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Fast Spectrometer Construction/Setup/Testing

April 15, 2012

Introduction

This paper describes the construction and operation of a medium resolution spectrometer used in the visual wavelength range. It is shop-made, but has built in guiding and calibration, is fully remote operable, and operates at a resolution $R=3000$. It features a fast f3.5 system, which allows it to be used with a fast telescope (18 inch f3.5) with no Barlow or other optical matching devices. Note: a companion paper describes detailed observational tests and initial observations using this spectrometer.

Background

Five years ago I completed an 18inch f3.5 Newtonian for use primarily in asteroid and stellar photometry as described in <http://menkesscientific.com/18inchscope.pdf>. However, soon after beginning this work, I obtained an SBIG DSS7 low resolution (5A) spectrometer. While the DSS7 is capable of very good work, the software and some of the hardware provided makes it very inconvenient to use. However, after several years of development, I was able greatly to improve the entire control system, and it has performed very well as described in <http://menkesscientific.com/spectroscopymethods.pdf>. One of the difficulties of using the DSS7 with the Newtonian was that it is an f10 instrument, thus requiring use of a 2.7x Barlow. While this works well, the resulting image scale at the slit is approximately 0.6a-s/pixel, thus putting extraordinary demands on the guidance system (which is partially open loop). In addition, the Barlow moves the optical train outboard, thus putting increased stress on the focuser.

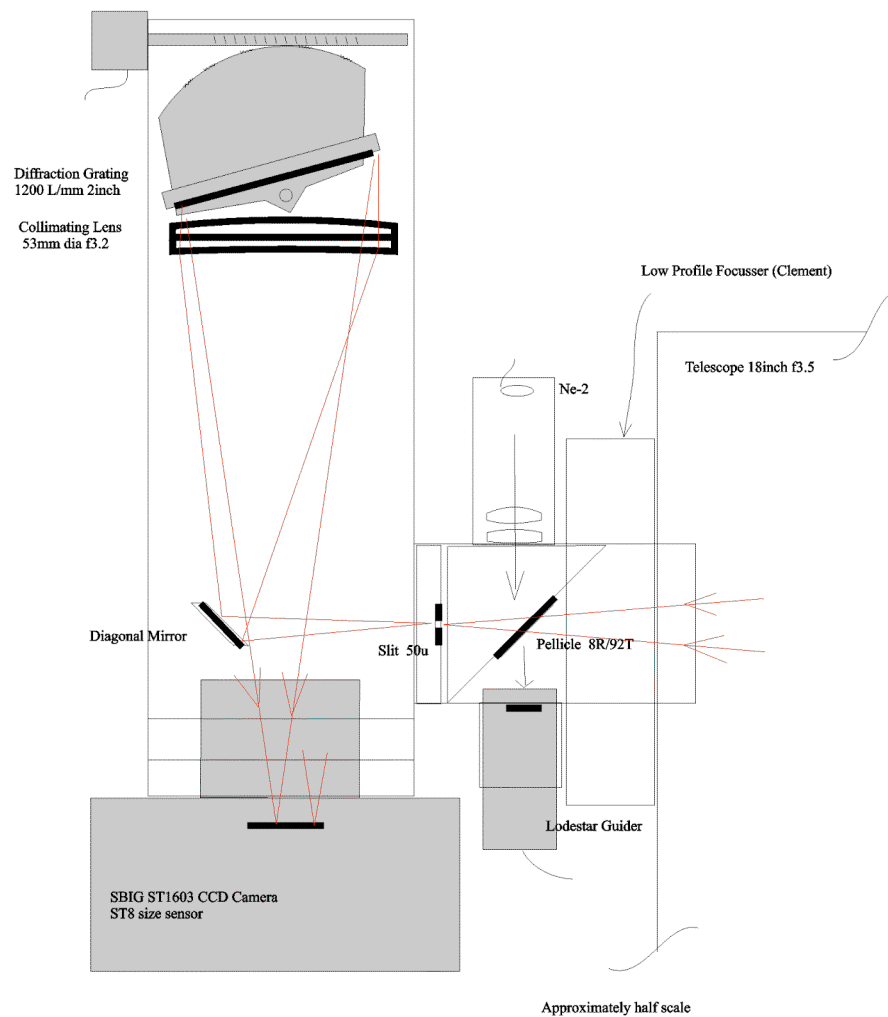
After several years, I saw the benefits of an instrument with increased resolution. The goals for the instrument would be

- Native operation at f3.5, i.e., no Barlow needed.
- Self Guiding in a closed loop
- Full remote operation
- Integral calibration source
- Inexpensive
- Reasonable weight and with good balance
- Construction using basic machine shop practices
- Operable with almost any CCD camera

A survey of the literature showed that such an instrument was not available, so I began the design of a unit that I could build with only average machining skills in a reasonably well-equipped shop. While there are always trade-offs in instrument design, the resulting design described here has been quite satisfactory and may be useful for other investigators.

Spectrometer Design

Figure 1 shows the overall spectrometer layout roughly to scale. The figure shows the optical elements and surfaces as heavy black.



Fast Spectrometer f3.5 R=3000

The biggest design challenge was to accommodate the fast f-ratio. The problem is not so much the optics, as it is that such a fast converging light beam from the telescope allows very little space for optical elements once it leaves the telescope and before it enters the slit. While one could build a spectrometer into the telescope, this would make instrument changeover very cumbersome.

As noted, the telescope for this instrument is an 18inch f3.5 thin mirror Newtonian that I had built several years previously. The telescope functions extremely well, except that the tube has significant flexure as it approaches the horizon. The mount is an AP1200. The focuser is a Clement design operated by a RoboFocus control system. TheSky V.5 controls the telescope mount. MaximDL is used to operate the main and guide cameras and for subsequent image processing.

After considering a variety of designs, I settled on my own version of a Littrow design (in which the light from the grating reflects back at approximately the entering angle) that appeared to meet the design goals.

Focuser. A key element in the design is the focuser itself. The focuser is an early Clement design as described in the above telescope write-up. This focuser features a highly constrained and stiff kinematic design that is only 1inch high at minimum and 4inches high fully extended. The amazing 3-inch travel and small minimum height makes operation with different optical attachments (such as this one) very easy. However, as manufactured, the focuser uses an **external** 4inch high post and screw to vary the focus with virtually no backlash. This post is mounted on the main mounting surface of the focuser, approximately four inches off the optical axis. The mechanism works extremely well for remote focusing using a stepping motor, but its placement interferes with mounting such a relatively large assembly as the spectrometer would be: i.e., the post and screw are in the way. To correct this, I modified the focuser drive by making a new adjusting screw which projects **into** the telescope (rather than external), and indeed, I also mounted the stepping motor inside (powered off except when changing focus). This change worked extremely well, the focuser still has virtually no backlash, has been trouble-free, and leaves the outer face of the focuser entirely clear. The intrusion of the parts into the telescope optical path may offend one's sensibilities, but has caused no other obvious adverse effects.

Guider. The telescope must be actively guided to keep the star on the slit. This telescope is approximately 1 a-s/pixel, and the slit opening at 50u would be about 5.5 pixels wide. Guiding to an a-s or better not only keeps most of the light in the slit, but also improves resolution if the target is substantially smaller than the slit. A major design issue was the type of guiding to use, with the usual choices being

- Use of an external guider for the telescope
- Reflection of the image off the slit
- Use of a partial mirror to pickoff a portion of the entering light beam

I knew from experience that telescope flexure over long total exposures would make an external guider very problematic, so immediately dropped this alternative. Using

reflected image off the slit could have a number of advantages including continuous guiding with little light loss. However, the biggest advantage is that it can provide an opportunity to see (via the guiding camera) where the target star is in relation to the slit, and to move it onto the slit using the telescope controls. The down sides of the system includes difficulty guiding on a highly focused star whose image is smaller than the slit opening, the need to put focusing optics aimed at the slit into a very tight space (especially in a fast system), and the limited FOV in the guider image.

The third alternative is to use a partially reflecting pickoff mirror in the optical path. This is a simple system to build and allows the guider camera potentially to see a large field. In turn, this helps in alignment and target identification, as well as guiding on a bright star in a field when the target star may be too faint or has a nearby, interfering star. Experiments and calculations appeared to show that the spectrometer might well reach about mag. 10, and that picking off 10% of the incoming light would be sufficient for a guide camera with 5s imaging.

Choosing the mirror system, I used an 8% reflection, 92% transmission pellicle (super thin mirror) for the optical element. This is mounted on a PVC carrier installed in the inlet 2inch tubing. The guide camera is a Lodestar camera, uncooled, no shutter, 8.5u pixels (closely matching the 9u pixels of the imaging camera). Because the Lodestar nosepiece is rather deep, I had to remove approximately 5/16 inch so that it could get close enough to the pellicle to focus. In practice, it has no trouble guiding on mag12 stars using 5 sec exposures.

The pellicle carrier is held in place with a simple set screw. To adjust the star position in the guider field, one simply removes the setscrew after a target is centered on the slit (process described below) and uses a sharp scribe through the setscrew hole to rotate the PVC pellicle carrier or move it in/out. Once the target is approximately centered in the guide camera, replace the setscrew.

Calibrator. I also built a simple neon calibrator that uses the rear of the pellicle mirror to reflect light into the slit. The Ne-2 neon bulb is driven by a 12VDC to 120VAC converter (remote controlled). Its light passes through several small diffusing sheets to create a reasonable area source, then through a lens that focuses at about f3-f4 off the back of the pellicle into the slit. Typically, 2s is sufficient exposure for a calibration. When the calibrator is lit the guider camera is saturated and cannot guide; however, this creates no problem since the calibrator is not needed continuously. Note that many Ne-2 drive circuits produce non-symmetric waveforms that basically put DC on the neon bulb causing the bulb to turn black in a few hours. An AC oscillator (square or sinusoidal) is far preferable.

Slit. The slit is a 50u 3mm high air (not glass) slit mounted in a PVC carrier in the inlet tube. The star image from the telescope is approximately 2.5a-s FWHM, which translates to about 25u. Thus, a 50u slit allows virtually all of a reasonably well-focused star to enter the spectrometer, while allowing for some pointing and guiding error.

Spectrometer Body. The incoming light tube is 1/8inch aluminum tubing of 2inch OD, while the guide camera and calibrator tubes are 1 1/4ID. The spectrometer body is 1/8inch aluminum tubing of square cross-section of 3inch outside dimension (2 3/4 inside). The 2inch incoming light tube has a threaded end that fits through a hole bored in the side of the spectrometer body and is held with an aluminum nut on the inside (finger tight).

The reflecting mirror for the incoming light from the slit is mounted on a simple section of aluminum angle and is adjusted by hand to that it picks up all the incoming light while sufficiently offset to allow the light from the grating to miss it on the way to the camera. This mirror is a simple elliptical flat for a small telescope.

The light from the slit diverges toward the collimating lens. This is a simple achromat of 55mm dia. and 170mm focal length mounted on a simple PVC holder that can slide along the long axis of the spectrometer. Adjustment screws allow the lens carrier to be tilted and turned approximately 3deg. The light passes through the collimating lens and leaves as a parallel beam. It then reflects off the grating (1200L/mm, 2inch square, blazed for 5000Å), back through the collimating lens, passes the elliptical flat, and enters the main camera (which is on axis). The camera is mounted to the spectrometer body using a machined block of PVC.

Returning to the grating, it is attached to a piece of 1/8 aluminum plate (using a relatively soft 5 minute epoxy), which in turn is mounted on a piece of aluminum angle with three sets of push/pull screws. This allows the user to tilt the grating and to tightly lock the setting. The aluminum angle containing the grating is mounted on a home-cut sector of worm wheel that is pivoted under the center front surface of the grating. The worm wheel was made from 1/4 in. aluminum plate in a homemade jig using a hand tap in a standard small lathe to cut the teeth. The wheel is turned by a stepper motor driving a length of 1/4-20 threaded rod acting as the worm. The system allows easy shift in the wavelength band, is stable in a given position, and has fairly small, easy to compensate backlash. The section of worm wheel was trimmed to allow the grating to be turned square to the light beam (i.e., as a simple reflector in Order Zero) as well as to turn far enough to reach the beginning of second order.

A serial controlled RoboFocus controller drives the stepping motor. That is, one dials in the desired setting, and the motor goes to the desired angle as predetermined using the neon calibrator. The controller incorporates anti-backlash logic so that all moves finish in the same direction. The stepping motor thus allows the user to select the center wavelength for the spectral region of interest. The RoboFocus controller also can turn the neon calibrator off and on remotely.

Setting Up the Spectrometer

In such a one-off design that included many uncertainties, I had to allow for easy modification and easy adjustments. The challenge was to construct the instrument so that it was easy to modify, yet stable when set—this was in fact accomplished. There are two steps in the setup:

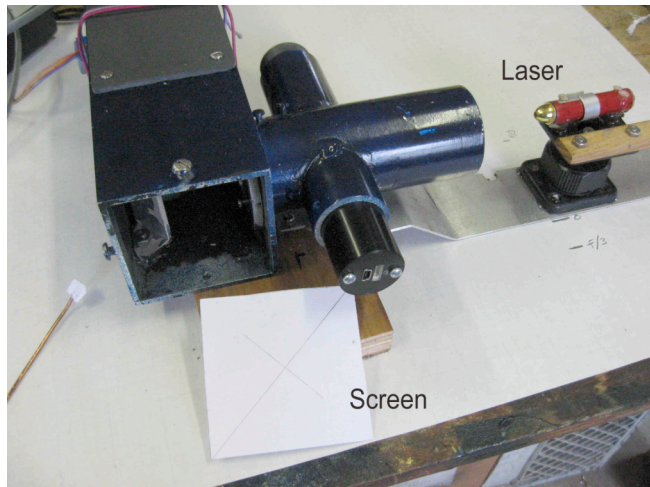
- Orienting and properly setting the optical components
- Getting the star properly (centered and focused) onto the slit.

Setting up the instrument requires establishing the positions and orientations of the optical elements appropriately. This should only need to be done once or very seldom as described. I used several simple devices in the alignment and testing process

- Neon light calibrator (light mostly orange to red)
- Small battery fluorescent light (lines throughout the visible spectrum)
- Small red laser for coarse alignment of elements (paper on a wire can be used to trace the beam path)
- Small red laser fitted with expanding lenses to provide a 1 inch dia. parallel beam)
- Sodium flame (salt on an alcohol lamp)

In general, I first aligned the parts by eye, and then used the red laser to trace the light through the spectrometer to get it out into the camera. I then adjusted the focus using the neon spectrum.

The laser alignment is worth some detail. The object is not to just get a central beam through the instrument, but rather to assure that all the incoming light in the f3.5 cone is getting through to the CCD. I set up a little red laser on an arm pivoted under the slit so that the laser remained aimed at the slit as the arm is swung to angles corresponding to an incoming f3 light cone. After squaring the grating to the optical axis (functions as a mirror at zero order), I then used a small piece of paper on a wire to trace the light beam inside the spectrometer to set the incoming elliptical flat so that the center and edges of the cone were reflected to the collimating lens, then back past the flat to a viewing screen (piece of thin paper) in the plane of the CCD. Once the beam is set to the center of the CCD position, the object is to have the beam always reach the center as the laser arm is swung over the f3 cone angle. However, at a wavelength other than the central wavelength of the spectral setting, the central beam of the light will return at a different angle. To simulate this, I shift the grating to an angle corresponding to the diffracted angle at the edge of the CCD frame for an incoming central ray, then check that the f3 rays also still reach the CCD. One then does the same for the opposite side of the CCD frame. One finds that there is a sweet spot (offset and angle) for the elliptical that allows the maximum symmetric optical performance.



These adjustments set the reflective components, but not the focus. For this, one uses the neon source and CCD camera to obtain proper adjustments to assure

- Slit images (the lines) were vertical in the camera image to within 1-2 deg (slit rotation)
- Slit images were sharply focused (camera focus and col. lens position and tilt/turn collimating lens adjustment)
- Spectrum band was horizontal (camera rotation)
- Spectrum was roughly vertically centered in the image (grating tilt)

A constraint is that one wants the light to the grating to be well collimated, i.e., parallel, thus requiring that camera to lens and slit to lens distances be close to equal.

Once a good spectrum is obtained, one can use the neon calibrator to measure the dispersion in A/pixels. For this, one has to identify a series of lines unambiguously. This does take some practice, using frequent reference to web sites (such as <http://astro.u-strasbg.fr/~koppen/discharge/index.html>) and various tables of emission lines. The sodium flame provides the D lines at 5889 and 5895, which helps verify operation of the spectrometer (this spectrometer will easily split these two lines).

Finally, one has a choice of alignment of the slit—will it be E-W or N-S on the sky. For several reasons, I prefer E-W so that variations in clock drive move the star along the slit, rather than off the slit.

Initial Targeting in the Field

The problem of getting the target star onto the slit the first time appears intimidating because the user cannot image the target star and slit at the same time. However, the process is in fact quite easy if one follows a step-by-step approach. Subsequent aimings are much easier and faster and in fact, are often no-brainers! It is assumed that the user has tested the spectrometer on the bench and achieved good spectra. However, when one installs the spectrometer onto the telescope, the focus will likely be WAY off, plus one has to find the slit with the star. So, how is this done, especially the first time?

I picked a very bright, fairly large target. My first one was the moon (1st Q), and my second was Jupiter (almost 40a-s diameter). Using my guide scope, I aim the telescope, knowing it was pointed accurately to several a-m (I use TheSky and an AP1200 mount). I then start taking spectral images. I should see strong evidence of the target as a bright spectral line across the image field I know that no part of the object is on or near the slit. If I do not, I begin systematically to search—moving E-W and N-S until the object shows some signs of life in the spectral image. The size of the movements is not critical—just so long as the moves are not much bigger than the object. Using the moon, I could easily use 1a-m movements of the telescope, which took only a few minutes.

Once I had the object at least partly on the slit, I began to adjust the focus and refine the scope position. What I was seeking was a narrow spectral band that was well-focused and as bright as possible. I started with the moon, got it onto the slit, calibrated the scope alignment, and then moved to Jupiter. Remember, the slit is 3mm high, corresponding to about 300pixels or about 300a-s=6a-m for my telescope. The spectral band for a focused

Jupiter will be about 40 pixels high (my telescope is about 1 arc-s/pixel). An out of focus Jupiter will show as a wider band, e.g., 100 pixels. One changes the focus to minimize the vertical bandwidth. If the new focus is such that the Jupiter image moves off the slit, it is easy to use TheSky to nudge the telescope N-S (across the slit) to get it more closely centered. Adjusting the focus and the scope position to optimum will take 3-5 minutes for this one-time operation.

Once the focus is reached, record the focus settings! Also, make an initial adjustment of the guider camera. Operate the guider camera—Jupiter should be in the FOV. You may need to change the pellicle position or angle to get it onto the guide camera. Once it is on the guide camera image, you can focus the guide camera (slide in/out) and make small adjustments on the pellicle carrier to roughly center the image on the guide FOV as discussed above. When you have the Jupiter image on a convenient spot of the guide image, make a note of its X and Y pixel! You can now use the guide camera to get a target star quite close to or even on the slit on the first try.

Now shift to a bright star, i.e., a target with minimal size but intense. Use the guide camera to aim the telescope as well as you can by putting the target on the guider coordinates determined earlier. If you do not see the spectral band, you can move the telescope S-N at a time N-S (perpendicular to the slit) until the stellar image crosses the slit and produces a spectrum. When this is done, again refine your focus and guide camera settings. You are now in business: you know the focus settings and the position on the guide camera field that puts the target on the slit. These numbers will stay the same so long as the slit-to-guider relationship is not changed.

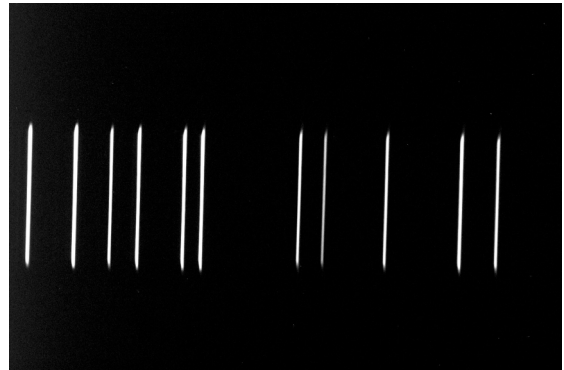
Although this process used the moon, Jupiter, and a star, it is almost as easy to do the initial setup simply using a very bright star. The only difference is that as one gets closer to focus, one must use smaller N-S telescope movements to avoid losing the star off the slit. One source of confusion is that the spectrum may show as two narrow parallel spectral bands caused by an out of focus Newtonian star image with opposite parts of the image “doughnut” on the slit. Continue changing focus until these coalesce (do not change the spectrum camera focus or collimating lens position as this will cause great distortions in the spectrum as well as waste light).

Note that once the guider chip and the entrance slit are calibrated in this process, i.e., made parfocal, the observer can use the target focus on the guider as an excellent surrogate for the focus of the target on the slit (the pixel sizes of the main camera and guider are very similar, so the sensitivity of focusing is the same for both). The slit position on the guider image is known from the calibration process, as is the slit width (in this case, 5.5 pixels) and this is easily translated onto the guide field using software or “grease pencils”. In practice, one can simply aim the scope to place the target in the vicinity (e.g. 20 pixels) of the proper guider coordinates, enter the desired guider pixel coordinates into the guide pixel settings (guide control software), then start guiding. The telescope will move the target star to the proper guider pixel location, and the star will be on the slit.

The user can always check that the focus and target location on the guider are still the correct ones by taking spectra of a bright star (to shorten exposures) for a few different target coordinates and focus settings. This test can be done in about ten minutes. In practice, unless the slit and guide camera relative positions are changed, these tests have always showed the focus and slit location calibrations to be stable.

Performance-Bench Testing

Figure 2 shows a typical neon spectrum. The range of the spectrum is approximately 6250 to 6800. The measured dispersion is 2.6 pixels/Å, in very close agreement with the design value. Using either neon lines or the sodium flame near 6000Å, the narrowest line measured is about 2 Å (5 pixels) FWHM, implying a resolution of about $R=3000$, also close to the design value. In this figure, band of the spectral lines slopes slightly downward, showing that the camera is rotated very slightly relative to the spectrometer.



The slit is also not quite vertical to the grating lines, thus causing the line tilts. The band is also very slightly below the center of the frame, which shows that the grating tilt is not perfect. For most stellar spectroscopy, this degree of imperfection is easy to handle in the image processing.

With such a fast (f3.5) spectrometer, various aberrations are more serious than with slower (f10) designs. For example, using the present ST8 size camera, the FWHM of spectral lines degrades in the left (short wavelength) side of the spectrum from perhaps 2Å wide to about 3Å wide. While a smaller format chip would show little of this, it is clear that an even larger format camera would not do well on this spectrometer. Interestingly, there appears to be little adverse effect from residual chromatic aberration, i.e., the spectrometer behavior is quite constant as one moves from 6500Å to shorter than 5000Å.

A combination of bench testing and star tests were done to determine the Grating Stepping motor behavior. This includes the calibration, i.e., what stepper values correspond to which center wavelengths, and the repeatability, i.e. how well does the spectrometer return to the same wavelength setting after changes. Over the roughly visual range of interest, the stepper calibration was reasonably linear, and the repeatability is within approximately 10Å.

Development and refinement of the spectrometer required multiple reassemblies, adjustments, and modifications of the components. During this work, I found the unit to be rather robust, i.e., performance returned to the same levels with little variation even as I tweaked various settings. In addition, those parts of the unit that I did not touch remained stable in their settings.

Performance-Sky Testing

The most encouraging event was the initial night of testing. As noted above, I started with the moon as a target aligned the instrument, then moved on to Jupiter and several stars.

Use of the spectrometer showed that the system could easily guide on stars fainter than 12 mag. that are substantially fainter than the working sensitivity of the spectrometer. How faint can the spectrometer operate? This depends on the purpose of the work and the noise level that is acceptable in the data. In general, good low noise spectra of 7.5mag stars take approximately 20 min. However, if one is only interested, for example, in the apparent wavelength of an H α line, a mag 9-10 star can be analyzed in under an hour. I embarked on a series of measurements with the spectrometer to explore its characteristics, and to learn more about the science the spectrometer can support. A summary of some of that work is given in the appendix.

While these spectrometer performance results were somewhat better than I had planned, it is equally important that the instrument operate robustly and easily. I have found that I can remove and install the spectrometer with no difficulty in a few minutes. Using guider calibrations established many sessions earlier, I am able to put a focused target star on the slit in a minute or two. Once on the target star and the guider activated, I generally take five-minute exposures and do not touch the system for hours at a time as it runs. Guider error is normally about 0.5-0.7pixels RMS.

Conclusion

This project has been fun and satisfying, and has resulted in a fully usable instrument. The cost was about \$500 for materials, and required about 150 hours of work (of course, a second one would be much faster to build). The spectrometer met or exceeded all the goals, and will be used to supplement the DSS7 spectroscopy at our observatory.

Parts Sources Used

Here is a list of the sources and parts that I used. I used the Internet to search for parts, and generally but not always picked the least expensive source. I make no implication that other parts suppliers cannot do as well or better than those I chose. Prices are approximate.

Grating. Edmund Scientific. 1200 l/mm blazed for 5000A. \$200

Elliptical. Edmund Scientific 1 1/4 x 1 \$30

Pellicle. Edmund Scientific. 1in dia. 8R/92T \$75

Slit. 50u XXXXXXXXXXXX \$35

Collimator Lens. Surplus Shed Achromat 53mmx170mm \$15

Guider. Oceanside. Lodestar \$650

Stepper Motor. XXXXXXXX \$12

RoboFocus. Technical Innovations. \$300 (Controller only)

Metal. Speedy Metals. Aluminum 1/8 thick. 3x3OD square, 2OD, 1 1/2 OD \$75
PVC, threaded rod, etc. McMaster-Carr

Tools used in construction included a 9inch South Bend lathe (turning, boring, threading), Mill Drill (milling and boring), Band saw, hand tools

Illustrations

