Spectrophotometric calibration system for DECam

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ABSTRACT

We present a spectrophotometric calibration system that will be implemented as part of the DES DECam project at the Blanco 4 meter at CTIO. Our calibration system uses a 2nm wide tunable source to measure the instrumental response function of the telescope from 300nm up to 1100nm. The system consists of a monochromator based tunable light source that is projected uniformly on a Lambertian screen using a broadband "line to spot" fiber bundle and an engineered diffuser. Several calibrated photodiodes strategically positioned along the beam path will allow us to measure the throughput as a function of wavelength. Our system has an output power of 0.25 mW, equivalent to a flux of approximately 100 photons/s/pixel on DECam. We also present results from the deployment of a prototype of this system at the Swope 1m at Las Campanas Observatory for the calibration of the photometric equipment used in the Carnegie Supernova Project.

Keywords: instrumentation, detector, DECam, calibration, photometry

1. INTRODUCTION

The discovery that the universe is *accelerating*, not slowing down from the mass it contains, is the surprise that sets the initial research program of 21st Century cosmology. The Dark Energy Survey is a next generation sky survey aimed directly at understanding this mystery. The survey will rely on DECam, an extremely red sensitive 520 Megapixel camera that has a 1 meter diameter, 2.2 degree field of view prime focus corrector, and a data acquisition system fast enough to take images in 17 seconds. DECam will be installed at the prime focus of the Blanco 4-meter telescope at CTIO, a southern hemisphere NOAO telescope.

We are building a spectrophotometric calibration system for this camera that will measure the throughput of the complete system versus. wavelength. The system will be installed permanently at the telescope. The goal is to monitor the throughput of the telescope at regular intervals (~every 1 month) during the 5-year survey to monitor the instrumental performance. The data from our calibration will also provide accurate knowledge of the filter transmission functions that can be used to calculate more accurately photometric redshifts, supernovae k-correction transformations and other valuable precision photometric results.

A spectrophotometric calibration system was successfully tested on the 4 meter CTIO Blanco[1] and more recently at the PanSTARRS Telescope[2] using a tunable laser as a light source. We plan to build a similar system using a monochromator based light source, which requires less maintenance and other personnel attention than a tunable laser and is better suited for routine use over a long period of time. Our system also has the advantage of being able to extend its wavelength coverage into the infra-red (up to 2400 nm) and deep ultraviolet (~310 nm) with relatively minor modifications.

We have successfully deployed a prototype of our system at the Swope 1-meter telescope located at Las Campanas Observatory in Chile. We measured the throughput of the u, B, V, g, r, i, filters used during the Carnegie Supernova Project with an accuracy of 1%. We present here the results of this calibration that was performed in January 2010. Continuing improvement is being made on the calibration system to meet the more stringent requirements of a permanent installation on the Blanco 4m telescope.

The experimental setup is described in detail in section 2. We present the operating procedure that was followed during the data acquisition in section 3. Section 4 presents the results of the calibration and we conclude in section 5.

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2. EXPERIMENTAL SETUP

2.1 General description

A schematic of the experimental setup is shown in figure 1. The experimental setup consists of a broadband light source from which we select a narrow bandwidth (2-5 nm FWHM) using a monochromator. The monochromator output is coupled into a fiber bundle and brought to the top of the telescope behind the secondary and then projected onto the flat field screen using beam projection optics that ensure uniform illumination of the screen. 4 NIST traceable calibrated photodiodes, also placed on the back of the secondary, measure the power on the screen. A sample of the illumination beam is fed to a spectrometer and monitors the wavelength with an accuracy of ~0.1nm.

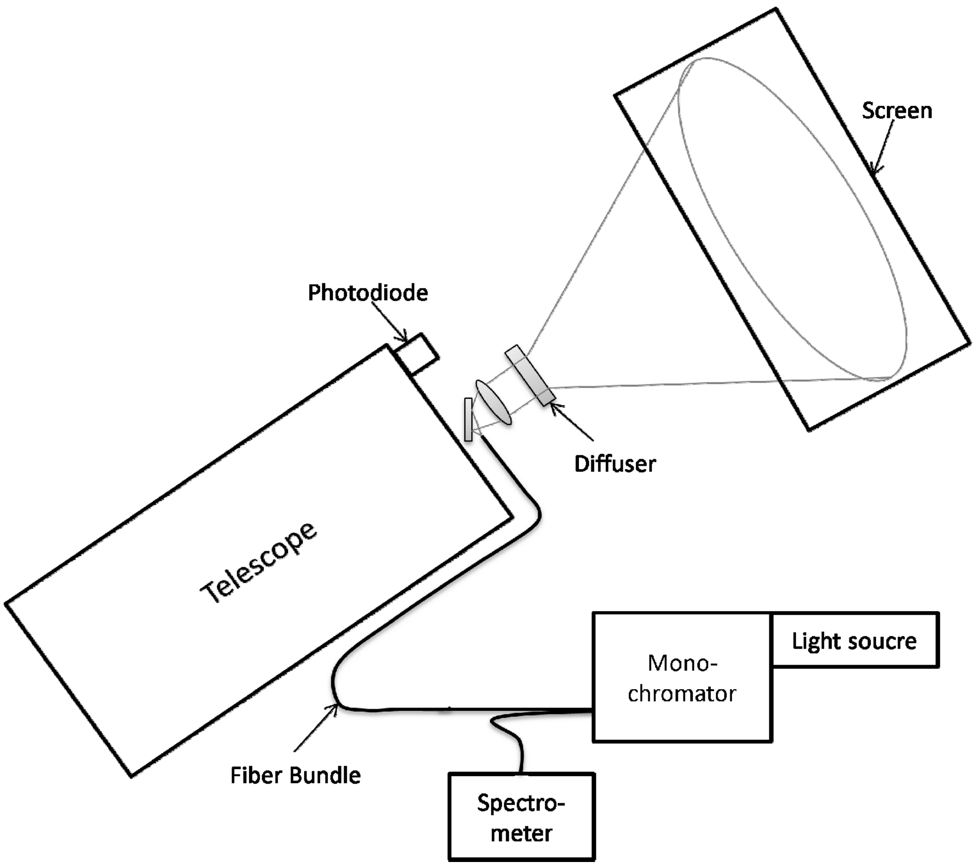

Figure 1. Experimental setup

2.1.1 Light source

We use two light sources to cover a broad wavelength range. A 75W compact xenon light source covers the region from 300 to 800nm; a 100W quartz Tungsten Halogen (QTH) is used to cover the infrared from 800nm to 2400nm. We choose not to use the xenon light above 800nm because of the presence of strong emission lines. Efficiently coupling the light from extended sources into a 0.5 mm wide monochromator input slit is challenging. The surface brightness of the source is the main factor limiting the coupling efficiency. The xenon light is well suited to coupling to a monochromator slit because of the intrinsic surface brightness of the arc. The coils in incandescent lamps like the QTH have lower surface brightness and thus lower coupling efficiency. Using a higher power lamp to increase the throughput of the system is not a good solution because higher power lamps tend to have proportionally bigger coils and lower surface brightness. The solutions are to use sources with the highest surface brightness available and to optimize the collimating optics of the lamps. Our xenon light source is equipped with an ellipsoidal reflector that envelops the lamp and collects 70% of the light output as opposed to 20% for a regular reflector.

2.1.2 Monochromator

We use a standard *f*/4 Czerzy-Turner monochromator with a dispersion of 4nm/mm with a 1200g/mm grating. We scan the wavelength remotely using a Labview software interface. The bandwidth of the light is adjusted with the input slit. The output slit width is fixed to 600 microns, the width of our linear fiber bundle. We use 3 gratings blazed at 400nm, 750nm and 1250nm to maximize throughput over the whole wavelength range. The 1250nm blaze grating has a 600g/mm ruling instead of 1200g/mm for the two others. The resulting bandwidth FWHM is 2.6nm for the visible gratings and 5nm for the IR grating. We use order sorting filters with cut-on wavelength at 295nm, 400nm, 595nm, 695nm and 1000nm depending on the wavelength band we are probing.

2.1.3 Fiber bundle

We use a custom 10m long fiber bundle assembled by Fibertech Optica that is made with special broad-spectrum fiber by Polymicro (FBP600660710). This fiber has excellent transmission both in the UV and the IR. This contrasts with most fibers where good transmission is only available in the infrared (low OH^- content) or in the UV (high OH^- content) but never at both end of the spectrum simultaneously. (see figure 2). The bundle consists of 10 fibers with 600 micron cores arranged in a straight line at the input end (monochromator) and in a compact circular pattern at the output end (top of the telescope). One of the fibers from the linear end is diverted from the main bundle and is fed into a spectrometer instead of going to the top of the telescope.

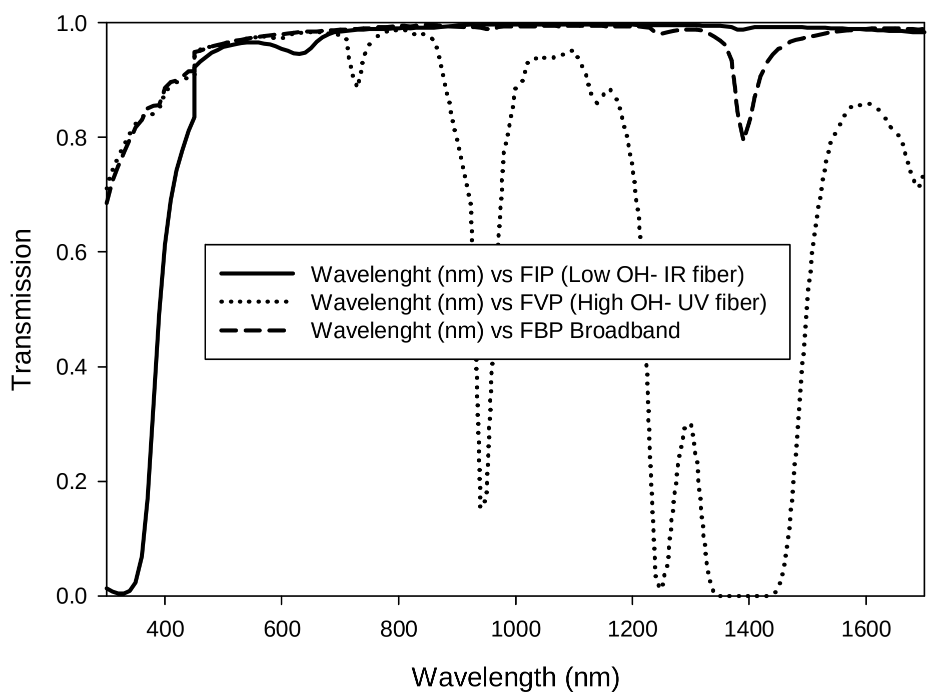

Figure 2. Internal transmission over 10 meter for different fiber types.

2.1.4 Projection system

The flat field screen doesn't need to be perfectly uniformly illuminated to produce a reasonably uniform illumination of the focal plane but one should avoid gradients on a large scale to keep the focal plane as flat as possible[3]. To ensure a uniform illumination of the focal plane area, we used an Engineered Diffuser from RPC Photonics to project the light from the fibers on the screen. These diffusers can be designed in such a way to distribute incident collimated light in almost any pattern. In our case we used a 30° angle cone diffuser that projects the light in a top hat shape with a diverging angle of 30 degrees. The uniformity of the illumination on the screen is measured to be around +/-10% within the 30° angle. Furthermore, more than 80% of the light exiting the fiber bundle ends up within the 30° cone of light. This method is far superior to the use of a regular diffuser where most of the light would be scattered away from the screen if we used a diffuser aggressive enough to achieve a +/-10% uniformity in a 30° cone. See figure 3.

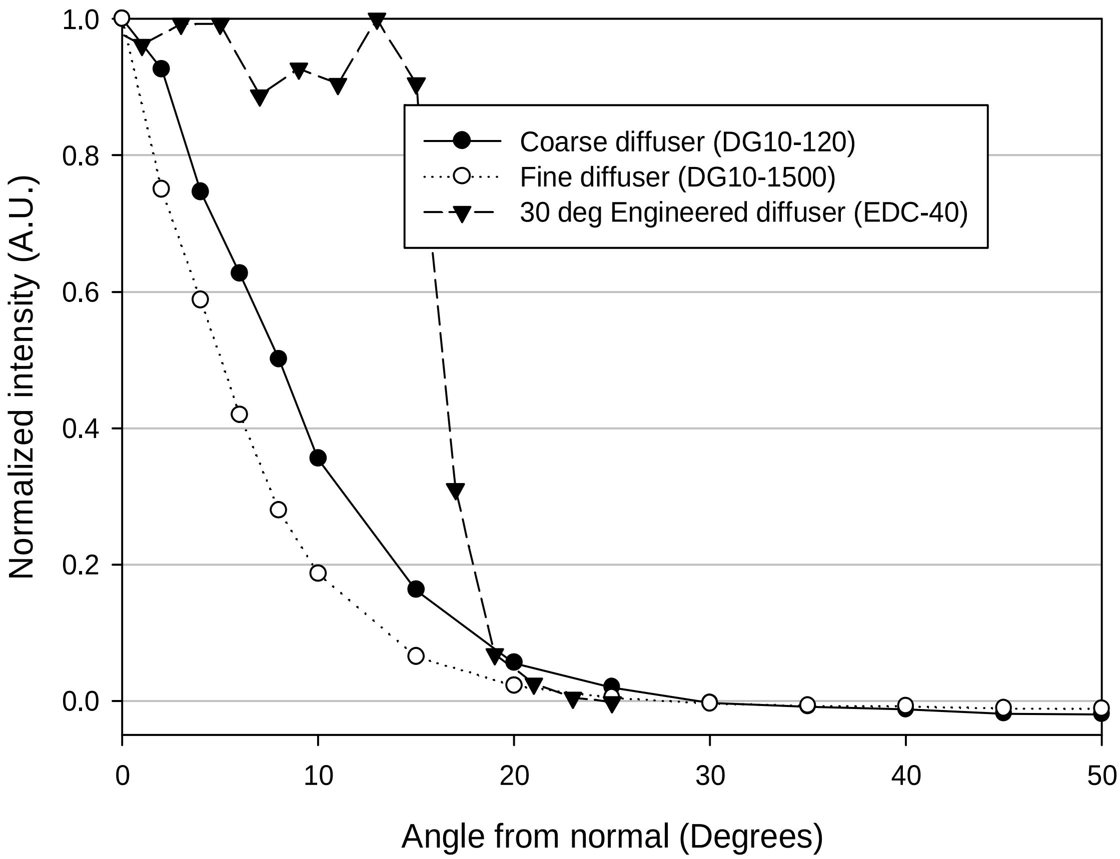

Figure 3. This figure shows the measured far field radial profile of a collimated HeNe laser 1 meter after transmission through 3 different diffusers. The two curves with the filled and empty circles represent the transmission through regular ground glass diffusers from Thorlabs. The triangles represent the transmission through the engineered diffuser from RPC photonics.

2.1.5 The flatfield screen

An ideal flatfield screen would have perfect reflectivity at all wavelengths of interest and would reflect light only within the acceptance angle of the telescope optics. Since the latter condition is almost impossible to satisfy, the next best thing to ensure uniform illumination of the focal plane is to use a screen with a Lambertian reflectivity profile. A Lambertian surface reflects light according to the following equation,

$$I_r = I_0 \cos\theta$$

Where I_r is the intensity of the reflected light, I_0 is the incident intensity and θ is the angle of the reflected light with the surface normal. In the case of a flat field illumination for a telescope, the angle θ corresponds to the field of view of the telescope and is usually very small. A Lambertuian surface thus ensures that all points on the screen illuminate the focal plane with the same angular profile regardless of where the illumination source is placed. If the telescope is well baffled, Lambertian reflectivity should be the equivalent of having limited angle reflectivity from the screen.

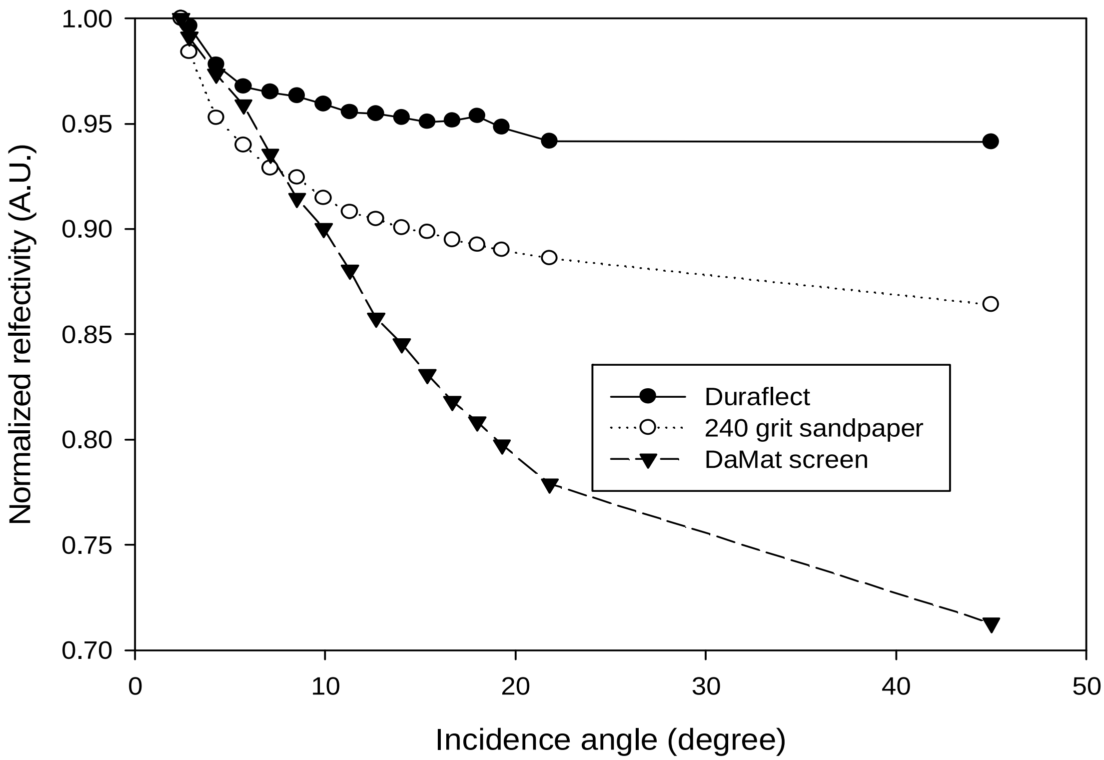

Figure 4. Normalized reflectivity at normal exit angle vs incident angle. Details of the various results are given in the text.

The screen we use is made of a lightweight aluminum honeycomb panel coated with a highly reflective and almost perfectly Lambertian coating called Duraflect from Labsphere. It is a coating that was developed and is used inside integrating spheres. We measured the reflectivity profile of different screen material candidates before settling on this one. Normally, to characterize the angular reflectivity of a surface, one would measure the bidirectional reflectance distribution function (BRDF). This is a four dimensional function that relates how incident light at any incident angle will be reflected of a diffuse surface[4]. Since telescopes have a narrow field of view of only a few degrees, we can simplify this function by taking into account only on the light that is reflected at 90° from the surface. Figure 4 shows the normal reflectance component for light with an incident angle from 2 to 45 degrees. We show results from 3 potential screen materials: the first is the Duraflect coating made by Labsphere,. The second is sandpaper (240 grit) coated with white paint and the third is a commercial video projection screen material from DaLite. The Duraflect reflectivity is flat to within 5% for angles at least up to 45°. By comparison, the sandpaper is flat only to 14% and the DaMat has a specular component that causes the normal reflectance to drop significantly at higher angles while.

The spectral reflectivity of the Duraflect coating is excellent with reflectivity over 95% from 350 to 1200nm and over 85% from 300 to 2200nm. This is shown in Figure 5.

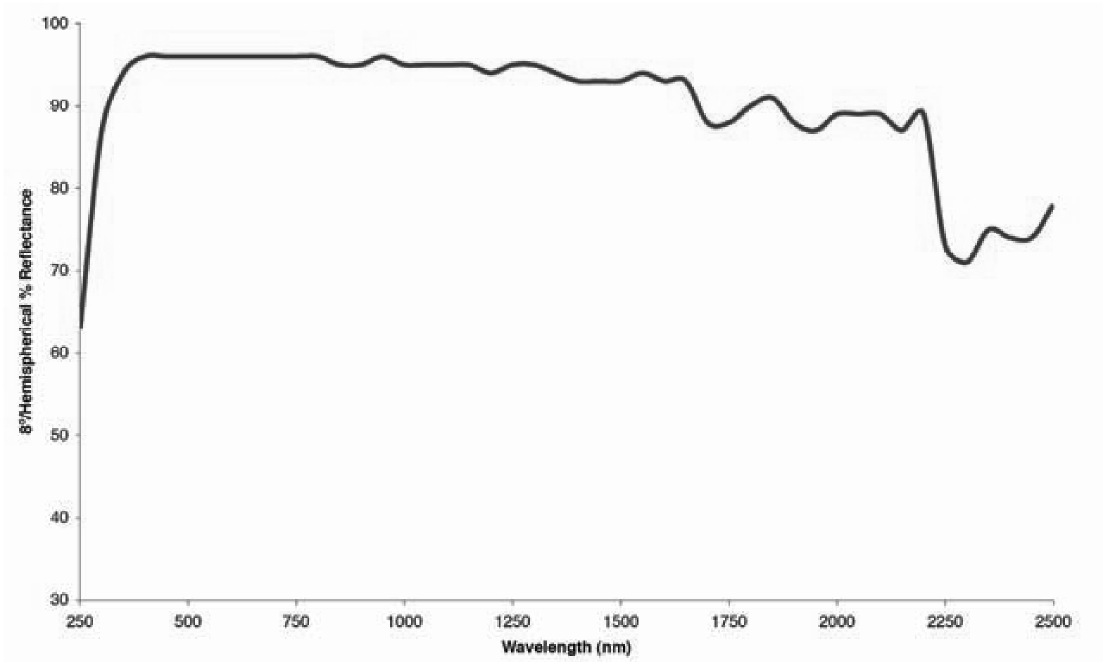

Figure 5. Duraflect reflectivity vs wavelength

2.1.6 Spectrometer

One of the fibers in the bundle is bifurcated toward a spectrometer to measure in real time the spectral content of the illumination source. The spectrometer measures both the central wavelength and the FWHM of the source. A spectrum is saved for every exposure and subsequently reduced to get the FWHM and central wavelength to 0.1nm. The spectrometer is calibrated every night with a Mercury calibration lamp. For our initial implementation of the system at the LCO Swope telescope we used a MS125 spectrograph from Newport.

2.1.7 Reference photodiodes

Reference photodiodes measure the amount of light reflected off the screen. They are positioned behind the secondary, facing the screen. They have a baffle that limits their field of view to the screen only so they don't receive any light reflected from the dome. We used 10mm Ø silicon photodiodes to measure the light from 300nm to 1150nm and 6mm Ø Germanium photodiodes were used for the infared (900nm to 1650nm). We measured signals on the order of 1 nW on the photodiode. These signals were amplified by a low noise trans-impedance amplifier with a selectable gain of 10^9 or 10^{10}. The amplifier had a cut-off frequency around 20 Hz to reduce noise levels. The amplified signal was read by an analog to digital converter acquiring signal at 10kHz. The signal was averaged down to 5 Hz for analysis. The photodiodes were calibrated in our labs using reference photodiodes from Gentec-EO that are NIST traceable.

We are interested in measuring the relative throughput of the instrument for different wavelength. The reference photodiode provide us with a relative measure of the light incident in the telescope providing that the following assumptions are fulfilled: 1-The field of view of the telescope doesn't change with wavelength, 2-the diffusion pattern of the screen doesn't change with wavelength, and 3-the sensitivity of the photodiodes has known corrections for wavelength dependence.

3. MEASUREMENT PROCEDURE

3.1 Calibration procedure

Here is the procedure followed during the calibration:

1. Take 10 darks with CCD, with light source shutter closed.

2. Start the DAQ acquisition

3. DAQ is acquiring Photodiode dark (60 s)

4. Turn light source shutter on

5. Start exposition on CCD (60 s)

6. DAQ is acquiring photodiode signal during exposure

7. When CCD exposure is done, turn light source off.

8. Step light source to next wavelength usually 2nm higher (with light source still off)

9. DAQ is acquiring Photodiode dark during CCD readout time (60 s)

10. Go to step 4 until scan is complete

This procedure generates a series of signal separated by darks. To obtain the net signal at a given wavelength, we average the signal over the duration of the exposure and then subtract the average of the two darks that were taken before and after this wavelength. This allows us to correct for any long-term drift in the photodiode's signal due to the amplifiers. The signal from the 10^9 gain Si photodiodes did not drift or change significantly with time. The change from one dark to the next was typically 10^{-5} V with the total drift during a 1-hour exposure being around 1 mV. The photodiode signal saturates at 2.5V.

The photodiode signal (V) is divided by the absolute photodiode sensitivity (V/W), which gives the number of photons incident on each photodiode, for each wavelength step. We measure for each corresponding CCD images the mean number of counts in a section of the chip that appeared to be void of defects or dust rings. The CCD mean count is divided by the number of photons seen by the photodiode to get the throughput of the telescope.

3.2 Experimental conditions

The data were taken from Jan 14 to Jan 26 2010 at the Swope telescope at LCO. The data were taken at night to ensure that the dome illumination stayed constant during the exposures. We made sure to mask all sources of light in the dome. The background light level read by the photodiode was below the offset level of our amplifiers ~10mV. We measured the throughput of the u, B, V, g, r, i, filters along with the throughput of the telescope and CCD with no filter present. We scanned the filters with narrow bandwidth light (2.6nm FWHM) with steps of 2nm between each measure. The telescope with no filter was scanned with a 5nm step from 300nm to 900nm. Each filter was measured twice on different non-sequential nights to evaluate the repeatability of the measure.

An integration time of 60s was chosen for the majority of the filters. This produced from 1000 to 5000 counts per pixel on the CCD at maximum filter transmission, depending on the wavelength. Since the output of our light source and the CCD quantum efficiency are lower in the UV, a 120s integration time was used for the u filter yielding a count of about 500.

4. RESULTS

4.1 Telescope throughput versus wavelength

The relative throughput of the telescope, including losses by the primary and secondary mirrors, corrector plate, filter, dewar window and CCD quantum efficiency, is shown in figure 6. The data has been normalized so the maximum transmission of the system without filter is 1.00 when there is no filter in line. For some of the filters, the curves are a composite of two or more scans. This allows us to remove any obvious outlier points caused by stray light and to piece together a single curve spanning several order sorting filter regions (like the no filter curve).

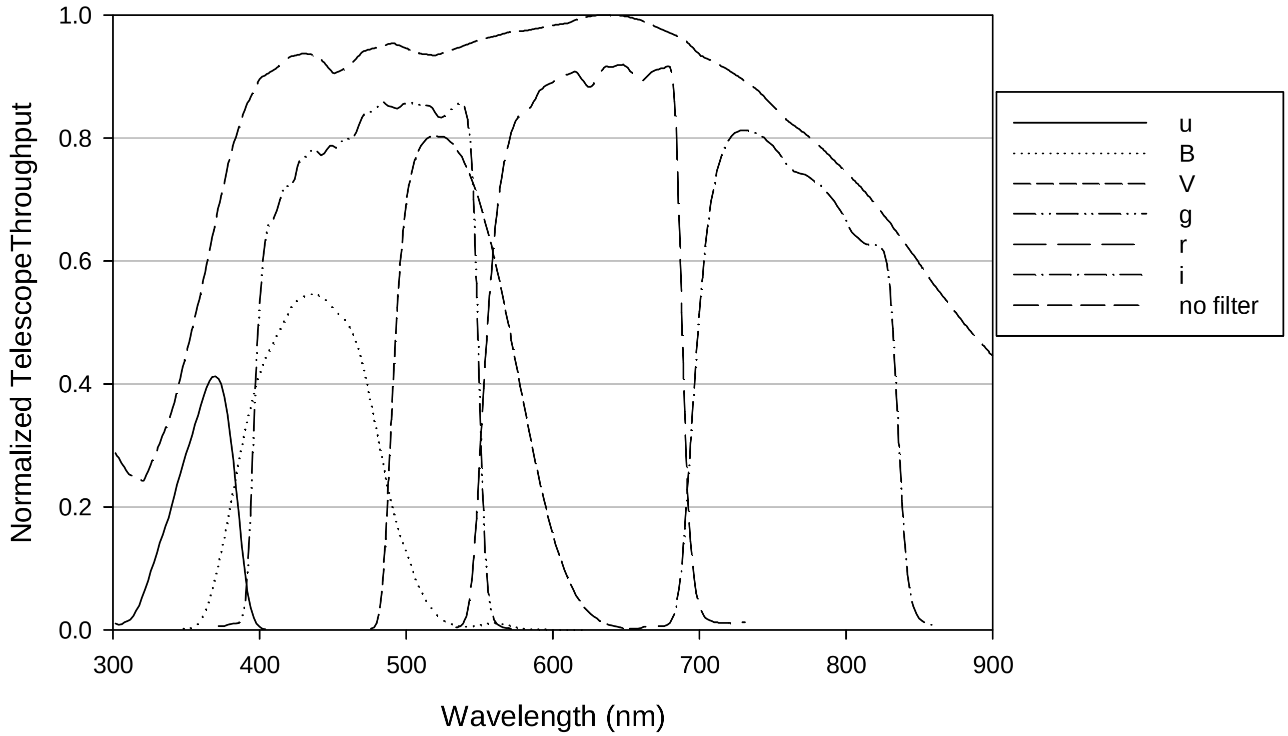

Figure 6. Swope Telescope Throughput

It is important to note that the relative amplitude of the different filters may be off by a few percent. We changed our setup many times during the run so the “CCD counts/Photons at photodiode” ratio may have changed from one night to the next because the pointing of the photodiodes changed slightly. The shape of the transmission curve for each filter will not be affected, only the relative amplitude of one filter to the next. We estimate that the relative uncertainties in the absolute throughput between the filters could be as high as 5%.

4.2 Repeatability

Figure 7 shows the results from two scans made 5 days apart for the g filter. The filter was scanned with 2nm steps and a 2.6nm FWHM wide spectral content.

In this figure, we first compare the data obtained simultaneously by 2 photodiodes pointed at the screen (relative to the CCD average pixel count) to evaluate how the photodiode placement affects the results. Each curve was normalized first because the absolute value changes with the pointing of the photodiode. The difference between the 2 photodiodes during the same scan is on the order of 0.3%. This implies that error in pointing and relative calibration of the photodiode does not affect the measurement significantly.

We then compare the measurement of the 2 different scans with the same photodiode. Again, the data from the 2 different scans are normalized because the photodiode pointing changed between the 2 scans. The data is repeatable over most of the filter bandpass to within 1%. The main source of error is caused by wavelength calibration uncertainties that translate into greater errors at the sharp edge of filters. At the filter edge, when the transmission function gets steeper, a small error on the wavelength calibration introduces a big difference in the relative transmission. That is what explains the increase of the error at the red edge of the filter. Our wavelength calibration is normally accurate to 0.1nm. Since the slope of the filter at the red edge is about 5% change in transmission / nm, a 0.1nm error in wavelength will cause a 0.5% error in transmission measurement. Having an accurate wavelength calibration is crucial to measure the filter edges correctly. We plan to improve the resolution and wavelength precision of the monitor spectrometer for the Blanco system.

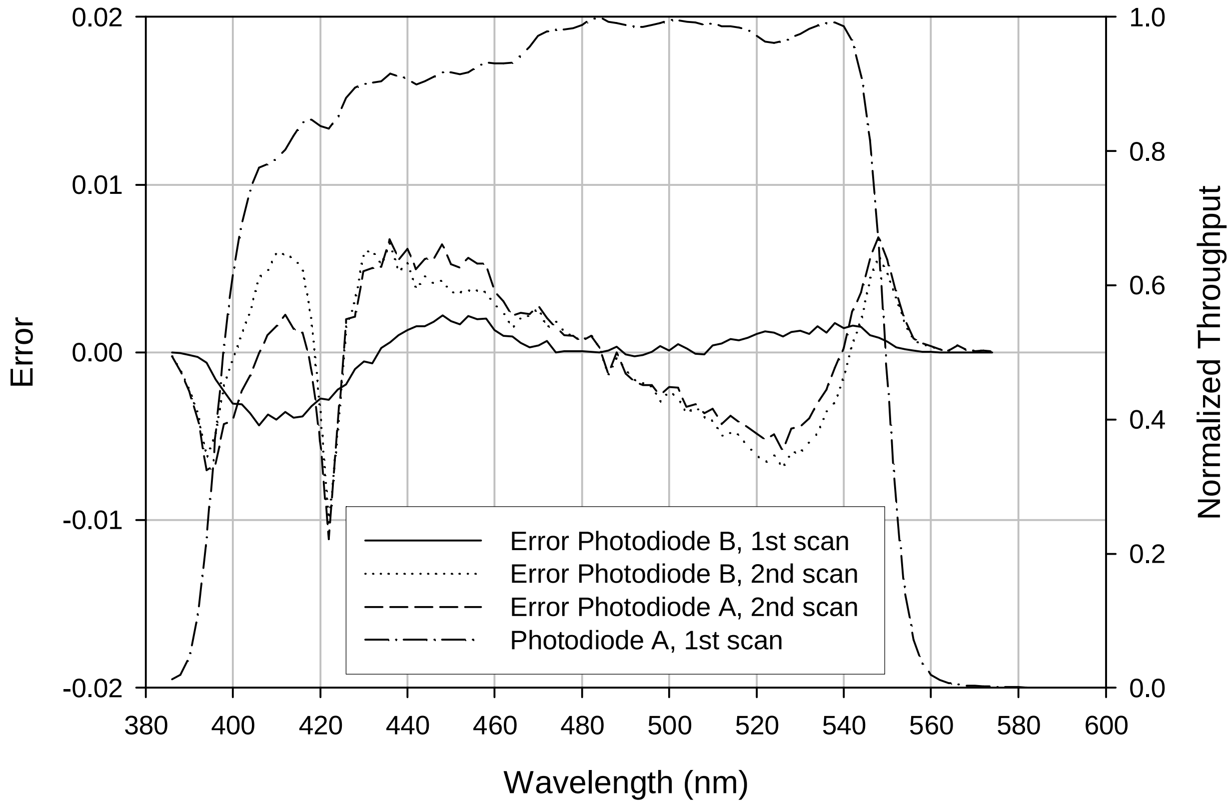

Figure 7. Repeatability of the g filter throughput for 2 separate scans. Error compared to Photodiode A and 1st scan

5. UPGRADES FOR CTIO 4 METER

We plan to upgrade the system for permanent installation on the CTIO Blanco 4 meter telescope. We will install a new screen in the dome in the summer of 2010. Towards the end of 2010, we will install a broadband LED based flatfield illumination system for nightly dome flats. The projection system, fiber and illumination system should be installed in the summer of 2011. This system will be generally available to the CTIO 4 meter user community. There are 2 main items that we need to address to successfully adapt the current setup to the CTIO 4meter telescope: increasing the light throughput of the system and fully automating the system

5.1 Light throughput improvements

We first will concentrate our efforts in increasing the light throughput of the system. Having more light will allow us to reduce the integration time, reduce errors caused by stray light in the dome and compensate for decreased transmission in the 75 meter long fiber required for the bigger telescope. We plan on upgrading to a monochromator with twice the dispersion. This will allow us to use slits twice as big while keeping the same bandwidth. This should make a significant difference since the throughput of a monochromator increases with the square of the slit size. We will also change to a bigger fiber bundle with 200 fibers that will couple to a wider slit and allow us to benefit from the increased throughput of the higher dispersion monochromator. A fourth grating with a blaze angle at 300nm will be used to maximize the throughput in the UV.

5.2 System automation

Our current software will be upgraded to integrate with the CTIO 4 meter control software. This will allow the user to change the spectrophotometric calibration parameters from the control room. These parameters include light source (xenon or quartz), illumination bandwidth, order sorting filter, gratings, wavelength step size and integration time. We also plan on automating the calibration sequence so all these parameters are adjusted automatically during the scan. The goal is to have the user initiate the sequence and have the software take over and scan every filter sequentially during the night without additional user input required.

6. CONCLUSION

We have measured the relative throughput of a complete telescope with an accuracy of 1% using calibrated photodiodes as a reference. The main sources of errors are the wavelength calibration of the light source and the calibration of the photodiodes. We have shown that with a uniform illumination of the screen, the measured relative throughput is independent of the pointing accuracy of the photodiode and a single photodiode pointed at the screen gives a reliable value of the light incident on the focal plane. We will make improvements to the system to implement it on the CTIO Blanco 4 meter telescope as part of a permanent calibration system. These improvements will include increasing the light throughput of the system by using a monochromator with a higher dispersion. We will fully integrate the controls of the calibration system (light source, data acquisition and wavelength monitoring) to the DECam control software.

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