Development of TCal: a mobile spectrophotometric calibration unit for astronomical imaging systems

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ABSTRACT

We describe TCal, a mobile spectrophotometric calibration system that will be used to characterize the throughput as a function of wavelength of 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 the detector. The system is comprised of a monochromator-based light source illuminating a dome flat field screen monitored by calibrated photodiodes, 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

Astronomy has long relied on imaging surveys to investigate the Universe. In recent years, due to modern technology, the scale and scope of imaging surveys has become more ambitious. 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 are then used to probe fundamental parameters of the Universe, and identify other astrophysically interesting phenomena to be studied in more detail with targeted facilities. The next generation of large astronomical projects includes the Large Synoptic Survey Telescope[6] (LSST), which will deeply image more than two thirds of the sky delivering synoptic monitoring of billions of stars and galaxies. To continue to benefit from previous surveys and to properly exploit the LSST catalog, it will be important to fuse new data with existing catalogs as well as to devote significant resources to LSST follow-up. This means that a greater importance must be placed on reducing systematic error when comparing results from multiple instruments, and that properly calibrating existing imaging systems will help increase the scientific yield of future projects.

One specific example, using LSST imaging data to explore properties of supernovae to z $\sim$ 0.8 is among thousands of LSST science goals where data fusion plays a major role. Determining these supernovae properties is useful in many cosmological applications. In particular, supernovae luminosity distances can be used as a direct measure of the redshift-distance relation. This relation will be used to distinguish between a constant equation of state and a redshift-dependent one, independently constrain the value of w to $< 5\%$, and further explore the physics of Dark Energy.[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

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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.

Typically, the spectrophotometric throughput of astronomical imaging systems is not very 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. They use a monochromator-based light source to project narrow band (~ 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. An example from previous work can be seen in Figure 1 which shows the relative throughput as a function of wavelength for the RetroCam instrument on the Swope telescope used in the Carnegie Supernova Project.[10]

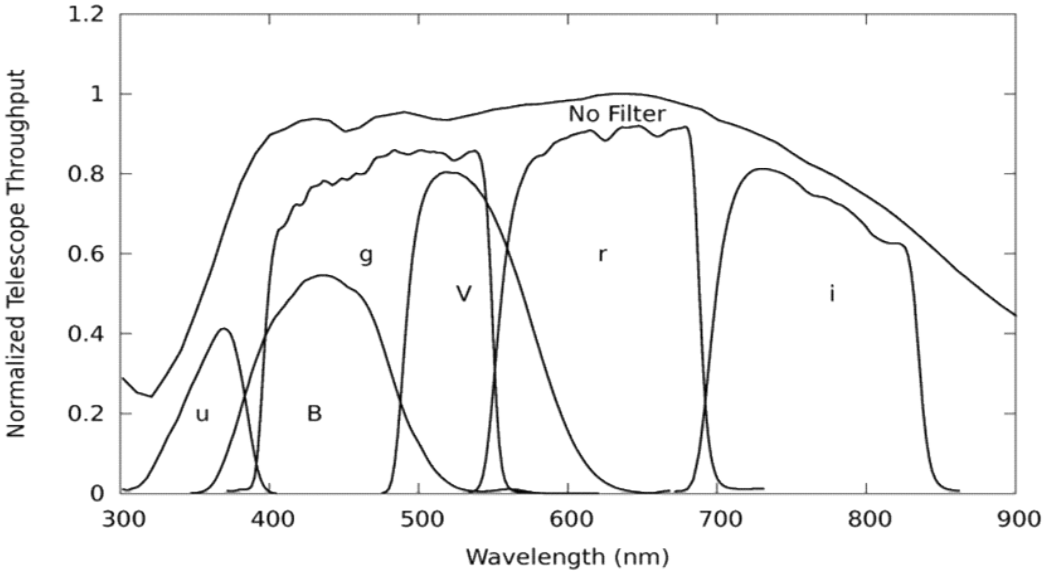

Figure 1. Scan of optical filters used in the Carnegie Supernova Project.[10] This is similar to the expected data product of TCal.

Building on this previous work, and in an effort to support the astronomical community in the age of LSST, we are developing TCal, a mobile spectrophotometric calibration system that will measure the throughput of the complete telescope plus instrument system as a function of wavelength. This system will be taken to multiple 1-8 m telescopes at observatories around the world that plan to spend significant time following up LSST or benefit from being photometrically calibratable to LSST data products. TCal will be used to characterize these systems' filter transmission functions from 300 nm $< \lambda <$ 1100 nm. This calibration will enable photometric measurements that are accurate to $< 1\%$ (< 0.01 mag), and generally reduce overall systematic errors.

The experimental setup of the TCal instrument is described in detail in Section 2. The software developed and the measurement procedure is discussed in Section 3. Finally we discuss the deployment timeline and conclude with Section 4.

2. EXPERIMENTAL SETUP

A schematic of the TCal system is shown in Figure 2. Briefly summarizing the system, a broadband light source is fed into a monochromator that selects a narrow bandwidth (∼1 nm FWHM). This narrowband light is fed into a fiber bundle with one of the fibers leading to a monitoring spectrometer and the rest of the bundle brings the signal to a diffuser at the top of the telescope. The monitoring spectrometer allows us to measure and verify in real time the central wavelength and bandwidth of the light leaving the monochromator. The diffuser uniformly projects the light onto a mounted flat field screen inside the telescope dome. This signal, coming off the flat field screen, is measured by the system to be calibrated and at the same time by commercial photodiodes mounted on the top of the telescope. The ratio of these two signals produces the measurement of instrumental transmission at a given wavelength. Detailed descriptions of subsystems are presented in the following section. Since many of the parts for TCal are repurposed from previous systems we have developed, past papers provide a good resource for additional information.[8–10, 13]

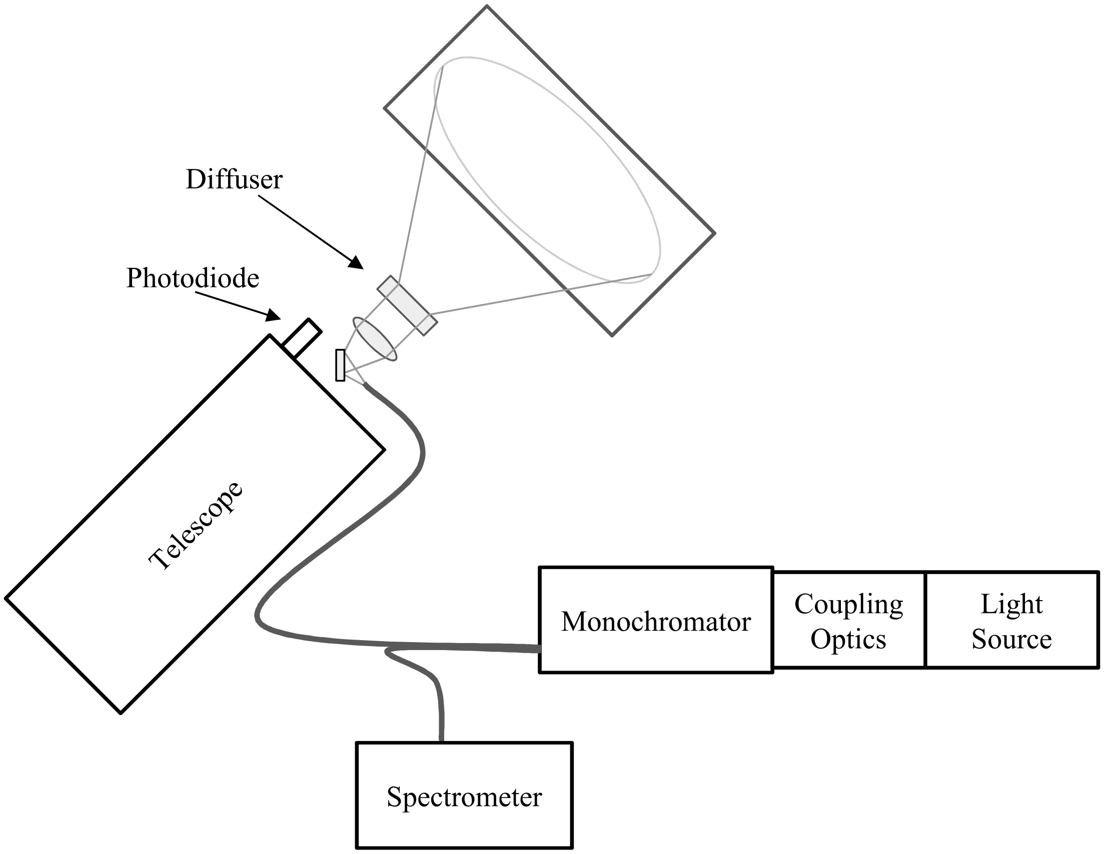

Figure 2. Schematic of the TCal system

2.1 Light source

We use a commercial laser driven light source, the EQ-99x, manufactured by Energetiq. This source strongly emits from 170-1700 nm as seen in Figure 3. This emission entirely encompasses the spectral range we plan to calibrate. The laser driven light source is a particularly good option because of its high surface brightness and radiance that is roughly 10 times that of a traditional quartz lamp (as was used in our previous systems).

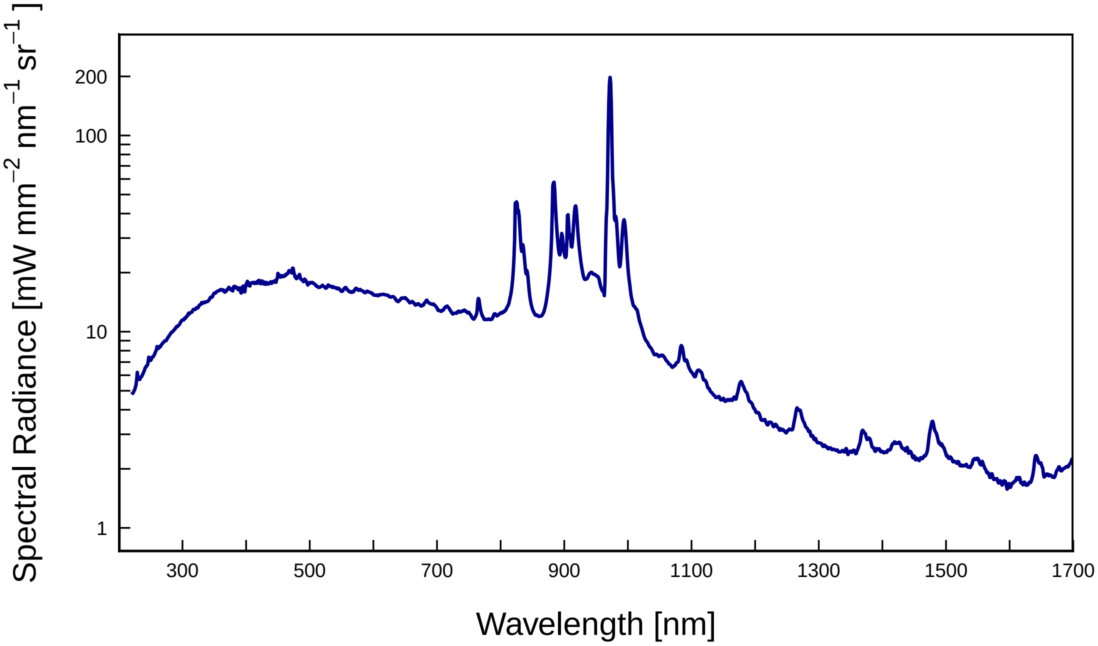

Figure 3. Spectral Radiance of EQ-99x as measured in the lab by Energetiq

2.2 Coupling Optics

Light from the light source is coupled to the monochromator via two off-axis parabolic (OAP) mirrors manufactured by Thorlabs. The assembly is mounted on a five axis stage to allow easy and repeatable alignment of the light source and the monochromator. There is a filter slot allowing for the inclusion of filters before the light enters the monochromator. The well baffled enclosure reduces the levels of stray light. The exiting beam is $f/4$ and is fed directly into the monochromator. Figure 4 shows an engineering drawing of the setup coupling the light source to the monochromator.

2.3 Monochromator

We use an $f/4$ Czerny-Turner type monochromator (manufactured by Horiba iHR-320) with a 1200 g/mm grating. This setup gives a dispersion of 4.2 nm/mm which is large enough to create the desired $\sim$1 nm bandpass, and small enough to scan from 300-1100 nm without switching gratings. Additionally, the exit slit size can be increased to create a larger bandpass. This helps to reduce measurement time when conducting an out-of-bandpass scan to ensure the filters do not leak outside their desired spectral range. For these out-of-bandpass scans the fine wavelength information is not necessary, and a coarser mode can be used.

2.4 Fiber Bundle

A custom 9 m long fiber bundle assembled by Fibertech Optica is used. This is a broad spectrum fiber that transmits well both in the UV and IR. The bundle contains 10 fibers with 600 micron cores arranged in a line at the monochromator output. One of the fibers is split off and illuminates the monitoring spectrometer. The rest of the fibers are arranged in a circular output that feeds into the diffuser mounted on the telescope.

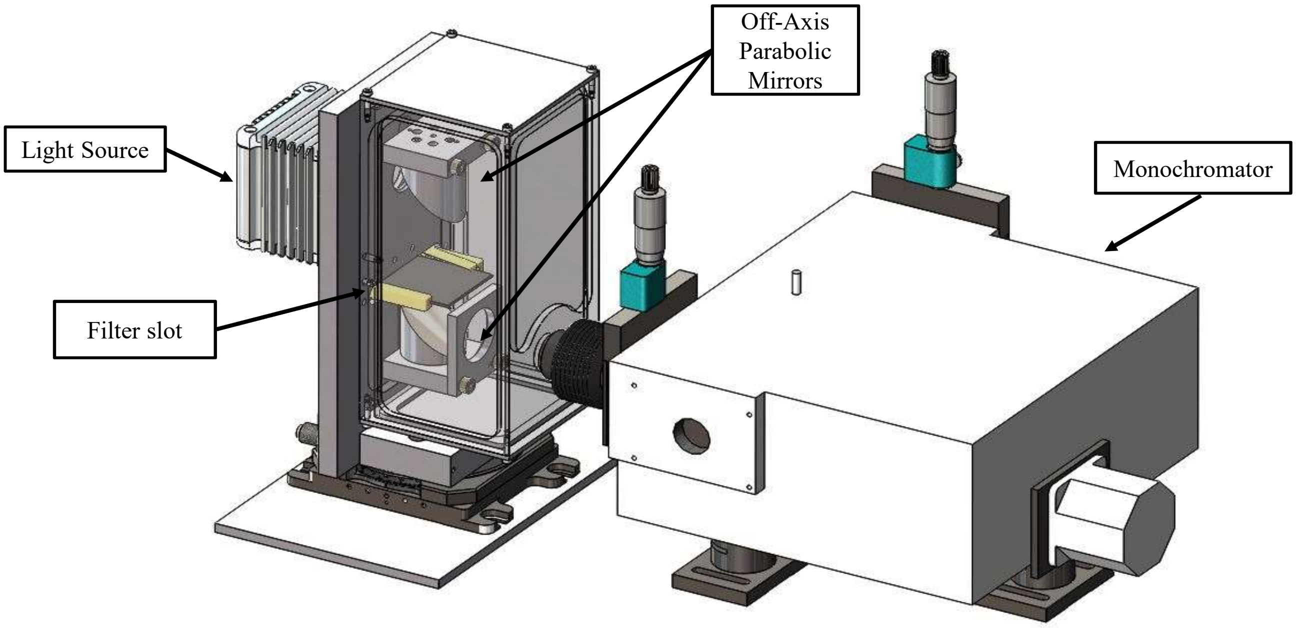

Figure 4. Light Source, Coupling Optics and Monochromator

2.5 Projection System

As discussed in previous work by our team, while it is not required for the illumination of the flat field screen to be completely uniform, large scale gradients should be avoided to keep the focal plane evenly illuminated.[14] To this end we use polymer-on-glass circular Engineered Diffusers (EDC) manufactured by RPC Photonics to project the light onto the flat field screen. Depending on the size of the telescope and the size/distance of the flat field screen, different diffusers with cones of light ranging from $30° - 60°$ can be used. This will ensure an even illumination of the screen for any of the telescopes we will calibrate.

2.6 Flat Field Screen

We conducted significant testing to find an appropriate portable screen material to be illuminated. A mixed nylon-spandex material from *stretchyscreens.com* was found to be both relatively Lambertian, and highly reflective as seen in Figure 5. More information on this and other measured white materials can be found Schmidt *et al. in prep.*[15] This material is easily mounted on a frame and hung inside the dome to provide a highly reflective standard flat field screen. Figure 5 shows a photograph of a 1.2 m flat field screen mounted in a commercial frame (also provided by *stretchyscreens.com*).

2.7 Reference Photodiode

We use a reference photodiode to measure the light reflected by the screen. The photodiode will be mounted on the side of the telescope and baffled so as to only be a measure of light reflected by the screen. Due to the increased throughput of the laser driven light source compared to the xenon and quartz lamps used in our previous designs we are able to use commercially available calibrated USB photodiode systems such as ThorLabs PM16-130 or Gentec PH100-SiUV. These photodiodes are used to provide a relative measure of the light incident on the telescope as long as the field of view and diffusion pattern are wavelength independent.

2.8 Monitoring Spectrometer

To monitor in real time the spectral information of the signal projected onto the screen, we feed one of the fibers from the bundle into a spectrometer. This monitoring spectrometer records a spectrum for each exposure that is a direct measure of the central wavelength and FWHM of the light leaving the monochromator. We use a spectrometer with high enough resolution to characterize the central wavelength and FWHM with a precision of ~ 0.1 nm. Our spectrometer is calibrated using Mercury calibration lamps.

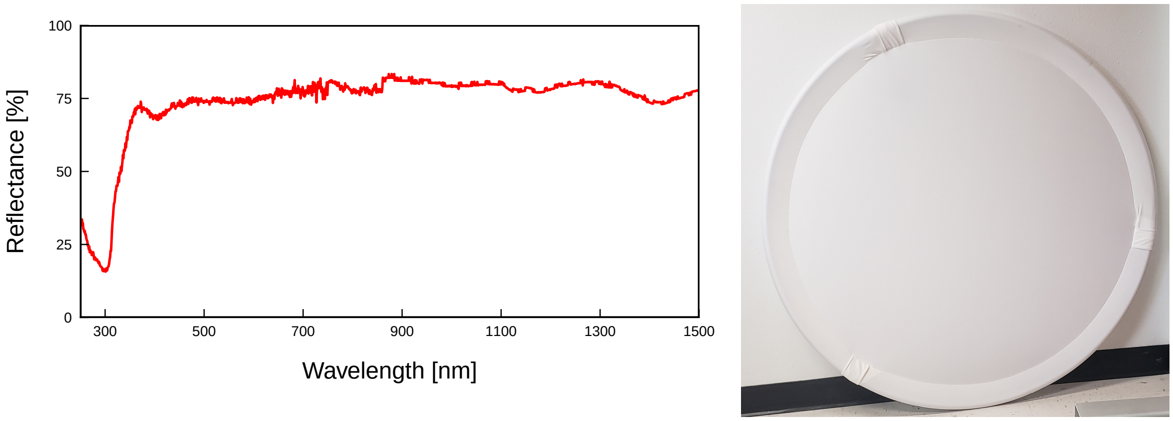

Figure 5. *Left*: Reflectance measurements for the mixed nylon-spandex material from Schmidt *et al. in prep*,[15] note that it reflects well into the UV unlike other screen materials tested. Right: Image of 1.2 m screen.

3. SOFTWARE AND MEASUREMENT PROCEDURE

3.1 Software

We plan to develop an almost fully-automated, easy-to-use setup that will allow one individual to run a scan of an instrument. A LabVIEW interface is used to communicate with all components of TCal and to control and execute a scan. In order to more finely control and automate a scan, we plan to interface directly with the control system of the imager to be calibrated. All of these design choices work towards creating a user-friendly interface that requires minimal interaction during the scanning process.

The image and photodiode data are acquired simultaneously to prevent any minor fluctuations in the lamp brightness from introducing systematic error into the throughput measurement. After measurements have been made, the corrected photodiode reading, central wavelength, and FWHM will be concatenated with the associated image on a separate computer. This allows easy recovery, backup, and creation of the final transmission vs wavelength function.

3.2 Measurement Procedure

Here we outline the procedure to be followed when making measurements with TCal.

1. Close light source shutter
2. Dark image:
    (a) Take CCD image that will be used to remove background light
    (b) Acquire photodiode data for the duration of CCD exposure
3. Open light source shutter
4. Light image:
    (a) Take CCD image
    (b) Acquire photodiode data for the duration of CCD exposure
5. Re-shutter light source
6. Move monochromator to next position, usually 1 nm higher
7. Repeat steps 2-6 until scan is complete

At the beginning of each scan a parameter file will be loaded to control the scan. Then we begin the scan; the scanning procedure creates a series of photodiode and CCD signal measurements as well as photodiode and CCD dark frame measurements at each wavelength. The net signal at a given wavelength is then obtained from the following steps. First, the spectrometer is checked to properly record the transmitted bandpass's central wavelength and width. Then the integrated photodiode measurement is dark-subtracted using the average of the photodiode darks taken on either side of the light measurement. Next the photodiode signal is corrected for wavelength sensitivity, amplifier gain, and temperature. This gives the reduced measurement of the number of photons seen by the photodiode over the integration time. The same procedure is used on the imager to be calibrated, resulting in a net light measurement. Dividing the CCD image by the photodiode measurement gives the relative throughput of the system to be calibrated at that wavelength. This procedure is repeated for every wavelength in the scan resulting in a characterized transmission function similar to that shown in Figure 1.

4. CONCLUSION

We have developed, and will soon deploy a traveling spectrophotometric calibration system, TCal. This system is similar to and will build on previous spectrophotometric calibration systems developed by our lab. TCal allows for the characterization of system transmission with ~1% precision as a function of wavelength and location on the focal plane. In late 2018, a TCal prototype will be tested at our local campus observatory and also at McDonald observatory in west Texas. Then its design will be refined and finalized. In the next 2-3 years we plan to calibrate various 1-8 m telescopes that expect to see significant scientific benefits from having their transmission function precisely characterized. This effort will serve to enhance the scientific return of LSST follow-up, which will benefit the entire astronomical community in the next decade and beyond.

5. ACKNOWLEDGEMENTS

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