex toward the secondary mirror. The radius of curvature of this surface is approximately 1 meter. The slit, or multi-object slitlet array, will be placed on this surface. This ensures the best match of slit sizes to telescope image quality with the greatest exclusion of background sky emission.

4.3 Field lens

A meniscus field lens is placed after the focal surface. This lens, in combination with the collimator mirror, positions the exit pupil of the telescope on the spectrograph grating at a convenient location in the instrument volume.

4.4 Dichroic

A dichroic beamsplitter reflects red light to the red channel of the spectrograph via an additional fold mirror. Light transmitted through the dichroic illuminates the blue channel. The dichroic can be removed to illuminate the blue channel only or replaced with a mirror to illuminate the red channel only. Light loss in either channel due to the dichroic will be less than 5%. The dichroic will have a transition from reflecting to transmitting over 50 nm band centered at approximately 550 nm allowing overlap between red and blue spectra to simultaneously calibrate both channels. The flat substrate of the dichroic introduces astigmatism into the blue channel. A weak cylindrical surface on the rear surface of the substrate reduces the astigmatism to an insignificant value.

4.5 Collimators

Two decentered paraboloidal mirrors 3.45-m from the f/15 Gregorian focal plane collimate the light from the slits. The mirrors are identical except for their reflective coatings. Each mirror produces 230-mm diameter collimated beams that converge to pupil images at the red and blue gratings.

4.6 Gratings

As many as three gratings and a mirror are available in each channel. Rotating selectors allow quick changes from imaging to spectroscopy at a choice of three different resolutions.

4.7 Cross-dispersion

Observations over the full spectral range at resolutions ≥ 10^4 will use gratings in a high order and filters or an order separating grism just in front of the camera. The grism will be a replica of approximately 170 lines/mm attached to an index matched glass substrate with an 80mm base and will disperse the 600nm to 1000nm wavelength range perpendicular to the primary dispersion direction. Initially, there are no plans to provide cross-dispersion in the blue channel of the instrument.

4.8 Cameras

Nearly identical 700 mm focal length cameras derived from a Maksutov-Schmidt design are used in both channels giving 0.15" per 15-micron pixel in imaging mode, and mapping a 0.6" slit onto four pixels when accounting for an anamorphic magnification of 1.2.

A unique feature of these cameras is that the dispersed beams are decentered with respect to the camera optical axes Fig. 1. The detectors and field flattening lenses are positioned entirely outside the incoming beams to the camera mirrors. This has two important advantages. First, the obstruction associated with the trapped focus of single mirror reflective cameras is eliminated. Second, any radiation reflected from the detector is not reflected back towards the grating to be reflected or re-dispersed into the camera. This eliminates narcissus reflections, an important source of the undesirable ghost images found in many spectrographs.

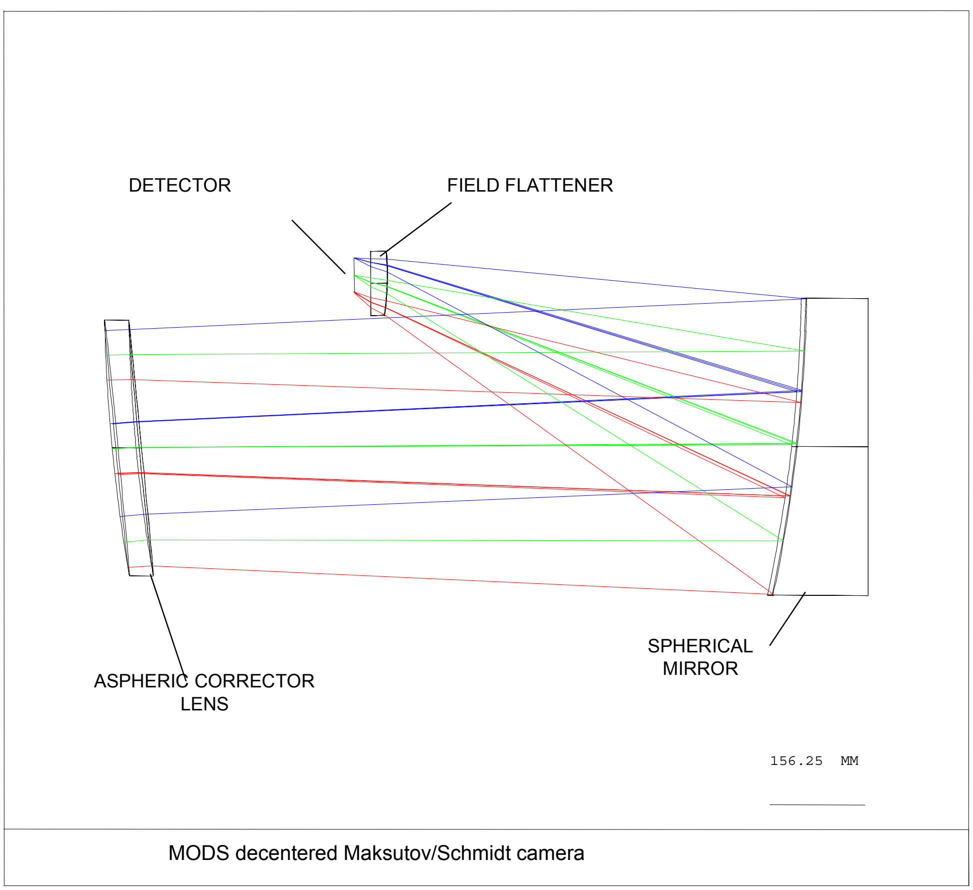

Figure 1. The decentered camera viewed in the plane of the slit perpendicular to the dispersion direction.

Several field flatteners are available for the cameras. As many as 8 field flatteners may be selected in each channel. The additional field flatteners are integrated with filters and will be selected to image in different band passes. In this way additional surface losses from individual filters are avoided.

A vacuum design will be used for the cameras. The corrector lens is the vacuum window for the camera eliminating the requirement for a window in front of the CCD detector. A schematic view of the layout of MODS showing the relative positions of the optical elements is shown in Fig. 2.

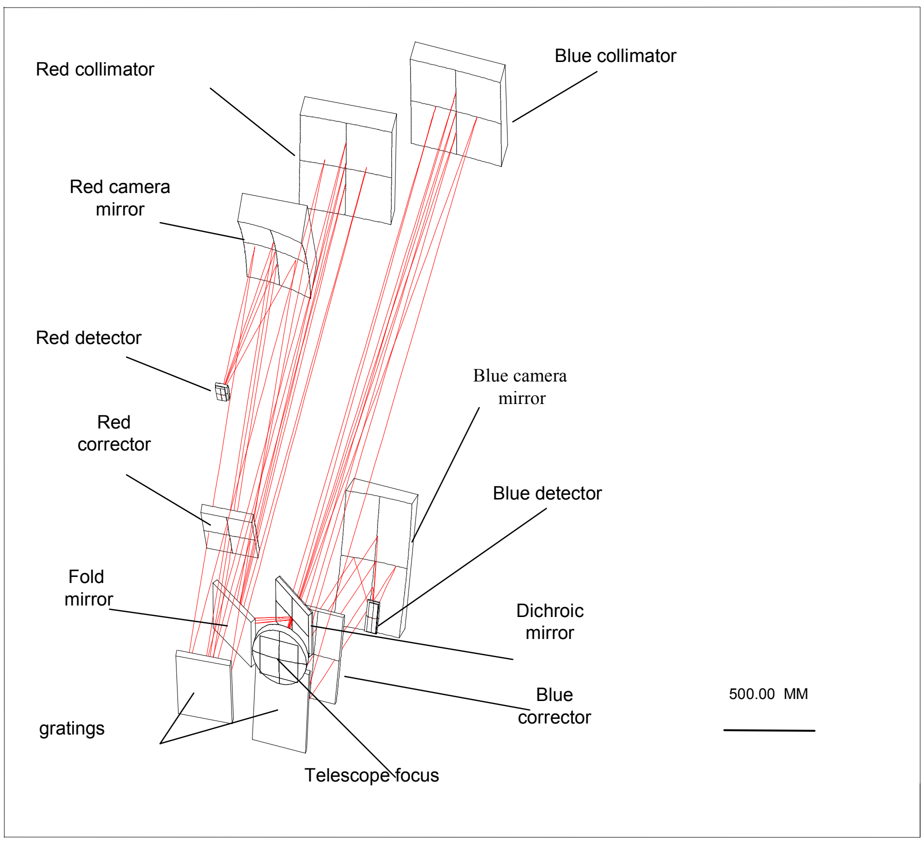

Figure 2. A Schematic view of the optical layout for MODS.

5. OPTIMIZATION OF THE DESIGN

The preliminary design strategy was to design the collimator and camera portions of the spectrograph separately

5.1 Field lens and collimators

The field lens in combination with the collimator re-images the telescope exit pupil onto the grating.

As described above, the red and blue beams are separated by a tilted dichroic mirror that introduces astigmatism into the blue channel. If the rear surface of the substrate is made cylindrical with a radius of ≈ 15 meters this astigmatism is reduced to an insignificant value. The collimator for the red channel is straightforward and only involves two reflections between the field lens and the collimator mirror. The angles between the telescope axis and the collimated beam axes (5.7^o) were chosen to allow the collimated beam from each collimator to clear the additional fold mirrors of the red channel as well as the field stop.

The angle between the collimator axis and the camera axis is 30 degrees. As this angle increases the anamorphic magnification of the grating increases. As the angle is reduced, the camera moves away from the grating. Both effects increase the dispersed beam size at the camera. The minimum camera aperture occurs close to a 30-degree value.

5.2 Cameras

The focal length of the cameras is chosen to image a slit width of 0.6 arc- seconds on to 4 - 15 µm CCD pixels at an anamorphic magnification factor of 1.2. The monochromatic f/ratio of the camera in the dispersion direction is then f/2.5. The camera field is determined by the length of the detector in the dispersion direction. Detectors up to a length of 120 mm in the dispersion direction can be accommodated. A Detector with 15 µm pixels has 2000 4 pixel resolution elements. A spectrum covering a 2:1 ratio in wavelength will have a resolution ($\lambda/d\lambda$) at the center of 3000. Each camera was optimized with gratings to give wavelength ranges of 300 nm – 600 nm for the blue and 500 nm – 1000 nm for the red. The Code-V optimization procedure used five zoom positions for wavelengths distributed over the selected spectral ranges at several field positions and included the effects of the collimator and telescope.

All the optical surfaces of the cameras are spherical excepting the inner concave surfaces of the correctors. These surfaces are sections of an extremely severe aspheres with departures from the vertex radii of curvatures of several millimeters. The departure from a best fit to the *nearest sphere* for the red corrector is still 500 µm. However, the techniques available for the production of surfaces such as this have advanced to the point that we are confident that the challenge of making this surface can be met. The radii of curvatures for the camera mirrors are identical. UV grade fused silica is used for the blue camera corrector and Schott BK7 glass for the red camera.

6. EVALUATION OF THE DESIGN

Examples of the optical performance of the complete system (telescope, collimator and camera) both imaging and spectrographic modes are shown on the following pages. The degradation of the images by the atmosphere is not included.

6.1 Imaging mode

In Fig. 3 we show values of the 80% encircled energy diameters (D_{80}) measured in arc-seconds for the images in the V-band. The curves show D_{80} for five y-axis values of the field, as a function of the positions on the x-axis, for a 4′ X 4′ square field. Even at a field diameter of nearly 8.5′, in the corners of a 6′ X 6′ field, the D_{80} is still only 1.2″ after re-focus for the best images.

For on axis imaging or spectroscopy re-focus of the camera will result in D_{80}'s ≅ 0.3″ in a 1′ X 1′ field.

6.2 Spectrographic mode

Fig. 4 shows D_{80} measures in microns for a spectrum covering the entire range of the red camera (600 nm – 1000 nm) for monochromatic images at several positions on a long (6′) slit centered on the axis of the telescope.

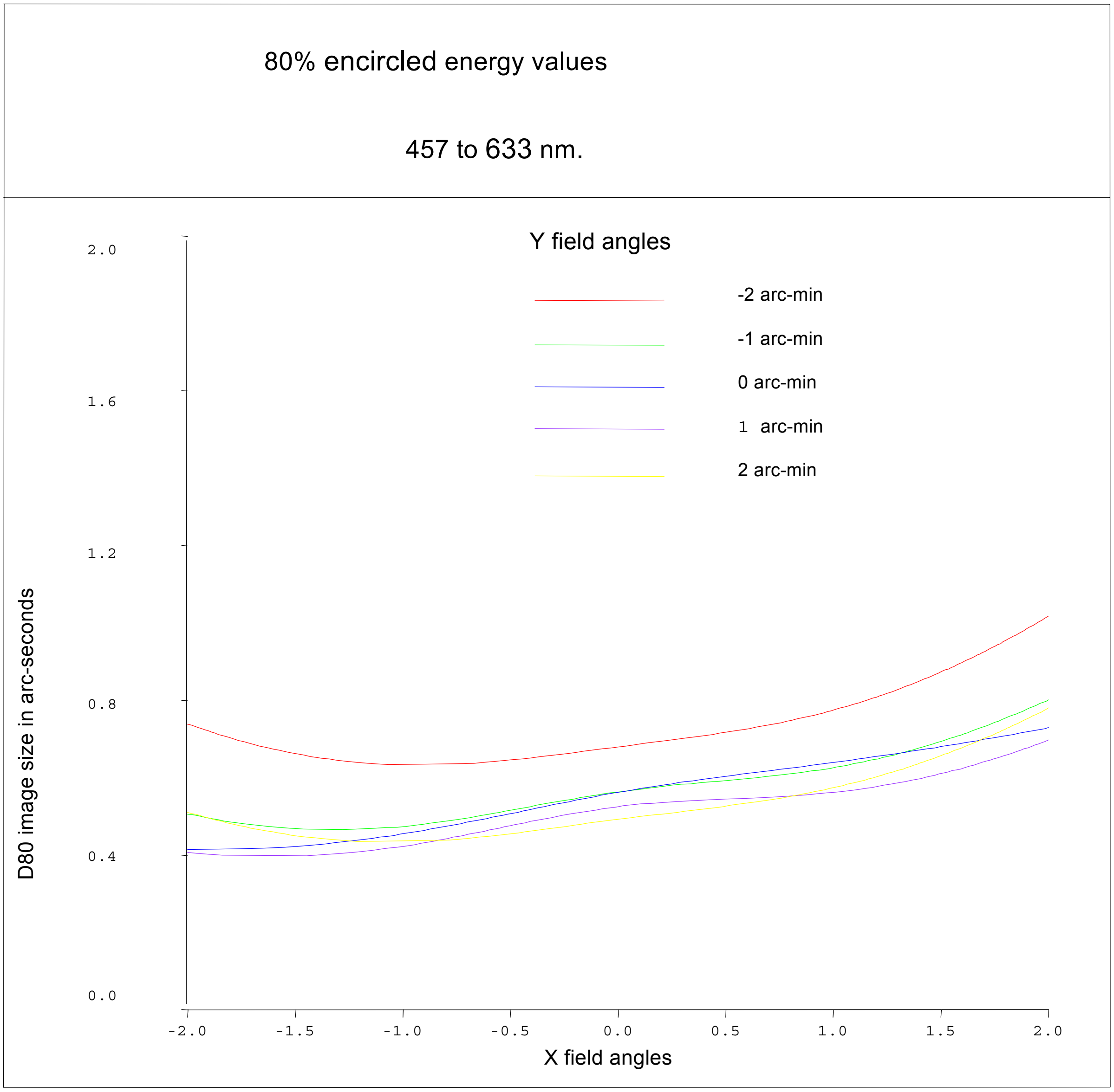

Figure 3. Image diameters enclosing 80% of the energy from a point source in the V- band for a 4 arc-minute square field as a function of field position.

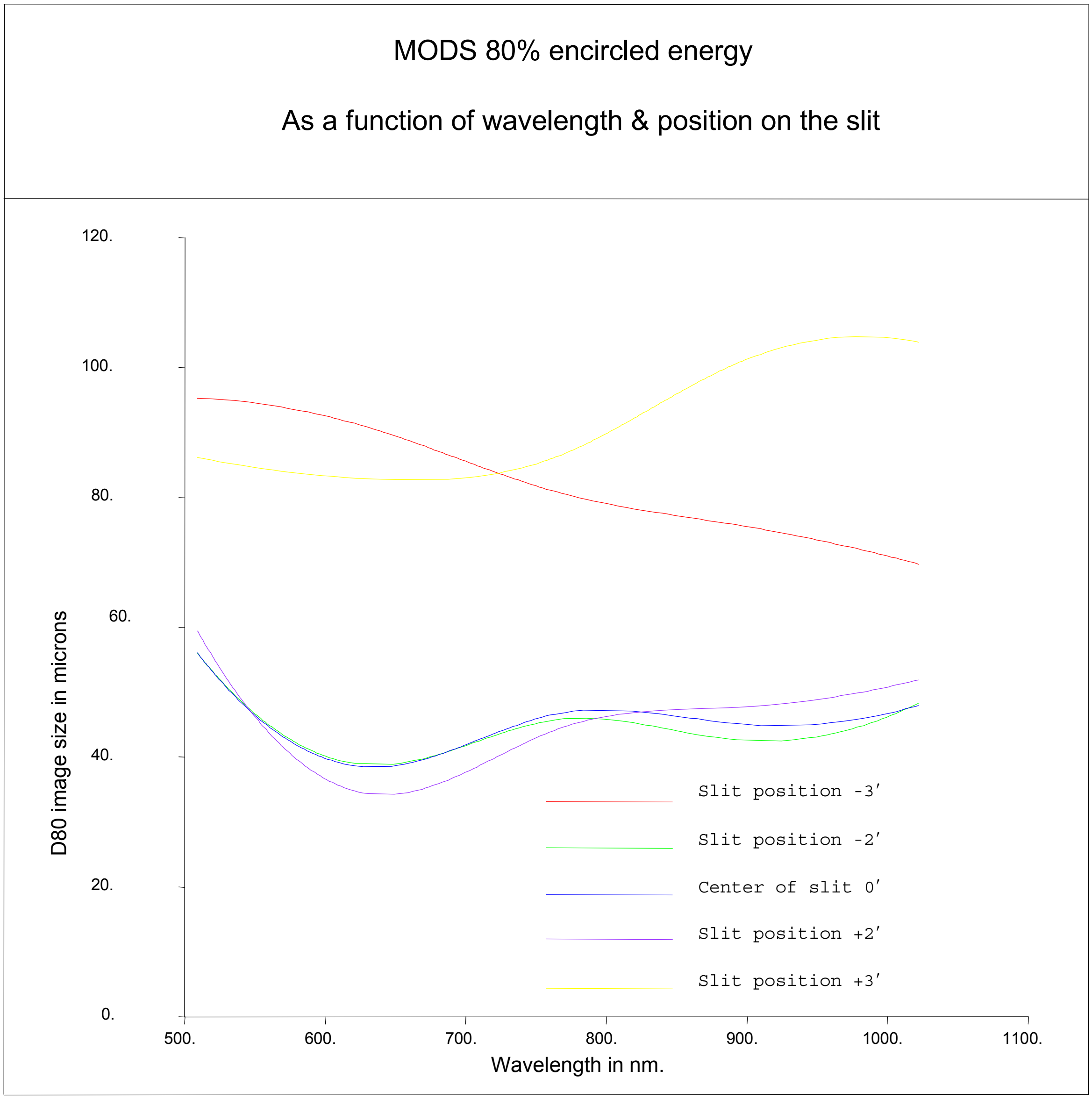

Figure 4. Image diameters (measured in μm) enclosing 80% of the energy from monochromatic point sources as a function of wavelength. 60 μm corresponds to a slit width of 0.6 arc-seconds.

7. SUMMARY

We describe the optical layout and optimization for a dual channel optical spectrograph for the Large Binocular Telescope. The design utilizes as few optical surfaces as possible. The instrumental throughput, excluding the atmosphere and telescope, has been estimated at $\gtrsim 40\%$ between 350 nm. and 850 nm. For a discussion of the efficiency and further details including planned scientific programs see Osmer et al. in these proceedings. The rendering of MODS Fig 5. indicates the size of the instrument.

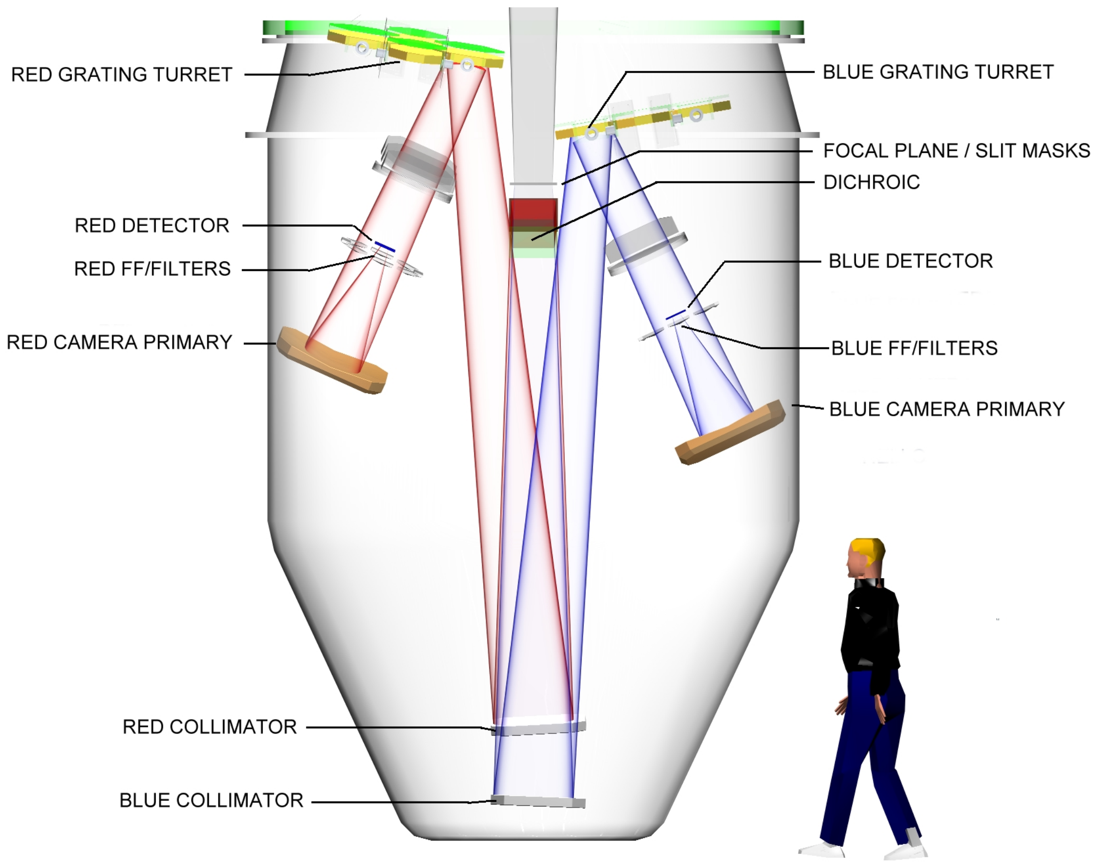

Figure 5. View of MODS