RESULTS OF ENGINEERING TESTS ON THE DUAL-IMAGING SPECTROGRAPH

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1. Engineering Tests

On the night of April 9, 1996, we performed a series of tests using the DIS. The primary goal of the tests was to measure the absolute throughput of the telescope/spectrograph as a function of wavelength. These tests were motivated by reports of low throughput from other ARC users as well as our own experience with the instrument. Recently, it has been suggested that degrading mirror reflectivity may be the cause of some of these observations. We address this issue in section 4.

Other tests were also performed to test the stability of the spectrograph with respect to instrument rotation, telescope position, focus, and wavelength calibration. These tests were motivated by recent reports of the illumination varying with instrument rotation angle (M. Carlson, NMSU) and from flux calibration variations, by A. Watson (possibly due to differences in focus). We report the initial results of these tests in this paper.

2. An Unusual Standard-Star Sensitivity Function Measurement

On the night of March 31, 1996, A. Watson observed the spectroscopic standard Feige 66 in low-resolution mode using a 1" slit, with two separate exposures separated by about 3 hours. The airmass for both exposures was 1.09 with exposure times of 60 seconds. In Figure 1, we show the two spectra (at the bottom) along with the measured ratio. The sky conditions included variable cirrus, which accounts for the change in absolute flux. However, clouds are thought to be very grey (no color-dependent extinction). Near the peak throughput wavelengths on each chip (5000$\AA$ and 7000$\AA$), the ratio is nearly constant at 0.75. However, blueward and redward of these wavelengths, 10-25% variations are observed. Atmospheric refraction can be ruled out, because the effect of refraction would be largest at blue wavelengths, and much less in the red. The slopes of the ratio either side of 5000

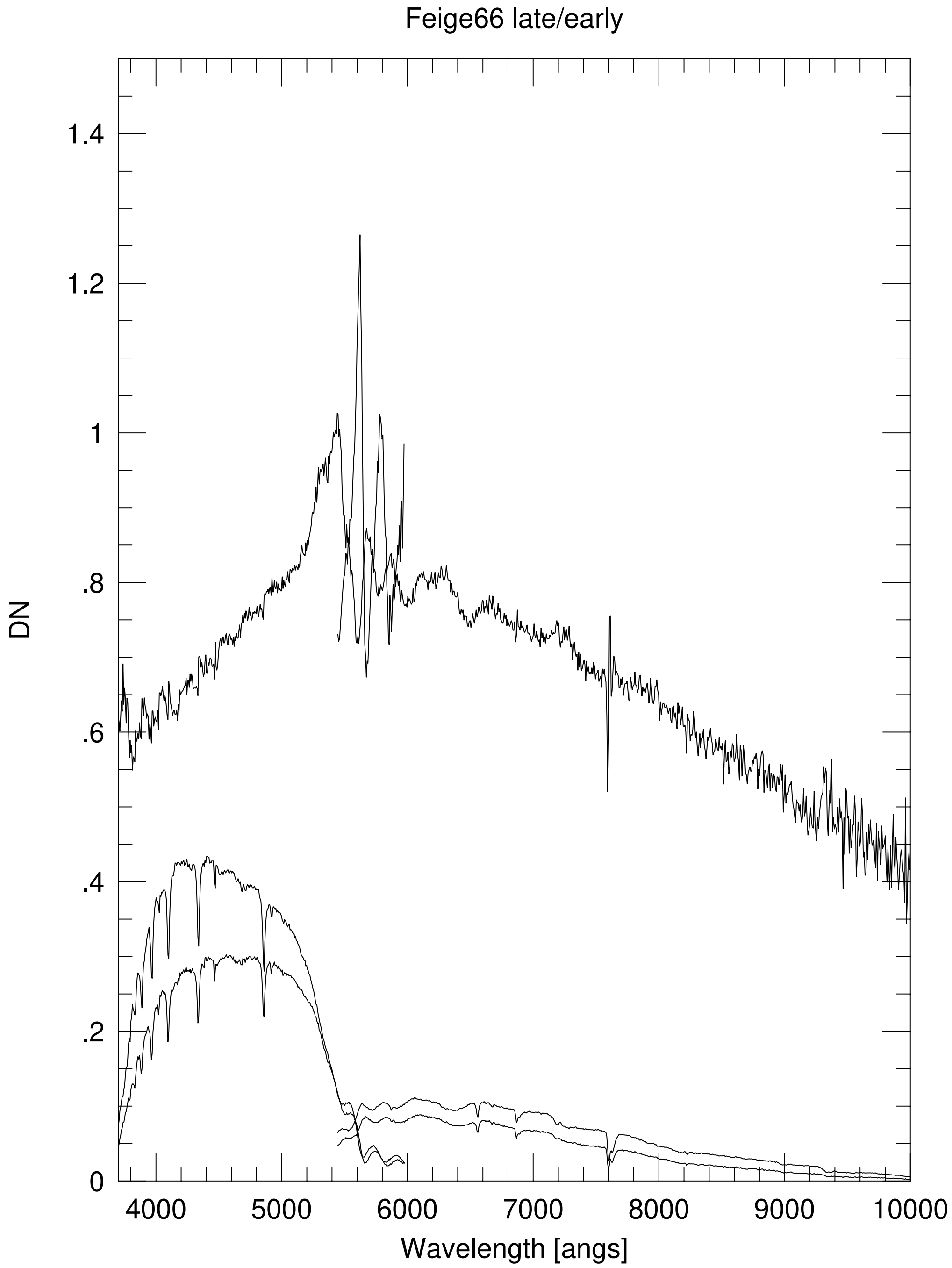

Fig. 1.— Ratio of the spectra for Feige 66 made at the same airmass several hours apart. Notice the strong color dependence.

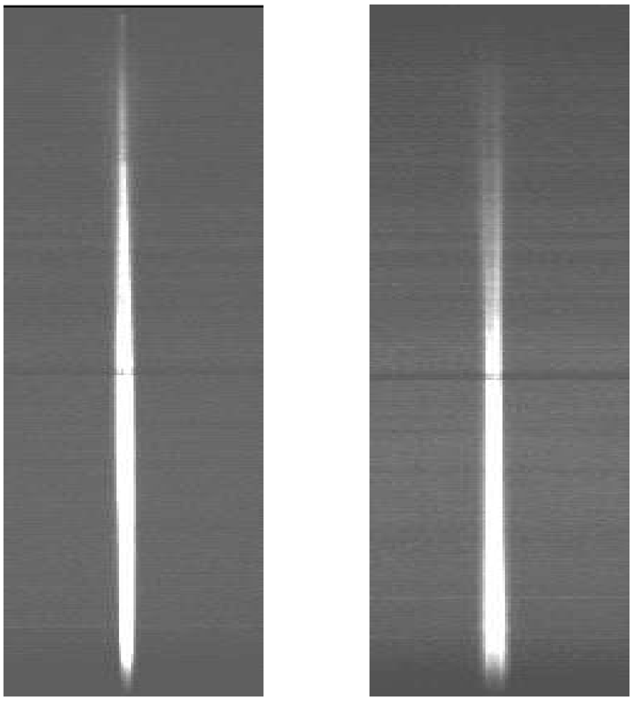

Fig. 2.— 2-D spectra of Feige 66 (as in Figure 1). Left : early spectrum; Right : last spectrum. The spectra are noticeably bowed along the dispersion axis.

and 7000$\mathring{A}$ are not consistent with refraction.

There were significant focus drifts and jumps through the night of these observations. In Figure 2, we show the 2-dimensional spectra for the same two observations of Feige 66. It is clear that the spectra is severely out of focus and also that the width of the spectrum varies along the dispersion axis. The first spectrum appears bowed with a minimum width at the ends and flaring at the center. The later spectrum is clearly out of focus, as both sides of the *doughnut* are seen at the ends of the spectrum.

From focus tests made on the night of April 9 during our engineering time, we observed very similar focus variations along the spectrum. Even at best focus, the width of the spectra was not constant. In fact, moving from negative to positive around the optimal focus value, we observed a inversion where the spectrum was bowed in the other direction (flared at the ends, narrow in the middle). We also encountered a continual focus drift throughout the night of the order of 25-50 microns every hour or so. There were no outside temperature variations during this time. We obtained slitless spectra of BD+262606 at 50-micron intervals ± 200 microns either side of optimum focus. We find no throughput variations with focus over this range. The focus range spanned by these tests may not have been large enough to duplicate the observations in figure 2, Further tests are needed to understand this observation, as we believe the effects to be real, and as yet unexplained.

3. CCD Characteristics

From a series of Bias frames and direct-imaging flatfields, we have measured the gain and read-noise of the detectors. Using two independent methods, we derive essentially identical results, which differ somewhat from quoted values on the APO Web-site.

By comparing a pair of bias frames and a pair of flatfields, the gain can be estimated from :

$$\text{Gain } (\text{e}^-/\text{DN}) \;\; = \;\; \frac{(<\text{flat1}> + <\text{flat2}>) - (<\text{bias1}> + <\text{bias2}>)}{\sigma^2_{\text{flat}} - \sigma^2_{\text{bias}}}$$

where $<>$ denotes the mean, and σ^2_{flat} and σ^2_{bias} are the variances of the difference between the pair of flatfield or bias images. For this analysis, it is important to choose regions of the flatfield which do not show strong gradients. This is particularly difficult for the Red chip, which has considerable cosmetic defects across the entire field-of-view. The read-noise is then calculated using the gain from :

$$\text{RN } (\text{e}^-) \;\; = \;\; \text{Gain} \;\; * \;\; \frac{\sigma_{\text{bias}}}{\sqrt{2}}$$

For the blue chip, we find : gain=0.99 e^-/DN and RN=16.0 e^-. For the red chip, we find : gain=1.98 e^-/DN and RN=15 e^-. The values for the blue are similar to previously quoted values, but the red-chip gain is significantly higher than the other reports (K. Gloria's calibration page has 1.83, the detector page has 1.47). Using an independent method, J. Holtzman also derived identical values. The gain determinations discussed above on the blue-chip include the ripple-bias pattern. J. Holtzman removed this pattern before calculating these values, with no measured difference in either the gain or read-noise.

4. Absolute Throughput

From observations of the spectroscopic standard star HD84937, we have measured the absolute throughput of the combined telescope/spectrograph system. HD84937 has published flux measurements from $3300 - 10200\mathring{A}$, which covers the entire free spectral range in the low-resolution mode of DIS.

Slitless spectra were taken of HD84937 at an airmass of 1.07 in a 3-second exposure. The data were reduced in a standard manner (overscan subtracted, zero-level corrected, flatfielded, wavelength calibrated, and background subtracted). Note that the flatfielding was done by fitting and removing the shape of the continuum lamp, leaving only ∼1% variations across the chip due to pixel-to-pixel wavelength-dependent senstivity variations. We then extracted a 1-d spectrum from the star to compare to standard flux measurements. The standard flux table (in the IRAF onedstds$redcal directory) is binned in 49 or 98$\AA$ bandpasses in units of magnitudes, and does not include the effects of atmospheric extinction. We corrected for extinction using the onedstds$kpnoextinct.dat file measured at the central wavelengths of the bandpasses. We ignored differential extinction across the bandpasses, but this should be a very small effect. These magnitudes were converted to predicted counts in $DN/\AA$ using the formula:

$$\mathrm{DN/Å} = 3.68 \times 10^{-20} * 10^{-0.4m} * 10^{-0.4m_{ext}} * \frac{c * 10^8}{\lambda(\AA)^2} * (\pi * \delta * \frac{D^2}{4}) * \frac{\lambda(cm)}{hc} * \frac{Exp}{Gain}$$

where m is the magnitude, m_{ext} is the extinction over that bandpass, $1 - \delta$ is the fractional obscuration in area of the primary by the secondary and its support structure, λ is the central wavelength of the bandpass, c is the speed of light (cm/s), D is the diameter of the primary mirror in cm, h is Planck's constant, and Exp is the exposure time in seconds. The zero-point (3.68×10^{-20} $ergs/cm^2/sec/Hz$) is based on a calibration of Vega and gives a flux of 3.52×10^{-20} $ergs/cm^2/sec/Hz$ (or a magnitude of 0.048) at 5556$\AA$. We used $\delta = 0.9$ (10% obscuration by the secondary and supports, estimated from optical design specs) and a primary mirror diameter of 340 cm (from ray tracing by E. Mannery (optical designer), 1995; the edges of the mirror are stopped/masked). Note that these numbers give an upper limit to the throughput efficiency (*i.e.* with less obscuration or larger collecting area the measured throughput is lower).

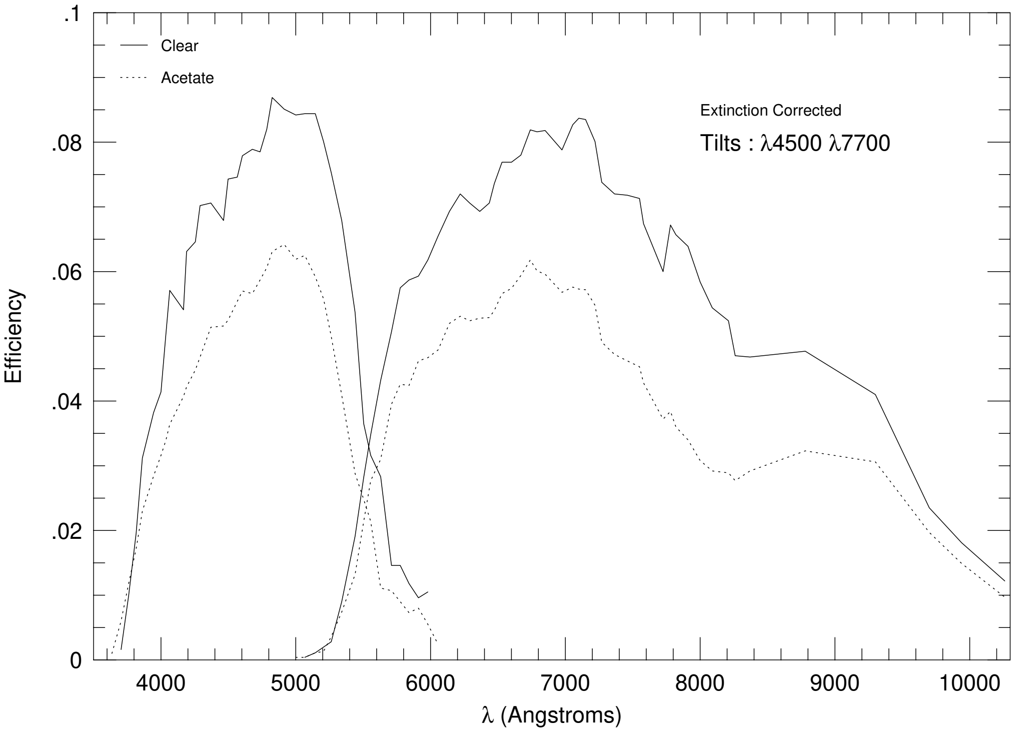

Fig. 3.— Efficiency curves for DIS + telescope in low-resolution mode for both blue and red CCD's. The dichroic cutoff wavelength is 5350Å. The solid curves are total throughput through a clear filter slot in slitless mode. The dashed curves were derived from an exposure through clear acetate material (also slitless).

The observed counts from our standard star observation were calculated by computing the sum counts over each spectral bandpass, and dividing these values by the bandwidth (in $\AA$ to get units of DN/$\AA$). The throughput is simply the ratio of these two numbers, and is shown in Figure 3. Absolute peak efficiencies are approximately 9% in the blue (at 4950$\AA$) and about 8.5% in the red (at $\sim$ 7000$\AA$). These are probably very close to the blaze wavelength values for the low-resolution gratings. These are absolute throughput efficiencies (slitless). Clearly, the observed throughput during actual observations (with slit) will be worse. These results also reinforce the need for a full set of open slits to allow one to take best advantage of the seeing conditions at the time of observations, and to maximize throughput.

These measurements were confirmed by J. Holtzman, who measured identical values from a totally independent method and analysis.

We also observed the same star through a piece of clear acetate material, placed in the filter slot. We have been using this material to manufacture our own slits and slit-masks. There is a 30% decrease in throughput through the acetate material, which is essentially color independent (see Figure 3). It was recently discovered (by K. Anderson) that the acetate material may be slightly polarizing, which may explain some of the light-loss as well as the color-independent transmission curves. K. Gloria also observed significant numbers of *bubbles* in the acetate material (under a microscope) which might act as individual scatterers. Since these bubbles are significantly larger than the observed wavelengths, the scattering could be wavelength independent. In either case, with the advent of the slit-viewing camera, it makes much more sense to think about using aluminized slits/slit-masks with **open** slits. Given the already low throughput, 30% losses are unacceptable.

Jim Gunn measured the DIS throughput back in June of 1994. He measured peak efficiencies of 16% in the blue and 12% in the red However, he used 1.47 e^{-}/DN for the gain in the red. Using our value of 1.98 would have increased his efficiency to 16%. Given the apparent uncertainty in the red-chip gain (has it varied???), it is not clear whether his numbers should be adjusted. For details of his calculations see message #7 in the apo-dis message archive. His measured efficiencies were roughly what was expected using a telescope throughput of 64% (0.88,0.88 and 0.8 for tertiary, secondary and primary mirror reflectivities measured at 6400$\AA$) and a spectrograph throughput of $\sim$26% (assuming dichroic=0.9, field optics=0.97, collimator=0.98, gratings=0.6, camera=0.92, CCD QE=0.5-0.6). The precipitous drop in throughput near 4000$\AA$ was also seen in June 1994. It was suspected that the coating of the field optics and camera block were responsible.

Almost two years later, we have now measured nearly a **factor of two** drop in absolute throughput at all wavelengths. Assuming the spectrograph throughput estimates are correct, and have not changed, this would require the telescope to contribute an average 10-30% drop in reflectivity at each mirror reflection ($\sim$70% reflectivity at each mirror). It is not obvious how the mirror reflectivities could be this poor at all wavelengths over only a few years time.

There have been very few reported measurements of the throughput in the time interval between the tests reported here. In one additional measurement, B. Greenawalt (NMSU) measured the DIS/telescope throughput in Q1/1995 through a 4" acetate slit, and found values of 7-8%. At this time, mechanical repeatibility of the turret wheel in DIS was very poor, and it was difficult to ensure that the objects were centered in the slit. This potential error along with the $\sim$ 30% light-loss from the acetate make the final results **very uncertain**. However, if one assumed that the star was centered and corrected these values by 30%, the resulting efficiencies are of order 10.5%.

It is possible that these results show a deteriorating condition, but it would be useful to have additional measurements at more frequent intervals to be certain. If anyone has throughput measurements made at any other times, please let us know. Mirror reflectivity measurements currently scheduled for the 3.5m may also help to understand these results.

5. Throughput as a Function of Rotator Angle, Grating Tilt, and Instrumental Polariz ation

We obtained slitless spectra of the standard star BD+262606. Observations were made at 7 different physical rotation angles (-180, -120, -60, 0, 60, 120, and 180). We find no dependence on throughput with instrument rotation angle.

For both the low-res and high-res gratings, we measured relative throughput as a function of grating tilt. For high-res mode, this enabled us to estimate the blaze wavelengths of the gratings. These values are essentially the same as for the low-res grating set (5000 & 7000$\AA$). The relative throughput at the blaze-wavelength was independent of grating tilt (as expected).

We obtained spectral flatfields in low-resolution mode in the standard way, and through a diffuser (a piece of paper placed over the filter-wheel slot. The idea was to test if there are throughput variations in illumination with respect to the instrumental polarization induced by the 45° reflection at the tertiary. Taking the ratio of these two flatfields (after block-averaging the flatfield along the spatial axis) indicated variations of less than 1% except in the spectral range which is affected by the dichroic. Near the wavelength cutoff of the dichroic, on both chips, there are approximately 3% variations in observed intensity. The ripples on the spectral flatfields, near the wavelengths affected by the dichoric, are also seen to vary with instrument rotation angle, and possibly telescope position. This was observed by M. Carlson and A. Watson some time ago, and motivated a number of these tests.

6. Filter Transmission, Grating Efficiency

From observations of BD+262606, we obtained filter transmission curves by taking the ratio of spectra with and without the Gunn (g,r) filters in the light-path. These transmission curves are shown in Figure 4, and are close matches to those available on the APO Web page.

By comparing the integrated flux from a slitless spectrum and a direct image (both through the Gunn filters) of BD+262606, we determined the *relative* efficiency of the gratings over these bandpasses (the efficiency is measured *relative* to the mirrors). We find for the Gunn g: 77%, and for Gunn r: 89%. Assuming typical mirror reflectivities of 85%, this translates to absolute grating efficiencies of 65% and 75% over the Gunn g and r bandpasses, respectively. These values are well within established averages using numbers from other observatories.

7. Wavelength Stability

We obtained $HeNeAr$ arc-lamp spectra at 7 instrument rotation angles (-180->180°). Pixel shifts were measured relative to the first spectrum taken at $-180°$ physical. These shifts were calculated for single columns along the chip, at the center, and at 60 columns inward from each edge. Pixel shifts were measured from the R-chip in low-resolution mode using a cross-correlation method. We find variations as high as 0.6 pixels, which is possibly correlated with the rotation angle (at large angles from the reference we find the largest shifts). This suggests that for precision work, either calibration lamps should be taken after each image, or the use of sky lines is necessary to determine accurate shifts. We didn't have time to test the stability as function of telescope position, and this should probably be checked.

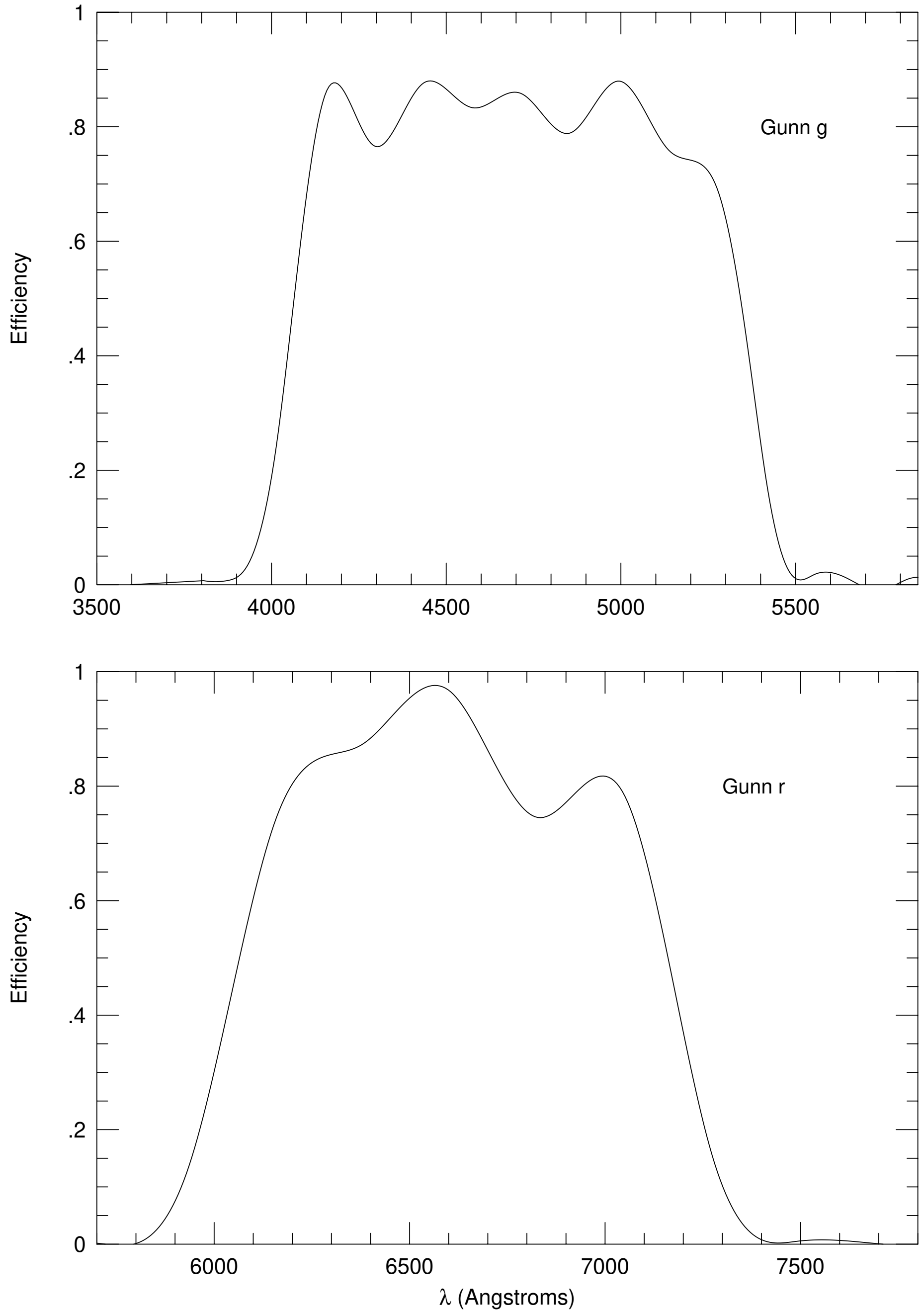

Fig. 4.— Filter transmission curves for the Gunn g,r filter set.

We also checked the wavelength calibration after moving the gratings out and back in to the same position. We find similar shifts as above.

8. Other Tests and Summary

We performed a few additional tests which have not yet been analyzed. These include a scattered-light test, charge-transfer efficiency (CTE), and focus variation across the field-of-view. We will issue an addendum to this report when the analysis is complete.

In summary, we have determined that the absolute throughput of the telescope/spectrograph system is of order 9% at peak. There is significant decrease in efficiency (30%) between 5000 and 4000$\AA$, with essentially no blue response below 4000$\AA$.

If previous calculations are correct, this implies nearly a factor of two degradation in system performance over all wavelengths over a two-year time span. It is not obvious (at least to these authors) that the mirror reflectivity can explain all of these observations. More tests are necessary in this regard. These results certainly motivate the acquisition of several aluminized slits of different widths (1.5-4" or so), which can be used to adapt to the seeing conditions and to maximize the already low throughput.

Stability tests show no significant variations in illumination with regard to focus or rotator angle, although more tests are probably warranted, particularly to explain the anamolous flux calibration measurement described in section 2.

Although the wavelength calibration is probably not a problem except for the most precise work (assuming one used the sky-lines for offsets), in high-resolution mode, it may still be necessary to do frequent arc-lamp exposures, especially in the blue. It would be useful to make this process less painful by automating the mirror covers remotely.

9. Acknowledgements

We would like to thank B. Gillespie for giving us a full night of photometric (!) weather to perform these tests. We also thank K. Gloria for her assistance during the engineering run.

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