ASYMMETRIC OFFNER SPECTROGRAPH

An Undergraduate Research Scholars Thesis

by

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RESEARCH COMPLIANCE CERTIFICATION

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ABSTRACT

Asymmetric Offner Spectrograph

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The design and construction of a long-slit spectrograph that uses an asymmetric Offner relay and grating is discussed. An asymmetric Offner relay is an Offner relay that uses three mirrors placed asymmetrically instead of symmetrically, and the third mirror's radius of curvature is the ratio of the product of the two radii of curvature divided by the difference in the radii of curvature. Having this be the radius of curvature for the third mirror creates an accessible pupil. The optical setup, as seen in Zemax OpticStudio, is shown. The goal of this design is to utilize the novel asymmetric Offner relay and to create a design that could be constructed relatively cheaply by an amateur astronomer by not using any custom optics, only commercially available ones, and heavily relying on 3D printing.

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NOMENCLATURE

Mirror relay	A mirror relay is a series of mirrors that transports light from one point to another via reflection off the mirrors.
Spectrograph	An instrument that separates incoming light by its wavelength and records the result in a multichannel detector.
Slit	Something which obstructs the passage of light, essentially selecting an object to get light from.
CMM	A coordinate measuring machine, something that helps accurately measure dimensions.
PETG	Polyethylene terephthalate glycol, a type of 3D printing filament.
CCD	Charge-coupled device, a digital imager.
CMOS	Complementary Metal-Oxide Semiconductor, a digital imager.
STL	Stereo-lithography, Standard Triangle Language, or Standard Tessellation Language, the file format used to store 3D models for 3D printing.
RMS	Root mean square, the square root of the mean of the squared values.
CTE	Coefficient of thermal expansion, a property of a material that determines how much it expands as its temperature changes.
RTV	Room temperature vulcanizing, usually referring to silicone rubber that cures at room temperature.
GE	General electric, the company.
PSM	Point source microscope, an optical alignment tool.
FITS	Flexible Image Transport System, a file type often used for images in astronomy.
SBIG	Santa Barbara Instrument Group, creates cameras for astronomy.
TAMU	Texas A&M University.

1. INTRODUCTION

1.1 Spectrographs

Spectrographs are a key instrument in astronomical observation. Through various means, they disperse incoming light into its component wavelengths. There are three main parts of a spectrograph, a slit, a dispersion method, and a detector. The purpose of a slit is to eliminate light from objects that are not your target object by physically obstructing everything but the target. There are a few types of slits (or lack thereof) used in spectrographs, including long slit, slitless, and multi-slit. In a long slit spectrometer, there is only one slit, and long slit spectrometers usually look at one object at a time. Long slit spectroscopy is commonly used to observe the rotation curve of galaxies, as well as stars, exoplanets, high redshift galaxies, and pretty much everything in the universe. In a slitless spectrograph, there are no slits, and they usually look at many objects at a time or observe one object over time. A multi-slit spectrograph has multiple slits, usually in adjustable locations, to look at multiple objects while excluding other light [1]. The most common methods of dispersion are prisms and diffraction gratings. A prism disperses light via its refractive index, which changes the speed of light a different amount based on the wavelength of light, which leads to the light dispersing into its component wavelengths. There are a few types of diffraction gratings, including reflective and transmissive gratings. All of these gratings work via constructive and destructive interferences based on the path differences of light rays hitting them. These gratings either have grooves or slits, which are just cuts into the surface or cuts completely through the surface, causing either a repeating pattern of a higher and lower surface, or a repeating open then closed surface. The grooves are used in reflective gratings, and the height difference caused by the grooves causes a path difference in the light's travel, which creates interference. Slits are used in transmission gratings, where light passes through them and creates secondary wavefronts that interfere at different angles [2]. The detectors used in spectrographs are either CCDs or CMOSs. A CCD has higher quantum efficiency but a slower readout time, while a

CMOS has a higher readout speed but lower quantum efficiency. CCDs and CMOSs can also have different wavelength ranges that they can capture, so they are often used for different purposes.

Analyzing the spectra produced by spectrographs can tell us the elemental composition of what we are looking at, which can provide context clues to help us figure out how old an object is, how far away it is, and if a planet may contain life. These clues come from the emission and absorption lines in the spectra we are observing and the wavelengths where they sit. These emissions and absorptions are caused by either the absorption of light to raise the electrons in a molecule's energy level or an electron's energy level falling to emit light at a specific wavelength. The light emitted or absorbed is based on the energy required to raise or lower the energy level of these electrons. If the wavelength of a recognized feature is different from its usual rest wavelength, that means it is either blue or redshifted due to the object moving toward or away from us. The vast majority of objects will be redshifted due to the expansion of the universe, and their redshift will depend on their distance from us. We can use this information to tell roughly how far away an object is, but this calculation may be thrown off by things like dust in the way of the light, causing the light to appear redder than it actually is.

1.2 Asymmetric Offner Relay

An Offner relay is a family of mirror relays described and patented by Abe Offner in 1973. Offner relays are commonly known to have 3 concentric spherical mirrors, one of which is convex, and two of which are concave, and the radius of curvature of the concave mirrors is twice that of the convex mirror. Alternatively, the two concave spherical mirrors can also be traded out for one larger, axially placed spherical mirror with the same radius of curvature. One trait of the Offner relay is its high optical quality, suffering only from 5th order astigmatism and Petzval field curvature. Astigmatism is where rays that propagate in perpendicular planes have different foci, causing the image to seem blurry. Petzval field curvature is a phenomenon where the place that the image forms curves rather than forming in a vertical plane. The design of a typical Offner relay can be seen in Fig. 1.

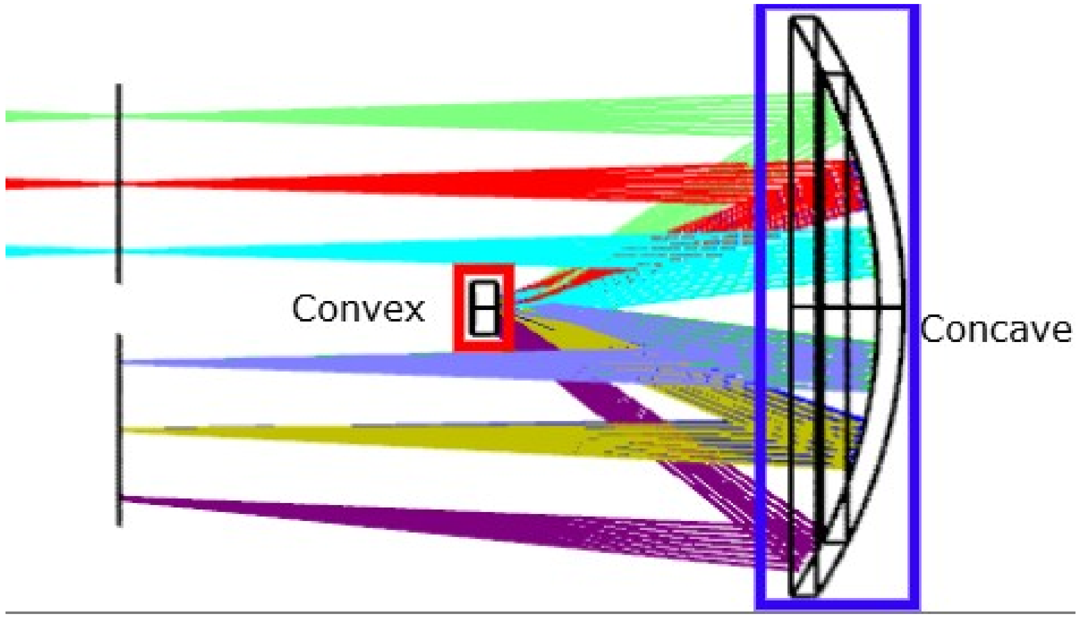

Figure 1: A usual Offner relay. Here, we have one convex and one concave mirror. They are both placed about their center of curvature at their radius of curvature.

However, as Rakich and Rogers pointed out in Ref. [3], there is another definition of an Offner relay that can satisfy the original criteria laid out by Abe Offner. It still consists of three mirrors, two concave and one convex, but now they all have different radii of curvature. Factoring in a correction to the Petzval curvature, we get an equation for the radius of curvature of the larger concave mirror (r_3) as a function of the radius of curvature of the smaller concave mirror (r_1) and the convex mirror (r_2) in Eq. 1:

$$r_3 = \frac{r_1 r_2}{r_1 \quad r_2} \tag{1}$$

By choosing the radii of 2 mirrors, one convex and one concave, you obtain the radius of curvature of a third mirror, which is concave and completes the asymmetric Offner relay. This asymmetric Offner relay maintains all of the good optical properties of the usual one, but it also opens up an accessible pupil in the design. An accessible pupil is a place in an optical setup where all of the light in the system passes through only once, in a constrained area. This accessible pupil is useful as it makes modifying the light in a system, such as putting it through a filter or dispersing it through a grating, easy to accomplish. If there were no accessible pupil, some of the light might travel through a filter or grating twice, which would throw off the design. An asymmetric Offner can be seen in Fig. 2, with the accessible pupil boxed in black.

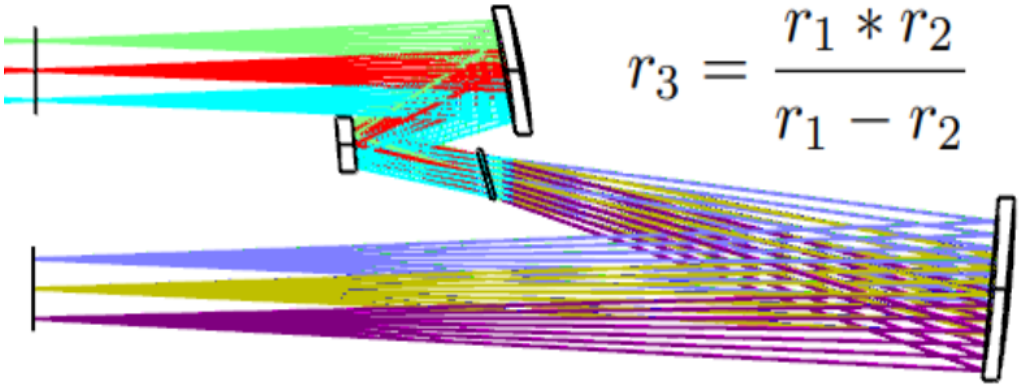

Figure 2: An asymmetric Offner relay.

1.3 Zemax OpticStudio

Zemax OpticStudio is the optical modeling software used to determine the precise placement of our optics in the asymmetric Offner relay and also to determine how much adding a 50/50 pickoff mirror for our guide camera would impact the final image at our detector. We used sequential optics modeling in our Zemax design, along with an f/11 focal length for input light, modeling light from a Celestron C14 telescope. We also used Zemax OpticStudio to tolerance the design, in order to see how much errors in optics placement would affect the image quality.

1.4 Solidworks

After finishing the optical design, we went to the software Solidworks. Solidworks is the CAD software that was used to create the mechanical design of the case, the mirror and grating mounting, the guide camera housing, and all sorts of tools to assist us in our endeavors. Most of the designs from Solidworks were either made into STLs to 3D print or into Solidworks drawings, which were sent to the physics machine shop for them to machine out of aluminum. We were able to import the optical design from Zemax OpticStudio into Solidworks and then build around that as a base.

1.5 Construction & Testing

After we were satisfied with our Solidworks design, we proceeded to machining, printing, and assembling all the parts, and then testing them. 3D printing was heavily used in this process, complemented with metal threaded inserts to create strong threads. The rest of the material used for the parts was machined aluminum.

1.5.1 3D Printing

3D printing, also known as additive manufacturing, has a long history, being first conceived in Sci-Fi novels in the 1940s, and a process for it was first patented in the 1980s [4]. It has come a very long way from its first use, now being used around the world for rapid prototyping, and even final products. There are four main qualities to 3D printing that are important for this project: affordability, speed, strength, and weight. The filament we used for 3D printing, PETG, is not too expensive, costing around $50 per kg of material. Although the raw PETG costs more than something like raw aluminum, the money you save on manufacturing costs makes it much cheaper. In addition, a part made of aluminum has more aluminum in it than a 3D printed part would have PETG due to the infill density of the 3D printed part being far less. As well as this, with 3D printing, it is extremely quick and easy to go from a part design to a finished part, as all one needs to do is send the design to a printer and let it print for a few hours [5]. While this is happening, you can put your focus on other things. Even more, the printed part is strong and you can customize the infill amount to control the amount of material used, the strength, and the weight. Generally, a 3D printed part will be much lighter than a machined aluminum part, with PETG being almost half the density of aluminum. In addition to the density being less, the total volume of a part made of PETG would be less than a part made of aluminum, thanks to the infill pattern, further decreasing the weight and material used. The infill pattern can also prioritize affording strength in particular directions if needed. In all of our 3D prints, we used the gyroid infill pattern at 20% infill, which optimizes for strength, weight, and an even stress distribution. As well as this, we have threaded inserts made of metal which we can push into the 3D printed part if we want stronger threads than those directly 3D printed. We do this by heating up the insert with a soldering iron, and melting it into the plastic, merging it with the structure of the part. Overall, from one spool of PETG, we can make a few dozen strong, light parts, and we are able to rapidly go from design to testing, thanks to 3D printing. The 3D printer we use in our lab is the Ultimaker S5. We also used black PETG when printing parts to further prevent any errant light reflection off of parts.

1.5.2 Assembly & Testing

When assembling the parts, our goal is to place all the optics where they are indented to be, as specified in the optical design, as the design has been optimized for image quality. The main obstacle to this is usually human error, so the designs were made to minimize the possible human error through the use of locating pins and 3D printed centering constraints and reference points. Although a lot of caution was taken in these designs, we will still need to align the optics after mounting them. We will do this by iteratively adjusting the tip tilt mounts that the mirrors are mounted on, changing their orientation and positions, and optimizing for the best quality image. We will also align the guide camera by moving it up or down in its clamp mount.

2. Zemax OpticStudio

2.1 Webscraping

We started with a webscraping program we wrote in Python to pick out various combinations of mirrors that would be able to form an asymmetric Offner relay (satisfying Eq. 1) from commercial retailers. The commercial retail websites we scraped from were Thorlabs, Edmund Optics, and Newport. We got many possible combinations, but ultimately picked out these: a 300mm radius of curvature and a 150mm radius of curvature concave mirrors from Thorlabs, and a 75mm radius of curvature convex mirror from Edmund Optics. This combination of mirrors satisfies Eq. 1, and the relay would be large enough physically to fit a grating into the accessible pupil, without worry for physical intersection of mounting elements, as well as providing space for going in and manually adjusting mounts by hand.

2.2 Optical Design

2.2.1 Optics

Specifically, the mirrors we picked out were the CM750-075-F01 and the CM750-150-F01 from Thorlabs, and the #87-657 from Edmund Optics. The grating we picked out was the #49-579 from Edmund Optics, which has 300 slits per mm and is a 25mm x 25mm square. The CM750-075-F01 from Thorlabs has a focal length of 75 mm, a radius of curvature of 150 mm, a diameter of 75 mm, and a total thickness of 16.7 mm. The CM750-150-F01 from Thorlabs has a focal length of 150 mm, a radius of curvature of 300 mm, a diameter of 75 mm, and a total thickness of 14.3 mm. The #87-657 from Edmund Optics has a focal length of -50 mm, a radius of curvature of -100 mm, a diameter of 25 mm, and a total thickness of 3mm. All of the mirrors' substrates are a type of crown glass called N-BK7.

2.2.2 Positioning

We positioned the mirrors in Zemax OpticStudio according to Equation 1 and then inserted the grating in the accessible pupil, in a place where there would be physical space for a grating mount. The slit is intended to be positioned where the light from the telescope initially comes to a point. We made sure the design was created to take f/11 light to be compatible with the C14 Celestron telescope. We then optimized the mirror placement to reduce the spot size at the detector. As seen in Fig. 3, the optical design of the spectrograph is straightforward, with only 4 optical components.

Figure 3: Zemax Optic Studio design of the Offner relay inside the spectrograph. Light passes through the slit, reflects off mirror 1, reflects off mirror 2, disperses through the grating and reflects off mirror 3 before landing on the detector.

2.3 Tolerancing

When tolerancing the design, at a positioning change of 0.2mm, the change in the RMS spot size was 0.01183424 mm, taking the RMS spot size from 3.37284681 mm to 3.38468105 mm, a change of 0.3%. This was a small enough change in spot size that we felt confident in mechanically aligning the optics, although there will need to be further optical alignment later, after the mirrors are mounted and screwed in to the base plate for testing. The change in spot size due to tolerancing can be seen in Fig. A.1.

3. Solidworks

From Zemax, we imported the optical design into Solidworks. In Solidworks, we designed a case and mounts for the mirrors, a grating mount, mounting plates for the optics and detector, and a guide camera/slit housing, which also functions as a telescope interface. The base plate where the optics are mounted and the front plate where the detector and interface are mounted were designed to be made out of aluminum, and the mounts for the mirrors were chosen from the lab. The remaining parts are designed to be 3D printable such that, as long as someone has access to a machine shop or a maker space and orders mirrors from Thorlabs/Edmund Optics, they can easily create this spectrograph. The overhead view of the complete Solidworks design (excluding the case) can be found in Fig. 4.

Figure 4: The Solidworks design from the top, excluding the lid. The mirrors are in red, the grating is in blue, and the guide camera housing is in black.

3.1 Guide Camera Housing

The guide camera housing has many functions, as it houses both the guide camera and the adjustable slit, as well as being the point where the spectrograph interfaces with the Celestron C14 telescope, via a machined T2 adapter. The guide camera is held in place with a custom-designed 3D printed clamp mount, which allows the guide camera to be moved up and down in order to focus.

The T2 adapter was machined out of aluminum to increase the strength of the attachment, but the rest of the guide camera housing was 3D printed using PETG filament to reduce both the cost and weight.

3.1.1 Slit

The slit we are using is the VA-100 adjustable mechanical slit from Thorlabs. The size of the slit can be adjusted between 0 mm and 6 mm. In order to mount it in the guide camera housing, we inserted a screw into the bottom thread, and in the design of the housing, had a raised bump to locate the slit as well as hold it in place to stop it from rotating.

3.1.2 Guide Camera

The guide camera we used is the DMK 21AU04 from The Imaging Source. To mount it, we designed a custom clamp mount in order to allow us to adjust the height of the camera from the beamsplitter and focus it. The camera is clamped in, and the clamp is screwed into the main body of the guide camera housing. A 50/50 45 beamsplitter feeds light to the guide camera, while the light that passes through go through the spectrograph to the main detector. The beamsplitter had a space designed for it in the housing, where it slots in and is then screwed down. The beamsplitter mount is the C45P Right Angle Kinematic Mount from Thorlabs, with the BSW26 - Ø1" 50:50 UVFS Plate Beamsplitter from Thorlabs placed inside of it.

3.1.3 Telescope Adapter

The telescope adapter was designed to thread into a T2 adapter, which is commonly used on amateur telescopes, including the Celestron C14. In order to ensure a strong connection, it was machined out of aluminum with M42 threads, and then screwed into the main body of the guide camera housing.

3.1.4 Main Body

The main body of the guide camera housing is all one piece, and was 3D printed with PETG, with very tight tolerances for fitting the slit, guide camera clamp, and beamsplitter. The internals of the guide camera can be seen in Fig. 5, and the main body can be seen in Fig. 6.

Figure 5: The internals of the guide camera housing. Pictured are the guide camera, guide camera clamp mount, beamsplitter, and slit.

Figure 6: The guide camera body plus telescope interface, along with the internals inside.

3.2 Main Optics

The main optics of the asymmetric Offner spectrograph are the slit which cuts down entering light, the three mirrors of the relay, the grating which disperses the light into the spectrum, and the detector which gathers the light.

3.2.1 Mirror Mounts

Originally, we were going to use optomechanical mounts from Thorlabs to mount the mirrors, but because we had some extra unused mounts in our lab, we modified the design to use those. The mounts we had in our lab were three-axis tip tilt mounts with a square aluminum mounting surface roughly 20mm x 20mm. These tip tilt mounts have the ability to move forward and backward in the optical axis and rotate in the directions perpendicular to the optical axis, but not rotate about the optical axis.

To ensure that we could mount our mirrors in the center of the square mounting surface, we would have to boost the height of the mounts, so we designed an extra mount on which to place the tip-tilt mounts and lock them in place. This extra 'bump-up' mount is 39.75 mm tall, 42 mm long, and 27.5 mm wide. The extra bump-up mounts were all 3D printed out of 14 grams of PETG and have 4 threaded inserts. The top threaded inserts are M4 and are for screwing the tip-tilt mount to the bump-up, and the bottom threaded inserts are M3 and are for holding the whole mount to the base plate. The design can be seen in Fig. 7.

Figure 7: The design of the bump ups for the tip tilt mirror mounts.

3.2.2 Grating Mount

To hold the grating in place, we designed a mount which would also be 3D printed out of PETG, and then screws with spring washers installed to hold the grating in place with tension. The mounting baseplate was also designed to allow the grating mount to rotate to zeroth order. This acts as a backup to allow us to better locate objects with the main detector if need be. The design can be seen in Fig. 8. The printed grating mount can be seen in Fig. A.6.

Figure 8: The design of the grating mount in Solidworks, with the curved slots that it swivels through highlighted.

3.3 Casing Design

The casing was designed to emphasize strength in the parts where it was needed, and increase mobility and reduce cost in parts where strength was not needed. It was also designed to be easy and quick to assemble and disassemble with minimal tools. All that should be needed is a screwdriver. The parts slide over each other, similar to a computer case, and then are screwed together.

The casing is divided into five main parts. The two most important parts are the front plate and the mounting plate, and because both of these need to be strong, they will be machined out of aluminum.

3.3.1 Front Plate

The front plate is designed to be machined out of aluminum. It is designed to allow the guide camera housing and the detector to connect to it. It is 1/4 in thick, 9.5 in long, and 5.9 in tall. It screws into the mounting plate. The screws go through the back on the plate into the M2.5 threads of the detector, and into the M3 threads of the guide camera housing. The design of the front plate can be found in Fig. A.3.

3.3.2 Mounting Plate

The mounting plate is designed to be machined out of aluminum. It is designed to allow the three mirror mounts and the grating mount to be mounted securely and precisely. To enable this precise mounting, we use locating pins around the optics with a tolerance of 0.09 mm. It is supposed to be screwed together with the front plate, and provides a solid surface for the rest of the case to screw into. The mounting plate is 1/4 in thick, 9.5 in wide, and 13.4 in long. The design of the mounting plate can be found in Fig. A.2.

3.3.3 Case Body

The body of the case is designed to be both cheap and lightweight, as all it needs to do is cover the optics and keep light from getting in, as well as protecting it from any dust or drops. In order to fulfill this, it is divided into 7 parts to allow it to be 3D printed out of PETG. After the parts are 3D printed, the smaller parts are pinned and glued together into 3 main parts: the lid, the bottom, and the case. Then, the case is able to screw into the front plate and mounting plate, and the lid and bottom can slide on and off quickly.

3.3.3.1 Lid

The lid is divided into two parts along the middle, put together with pins and adhesive. There are 3 M3 metal thread inserts on the front and back of the lid. At the front, they screw into the aluminum front plate, and at the back, they screw into the circumferential case. The Solidworks design of the case lid can be found in Fig. A.8.

3.3.3.2 Circumferential Case

The circumferential case is divided into 3 parts, which are all put together with pins and adhesive. The 3 parts are two side walls, and one part that acts as a back plate. The side walls are both attached to the back plate on either side and have 3 M3 threaded inserts on the top of the slip in the middle. The back plate subpart has 3 M3 threaded inserts on the top. The bottom of the circumferential case has 4 M3 threaded inserts, 2 at the front and 2 at the back. The Solidworks design of the circumferential case body can be found in Fig. A.7.

The bottom clearance holes of the slip provide clearance for the aluminum base plate, where screws will come through, securing the case.

3.3.3.3 Bottom

The bottom is divided into two parts along the middle, put together with pins and adhesive. It is not necessary to be put on along with the rest of the case, it serves only to completely seal the case from light. It has 4 M3 clearance holes along the bottom, 2 at the front, 2 at the back. The Solidworks design of the case bottom can be found in Fig. A.9.

4. PUTTING IT ALL TOGETHER

4.1 Creating Parts

After ensuring that the Solidworks design was sufficient, we began creating the parts with a combination of 3D printing and machining, using the metal threaded inserts in our 3D printed parts for stronger threads.

When we had our parts machined, we had them machined out of aluminum as it has the best combination of strength, price, and weight. The only parts that were machined were the telescope T2 adapter interface, the front plate, and the mounting baseplate of the case.

4.2 Mirror Mounting

4.2.1 Precision

To ensure the precise placement of the mirrors, a point source microscope (PSM) was used in combination with a FaroArm. The PSM was used to check the leveling of the mirrors when mounting them to see if they were perpendicular to the light emitted from the PSM and thus flat on the mounting surface. The FaroArm was used to check the accuracy of our designs created for the tip tilt mounts. A big problem is that we couldn't identify the name or producer of the tip tilt mounts we found in our lab, so instead of downloading a 3D model from online, we had to reverse engineer the design by measuring it with calipers and modeling it in Solidworks. Although this design captured most of the tip tilt mount, it has an inherent level of uncertainty thanks to human measurement.

To counteract this inherent uncertainty, we created a number of accessories to ensure consistency between mounts and a precise placement of the mirrors. The first accessory to be designed was a leveling accessory, which ensured that the mounting surface of the tip tilt mount was the same distance away from the bump up for each tip tilt mount, and ensuring that distance is the one specified in the design. This ensures the proper mirror placements along the optical axis, which we'll call the z-axis. The second accessory was to ensure the proper mirror placements perpendicular to the optical axis in the x-y plane. This accessory clipped onto the bump up and acted as a physical placement guide for the mirror, constraining where it could be placed to where it should be placed. The third accessory was a similar constraining accessory, but modified to fit the smaller convex mirror. The first accessory was used before mounting the mirrors, getting the mounting surface to the right distance by adjusting the screws on the back. The second and third accessories were only used when initially mounting the mirrors to the mounting surface of the tip tilt mount with elastomer. Once the elastomer was cured, they were removed. The mounted mirrors and accessories can be seen in Fig. 9.

Figure 9: The mounted mirrors, along with their mounting accessories. The accessory labeled 1 was used to ensure that the mounting surface of each mount was the same distance away from the bump up. Label 2 was a centering accessory that clipped onto the bump up and constrained the placement of the mirror for the concave mirrors. Label 3 was also used to constrain the placement of the mirror, but for the convex mirror.

Due to the precision of 3D printing, the overall error in placement cannot exceed 0.15 mm. To adhere the mirrors to the mounts, a mixture of RTV silicone and glass beads can be used, whose application thickness will be determined by Equation 2:

$$t_e = \frac{D_M}{2} \quad \frac{{}_{Mo} \qquad {}_{Mi}}{{}_{e} \qquad {}_{Mo}} \tag{2}$$

The thickness is determined by a ratio of the differences in the coefficient of thermal expansion between the mount and mirror, and the elastomer and mount, multiplied by the radius of the mirror [6]. The motivation for this is to counteract the effects of thermal expansion on the mirror's position. The mirror's substrate are all comprised of the same type of crown glass, N-BK7, which as a CTE of $7{:}1 \quad 10^{6}$. The elastomer used to adhere the mirrors is GE Advanced Silicone 2, which has a CTE estimated to be $2 \quad 10^{4}$ per degree C, which is the CTE of other similar silicone adhesives. Although we contacted GE to inquire about the CTE for the elastomer, they did not have an answer, so we could only estimate it to be similar to other silicone adhesives. The 3-axis tip tilt mounts used for mounting have a mounting surface of aluminum, which has a CTE of $23{:}1 \quad 10^{6}$ per degree C. When plugging these numbers into Eq. 2, for each mirror, we find that we want a thickness of elastomer of 3.39 mm for the concave mirrors, and 1.13mm for the convex mirror.

To ensure we get the correct thickness of elastomer, we again designed 3D printed accessories. This time, the accessories would click onto the aluminum mounting surface instead of the bump up. We designed two wells, one with a height of 3.39 mm and one with a height of 1.13 mm. The wells encompass the 40mm x 40mm mounting surface with a thickness of 2 mm and are able to sit on top, thanks to an inner lip with a thickness of 0.2 mm. During the procedure, we would fill these wells up with elastomer, using 35 mesh glass beads to ensure the elastomer doesn't flow out of the well and holds its shape well. We also designed accessories to scrape excess elastomer off of the well to level the surface, as well as a tamper to pack the wells tightly with elastomer.

4.2.2 PSM Alignment Procedure

A point source microscope (PSM) is an optical alignment tool developed by Optical Perspectives, and costs $23,950. It is unique in that it is a lightweight and small solid-state light source. This allows it to be easily attached to a variety of different locations, and attached to 3-axis or 5-axis stages. It has several functions, including autostigamtic microscope, autocolimater, and full-field video microscope. The output of its detector connects to a windows laptop which has its custom software installed on it.

The PSM was mounted on a 5 axis tip tilt mount, and fitted with a 90 reflector, then put on top of a opto-mechanical mounting pipe. Then, along the mounting pipe, two 1 mm precision pinholes were placed at the same height from the pipe. To align the PSM and ensure that its light was parallel to the mounting pipe, we just adjusted the PSM until its light went through both the first pinhole and second pinhole, and when reflected back with a mirror, showed up on the PSM's detector. At the bottom of the setup, there is a clamp attached to a 3-axis stage that holds the mirrors. The clamp is attached to the 3-axis stage with a custom-designed 3D printed part. The PSM setup can be seen in Fig. 10.

Figure 10: The PSM setup used to help precisely mount the mirrors. We first see the 90 reflector attached to the PSM, which sends its laser beam down through the first pinhole, through the second pinhole, and onto the mirror, before reflecting back through the pinholes, into the PSM and onto the detector.

4.2.3 Mounting Procedure

The procedure used to mount the mirrors is as follows

1. First, bring the mounting plate to the correct level specified in the design by using the leveling attachment.
2. Second, clean the mounting surface by sanding it down lightly to remove any debris, then cleaning it with isopropyl alcohol.
3. Third, clip the proper well onto the mounting surface, fill the edges with 35 mesh glass beads for structure, then fill the well with elastomer, level the well off, and add more glass beads.
4. Fourth, remove the well, and place the correct centering attachment on the base.
5. Fifth, place the mirror in the correct location with the help of the centering attachment, and let cure for 48 hours. You can check the leveling of the mirror by using the point source microscope.

6. Finally, after the elastomer has cured, remove the centering attachment.

4.3 Assembly

4.3.1 Optics

The guide camera used is a DMK 21AU04 from The Imaging Source. The detector used is an SBIG STF-8300M. The STF-8300M is mounted onto the front plate in its correct position by sending screws through the back of the front plate into the STF-8300M's M2.5 threads, holding it in place. The guide camera is held in the guide camera housing by the 3D printed clamp mount. The mirrors are mounted onto the 3D printed bump-ups and held onto the base plate with screws through the bottom. The grating is mounted into its 3D printed mount which is held onto the mounting baseplate with screws through the bottom.

4.3.2 Case

To assemble the case, we start with the aluminum parts, the front plate and base plate. We send screws through the clearance holes on the front plate into the threaded holes of the base plate at the bottom, holding them together. Once we have completed this step, we can add all the optics in their proper places, then we can assemble the rest of the case.

Next, we start putting on the 3D printed case parts, starting with the largest part, the circumferential case part. We slide this over the base plate, then send screws through the top clearance holes, through the clearance holes in the base plate, and into the threaded holes in the bottom part of the circumferential case piece. Then, we send screws through the clearance holes in the front plate, into the threaded holes in the circumferential case piece.

After the circumferential case piece, we slide on the case cap. Then, we secure it by sending screws through the front clearance holes into the threaded holes on the front plate, and similarly through the back clearance holes into the threaded holes on the back of the circumferential case piece.

Finally, we can add on the optional case bottom, which will slide through the circumferential case piece, and send screws through the front bottom holes, up through a clearance hole, through a clearance hole in the circumferential case piece, into the threaded holes on the bottom of the front plate. Then we follow this up by sending screws up through the bottom into threaded holes at the back of the circumferential case piece. Now, the spectrograph is fully assembled with case and optics, and is ready to test.

Solidworks images of the case in various stages of assembly can be seen in Figures A.10, A.11, A.12, and A.13.

4.4 Testing

This project is still a work in progress, which will be completed in the next few months, but we already have plans for testing. We have just gotten the front plate and base mounting plate back from the machine shop, and they can be seen in Figures A.14 and A.15. Our assembly progress can be seen in Figures A.16 and A.17.

After the mirrors are mounted, we will test their alignment with a setup imitating a Celestron C14 with an f/11 focal length. The light will come through the slit, reflect off the mirrors, disperse through the grating, and land on the detector. We will look at the focus and the spot size and adjust the tip tilt mounts to minimize the spot size.

Once we have aligned the optics the best we can, we will move on to calibrating the system in order to see which pixel corresponds to which wavelength, which we can do by feeding light sources with features at known wavelengths into the spectrograph. We will then mark the pixels those features appear at with their given wavelength, and we should be able to then correlate each pixel to a wavelength, since they should be linearly proportional.

4.4.1 Code

We are currently working on a Python program to process the FITS files that the main detector produces while using its free software CCDOps. The main goal of the program is to determine the spectrum of the light, and display the features. To do this, we will use the popular

Python packages astropy, scipy, and numpy. We will sample the image generated by the detector on a given line of pixels to generate the spectrum via the correlating the count at each pixel along the line with the signal at a given wavelength.

5. CONCLUSION

In our work on building a spectrograph which utilizes an Asymmetric Offner Relay, we have gained a wide variety of skills, and a lot of practical experience. We have learned how to use the optical design software Zemax OpticStudio, the CAD software Solidworks, how to use a point source microscope, how to use a FaroArm to compare objects to 3D models and measure their dimensions, a great wealth of experience in using 3D printing for rapid prototyping, and a lot of hands on optics experience. We have learned how to interact with machine shops to get our parts machined in the way we need, we have learned how to create drawings of parts in a comprehensible manner. We intend to use the spectrograph at the TAMU teaching observatory on one of the Celestron C14 telescopes. There, we can gather real data with it, and perhaps other astronomy students can use it. We also intend to publish the design in either the research notes of the AAS or maybe a more instrumentation focused journal, where hopefully, some other amateur astronomers with the necessary tools can build it as a hobby project. Although we have used machining and some parts found in the lab, amateur astronomers can replace both of those with 3D printed parts, though it will make the design less strong and less adjustable, but lighter and cheaper.

The total cost of building the spectrograph was about $6075. The main detector, the STF-8300M costs $3,290 at maximum, but it can often be found for much cheaper. The guide camera, the DMK 21AU04, costs roughly $200. The mirrors cost $444 in total, with the two from Thorlabs costing $199.5 each and the one from Edmund Optics costing $45. The grating from Edmund Optics cost $122.00. The adjustable slit, the VA-100 from Thorlabs, cost $294.64. The right angle kinematic mount from Thorlabs cost $180.52, and the 50/50 beamsplitter from Thorlabs cost $339.74. Although we are unable to find the same mounts online as the 3-axis tip tilt mounts we used for mounting our mirrors, we can estimate their maximum cost to be around $200 each, as more sophisticated mounts from Thorlabs cost about that much. Aside from these parts, the cost of material comes to roughly $150 from the 3 kg of PETG used in 3D printing, and $450 from the roughly 2.07 kg of aluminum used to machine parts, and the cost for getting those parts machined. The threaded metal inserts cost $14 to order from Amazon. To build the spectrograph from scratch would take about 205 hours: approximately 200 for the 3D printing and approximately 5 for assembling everything. We assume that the machining can be done at the same time as the 3D printing, if not, it would take an extra 20 hours.

This project is nearing completion. We have just gotten our final parts back from the machine shop. After we assemble everything, we will be able to begin testing, and after we finish testing, we will send it to the teaching observatory. We will also publish the Solidworks part files, STL files, and our data reduction pipeline to a public GitHub so anyone can access them, and attempt to build their own spectrograph.

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APPENDIX

Figure A.1: The spot size diagram when tolerancing in Zemax OpticStudio.

Figure A.2: The design drawing of the base mounting plate.

Figure A.3: The design drawing of the front mounting plate.

Figure A.4: The assembled guide camera housing.

Figure A.5: The back view of the assembled guide camera housing.

Figure A.6: The printed grating mount, no grating in it currently.

Figure A.7: The circumferential case design in Solidworks.

Figure A.8: The top part of the case design in Solidworks.

Figure A.9: The bottom part of the case design in Solidworks.

Figure A.10: The full 3D printed case all together.

Figure A.11: The full 3D printed case all together. The base mounting plate has been inserted in this case.

Figure A.12: The full 3D printed case all together. The base mounting plate and front plate have been inserted in this case.

Figure A.13: The full 3D printed case all together. The base mounting plate and front plate have been inserted in this case. The SBIG detector and guide camera housing have been mounted on the front plate.

Figure A.14: The machined front plate.

Figure A.15: The machined mounting base plate.

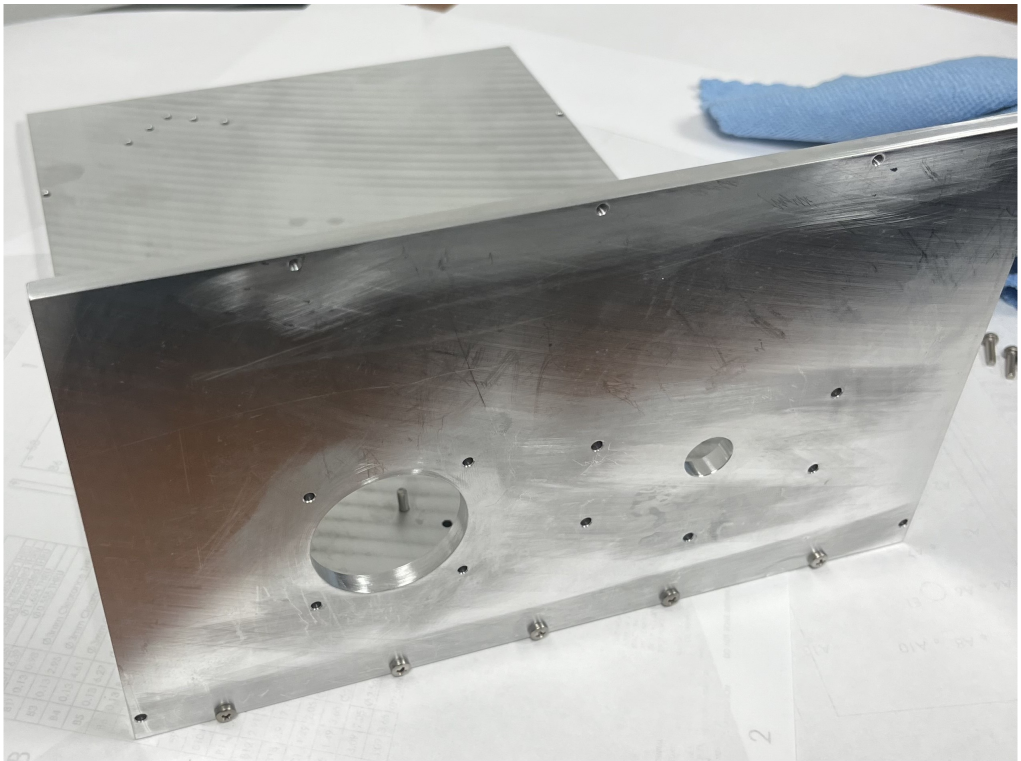

Figure A.16: The machined front plate and mounting base plate after being connected with M3 screws.