Optical Design of a Red-Sensitive Spectrograph

Emily C. Martin, D.L. DePoy, and J.L. Marshall

Texas A&M University Department of Physics and Astronomy, 4242 TAMU, College Station, TX 77843

Introduction

Many current and planned astronomy projects, including Dark Energy surveys, Supernovae surveys, and other large surveys are focused on observations in the red part of the optical window. We seek to build a red-sensitive, single-object optical spectrograph for the 2.7-m Harlan J. Smith Telescope (HJST) at McDonald Observatory. There are currently several other instruments designed for this particular telescope, however none of these instruments are optimized to work in the red. We aim to provide the telescope with a viable option for studying red objects with a moderate resolution.

This instrument is also being considered as a candidate for a prototype of the DESpec instrument, which is a proposed upgrade to the Dark Energy Survey instrument, DECam, currently installed at Cerro Tololo Inter-American Observatory (CTIO). In the spirit of the VIRUS spectrographs for HETDEX, DESpec aims to use an assembly of identical spectrographs with a small, simple design layout as opposed to a large instrument with larger, more expensive optics.

The spectrograph described below will work primarily in the 600-1000 nm wavelength range. It is designed to fit on the Cassegrain f/8.8 focus of HJST and use a 1 arc second slit width. In the spectrograph design, we also assume the use of a standard science-quality commercially available detector. For the purposes of design, we assume the CCD has 2000 15 µm pixels.

Optical Design

The optical design was primarily completed using Zemax optical design software. A layout is shown in Figure 1. The design uses an off-axis parabolic mirror, an 800 nm blazed reflective grating, 4 custom designed lenses, 1 commercially available lens, and a generic CCD detector. Light enters the spectrograph through a 1 arc-second (115 µm) wide slit and is collimated by the off-axis parabolic mirror. The collimated light is then reflected by the grating, imaged by the camera, and focused onto the detector.

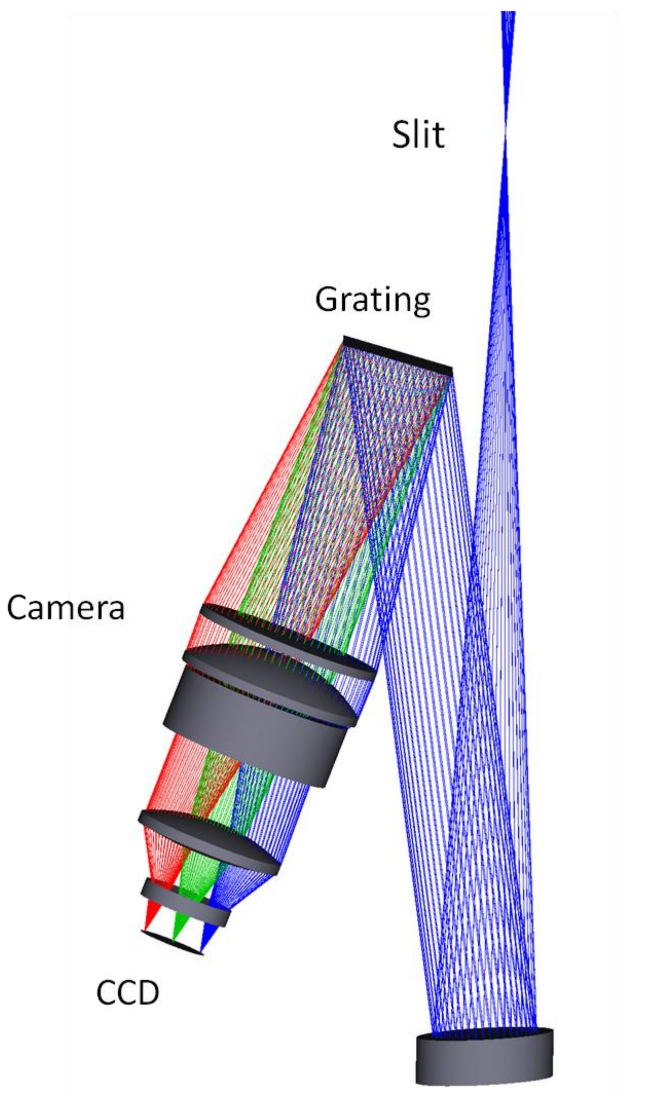


Figure 1. Optical layout of the red sensitive spectrograph. Wavelengths shown are 1000 nm (red), 800 nm (green), and 600 nm (blue).

Collimator

To collimate the incident light, we chose to use an off-axis parabolic mirror to maintain high throughput in the design. The mirror featured in this particular design has a focal length of 400mm and a diameter of 60mm.

Grating

The design uses an 800 nm blazed reflective grating. This grating is 50 mm square, has a groove spacing of 600 lines/mm, and should be readily available to buy commercially.

Abstract

We present a preliminary design for a red-sensitive spectrograph. The spectrograph is optimized to operate over the 600-1000 nm spectral range at a resolution of R = $\lambda/\Delta\lambda$ ~2000 and is designed specifically for the 2.7-m Harlan J. Smith Telescope at McDonald Observatory. The design is compact and cost effective and should have very high throughput. The principles of the design can be extended to other purposes, such as a unit spectrograph for the DESpec project or other projects that require good performance in the red. We discuss the selection of components as well as the choice of optical layouts and the theoretical throughput of the instrument.

Camera Design

We completed two designs for a camera using Zemax and a default merit function. Two designs were created to determine whether we could take a completely custom design and use off-the-shelf optics to replace some of the lenses without compromising the quality of the image. The first design consists of five custom-made spherical lenses, while the second design uses one commercially available lens and four custom spherical lenses. Our merit function allowed us to optimize for RMS spot size over three wavelengths: 600 nm, 800 nm, and 1000 nm. The designs were also optimized across three different fields along the slit: 0 arc-seconds, 15 arc-seconds, and 30 arc-seconds. We used several iterations of both a local-minimum merit function and a global hammer function to arrive at our final designs. The two different camera designs are shown below in Figure 2.

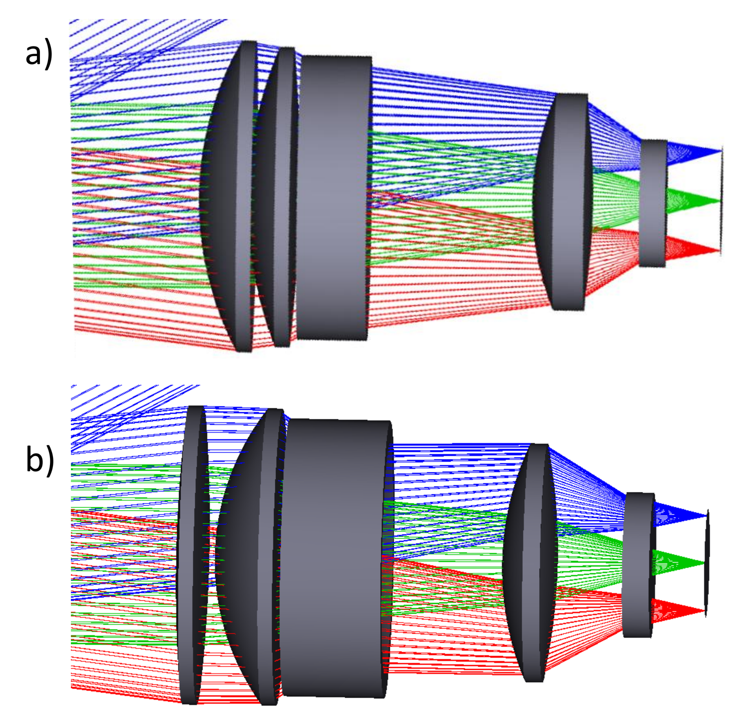


Figure 2. a) 3D shaded model of design for camera 1 using 5 custom lenses. b) 3D shaded model of design for camera 2 using 4 custom lenses and 1 commercial lens. The wavelengths pictured here are 600 nm (blue), 800 nm (green), 1000 nm (red).

Performance Analysis

Based upon the camera design the slit size on the detector will be approximately 32 µm wide, just slightly over two pixels. With a dispersion of ~2.1 Å/pixel, we obtain a resolution of R~1930 at the central wavelength of 800 nm. Spot sizes for both camera designs in various wavelength and field positions are shown in Figure 3.

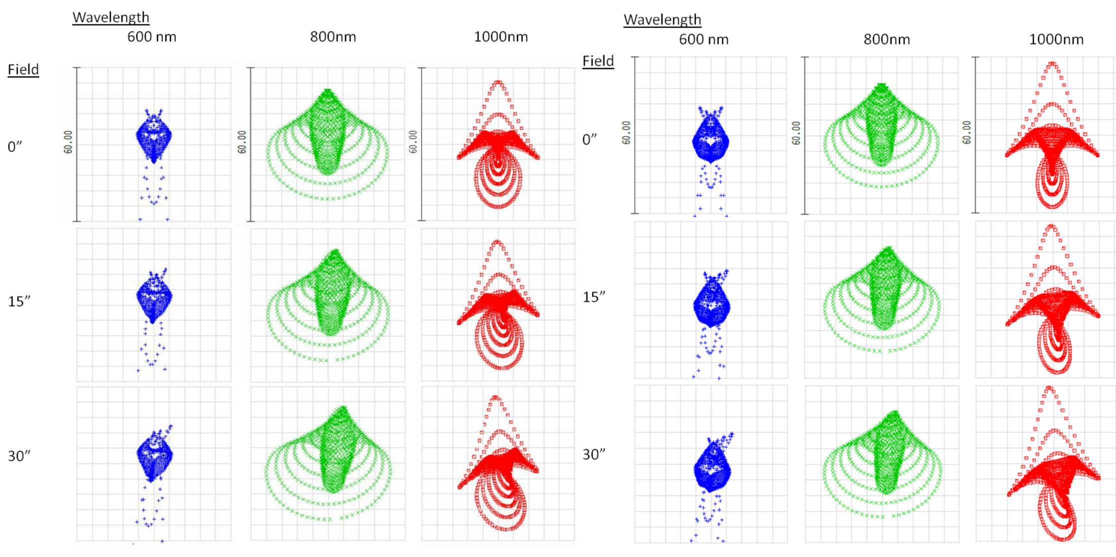
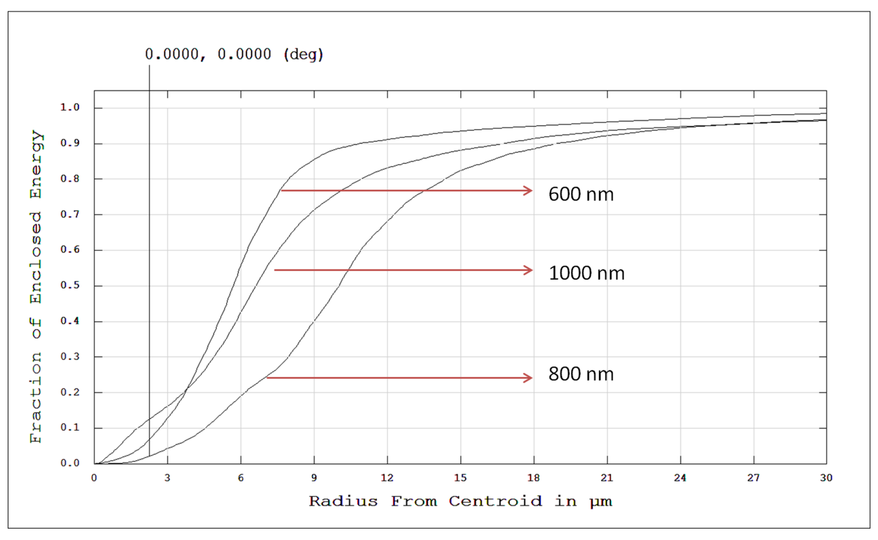


Figure 3. Spot diagrams for camera 1 (left) and camera 2 (right) at various wavelengths and field positions. Each grid measures 60 µm x 60 µm, which represents 4x4 pixels.

Figure 4 shows the encircled energy plots for both camera designs. Overall, the use of a commercially available lens will improve the design and allow for a more cost-effective instrument with quicker production time. However, our analysis of the design shows that the use of additional commercial optics will not benefit the design but will cause the image quality to degrade such that we can no longer meet our design specifications.

Camera 1



Camera 2

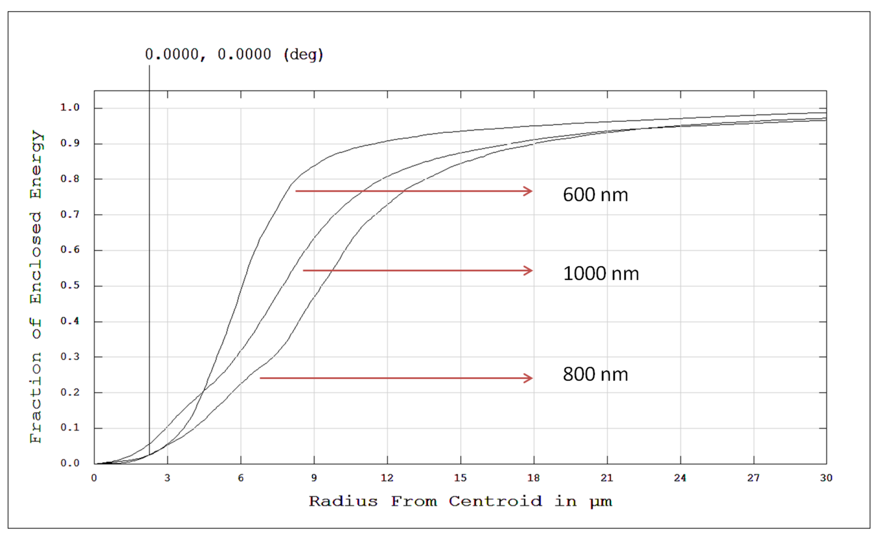


Figure 4. Encircled Energy vs. Radius for both camera designs at 600 nm, 800 nm, and 1000 nm.

Tolerance Analysis

Using Zemax we have performed a tolerance analysis on the various optical components to determine which displacements and element tilts will be most detrimental to the spot sizes for camera 2. The tolerance merit function was based upon the RMS spot size of the same three wavelengths used to optimize the instrument. We chose to use the back focus of the detector as the compensator. As operands for the merit function, we considered only the mechanical constraints of each element. We find that no tolerances need be tighter than 25 microns in de-centering or 0.5 arc-min in tilt. Such precisions are comparable to standard machine tool precision and can easily be measured with coordinate measuring machines.

Conclusions

We have presented two designs for a single-object optical spectrograph optimized for the wavelength range 600 nm < λ < 1000 nm. Both designs are compact and meet the science requirements for spectral resolution of R~2000 and wavelength coverage in the red end of the visible spectrum. The designs include several commercially available optical components which will decrease costs as well as production time.

Future Work

We plan to continue to optimize the design, paying particular attention to the angles between the collimator, grating, and camera. Further studies will also be done to determine which particular commercial optical components will provide us with the most effective design. The Munnerlyn Astronomical Instrumentation Lab at Texas A&M University plans to construct this instrument over the next 2-3 years.

Texas A&M University Department of Physics and Astronomy is an institutional member of:

GMT · Munnerlyn Astronomical Instrumentation Lab, Texas A&M University · HETDEX Hobby-Eberly Telescope Dark Energy Experiment, Illuminating the Darkness · LSST Large Synoptic Survey Telescope · Dark Energy Survey

Acknowledgments

Texas A&M University thanks Charles R. '62 and Judith G. Munnerlyn, George P. '40 and Cynthia Woods Mitchell, and their families for support of astronomical instrumentation activities in the Department of Physics and Astronomy.

We would also like to thank the University of Texas at Austin and McDonald Observatory for providing us with information on the Harlan J. Smith Telescope.