Calibration Systems for LSST
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ABSTRACT

The Large Synoptic Survey Telescope (LSST) relies on a set of calibration systems to achieve the survey photometric performances over a wide range of observing conditions. Its purpose is to consistently and accurately measure the observatory instrumental response and the atmospheric transparency during LSST observing. The instrumental response calibration will be performed regularly to monitor any variation of the transmission during the duration of the survey. The atmospheric data will be acquired nightly and processed to atmospheric models. In this paper, we describe the calibration screen system that will be used to perform the instrumental response calibration and the atmospheric calibration system including the auxiliary telescope dedicated to the acquisition of spectral data to determine the atmospheric transmission.

Keywords: LSST, Calibration

1. INTRODUCTION

The Large Synoptic Survey Telescope (LSST) [1] is a proposed 8.4-meter diameter, 3.5-degree field of view (FOV) observatory dedicated to an optical sky survey in six filter bands (u, g, r, i, z, and y) during an anticipated decade of operation. The photometric requirements for the LSST survey data place challenging requirements on the calibration systems to characterize the instrumental throughput and to monitor in real-time the optical transmission function of the atmosphere. Photometric zeropoints are required to have a temporal stability of 0.5% rms or better, and to be uniform across the survey area to better than 1% rms. Data from the calibration systems will be combined with a global photometric self-calibration procedure [2] to achieve this level of photometric calibration. The self-calibration procedure takes advantage of the rapid cadence of the LSST survey to monitor photometric stability and uniformity using the repeated measurements of non-variable stars.

The instrumental and atmospheric calibration approach is based upon two distinct measurements [3, 4]: 1) the determination of instrumental sensitivity using a well calibrated photodiode detector, and 2) direct measurement of the atmospheric transmission. The LSST calibration approach is detailed in [5] describing how the instrumental and atmospheric measurements and calculations can be used to reconstruct the total system throughput of light from the top of the atmosphere to the signals read from the detector electronics. A similar approach was also adopted by the Dark Energy Survey (DES) [6 and references therein].

In this paper, we focus on the LSST calibration systems layout and components that will be used during operations. A calibration screen system will be built to measure the instrumental response of the LSST telescope. Recent analyses have relaxed the requirements on this system. In addition, an atmospheric calibration system, composed of a suite of instruments, will be installed near the main LSST telescope to monitor the atmosphere. Notably, a dedicated atmospheric calibration telescope will be constructed to continuously take spectroscopic measurements of bright stars to characterize the atmosphere. The implementation of the calibration data product software pipeline and instrumental signature removal will be described elsewhere.

2. CALIBRATION SCREEN SYSTEM

Located within the telescope enclosure, the LSST Calibration Screen System (CSS) will generate “dome flats” for calibration. The system design will use a broadband “white” light and a tunable laser source. The light projection system will be located on the telescope top end pointed toward the calibration screen. The laser light will be delivered by a fiber optics bundle. NIST-calibrated photodiodes will be mounted on the telescope to monitor the flux emitted from the calibration screen. Additionally, a spectrometer will measure the spectral energy distribution (SED) of the emitted light. This CSS design will permit to calibrate the overall instrumental signature of the LSST telescope, including the reflectivity of the mirrors, transmission of the camera refractive optics and filters, the quantum efficiency of the sensors in the camera, and the gain and linearity of the sensor read-out electronics.
2.1 CSS Requirements

The calibration screen system requirements have been updated recently as a result of self-calibration algorithmic improvements. The calibration screen system must uniformly illuminate the entire diameter telescope pupil over its field of view at desired monochromatic wavelengths in a way that allows the measurement of the total system throughput from entrance pupil to the digitization of charge in the camera electronics. The maximum spatial variation in the illumination was relaxed to 10% uniformity.

Two types of sources are required: 1) a broadband "white" light (WL) with a known spectral energy distribution without discontinuities from 320nm to 1100nm. The WL intensity emitted by the calibration screen shall be sufficient to produce a spectral radiance of at least 3 milli-Jansky per arcsec². 2) a tunable monochromatic light from 320nm to 1125nm with a maximum line width of 1nm and a minimum tuning step of 1nm. Its center wavelength must be known to a maximum uncertainty (1-sigma) of 1nm.

The optical flux emitted from the screen per exposure must be known to a relative precision of 0.2% RMS in the (g, r, i and z) filter bands and 0.3% RMS for the (u, y) filter bands.

The CSS shall be usable during the afternoon to permit long bandpass scan calibrations using the monochromatic light source. Further, the screen shall be usable during the hour just before evening twilight and the hour just after morning twilight of each night’s observing. Setting up the CSS and taking calibration data shall be possible within 30 minutes and it shall not take more than 5 seconds to change the wavelength of the monochromatic light source. Altogether, a filter scan shall be accomplished in 4 hours or less.

2.2 Calibration Screen

The previous design of the calibration screen incorporated an array of individual projectors pointed toward the telescope to fill the entrance pupil in order to meet the spatial uniformity requirements [7]. Thanks to the requirement relaxation, this design has been replaced with a simpler 10m diameter reflective surface screen and a new position was designated for its location on the dome (figure 1). The flat field screen will be at a distance approximately 13m away from the M1M3 mirror vertex. It is expected to be built from multiple panels and installed in the dome using a temporary hoist attached to the dome structure. The screen will have a 4m diameter hole in its center to match the large central obscuration of the LSST optical design. This central obscuration will be centered on one of the dome air vents to minimize the obstruction to the air flow flushing inside the dome when the air vents are opened.

During calibration, the telescope will be pointed toward the screen at an elevation angle of 23 degrees. A baffle will be located around the outside periphery of the screen. Additionally, the dome section located behind the screen will be either painted black or a retractable cover will be installed in the central obscuration to minimize scattered light during
calibration. The screen will be able to tilt from its calibration position to a vertical position to allow access behind the screen for maintenance of the dome vents. The screen will be coated with a special coating either from Labsphere called “Duraflect” [6] to obtain a lambertian surface or may have a Draper profile with a gain depending on the viewing angle. Small samples coated with the same coating will be placed near the calibration screen in the dome. These samples will be used to measure the coating bidirectional reflectivity distribution function (BRDF) and to monitor its aging over time.

### 2.3 Telescope Top End Assembly

The top end assembly (TEA) is principally composed of the spider and ring assembly, the secondary mirror (M2) cell assembly with hexapod and baffle, and the camera support assembly. The spider and ring assembly is composed of the spider spindle in its center, an outer ring and a set of 16 spiders to connect them together. Most of the light sources, projection system and photodiodes will be attached to the TEA either on the spider spindle or the outer ring. Four electrical cabinets will be installed on the exterior of the spider spindle with one cabinet dedicated to the calibration screen system. These cabinets will be thermally controlled to avoid releasing heat inside the dome.

![Telescope Top End Assembly](image)

**Figure 2 Telescope Top End Assembly (right) and electrical cabinet located on spider spindle (left)**

### 2.4 Light Sources

Stabilized quartz tungsten halogen lamps or similar will be located on the telescope top end to provide a broadband "white" light. These lamps provide a stable and smooth spectral curve without discontinuities that will cover the 6 filter bands. High power supercontinuum lasers offer another viable option although their spectral curve may not completely cover the required spectral range.

A tunable laser will be used to produce the tunable monochromatic light required for the calibration. The Ekspla NT242 tunable pulsed laser appears to meet most of the requirements. This laser was used previously for Pan-STARRS calibration [8]. As previously reported, the laser short pulse duration will remove the potential risk of speckle patterns. The laser source will be located in a designated room near the base of the telescope pier. Light from the tunable laser will be split off via optical fiber for delivery to the light projection system located on the telescope top end. The optical fiber will help randomize the polarized light produced by the laser. Its length will be around 80m as it will need to go through two cable drapes before reaching the telescope top end. Special optical fibers will be used to limit the amount of transmission loss over this long length.
Generating monochromatic dome flats in the u band filter will be the most challenging. The tunable laser output is limited, the optical fibers are lossy, and the system throughput is low below a wavelength of 400nm. So we are also exploring additional solutions for the calibration of the u-band.

2.5 Monochromatic Light Projection System

The monochromatic light emerging from the optical fibers will be projected from the telescope top end toward the calibration screen to illuminate it. The distance between the calibration screen and the light projection system will be around 4m. The radial distance will be around 1.3m from the calibration screen central axis to the sources located on the telescope top end spider spindle (inner ring) and around 4.7m to the sources located on the outer ring. To meet the uniformity requirement, a total of 24 sources have been considered so far for the baseline configuration, with 12 sources on the spider spindle (forming an inner ring) and 16 sources on the TEA outer ring. Because of the geometry, the inner ring sources will be tilted toward the calibration screen with an aim angle of approximately 19 degrees and the outer ring sources with an aim angle around 8.5 degrees. Each source will be built with a mask aperture to partially illuminate a region on the calibration screen. This baseline configuration will be revisited to explore reducing the number of sources while maintaining the uniformity requirement.
2.6 **Calibrated Photodiodes**

U.S. National Institute of Standards and Technology (NIST) calibrated photodiodes will be used to meet the optical flux measurement requirements. These NIST-calibrated photodiodes will be installed on the telescope top end facing the calibration screen to monitor the light emanating from its surface. The plan is to use Hamamatsu S2281 photodiodes mounted with temperature sensors. Each photodiode will monitor only a section of the calibration screen.

The output flux measured with the calibrated NIST photodiode will be compared to the flux measured by each pixel in the LSST camera. The full instrument throughput will be determined as a function of wavelength by scanning each filter bandpass spectrally using 1nm steps. During a scan, additional exposures will be recorded with the laser light shuttered off to compensate for ambient light present in the dome.

2.7 **White Light SED Spectrometer**

A separate spectrograph will be used to measure and to monitor the SED of the broadband white light emitted by the calibration screen. For this purpose, a possible commercially available instrument would be the CAS 140CT spectrometer from Instrument Systems.

This spectrometer covers the spectral range required and can be equipped with different probes to determine either the spectral radiance or the irradiance of a target. During calibration, the screen spectral radiance would be measured by locating the spectrometer on one of the telescope platforms from a position where a section of the calibration screen is directly visible. In addition, during integration and test, the screen irradiance could be computed from measurements in the LSST telescope focal plane before installation of the camera. Finally, it should be noted that this spectrometer could
also be used in conjunction with the monochromatic dome flats either to check the spectrograph spectral calibration
directly in the field or to measure the monochromatic radiance of the calibration screen.

2.8 Collimated Projector

A collimated projector will be used to discriminate focusing from stray and scattered light paths, and will be used in
conjunction with the calibration screen to measure the system throughput, using the NIST-calibrated photodiode as a
metrology standard. This projector will be installed on the dome main platform and pointed toward the telescope. This
location will allow for easy access for maintenance. The telescope will be pointed to an approximately 40 degree zenith
angle. The collimated projector will also be used to produce arbitrary patterns that can be re-imaged onto the LSST focal
plane, at a magnification given by the ratio of the LSST focal length to that of the collimator. This will allow us to obtain
precise measurements of crosstalk coefficients, by projecting a high-contrast array of spots. Finally, we believe that
projecting an image with a strong gradient in surface brightness will assist us in distinguishing charge transport
anomalies (arising from lateral electric fields within the CCDs) from actual QE variations.

2.9 CSS Control Software

To meet the operational requirements, a CSS control software will be developed to allow remote operation in an
automatic fashion of the calibration screen system. All relevant data and metadata will be saved in the engineering
facility database using the data distribution system selected by LSST. The CSS control software will interface with the
observatory control system to synchronize the timing of the photodiodes data acquisition with the camera images. An
engineering user interface will be developed in LabVIEW to control and to test all the components of the CSS.

Figure 7: Collimated projector located on the dome main platform and pointed toward the LSST Telescope
3. ATMOSPHERIC CALIBRATION SYSTEM

The purpose of the atmospheric calibration system (ACS) is to measure spatial and temporal variations of the atmospheric extinction independently of the main survey. This goal will be achieved by observing a set of probe stars with a dedicated calibration telescope called the auxiliary telescope located near the main LSST telescope and by deploying a set of instrumentation to monitor precipitable water vapor and cloud cover. The auxiliary telescope will be instrumented with a low resolution spectrograph to measure spectra of standard stars blended with atmospheric spectral features. These measurements will be combined with MODTRAN atmospheric models to fit and to characterize the atmospheric components present in the atmosphere and to monitor their variations. Finally, to cross-check with the nighttime measurements, we may also install on site a sun monitor system to measure atmospheric aerosol loading during daytime.

3.1 ACS Requirements

An Auxiliary Telescope (AT) shall be provided to measure spectra of stars with sufficiently fine sampling in spatial coordinates and time to determine the wavelength dependence of optical transmission of light through the atmosphere. The AT is expected to be operated remotely in an automatic mode following a programmable observing schedule. It shall be able to obtain an observation within a cadence of 5 min and be capable of observing from 20 degrees to 86.5 degrees in elevation.

The AT shall be instrumented with a spectrometer with a minimum spectral resolution of 1.5nm and a [400, 1125nm] wavelength range, and instrumented with calibration arc lamps over the full spectral range. The spectral calibration shall be predictable to within 1nm per night of observation and the detector gain (e-/ADU) shall be stable to 2% over that same period.

The integrated spectral Signal to Noise Ratio (SNR) shall be at least equal to 500 over the (g, r, i and z) filter bands and 300 for the (u, y) filter bands. This SNR requirement shall be achieved on source targets with an r-band magnitude m=12. The AT is required to meet the integrated SNR without saturating for an r-band magnitude m=8.

The atmospheric calibration system is also required to include a water vapor monitoring system. In addition, the system is required to map and to monitor cloud cover to provide a 2-D map of the extinction.

3.2 Auxiliary Telescope

An auxiliary telescope (AT) located on Cerro Pachón near the main survey telescope is included in the LSST design. This auxiliary telescope already exists and was operated for two years by LSST. It was located on Kitt Peak near Tucson in Arizona and known as the Calypso Telescope.

Figure 8: Auxiliary telescope on Kitt Peak, AZ called the Calypso Telescope
This Ritchey-Chretien telescope contains a 1.2m clear aperture primary mirror with an f-number of 18. It is designed with two Nasmyth platforms, each with a maximum field of view of 30 arcmin in diameter. The plate scale is equal to 100 micron per arcsec at the Nasmyth focus. Dynamic measurements taken on Calypso showed minimal image jitter thanks to its high telescope natural frequencies. The telescope was just recently moved from Kitt Peak to the National Optical Astronomy Observatory (NOAO) in Tucson where its control system will be refurbished before shipping to Chile. The telescope drives and control system will be updated to be operated remotely in an automatic mode and to keep up with the observing cadence required during operation.

Figure 9: Auxiliary telescope at NOAO where it will be refurbished

Figure 10: Auxiliary Telescope new building on Cerro Pachón
The AT will patrol the area surveyed by the LSST main telescope by observing repeatedly a set of probe stars. These stars will be adequately spaced on the sky to sufficiently sample the surveyed fields spatially in order to interpolate the measured data for any pointing direction. The M2 hexapod will be upgraded to a high-reliability commercial system for focus and alignment control. The retrofit to the telescope drives will also allow reducing the slew duration in between observations. The auxiliary telescope will be sited in a new building on Cerro Pachón with a new 9.3m diameter dome from Ash-Dome. This dome will be instrumented to permit automatic operations with limited operator intervention.

3.3 Low Resolution Spectrograph

One of the AT Nasmyth platforms will house a low resolution spectrograph. A conceptual design for a slit spectrograph was optimized for the AT. This design is based on using two silica prisms to provide a spectral resolution of better than 300 over the [400nm – 1125nm] range for a slit size of 0.8 arcsec. The slit size was selected to match the expected seeing. It includes a 4Kx2K CCD detector with 15 micron pixel size and a plate scale of 0.27 arcsec/pixel to image the whole spectral range on the CCD.

Provision for a fold mirror was included in the spectrograph design for a calibration beam to be inserted in the main beam for spectral calibration. Calibration exposures will be taken using spectral lamps and spectrophotometric standard stars will also be observed many times for calibration. Finally an optical layout for a slit viewer was also incorporated in the design to help centering the target on the slit. This slit will be reflective on the viewer side for guiding during an observation. The other Nasmyth platform will have imaging and wavefront sensing capabilities to be used during commissioning and for alignment of the telescope during operations.
3.4 Precipitable Water vapor and Cloud Monitoring

A microwave radiometer and a global positioning system (GPS) will be deployed on Cerro Pachón to monitor the amount of precipitable water vapor (PWV) in the atmosphere. All-sky infrared and visible cameras will be used for cloud monitoring.

3.4.1 Microwave Radiometer

Microwave radiometer networks have been operated for many years to record atmospheric radiation measurement for climate research [9]. A possible radiometer to install on Cerro Pachón would be the MP-1500 microwave radiometer from Radiometrics. It can measure precipitable water vapor with an accuracy of +/-1mm or better. In the standard observation mode, the instrument makes a complete set of channel acquisitions, including tip data, in less than a minute. This duration could be shortened by observing on fewer channels. It is also possible to reduce noise by integrating for longer time periods, but at the cost of increasing the observation time. The radiometer does not require an external calibration target; it uses an internal target and the sky for calibration (Tip cal). Its field of view is approximately 6 degrees. The radiometer would be mounted on a tripod with an azimuth positioner to reorient the radiometer to make measurements in any azimuth direction. In addition, a fold mirror mounted on a stepper motor would allow measurement at any zenith angle. Every sky observation command would include the zenith and azimuth observation angles of the LSST telescope to point the radiometer to the same observed field. The observation commands would be included in a procedure file, which would automate the radiometer observation. The azimuth positioner rotates at a velocity of approximately 15deg/sec and the elevation moves even faster (~5deg/100ms) so the instrument would be able to change pointing very quickly. The system can start collecting data immediately once the azimuth and elevation motions are completed. The pointing accuracy is limited by the resolution of the stepper motors; it is within +/- 0.1 degrees of the specified elevation and azimuth angles. In addition, the data would be collected and analyzed to provide pressure and temperature profiles up to 10km height.

3.4.2 GPS Receiver

A GPS receiver will be installed at the summit to continuously monitor the PWV during daytime and nighttime. A Trimble NetR9 GPS receiver was identified as a good candidate. Other observatories have already employed this type of instrumentation for that purpose, converting the wet tropospheric zenith delays derived from the GPS data to an amount of PWV. The system will be able to store all the required data to be analyzed off-site by a third party like the SuomiNet GPS network. We will also investigate being able to analyze the GPS data on-site for shorter latency.

Figure 13: Low resolution spectrograph with calibration optics fold mirror optical layout
3.4.3 All-Sky Cameras

The All Sky Infrared Visible Analyzer (ASIVA) system from Solmirus will be installed on Cerro Pachón for cloud detection and monitoring [10]. It includes a thermal mid-infrared camera to detect directly the emission from clouds and also a visible camera to combine both visible and infrared cloud analysis in one instrument. The IR camera subsystem features a 640 × 512 uncooled microbolometer array sensitive to 8–14 $\mu$m radiation, a 180-degree (all sky) custom lens, and a six-position filter wheel. The visible camera subsystem includes a 3296 × 2472 imaging array with an F2.8 fisheye lens and a filter wheel capable of holding 8 filters. Both cameras are protected from the weather by a common hatch that covers the lenses in its closed position. This instrument will provide the LSST scheduler with real-time measured conditions to optimize the observing cadence. The analysis of both infrared and visible images will also provide an estimation of the optical opacity of the clouds and the ability to construct a transparency map of the atmosphere.

![Figure 14: ASIVA all-sky camera with hatch closed (left) and with hatch open (right).](image)

REFERENCES