Spectrophotometric calibration system for DECam

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ABSTRACT

We describe a spectrophotometric calibration system that is being implemented as part of the DES DECam project at the Blanco 4 meter at CTIO. Our calibration system uses a 1nm wide tunable source to measure the instrumental response function of the telescope optics and detector from 300nm up to 1100nm. This calibration will be performed regularly to monitor any change in the transmission function of the telescope during the 5 year survey. The system consists of a monochromator based tunable light source that provides illumination on a dome flat that is monitored by calibrated photodiodes that allow us to measure the telescope throughput as a function of wavelength. Our system has a peak output power of 2 mW, equivalent to a flux of approximately 800 photons/s/pixel on DECam.

Keywords: instrumentation, detector, DECam, calibration, photometry

1. INTRODUCTION

Current and future generations of large scale cosmological surveys will rely heavily on precise calibration of astronomical datasets to produce precision results. Surveys such as Pan-STARRS [1], LSST [2], the Dark Energy Survey[3] (DES), and others like them, will produce data that are capable of making high precision cosmological measurements of the Universe. These measurements are made possible in part by photometric datasets that are precise to better than 0.01 magnitude and are only achievable when properly calibrated. Carefully constructed calibration systems are being planned, constructed, and tested for these surveys[4,5,6]. In this paper we describe recent progress on the calibration system that we have designed and constructed to calibrate the Dark Energy Survey data products.

The Dark Energy Survey is a deep, wide, multi-band imaging survey, spanning 525 nights over five years beginning in late 2012. The Dark Energy Survey is made possible by a new instrument for the Cerro Tololo Inter-American Observatory (CTIO) 4 meter Blanco telescope, known as DECam. DECam is a 2.2 degree field-of-view optical camera with 519 megapixels that operates in the grizY bands (400nm< λ < 1050nm). The DES calibration system, referred to as DECal, comprises a spectrophotometric calibration system in addition to a more typical daily flat field system. The daily flat field system uses LEDs to illuminate a new flat field screen that has been installed in the CTIO 4m telescope dome and is similar to that described by Marshall & DePoy[7]. The LEDs will be mounted at the top of the telescope and will provide a uniform illumination of the flat field screen across the entire field of view. This simple system is not described in this paper.

The DECal spectrophotometric calibration system has been fully prototyped[6,8] and is ready to be installed on the telescope. The spectrophotometric calibration system illuminates the flat field screen with monochromatic (1 nm wide bandwidth) light. The system can produce light from 300 nm < λ < 1100 nm, and when the screen is imaged by DECam the system can produce full throughput measurements of the telescope + camera system that are accurate to 1%. These measurements can be used to correct the photometry produced by the DES survey to produce sub-1% accuracy in the photometric data, and is particularly useful for supernova measurements, accurately measuring photometric redshifts, and monitoring the instrument health (e.g., changes in filter transmission) of the telescope + camera system.

In this paper we describe the completed system. The experimental setup is described in detail in section 2. We present the software and automation of the system in section 3. Section 4 discusses the integration of the calibration data with the DES database 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 (e.g., 1 or 2 nm FWHM) using a monochromator. The monochromator output is coupled to a fiber bundle made of 87 fibers aligned in 3 rows. The fiber bundle brings the light to the top of the telescope where it splits into 4 equal branches around the top ring of the telescope. Light is projected onto the flat field screen from 4 different points using beam projection optics that ensure uniform illumination of the screen. 4 NIST-traceable calibrated photodiodes, also placed on the top ring of the telescope, measure the power on the screen. A sample of the illumination beam is fed to an echelle spectrometer that monitors in real time the illumination wavelength with an accuracy of ~0.1nm.

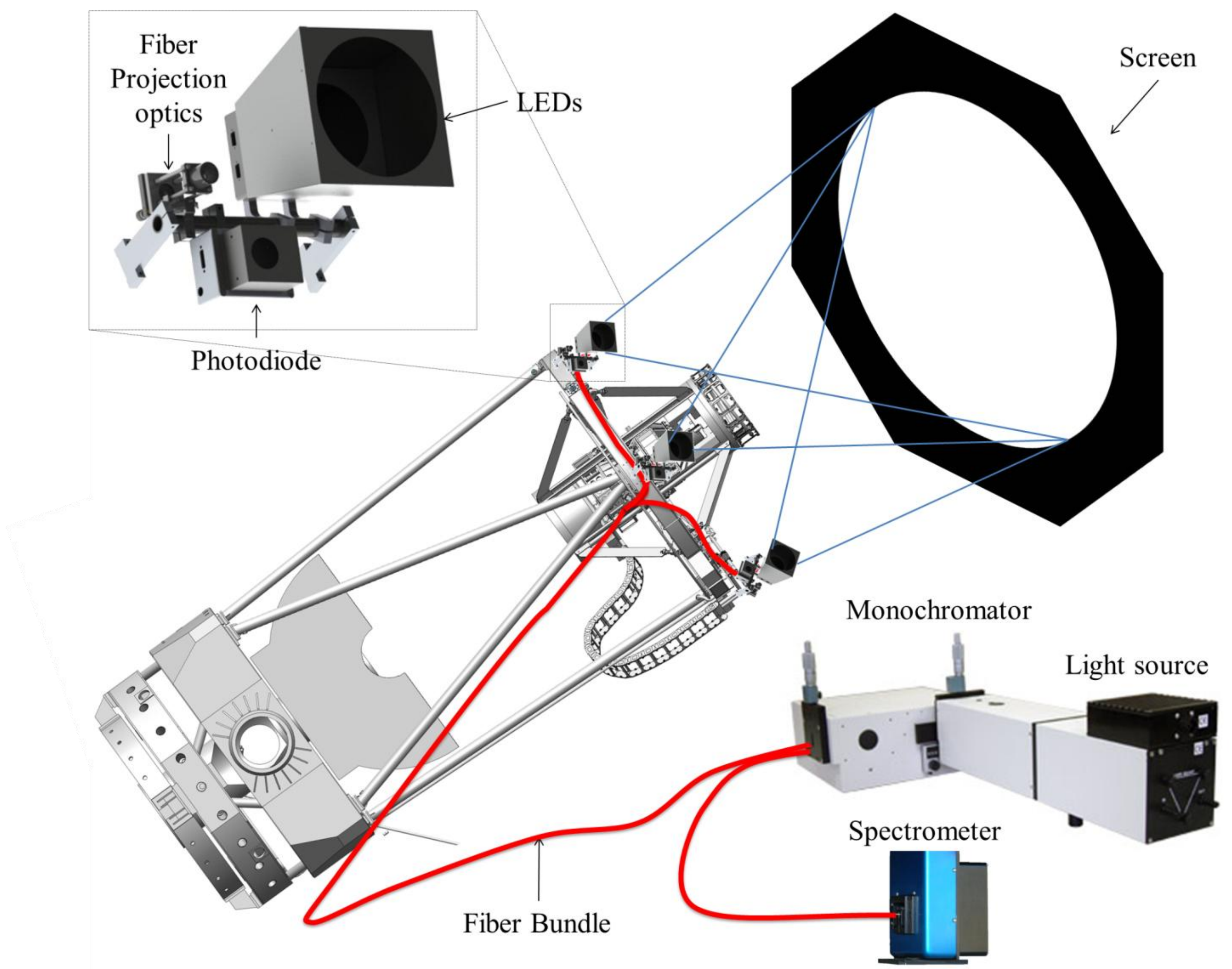

Figure 1. Experimental setup

2.2 Light source

DECal operates continuously over a very wide wavelength range (300 nm < λ < 1100 nm). We had difficulty identifying a single light source to provide adequate signal over all required wavelengths. As a result, we use two light sources to cover the entire wavelength range. A 150W compact xenon arc lamp light source (Optical Building Blocs Corporation, PowerArc series) covers the region from 300 to 800nm. A 250W Quartz Tungsten Halogen lamp (Horiba, LSH-T250) is used to cover the infrared from 800nm to 1100nm. The xenon light source cannot easily be used redward of 800nm because of the presence of strong emission lines.

Since the speed at which we can make the measurements is limited by the amount of light generated by our light source, a lot of effort has been invested to maximize the output power of our system. 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 source is well suited to coupling to a monochromator slit because of the intrinsic high surface brightness of the arc. The coils in incandescent lamps like the Quartz Tungsten Halogen (QTH) lamp 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 solution is 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. Such a reflector was not available for the quartz lamp, however the output power of the quartz lamp is sufficient for our purposes.

2.3 Monochromator

We use a fully automated *f*/4.1 Czerny-Turner monochromator (*Horiba, iHR-320*) having a high reciprocal dispersion of 2.3nm/mm when used with a 1200g/mm grating. The high dispersion is crucial in achieving a good throughput: for a constant output bandwidth, the throughput of a monochromator goes with the square of the dispersion. We adjust the bandwidth of the light by varying the input slit width. The output slit width is fixed to 900 microns, the width of the linear fiber bundle. The monochromator has two input ports that host the two lamps; a flip mirror allows us to change from one lamp to the other without interruption.

Due to the broad wavelength sensitivity of DECam, we use order sorting filters to prevent second order light from reaching the fiber. The filters are hosted in an automated filter wheel and have cut-on wavelength of 295nm, 320nm, 550nm, 830nm. In the UV, where contamination from second order is unlikely, we use a short pass filter instead of a long pass filter to prevent any stray light redward of 400nm from reaching the fiber. This is necessary because the lamps are much brighter in the visible than in the UV and because the fiber bundle transmission in the UV is low.

We use 3 gratings blazed at 330nm, 630nm and 900nm to maximize throughput over the whole wavelength range. The 330nm blaze grating has a 2400g/mm ruling instead of 1200g/mm for the two others. This increases the dispersion in the UV region which allows us to increase the input slit size while keeping the same bandwidth. The higher throughput in the UV will help compensate for the absorption by the fiber in the UV region.

2.4 Fiber bundle

We use a custom 75m long fiber bundle assembled by Fibertech Optica that is made with special broad-spectrum fiber by Polymicro (FBP300660710). 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 87 fibers with 300 micron cores. At the input end, the fibers are arranged in 3 parallel lines of 29 fibers. (See Figure 3) The bundle brings the light from the calibration room (located under the telescope main floor) up to the telescope top ring. At a length of 65 meters, the fiber bundle splits into 4 branches, each 10 meters long and containing 21 fibers. These 21 fibers are placed in a compact circular arrangement and coupled to the projection system. Each of the 4 branches sample the monochromator slit evenly to ensure that the four projection units each have the same intensity and spectral content.

A 5th branch bifurcates from the main bundle 1 meter from the input slit. It contains the 3 central fibers and is fed to an echelle spectrometer. This allows us to measure the spectral content of the light source in real time as the data is taken. To ensure that any absorption present in the fiber does not change the measured wavelength profile, this 5th branch is also 75 meters long, even though the spectrometer is only 1 meter from the monochromator.

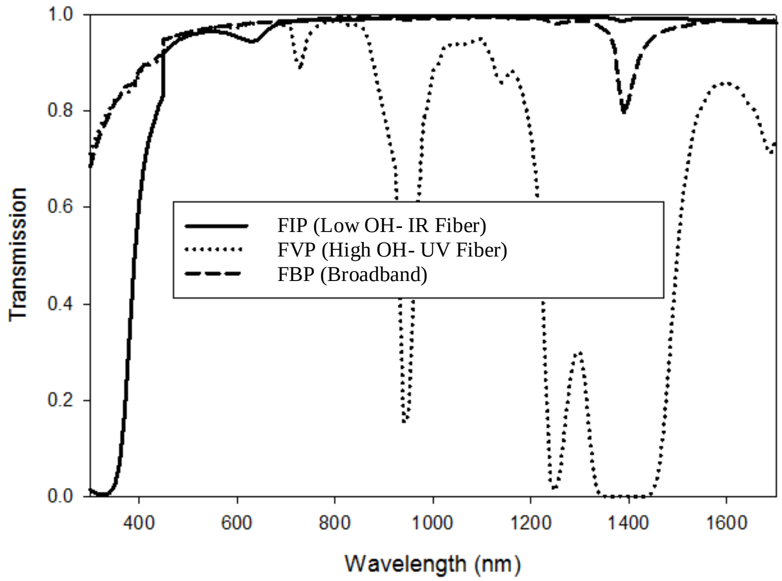

Figure 2. Internal transmission for different fiber types. All of the fibers have 10 m length.

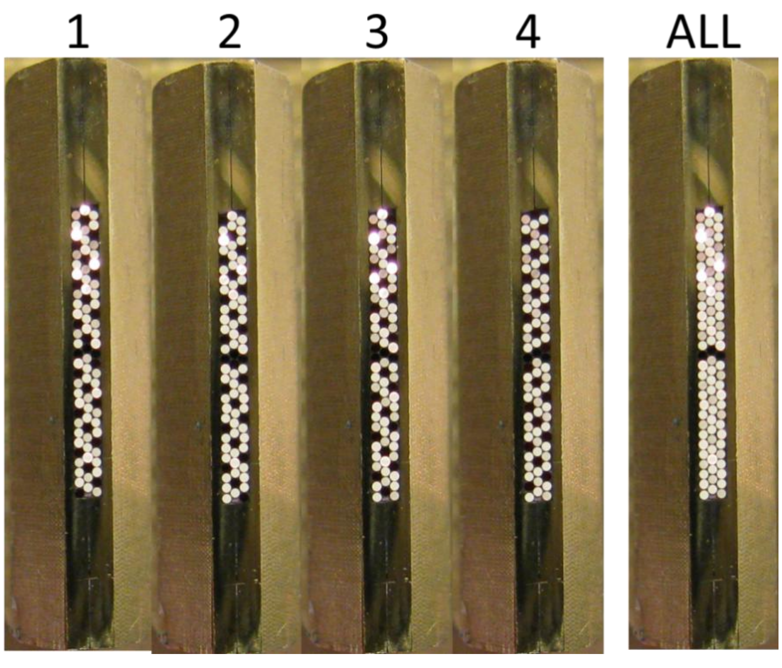

Figure 3. Fiber bundle input slit. This figure shows the mapping of the 5 output branches on the input slit. The 4 images on the left were taken while shining light in 3 out of the 4 main output fiber bundles. The 5th picture labeled "ALL" was taken with all the fiber bundles illuminated except for the wavelength sampling bundle that feeds the spectrograph.

2.5 Projection system

The flat field screen does not 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[7]. To ensure a uniform illumination of the focal plane area, we use a 20° half-angle cone Engineered Diffuser from *RPC Photonics* to project the light from the four projection units onto the screen.

Ideally, one would illuminate the screen from a location centered on the telescope field of view; usually this location would be on the back of the camera or secondary located at the prime focus of the telescope. In our case, this was not possible because the back of the camera holds a secondary mirror that must be rotated in place of DECam when DECam is not in use. We decided to split the fiber bundle into 4 smaller bundles and illuminate the screen from 4 evenly spaced positions on the telescope ring. A Zemax non-sequential model of the illumination pattern from 4 fiber bundles using the 20° engineered diffusers was made to evaluate the illumination uniformity. The fibers are placed on the top ring of the telescope, 2.5 meters from the telescope axis; the distance from the flat field screen from the telescope ring is 7 meters. Figure 4 shows the results of the model. It confirms that the screen illumination should be uniform to 95% in the central 4 meters of the screen.

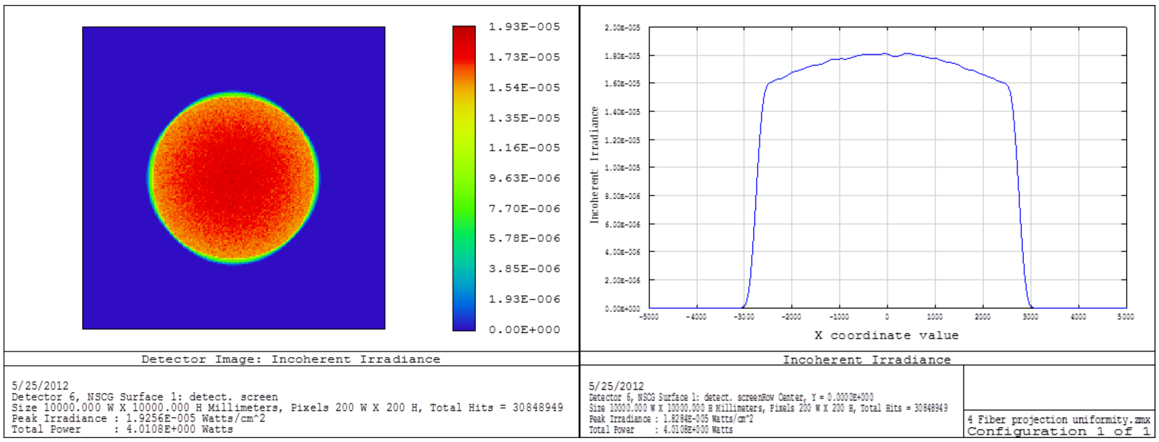

Figure 4. Left: illumination pattern from the 4 fibers projected on the flat field screen. Right: a horizontal cross-section of the light pattern.

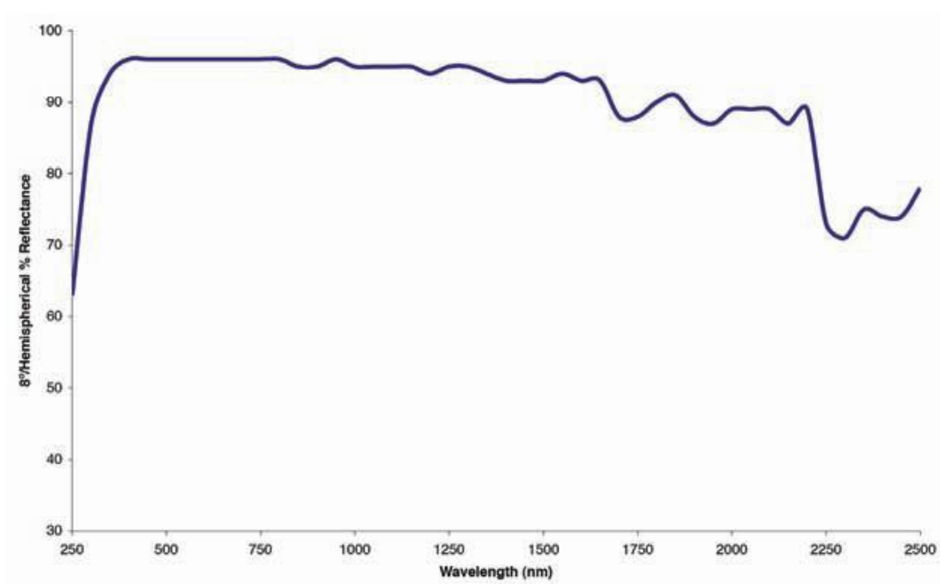

Figure 5. Duraflect reflectivity as a function of wavelength.

2.6 The flat field screen

A new flat field screen was installed in the CTIO Blanco telescope dome as part the DECam telescope upgrade. This was mainly done to ensure high reflectivity at all wavelengths including the UV as well as a nearly Lambertian reflectivity profile. The new screen 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 used for coating the internal surfaces of integrating spheres. In addition to exhibiting an almost perfectly Lambertian reflectivity profile, the *Duraflect* coating has a very high and uniform reflectivity over our wavelength range. It has over 95% reflectivity from 350 to 1200nm and over 85% from 300 to 2200nm. This is shown in Figure 5.

2.7 Spectrometer

To monitor in real time the spectral content of the illumination source, a branch bifurcates from the main fiber bundle and feeds an echelle spectrometer (*Optomechanics Research , SE-100*). The spectrometer measures both the central wavelength and the FWHM of the source. A spectrum is saved for every exposure and subsequently reduced to measure the FWHM and central wavelength of the illumination light to an accuracy of 0.1 nm. The spectrometer calibration is verified with a Mercury calibration lamp (*Ocean Optics, Cal-2000*). The echelle spectrometer calibration process is completely automated. The automation was made possible by the use of a "Y" fiber that combines the light from both the main source and the Mercury calibration lamp into the same fiber. This "Y" fiber was custom for us made by Ocean Optics. A regular fiber bundle that bifurcates into two branches would not have been suitable since the common end still has two fibers. Since the fiber position at the entrance of the echelle spectrograph defines the slit position, two different fibers in the same bundle will have slightly different calibrations. By using a "Y" fiber where the two branches are fused together in a single fiber, we are sure that the light from both branches enter the spectrometer at the same position.

2.8 Reference photodiodes

At the top of the telescope, four reference photodiodes measure the amount of light reflected off the flat field screen. They are mounted in the same locations as the fibers at four points on the top ring of the telescope, facing the screen. See insert in Figure 1 for details. They have a baffle that limits their field of view to the screen only so they do not receive any light reflected from the dome. We use 10mm diameter silicon photodiodes (*Hamamatsu, S2281*) to measure the light from 300nm to 1100nm. The photodiodes have a NIST-traceable calibration performed by Gentec-EO. We anticipate signals on the order of 1 nW on the photodiode. These signals will be amplified by a two-stage, low noise, trans-impedance amplifier with a variable gain from 10^8 to 10^{11}. The amplifier has a cut-off frequency around 20 Hz to reduce noise levels. The amplified signal is read by a 16-bit analog-to-digital converter (ADC, *National Instruments, ENET-9215*) acquiring signal at 100 kHz. The signal is averaged to 100Hz in the ADC and sent over Ethernet to the control computer where data are saved and analyzed.

The Hamamatsu S2281 photodiodes exhibit a slight change in sensitivity as a function of temperature at the red end of their sensitivity range. This effect is negligible below 1000nm but can reach a sensitivity change of up to 1% per °C at 1100nm. We monitor the photodiode temperatures in real time and correct for it in the data reduction process.

3. SOFTWARE AND AUTOMATION

One of the requirements for this project was for the instrument to be completely automated and easy to use by telescope personnel. DECalS (Dark Energy camera CALibration Software) is a LabVIEW software that we wrote to achieve this task. It has a user-friendly interface that controls the different components of the system with minimal intervention required by the telescope operator or observer.

3.1 Software description

When turned on, DECalS loads an .ini file that contains all of the parameters used during a spectrophotometric calibration scan. The user can modify some of the parameters if necessary, including which of the DECam camera filters (g, r, i, z, Y) will be scanned. Pressing the START button starts an automated scan that will measure the throughput of each of the filters at a rate of approximately one filter per hour. The DECalS user interface displays in real time the photon count at the photodiodes to allow the user to monitor progress of the scan sequence. Once the scan is completed, DECalS creates a calibration file containing all of the data and scan parameters and uploads the file to the main database for final data reduction and analysis.

DECalS communicates with SISPI, the DECam software interface, to synchronize the timing of the DECam images with the photodiode data acquisition. This synchronous measurement allows for compensation of any fluctuation in the lamp output power. Each DECam image is linked to the data from the photodiodes by a unique image number generated by DECam and stored in the DECalS data file and in each DECam image header.

3.2 Measurement procedure

Here is the procedure followed by DECalS during one wavelength step of the calibration sequence:

1. Begin with the DECal light source turned off.
2. Dark image acquisition:
    a. Take DECam image. This will be used to monitor and remove the background light level in the dome.
    b. Acquire the photodiode data for the duration of the DECam image exposure.
3. Turn on the DECal light source.
4. Light image acquisition:
    a. Take DECam image. This is the calibration image.
    b. Acquire the photodiode data for the duration of the DECam image exposure.
5. Turn off the DECal light source.
6. Step light source to next wavelength
7. Repeat until the end of the wavelength range of the scan is reached.

This procedure generates a series of alternating “light” and “dark” images from DECam and a series of “light” and “dark” photodiode data for each wavelength and filter. The final throughput of the telescope is obtained by following these steps.

1. Integrate (sum) the photodiode signal over the exposure time to get the total number of photons seen by the calibration photodiodes. The photodiode signal is corrected for wavelength, temperature and amplifier gain. The output is the net, background subtracted, number of photons for a given wavelength by subtracting the average number of photons of the two darks that were taken before and after this wavelength from the number of photons in the light image.
2. The same principle is applied to the DECam images: a net light image is obtained by subtracting the average of the two neighboring dark images from the light image.
3. The relative throughput at each wavelength is obtained by dividing the net light image by the net photon count on the photodiode. This gives us a relative throughput for each pixel at each wavelength for each filter.

4. INTEGRATION WITH THE DES DATABASE

The main goal of this instrument is to monitor the throughput of the telescope to help the Dark Energy Survey reach its goal of sub-1% photometry. Our contribution will be two-fold: a precise measurement of the transmission function of the telescope as a function of wavelength and a monitoring of the evolution of that transmission function over the duration of the survey.

The DECal instrument is designed to provide the DES with a precise and accurate measurement to better than ±1% of the relative telescope throughput from 300 nm to 1100 nm. That measurement monitors losses introduced by the primary mirrors, corrector, filter, Dewar window and the CCD quantum efficiency. Knowledge of the instrument response function is important for many aspects of the survey, including calculating accurate photometric redshifts of galaxies and applying supernova K-corrections.

The DECal system will measure the telescope throughput on a regular interval to make sure that it stays constant with time. Since the survey will span a period of 5 years, there is a possibility that the transmission characteristics of some of the components will change during that period of time. Any change in the telescope throughput will introduce artifacts in the data and reduce the usefulness of the survey. By monitoring the telescope on a regular basis, we will be able to take corrective action in the (unlikely) case of a major change in the transmission function of one component. Even if there are no major changes, we can expect small changes in the transmission function over a 5 year period due to mirror surface degradation or dust on the optical surfaces, for example. The survey data can be corrected for these changes using the DECal calibration results.

4.1 Spatial correction

The telescope calibration data generated by DECal will take the form of a data cube that characterizes the sensitivity vs. wavelength for each of DECam's 519 million pixels, for each filter, over a period of 5 years. Even if the data are available, correcting on a pixel-by-pixel basis will be very time consuming and is probably not the most efficient way to correct for changes in throughput. For example, we expect the response of the CCDsas a function of wavelength to be uniform within each CCD, so a single correction point per CCD may be sufficient. The exact frequency of spatial correction required to adequately calibrate DES survey data will be determined once the camera is characterized for the first time with DECal.

We expect the filter bandpasses to shift slightly with distance from the center of the image. This is due to the change in incidence angle of the beam away from the optical beam center. This problem is more pronounced in the case of DECam because of the very wide 2.2 degree field-of-view. We plan on characterizing the edges of the filter bandpass carefully with a narrower bandwidth and shorter steps. The extent to which this feature will affect DES syrvey data will be determined once DECam is calibrated on the telescope using DECal.

5. CONCLUSION

DECal is an instrument that will monitor the transmission function of the new DECam imager and Blanco telescope used for the Dark Energy Survey. It is currently being installed on the telescope and will be commissioned later this year as the DECam activities are ramping up. DECal will measure the relative throughput as a function of wavelength of the telescope+instrument optical path from the primary mirror reflectivity all the way to the quantum efficiency of every pixel over a five year period with repeatability better than ±1%.

Building on the experience gained from previous prototypes we have maximized the system throughput and detector sensitivity to increase the signal-to-noise ratio and thus reduce the time required to scan each filter. This, coupled with the full automation of the system, will allow the operator to take a full measurement of the telescope+instrument system throughput as a function of wavelength in one night with minimal interaction. The system's simple operation also allows the possibility of using parts of a night during which bad weather prevents observing to perform the telescope calibration instead of reserving a full engineering night for calibration.

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