

LSST's Calibration Pipelines

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1 Introduction

This document outlines the software required to produce calibration products, and then apply them.

Appendix A lists the available inputs to the calibration products, and datasets listed therein are referenced as *e.g.* (inputs: ¶4).

2 Calibration Products

2.1 Biases

Bias frames will be produced by taking the median of several-to-many bias exposures. (inputs: ¶1).

The individual frames will be overscan-corrected and then combined using standard LSST image stacking code. With the LSST 2s readout, we do not expect to need to remove cosmic rays explicitly, but a robust stacking algorithm will be required. If the readout noise in any channels is too low (relative to the gain) to properly sample the noise distribution, a simple fix is to add sets of n (*e.g.* 3) bias exposures before creating the stacked image.

2.2 Linearity

We care about linearity for a number of purposes:

- Correcting potential photometric errors.
- Making the PSF independent of brightness level.
- Matching background levels for different readout amplifiers.

We expect the camera team to deliver linearity curves (inputs: ¶8).

We will be able to check these values, and their stability, in at least three ways:

- Looking at the flux of objects as a function of the background level.
- Looking at PSF residuals as a function of brightness and background level.
- Looking at the offsets between amplifier segments in flat fields taken at different light levels.

2.3 Crosstalk

We expect the camera team to deliver a crosstalk matrix coupling every amplifier to every other amplifier (inputs: ¶9); we hope and expect that most of these matrix elements will be 0.

We can also check the cross talk coefficients using CBP data (inputs: ¶6f), saturated stars' bleed trails, or cosmic rays. The latter two measurements are likely to only be useful for checking crosstalk coefficients, while a suitably chosen set of CBP spots would allow us to make measurements *ab initio*.

2.4 Darks

Dark frames will be produced by taking the median of several-to-many dark exposures, each of length c. 300s; (inputs: ¶2).

The individual frames will be run through standard ISR processing (including cosmic ray removal) before being combined; the combination may be done using standard LSST image stacking code. If we disable the cosmic ray removal a much larger number of exposures will be required.

2.5 Flat Fields

Even with high-QE devices such as those in the LSST camera, the sensitivity of the detectors is a function of the SED of the light illuminating them; this is made worse by any spatial structure in the transmission of the filters or of any other optical elements in the system. Additionally, the light received at a point in the focal plane is the sum of the focused light and of any ghost or scattered contribution.

For photometry of objects only the focused part is of interest, while for background subtraction it is the total incident light that matters.

We plan to apply corrections to the data for the static part of the pixel size non-uniformity. It is *very* important that the same corrections be applied to the flat fields.

2.5.1 Broadband and Monochromatic Flats

We will take both broadband (inputs: ¶3) and ‘monochromatic’ (inputs: ¶4) flat fields. As discussed below, we will use the latter to estimate the correct flat field for light with the SED of the night sky, and the former to correct our data for the effects of dust on the filters and other effects that change on a short time scale.

2.5.2 Contamination of Filters and Other Optical Elements

Dust motes appearing on filters have an affect upon the system flat fields. This is not expected to be a serious effect for LSST as the beam at the filter has a diameter of *c.* 10cm (effective diameter *c.* 8cm) so only an unexpectedly large contaminant will have a measureable effect.

However, we expect to take broadband flats (inputs: ¶3) every time we put a filter into the filter changer, and probably as a routine part of afternoon checkout. We will synthesise a broad-band flat from the monochromatic flats (inputs: ¶4) and filter transmissions (inputs: ¶7), and divide the measured by the synthetic flats; by taking contaminants to be gray (*e.g.* opaque, but with a small covering factor) we will use the ratio to correct the monochromatic flats for any changes since they were taken.

Another approach would be to use a broadband flat taken at the same time as the monochromatic flats as the reference image. In reality we will do both; any discrepancy will be a sign of potential drift in the filter curves (see Sec. 2.7).

2.5.3 Flats for Background Estimation

The calibration system will produce a low-resolution spectrum of the night sky (inputs: ¶5), and we will use this to synthesise a flat field image for the sky’s SED from the monochromatic dome flats (inputs: ¶4).

We expect that this image will have large scale structures different from those seen in sky image that are due to illumination gradients on the flat field screen, the screen’s non-uniform BDRF, and the fact that the screen is not at infinity. We do not expect these gradients to cause problems in the background subtraction, and will not discuss them further except to say that if desired we could correct them using median night-time sky frames.

Note that we are not proposing using twilight or nighttime sky flats as they do not have the desired SED and may cause extra problems due to polarization.

2.5.4 Flats for Photometry

The flat fields described in Sec. 2.5.3 are not suitable for photometry of astronomical objects for at least two reasons; they include indirect light, and they have the wrong SED. We can use

the Collimated Beam Projector (CBP; (inputs: ¶6)) in conjunction with the monochromatic flats (inputs: ¶4) and filter transmission curves (inputs: ¶7) to solve this.

All the CBP data will be processed using the standard LSST ISR, except that no flat fields will be applied. We will then use standard LSST aperture photometry to measure the number of counts in each CBP spot.

- Estimation of the Photometric Flats at a Finite Number of Points.

If all the spots projected by the CBP were known to have the same intensity, then the spot fluxes measured from a scan in wavelength (inputs: ¶6a) would give us the relative QE at a set of points in the camera. In reality the spots are not all equal (due to an imperfect mask, non-uniform illumination, and varying plate scale) so we need to solve for their relative intensities; we can do this by moving the spots around the camera, (inputs: ¶6b), in a manner similar to the standard processing of star flats.

We can then correct the monochromatic spots (inputs: ¶6a) and arrive at the relative QE at a set of points in the camera, as a function of wavelength, in the absence of a filter.

- Estimation of the Photometric Flats for All Pixels

These spot data (inputs: ¶6a) only sample one point on M1, and therefore only one path through the optical system. We then use the data taken at different points in M1 (inputs: ¶6c) to correct these data so that they reflect the performance of the entire optical system. We could sample all of M1, but in practice we expect to use many fewer pointings.

If we could repeat this operation putting the CBP spots down on every pixel we would have our desired flat field; unfortunately this is impracticable.

Instead, we will take the monochromatic dome flats (inputs: ¶4) and use the known QE at the position of the CBP spots (without applying the filter transmission curves) to correct for ghosting. A sketch of the procedure is:

- Fit a surface through the CBP values (either per-CCD or for the whole camera); a spline would be a reasonable choice (either the product of two 1-D splines, or a thin plate spline. I would start with the former as they are easier to understand).
- Divide the dome flat by this curve, giving an estimate of the illumination and chip-to-chip correction
- Fit a curve to this correction, and correct the dome screen. This should be close to the values derived from the CBP data (and can preserve discontinuities in the QE across chips which the fitted curves have a hard time following).
- Iterate a couple of times; each iteration should result in a smaller and smoother correction, which we are therefore better able to model.

Repeat this operation at a suitable set of wavelengths, chosen so that the variation of these corrections as a function of wavelength is well captured; we now know the the relative QE for all pixels in the camera, as a function of wavelength, in the absence of a filter.

Using the filter transmission curves (inputs: ¶7) we can derive the relative QE for all pixels in the camera for each filter at 1nm resolution; this is our monochromatic photometric flatfield.

N.b. we are in a position to provide a model of the ghosting following this analysis in two ways:

- By analysis of the CBP data, concentrating not on the spots but on the scattered/ghost light

- By looking at the corrections applied to the CBP spot data to arrive at the dome screen data

We do not need this information to calibrate LSST, but it will provide a valuable cross-check, and will inform the camera and telescope teams about the state of the optical elements.

2.6 Fringe Correction

Although the thick, deep-depletion LSST CCDs reduce the amplitude of fringing they do not remove the necessity to handle it correctly in the z and y bands. Fringing is a QE effect, and this QE variation coupled to night sky line emission (mostly from OH) leads to spatial structures in the background.

The classical approach to fringing is to subtract a multiple of a fringe frame, made by taking the median stack of a very large number of science exposures scaled by their sky intensity. Because the lines in the night sky spectrum vary in relative intensity during the night the structure of the fringing will, in general, vary.

In addition, the night sky shows spatial structures in rotational temperature and intensity with wavelengths of *c.* 2km (the OH emission is at *c.* 100 km, so wavelengths of *c.* 1 degree, or 4 CCDs). With a windspeed of 60 km/s the smoothing scale (in the wind direction) is *c.* 1 CCD. These spatial structures change on time scales of *c.* 10 minutes.

If a CCD is of more-or-less of constant thickness with small ($\ll 1\mu\text{m}$) variations the relative variation of the line intensities do not significantly affect the structure of the flats as the fringe patterns from different lines are very similar (although of different amplitude and phase). However, at least some of the LSST chips show 20 fringes at $1\mu\text{m}$ from centre to edge of the device, which implies that the *pattern* of the fringing will change as the line ratios change.

For small fields of view, or long integrations, where the spatial structure in the night sky brightness may be ignored it is possible to model the variation in the fringing using a PCA decomposition of sky frames. Unfortunately LSST will show changes in fringe patterns and intensities coming from both the spectral and spatial variation of the sky and we are planning to use a different approach.

As described in Sec. 2.5.3 we will synthesise flat fields that match the night sky's SED. In a little more detail relevant to fringing, the calibration system will produce a spectrum of the night sky with resolution *c.* 200, and this is sufficient to predict the distribution of night sky line intensities (inputs: ¶5). We will then use this low-resolution spectrum to construct a flat field from the monochromatic dome flats (inputs: ¶4) that flatten the night sky spectrum, removing small-scale structure due to the sky emission.

Note that we assume that a single spectrum within the field of view is sufficient to constrain the night sky spectrum, whereas in reality the (atmospheric!) gravitational waves producing spatial structure have the ability to modify the emission spectrum. As timescales in the atmosphere are *c.* 10-20 minutes we will have many realisations of the spectrum at different points in the sky, and will be able to use these to confirm that the effective fringe image is spatially uniform; if it transpires that this is not the case we will be able to construct a small number of flats that capture the variation, and use them to remove the variation in the spatial structure.

2.7 Filter Transmission Curves

The filter transmission curves (inputs: ¶7) will be provided by the camera team, but by using monochromatic spots from the CBP with (inputs: ¶6d, 6e) and without filters in the beam (inputs: ¶6a) we can monitor the filters for any evolution, including light leaks.

Note that we are not exploring all possible light paths through the filters; while 2.5 CBP spots per CCD mean that we have light passing through every point on the filter they are not passing through every patch on the filter at every angle.

In theory we can measure the filter curves using the CBP, but it'd take a long time; in full generality *c.* 470 exposures for each 1nm step. If we are willing to make strong enough symmetry assumptions this can be reduced to *c.* 6 exposures per wavelength step; an extension of (inputs: ¶6c) to higher spectral resolution, and with the filter in the beam.

2.8 Pixel Size Effects

It has become clear that much of the pixel-to-pixel variation seen in flat field images is in fact due to variations in the sizes of the pixels. These are popularly divided into two parts:

- Large scale features such as the “tree-rings” due to variation in the properties of the silicon, or perturbations in the electric field (*e.g.* “glowing edges”).
- Small-scale, quasi-random, variations in the pixel sizes.

If we interpret the flat fields in terms of QE variation we will make errors measuring fluxes (although not while estimating surface brightnesses).

The pixel size variation may be thought of as a 2-D vector field ξ , the offset of each corner of each pixel from a regular grid. There are various approaches being taken to measure the sizes of the pixels.

If you can reduce the distortion to a 1-dimensional function (*e.g.* tree rings with circular symmetry about a point; ‘glowing edges’ that are a function of distance from the edge of the sensor) then high-signal-to-noise flat fields can be used to determine the distortions (inputs: ¶3).

The small-scale variations are harder. If we are willing to make the arbitrary assumption that ξ is the gradient of a scalar we can solve for it from flat field data. Aaron Rudman’s group, working on DECam data, makes the surprising claim that they can find ξ by looking for a solution close to $\xi = 0$.

If such approaches fail, it is probably possible to measure ξ by using images of 1-D sinusoids projected onto the CCD, either by the camera team or on the mountain using the CBP.

See Sec. 3.6 for a discussion of how we will use ξ once it is known.

2.9 Brighter-Fatter

The measurements needed to characterise Brighter-Fatter effects are not yet clear. Current state of the art is to use pixel-to-pixel correlations in flat fields taken at different flux levels (inputs: ¶3). It is possible that we’ll need other measurements, possibly generated by projecting masks onto the camera using the CBP.

2.10 Atmospheric Absorption

The calibration telescope will deliver a spectrophotometrically calibrated spectrum for a bright (≤ 8) star in the field of almost all 8.4m visits (inputs: ¶10), covering at least the bandpass of the filter currently in use. These stars will be chosen to have well-known spectrum (inputs: ¶11) based on their photometry. **XXX This requires more thought!**

Using atmospheric models (*e.g.* MODTRANS, extended to include a variable spectral index for the aerosols) we will fit these two spectra to derive current atmospheric parameters in the

direction of the boresight. We expect to make use of other atmospheric information (inputs: ¶12) such as barometric pressure and O_3 satellite data.

We will also use known photometry in the same field (inputs: ¶??) to help break the degeneracy between *e.g.* aerosol index and gray absorption.

We do not yet know how we will make use of the time-series of atmospheric parameters, nor how we will use this series to fill in the cases where the calibration telescope fails to keep up with the 8.4m.

N.b. It is probably not necessary to know the true spectrum of the star, as we only need to reduce the atmospheric absorption to standard conditions using the ensemble of all star spectrophotometric data.

3 Applying Calibration Products

3.1 Biases

We will fit the overscan using a suitable function in the row direction (*e.g.* a spline), taking due account of cosmic ray hits during readout and bleeding into the overclock as saturated stars are clocked away from the amplifier splits.

We will then subtract the bias frames.

3.2 Linearity

After bias subtraction we will correct for non-linearity. *N.b.* this assumes that the sole source of non-linearity is in the readout amplifier. If there is significant non-linearity introduced further down the signal chain – which seems unlikely – we may need to extend out non-linearity corrections.

3.3 Crosstalk

We next correct for crosstalk, including intra- and inter-chip corrections if necessary.

3.4 Darks

After cross-talk correction we will subtract scaled dark frames.

3.5 Flat Fields

We next flat field the data, using the flat constructed using the sky SED.

Note that this flat should correct for fringing, so there is no need for any fringe subtraction. As discussed in Sec. 2.6 it is possible that spatial and spectral variation over the field will lead to residual fringe structures, in which case we will also performance of classical fringe frame subtraction.

3.6 Pixel Size Effects

Given the field ξ we may redistribute flux between pixels (it's easier to think about this as a correction in first x then y). Linear estimation of the flux density at the pixel boundary is probably sufficient, although higher order weights based on a nominal PSF might be better.

This flux redistribution causes a small correlation between the pixels which we need to track with some level of accuracy.

Note that the same corrections were applied to the flat fields, so the combination of these two corrections leaves the uniform unstructured nature of the background undisturbed.

3.7 Brighter-Fatter

We then redistribute flux between pixels to correct for the brighter-fatter effect. Note that this does *not* cause correlations between pixels, rather it removes the correlations induced by the electric field shifts that resulted in brighter-fatter in the first place.

3.8 Background Subtraction

We now proceed with normal image processing activities, leading to photometric and astrometrically calibrated images. At some point (*e.g.* after background matching) we subtract the background.

3.9 Final Photometry

For each observation of each object we know:

- The QE of the device as a function of wavelength at the position of the object; including the effects of the filter
- The QE of the device as a function of wavelength assumed when flat fielding;
- The atmospheric transmission;
- The object's colour

(Yes, there is an apparent circularity here. But we don't need very good colours – a few % is fine – so this is not a fundamental problem; however the details of how we arrange the computation efficiently requires thought).

We then (at least logically – this may not describe in detail the actual operations carried out):

- Measure the object's flux.
- Undo the flat fielding, assumed constant over the scale of the object.
- Look up the canonical SED corresponding to the object's colour (*i.e.* the mean SED for objects with that colour; this may not be correct, although most degeneracies in photo-z estimation are due to similar observed SEDs from objects with different intrinsic SEDs).
- Correct this SED for the atmospheric absorption
- Calculate the proper flat field for this SED, assumed constant over the scale of the object.
- Correct the flux for the incorrect flat fielding we applied.
- Record the raw and corrected flux, allowing us to repeat this calculation for any user-provided SED.

Note that

A Inputs to LSST’s Calibration Pipelines

We will have the following datasets available:

1. ¶1 Sets of bias frames.
2. ¶2 Sets of 300s dark frames.
3. ¶3 Sets of flats taken through the standard LSST filters. We will need flats taken at a number of flux levels to measure brighter-fatter and check linearity.
4. ¶4 Sets of ‘monochromatic’ (*c.* 1nm) flat-field screen images taken without the filter in the beam.
5. ¶5 Spectra of the night sky near the Calypso boresight, with $R \sim 200$.*
6. ¶6 Sets of *Collimated Beam Projector* images. The proposed resolutions and steps in these datasets are preliminary.
 - ¶6a Sets of CBP images scanned in wavelength at 1nm resolution every 1nm for a fixed set of spot positions on the camera, and for fixed footprint on M1. No filter should be in the beam.
 - ¶6b Sets of CBP images scanned in wavelength at 20nm resolution every 100nm, while rotating the CBP about a pupil to move the spot pattern around the camera for a fixed footprint on M1. No filter should be in the beam.
 - ¶6c Sets of CBP images scanned in wavelength at 20nm resolution every 100nm for a fixed set of spot positions on the camera, and for a number of footprints on M1; the minimum number of footprints is *c.* 6 for a 30cm CBP, but in reality we will explore more pointings to test azimuthal symmetry. No filter should be in the beam.
 - ¶6d Sets of CBP images scanned in wavelength at 1nm resolution every 1nm for a fixed set of spot positions on the camera, and for fixed footprint on M1. Repeated for every filter. *N.b.* the wavelength range for each scan need only cover the range for which the filter transmits appreciable light.
 - ¶6e Sets of CBP images scanned in wavelength at 20nm resolution every 20nm for a fixed set of spot positions on the camera, and for fixed footprint on M1. Repeated for every filter.
 - ¶6f Sets of CBP images taken with a suitable designed sparse mask to allow us to identify and measure all crosstalk images. The simplest sparse mask would have only a single spot, used to illuminate each amplifier in the camera in turn (but less sparse solutions are probably also possible). The wavelengths used are unimportant, and there are no constraints on beam footprints on M1 or filter choice.
7. ¶7 Transmission curves for all the filters as a function of position.
8. ¶8 The linearity curve for every amplifier.
9. ¶9 The crosstalk matrix for every pair of amplifiers in the camera.
10. ¶10 Spectrophotometrically-calibrated spectra for stars in the field of view of almost all visits.

*It is not entirely clear whether these will be taken on the Calypso or 8.4m boresight.

11. ¶11 Known spectra for bright stars in the field of view of all visits.
12. ¶12 Externally measured parameters of the atmosphere, for example barometric pressure and ozone.
13. ¶13 Photometric standards, of a range of colours. GAIA is a likely source for these data.