

Level 2 Photometric Calibration for the LSST Survey

Lynne Jones, David Burke, Željko Ivezić, and the Photometric Calibration Team

1. Introduction

Two levels of LSST photometric calibration will be carried out at differing cadences and with differing performance targets. A nightly data calibration based on the best available set of prior calibrated observations will provide best-effort precision and accuracy. This calibration will be used for quality assurance, generation of alerts for transient objects, and other quantities appropriate for nightly data generation (Level 1 Data Product in LSST Data Management terms). A more complete analysis will recalibrate the data accumulated by the survey at periodic Data Release dates (aka Level 2 Data products). It is this repeated calibration of the accumulated survey that will be held to the survey requirements for photometric repeatability, uniformity, and accuracy. This document describes the calibration requirements and processes for the Level 2 photometric calibration.

Section 2 reviews the survey requirements for photometric calibration, while Section 3 describes the philosophy behind LSST's calibration procedure, first motivating this procedure by describing the true path of a photon through the atmosphere and LSST system and then from the calibration point of view, trying to recreate the transmission of those photons to the focal plane. Section 4 describes details of each step of the calibration procedure, including how each calibration measurement is obtained and applied to the science data along with expected errors originating from each step.

LJ - add exciting info somewhere here on why 2x better (-*i* 10x better in color/color space). and why we think we can do 2x better.

2. Photometric Requirements

The LSST Science Requirements Document (SRD) specifies that the survey must deliver photometry with the following characteristics:

1. **Repeatability:** the median value of the rms of calibrated magnitude measurements around the mean calibrated magnitude for each star will not exceed 5 millimags in *gri*, 7.5 millimags in *uzy* for bright unresolved objects (bright implying that the measurement of the star's brightness is not dominated by photon statistics, approximately 1-4 magnitudes fainter than the saturation limit in a given filter). No more than 10% of

these objects should have an rms larger than 15 mmag in *gri*, 22.5 mmag in *uzy*. This specifies the distribution of random photometric errors (σ) and constrains both the repeatability of extracting counts from images and the ability to monitor (or model) the changes in normalized system response (ϕ). It could be thought of as making the photometry of a single source consistent over time.

2. **Uniformity:** the rms of the internal photometric zeropoint error will not exceed 10 millimags in *grizy*, 20 millimags in *uzy*, again for bright unresolved sources. No more than 10% of these sources should be more than 15 mmag in *gri* or 22.5 mmag in *uzy* from the mean internal zeropoint. This places a constraint on the stability of the photometric system across the sky as well as places an upper limit on various systematic errors, such as any correlation of photometric calibration with varying stellar populations (or colors). This makes the photometry of many sources comparable over the entire sky, which when combined with the previous requirements creates a stable photometric system across the sky and over time, in a single filter.
3. **Band-to-band photometric calibration:** The absolute band-to-band zeropoint calibration for main sequence stars must be known with an accuracy of 5 millimags for any color not involving *u* band, 10 millimags for colors constructed with *u* band photometry. This places an upper limit on the systematic error in the measurement of the system throughput as a function of wavelength. This requirement ties photometric measurements in different filters together, enabling colors to be measured for sources with unknown spectral energy distributions (SEDs) or (for sources with known SEDs) magnitudes in different filters to be directly compared.
4. **Absolute photometric calibration:** The LSST photometric system must transform to an external physical scale (*e.g.* AB mags) with an accuracy of 10 millimags. This requirement ties LSST internal photometry to a physical scale, and places a constraint on the upper limit of the systematic error in the measurement of the total system throughput. This final step enables LSST photometry to be compared with photometry from other telescopes using other photometric systems.

Requirements 1 and 2 must be met by compensating for changes in system sensitivity as a function of time, location in the sky or focal plane, and result in a relative calibration within a single filter. Requirements 3 and 4 require additional measurements of sources with known colors and absolute magnitudes, providing a relative calibration from filter to filter as well as an absolute physical scale for the overall system.

Only photometric measurements released as part of the data release products (generated annually) will be held to the requirements above. On a nightly timescale, photometric

measurements needed for alert generation, quality assurance, or other short-timescale data products will be generated to “best-effort” precision and accuracy using the best-available prior calibrated observations.

3. Overview of the photometric calibration process

In traditional photometric calibration, a set of standard stars are observed at a range of airmasses to calculate zeropoint offsets and (typically) a single color-dependent extinction term. This is sufficient for photometry at the few percent level on photometric nights, however, historical weather data from Cerro Pachon tells us only 53% of the available observing time can be considered photometric even at the 1–2% level. To take advantage of the full 85% of the available observing time which is usable (total cloud extinction less than 1.5 magnitudes), and to reach the SRD specified requirements – 0.5% level photometric repeatability and 1% photometric uniformity – requires a new approach.

This new approach lies in splitting the measurement of the *normalization* of the throughput in each observation (the gray-scale zeropoint) from the *shape* of the throughput curve (the color dependent terms), and further, using separate procedures to measure the contributions of the telescope hardware response (to the total normalization and bandpass shape) from the atmospheric throughput (to normalization and shape). This allows the use of optimized methods to measure each individual component affecting the final measured magnitudes, allowing us to achieve photometric calibration at the required levels.

This section will provide an overview of the calibration measurements required and motivate the process itself, starting with a review of what is physically happening to photons in their path toward the focal plane (the ‘truth’) then followed by an outline of how the measured ADU counts can be translated back to photons above the atmosphere (the ‘model’).

3.1. From photons to counts

Let us first consider how the photons from an astronomical object are converted into ADUs in the detector, paying attention to what variations (including their time and spatial scales for variability) might arise in the LSST system to affect the final ADU counts. This is the ‘truth’ that the calibration procedure must attempt to recreate.

Note - while $F_\nu(\lambda, t)$ and other quantities that are functions of time could vary more quickly than the standard LSST exposure time of 15s, it is assumed that all such quantities are averaged over that short exposure time, so that t refers to quantities that can vary from

exposure to exposure.

Given $F_\nu(\lambda)$, the specific flux of an object at the top of the atmosphere, at a position described by (alt, az) , the flux transmitted through the atmosphere to the telescope pupil is

$$F_\nu^{pupil}(\lambda, alt, az, t) = F_\nu(\lambda) S^{atm}(\lambda, alt, az, t), \quad (1)$$

where $S^{atm}(\lambda, alt, az)$ is the (dimensionless) probability that a photon of wavelength λ makes it through the atmosphere,

$$S^{atm}(\lambda, alt, az, t) = e^{-\tau^{atm}(\lambda, alt, az, t)}. \quad (2)$$

Here $\tau^{atm}(\lambda, alt, az)$ is the optical depth of the atmospheric layer at wavelength λ towards the position (alt, az) . Observational data (Stubbs et al. 2007b; Burke et al. 2010) show that τ^{atm} can vary as a function of wavelength and position (alt, az) on the order of 5-10% per hour due to changes in water absorption, aerosol scattering, rayleigh scattering, and molecular absorption. Clouds represent an additional gray (non-wavelength dependent) contribution to τ^{atm} that can vary even more rapidly, on the order of 2-10% of the total extinction at 1° scales within minutes (Ivezic et al. 2007).

Given the above $F_\nu^{pupil}(\lambda, alt, az, t)$, then the ADU counts recorded at a position within the field of view described by (x, y) can be written as

$$C_b(alt, az, x, y, t) = C \int_0^\infty F_\nu^{pupil}(\lambda, alt, az, t) S_b^{sys}(\lambda, x, y, t) \lambda^{-1} d\lambda. \quad (3)$$

Here, $S_b^{sys}(\lambda, x, y, t)$ is the (dimensionless) probability that a photon will be converted into an ADU count, and the term λ^{-1} comes from the conversion of energy per unit frequency into the number of photons per unit wavelength (and b refers to a particular filter, $ugrizy$). The dimensional conversion constant C is

$$C = \frac{\pi D^2 \Delta t}{4gh} \quad (4)$$

where D is the effective primary mirror diameter, Δt is the exposure time, g is the gain of the readout electronics (number of photoelectrons per ADU count, a number greater than one), and h is the Planck constant. The system response function, $S_b^{sys}(\lambda, x, y)$, includes the effects of the mirror reflectance, optics transmission and detector sensitivity. Here the wavelength-dependent variations in S_b^{sys} generally change quite slowly in time; over periods of months, the mirror reflectance and filter transmission will degrade as their coatings age. A more rapidly time-varying wavelength-dependent change in detector sensitivity (particularly at very red wavelengths in the y band) results from temperature changes in the detector, but only on scales equivalent to a CCD or larger. There will also be wavelength-dependent

spatial variations in S_b^{sys} due to irregularities in the filter material; these are expected to vary slowly from the center of the field of view to the outer edges, equivalent to a bandpass shift on the order of 1-2% of the effective wavelength of the filter. Wavelength-independent (gray-scale) variations in S_b^{sys} occur more rapidly, on the timescale of a day, and at spatial scales as small as the pixel level. There are a range of causes for these variations: dust particles on the filter or dewar window, gain changes between amplifiers, or pixel-to-pixel detector sensitivity variations.

From equation 3 and the paragraphs above, we can see that the generation of counts $C_b(alt, az, x, y, t)$ from photons is imprinted with many different effects, each with different variability scales over time, space, and wavelength. In particular the wavelength-dependent variability (bandpass shape) is typically much slower in time and space than the gray-scale variations (bandpass normalization). These different scales of variability motivate us to separate the measurement of the normalization of S_b^{sys} and S^{atm} from the measurement of the wavelength-dependent shape of the bandpass.

This then leads us to introduce a ‘normalized bandpass response function’, $\phi_b(\lambda, alt, az, x, y, t)$,

$$\phi_b(\lambda, alt, az, x, y, t) = \frac{S^{atm}(\lambda, alt, az, t) S_b^{sys}(\lambda, x, y, t) \lambda^{-1}}{\int_0^\infty S^{atm}(\lambda, alt, az, t) S_b^{sys}(\lambda, x, y, t) \lambda^{-1} d\lambda}. \quad (5)$$

for each observation. Note that ϕ_b only represents *shape* information about the bandpass, as by definition, $\int_0^\infty \phi_b(\lambda) d\lambda = 1$.

From Equations 1 and 3, we can then recast the counts received from an object as

$$\begin{aligned} C_b(alt, az, x, y, t) &= C \int_0^\infty F_\nu(\lambda, t) S^{atm}(\lambda, alt, az, t) S_b^{sys}(\lambda, x, y, t) \lambda^{-1} d\lambda \\ &= C'^{atm}(alt, az, t) C'_b^{sys}(x, y, t) \int_0^\infty F_\nu(\lambda, t) \phi_b(\lambda, alt, az, x, y, t) d\lambda \end{aligned} \quad (6)$$

where $C'^{atm}(alt, az, x, y, t)$ and C'_b^{sys} are wavelength-independent values that depend only on the *normalization* of the independent atmospheric and system throughputs. We can thus measure and apply corrections for the normalization of the atmospheric and hardware transmission separately, without consideration of the shape of the bandpass. We can also introduce a well-defined ‘standard’ bandpass response, $\phi_b^{std}(\lambda)$, chosen during commissioning, so that

$$\begin{aligned} C_b(alt, az, x, y, t) &= C'^{atm}(alt, az, t) C'_b^{sys}(x, y, t) \times \\ &\quad \left(\frac{\int_0^\infty f_\nu(\lambda, t) \phi_b^{obs}(\lambda, alt, az, x, y, t) d\lambda}{\int_0^\infty f_\nu(\lambda, t) \phi_b^{std}(\lambda) d\lambda} \right) \times \\ &\quad \int_0^\infty F_\nu(\lambda, t) \phi_b^{std}(\lambda) d\lambda \end{aligned}$$

(7)

where $F_\nu(\lambda, t) = F_o(t) f_\nu(\lambda, t)$, separating the normalization (F_o) and shape (f_ν) of the source spectral energy distribution ($m_{AB} = 2.5 \log_{10}(F_o/3631 \text{ Jy})$). It's worth noting that $\int_0^\infty F_\nu(\lambda, t) \phi_b^{std}(\lambda) d\lambda$ is a constant value for a non-variable source. For convenience, the middle term above can be written as

$$K' \left(\int f_\nu \phi_b^{obs} d\lambda \right) = \left(\frac{\int_0^\infty f_\nu(\lambda, t) \phi_b^{obs}(\lambda, alt, az, x, y, t) d\lambda}{\int_0^\infty f_\nu(\lambda, t) \phi_b^{std}(\lambda) d\lambda} \right) \quad (8)$$

where K' is a value that depends only on the *shape* of the system throughput during a particular observation and the *shape* of the SED of the astronomical object, but does not depend on the normalization of the total throughput or the total flux of the object. Note that K' simplifies to unity if the source SED, $f_\nu(\lambda)$, is constant with wavelength (i.e. a flat SED). The variation in the total counts arising from the K' term is dependent on the cumulative effect of both the atmosphere and the hardware transmission curves on the source SED, thus while the underlying wavelength-dependent (shape) variations in S_b^{sys} and S^{atm} are independent and can be measured separately, the resulting effect can only be applied as a combined correction.

Examples of the effects of variations in the $\phi_b^{sys}(\lambda)$ (hardware response) and $\phi^{atm}(\lambda)$ (atmospheric response) curves on the final observed counts are shown in Figure 1 and Table 1. Two main sequence stellar models (Kurucz 1993) – one with temperature 35000K (blue) and one 6000K (red) – were combined with three different atmospheric response curves and two different hardware response curves to illustrate the resulting changes in observed magnitudes. In Figure 2, the $X = 1.5$ atmospheric response is combined with the 1% shift in filter bandpass (altering the hardware response) for many main sequence kurucz models, spanning a range of $g - i$ colors, and the resulting changes in observed magnitudes are plotted. These examples demonstrate that the scatter in observed magnitudes induced by expected atmospheric and hardware transmission curve shape changes alone (without any gray-scale changes) can be larger than the SRD repeatability requirements would permit. Adding variations in the gray-scale normalization due to the hardware response (typically on the order of 0.01 magnitudes) and cloud extinction (could be up to a few magnitudes) will increase the scatter in observed magnitudes.

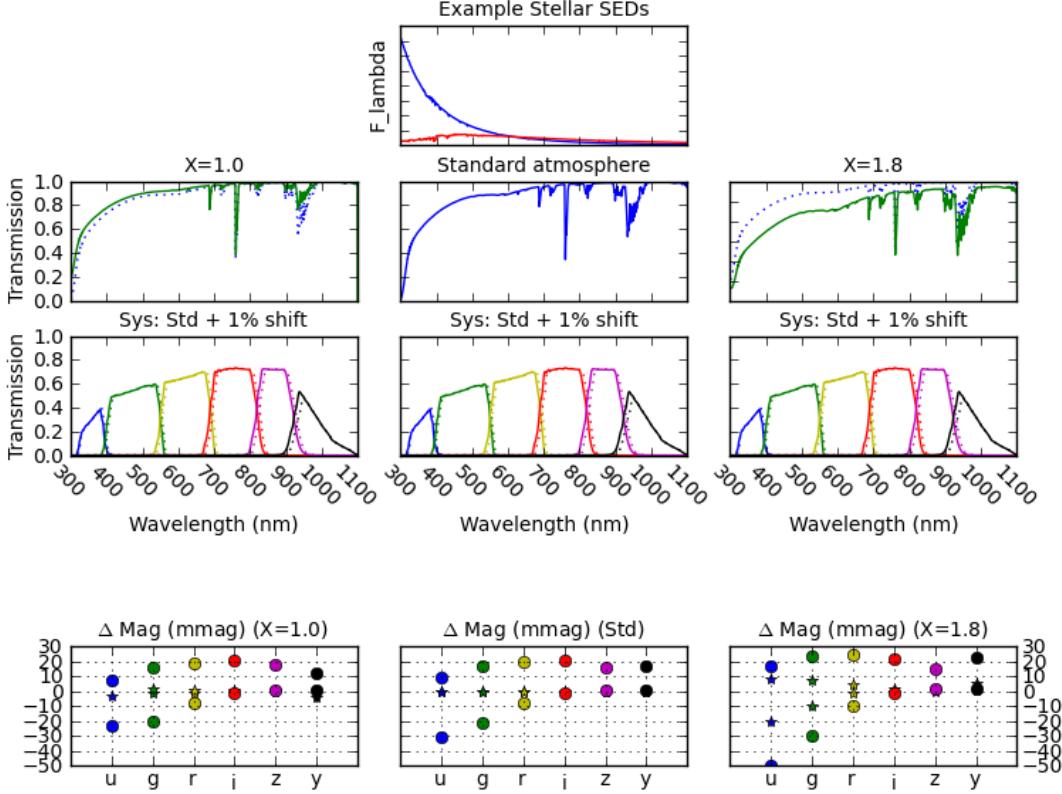


Fig. 1.—: **Changes in observed magnitudes (counts) due to variations in hardware and atmospheric bandpass shape.** Two main sequence kurucz model stars, one blue (35000 K) and one red (6000 K), were used to generate observed magnitudes (equivalent to $-2.5 \log(C_b)$ - the counts in Eqn 7) using three different atmospheric transmission profiles and two different hardware transmission profiles. The stellar flux profiles are shown in the top center panel, while the atmospheric transmission functions ($S^{atm}(\lambda)$) are shown across the second row and the two hardware transmission profiles ($S_b^{sys}(\lambda)$) are duplicated across the third row. The atmospheric transmission profiles correspond to an airmass=1.0, 1.2 and 1.8 (from left to right), with variable atmospheric absorption components. The X=1.0 atmosphere is very similar but not identical to the current LSST default X=1.2 atmosphere throughput curve, which is used as ‘standard’ here. The hardware transmission profiles consist of a ‘standard’ profile (matching the LSST current expected values) and version where the filter throughputs have been shifted by 1% of the effective wavelength of each filter (consistent with the shift expected near the edge of each filter). The final row demonstrates the changes in observed magnitudes produced by the X=1.0, ‘standard’ and X=1.8 atmospheres (left to right, respectively), combined with both the ‘standard’ hardware transmission (represented by the star points) and the +1% shifted hardware transmission (represented by the filled circles) for both the red and blue stars. The exact differences in magnitudes resulting from this calculation are listed in Table 1.

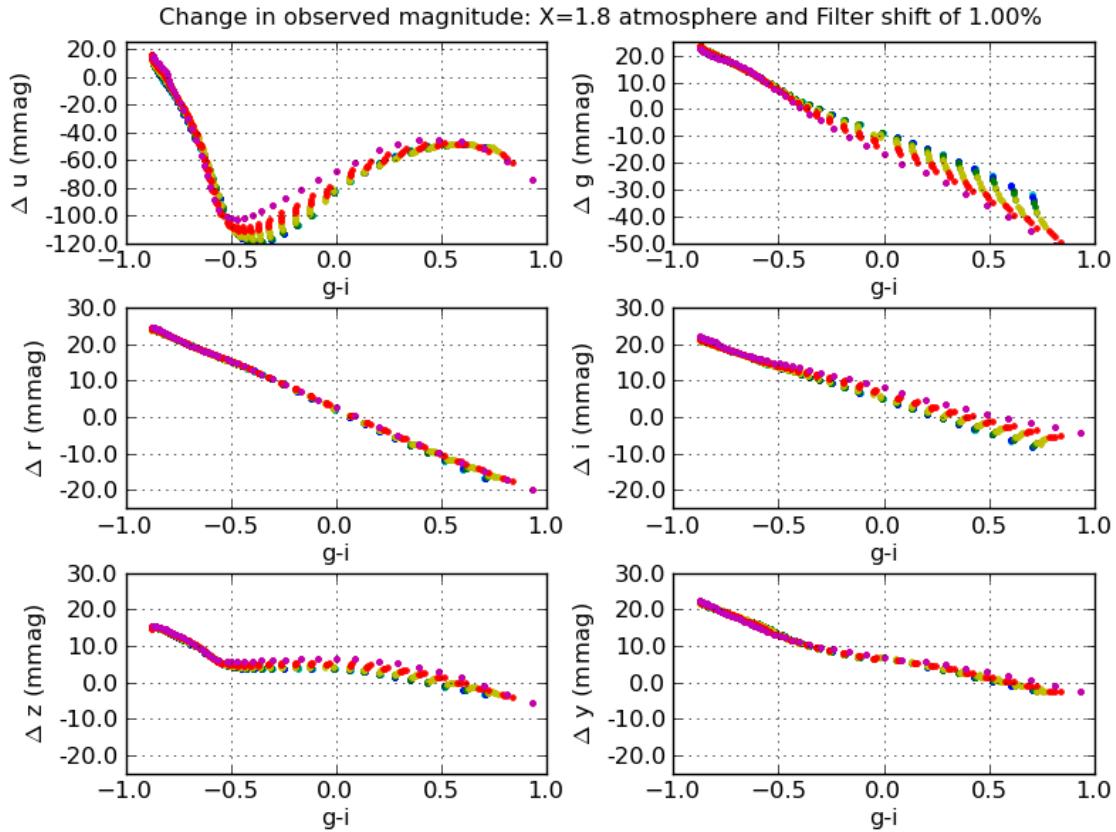


Fig. 2.—: **Changes in observed magnitudes (counts) due to a change in bandpass shape corresponding to a filter shift of 1% and an $X = 1.8$ atmosphere.** 850 Kurucz models with temperatures between 5000K and 35000K and metallicity indexes between -5.0 and 1.0 (solar) were combined with a standard system response (standard atmosphere and standard hardware bandpasses), then with a total system response where the atmosphere was replaced by an $X=1.8$ atmosphere and the filter component of the hardware transmission was shifted by 1% (as in Fig 1). It can be seen that the relationship between Δm and $g - i$ can be parameterized, although generally not with a simple linear relationship. In some cases (such as seen in the Δu and Δg panels), calculating Δm to SRD levels may require more than a simple $g - i$ color, but this is then primarily a function of metallicity which is possible to determine given the $u - g$ color in addition to the $g - i$ information. The points in each plot are color-coded by metallicity, in steps of 1 dex between -5.0 (blue) to 1.0 (magenta).

Table 1:: Changes in observed magnitudes due variations in system and atmospheric bandpass shape (see also Fig 1). The first two rows show the baseline (‘true’) magnitude of the star. All other rows show the *change* in magnitude (in mmag) due to the changes listed at left.

		<i>u</i>	<i>g</i>	<i>r</i>	<i>i</i>	<i>z</i>	<i>y</i>
Standard atm, std sys	red	21.472	20.378	20.000	19.911	19.913	19.913
Standard atm, std sys	blue	19.102	19.503	20.000	20.378	20.672	20.886
Standard atm, +1% sys shift	red	-30.509	-21.591	-8.016	-1.505	0.889	0.944
Standard atm, +1% sys shift	blue	9.480	16.838	19.624	20.462	16.088	16.300
X=1.0, std sys	red	7.470	1.747	0.332	0.045	-0.132	-0.522
X=1.0, std sys	blue	-2.864	-1.319	-0.964	-0.279	0.870	-3.839
X=1.0, +1% sys shift	red	-23.780	-20.165	-7.673	-1.463	0.695	0.451
X=1.0, +1% sys shift	blue	6.966	15.703	18.601	20.249	17.553	12.099
X=1.8, std sys	red	-20.742	-9.581	-1.546	-0.189	0.145	0.634
X=1.8, std sys	blue	7.698	7.515	4.328	1.554	-0.584	5.657
X=1.8, +1% sys shift	red	-49.921	-30.023	-9.531	-1.677	1.088	1.540
X=1.8, +1% sys shift	blue	16.480	23.797	24.042	21.880	14.780	22.326

3.2. From counts to photons

The previous section laid out the origins of ADU count variability from one observation to another. Now we will consider how we can, in practice, acquire the information necessary to convert a particular observed ADU count to a measurement of $F_\nu(\lambda, t)$ above the atmosphere for a particular object. In other words, how we can recreate the ‘truth’ by compensating for the variations in $S^{atm}(\lambda, alt, az, t)$ and $S_b^{sys}(\lambda, x, y, t)$, using the separability of the normalization and shape of the total system response.

Let us first consider measurement of the variations in $S_b^{sys}(\lambda, x, y, t)$. By using a dome-screen system that is capable of producing light at a range of individual wavelengths, we can measure the sensitivity of the hardware (mirrors + lenses + filter + detector) transmission as a function of x, y at each wavelength, producing a data cube of ‘narrow band flat fields’. At a particular x, y location, this data cube records the shape of the transmission response in λ (measuring $\phi_b^{sys}(\lambda, t)$). By flattening the data cube through the λ axis using a chosen spectral energy distribution, the resulting 2-dimensional (x, y) ‘synthetic flat field’ records the normalization of $S_b^{sys}(x, y, t)$. Generation of the synthetic flat field in this manner is time-consuming (requiring many hours to scan through all 6 filters at the necessary wavelength intervals, $\sim 1nm$), however the wavelength-dependent effects are expected to vary only

slowly over time, so the full narrow band flat field scan will only be repeated every 30 days. Since gray-scale normalization changes are likely to occur on a much more rapid timescale, standard white-light flat fields will also be acquired at the start and end of each night. These will be used to correct the normalization of the system response on a nightly basis, updating the synthetic flat field (which has the desired SED) for the current changes in normalization. This flat field correction is particularly important over small spatial scales, as no later calibration stage can contribute to normalization corrections at less than a few times the Point Spread Function (PSF).

It is worth noting that these flat fields (both narrow band and white-light) must themselves be corrected for the effects of pixel scale variations across the field of view, for ghosting caused by internal reflections in the camera and for the presence of stray or scattered light captured in the flat. This correction is called the ‘illumination correction’. The illumination correction will be generated by combining the measurements of the system throughput from the dome screen narrow band flats, measurements of bright, dense star fields rastered across the field of view during specialized observing sequences, and measurements of the ghost patterns at various wavelengths and incident angles obtained with the ‘camera calibration optical bench’ (CCOB). It is likely (as the ghosting pattern is wavelength-dependent) that this illumination correction will have some wavelength dependence. See Figures 4 and 5 for a visual example of the illumination correction and effect on image processing. The illumination correction is expected to be stable with time and will be remeasured only when the optical path of the telescope is altered.

Next, considering $S^{atm}(\lambda, alt, az, t)$, we will again separate the measurement of the shape of the atmospheric response and the measurement of normalization of the transmission. The wavelength-dependent variations in $\phi^{sys}(\lambda, t)$ change smoothly over spatial scales larger than the field of view and over several minutes. By using an auxiliary telescope equipped with a spectroscope to observe bright stars with known SEDs, we can measure atmospheric absorption at a variety of positions in the sky every 5–10 minutes throughout the night. These observations are used as constraints for MODTRAN atmospheric models, generating simpler representations of the atmospheric throughput (in the form of a set of absorption components as a function of alt, az, t). These components can be interpolated to generate a wavelength-dependent atmospheric absorption profile, $S^{atm}(\lambda, alt, az, t)$, for each observation. In order to correct for the higher frequency gray-scale variations in the normalization of $S^{atm}(alt, az, t)$ due to cloud extinction, we must use the observations of stars in the images themselves, as the cloud extinction can vary up to 0.01 magnitudes on the scale of a CCD (Ivezic et al. 2007) as fast as a few minutes. This ‘self-calibration’ procedure could be thought of as creating a massive calibration ‘standard’ star catalog, where the calibration stars are all of the non-variable, main-sequence stars in the science images; the main difference is that the

true magnitudes of the calibration stars have to be bootstrapped from the many different observations of the survey. The calculation of the calibration star magnitudes and the determination of the normalization for $S^{atm}(alt, az, t)$ are achieved simultaneously. First the previously described corrections for $\phi^{atm}(\lambda, t)$, $\phi_b^{sys}(\lambda, t)$ and the flat field normalization must be added to each observation, producing a ‘standardized’ magnitude for each star, and then in ‘self-calibration’, we minimize the difference between the standardized magnitude and a model magnitude,

$$\chi^2 = \sum_{ij} \left(\frac{m_{b,ij}^{std} - m_{b,ij}^{model}}{\sigma_{b,ij}^{std}} \right)^2 \quad (9)$$

where the model magnitude is derived from the best-fit ‘true’ magnitude of the calibration star and the normalization constant (zeropoint offset) for this ‘patch’ (equivalent to the size of a CCD)

$$m_{b,ij}^{model} = m_{b,i}^{best} - \delta z_{b,j}. \quad (10)$$

This produces best-fit magnitudes for the calibration star catalog as well as zeropoint offsets (normalization constants) for each CCD in every observation. This procedure can also correct for variations in the normalization of the total system throughput beyond those contributed by cloud extinction, but will not be sensitive to changes on scales smaller than a patch. This is similar in nature to the ubercal method applied to SDSS in Padmanabhan et al. (2008).

Using Equation 7, we can define a ‘natural magnitude’

$$m_{nat} = -2.5 \log_{10} \left(\int_0^\infty F_\nu(\lambda, t) \phi_b^{std}(\lambda) d\lambda \right) \quad (11)$$

$$= -2.5 \log_{10} \left(\frac{C_b(alt, az, x, y, t)}{C'^{atm}(alt, az, t) C'^{sys}_b(x, y, t) K'(\int f_\nu \phi_b^{obs} d\lambda)} \right) \quad (12)$$

describing the quantity we wish to derive from the measured ADU counts. The natural magnitudes can be related to the corrections just described above by

$$\begin{aligned} m_b^{nat} &= -2.5 \log_{10} (C_{b,raw}(alt, az, x, y, t)) \\ &\quad + \delta z_b^{ff}(x, y, t) + \delta z_b^{selfcalib}(alt, az, t) \\ &\quad + \delta k_b^{atm+sys}(alt, az, x, y, SED, t), \end{aligned} \quad (13)$$

where δz_b^{ff} comes from the normalization constant derived from the illumination-corrected synthetic flat field, updated for variations in normalization on a night-to-night basis by the white-light flat (and applied directly to the science images at the pixel level in the traditional manner), $\delta z_b^{selfcalib}$ comes from the normalization constant derived from the self-calibration method, and $\delta k_b^{atm+sys}$ depends on the shape of the total system response (atmosphere +

hardware measured from the auxiliary telescope and the narrow band flat fields) as well as the shape of the source SED. The color-term correction $\delta k_b^{atm+sys}$ is effectively a lookup table for each observation, where $\phi_b^{sys}(\lambda, x, y, t)$ and $\phi^{atm}(\lambda, alt, az, t)$ are combined with a series of model SEDs and the resulting magnitude variation is recorded as a function of source SED and x, y in the focal plane (as the atmospheric variation is roughly constant across the field of view). For many sources (but not calibration stars) LSST will simply assume a flat SED, at which point the $\delta k_b^{atm+sys}$ correction becomes zero, and users may create their own SED and correction tables based on their knowledge of the true SED (see Appendix B).

These natural magnitudes are calibrated for variations in the observed bandpass shape (where applicable) and normalization, thus are directly comparable from one observation to another. However, they are not tied to an external physical scale (or from one filter to another), and thus only define an internally calibrated LSST magnitude in a particular filter.

To fulfill SRD requirements 3 and 4, these internally calibrated natural magnitudes must be tied from one filter band to another, and then tied to an absolute external physical scale. For this, a further set of measurements is needed. In all filters, a set of objects with a well-known spectral type (such as main sequence stars or white dwarfs, preferably with direct observations of the SED of the specific object) must be observed and calibrated, in individual filters, as above. The prior knowledge of each SED is combined with the standard bandpass shape to generate synthetic color photometry. These synthetic colors are then compared with the calibrated measured natural magnitudes to calculate Δ_{b-r} , the corrections needed to tie measurements in each filter together (referenced to r band). At this point, only one final measurement is necessary to tie the entire system to an external physical scale: an r band LSST natural magnitude measurement of an absolutely calibrated source on a photometric night. Although in theory these last two steps could be done with a single externally calibrated object, on a single photometric night, a larger set of external reference objects with well known AB magnitudes will be used to reduce systematic errors. This defines an AB magnitude,

$$m_b^{AB} = m_b^{nat} + \Delta_{b-r} + \Delta_r \quad (14)$$

which can be compared to absolute physical flux scales.

The sequence for photometric calibration is then:

1. Acquire narrow band flat fields on a monthly basis, acquire white-light flat fields to update the narrow band flat fields on a nightly basis, and generate an illumination correction on a many-monthly basis. Apply the illumination correction to the narrow band flat fields and combine the narrow band flat fields into a synthetic flat using

a chosen SED (perhaps mimicking the night sky SED). Scale the synthetic flat for any measured changes in the white-light flat occurring since the generation of the synthetic flat. Apply final synthetic flat to images directly, dividing science images by the synthetic flat field.

2. After remaining image processing (bias correction, fringe correction, etc) extract ADU counts of sources from images.
3. Acquire spectra of known stars on a 5–10 minute timeline throughout each night, fit for atmospheric absorption coefficients and generate atmospheric response curve for each science image’s alt, az, t based on MODTRAN models, retrieve hardware response curve from narrow band flat fields at various x, y locations within the focal plane. Using a range of model SEDS, generate a table of $k_b^{atm+sys}(x, y, SED)$ corrections for each observation. Apply $k_b^{atm+sys}$ corrections to stars chosen for self-calibration.
4. At appropriate intervals (such as at Data Release), minimize χ^2 from Equation 9 for the self-calibration stars and record $\delta z_b^{selfcalib}$ for each patch (each CCD in each observation).
5. Apply $\delta z_b^{selfcalib}$ to all stars in calibration patch. If an SED is known or has been chosen for particular science targets, apply appropriate $k_b^{atm+sys}$ correction.
6. Apply measured corrections Δ_{b-r} and Δ_r .

resulting in calibrated m_b^{AB} values in a standardized bandpass shape, with above-the-atmosphere fluxes.

4. The internal calibration process

The next subsections expand on each of the internal calibration steps leading to natural magnitude measurements described above, including how each correction is measured, calculated and applied. These steps described in this section are applied to each filter independently. The end result of the internal calibration process is a set of natural magnitudes, m_b^{nat} , measured for each object in each visit, together with a record of $\phi_b^{sys}(\lambda, x, y, t)$ and $\phi^{atm}(\lambda, alt, az, t)$ (the shape of S_b^{sys} and S^{atm}), the flat field applied (normalization of S_b^{sys}), the zeropoint offset calculated for cloud extinction (normalization of S^{atm}) and the spectral energy distribution assumed for the object to calculate m_b^{nat} (which may be a flat SED, in which case m_b^{nat} only includes normalization corrections).

4.1. Normalization of the hardware transmission

Compensation for variations (in x, y, t) in the normalization of the hardware transmission (S_b^{sys}) will be done using a flat field measured using narrow band and white light flat fields, after these are corrected for differences in illumination patterns between the dome screen and the night sky (the ‘illumination correction’). This is the first step in photometric calibration and is necessary to correct for variations in the normalization of S_b^{sys} that are smaller than a few times the PSF (and in the current calibration implementation, smaller than the scale of a CCD).

The specialized hardware for this flat field measurement is an array of projectors mounted in the dome of the LSST enclosure instead of the traditional ‘dome screen’. These projectors will be illuminated with both broadband (e.g. quartz lamp) and tunable narrow band (essentially monochromatic) light sources. Adjustment of the wavelength of the tuneable narrow band light source can be as fine as 1 nm. The projectors are designed to fill the LSST etendue with a uniform illumination, smoothly varying by less than 1% across the camera field of view (corresponding to less than 10% variability across the projector surface) and less than 0.25% on scales smaller than 0.5° (a little larger than the size of a CCD). The projectors will also be designed to limit the extent of light emitted outside the range of angles seen by the camera to reduce stray light in the flat fields (Gressler et al. 2010). A set of precision diodes will be used to normalize the photon flux integrated during flat field exposures, thus allowing a precise comparison of the system response at different wavelengths when using the narrow band light sources. These photodiodes, together with their read-out electronics, will be calibrated at the U.S. National Institute of Standards (NIST) to $\approx 0.1\%$ relative accuracy across wavelengths from 450 nm to 950 nm. The response of these diodes varies smoothly across this range of wavelength and provides a well-behaved reference for determination of $S_b^{sys}(\lambda)$. Further details of the LSST narrow band flat field apparatus can be found in Gressler et al. (2010). Preliminary results from a similar apparatus tested at PanSTARRS can be found in Stubbs et al. (2010), as well as earlier experiments from CTIO described in Stubbs et al. (2007a).

In each filter, a set of narrow band flats will taken at a series of wavelengths to form a data cube of flat fields in (x, y, λ) . Using the photodiode measurements of the light emitted at each wavelength, the data cube can be collapsed to a single ‘synthetic flat field’ image (x, y) by choosing a desired spectral energy distribution, then combining the individual narrow band images after applying an appropriate illumination correction (see subsection 4.1.1 for details on the illumination correction) for each wavelength and weighting by the goal SED and the photodiode measurements. The desired SED could be a single, constant SED or could be a set of SEDS, but will be clearly defined during the commissioning period. One

choice might be a night sky SED to match the majority of pixels in each image; the goal SED would then vary throughout the lunar cycle.

The narrow band flats are time-consuming to acquire. Scanning through all 6 filters at 1 nm intervals requires many hours worth of exposures, but must also be done in minimal levels of ambient light. Luckily, any wavelength dependent variations in the synthetic flat are expected to change relatively slowly so the full set of narrow band flats only need to be acquired approximately once a month, which could be done during cloudy nights. However, gray-scale variations in the hardware normalization (due to dust particles on the filters, etc.) will occur on a much shorter timescale. Thus, it is necessary to use a standard white-light flat to correct for these short timescale gray-scale variations in the system throughput. The white-light flat fields will be obtained with the same apparatus as the narrow band dome flats, but as the number of exposures required to characterize a filter is dramatically reduced, these white-light flats can be obtained at the start and end of every night of observing.

The white-light flat is not applied directly to images, as it does not have the desired spectral energy distribution. Instead, changes in the white-light flat from night to night will be transferred to the data cube of narrow band flat fields, adjusting the narrow band flats for small-scale changes in gray-scale throughput. This can be done by taking a white-light flat simultaneously with the acquisition of the narrow band flat data cube. White-light flats obtained over the next month are compared to the ‘simultaneous’ white-light flat, and then the narrow band flat data cube can be multiplied by any observed differences.

The light generated by the quartz lamp must be stable over the time interval between monthly narrow band flat measurements, to reduce changes in ghosting or color-dependent sensitivity variations in the white light flats.

4.1.1. Generating the illumination correction

The ideal flat field would demonstrate the hardware response to a focal plane illuminated exactly as it would be with a dark night sky, empty of ghosts, glints, stray or scattered light - recreating the hardware sensitivity variations across the focal plane as well as the effects of vignetting, both of which must be accounted for in the science images. The measured flat field, however, not only contains the actual vignetting and hardware sensitivity variations but also variations in the actual illumination pattern of the dome screen projectors, stray light, ghost images of the dome screen, and the effect of pixel scale variations across the field of view, which must be removed using the illumination correction.

The dome screen projectors will be designed to be uniformly illuminated to 1% over the

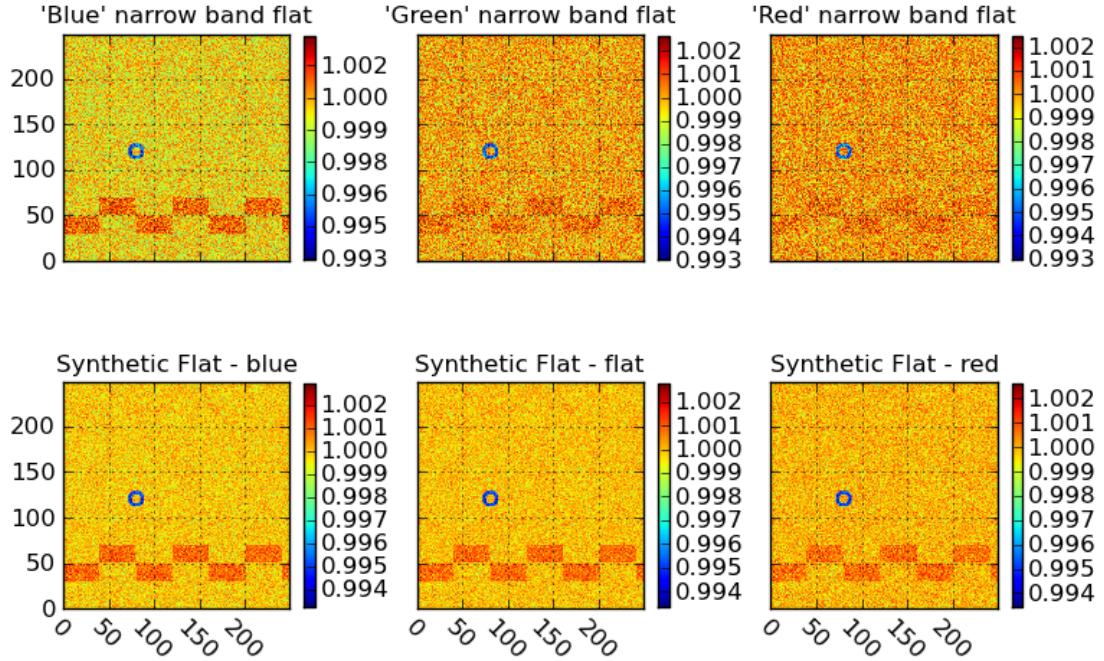


Fig. 3.—: **Simplified examples of synthetic flat generation.** The top panel illustrates simplified narrow band flats, at 'blue', 'green' and 'red' wavelengths. These represent illumination corrected (thus the relatively flat illumination pattern!) narrow band flat fields, where the detector shows a sensitivity pattern that is more pronounced in the blue wavelength flat field. The bottom panel shows the result of combining these flats to create a synthetic flat with a desired SED that is either weighted toward blue wavelengths ($1.5 \times \text{blue} + 1.0 \times \text{green} + 0.5 \times \text{red}$), a completely even distribution, or a synthetic flat weighted toward red wavelengths ($0.5 \times \text{blue} + 1.0 \times \text{green} + 1.5 \times \text{red}$). In operations, the synthetic flat will be created using a well-defined SED that will best correct the system normalization for science targets in the field.

focal plane, but this is already beyond the SRD specifications for photometric uniformity. There will be also light scattered within the camera dewar and some fraction of the light within the etendue will have undergone multiple reflections within the camera refractive optics (creating ‘ghost’ images of the light from the dome screen). Estimates by Photon Engineering, Inc. (Tucson, AZ) indicate that $\approx 1 - 2\%$ of the light that reaches the camera focal plane may be stray light that did not originate within the LSST etendue. In addition, projection effects cause a variation in the pixel scale from the center to the outer edges of the field of view, so that the pixels subtending a larger area (the center of the field) gather more light from the dome screen. This effect *is* present in the night sky science images as well, but does not affect the total flux measured from astronomical objects, so this gradient must be preserved in the science images (and thus removed from the flat field through the illumination correction).

Illustrative examples of these effects in a theoretical dome flat and the corresponding illumination correction are shown in Figure 4, and the effect of this illumination correct on final measured counts are shown in Figure 5.

Illumination corrections (one per filter) will be generated whenever the camera is removed from the telescope or the focal path undergoes significant changes (such as a filter being replaced or the mirrors being realuminized), but should be stable otherwise. The corrections will be created by combining information from a ZEMAX model of ghosting in the camera constrained by measurements from the Camera Calibration Optical Bench (CCOB), measurements of the observed individual narrow band dome screen (DS) flats, and dense star fields rastored across the focal plane on a photometric night.

The first of these components, **Camera Calibration Optical Bench (CCOB)**, provides a method to calibrate the spatial and wavelength-dependent response of the focal plane, unmounted from the telescope, using a well controlled, wavelength-variable, light source calibrated using a NIST photodiode. This light source, which produces a spot in the focal plane approximately the size of or smaller than the PSF, will be scanned across the detector (x, y) at a variety of beam incident angles, (θ, ϕ) and at a variety of wavelengths (λ). The response of the detector will be measured in two different configurations: one with only the detector and the dewar window - which doubles as lens 3 (L3) - and one with the detector, L3, L2, L1, the filters and the camera shutter. In the L3-only configuration, the detector response should include only relative simple ghosting, primarily 3 ghost images from reflections between the CCD surface and L3. In the full refractive optics configuration (with L3, L2, L1, the filter and camera shutter), the detector response will include a more complicated ghost pattern. Current simulations indicate the strongest ghosts are expected to originate from reflections between the CCD surface and L3, where the resulting ghosts are expected

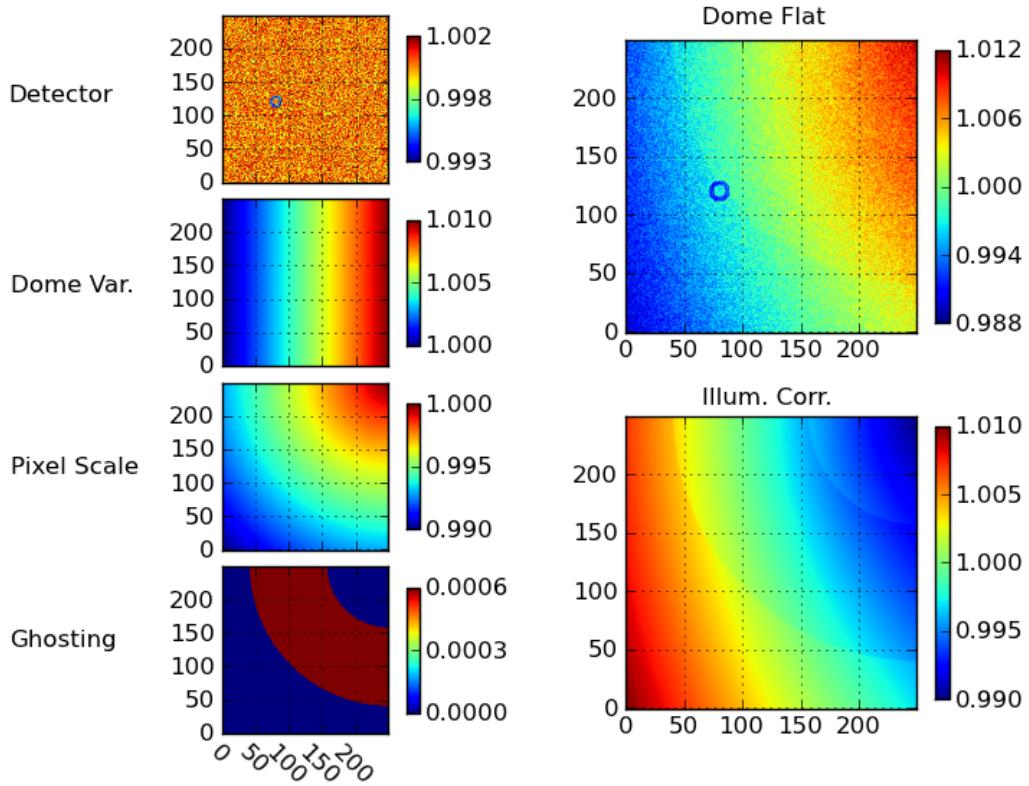


Fig. 4.—: **Components of the illumination correction.** Any flat field obtained from the dome screen includes not only a measurement of small-scale variations in detector sensitivity (Detector panel, top left), but also records unwanted effects such as variations in the dome screen illumination as a function of position (Dome Var. panel), variations in brightness that result from variations in the amount of sky observed by each pixel (arising from variations in the pixel scale over the focal plane) (Pixel Scale panel), and ghosting caused by internal reflections in the camera (Ghosting panel). Each panel on the left demonstrates the effect on the total flat field attributable to each of these variations, in a simplified manner. Variations are generated as follows: pixel-to-pixel variation in detector sensitivity is 0.4% (as well as a small dust ring), the dome screen has a 1% gradient across the field of view, the pixel scale changes by 0.5% from corner to corner, and the ghosting is generated by adding 0.1% of the total light into a ring reflection. The top large panel on the right shows the dome screen flat field that would be observed after combining all of the effects on the left. The bottom large panel on the right shows the illumination correction that must be multiplied with this flat field to remove the effects of the dome screen variation, the pixel scale variation, and the ghosting. Note that no photon noise was introduced in this simulation.

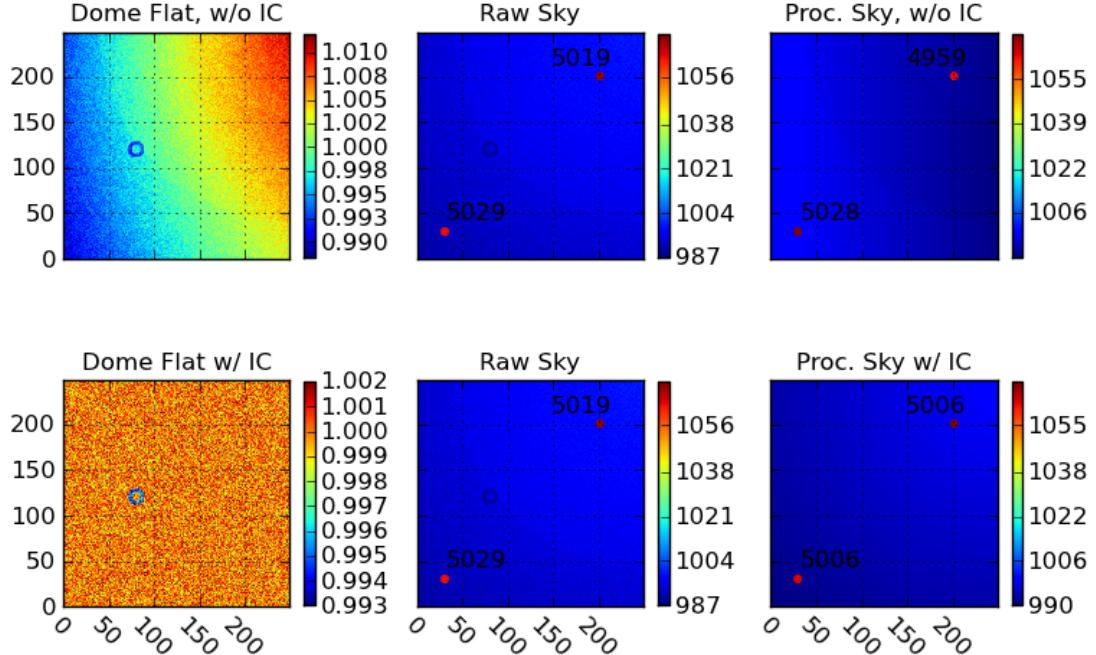


Fig. 5.—: **Effect of illumination correction on photometry.** The left top panel shows a flat field obtained from a dome screen, creating with the same conditions as in Figure 4, without multiplying by an illumination correction. The central top panel shows a raw ‘image’ of the sky, generated by adding a background sky value of 1500 counts per pixel (scaled by the pixel area, as in Fig. 4, to two stars. The stars were generated by placing 5000 counts over a circular aperture the size of the PSF at the location of the star. A ghost image was created as in Fig. 4. The right top panel demonstrates the result of processing the raw sky image by subtracting the ghost image and then dividing by the dome flat without an illumination correction. The left bottom panel shows the illumination correction applied to the same flat field. The middle bottom panel shows the same raw sky image as the top row. The bottom right panel demonstrates an improved processing of the raw sky image, by subtracting the ghost image and then dividing by the illumination corrected flat field. Note that the sky background does not appear flat but is correct for preserving stellar photometric accuracy. In every image with stars, the numbers next to each star indicate the counts measured within an appropriate circular aperture for the star. In the raw images, these counts are not equal because of the variation in pixel to pixel sensitivities.

to have an amplitude $5 \times \approx 10^{-4}$ relative to the flux of the source. Other ghost images, due to reflections between lens surfaces, should contain about $\approx 10^{-5}$ times the flux of the source. See Figure 6 for an example of simulated ghosting in the LSST focal plane. These measurements of the focal plane response in different optical configurations with a known incoming light source do not directly measure the illumination correction (for example, neither pixel scale variation due to projection effects nor the full stray/scattered light from the dome projectors are included), but it does provide constraints for model calculations (such as a ZEMAX model) of the illumination pattern in the camera as a function of wavelength, position in the focal plane, and beam incident angles, which are necessary for the creation of the full illumination correction, as well as constrain the focal plane response itself.

More details about the requirements and physical apparatus of the CCOB are available in LSST-10015 and LSST-8217.

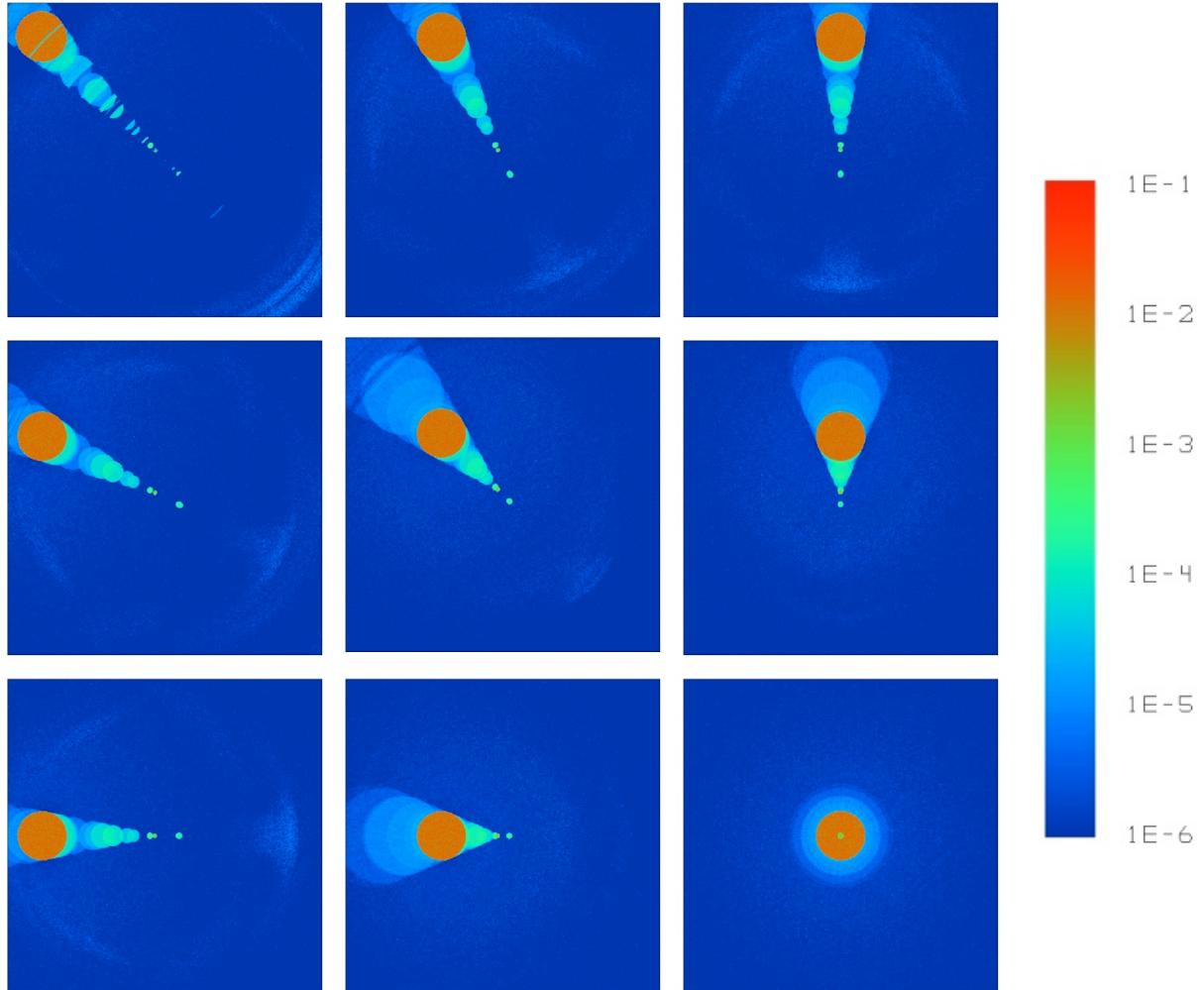
The ZEMAX model describes how light scatters inside the camera creating ghosts at each wavelength. If the dome screen projectors were perfectly uniform and no stray light was scattered into the LSST etendue, the narrow band dome flats plus the predictions from the ZEMAX model would suffice to create a perfect illumination corrected synthetic flat. Stray light scattered into the LSST etendue can be modeled using work similar to that of Photon Engineering, Inc., and then the model constrained by taking measurements of the focal plane response while blacking out M2 (to image only the stray light). This creates a preliminary estimate of the illumination correction, which is particularly useful for small spatial scales (smaller than a CCD) which may not be well sampled in the next, raster-scan step.

To account for illumination variations from the dome screen projectors on large spatial scales (which could be up to 1% across the field of view), stray light scattered from other unmodeled surfaces, or systematic differences in exposure time due to the camera shutter movement, a dense network of stars of a variety of spectral types must be rastored across the focal plane on a photometric night. The images will be divided by the synthetic flat field corrected by the preliminary illumination correction, and then the counts for each star corrected for varying color terms in the atmosphere and hardware response, as further described in subsection 4.2. The final update to the illumination correction can then be determined by minimizing over all stars i in all observations j ,

$$\chi^2 = \sum_{i=N_{stars}, j=N_{obs}} \left(\frac{m_{ij}^{meas}(x, y) - m_{ij}^{model}(x, y)}{\sigma_b} \right)^2 \quad (15)$$

where the model magnitude of each star in each observation is given by

$$m_{ij}^{model}(x, y) = m_b, i^{best} - \delta k_{b,j}^{atm+sys}(x, y, alt, az, SED, t) - \int d\lambda dZ_{IC}(x, y, \lambda) \quad (16)$$



K. Bechtol (SLAC/KIPAC). Image from LSST Document 10008.

Fig. 6.—: **Simulations of LSST camera ghost images, as measured by CCOB.** Various beam incident angles, positions and wavelengths will be explored by the CCOB, creating focal plane measurements similar to those simulated above. These measurements will be combined to constrain a ZEMAX model describing the optical paths in the camera (including the effect of the actual coating reflectivities of the CCD and lens surfaces, etc).

where $m_{b,i}^{best}$ is the best-fit, constant magnitude of the star in this filter, $k_{b,j}^{atm+sys}$ is the color-term correction (partially determined by the constant from exposure-to-exposure hardware throughput curve and partially determined by the varying with each exposure atmospheric throughput curve), and dZ_{IC} is the update to the illumination correction which is produced by this dense rastor scan. Similar applications of rastor scans have been successfully used in previous surveys, (*e.g* Regnault et al. (2009); Magnier & Cuillandre (2004); Manfroid (1996)), providing an illumination correction accurate to the sub-percent level. With the additional information from the CCOB and the better intrinsic uniformity of the dome screen illumination, we expect the illumination correction for LSST to be at least factor of 2 more accurate.

4.1.2. Error in the Normalization of the Hardware Transmission

The dome screen projectors will be designed to be uniform to better than 0.25% (2.5 mmag) over scales less than 0.5° (slightly larger than a CCD). Translating from this engineering requirement (a strict limit) to the RMS of expected measurements implies a resulting RMS of 0.7 mmag ($=2.5 \text{ mmag}/\sqrt{12}$) in the dome illumination uniformity on scales smaller than a CCD. After using the measurements from the CCOB to model ghost reflections and scattering within the camera, the uniformity of the dome screen projectors is expected to be the limiting factor on these small scales. Applying the dense rastor scan of stars to correct for larger illumination variations from the dome screen projectors on the scale of the entire field of view, plus to correct for the effects of 1–2% stray light and systematic exposure differences due to camera shutter travel, adds an additional error of about 2.8 mmag, increasing the expected error in the illumination corrected synthetic flat field to 2.9 mmag.

The illumination corrected synthetic flats are created on a monthly basis and then must be updated for gray-scale nightly changes in the hardware transmission (due to dust,etc) using the white-light flat fields acquired using the quartz lamp in the dome screen projectors. As this update only depends on changes in the white light flats, not their absolute values, the only requirement is that the quartz lamps produce an illumination pattern in the focal plane which is stable over time at the same level as the initial illumination uniformity requirement, or stable to within 0.25% within a CCD. This means that the quartz lamps should not change their spectral profile (which may change the ghosting pattern due to wavelength dependent effects) or their illumination pattern by more than an amount which would produce changes of more than 0.25% in the focal plane, adding a further 0.7 mmag rms scatter, for a final total of 3 mmag expected error in the normalization of the hardware throughput.

4.2. Shape of the Hardware and Atmospheric Response

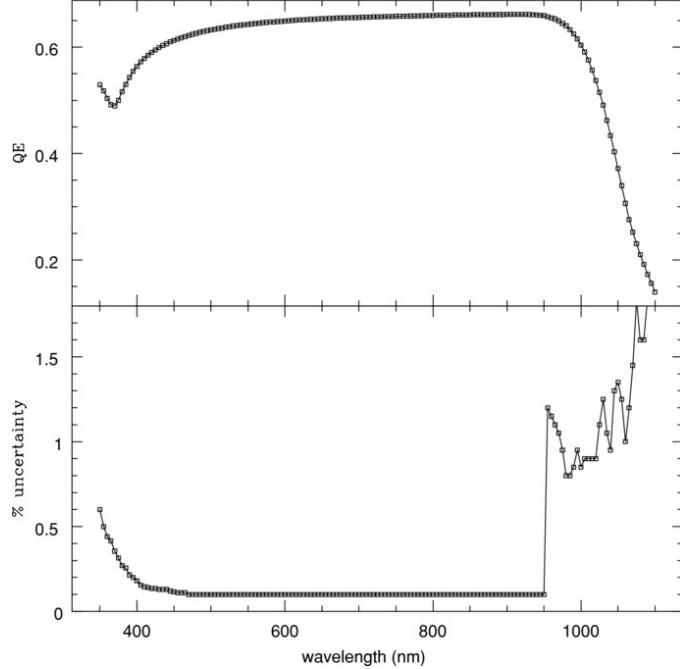
Compensation for the changes in observed magnitudes caused by variations in the wavelength dependence (shape) of the hardware and atmospheric response curves, $\phi_b^{sys}(\lambda)$ and $\phi^{atm}(\lambda)$, will be done using independent measurements of the hardware response curve (from the narrow band flat fields) and the atmospheric response curve (from atmospheric extinction models generated from measurements from the auxiliary telescope). While the measurement of the shapes of the hardware and atmosphere curves are independent, the actual correction that must be applied depends on the combination of atmospheric and hardware response curves as well as the SED of the astronomical object. This correction is necessary for precision photometry, but as it requires knowledge of the object’s SED, most LSST reported magnitudes will include either no correction or a (potentially rough) correction along with an indication of what SED was assumed to generate this value. However, for stars which will be used in self-calibration (see subsection 4.3) to determine photometric zeropoints in each exposure, a model SED well-matched to the object’s colors will be chosen and used to generate the $\delta k_b^{atm+sys}$ corrections described in this section.

It is worth emphasizing as we start this section that $\delta k_b^{atm+sys}$ is a correction for changes in the *shape* of the bandpass only; any grayscale components to the changes in bandpass shape discussed here are not part of $\delta k_b^{atm+sys}$ and instead belong to either the hardware or atmospheric *normalization* corrections.

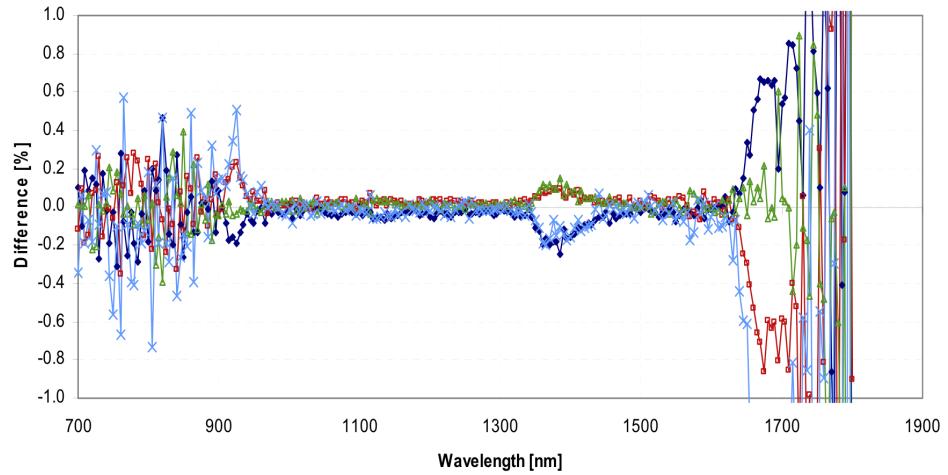
4.2.1. Measuring the shape of the hardware response curve

The hardware response curve is measured directly using the individual narrowband flat fields described in section 4.1. At each wavelength, the narrowband flat field will be illumination corrected and then used to measure the total hardware response over all x, y positions. The dome screen photodiodes will be used to track the relative intensity of the light produced by the projectors at each wavelength. These NIST-calibrated photodiodes are expected to be accurate to within 0.1% between 400-900 nm (g, r, i, z bandpasses) with current technology, which can be extended to 1600 nm (into the y band) using techniques under development (which also have the possibility of achieving 0.01% accuracy in the diode calibration at NIST) (Eppeldauer et al. 2009), as shown in Figure 7.

These measurements will be updated on a monthly basis, as the hardware response curve is expected to change only slowly over time due to aging in the filter and mirror coatings. It is expected that the shape of the response curve will be primarily a function of radius due to variations in the thickness of the filter coatings caused by the mechanism used to deposit



(a) Stubbs et al. (2010)



(b) Eppeldauer et al. (2009)

Fig. 7.—: Quantum efficiency curve and fractional uncertainty for NIST-calibrated photodiode, from Stubbs et al. (2010) and Eppeldauer et al. (2009). Panel (a): Between 400 and 900 nm, calibration methods already in use in test systems indicate photodiode accuracy is better than 0.1%, as in the bottom part of this panel. The sudden decrease in calibration accuracy below 900 nm is due to calibration methods used by NIST in 2005. Panel (b): More recent photodiode calibration efforts by Eppeldauer et al. (2009) show better than 0.1% accuracy can be achieved to beyond 1200 nm, the limit of detector response for LSST, as shown here in the response curves resulting from multiple scans of a single source using the same photodiode.

those coatings. The variation due to filter nonuniformities is specified to be less than 1% across the focal plane, most likely in the form of a bandpass shift as shown in Figure 8. For main sequence stars, the resulting changes in observed magnitude as the bandpass shifts by 1% of the central wavelength can be as much or more than 0.04 magnitudes (40 mmag) - even larger in the u band (see Figure 9). However, as long as the variation in the hardware response curve is measured to better than 0.05% – equivalent to approximately a 30 Angstrom error in wavelength calibration of the monochromatic light source throughout the bandpass or a 0.5% error in photodiode calibration assuming that the shape of each bandpass is determined using at least 100 independent measurements (i.e. 1 measurement every few nanometers within the bandpass) – the maximum error contribution towards calibrating these observed magnitudes will be less than 2 mmag for all bandpasses other than u , where the error could be as much as 5 mmag for certain main sequence stars (see Figure 10).

Because the shape of the hardware response curve varies as a function of filter radius, it is also necessary to monitor any offsets of the filter position from dead center after any filter changes. Assuming the filter response curve varies linearly with radius, the filter location must be measured to better than 0.025% for the filter positioning to remain less than a 1 mmag source of error.

4.2.2. Measuring the shape of the atmospheric transmission curve

The atmospheric transmission curve appropriate for each observation will be generated using data from spectroscopic measurements of bright stars obtained with the LSST auxiliary telescope, which is fit to an atmospheric extinction model to determine the atmospheric transmission profile at all points on the sky at all times. This atmospheric extinction model is a combination of a basic model of the sources of atmospheric extinction, some prior knowledge of how these sources change with time and location on the sky, and the actual atmospheric extinction profiles of these sources at various airmasses generated using MODTRAN (Berk et al. 1999; Anderson et al. 2001).

The shape of the atmospheric transmission curve, $\phi^{atm}(\lambda, alt, az, t)$, is determined by three major sources of atmospheric extinction: molecular scattering (Rayleigh scattering), aerosol scattering (Mie scattering), and molecular absorption. Molecular scattering, or Rayleigh scattering, is due to elastic scattering off atoms and molecules in the air. Atmospheric absorption due to Rayleigh scattering has an optical depth $\tau \propto (\lambda/\lambda_o)^{-4} (BP/BP_o)$, where BP is the barometric pressure (Hansen & Travis 1974). Aerosol scattering, or Mie scattering, occurs when visible light is scattered by particles suspended in the atmosphere with a size similar to its wavelength. This gives rise to an absorption curve with a vari-

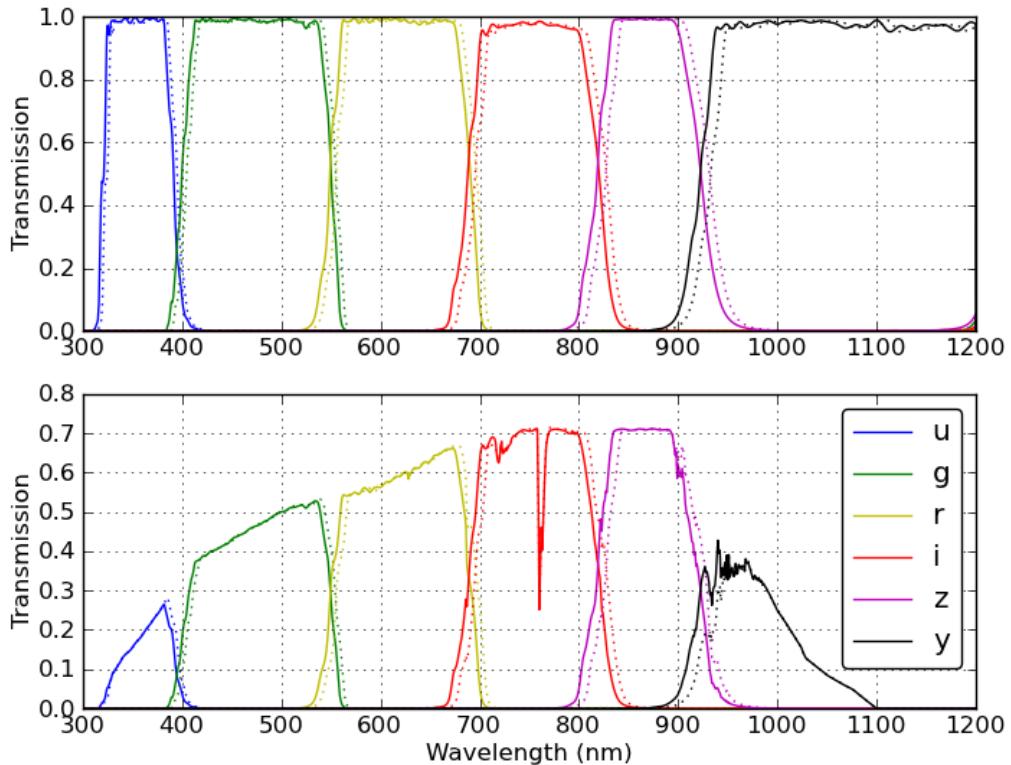


Fig. 8.—: **Baseline filter curves and a potential (1% of the central wavelength) shift due to nonuniformity.** The solid lines indicate standard filter bandpasses (top panel: filter alone, bottom panel: filter plus standard mirror, lens, detector and atmosphere response curves) while the dashed lines indicate the same bandpass shifted redward by 1% of the central wavelength.

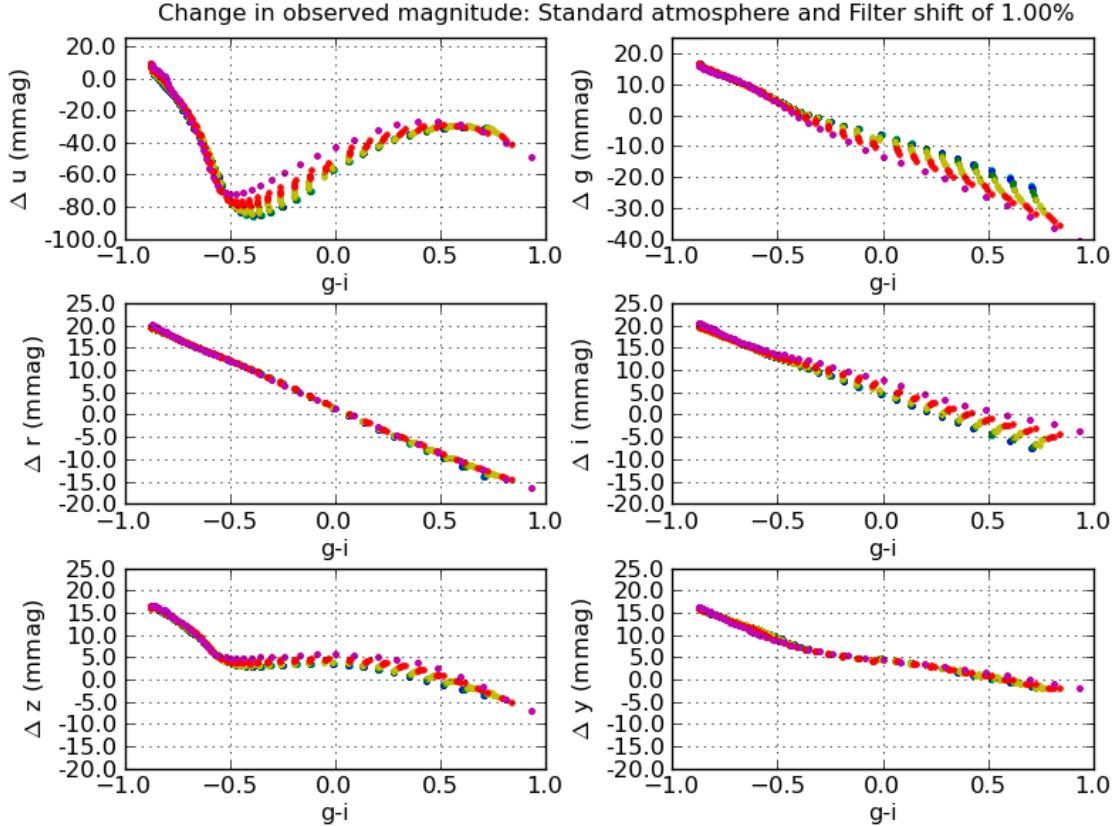


Fig. 9.—: Changes in observed magnitude (measured counts) due to a hardware response curve shift of 1% of the central wavelength of each bandpass. 850 Kurucz models with temperatures between 5000K and 35000K and metallicity indexes between -5.0 and 1.0 (solar) were combined with a standard atmosphere and standard hardware bandpass, and then with a total system response where the atmosphere remained constant but the hardware response was shifted by 1% of the central wavelength of each bandpass (as in Fig 8). Changes in magnitude on the order of 20 mmag are typical, except in u band where the shift can create a δu of closer to 80 mmag for certain kinds of main sequence stars. The points in each plot are color-coded by metallicity, in steps of 1 dex between -5.0 (blue) to 1.0 (magenta).

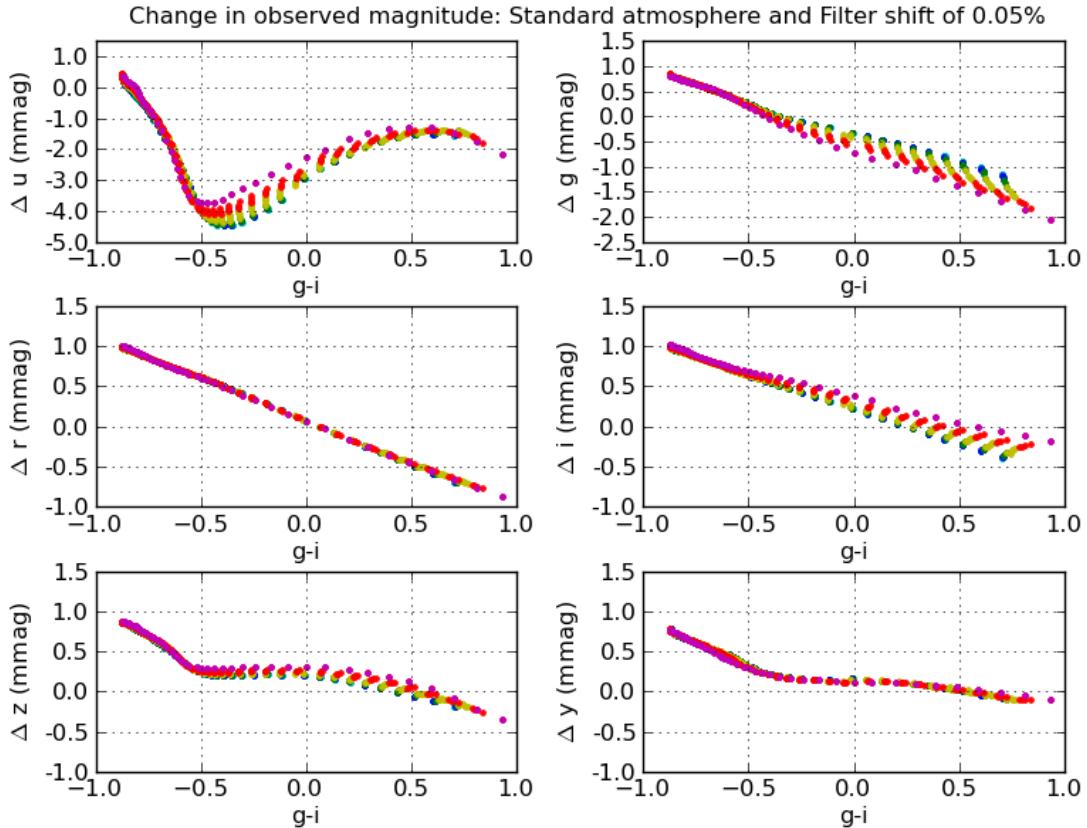


Fig. 10.—: Changes in observed magnitude (measured counts) due to a hardware response curve shift of 0.05% of the central wavelength of each bandpass. Similar to Fig 9 except that the hardware response was shifted by only 0.05% of the central wavelength, an amount representing an unmeasured shift in the hardware response and thus contributing directly to the final error in the calibration of the observed magnitudes. Note that the y scale here is 1/10th of the scale in the previous figure.

able wavelength dependence, where $\tau \propto (\lambda/675\text{nm})^\alpha$, α measured to range between -0.9 to -1.7 in observations from CTIO (Burke et al. 2010). Both molecular and aerosol scattering produce transmission curves that scale directly with airmass, $S(\lambda, X) \propto e^{-\tau X}$. Molecular absorption produces a more complex set of absorption bands and features, originating from line absorption due to ozone (O₃), oxygen (O₂), water (H₂O) and other trace elements (OH, N₂O, etc.). The resulting atmospheric absorption features are largely due to narrow saturated Lorentzian-shaped lines spaced closely in wavelength and, due to this saturation, scale non-linearly with airmass, $S(\lambda, X) \propto e^{-\tau \sqrt{X}}$ (Stubbs et al. 2007b). Figure 11 demonstrates the wavelength dependency of each of these components.

Using MODTRAN we can generate atmospheric transmission profiles for each of these major sources of atmospheric extinction – molecular (Rayleigh) scattering, aerosol (Mie) scattering, and molecular absorption from each of O₃, H₂O, and combined O₂/trace elements, as is shown in Figure 11, for a standard atmospheric composition (the 1976 US Standard) at a variety of airmasses. These profiles capture the wavelength dependence of each component individually, over a grid of airmasses, and can then be used as templates to generate new atmospheric transmission curves for any desired atmospheric composition as follows:

$$\begin{aligned} S^{fit}(alt, az, t, \lambda) = & e^{-\tau_{aerosol}(alt, az, t, \lambda) X} \\ & \times (1 - C_{mol}(BP(t)/BP_o) A_{rayleigh}(X, \lambda)) \\ & \times (1 - \sqrt{C_{mol}(BP(t)/BP_o)} A_{O2}(X, \lambda)) \\ & \times (1 - C_{O3}(t) A_{O3}(\lambda, X)) \\ & \times (1 - C_{H2O}(alt, az, t) A_{H2O}(X, \lambda)) \end{aligned} \quad (17)$$

where each of the $A_{rayleigh/O2/O3/H2O}$ values are taken as one minus the transmission template ($A_{O2}(X) = 1 - T_{O2}(X)$, where $T_{O2}(X)$ is the individual component profile template from MODTRAN). Each of $C_{mol/O3/H2O}$ are values which describe the composition of the atmospheric extinction, and are what are fit from the auxiliary telescope data along with the aerosol extinction, $e^{\tau_{aerosol}}$. An example of an atmosphere generated in this fashion is shown in Figure 12.

The coefficients $C_{mol/O3/H2O}$ and aerosol extinction will be determined using spectra of bright stars obtained from the 1.2-m LSST auxiliary telescope. The auxiliary telescope will be equipped with a modest resolution ($R \sim 400$) spectrograph, sufficient to capture the signatures of the atmospheric extinction components, and covering the entire wavelength range of LSST ($300 < \lambda < 1100$ nm) in each exposure. The stars observed with the auxiliary telescope will be $r < 12$ and either white dwarfs or F stars – stars with relatively simple and well-understood SEDS to minimize confusion with the atmospheric extinction. Generally,

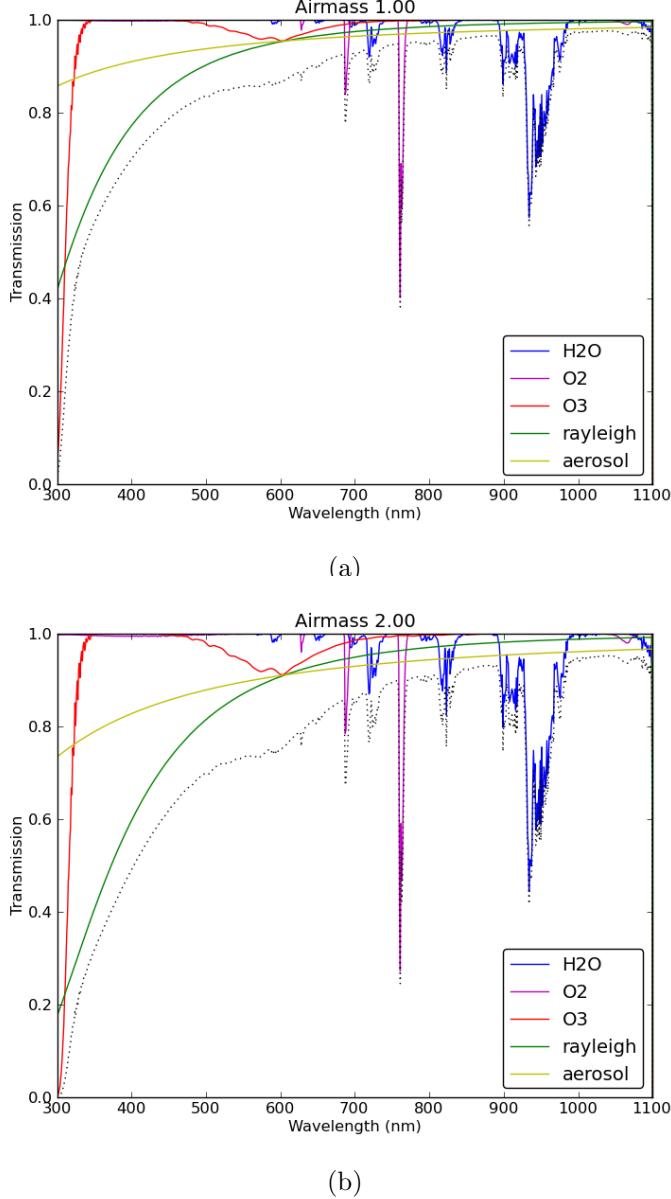


Fig. 11.—: Components of atmospheric absorption. The wavelength dependence of the various components of atmospheric absorption at zenith (panel a) and at airmass=2.0 (panel b) is shown here. The H₂O (blue) and O₃ (orange) molecular absorption contributions are shown separately, while the O₂ absorption is combined with other trace elements (red). A typical example of aerosol scattering (Mie scattering) is included (yellow), as is molecular scattering (Rayleigh scattering) (green). All components except aerosol scattering were generated using MODTRAN4 with the US Standard option (aerosol scattering is not part of the US Standard atmosphere). The resulting total absorption curve is the product of each of these effects and is shown with the dotted black line. This is an illustrative atmosphere; under actual observing conditions the molecular absorption components will vary in strength with time and the square root of the airmass, the molecular and aerosol scattering will depend on airmass, and the aerosol scattering profile will also vary with time.

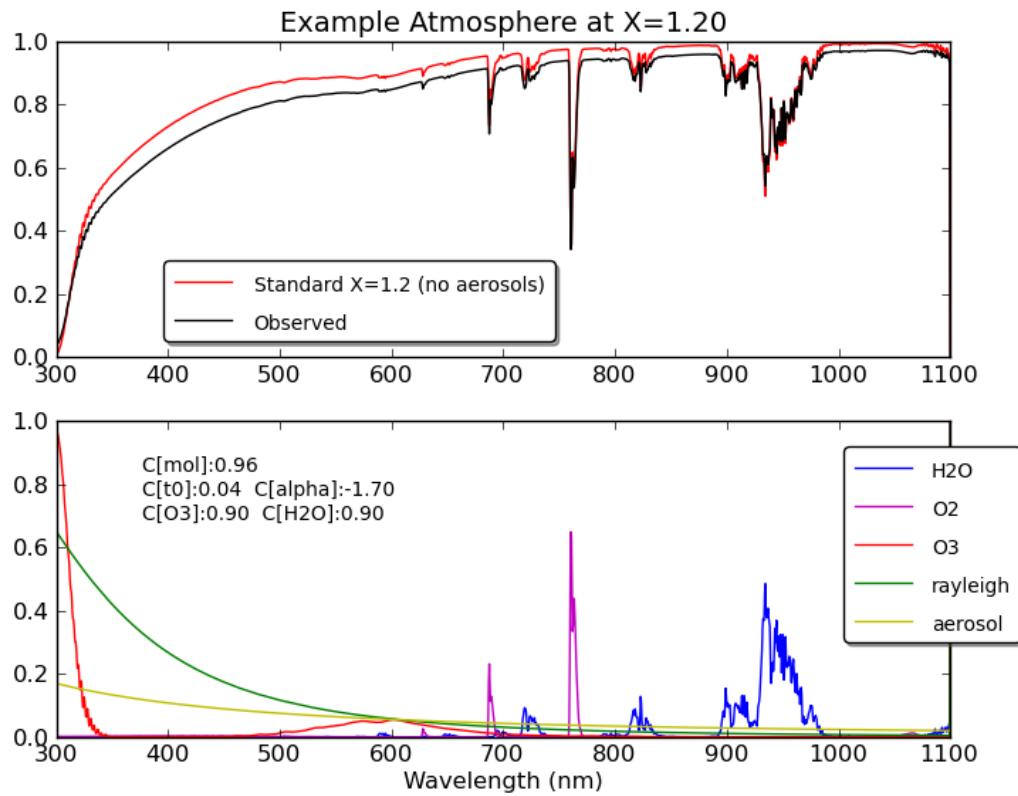


Fig. 12.—: **Example of an atmosphere generated from a typical mix of atmospheric components.** The bottom panel shows the MODTRAN absorption templates at this airmass used in generating the final atmosphere (the $A_{rayleigh}/O_2/O_3/H_2O$ and $A_{aerosol} = 1 - e^{\tau_{aerosol}}$ from Equation 17). The top panel shows the final combined atmospheric transmission curve in black, as well as a ‘standardized’ atmospheric transmission curve in red.

the auxiliary telescope will not observe stars along the same line of sight as LSST, but will instead gather data on the distribution of atmospheric extinction components using stars observed at a wide variety of airmasses, locations on the sky ranging far N/S/E/W, and utilizing repeat observations of the same star throughout a night to improve separation of the atmospheric extinction from stellar or instrumental properties. The extinction coefficients, $C_{mol/O3/H2O}$ and $\tau_{aerosol}$ will then be fit to the entire set of observed spectra by applying a model of how these components are expected to vary across the sky and with time.

Stubbs et al. (2007b) summarizes the spatial and temporal dependence of each of the major extinction components as follows. The Rayleigh scattering is expected to be axisymmetric about the zenith, with a total column height dependence driven only by pressure variations. The O₂ molecular absorption is similar, although proportional to only the square root of the barometric pressure. These two components are thus fit with a single parameter C_{mol} which simply scales the barometric pressure at the site to generate the appropriate extinction. The O₃ molecular absorption can vary 5-10% day to day, with seasonal variations of 25% or so, but is not expected to have a strong spatial variation. The total extinction resulting from O₃ is fit with a single C_{O3} value per night, although this could also be correlated with satellite data on total ozone content if a more accurate fit becomes necessary. The aerosol extinction varies up to 5% within a day, with larger seasonal variations, and also spatially and even in wavelength dependence; the aerosol extinction is thus modeled as

$$\tau_{aerosol}(alt, az, t, \lambda) = (\tau_0 + \tau_1 \text{EW} + \tau_2 \text{NS}) \left(\frac{\lambda}{\lambda_0} \right)^\alpha \quad (18)$$

where EW and NS are defined as $\text{EW} = \cos(alt)\sin(az)$, $\text{NS} = \cos(alt)\cos(az)$, projections of the telescope pointing in the EW/NS directions, where τ_0 , τ_1 , τ_2 and α are fit for each night of observing. The fitted values for τ_1 and τ_2 are very small and even zero on 4 out of the total 6 nights of observing. The H₂O molecular absorption is the most variable in both space and time, on scales as short as 10–20 minutes. C_{H2O} is thus fit as

$$C_{H2O}(alt, az, t) = C_{H2O}(t) + \frac{dC_{H2O}}{d\text{EW}} \text{EW} + \frac{dC_{H2O}}{d\text{NS}} \text{NS} \quad (19)$$

using a single spatial gradient per night and a $C_{H2O}(t)$ that is fit to each stellar observation (and interpolated between these times).

Burke et al. (2010) details a series of observing runs where spectroscopic observations of stars were obtained at CTIO and fit using this method. Using the extremes of the range of C_{mol} , C_{O3} , C_{H2O} , τ_i and α parameters from these runs, Figure 13 shows the resulting changes in observed magnitudes due to the changes in bandpass shape when applied to our set of main sequence star Kurucz models. Varying C_{H2O} only affects z and y bands, while changing

C_{O_3} , τ_0 , and α affect ug and, to a lesser extent, r bands. Combining all of these ‘worse-case’ scenarios to examine the maximum δ mag that could result, at $X = 1.2$ we find that the maximum $\Delta u = 14$ mmag, $\Delta g = 7$ mmag, $\Delta r = 4.5$ mmag, $\Delta i = 1.5$ mmag, $\Delta z = 2$ mmag, and $\Delta y = 7$ mmag. The atmosphere transmission curves used to generate this info, and a plot of the resulting changes in magnitudes are in Figures 14 and 15.

These changes in observed magnitudes, if uncorrected for, would be larger than the variations allowed in the SRD. However, by measuring each component to only 30% accuracy and applying a correction to the observed magnitudes based on the SED of the source, we can reduce $\Delta grizy$ to less than 2 mmag and Δu to less than 4 mmag. Given that observations show the O3 and aerosol components vary this much only seasonally (with much smaller variations within a night), a better estimate on the accuracy of the coefficients for these components is about 10%. With a 10% accuracy on the O3 and aerosol coefficients, but a larger 30% efficiency for the H2O coefficient due to its greater variability with time, the resulting changes in magnitude (see Figure 16) are less than 1 mmag in all bands except y , where it remains 2 mmag.

The variation in observed magnitudes is actually larger with changes in airmass than with changes in these atmospheric extinction components, as in Figure 17, however the effect of changes in airmass are included in the atmospheric extinction templates generated by MODTRAN and can be accurately corrected. These correction factors can be significantly different *across the field of view* in u and g (on the order of 6 mmag). This is understandable, given that with a 3° diameter field of view, a field observed at $X = 2.0$ will reach from $X = 1.9$ in the direction toward zenith to $X = 2.1$ at the lower edge.

4.2.3. Errors in the shape of the hardware and atmospheric response

Correcting observed counts for the difference between the measured shape of the hardware and atmospheric response curves and the standard normalized bandpass, $\phi_b^{std}(\lambda)$, requires knowledge of the SED of each star. However, with this knowledge, it is possible to create lookup tables of $\delta k_b^{atm+sys}(x, y, alt, az, SED, t)$ (as in Equation 13) for various locations in the focal plane in each exposure. A rough example is given in Table 1.

Assuming that the errors in the combined shape of the hardware and atmospheric response curves add in quadrature, with the limits described above (2 mmag error in $grizy$, 5 mmag error in u due to the hardware response curve; 1 mmag in $ugriz$, 2 mmag error in y due to the atmospheric response curve), the final error in observed magnitude due to both of these effects would be < 3 mmag in $grizy$ and 5 mmag in u . There is an additional

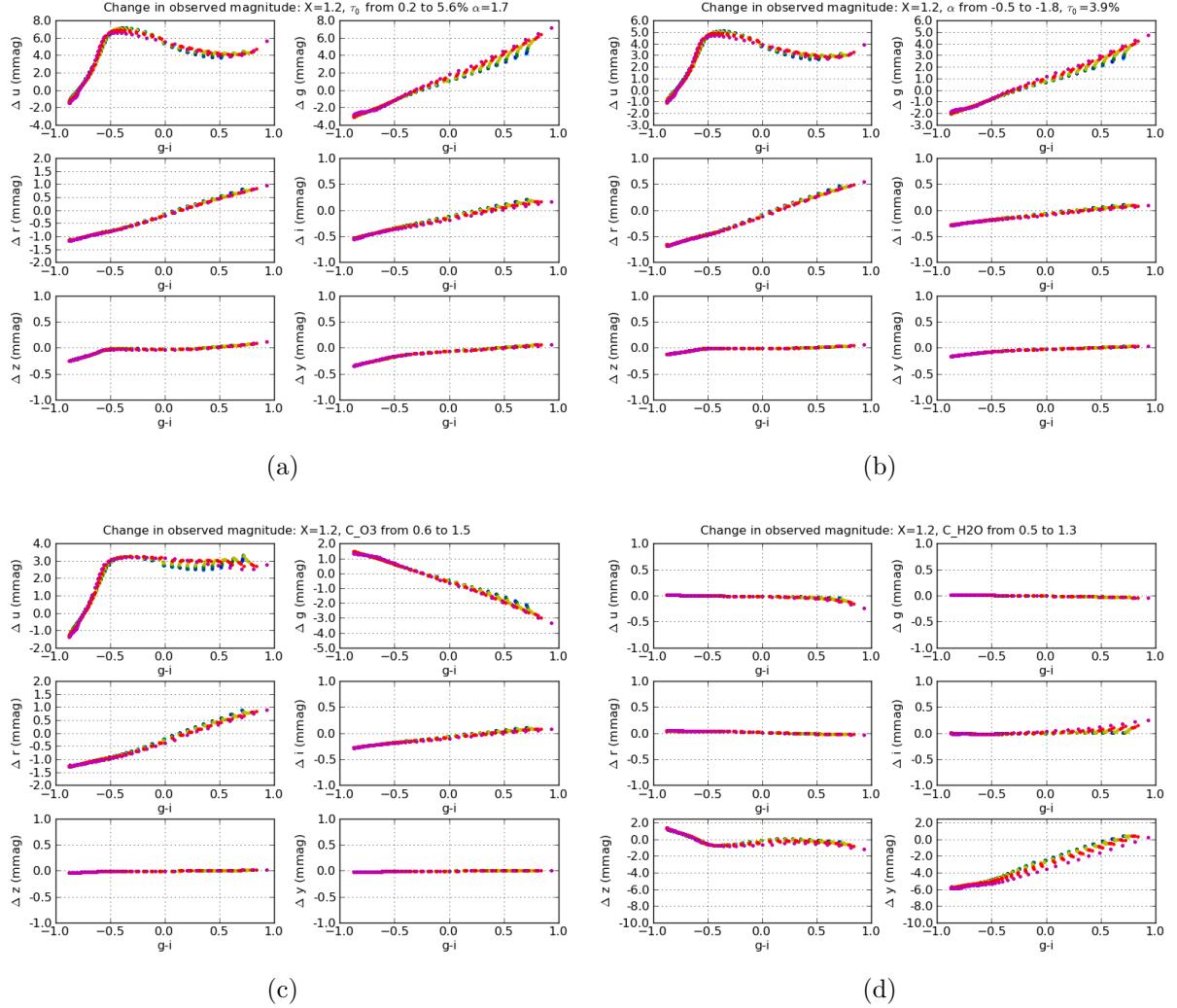
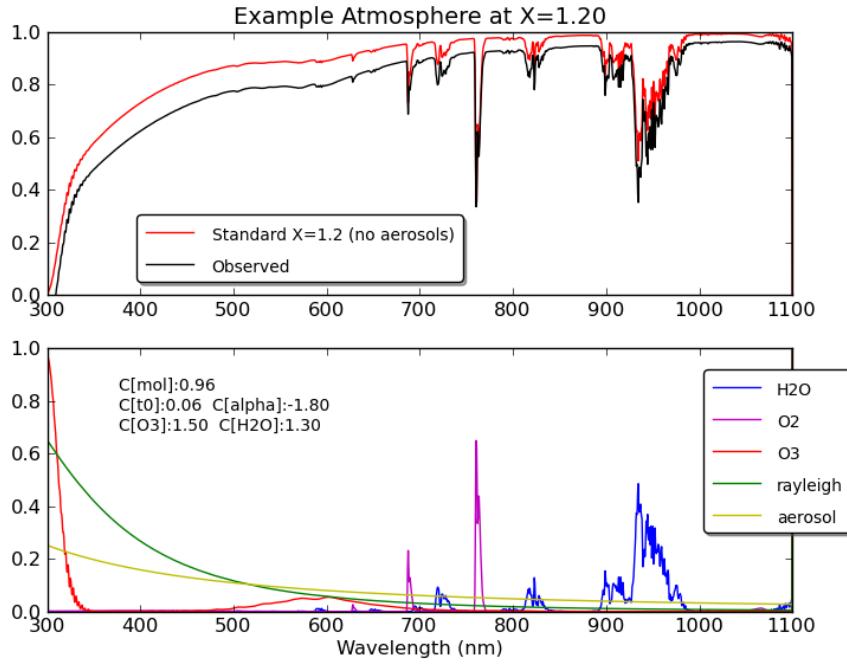
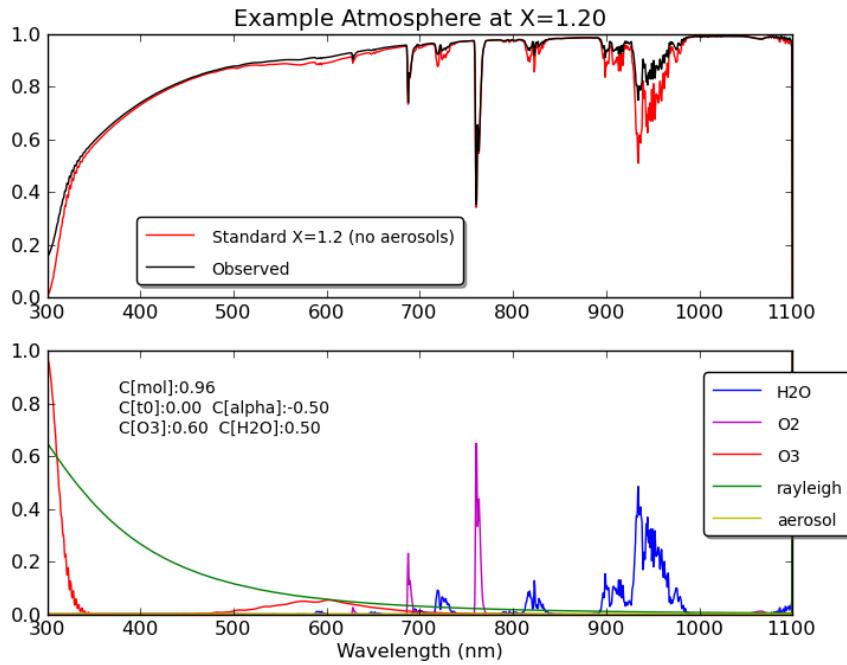


Fig. 13.—: **Changes in observed magnitudes due to variations of each individual absorption component.** Each atmospheric transmission curve (at $X=1.2$) was combined with the set of main sequence Kurucz curves to determine the resulting changes in observed magnitudes, as in Figure 9. 13a and 13b show the effects of varying aerosol absorption in τ_0 and α respectively, 13c shows the effect of varying O₃ absorption. These effects are concentrated in u and g bands, with a negligible effect in izy . 13d shows the effect of varying the H₂O absorption, which is strongest in y , with some effect in z and no effect in $ugri$.



(a)



(b)

Fig. 14.—: ‘Extreme’ atmospheres generated from MODTRAN profiles and extremes of atmospheric coefficients. Using the extremes of $C_{\text{H}_2\text{O}}$, C_{O_3} , and τ_0 and α from Burke et al. (2010), two test atmospheres with $X = 1.2$ were created using Equation 17.

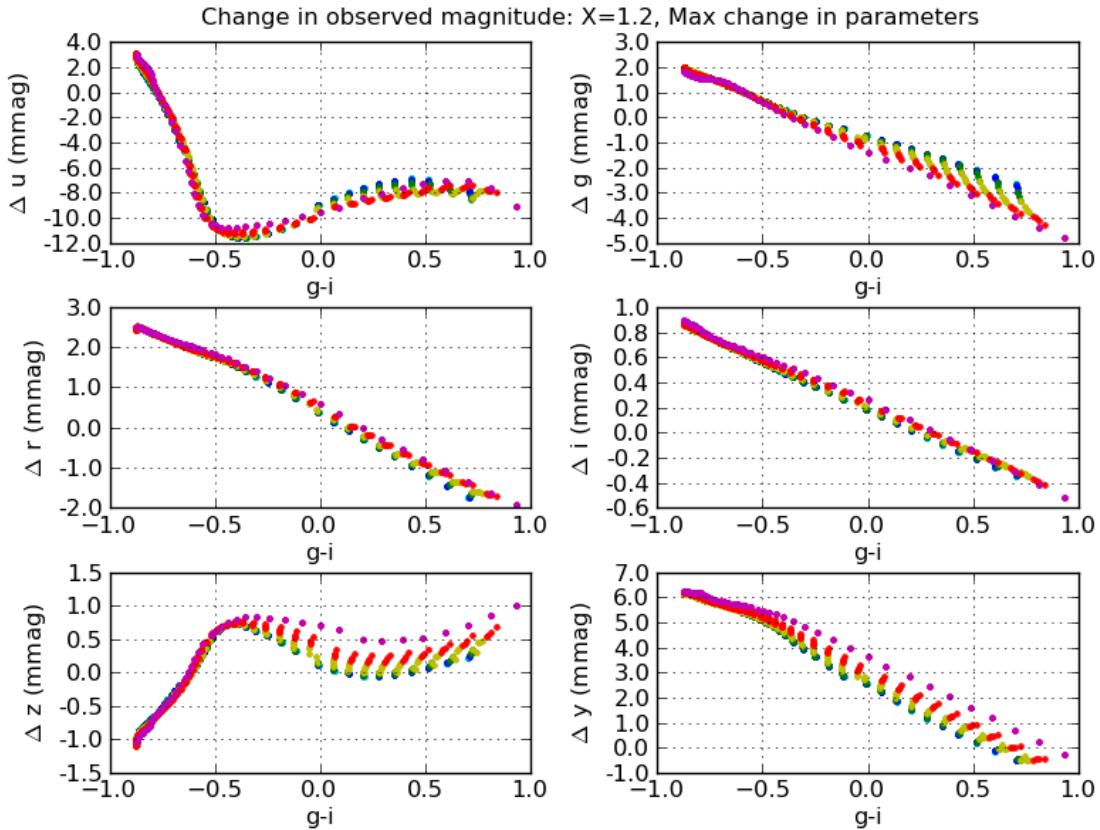


Fig. 15.—: **Changes in observed magnitudes due to ‘extreme’ variations of atmospheric transmission.** Two atmospheric transmission curves were created using Equation 17 and the widest variations of atmospheric extinction coefficients from Burke et al. (2010). The wavelength profile of these atmospheres is shown in Figure 14. These atmospheric transmission curves were combined with the baseline LSST hardware transmission curves, and used to generate magnitudes for 850 Kurucz models with temperatures between 5000 K and 35000 K and metallicities between -5.0 and 1.0 (solar). The differences in observed magnitudes between the two extremes of the atmospheric transmission in each filter are shown above.

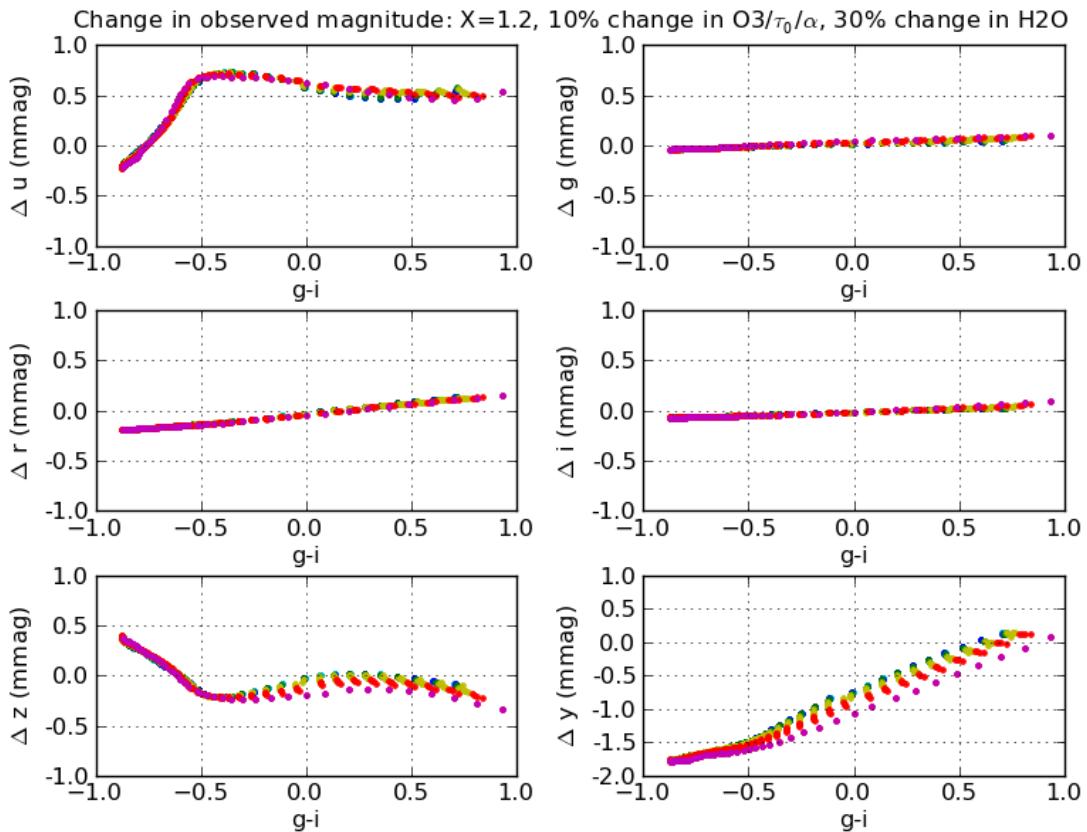


Fig. 16.—: Changes in observed magnitudes due to 10% variations of atmospheric transmission in O_3 and aerosol, with 30% variation of H_2O . This is similar to Figure 15, except C_{O_3} , τ_0 and α were only varied by 10% of the total range of values measured in Burke et al. (2010), and C_{H_2O} was varied by 30% of the total range.

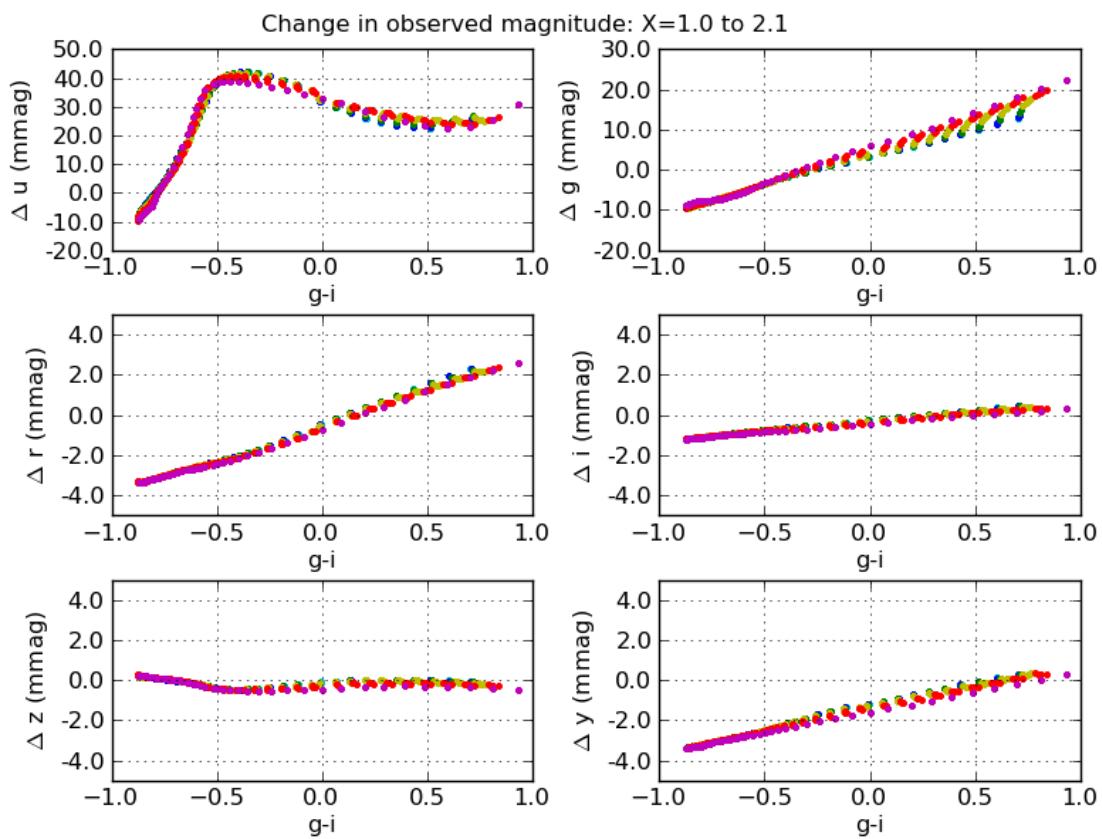


Fig. 17.—: Changes in observed magnitudes due to changes in airmass from $X = 1.0$ to $X = 2.1$, for a typical atmospheric transmission response curve.

potential source of error in these $\delta k_b^{atm+sys}$ corrections – the understanding of the true SED of the source.

LJ - Generate: errors due to bad knowledge of SED

4.3. Normalization of the Atmospheric Transmission

After applying each of the previous corrections, the raw counts have been corrected to a ‘standard’ bandpass for each filter, $\phi_b^{std}(\lambda)$, using both the narrow band flats and the atmospheric model derived from the auxiliary telescope observations. Small scale (< several times the PSF) gray-scale zeropoint variations have also been removed by the synthetic flat. However, there still remain variations in the normalization of the system response that result from gray-scale extinction due to clouds. The self-calibration procedure is necessary to correct for these zeropoint offsets.

The self-calibration procedure selects bright, isolated main sequence and white dwarf stars (or any star with well-known colors and a well-known SED, to reduce errors in the applied δk values) from the sample of all observed stars after they are corrected to the standard bandpass (‘standardized’). Only non-variable stars will be selected for self-calibration, based on approximately calibrated data (say, a few percent) which will suffice in this context. It then uses the many repeat observations j of each star i in a particular filter to minimize

$$\chi^2 = \sum_{ij} \left(\frac{m_{b,ij}^{std} - m_{b,ij}^{model}}{\sigma_{b,ij}^{std}} \right)^2 \quad (20)$$

where the m_{model} includes any remaining photometric corrections that must be applied. In our current calibration plan, this would be only the gray extinction from clouds, applied by requiring the photometric zeropoint offset over a small patch of sky in a given observation, δz_j , be constant:

$$m_{b,ij}^{model} = m_{b,i}^{best} - \delta z_{b,j}, \quad (21)$$

where the patch size is approximately one CCD in size. A more complicated model, *e.g.* a δz_b with structure, could be used if found desireable. Simulations of the Milky Way based on a model by Mario Juric (JuricREF) indicate that there will be approximately 50–100 suitable calibration stars per patch over the entire sky.

Minimizing Equation 20 requires solving for approximately, $10^8 m_{b,i}^{best}$ and $10^8 \delta z_j$. Of course, not all stars will be observed on all calibration patches, so there will be only about 10^{10} non-zero values of $(m_b^{std})_{ij}$ (per band). Preliminary work using a conjugate gradient

method to compute m_b^{best} and δz_j for approximately 10^6 stars and 10^6 patches was very successful; the same method could be relatively easily parallelized for the full data set.

With the known values of $(\delta z)_j$, all measurements from that patch can be re-calibrated, then analyzed for systematics in $[(m_b^{std})_{ij} - (m_b^{best})_i]$ and $[(m_b^{obs})_{ij} - (m_b^{best})_i]$ residuals (e.g., as a function of observation time, position on the focal plane, airmass, seeing, stellar color, brightness, seeing, etc.). The self-calibration step can be repeated if necessary, with corrections for systematics incorporated in the next-iteration values for $(m_b^{std})_{ij}$ or added directly into the model magnitudes used for the self-calibration solution. Thus this step provides a potential avenue for improvement in errors introduced at earlier stages (such as a mis-measurement of the atmospheric throughput or flat-field).

The self-calibration step can be successful only if patches overlap on the sky so that the same star is observed on multiple patches. It is good to note that $(m_b^{best})_i$ and $(\delta z)_j$ are constrained only up to an arbitrary additive constant. For convenience, this constant can be set so that stars have roughly correct AB magnitudes, however the goal after self-calibration is only to have a rigid, self-consistent magnitude system, equivalent to the natural magnitudes.

More details of the self-calibration procedure can be found in Docushare Document-8619 and Jones 2010 (SPIE paper).

LJ - there is more to go here. Perhaps figure with milky way density in all bandpasses. Definitely more info from more recent sims that follow error distribution up to this point. Also describe some limits to selfcal.

5. Fixing LSST to an external scale

The next two subsections describe how the internally calibrated natural magnitudes, independently calibrated in each filter bandpass, are fixed to an external scale such that the flux in a single band can be compared to the flux in another filter band (SRD requirement 3) and that the flux in a particular filter band can be compared to an absolute external system (SRD requirement 4). This is equivalent to determining Δ_{br} and Δ_r from Eqn 14.

5.1. Band to band (color)

The band to band calibration for each filter b (the Δ_{br} values) will be determined by measuring the flux from one or more celestial objects whose physics and chemistry are

believed to be well understood. In principle, a single object with known colors would be sufficient, however many objects across the LSST footprint will be used to evaluate possible systematic effects in the internal calibration process.

Hot hydrogen (DA) and helium (DB) white dwarf stars have simple atmospheres that are reasonably well understood (model colors are currently reliable to about 0.01 magnitudes). It is estimated that there will be $\approx 100/10$ DA/DB WD stars with $r < 24$ in each LSST image at the South Galactic Pole. Catalogs of WD stars visible from Cerro Pachon have been constructed (Bergeron 1992, Eisenstein 2006), and a ‘white dwarf calibration system’ has been developed (Holberg & Bergeron 2006). The locus of main sequence stars in color-color space is also reasonably well understood and has been used to calibrate photometry with success in previous surveys (MacDonald 2004, Ivezić 2007). The use of the main sequence stellar locus in addition to WD stars will provide a valuable check on systematic effects that may arise from using (primarily) white dwarfs in the determination of $\phi^{atm}(\lambda, alt, az, t)$.

The values for Δ_{br} will be determined by generating model m_b^{nat} values for each band-band calibration object, then minimizing

$$\chi^2 = \sum_i \left(\frac{(m_{b,i}^{nat} - m_{r,i}^{nat})^{meas} - (m_{b,i}^{nat} - m_{r,i}^{nat})^{model}}{\sigma_{b-r,i}} \right)^2. \quad (22)$$

This comparison can be done using subsets of objects from low galactic extinction regions, and then bootstrapping to the entire sky to check for systematic effects, perhaps by using the main sequence stellar locus as an additional method to determine the amount of galactic extinction.

LJ - there is more to come here, based on notes from Zeljko. Include stellar locus / quasar locus / white dwarf locus and how this can help constrain band-to-band color variations (particularly with different sensitivities to dust)

5.2. Single bandpass to external flux system (absolute scale)

After determining the band to band calibration, there is a single number required to calibrate the entire system to an absolute flux scale: Δ_r . This can again be determined using a single object with a well-known flux and spectral energy distribution, however multiple external calibrators provide a valuable check on systematic effects.

Several WDs in the Northern hemisphere have been very precisely calibrated with HST STIS measurements (Bohlin & Gilliland 2004) and it should be possible to obtain similar HST measurements of one or more targets for use in the Southern hemisphere. Identification

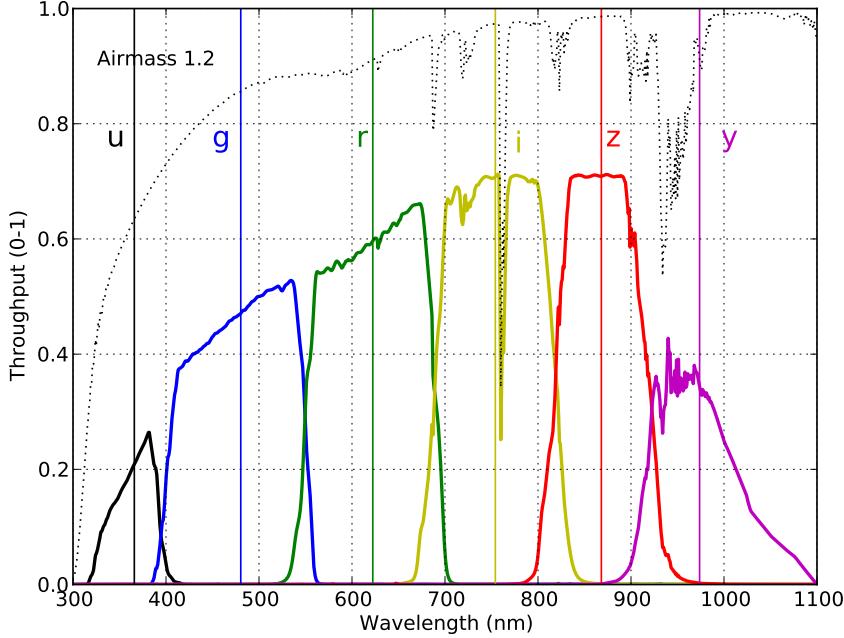
of these targets has not yet been done.

REFERENCES

- Anderson, G. P., et al. 2001, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4381, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, ed. S. S. Shen & M. R. Descour, 455–459
- Berk, A., et al. 1999, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 3756, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, ed. A. M. Larar, 348–353
- Burke, D. L., et al. 2010, *ApJ*, 720, 811
- Eppeldauer, G. P., Yoon, H. W., Zong, Y., Larason, T. C., Smith, A., & Racz, M. 2009, *Metrologia*, 46, 139
- Gressler, W. J., Doherty, P., Krabbendam, V. L., Liang, M., Saha, A., Stubbs, C. W., & Vaz, A. 2010, in Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference, Vol. 7739, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series
- Hansen, J. E., & Travis, L. D. 1974, *Space Sci. Rev.*, 16, 527
- Ivezić, Ž., et al. 2007, *AJ*, 134, 973
- Kurucz, R. L. 1993, *VizieR Online Data Catalog*, 6039, 0
- Magnier, E. A., & Cuillandre, J. 2004, *PASP*, 116, 449
- Manfroid, J. 1996, *A&AS*, 118, 391
- Padmanabhan, N., et al. 2008, *ApJ*, 674, 1217
- Regnault, N., et al. 2009, *A&A*, 506, 999
- Stubbs, C. W., Doherty, P., Cramer, C., Narayan, G., Brown, Y. J., Lykke, K. R., Woodward, J. T., & Tonry, J. L. 2010, *ApJS*, 191, 376
- Stubbs, C. W., et al. 2007a, in Astronomical Society of the Pacific Conference Series, Vol. 364, The Future of Photometric, Spectrophotometric and Polarimetric Standardization, ed. C. Sterken, 373–+

Stubbs, C. W., et al. 2007b, PASP, 119, 1163

A. Filter Set



B. Improvements in photometric accuracy

To conduct science with the catalogs from LSST, the natural magnitudes, m_b^{nat} , for each astronomical object in each visit must obviously be recorded, resulting in approximately 2×10^{13} measurements. However, in order to permit scientists to generate higher precision photometry for objects with known SEDs (which are likely to be different than the SEDs LSST used to create those m_b^{nat} measurements), $\phi_b^{meas}(\lambda, alt, az, x, y, t)$ and the zeropoint offset from the self-calibration procedure must also be available. With these additional pieces of information, scientists can generate more precise $\delta k(alt, az, x, y, SED, t)$ corrections to m_b^{nat} .

For many objects, LSST will assume a flat SED when generating m_b^{nat} values, implying that no $\delta k(alt, az, x, y, SED, t)$ correction was applied. Sections 4.2.1 and 4.2.2 outline the typical magnitudes of these corrections; for some main sequence stars these corrections can easily be on the order of 20 mmag for *gri*, or even 100 mmag in *u* band. For more extreme SEDs, these corrections may be even larger.

CREATE FIGURE: the likely magnitude of these corrections

Data management could record a full $\phi_b^{meas}(\lambda, alt, az, x, y, t)$ value for every object in every visit, where the resolution on $\phi(\lambda)$ will need to be at least 0.5 nm. It should also be possible for data management to simply record the full narrow band flat field data cube, the SED used to create the synthetic flat field, the interpolated components for the atmosphere (approximately 6 parameters per visit), and the zeropoint applied to each patch (approximately 369 per visit). Together with provenance information on how each of these was used to generate the observational corrections, it would then be possible to regenerate a higher precision m_b^{nat} .