OPTICAL DESIGN OF A RED SENSITIVE SPECTROGRAPH

A Senior Scholars Thesis

by

EMILY CATHERINE MARTIN

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

May 2012

Majors: Physics
French

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Approved by:

Research Advisor: Darren DePoy
Associate Director, Honors and Undergraduate Research: Duncan MacKenzie

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ABSTRACT

Optical Design of a Red Sensitive Spectrograph. (May 2012)

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We present a preliminary design for a red-sensitive spectrograph. The spectrograph is optimized to operate over the 600-1000nm spectral range at a resolution of ~2000 and is designed specifically for the 2.7-m Harlan J. Smith Telescope at McDonald Observatory. The design was primarily done using ZEMAX, along with preliminary design work using intrinsic properties of spectrographs and geometric optics. It 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. In this paper, we will discuss the selection of components as well as the choice of optical layouts and the theoretical throughput of the instrument. We have succeeded in designing an optical spectrograph capable of taking data in the 600-1000nm range, at a minimum spectral resolution of 1979, which is adequate for our scientific goals.

ACKNOWLEDGEMENTS

I thank Dr. Darren DePoy for his help on this project. Without his knowledge and willingness to spend hours explaining things to me, I would never have been able to finish. I also thank Dr. Jennifer Marshall for hiring me to work in the instrumentation lab. She is an inspiring role model and has helped me to discover my love of astronomy and scientific research.

Thanks to Jean-Philippe Rheault for helping me with ZEMAX and keeping me from getting stuck too many times. I also thank the entire Astronomical Instrumentation Lab for being such a wonderful group of people to work with and for their encouragement and support.

I also thank my family for always being there for me, supporting me, and helping me achieve my dreams.

NOMENCLATURE

f/#	F Number (Ratio of Focal Length to Aperture Diameter)
k	Grating Order
α	Collimator/Grating Angle
d_{coll}	Diameter of Collimator
f_{coll}	Focal Length of Collimator
CCD	Charge-Coupled Device
f_{cam}	Focal Length of Camera
X	Distance between Grating and Camera
d_{cam}	Diameter of Largest Lens of Camera
r	Anamorphic Factor
β	Grating/Camera Angle
ρ	Angular Dispersion
λ	Wavelength
R	Spectral Resolution
RMS	Root Mean Square
ZEMAX	Optical Design Software
HJST	Harlan J. Smith Telescope

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CHAPTER I

INTRODUCTION

An astronomical spectrograph is an optical instrument which receives light from distant galaxies and stars and disperses the light through a grating or prism so that astronomers can detect the spectrum of the incident light (Hearnshaw, 2009). The spectrum that we view can tell us many things including the composition of stars, their location in the universe, and their proper motion. As we make advancements in technology, we can build increasingly better astronomical instruments. These instruments make it possible for astronomers around the world to do better science, take better data, and get more accurate results, even from galaxies that are millions of light years away.

The Astronomical Instrumentation Laboratory at Texas A&M University is involved in various instrumentation projects with the McDonald Observatory, operated by the University of Texas at Austin. Astronomers at Texas A&M University are interested in studying late-type metal-poor M stars, which are the oldest and most numerous stars in our galaxy (Marshall, 2007; Marshall, 2008). The hope is that learning more about these incredibly old stars will tell us more about how our galaxy formed. The world-class telescopes at McDonald Observatory are capable of meeting these science goals, but

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This thesis follows the style of *Publications of the Astronomical Society of the Pacific*.

they lack the appropriate instrumentation to observe these very red objects.

We seek to build a red sensitive spectrograph for the 2.7m Harlan J Smith Telescope at McDonald Observatory. The telescope was built in 1969, and at the time was the world's third largest telescope. There are currently several other instruments designed for this particular telescope, however none of these instruments are optimized to work in the red part of the visible spectrum. We aim to provide the telescope with a viable option for studying red objects.

The spectrograph will work primarily in the 600-1000 nm wavelength range. It is designed to fit on the Cassegrain f/8.8 focus of the telescope. The spectrograph will be comprised of an off-axis parabolic collimator mirror f/8.8 to match the focus of the telescope, an 800 nm reflective blazed holographic grating, a camera lens, and a 2000 pixel-wide CCD that has a pixel size of 15 microns.

Our decisions about which components to use are primarily driven by our science goals. The spectrograph will have a 1 arc second slit width, chosen to accommodate the average seeing at McDonald Observatory. It will have a resolving power of approximately 2000 at 800 nm, our central wavelength. These specifications should provide us with an instrument capable of studying red objects in the galactic halo.

CHAPTER II

METHODS

The spectrograph design was done using a modified version of SimSpec, an Excel spreadsheet designed to aid in spectrograph design, and ZEMAX, optical design software. We started with the basic science requirements of wanting a spectral resolution of approximately 2000, and a wavelength range spanning 600-1000nm. We also wanted to keep the design as simple as possible, in order to keep construction costs low.

The first steps we took in the design process were to determine some initial parameters for the spectrograph. We accomplished this using SimSpec, as well as various equations that govern the relationships between optical components of a spectrograph. We then input the initial spectrograph layout into ZEMAX, where we focused on optimizing various individual components and optimizing the layout as a whole.

Initial calculations

Our spectrograph will be used on the Harlan J. Smith 2.7m telescope, at the f/8.8 Cassegrain Ritchey-Chretien focus. Our spectrograph will be constrained to properly accept all of the light from the telescope, i.e. the collimator has the same f/number as the telescope. The collimator may be either a lens or mirror that takes all of the incoming light and makes the rays parallel to each other. It must also not produce a beam that exceeds the size of the grating. For ease of availability, we chose a Shimadzu brand blazed holographic reflective grating that is 50mm square, with 600 lines/mm and a blaze angle of 800nm, in the middle of our spectral range. We will be using the first diffraction order of the grating (k = 1).

We started with a 28 degree separation between the collimator and grating (α). The minimum required collimated beam diameter (d_{coll}) is found using Equation 1. We get a minimum collimator diameter of 44.15mm.

1. Grating Size [mm] × cos(α) = d_{coll} [mm]

Then, we used Equation 2 to solve for the focal length of the collimator (f_{coll}):

2. $d_{coll} \times f/\# = f_{coll}$

Here, f/# is 8.8, as dictated by the telescope layout. Our collimator must have a focal length near 390.3mm. We chose an off-axis parabolic mirror with a focal length of 400mm, which will be easier to find ready-made. This means our new minimum collimator diameter is 45.45mm, using Equation 2 to solve again for d_{coll}.

To calculate the specifications of the camera, we first have to determine the demagnification factor between the collimator and camera. This is determined by the desired slit size on the detector. Our slit width is 1 arcsecond, which in µm is:

3. $$\frac{1\text{arcsec}}{206265\frac{\text{rad}}{\text{arcsec}}} \times 23910\text{mm} \times 1000\frac{\mu\text{m}}{\text{mm}} = 115.92\ \mu\text{m}$$

We want to have each slit width across 2.5 pixels, and since each pixel is 15 µm, one slit width on the CCD will be approximately 37.5 µm. The demagnification factor is the ratio of the focal length of the camera (f_{cam}) to the focal length of the collimator (f_{coll}), which is also the ratio of the slit's image on the CCD to the actual slit width:

$$4.\quad \text{demagnification} = \frac{37.5\,\mu\text{m}}{115.92\,\mu\text{m}} = 0.323 = \frac{f_{cam}}{f_{coll}}$$

We get a value of 129.4 mm for f_{cam}. To calculate the value of the diameter of the camera at a distance X from the grating:

$$5.\quad d_{cam} = d_{grating} + \frac{X\,[\text{mm}] \times \text{pixel size}[\text{mm}] \times \text{pixels}}{f_{cam}[\text{mm}]}$$

$d_{grating}$ is calculated with Equation 6:

$$6.\quad d_{grating} = \frac{d_{coll,min}}{\cos(\alpha)} = 51.5\text{mm}$$

So our value for d_{cam} with X = 50mm is 63.1mm. Thus our camera will be approximately f/2. This will be the hardest requirement to satisfy, as cameras with low f/numbers are harder to manufacture and thus more expensive, and they also are more prone to aberrations.

Now, we consider the wavelength range and the spectral resolution, two of our main science requirements. To do this, we will first consider the number of pixels one slit width will cover. We earlier assumed it to be 2.5 pixels, but now we calculate it based on our current parameters using Equation 7.

$$7.\quad \frac{\text{pixels}}{\text{slit width}} = \frac{\text{slit width}[\mu\text{m}] \times \text{demagnification} \times r}{\text{pixel size}[\mu\text{m}]}$$

Here, r is our anamorphic factor, found in Equation 8, where α is the collimator-grating angle, and β is the grating-camera angle.

$$8.\quad r = \frac{\cos(\alpha)}{\cos(\beta)}$$

We have a value of r = 0.8825 with our current configuration. This provides us with an actual value of 2.206 pixels/slit width.

Next we find the angular dispersion (ρ) on the CCD detector, in Angstroms/pixel using Equation 9. We get a value of ρ = 1.932 Å/pixel.

$$9.\quad \rho\left[\frac{\text{Å}}{\text{pixel}}\right] = \frac{\text{pixel size}[\text{Å}]\times\cos(\beta)}{k\times\frac{\text{lines}}{\text{mm}}\times f_{\text{cam}}[\text{mm}]}$$

Now we can find the angular dispersion per slit width (Δλ) as in Equation 10:

$$10.\quad \Delta\lambda = \frac{\text{pixels}}{\text{slit width}}\times\rho$$

This gives us a value of 4.262 Å/ slit width. Then our resolution at the central wavelength of λ = 8000Å can be calculated as follows.

$$11.\quad R(\lambda) = \frac{\lambda}{\Delta\lambda}$$

We get R = 1876.9, which is in our range for an acceptable resolution. We will attempt to raise the angular resolution as we optimize in ZEMAX.

To obtain the wavelength range, we can calculate the minimum and maximum wavelengths as follows:

12. $\lambda_{min} = \lambda_{mid} - \frac{\#\,\mathrm{pixels} \times \rho}{2}$

13. $\lambda_{max} = \lambda_{mid} + \frac{\#\,\mathrm{pixels} \times \rho}{2}$

We have λ_{min} = 6068.1Å and λ_{max} = 9931.9Å. This wavelength range is slightly smaller than we would prefer, but we hope to fix that during our optimization of the layout using ZEMAX.

Optimization

The majority of the optimization of our spectrograph was done using ZEMAX. ZEMAX is optical modeling software capable of handling a wide variety of mirrors, lenses, diffractive optics, and other optical components. It allows the user to define values for each optic, such as radius of curvature, diameter, and distance between components. The user also has the choice of which wavelengths of light will be transmitted through the system, as well as the fields (location) of the incoming light, and the system aperture. ZEMAX may be used as a modeling tool, or if the user specifies any of the parameters as variable, ZEMAX can optimize the system. The software has a merit function which when run, will alter the values of any variables until it reaches a minimum value.

To fully make use of ZEMAX, we input our initial parameters calculated earlier in this section. We started with the ZEMAX file for the Harlan J. Smith Telescope, provided by the University of Texas. This way we ensure that the light entering the spectrograph is in the same configuration in the model as it will be in actuality. For the collimator, we input the type of glass (mirror), the radius of curvature, thickness, semi-diameter, and conic value. For the grating, we input similar characteristics as well as the number of lines/mm and diffraction order. We also added coordinate breaks where necessary, to account for the geometry of the system. Finally, we set the size of the detector as the semi-diameter of our focal plane.

The camera design was initially done separately to the spectrograph design. We started with a Zebase file for a Cooke Triplet, which we altered and optimized to achieve f/2 with a focal length of approximately 130mm and minimal aberrations to the wave front. After reviewing the spot size and point spread functions of the initial layout, we determined that in order to achieve higher resolution, we would need more lenses to adjust for aberrations. We added two new lenses and reran the merit function editor, correcting for astigmatism, coma, axial color, and spherical aberrations in addition to the default merit function provided by ZEMAX. We then used that prescription data to insert the lenses into our ZEMAX spectrograph layout.

Once we imported the camera lens from the initial design into the spectrograph design, it became obvious that we had miscalculated the distance needed between the grating and camera to avoid vignetting the light from the collimator to the grating. We adjusted this distance, and restarted the optimization process. This adjustment requires a larger camera diameter and thus smaller f/#, which was even more difficult to obtain. After optimization, we adjusted values and checked the 3D layout to ascertain the impact these changes have on the design. We ran several iterations of this optimization process, continually looking for a smaller value for the merit function.

After obtaining a model for our spectrograph, we then began to research different commercially available lenses that could be used to replace any of the ideal components of our camera. Substituting a commercial lens for a custom made lens significantly cuts costs and production time. We found suitable substitutes for each of the 5 lenses in our design and placed them in the design one at a time. We re-optimized each configuration and then compared the results to see which of the commercial lenses would potentially provide the best layout. The goal was to change the design without increasing our spot size too greatly, which would decrease our resolution. The optical layouts are shown in the following section, along with a discussion of their respective properties and merits.

CHAPTER III

RESULTS

Spectrograph design

Our final spectrograph design consists of both commercial and custom-made optical components. The complete optical design with incident light coming from the Harlan J. Smith Telescope is shown in Figure 1. The incident light passes through a 1 arc-second slit width (0.1159 mm) and is reflected by an off-axis parabolic mirror. The collimated light is then reflected by the grating, and imaged by the camera we have designed. The camera lenses focus the image of the slit width onto the commercial CCD.

The collimator we have chosen is sold commercially by Opti-Surf. It has a 400mm focal length, and reflects the light off-axis by 8.6°. To achieve maximum reflectivity in our spectral range, the mirror has a gold surface with $\lambda/10$ accuracy. The diameter of the off-axis parabolic mirror is 60 mm, which is larger than necessary for our particular geometry.

The grating is a Shimadzu brand grating, 50mm square with a blaze angle of 800nm and with a groove spacing of 600 lines/mm. The grating has an aluminum coating. Our camera design was done primarily in ZEMAX. The final optical component, the CCD, is a generic commercial CCD that is 30mm square. It is 2000 pixels wide, with a pixel size of 15 µm. These CCDs are readily available and are quite inexpensive.

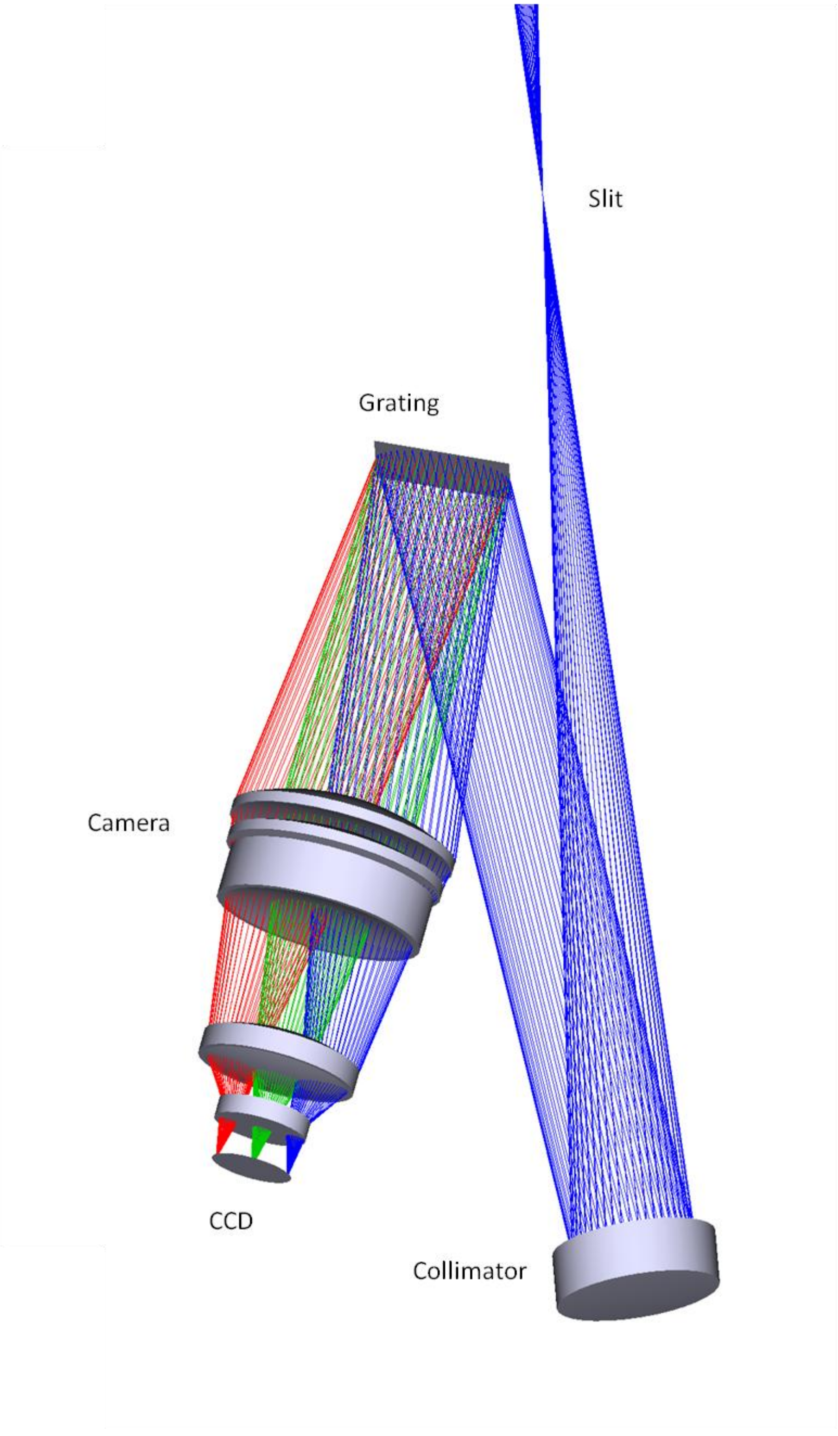


FIG. 1- Optical layout of the spectrograph. The incident light is from Harlan J. Smith Telescope. The various colors of rays represent different wavelengths of light. Blue is 600nm, green is 800nm, and red is 1000nm.

Camera design

We completed two designs for a camera for the spectrograph. The first design consists of 5 custom-made lenses, and the second design uses one commercially available lens and 4 custom-made lenses. The completely custom-made camera design was created in ZEMAX by modifying the merit function as described in chapter II. The lens prescription data is listed below, in Table 1. The thickness listed is either the thickness at the center of the lens (for lens fronts) or the distance to the following lens (lens backs).

TABLE 1

Lens Data for Camera 1

Lens	**Radius of Curvature**	**Thickness [mm]**	**Diameter [mm]**	**Glass Type**
1-front	86.499	11.271	84.33	N-LAK34
1-back	234.790	2.00	83.062	N-LAK34
2-front	106.446	14.003	81.24	LAK31
2-back	-403.761	3.602	79.234	LAK31
3-front	-210.519	12.154	76.996	SF59
3-back	199.402	47.501	71.26	SF59
4-front	73.274	16.513	58.81	N-LAK33B
4-back	-189.087	15.904	54.548	N-LAK33B
5-front	-49.943	4.00	34.582	SF59
5-back	-238000	15.00	33.504	SF59

The camera layout is shown in Figure 2. The camera was optimized for 3 wavelengths: 600nm, 800nm, and 100nm, which are shown in blue, green, and red, respectively. We also optimized across 3 different fields along the slit: 0 arc-seconds (centered), 15 arc-seconds from the center, and 30 arc-seconds from the center.

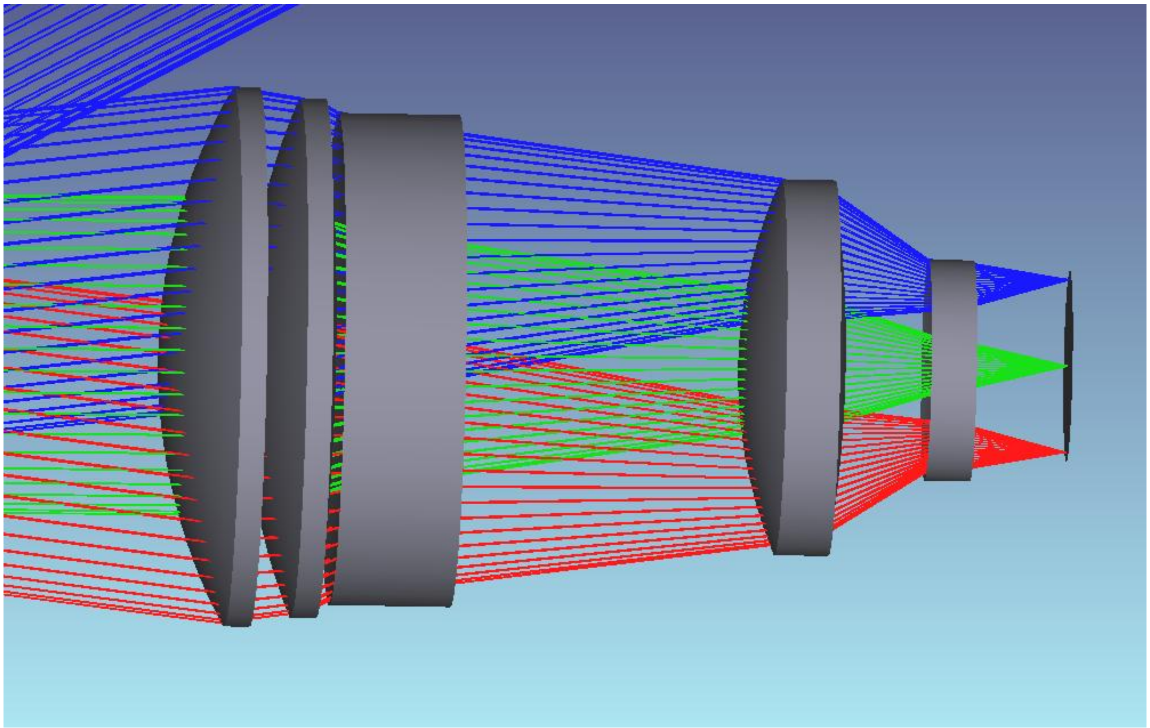
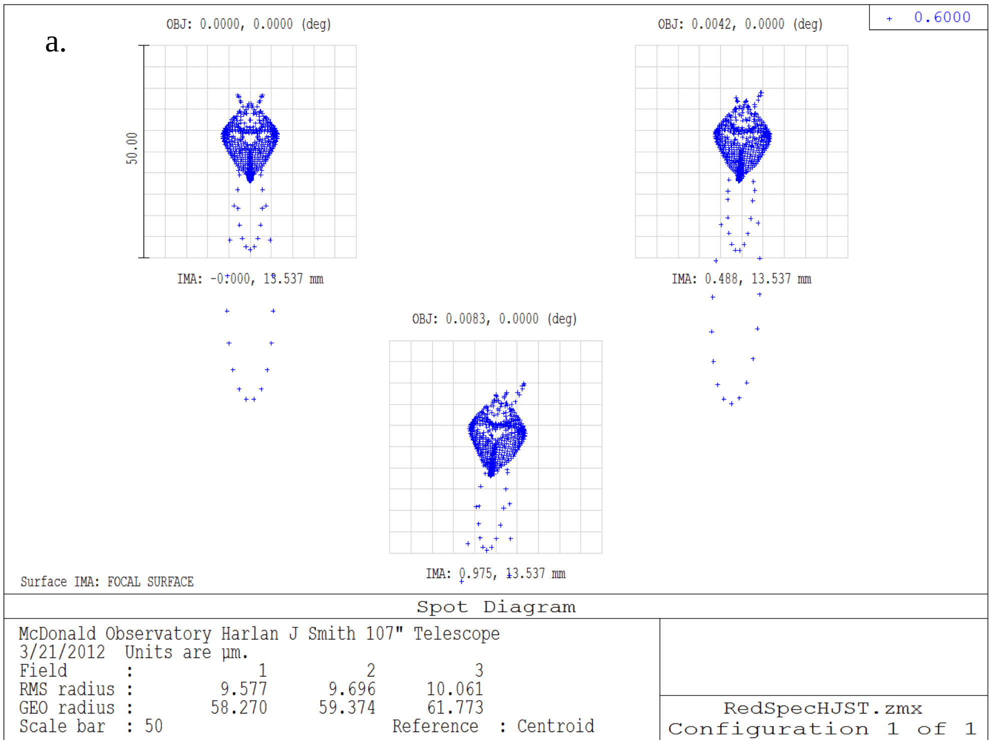


FIG. 2- Optical layout of camera 1. The camera lenses and CCD focal plane are shown in the configuration as they will be placed in the spectrograph. Blue rays represent 600nm, green rays are 800nm, and red rays are 1000nm.

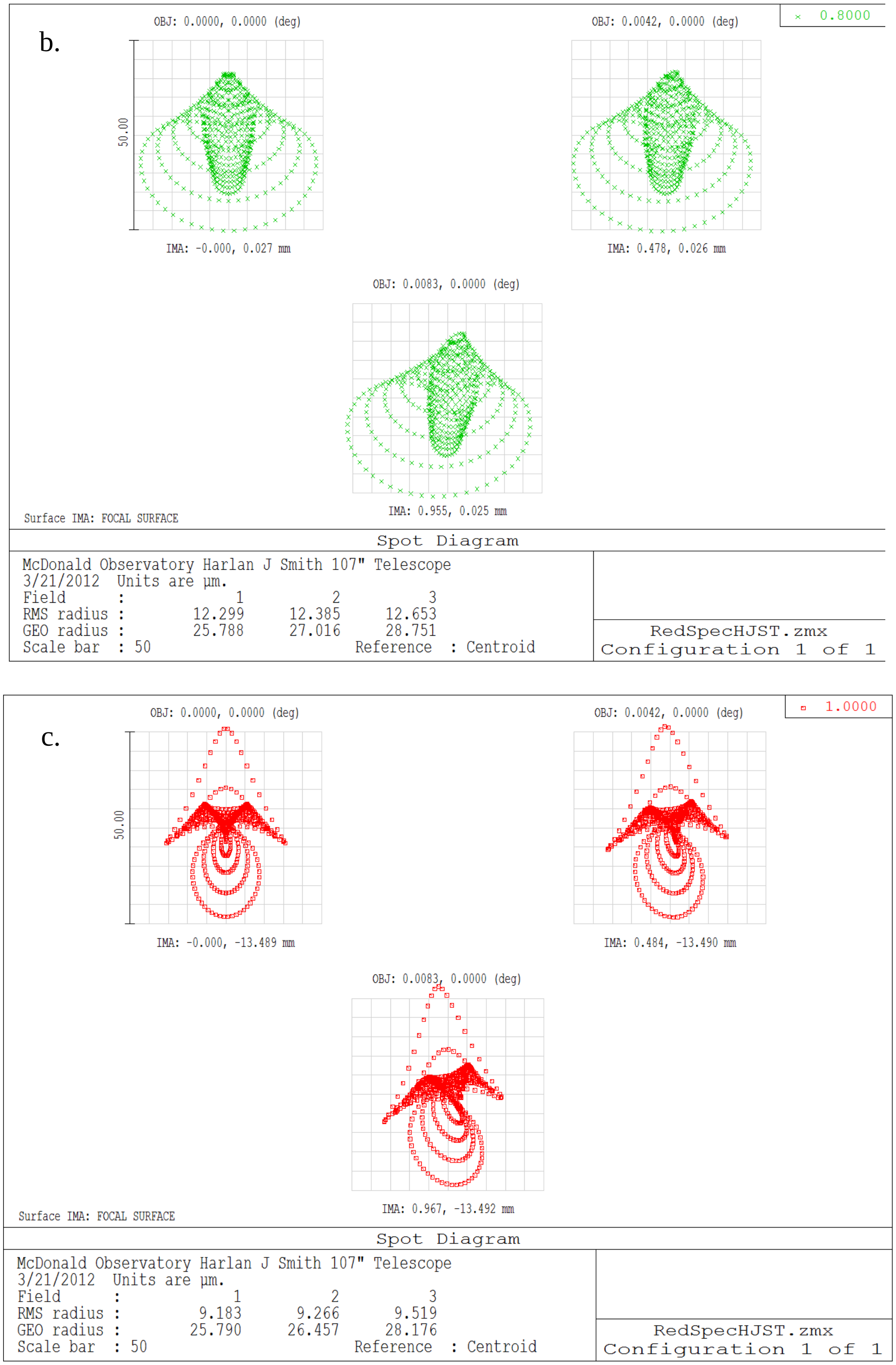
Spot size diagrams for camera 1 are shown in Figure 3. Spot size diagrams show theoretical traces of paths travelled by light rays in the spectrograph, and where they will land on the focal plane. They give both the RMS radius and the geometric radius of the spot size. The RMS radius is the root mean square radial size of the distribution of rays traced through the system. The geometric radius is the radius of the circle centered at the reference point which encloses all the rays. We look mainly at RMS radius to tell us whether or not our optical design is good enough. We want our spot size to cover roughly 2.5 pixels (37.5 µm) in order to adequately sample the image with the detector so an RMS radius of 18.75µm or less is ideal.



```
McDonald Observatory Harlan J Smith 107" Telescope
3/21/2012  Units are µm.
Field      :         1          2          3
RMS radius :     9.577      9.696     10.061
GEO radius :    58.270     59.374     61.773
Scale bar  : 50              Reference  : Centroid
```

```
RedSpecHJST.zmx
Configuration 1 of 1
```

FIG. 3- Spot size diagrams for camera 1. Spot sizes at 3 different fields for a) 600nm, b) 800nm, c) 1000nm. Radii listed in µm.



```
McDonald Observatory Harlan J Smith 107" Telescope
3/21/2012  Units are µm.
Field      :          1          2          3
RMS radius :     12.299     12.385     12.653
GEO radius :     25.788     27.016     28.751
Scale bar  : 50                Reference  : Centroid

RedSpecHJST.zmx
Configuration 1 of 1
```

```
McDonald Observatory Harlan J Smith 107" Telescope
3/21/2012  Units are µm.
Field      :          1          2          3
RMS radius :      9.183      9.266      9.519
GEO radius :     25.790     26.457     28.176
Scale bar  : 50                Reference  : Centroid

RedSpecHJST.zmx
Configuration 1 of 1
```

FIG. 3- continued.

Another quality test for an optical design can be found by looking at its encircled energy diagrams, shown in Figure 4. Encircled energy is the percentage of total energy enclosed as a function of distance from the image centroid at the focal plane. We show the encircled energy for each of the 3 wavelengths and at each field. The diffraction limit is also shown, as an indicator of the maximum obtainable fraction of energy for this particular optical system.

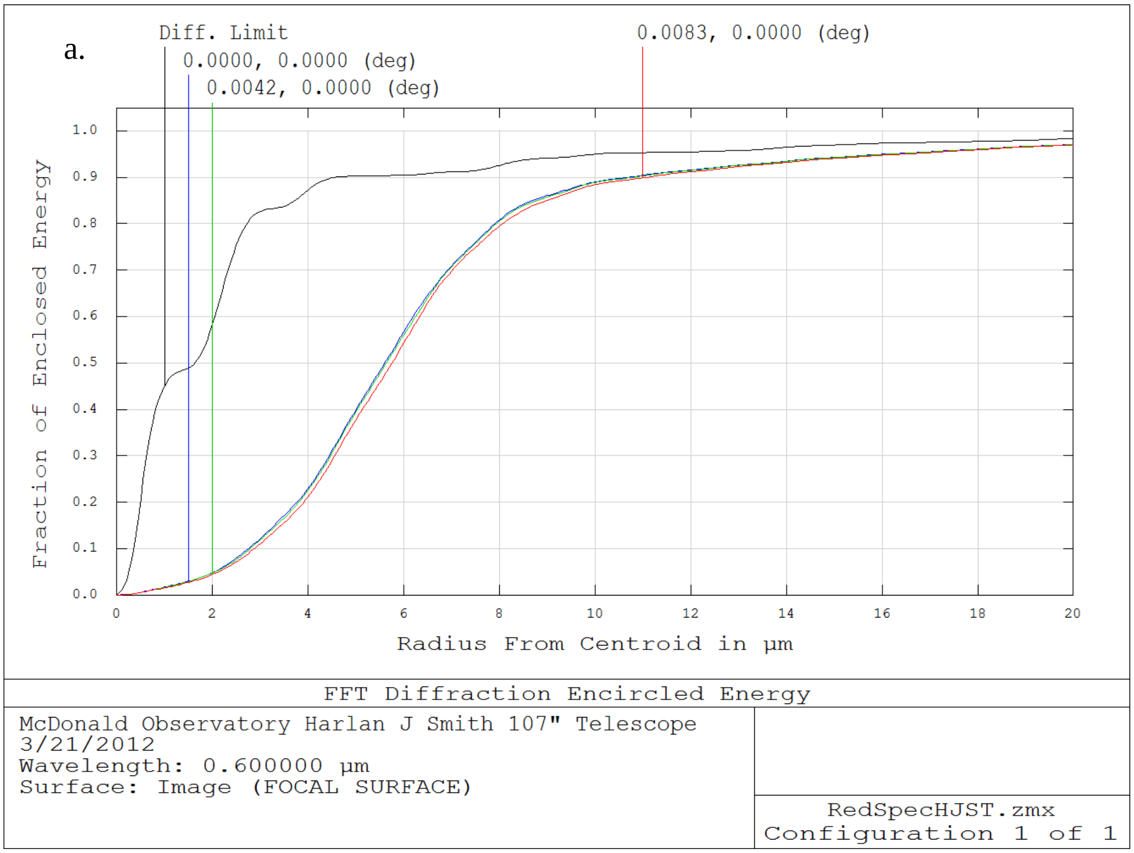


FIG. 4- Encircled energy for camera 1. Fraction of encircled energy vs. distance from centroid at each field position and diffraction limited for wavelengths of a) 600nm, b) 800nm, c) 1000 nm.

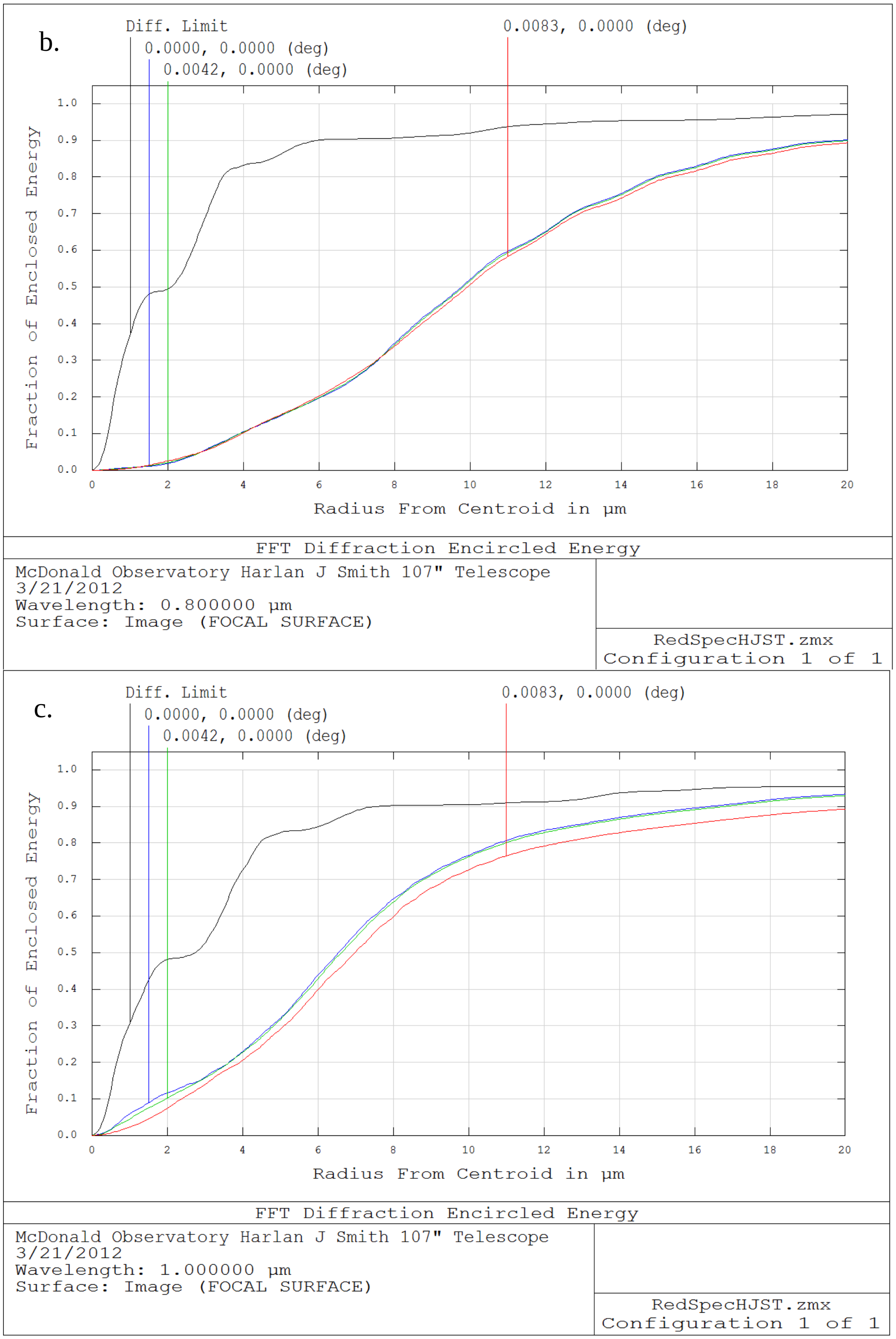


FIG. 4- continued.

In Figure 5, we show the final layout for our optimized camera with one substitute lens (camera 2). We substituted a Rolyn Optics lens for the fifth lens in the design, and then re-optimized to get our final result. The lens is Rolyn #12.0055 (a plano-concave lens with a focal length of 90mm, a center thickness of 3mm, and an edge thickness of 7.5mm). The slit, collimator, grating, and CCD parameters were unchanged. Camera 2 was optimized utilizing the same merit function we used for camera 1, for the same field positions and wavelengths as well.

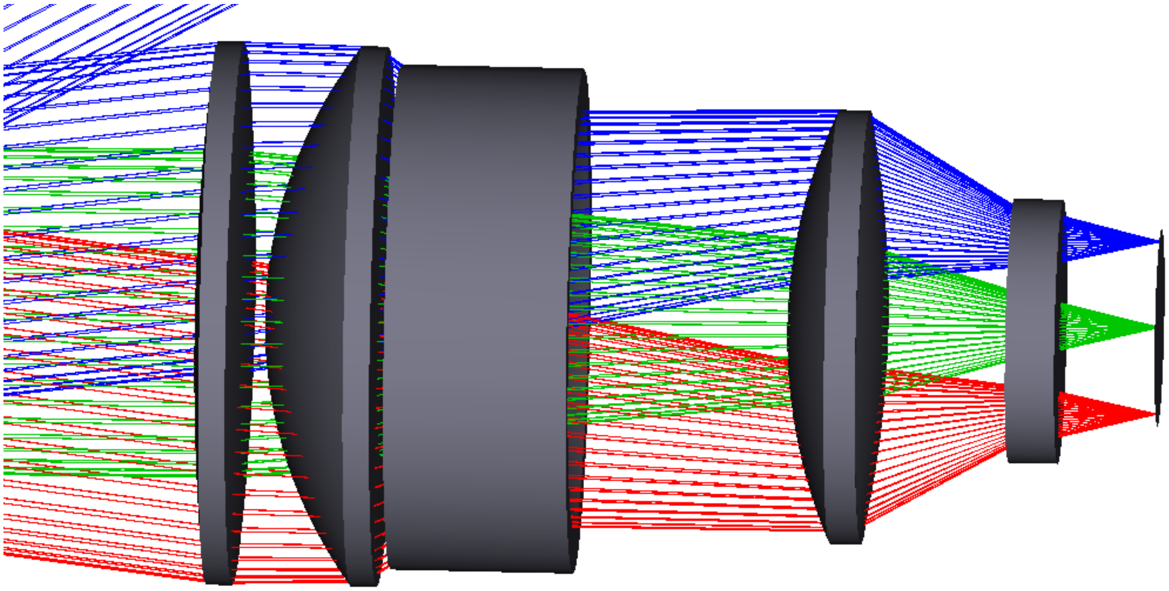


FIG. 5- Optical layout of camera 2. The camera lenses and CCD focal plane are shown in the configuration as they will be placed in the spectrograph. Blue rays represent 600nm, green rays are 800nm, and red rays are 1000nm.

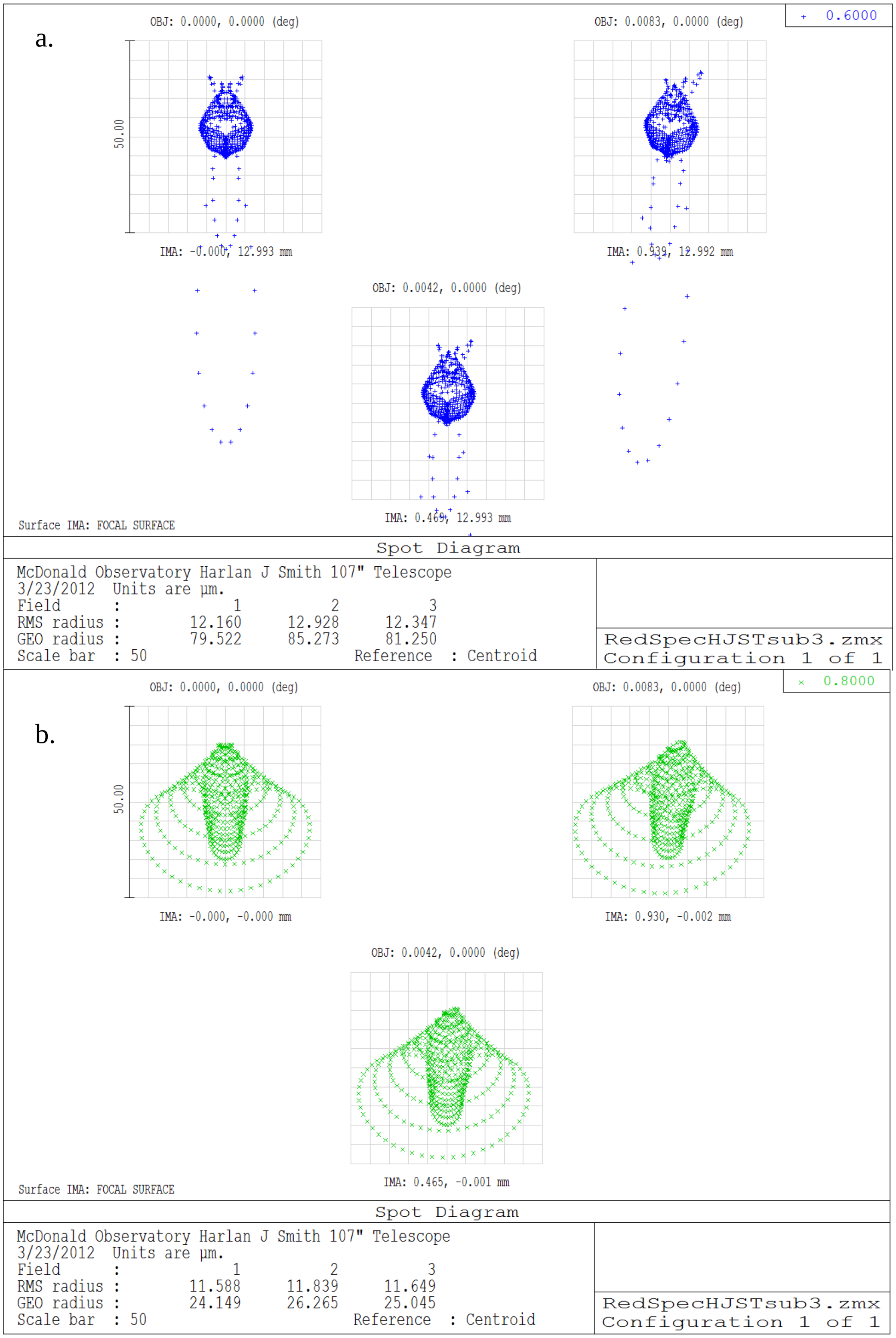
The lens prescription data for camera 2 is listed in Table 2.

TABLE 2

Lens Data for Camera 2

Lens	Radius of Curvature	Thickness [mm]	Diameter [mm]	Glass Type
1-front	380.778	8.311	82.06	LAKL12
1-back	-405.664	2.00	82.32	LAKL12
2-front	67.635	17.984	81.798	N-LAF32
2-back	-4213.039	3.980	79.194	N-LAF32
3-front	-338.689	17.826	76.494	SF59
3-back	69.591	39.491	63.722	SF59
4-front	79.754	15.086	65.732	N-LAF36
4-back	-159.217	23.304	64.002	N-LAF36
5-front	-47.072	3.00	40.00	B270
5-back	Infinity	15.00	40.00	B270

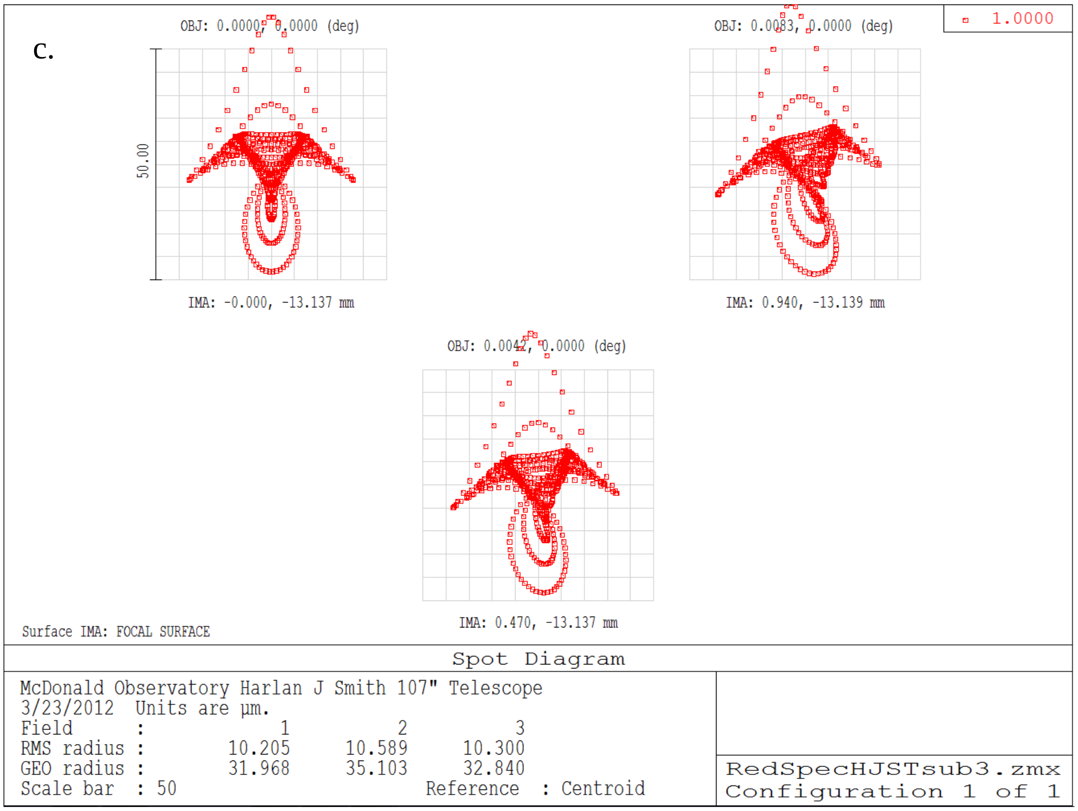
Spot size diagrams for camera 2 are shown in Figure 6 for 600nm, 800nm, and 1000 nm. The diagrams were traced with a ray density of 15, and use the centroid as the reference point to calculate RMS and geometric radii.



```
Spot Diagram
McDonald Observatory Harlan J Smith 107" Telescope
3/23/2012  Units are µm.
Field       :          1          2          3
RMS radius  :     12.160     12.928     12.347
GEO radius  :     79.522     85.273     81.250
Scale bar   : 50                  Reference  : Centroid
RedSpecHJSTsub3.zmx
Configuration 1 of 1
```

```
Spot Diagram
McDonald Observatory Harlan J Smith 107" Telescope
3/23/2012  Units are µm.
Field       :          1          2          3
RMS radius  :     11.588     11.839     11.649
GEO radius  :     24.149     26.265     25.045
Scale bar   : 50                  Reference  : Centroid
RedSpecHJSTsub3.zmx
Configuration 1 of 1
```

FIG. 6- Spot size diagrams for camera 2. Spot sizes at 3 different fields for a) 600nm, b) 800nm, c) 1000nm. Radii listed in µm.



```
Surface IMA: FOCAL SURFACE
                          Spot Diagram
McDonald Observatory Harlan J Smith 107" Telescope
3/23/2012  Units are µm.
Field      :           1          2          3
RMS radius :      10.205     10.589     10.300
GEO radius :      31.968     35.103     32.840
Scale bar  : 50                    Reference  : Centroid

RedSpecHJSTsub3.zmx
Configuration 1 of 1
```

FIG. 6- continued.

The encircled energy diagrams for camera 2 are shown in Figure 7. We plot the fraction of encircled energy versus distance from the centroid for each wavelength and field, along with the diffraction limit.

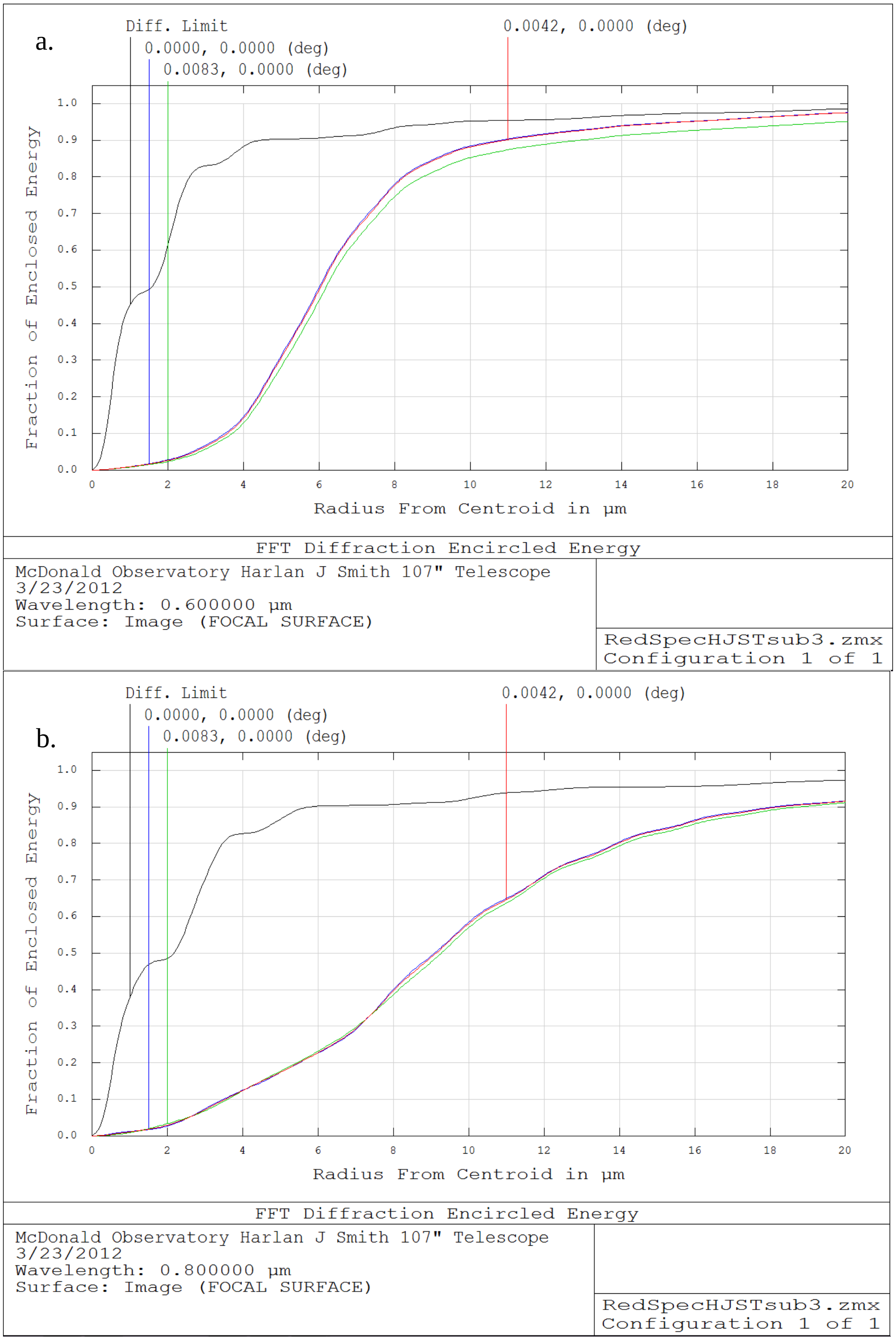


FIG. 7- Encircled energy for camera 2. Fraction of encircled energy vs. distance from centroid at each field position and diffraction limited for wavelengths of a) 600nm, b) 800nm, c) 1000 nm.

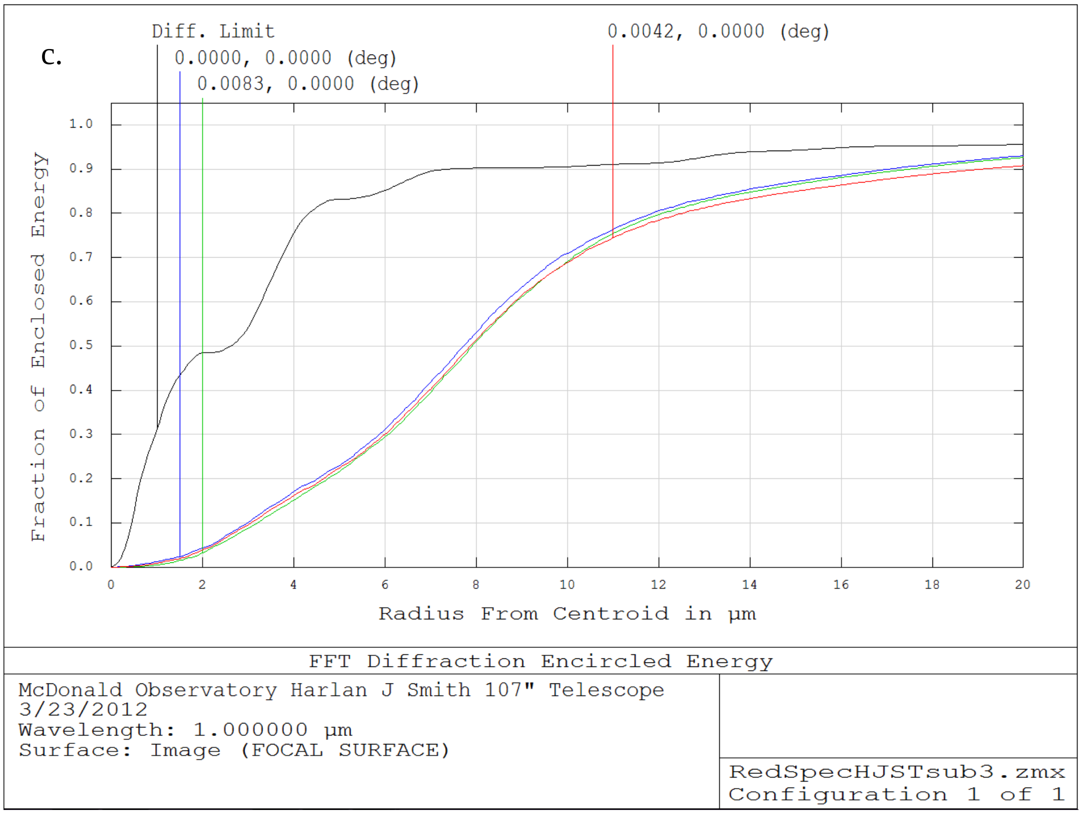


FIG. 7- continued.

Cameras 1 and 2 are quite similar in design, though there are some marked differences. Camera 1 has an overall better design, but camera 2 is more than good enough and will be cheaper and easier to build. A more in depth discussion of their relative merits is in the following section.

CHAPTER IV

CONCLUSIONS

We have successfully designed two options for an optical spectrograph optimized to work in the red part of the visible spectrum. Our designs are compact, and meet our science requirements for spectral resolution of approximately 2000 and wavelength range from 600nm-1000nm. The designs include several commercially available optical components which will help to decrease costs as well as production time. In Table 3, we show the spot sizes at each wavelength for both designs, as well as the spectral resolution for the RMS and 80% energy radii.

TABLE 3

Spot Sizes and Spectral Resolution

	Camera 1 Spot Size Radius [µm]			**Camera 2 Spot Size Radius[µm]**		
Wavelengths:	**600 nm**	**800nm**	**1000nm**	**600 nm**	**800nm**	**1000nm**
RMS	9.577	12.299	9.183	12.160	11.588	10.205
Geometric	58.270	25.788	25.790	79.522	24.149	31.968
80% Encircled Energy	8	15	11	8.5	14	12
Resolution at RMS	2169.68	2252.66	3771.29	1708.81	2390.87	3393.61
Resolution at 80% Energy	2597.38	1847.03	3148.34	2444.60	1978.96	2885.98

In Table 4 we list the properties of the spectrograph design.

TABLE 4

Spectrograph Parameters

Collimator Focal Length	400 mm	**Blaze Angle**	800 nm 13.887°
Collimator Diameter	60 mm	**Grating/Camera Distance**	130 mm
Collimator/Grating Angle	15.142°	**Grating/Camera Angle**	5°
Collimator/Grating Distance	300 mm	**Anamorphic Factor**	0.96897
Grating Width	50 mm	**Number of Pixels**	2000
Grating Lines/mm	600	**Pixel Size**	15 µm

Camera 1 design

Camera 1 uses 5 lenses each of which must be custom made. The lenses range in size, with diameters from 33.504mm to 84.33mm, and thicknesses from 4.00mm to 16.513mm. The radii of curvature range from 73.274mm to 238000mm. These are all well within the capabilities of most manufacturing companies.

The spot sizes for camera 1 are all small enough to ensure that we should get at least a spectral resolution of 2000. The largest RMS spot size radius for camera 1 is 12.299µm at 800nm. At our central wavelength, we have a spectral resolution of 2252.66, which is greater than what we originally hoped to achieve. If instead we calculate spectral resolution using the spot size found in which 80% of the energy is found, the largest spot size radius is again at 800nm, with a radius of approximately 15µm. This will give us a spectral resolution of 1847.03, which is lower than we would like, but is still acceptable. Spectral resolutions at 600nm and 1000nm are even better than at our central wavelength, so this design meets our objective.

Camera 2 design

Camera 2 contains four custom lenses and one commercial lens. The custom lenses have diameters ranging from 64.002mm to 82.32mm, thicknesses between 8.311mm and 17.984mm, and radii of curvature from 67.635mm to 4213.039mm which are all acceptable values for custom made optics. We found the commercial lens in the Rolyn Optics catalogue, model number 12.0055. It is a plano-concave lens with a diameter of 40mm, a center thickness of 3.0mm, and an edge thickness of 7.5mm. The lens is pitch polished B270 glass, and only costs $26.63. Using just one commercial lens will decrease our costs by several thousand dollars.

After re-optimization, we ended up with a design that is not too different from our completely custom-made design. Our largest RMS spot size radius occurs at 600nm, with a radius of 12.160µm. At 800nm, the spot size is 11.588µm which gives us a central spectral resolution of 2390.87, which is actually better than our first design. If we look also at the 80% encircled energy radius, the largest is at 800 nm, with a radius of 14μm, thus giving a spectral resolution of 1978.96. This is also better spectral resolution than the original design.

Though the spectral resolution for camera 2 is better at the central wavelength, it is not better than camera 1 at 600nm and 1000nm. However, the design is still good for our science goals and the payoff for using a commercial lens will be in our favor.

Future work

In continuing this project, we will perform a tolerance analysis to see how precisely each of our optical components needs to be located in order to achieve small enough spot sizes. This will give us a good idea of how well the mechanical structure will need to be designed, and may help us determine which of the two camera designs we should use. Another further study could be performed to determine how changing the collimator would affect our output. We could try other commercially available collimators, and we could also place a correcting lens in between the collimator and grating to correct for the off-axis errors introduced by the collimator before dispersing the light.

With either of our designs, we have a model for a compact spectrograph with high throughput and moderate resolution. This instrument will be capable of studying red objects in our galaxy, and will also serve as a prototype for DESpec(Kent et al., 2012), an instrument planned as an upgrade to the Dark Energy Survey on the Blanco 4-m telescope at CTIO in Chile. The Astronomical Instrumentation Lab at Texas A&M University plans to construct this instrument within the next 2-3 years.

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