The LSST calibration hardware system design and development

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ABSTRACT

The Large Synoptic Survey Telescope (LSST) is currently under construction and upon completion will perform precision photometry over the visible sky at a 3-day cadence. To meet the stringent relative photometry goals, LSST will employ multiple calibration systems to measure and compensate for systematic errors. This paper describes the design and development of these systems including: a dedicated calibration telescope and spectrograph to measure the atmospheric transmission function, a collimated beam projector to characterize the spatial dependence of the LSST transmission function and a flat-field screen illumination system to measure the high-frequency variations in the global system response function.

Keywords: Calibration, LSST, photometry, operations, spectrograph, atmospheric transmission

1. INTRODUCTION

The Large Synoptic Survey Telescope (LSST) Project[1] will perform precision photometry over the visible sky at a 3-day cadence using an 8.4 m diameter telescope that forms an image of the sky on a 3.2 Gigapixel focal plane array.[2] The telescope, camera and infrastructure are currently under construction[3] and are scheduled to begin commissioning in 2019 with the 10-year survey starting in 2022. One of main deliverables for LSST data is precision photometry of both resolved and un-resolved objects (e.g. galaxies and stars). The relative photometric design requirements are specified to be 5 mmag (0.5%) repeatability in the *bvri* filters and 7.5 mmag in the *uzy* filters, for bright unresolved point sources under a wide range of observing conditions. The scientific benefits of such high quality measurements impact several science cases including: photometric redshift determination of galaxies, photometric metallicity determination of stars, and high-fidelity determination of supernovae redshifts; one of the fundamental probes in exploring the nature of Dark Energy and measuring the expansion rate of the universe.

Meeting the photometric precision requirements is a significant challenge and necessitates the calibration and correction of multiple forms of systematic error. One example of systematic error that plagues photometry measurements is the effect of atmospheric transmission since it is known to evolve both temporally and spatially over the course of ∼2-3 LSST pointings. Similar to other surveys, calibration measurements and corrections must also be determined for static effects such as vignetting and for system properties that may evolve over longer timescales, such as optical throughput. This paper describes multiple hardware systems that LSST is developing to measure and compensate for numerous sources of systematic errors, particularly errors impacting photometry measurements.

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Characterization of the optical properties of LSST is accomplished using two independent systems that are located inside the main telescope rotating enclosure (dome). The first system, discussed in Section 2 is a custom-made Collimated Beam Projector (CBP) that projects a field of sources onto user-defined discrete sections of the telescope optics. This device enables the ability to characterize the low to mid frequency spatial dependence of the telescope and instrument transmission function, monitor filter throughput evolution and assist in the characterization of ghosting effects. The second system is a calibration (flat-field) screen that will be illuminated by both a white-light and a tunable monochromatic illumination system. The calibration screen system will produce data to measure the high-frequency variations in the global transmission function.

To compensate for the effects of atmospheric transmission and its temporal and spatial variability, LSST will utilize a robotic 1.2-meter diameter auxiliary telescope dedicated to measuring absorption features caused by earth's atmosphere that are imprinted in the observed spectra of bright stars. Section 3 of this paper describes the Auxiliary Telescope, its enclosure, and the spectrograph that is being specifically optimized to characterize the atmospheric transmission properties at high cadence in coordination with the main telescope.

2. MAIN TELESCOPE IN-DOME CALIBRATION HARDWARE

This section describes the equipment located inside the main telescope building that is used as part of routine calibration activities. The characterization of the telescope transmission function is performed using a combination of measurements using the calibration screen and the collimated beam projector. Both of these systems are mounted to the dome, as shown in Figure 1. The calibration systems have undergone significant redesign from the previous publication[4] to minimize technical risk and to increase the operational efficiency. The inclusion of the CBP to the In-Dome Calibration hardware complement enabled the relaxation of the illumination uniformity requirement on the calibration screen therefore lower-risk designs could be accommodated. The following subsections describe the components of the In-Dome Calibration systems and the hardware that facilitates their operation.

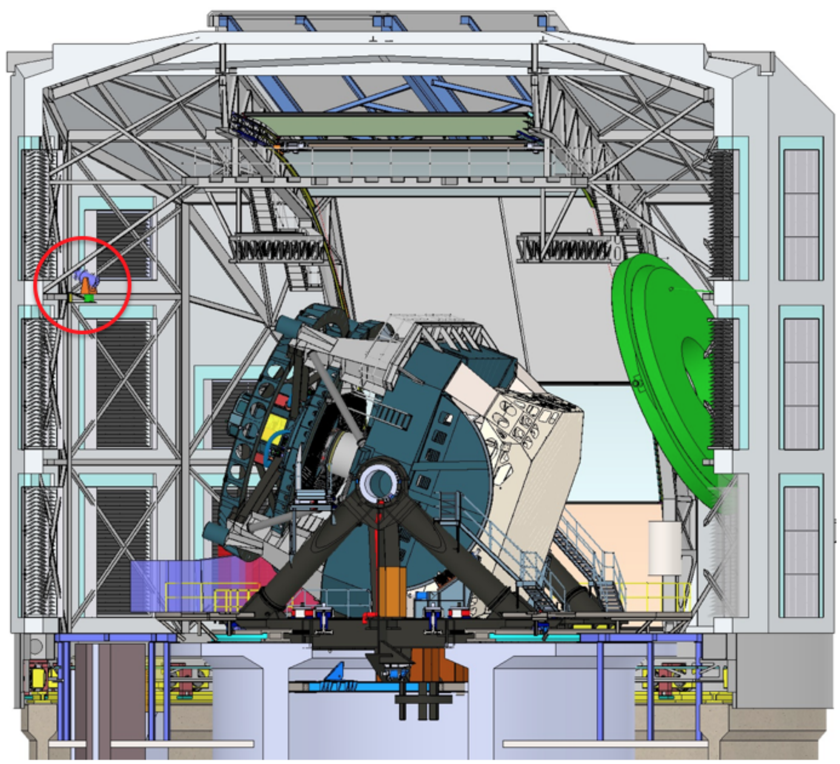

Figure 1. The location of the calibration screen (shown in green) and collimated beam projector (indicated by the red circle) in the LSST dome.

2.1 Collimated Beam Projector (CBP)

Determination of the optical transmission function and how it evolves with time is traditionally performed using dome or sky flats (uniform illumination of the entire field of view) and/or star flats, where a field of stars is rastered around the focal plane and the change in their properties is examined. Performing observations to create star flats is a time consuming endeavour and should be done in photometric conditions; arguably the most valuable time to perform science observations. Furthermore, dome flats, sky flats, and star flats all measure the integrated transmission function of the optical system. With the collimated beam projector, the equivalent of star flats can be reproduced from inside the telescope dome for fractional areas of the telescope pupil at user-defined positions. Moreover, the measurements can be performed with and without a filter in the beam to separate filter transmission properties from the other optical elements.

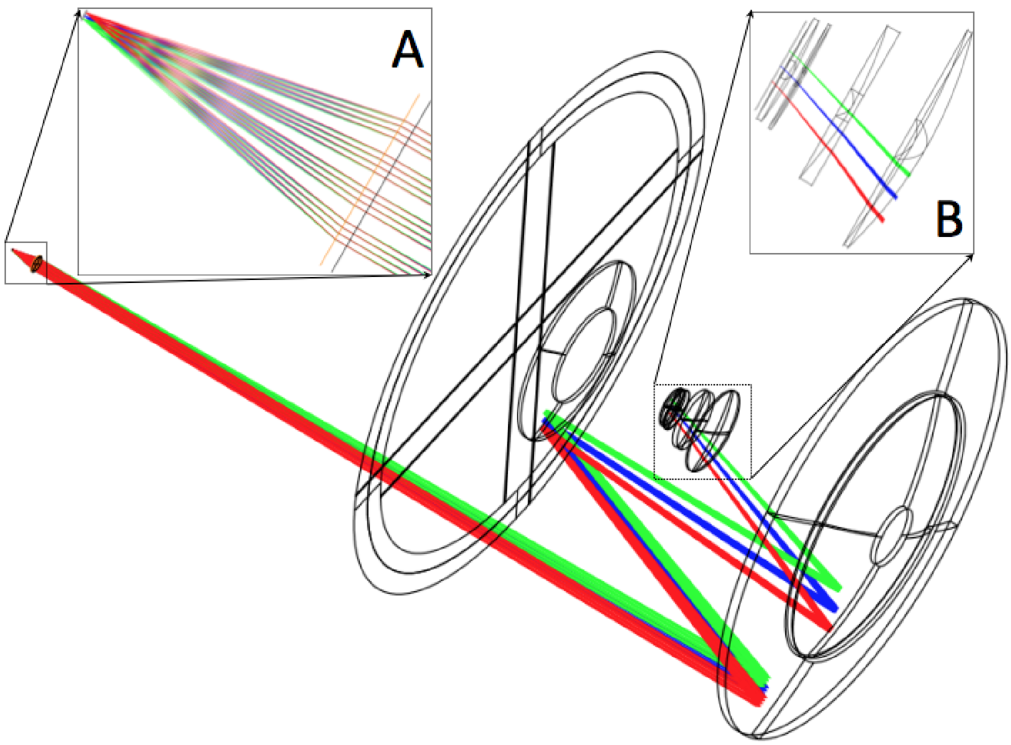

Figure 2. The Collimated Beam Projector is a small ∼30 cm telescope used as a projector (modeled as a paraxial lens in inset A), to propagate the image of a series of simulated stars (pinholes) through the telescope, camera and onto the LSST focal plane (camera shown as a side view in inset B). By articulating the projector and telescope the entire transmission function of the telescope can be measured. Field angles shown are $\pm1^{\circ}$.

The CBP is located in the telescope dome opposite the calibration screen between the top two rows of vent gates, as indicated by the red circle in Figure 1. The optical telescope assembly used for the CBP will be a wide-field ∼30 cm diameter telescope on an actionable mount. Located at the CBP focal plane will be a mask that is illuminated via a wavelength tunable monochromatic source (further discussed in section 2.3). The mask will be held in a mask wheel that will allow observers to switch between multiple mask designs. The nominal mask will consist of single pinhole for each CCD, including the guiders and wavefront sensing devices. The CBP will be used to measure the low to mid- spatial frequency variations of the transmission function. In traditional dome and sky flats these measurements are often highly contaminated from ghosting effects that can manifest as systematic error in the photometric measurements. Because the CBP only illuminates a small portion of the pupil at a time, ghosting contamination is avoided. Multiple prototypes of the CBP have been tested and used to help define the LSST CBP design. Delivery of the device is expected in 2017. Readers are encouraged to see Coughlin et al[5] from these proceedings for details on CBP design evolution and operation.

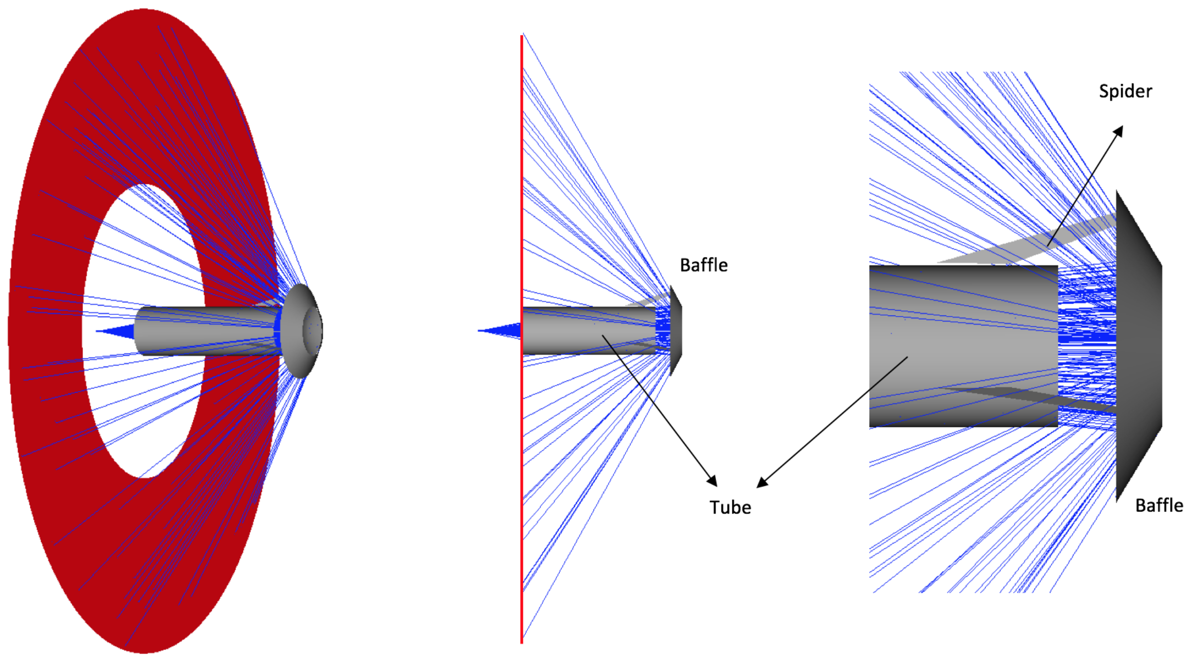

Figure 3. The calibration screen will be illuminated from a single central optic. The use of a single optic ensures only low-frequency illumination non-uniformity whose effects are mitigated through Collimated Beam Projector measurements. Mitigation of scattered light is performed via baffles near the central optic and from blackening the surfaces not visible to the LSST focal plane.

2.2 Calibration Screen

The calibration screen is used for obtaining flat-field calibration frames in both monochromatic and polychromatic light. The reflective portion of the screen is an annulus with an inner and external diameters of 4.2 and 9.3 m, respectively. A blackened area surrounding the reflective portion is present to minimize scattered light from angles exceeding the 3.5° LSST field-of-view. During operations, the screen rests in tilted the position shown in Figure 1. The screen is of normal incidence to the telescope boresight at an elevation angle of 22° . To facilitate maintenance of the dome vent gates and to allow servicing of equipment located on the calibration screen structure, the dome screen may be rotated into a vertical position. The reflective material used on the calibration screen has yet to be selected. Due to the large wavelength range of the LSST survey and the requirement for monochromatic flats taken at 1 nm increments, a smooth reflectivity profile is required. Surfaces exhibiting diffuse reflectance under consideration include Spectralon, however, another option may be purchasing a commercial prefabricated screen, such as the Draper M1300.

The illumination of the calibration screen will utilize a single optical element that protrudes from the calibration screen at the center of the annulus. An example of a design under consideration is shown in Figure 3. This is a significant design evolution from the previously presented design where the illumination sources were located on the top-end of the telescope. In using a single reflection element, the illumination pattern on the screen is limited to only low-frequency illumination non-uniformity. The only higher-frequency non-uniformity's would originate from the support structure for the reflector, or the reflecting screen itself. The conceptual design in Figure 3 has a diverging beam originating from the light source that is reflected and dispersed by an aspheric optical element. Because the optical quality of this component is not of critical importance due to the calibration screen utilizing a diffuse reflective material, the piece could be machined from aluminum then polished to reduce figuring artifacts. This results in the central optic being easy to fabricate, light-weight, straightforward to mount, and cost-effective. The calibration screen will be delivered to the site and integrated in late 2018.

Because the light source is originating from the backside of the calibration screen and our operational requirements dictate that broadband dome flat fields are taken daily while the dome is in the park position, the white light source(s) must be mounted directly to the calibration screen. Due to environmental considerations and safety concerns, the monochromatic source will not be located in the dome or on the observatory floor. Light delivery systems are further discussed in section 2.3.

2.3 Light Sources and Delivery Systems

The calibration screen will be illuminated by both broadband light sources and a tunable monochromatic source. The monochromatic source is expected to be a tunable laser that covers the 320-1125 nm bandpass range in 1 nm increments. The laser will be located in an enclosed section of the camera utility room on the base enclosure level (level 5) of the facility just outside the lower enclosure. Transporting this light from the source to the calibration screen and CBP is a non-trivial problem.

Original plans to transport the light to the previous multi-projector system located on the top-end of the telescope mount utilized a broadband fiber optic nearly 80 m in length. The absorption of blue light over this length of fiber (∼90%) made this design challenging operationally due to the amount of time required to perform the measurements. Various fiber optic configurations were considered for the central illuminator design discussed in Section 2.2, but all suffered from absorption in the blue and the need for human intervention to connect the fiber to the dome when needed. For these reasons, it was decided to free-space propagate the laser in enclosed tubes from the laser room to the calibration screen and the collimated beam projector. This both removes the fiber absorption issue and ensures that calibrations can be performed without human intervention.

The monochromatic light will be propagated from the source, through a shutter and beam expander system, reflected vertically into the ceiling then propagated horizontally through a hole in the concrete wall of the lower enclosure. From the lower enclosure, a powered steering mirror will then direct the light vertically through a hole in the observing floor and up to the lower-enclosure and dome interface. From this point, the light must be directed to calibration screen and the CBP (albeit not simultaneously). Because the dome azimuth repeatability requirement subjects the laser tube placement to a 2.5 cm displacement error, a beam steering system is required where one steering mirror is located in the lower-enclosure (as mentioned previously) and the other is on the calibration system mounted in the dome. The beam position will be determined using two cameras, one looking at the focus to measure pointing, the other imaging a conjugate pupil to measure beam centering.

Because the CBP observations must be performed during the day while the dome is in the park position, and the CBP is not located directly above the laser tube originating from the lower enclosure, an optical bench will be placed high in the dome to steer the beam into a CeramOptec PowerLightGuide fused end fiber bundle to transport the light to the CBP. Transmission losses in the fiber are not of significant concern since the light required for the CBP is only a small fraction of the power required for the calibration screen.

In order to use the monochromatic source with the calibration screen, the dome must be rotated away from the park position. In this configuration the dome cooling is reduced. Maintaining cooling during the day is critical for minimizing dome seeing effects. This is one of the reasons why the monochromatic flat field observations will be performed during cloudy nights. Other reasons include: minimal scattered light, multi-hour windows to perform the calibration and optimization of daytime telescope access. Monochromatic flats need only be measured 3-4 times per year, whereas broadband flats must be taken daily to track dust movement on the optical elements.

Because broadband flats will be taken daily, the dome must remain in the park position to ensure effective cooling. For this reason, the broadband source(s) will be mounted on the calibration screen itself and the light will be directed to the central illumination optic. The broadband sources are also less subject to environmental constraints and the safety precautions to personnel are significantly reduced. Light sources currently under consideration include LEDs similar to what is used for DECam calibration[6] and broadband sources such as the Horiba KiloArc and the Energetique EQ-1500.

2.3.1 Illumination Characterization Systems

Characterization of the calibration screen illumination is pertinent to ensuring no systematic error is introduced into the photometric corrections. The monochromatic dome flats will be used to synthesize a flat-field image matching a spectrum of the night sky for use in accurate background subtraction. The broadband flats will be used to monitor changes to the dust patterns on the optical components (particularly the filters). By examining the evolution in the daily broadband flats, corrections can be made to the monochromatic flats so long as the spectral energy distribution of the broadband flat is known. For this reasons, a fiber-fed spectrograph will be used to measure the spectral energy distribution of the light reflected from the calibration screen. The spectrograph can also be used to measure the line width of the monochromatic source. For this purpose, two AvaSpec-ULS2048x64 TEC spectrographs, one for red wavelengths and the other for blue wavelengths, from Avantes have been selected to measure the spectral energy distribution to up to a resolution of 0.7 nm. Although the spectrographs will have an illumination calibration, we will perform monitoring of the variation of flux levels using photodiodes.

The National Institute Standards and Technology (NIST) has calibrated the quantum efficiency of Hamamatsu S2281 photodiodes to accuracies that surpass photometric standard stars by an order of magnitude. Several studies on the use of these photodiodes for astronomical calibration discuss their advantages in detail[7–9] and their usage amongst the community is increasing.[6,10] The LSST calibration plan includes several of these photodiodes throughout the calibration procedure as a basis for comparison of calibration frames. Having a standard at this level of precision enables accurate monitoring of the transmission response and absolute transmission of filters. It also provides a mechanism to ensure each monochromatic flat field frame has the desired signal. This is facilitated by using a shutter located at the output of the laser, rather than relying upon the camera shutter. The current of the photodiodes will be measured using Keithley 6517b electrometers that will be located in cooled electronics cabinets located on the secondary mirror support assembly of the main telescope.

3. AUXILIARY TELESCOPE AND SPECTROGRAPH

Characterization of the absorption properties of the atmosphere during LSST observations will be performed by 1.2 m diameter Auxiliary Telescope located ∼300 m north-east of the main telescope. At the time of writing, the excavation for the building foundation and pier have performed but neither have been poured. The telescope will housed in a 30 foot (9.1 m) diameter circular two-storey building. The lower floor will contain the control electronics and observatory support equipment[11] as well as four remotely operable vent gates. The Auxiliary Telescope does not have a high-image quality requirement hence the building does not require an active air conditioning system. However, efforts are being made to promote efficient passive cooling. The observing floor (2nd floor) is made of a grating to promote air flow entering through the dome shutter then passing through the building and out of vent gates on the lower floor. The telescope mount, mirror cell and pier has fan-driven circulation units to assist in temperature stabilization and uniformity. The Auxiliary Telescope dome is currently under construction by Ash Manufacturing Company and is scheduled for delivery early summer, 2017. The enclosure will be equipped with the SmartDome controller developed by Astronomical Consultants & Equipment Inc. The dome rotation speed will also be increased by using four motors rather than the nominal two motor system.

The Auxiliary Telescope, previously known as the Calypso Telescope (shown in Figure 4), was located on Kitt Peak and has been brought to the National Optical Astronomical Observatory (NOAO) facility in Tucson to undergo a significant refurbishment before being transported and re-commissioned in Chile. Astronomical Consultants & Equipment Inc. was awarded the contract. The refurbishment work includes replacements of all drive motors, controllers and electronics. Maintaining compatibility of components with the main telescope is a common theme throughout hardware selection for all components. Wherever possible, Kollmorgen motors and Copley Motor controllers are being utilized and interfacing will utilize National Instrument (NI) Compact RIO devices. The mirror cell will be refitted with new bellows systems. The secondary mirror support system will be re-worked to include a new commercial off-the-shelf 6-Axis Hexapod. The most significant change to the original telescope design is the the installation of Heidenhain Tape encoders to the azimuth axis, and Heidenhain Ring Encoders to the elevation axis and instrument rotators. During operation at Kitt Peak, the telescope suffered from pointing problems. This was due to multiple reasons such as temperature induced expansion and contraction of azimuth drive surface that was not accounted by the rotary encoder and/or control software. Furthermore, the instrument rotators used a combination of friction drives and rotary encoders that were subject to slipping. Preserving that system would make satisfying the LSST pointing requirements challenging. In order to install the azimuth tape encoder, a new surface to support the tape is being machined and installed above the drive

Figure 4. The Auxiliary Telescope while located on Kitt Peak. The telescope is now undergoing refurbishment and will be ready for observations in June 2018.

surface and below the telescope fork. Fabrication of this new encoder disk is now underway. Encoder rings are being installed on the elevation axis, and the rotary encoders are being replaced with ring or tape encoders for the instrument rotators.

The refurbishment being done in Tucson is expected to be completed in April, 2017. The telescope will then remain in Tucson for a period of ∼4 months to be used as a testbed for the Telescope and Site software team to perform software testing and demonstration of the Observatory Control Software,[12,13] Telescope Control System,[14] and Communications Middleware.[15] During this time, the secondary and tertiary mirrors will have their coatings removed and will then be hard-coated with high-reflectivity metallic coatings. Upon the installation of the dome and the completion of the Auxiliary Telescope building, the entire telescope will be shipped to Chile for integration, test, and final acceptance. After verification of the telescope performance, the telescope will be ready for use in summer 2018, when the spectrograph will be commissioned.

The spectrograph being designed to perform characterization of the atmospheric absorption profile has undergone significant evolution from what was previously presented.[4] The conceptual observing plan for the Auxiliary Telescope had it operating independent of the LSST position, slewing about the sky to a fixed table of targets spanning large ranges of airmass. The observing plan has been expanded to support multiple observing strategies for characterizing the atmospheric transmission as a function of time and position that can be optimized for observing conditions and/or LSST filter. The most demanding strategy is where the Auxiliary Telescope follows the pointing of the LSST telescope as closely as possible. This puts increased time pressure to measure the sky spectrum since the LSST telescope changes pointing every ∼40 seconds and has a fast slew speed.[16] To assist in the determination and observing scheduling, a greatly simplified version of the LSST Scheduler[17] is envisioned. This reduced Scheduler will utilize the same telemetry used to determine the LSST pointing and will use the predicted future pointings of LSST in determining the pointings for the Auxiliary Telescope.

To increase the observing cadence of the Auxiliary Telescope, the spectrograph now utilizes a slitless design. This has multiple benefits including: removing the acquisition sequence required to position the target in the slit, relaxing the pointing requirement and the removal of differential slit losses that are particularly problematic at higher airmasses. Calculations of water vapour absorption at red wavelengths (800-980 nm) as a function of spectral resolution demonstrates that the resolution requirement on the spectrograph may be reduced to R=150 for wavelengths longer than 800nm. This also results in a lesser exposure time to obtain the required signal-to-noise ratio.

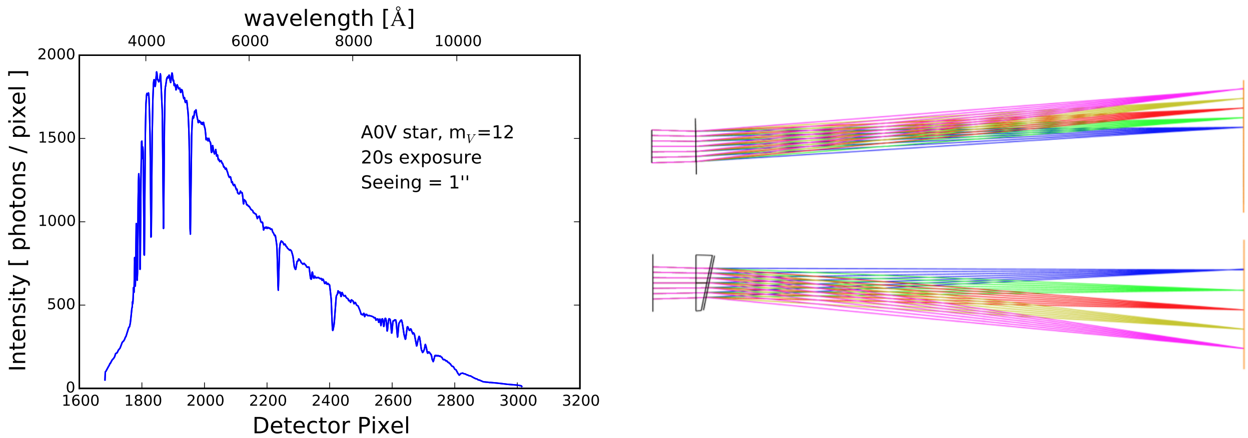

Figure 5. *Left:* The simulated spectrum as measured on the detector when using the Ronchi Grating. *Right:* The priliminary optical design starting at the instrument flange for a Rochi Grating (R∼ 100) and a Grism (R∼ 300). A variety of dispersers will be held in a disperser wheel assembly that will enable selection of the appropriate instrument setup depending on observing conditions and strategy.

The current spectrograph design is meant to have high throughput, minimal internal reflection, and support multiple observing setups to accommodate flexible observing strategies. Throughput measurements indicate that adequate signal to noise can be achieved in 20 seconds on 12th magnitude star but the high majority of observations will use stars in a magnitude range of $5 < m_V < 8$. The instrument will also have an imaging mode with a small (∼1x1 arcminute) field of view which may be used for alignment and telescope collimation purposes. Because of the Auxiliary Telescope's slow (f/18) beam, it is possible to put dispersive elements into the converging beam with minimal increase in wavefront aberration. This type of design minimizes internal reflections and maximizes throughput. A successful demonstration of such a system was performed by inserting a Ronchi grating into the filter wheel of the 0.9m SMARTS Telescope at Cerro Tololo [*].

The filter and disperser combination will be implemented using a dual-wheel design. The filter selection will include the LSST filter bandpasses plus long and short pass broadband filters that may be used to measure and/or remove effects from disperser selection such as order contamination. The nominal observing mode will utilize either an Amici Prism or a Ronchi grating to provide simultaneous wavelength coverage from 350-1050 nm. Each system is optimized to have maximum spectral resolution in the 900-980 nm water feature. Using higher dispersion will also be an option via a Grism, such as the one shown in Figure 5. After a 2-month commissioning period, the Auxiliary Telescope will begin characterizing the night sky in efforts to measure the time evolution and variation in spatial structure over Cerro Pachón. These observations combined with the anticipated nightly LSST observing schedule will be used to optimize the Auxiliary Telescope Observing strategy to provide the highest fidelity photometric correction for LSST data.

3.1 Auxiliary Telescope Calibration

The Auxiliary Telescope will have its own array of calibration instruments albeit with reduced functionality from the calibration equipment for the main telescope. A small calibration screen will be used to obtain dome flats. The calibration screen will be front-illuminated using a Horiba Tunable Kiloarc that enables narrowband flat fields over the entire 350-1050 nm wavelength range. The monochrometer will also contain a flat mirror that will allow broadband illumination. A single NIST-calibration photodiode system will monitor any changes in light source intensity. A AvaSpec-ULS2048x64 TEC spectrograph from Avantes will be used to monitor the spectral energy distribution of the source at a spectral resolution of ∼2 nm.

[*] Mondrik et al in prep

4. CONCLUSION

The calibration hardware for LSST is being finalized and procurements are underway. The Auxiliary Telescope refurbishment has commenced and will result in the telescope being ready for observations in summer, 2018. The spectrograph will then be commissioned to ensure full operational support for commissioning activities and observations. The introduction of the Collimated Beam Projector to the hardware resulted in the relaxation of the calibration screen requirements and has enabled the construction of a lower technical risk, higher throughput design. A targeted design optimization study is now ongoing with delivery expected in late 2018. All systems are fully expected to remain on schedule, within budget and meet or exceed their operational requirements.

5. ACKNOWLEDGMENTS

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