Conceptual design of a low resolution spectrograph for the Astronomical Observatory of Córdoba

D.Q. Nagasawa, J.L. Marshall, D.L DePoy, N. Mondrik

Texas A&M University Dept. of Physics and Astronomy, College Station, Texas 77840

ABSTRACT

We present a conceptual design for a low resolution optical spectrograph for the Astronomical Observatory of Córdoba 1.54m telescope. The simple instrument is required to cover a broad wavelength range (4000Å$<\lambda<$9000Å with 3000Å simultaneous coverage) at a resolution of R=$\lambda/\Delta\lambda \sim 500$, allowing its use as a versatile astronomical spectrograph. In particular, we explore the use of inexpensive commercial off-the-shelf lenses, gratings, and a CCD system to create a small and simple spectrograph that has reasonable performance. We carefully measure properties of the lenses and demonstrate that they have excellent image quality and high throughput.

Keywords: low resolution spectrograph, optical spectrograph, commercial-off-the-shelf system, photographic lens, Astronomical Observatory of Córdoba

1. INTRODUCTION

Spectroscopy has been a staple of astronomical studies since its introduction several centuries ago. To that end, hundreds of spectroscopic instruments have been designed, built, and deployed to collect the vast amounts of data required for meaningful studies of the universe, both local and distant. As the needs of the field have evolved, so too has the instrumentation; for example, modern spectroscopic instruments are used in large scale survey studies (Sloan Digital Sky Survey[1] and DESI[2]) and for very large telescopes[3].

The field of modern astronomy is focused on studying the universe at large and small scales. Several large imaging surveys are currently underway or planned, particularly in the southern hemisphere. These surveys, such as DES[4] and LSST[5], will discover enormous numbers of interesting targets that require spectroscopic follow-up[6]. Furthermore, various planetary transit and variability surveys are currently in operation that identify relatively bright objects[7]. These sorts of surveys, among many others, require spectroscopic follow-up studies in order to fully realize the scientific potential of the surveys.

In this paper, we describe a conceptual design for a simple spectrograph for the 1.54m telescope at the Astronomical Observatory of Córdoba in Argentina. This telescope is old, but offers a stable platform and substantial observing time, and, if properly instrumented, could be usefully employed for a variety of spectroscopic follow-up programs. Here, we concentrate on an instrument with moderate resolution and relatively wide wavelength coverage. The budget for the instrument is small; as a result, we have carefully investigated the use of commercial-off-the-shelf (COTS) components in the design of the instrument. We also quantitatively measure some pertinent properties of these sorts of components. Such an instrument would allow the 1.54m telescope to be used for a variety of research projects including identification of quasi-stellar objects (QSO's) and identifying spectral types of variable stars. The telescope's location in the southern hemisphere enables spectroscopic follow-up of objects found in several large scale imaging surveys such as DES and LSST.

Our science goals for this instrument are to follow-up single interesting objects found in imaging surveys. We want a system that can perform initial spectroscopic classification of interesting or unusual objects at optical wavelengths (4000Å$<\lambda<$9000Å).

Further author information:
D.Q.N. : Email: dqnagasawa@physics.tamu.edu, Telephone: 1 979 845 4401

2. PRELIMINARY DESIGN

Our science goals require a low-resolution spectrograph with R=$\lambda/\Delta\lambda \sim 500$. To provide low-resolution dispersion, a 300 line/mm Shimadzu holographic grating blazed at 8000Å was acquired to be the dispersing element of the spectrograph. A Santa Barbara Instrument Group (SBIG) ST-8300M 3326 $\times$ 2504 pixel CCD, each pixel 5.4μm $\times$ 5.4μm, was chosen to be the detector. We chose a camera-collimator angle of 22.5° and a grating-camera distance of 150mm to enable efficient packaging of the instrument.

Since this spectrograph is designed for an $f/4.9$ telescope, the $f/\#$ of the collimator must also be at most $f/4.9$. Because commercial lenses are only available at certain focal lengths and $f/\#$'s, this limited the choices of usable lenses when using COTS optics. We chose an $f/4$ lens with a 200mm focal length as our collimator. This lens, combined with the 150mm grating-camera distance, yields a 57mm diameter beam. This means that the camera has to have an aperture of at least 57mm to prevent vignetting. Of the available COTS lenses, we select an 180mm focal length, $f/2.8$ lens as our camera.

This combination of optical components yields a resolution of $R = \lambda/\Delta\lambda \sim 793$ at a wavelength of 7846Å and simultaneous coverage of 3200Å for a 3326 pixel (5.4μm) CCD system.

The two commercially available lenses described above are manufactured by Nikon and are designed for 35mm photography. In order to demonstrate the adequacy of these lenses for scientific use, we performed several tests on each individual lens assembly, described in the next section.

3. TESTS OF INDIVIDUAL SYSTEM COMPONENTS

3.1 Lens Image Quality Tests

Our first tests were to ensure that these lenses could take science-quality astronomical data when combined with a commercially available CCD. We attached each lens at its full aperture (180mm focal length at $f/2.8$ and the 200mm focal length at $f/4$) to a SBIG ST-8300M CCD system. We then utilized these lenses in observations of the Pleiades star cluster (RA: 03:47:24, Dec: +24°07'00"), a bright dense cluster which we could use as a collection of point sources. The pixel scale for a 200mm focal length lens and a 180mm focal length lens are 5.5"/pixel and 6.2"/pixel respectively. Since seeing conditions that night were much smaller than 1 pixel (∼2"), this provides a direct probe into the image quality of each of these lenses.

We characterize the image quality of the lenses using observations described above. An example of one of our images, a 60 second guided exposure, can be seen in Figure 1. We measured the FWHM of every non-saturated star. The mean FWHM of the stars in the image was 12μm. In order to see if this degraded as a function of distance from the center of the CCD, we plot the FWHM of each star against its distance from center of our image; this we show in Figure 2. We measure no significant change in the FWHM over a ∼10mm field radius, which was to be expected given these lenses' use for 35mm film photography.

3.2 Throughput Tests

We also wanted to test the throughput of each of these lenses to ensure there were no significant losses in our wavelength range of interest. To measure absolute throughput, we utilized a National Institute of Standards and Technology (NIST) calibrated Gentec-E Solo-2 laser power meter with a Si photodiode. The output energy of several ThorLabs laser diode modules of wavelengths 405nm, 532nm, 650nm, 670nm, and 780nm were measured using the laser power meter after ∼60cm of travel through air. After the output energy of the lasers were measured, the 200mm focal length lens and the 180mm focal length lens were each placed in the path of the beam. The voltage output of the photodiode with the lens was then divided by the voltage output of the unimpeded beam. The results from this as a function wavelength can be seen in Figure 3.

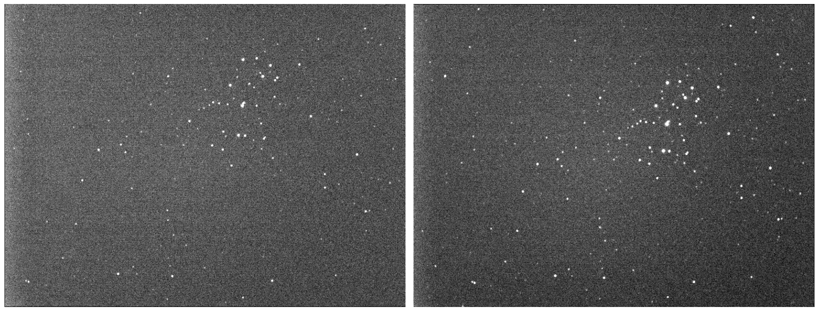

Figure 1. Image of the Pleiades star cluster (RA: 03:47:24, Dec: +24°07'00") using the 200mm focal length, $f/4$ Nikon lens (left) and the 180mm focal length $f/2.8$ Nikon lens (right) in a 60 second exposure. These images were taken using an SBIG ST-8300M CCD.

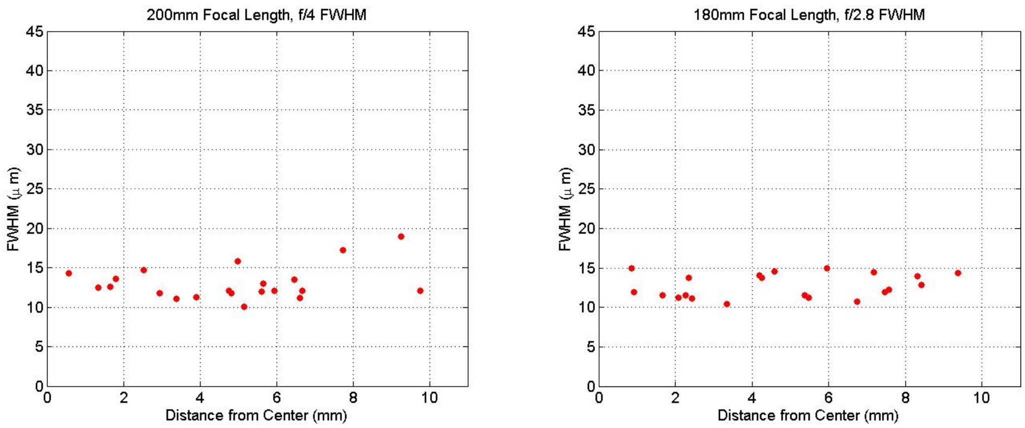

Figure 2. FWHM of the images of stars as a function of distance from the center of the CCD in mm. From this, we see no significant deviation from the mean FWHM of 12μm for both the 200mm focal length, $f/4$ lens and the 180mm focal length, $f/2.8$ lens.

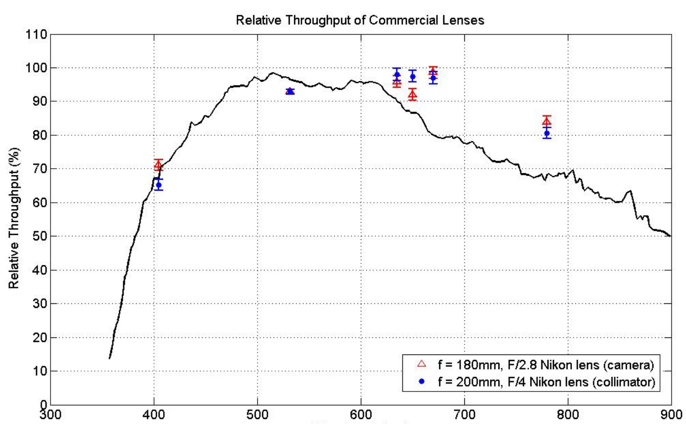

Figure 3. Throughput analysis of the collimator (Nikon 200mm focal length, $f/4$ lens) and the camera (Nikon 180mm focal length, $f/2.8$ lens). The black line represents a relative throughput of a 50mm focal length, $f/1.8$ Nikon lens using the PreCal system; this was normalized by setting the peak throughput of the 50mm focal length lens equal to the peak throughput of the camera. We see that the throughput of the lenses we are using for the spectrograph never falls below 60% in the blue and, presuming the behavior of all Nikon lenses are similar, 50-60% in the red.

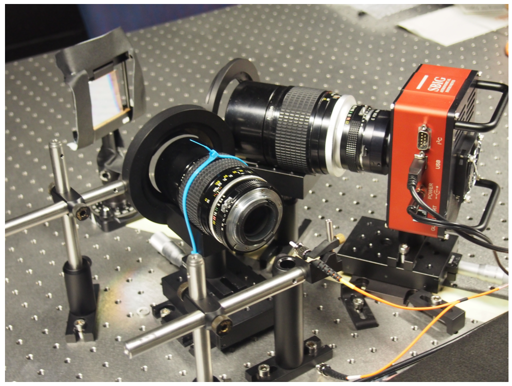

Figure 4. Photograph of the prototype spectrograph constructed using commercially acquired components. The collimator is a Nikon 200mm focal length, $f/4$ lens while the camera is a Nikon 180mm focal length, $f/2.8$ lens.

We also performed a relative throughput test using a CCD on a separate 50mm focal length, $f/1.8$ Nikon lens. The relative throughput was measured using the PreCal system which takes CCD images of monochromatic light reflected off of a Lambertian surface, the monochromatic light produced by a OBB, Czerny-Turner type monochromator. This average counts per image are normalized by the intensity incident on a NIST-calibrated photodiode pointing at the same surface. By dividing the mean counts by the relative photon emission at each wavelength, we can measure the throughput of the CCD and the optics combination. By dividing by the quantum efficiency of the detector (in this case, an SBIG ST-8300M CCD), we have the unnormalized throughput of the optics alone. We present a 20Å sampled scan of this additional lens in Figure 3 as well; in this figure, we scaled the relative throughput scan so that the peak throughput of the 50mm focal length lens matches that of the peak throughput of the 180mm focal length, $f/2.8$ Nikon lens.

We find that the maximum throughput of the lenses is ∼97% near 6500Å. We also see that, at bluer wavelengths, the throughput of the lenses drops dramatically; however, at the blue edge of our wavelength range of interest (4000Å$< \lambda <$9000Å), we maintain >65% throughput. We measure a throughput of >80% at 7800Å. If the 180mm and the 200mm lenses are similar to the 50mm lens, the we expect the throughput to remain >50% at 9000Å.

4. TESTS OF FULL PROTOTYPE SYSTEM

4.1 Prototype Design Details

We constructed a spectrograph using the commercial lenses and the CCD used in the previous photometric and throughput tests on an optical bench. The 200mm focal length, $f/4$ Nikon lens is used as the collimator. The light is then dispersed by a 300 line/mm, 8000Å blazed Shimadzu holographic reflection grating and re-imaged by the 180mm focal length, $f/2.8$ Nikon lens, which serves as the camera. The camera-collimator angle is held at 22.5°, with the grating held in the camera-pointing configuration (where the angle of diffraction is smaller than the angle of incidence). Finally, the camera focuses light onto the SBIG ST-8300M CCD. A picture of the prototype can be seen in Figure 4. The resulting system has a dispersion of 0.97Å/pixel and can be used for a wavelength range of 4000Å$< \lambda <$9000Å.

4.2 Test Spectra of Hg Lamp

After construction of the spectrograph prototype, we fed the system with a 62.5 μm diameter fiber illuminated by a $f/4.9$ telescope simulator (to match the Córdoba 1.54m telescope) which is fed by an integrating sphere. Light from a Hg arc lamp was fed into the integrating sphere. The fiber size in this simulated system would correspond to 1.725” in the sky. The resulting spectrum can be found in Figure 5.

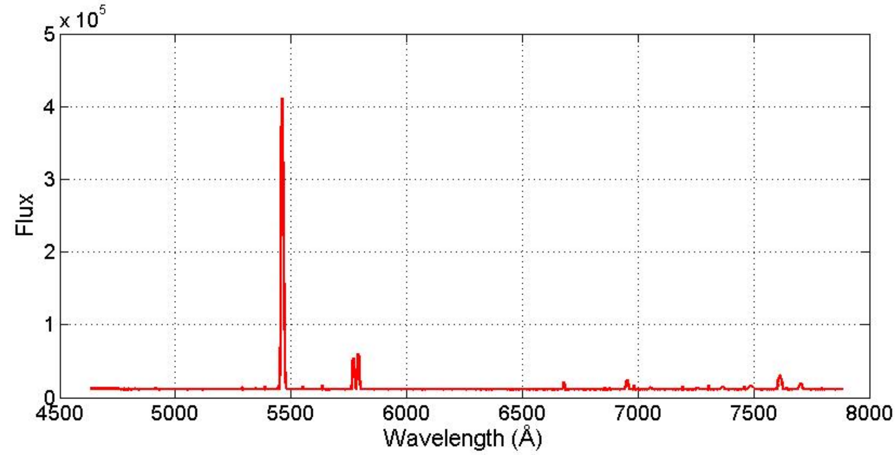

Figure 5. Mercury spectrum taken using the prototype commercial system fed by a 62.5μm fiber through an $f/4.9$ telescope simulator. The 300 line/mm grating, blazed at 8000Å, provides a dispersion of 0.97Å/pixel and, ultimately, a resolution of R$\sim$670 at 5769Å.

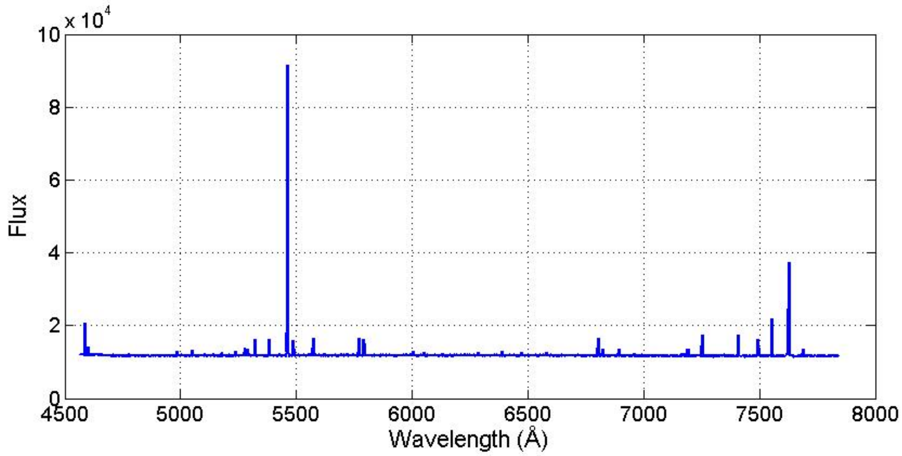

Figure 6. Mercury spectrum taken using the prototype commercial system fed by a 10μm pinhole. In this case, we wanted to simulate an extreme case where the system is limited by the optics themselves rather than slit size. From this test, we conclude that, given the optics produce a spectrum that had lines of 11μm FWHM, our optical system is not encumbered by the use of commercial optics.

We note that, for the set-up described above, the FWHM of the Hg lines at 5769Å and 5790Å is 8.5Å. We use these lines to calculate a resolution of R$\sim$670, which is as predicted for this particular configuration. We note that the wavelength coverage is from $\sim$4650Å to $\sim$7850Å, providing $\sim$3200Å of simultaneous coverage, again as expected.

We also wanted to test an extreme case where we investigate the limits of the optics in the spectrograph; this would be relevant if the seeing conditions at the telescope were very good or if we wanted to reduce the slit size in order to achieve a higher resolution at the expense of throughput. We placed a 10μm pinhole in front of the 62.5μm fiber, which would correspond to 0.275" in the sky, and acquired the resulting spectrum using a much longer exposure time (15 minutes compared to 2 minutes). Our result for this test can be seen in Figure 6.

In the resulting Hg spectrum, we can achieve a FWHM of ∼1Å for the same lines as before, which corresponds to 1-2 pixels on our CCD. Thus, we conclude that even for the extreme case, we are not limited by the quality of our optics in our prototype; that is, slit width will limit the resolution of the spectrograph, not the quality of the optics.

5. CONCLUSIONS

Based upon our previous tests using a spectrograph composed of commercially available components, we have arrived at several conclusions regarding the suitability of the system as a scientific instrument. First, we have demonstrated that the commercial lenses we intend to use have, when imaging an infinitely far point source, a 12μm FWHM spot. We also note that there is no significant deviation from this mean up to 10mm from the center of the focal plane. We have also demonstrated that the throughput of these lenses does not drop below 60% at the blue edge of our range and estimate that it will not drop below ∼50-60% at the red edge of our range. Finally, we have demonstrated that we can take spectra using this system with a peak resolution of R∼670.

We also could, in principle, build the entire system from custom optics rather than COTS optics. While we were able to design a system using ZEMAX with a minimal spot size of 10μm, we required a 6-element lens assembly including one even aspherical surface. Subsequent tolerance analysis also reveals a design very sensitive to tilt. This would mean that a significant amount of engineering would be needed to ensure the alignment and the stability of the lens assembly. We also suspect that the Nikon lenses are similarly designed to our custom optics (3 groups of 2 elements). We conclude that, although a custom-design could probably out-perform a COTS system, there would be a significant increase in both cost and complexity.

We therefore conclude that, based on these considerations, the use of commercial lenses in this particular project is both scientifically adequate and financially preferable.

There are a few remaining tests to perform before the construction of the spectrograph proper. A telescope-ready prototype spectrograph is currently in development to fully test the feasibility of a COTS component system. This spectrograph, mounted on a much smaller telescope than the one at the Astronomical Observatory of Córdoba, will be used to conduct scientific observations. This work will be carried out at the Texas A&M University Physics & Astronomy Teaching Observatory. Based on an evaluation of the prototype's performance, a final decision will be made regarding whether the commercial lens-based system performs well enough for our purposes or whether a fully customized design would be more prudent despite its significantly larger cost.

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