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Further development and testing of TCal: a mobile spectrophotometric calibration unit for astronomical imaging systems

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ABSTRACT

We describe and present initial testing of TCal, a mobile spectrophotometric calibration system that will be used to characterize the throughput as a function of wavelength for imaging systems at observatories around the world. TCal measurements will enhance the science return from follow-up observations of imaging surveys such as LSST (Large Synoptic Survey Telescope) and DES (Dark Energy Survey) by placing all tested imaging systems on a common photometric baseline. TCal uses a ~ 1 nm bandpass tunable light source to measure the instrumental response function of imaging systems from 300 nm to 1100 nm, including the telescope, optics, filters, windows, and detector. The system is comprised of a monochromator-based light source illuminating a dome flat field screen monitored by a calibrated CCD, which allows determination of the telescope throughput as a function of wavelength. This calibration will be performed at 1-8m telescopes that expect to devote time towards survey follow-up. Performing the calibration on these telescopes will reduce systematic errors due to small differences in bandpass, making follow-up efforts more precise and accurate.

Keywords: TCal, Instrumentation, Spectrophotometric Calibration, Calibration, Detector, Photometry

1. INTRODUCTION

In Astronomy, photometric surveys are one of the fundamental tools used to investigate the Universe. Recently these surveys have become increasingly ambitious in their goals, and as a result increasingly reliant on precise calibrations of their data products. Projects such as the Sloan Digital Sky Survey,[1] 2MASS,[2] Pan-STARRS,[3] the Dark Energy Survey,[4] and The Palomar Transient Factory[5] have produced rich catalogs containing multi-color and/or multi-epoch data. These data can then be used to probe fundamental parameters of the Universe and investigate astrophysically interesting phenomena. The next generation of large astronomical projects includes the Rubin Observatory Legacy Survey of Space and Time[6] (LSST), which will deeply image more than two thirds of the sky synoptically monitoring billions of stars and galaxies. To fully exploit the LSST catalog, it will often be important to combine LSST observations with previous surveys or dedicated follow-up observations. This makes it crucial that existing imaging systems are properly calibrated to reduce systematic errors incurred when combining measurements from multiple facilities. This calibration will work to greatly increase the yield of future projects.

One specific example, using LSST imaging data to explore properties of supernovae to $z \sim 0.8$, is among many that demonstrate the importance of reducing errors when combining datasets. The luminosity distances of these supernovae act as a direct measure of the redshift-distance relation. This relation will be used to investigate the equation of state parameter w; determining whether it evolves with redshift and precisely constraining its value to $< 5\%$ uncertainty.[7] But, LSST does not plan frequent filter changes, meaning that to take full advantage of LSST, other observatories will have to devote significant resources to rapid follow-up to characterize the color and evolution of these transient events. LSST plans to have photometry that is stable and uniform over the sky to $< 1\%$ (< 0.01 mag). It is then obvious that follow-up efforts will also require extremely precise and accurate photometry (0.01 mag) when combined with LSST observations to enhance the scientific return of the survey.

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Typically, the spectrophotometric throughput of astronomical imaging systems is not well known. Filter transmission profiles, quantum efficiency versus wavelength for detectors, reflectivity of mirrors, and lens throughput are estimated from vendor-supplied information and multiplied together to form an estimate of the total system performance. This process is subject to many assumptions, critical measurement errors, and relatively large uncertainty. In order to robustly calibrate modern wide field imaging data, an *in situ* measurement of the response function of the complete imaging system must be made.

Our lab has previously deployed systems to make this measurement of the response function. We designed, built, and deployed DECal, a spectrophotometric calibration system for the u, g, r, i, z, Y filters used in the Dark Energy Camera (DECam) on the 4 m Blanco telescope at Cerro Tololo Inter-American Observatory.[8–10] This permanent system has allowed us to monitor the response function of DECam both as a function of position on the focal plane and as a function of time. This constant monitoring and calibration of DECam has helped the Dark Energy Survey achieve $< 1\%$ errors on its photometry.[11,12] Additionally, in the past we characterized the spectrophotometric properties of the imaging equipment used by the Carnegie Supernova Project. In particular we measured the throughput of the u, g, r, i, B, V, Y, J, H, and K_s filters used in the WIRC and RetroCam instruments at the Swope 1 m and du Pont 2.5 m telescopes at Las Campanas Observatory to an accuracy of $< 1\%$.[13]

DECal and the system used at Las Campanas are similar in design to TCal. They use a monochromator-based light source to project narrow band ($\sim$ 1 nm) light onto a flat field screen. This signal is then measured by a photodiode with known response function and at the same time the instrument to be calibrated acquires an image. The ratio of the signal seen by the photodiode and the signal on the instrument detector is an *in situ* measurement of the instrumental throughput at that wavelength. This measurement is repeated at different wavelengths resulting in a defined response function over the desired spectral range.

Our previous paper on TCal described the initial development of this system.[14] Since then we have updated the design in a number of key ways that are discussed below in section 2. Additionally, we have developed software to automate the scanning process and written a data reduction pipeline as described in section 3. Finally, in section 4 we present the results of the inital deployment of our system at McDonald Observatory.

2. EXPERIMENTAL SETUP

A schematic of the TCal system is shown in Figure 1 and a detailed model/image are shown in 2. To summarize, the system consists of a broadband light source that passes through a filter wheel and into a monochromator. This monochromator is used to select a narrow bandwidth ($\sim$ 1-2 nm Full Width Half Maximum; FWHM), and the narrow-band light is fed into a fiber bundle; one of the fibers leads to a monitoring spectrometer, and the rest of the fibers send the light to a diffuser based projection system at the top of the telescope. The monitoring spectrometer gives real-time measurements of the projected bandpass to verify the width and central wavelength of the signal. The projection system uniformly illuminates a flat field screen mounted inside the telescope dome. A signal, from the flat field screen, is measured simultaneously by the system to be calibrated (Target CCD) and the TCal monitor charge coupled device (Monitor CCD). Then, the ratio of these two signals can be used to determine the instrumental transmission at a given wavelength. TCal is designed to measure the response function of imaging instruments over the spectral range of 300 nm to 1100 nm. For this paper we focus on describing the subsystems that are new/have changed since our last paper. In particular the filter wheel, monitor CCD and instrument enclosure/table. Detailed information on the light source, coupling optics, monochromator, fiber bundle, projection system, flat field screen, and monitoring spectrometer can be found in our previous paper.[14]

2.1 Filter Wheel

We use a computer controlled filter wheel from ThorLabs, specifically the FW102. The filters are placed between the coupling optics and the monochromator as shown in figure 2. This allows us to easily change as a function of wavelength the broadband light signal that is fed into the monochromator. At blue wavelengths 350-445 nm we use short pass (SP) filters to remove out-of-band light that was scattering into the fiber as discussed in more detail in section 4.1. At redder wavelengths we use long pass (LP) filters to block higher order diffractions. This removes bluer out of band light that would otherwise be injected into the fiber bundle. In total the filter wheel

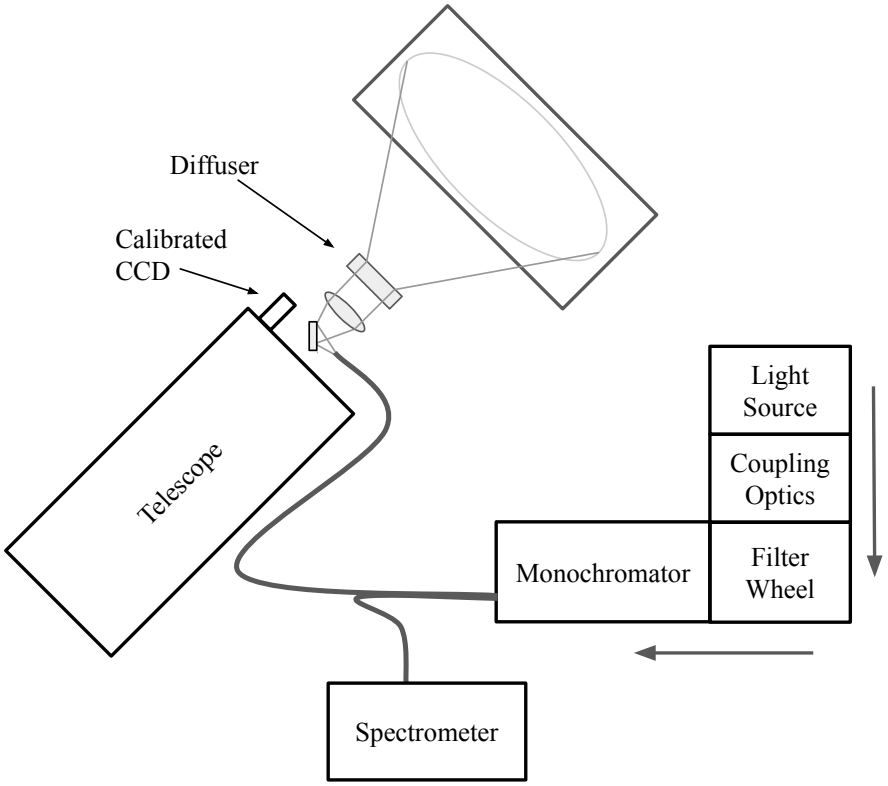

Figure 1. Schematic of the TCal system. The large arrows on the right hand side show the direction that light travels through these components of the system.

has 6 slots. We use 3 for SP filters (400, 425 and 450 nm) 2 for LP filters (500 and 550 nm) and leave one slot open. This setup allows us to create a pure narrowband signal ranging from 350-1100 nm.

2.2 Monitor CCD

For TCal we use the commercially available STF-8300M CCD from SBIG as a calibrated monitoring device to measure the signal reflected off of the screen. This CCD will be mounted on the telescope and baffled using an adjustable aperture; to only be a measure of the light reflected from the screen and not saturate during the course of a scan. We chose to use a CCD system unlike our previous system DECal, which use a NIST-calibrated photodiode. This choice was made because of how easily a CCD based system integrates with TCal and the flexibility it gives us when setting up TCal in many different configurations. The system functions well over our desired spectral range (350-1100 nm), and has pre-written drivers that are easy to integrate with our custom LabVIEW software. We have found it to be quite stable over a single scan due to the built-in cooling system. Additionally, our ability during reduction and processing to only include pixels that measure signal allows us to easily and quickly setup and optimize the system for any desired deployment. The monitor CCD has been calibrated using a NIST calibrated photodiode in the lab. This calibration was done by running 15 spectral scans (using the methodology described in section 3.2) with the photodiode acting as a monitor and the STF-8300M as the system to be calibrated. Then, the median value at each wavelength of these scans is used as the relative response function of the CCD.

2.3 Instrument Enclosure/Stand

Due to the mobile nature of TCal we designed a compact and collapsible enclosure/stand for this system. The enclosure, a black box, is shown on the right side of Figure 2. This baffles the system and ensures that there is no stray light introduced from TCal during a scan. Since there is no longer good air circulation, we have also

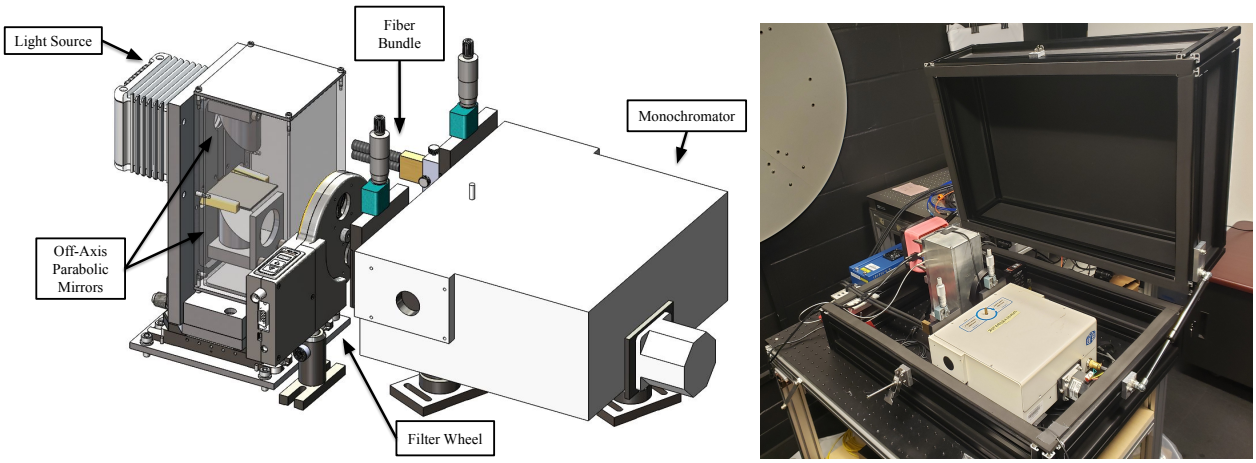

Figure 2. *Left:* A model of the light source, coupling optics, filter wheel and monochromator. *Right:* Image of the TCal system in the lab, including the enclosure and dedicated table.

implemented an active cooling system for the laser driven light source consisting of the pink shroud and fan seen in figure 2. Both TCal and the enclosure are mounted on an aluminum breadboad that allows for easy setup and alignment of the system. A collapsible item rail based stand supports the breadboard. The lower shelf of the stand compactly holds a computer, the monitoring spectrometer, the control system for the monochromator, and various cables. Plastic panels are used to baffle the lower shelf further reducing scattered light. This compact infrastructure contributes to the flexibility of TCal allowing us to quickly and robustly set up the system in a wide range of situations.

3. SOFTWARE

This section discusses in detail the software we have developed to run a scan and the data reduction pipeline we have developed to process a scan once the data has been taken. The scan software is mainly written in LabVIEW and communicates with the TCal system as well as the control system of the imager to be calibrated (target CCD). The scan software and reduction pipeline have been designed to be user-friendly letting one individual easily and remotely run a scan with minimal effort. Additionally we have made the software with an eye towards flexibility, so it can be easily adjusted to integrate a range of imaging systems.

3.1 Scan Software

Below we outline the steps taken when making measurements with TCal. The graphical user interface for a TCal scan is shown in figure 3. This interface is used to setup a scan and monitor the current progress of a scan. The left hand panel is used to set up and configure a scan, whereas the right hand region shows the overall progress and progress in an individual step.

The target and monitor data are acquired simultaneously to prevent any minor fluctuations in the lamp brightness from introducing systematic error into the throughput measurement. Additionally, dark images are taken between each observation so that gradual changes in scattered light or background illumination do not bias the measurement. After measurements have been made, the data reduction pipeline concatenates measurements of the Target CCD signal, Monitor CCD signal, central wavelength, measured FWHM, and our final measurement, the transmission of the imager to be calibrated as a function of wavelength.

3.1.1 Scan Initialization

Prior to the start of a scan the following parameters are set:

- File location
- Scan name

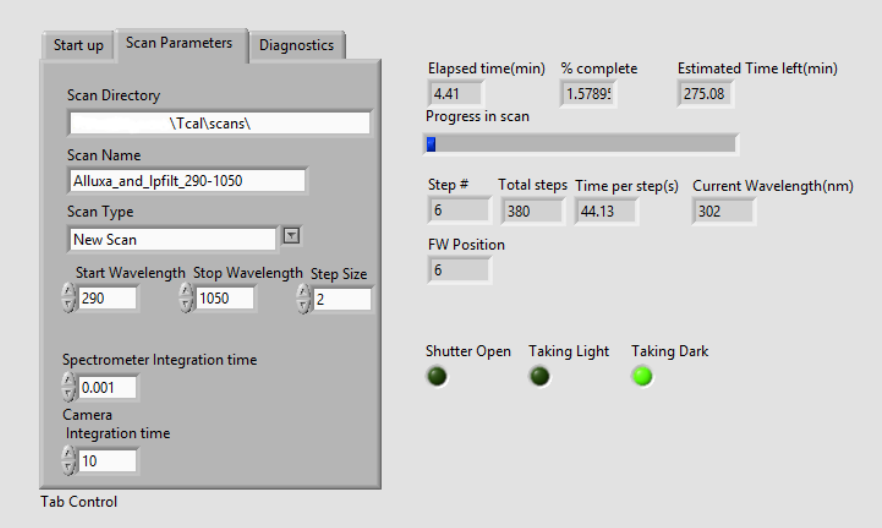

Figure 3. Graphical Control for TCal scan written in LabView.

- Beginning and ending wavelengths
- Step size
- Monitoring spectrometer integration time
- Monitor CCD integration time

The monitor CCD integration time can also be set to depend on wavelength but is set to be the same as the target CCD integration time.

3.2 Scan Procedure

During a scan our LabVIEW code controls all of the elements of TCal the steps taken are listed below.

1. Close light source shutter
2. Check current wavelength and ensure proper filter is in place.
3. Dark image:
   (a) Take target CCD image that will be used to remove background light
   (b) Expose monitor CCD for the duration of target CCD exposure
4. Open light source shutter
5. Light image:
   (a) Take target CCD image
   (b) Expose monitor CCD for the duration of target CCD exposure
6. Re-shutter light source
7. Move monochromator to next position, usually 1-2 nm higher
8. Repeat steps 2-7 until scan is complete

3.3 Data Reduction Pipeline

Once a scan has been completed, the extraction of the transmission of the target system as a function of wavelength is performed in the following manner. At the beginning of each deployment of TCal, we identify the pixels on the Target CCD that are illuminated. Only these pixels are considered as part of the signal to reduce overall noise. Then for each step of the scan, the monitor spectrometer is used to define the true central wavelength and bandpass width. The light images from the Monitor and Target systems are dark-subtracted using the average of the dark images taken before and after each light image. For the Monitor CCD, the previously identified illuminated pixels are summed and corrected for wavelength sensitivity, amplifier gain, and temperature. This gives a measurement of the number of photons seen by the Monitor CCD over the integration time. Then each of the Target systems pixels are divided by the Monitor signal giving the relative throughput of the system at that wavelength. In general, to increase the signal to noise of the measurement we bin the signal from the pixels of the Target CCD. This is done by splitting the Target CCD into regions and summing the pixels within a region. This binning is flexible and can be customized for each deployment of TCal. This procedure is repeated for every step in the scan resulting in a characterized transmission function such as the one discussed in Section 4 and shown in Figure 4.

4. TESTING OF PROTOTYPE

To test the TCal system we took a prototype version to McDonald Observatory during the summer of 2019. During this period, a protoype version of the Exoplanet Transmission Spectroscopy Imager (ETSI) was mounted on the 0.9 m telescope. A detailed description of the ETSI instrument can be found in *Limbach et al. in prep.*[15] Briefly summarizing, this instrument used a SBIG STF-8300M CCD, a Chroma 435 nm LP filter and and Alluxa ULTRA series quad-bandpass filter (https://www.alluxa.com/). The Alluxa filter bandpasses had central wavelength of 431, 509.5, 592 and 681 nm and FWHM of 30, 16, 30, 38 nm respectively. The dashed line in Figure 4 shows the expected relative transmission of the SBIG CCD $\times$ Alluxa Quad filter $\times$ Chroma LP filter convolved with a Gaussian the same size as our scan bandpass (FWHM=5 nm). The theoretical bandpasses of the two filters are provided online by their vendors.

The goal of this test was to ensure TCal could precisely measure the transmission function of an imaging instrument and that TCal could easily be configured in a remote environment. We setup TCal and ran two scans of the ETSI instrument. The spectral range of these scans was from 400-750 nm. We used a 1.2 mm slit on the monochromator output resulting in an output bandpass FWHM of 5 nm. We did not split the ETSI detector into regions, but rather summed the signal over the entire detector. Figure 4 shows the results of these scans; a measured relative throughput of the prototype ETSI instrument. The blue line shows the average of two TCal scans.

The error on this measurement can be broken down into a few components. The systematic uncertainty on the Monitor CCD is estimated to be 1%. The relative noise level of both the Monitor CCD and the ETSI CCD measurements was found to be 0.03%. This when added in quadrature gives a total uncertainty of 1%. Due to the precision of the monitoring spectrometer, we find the uncertainty on the central wavelength of the projected bandpass to be 0.1 nm.

Overall this test was successful; we were able to quickly and easily deploy TCal in a remote environment. The results of the scan (blue line) show the cut-on and cut-off wavelengths and general shape of the relative transmission function largely agrees with the expected transmission (black dashed line). The measured signal at wavelengths less than 430 nm is discussed in the next subsection. The other differences seen between the prediction and measurement showcase the importance of this calibration.

4.1 Stray Light At Blue Wavelengths

At blue wavelengths (< 430 nm) it can be seen that we detected a small but significant signal although there is predicted to be no transmission from both the 435 nm LP and Alluxa filters at these wavelengths. Taking spectra in the lab through both filters confirms this. What we did find was that light redward of the desired bandpass was being scattered onto the exit slit of the monochromator. This scattered light component appeared

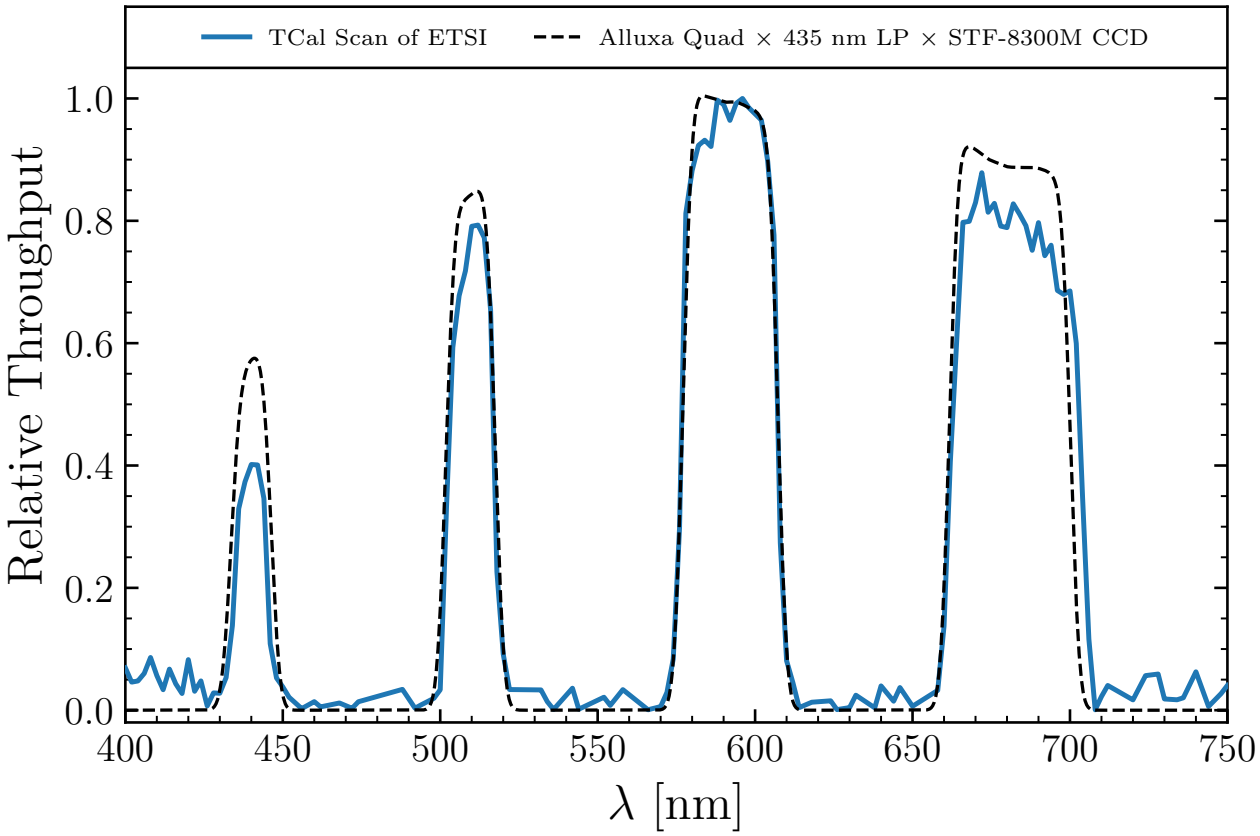

Figure 4. The results of our scan of ETSI mounted on the 0.9 m telescope at McDonald Observatory. The blue line shows our measurement the relative transmission as a function of wavelength for ETSI. The dashed line is a prediction of the bandpass solely taking into account the theoretical transmission functions of the Alluxa Quad filter and 435 nm long pass (LP) filter and our lab measured transmission function of the STF-8300M CCD.

to have a wavelength of 440 nm. This component was strongest when the monochromator was set to $\sim$ 390 nm but appeared to mainly affect the range from 370-420 nm.

A number of approaches were taken to address this scattered light component. First, we tried to increase the baffling inside the monochromator as much as possible, but the light appeared to be a spatially diffuse signal mainly on the optical axis of our $f/4$ Czerny-Turner type monochromator. So, baffling was unable to address the issue. We tried 3D printing a mask for the diffraction grating to remove doubly diffracted on-axis stray light as discussed by other authors.[16,17] Again this failed to removed the stray light component. The solution that we settled on was to use multiple short pass filters to prevent the red light from entering the monochromator when scanning the affected spectral region. For wavelengths blueward of 390 nm, we use a 400 nm SP filter. From 390-415 nm a 425 nm SP filter is used, and from 415-440 nm a 450 nm SP filter is used. From extensive in-lab testing this appears to have removed the out-of-band signal.

5. CONCLUSION

We have fully developed and tested a traveling spectrophotometric system, TCal. This system builds on previous systems developed by our lab but is more compact and easily deployable. We discuss the recent hardware developments, consisting of a filter wheel, calibrated Monitor CCD, and instrument enclosure. Next, a newly developed scan software and data reduction pipeline are explained. Finally, we describe our successful testing of a prototype version of TCal at McDonald Observatory. TCal can be used to measure system transmission as a function of wavelength and location on the focal plane with $\sim$ 1% precision. In the next 1-2 years we plan to

calibrate various 1-8 m telescopes that expect to see significant scientific benefits from this calibration. This will serve to enhance the scientific return of LSST follow-up, benefiting the astronomical community as a whole.

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