

Tree Rings in LSSTCam CCDs

ANDRÉS A. PLAZAS MALAGÓN ^{1,2} AGNÈS FERTÉ ¹ ALEXANDER BROUGHTON ²
AND PIERRE-FRANÇOIS LÉGET ³

¹*SLAC National Accelerator Laboratory, 2575 Sand Hill Rd., Menlo Park, CA 94025, USA*

²*Kavli Institute for Particle Astrophysics and Cosmology, SLAC National Accelerator Laboratory,
2575 Sand Hill Rd., Menlo Park, CA 94025, USA*

³*Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*

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ABSTRACT

This paper provides a focal-plane-wide, band-dependent characterization of the *LSSTCam* tree rings from flat-field observations, derives detector-specific calibration templates suitable for pipeline use, and estimates their impact on photometry, astrometry, shear.

We provide per-detector, per-band radial profile templates with uncertainties and validation metrics, and describe their integration into the *LSST* Science Pipelines calibration chain. These results establish the phenomenology of tree rings across the *LSSTCam* focal plane and deliver practical calibration products for mitigating their impact on *LSST* science.

1. INTRODUCTION

Fully-depleted, abck illuminated CCDS are in used in modern mosaic CCDS cameras... LSSTCam one of them, largest digital camera in the world.

Transverse / lateral E-fields, static, dynamic...

Tree rings are...

The Legacy Survey of Space and Time (LSST), conducted with the Vera C. Rubin Observatory, will image the entire visible southern sky every few nights for ten years, generating an unprecedented photometric and astrometric dataset (Ž. Ivezić et al. 2019). The LSST Camera (*LSSTCam*) is the largest digital camera ever built for astronomy, featuring a 3.2-gigapixel focal plane with 189 science CCDs (A. Roodman et al. 2023).

Tree rings affect multiple science domains:

- **Flat-field calibration:** Tree rings introduce radial QE variations that must be separated from other sensor signatures (amplifier boundaries, QE residuals, mid-line breaks) to achieve percent-level flat-field accuracy.

- **Astrometry and World Coordinate Systems (WCS):** Radial QE modulations induce systematic centroid shifts in stellar images, leading to position-dependent astrometric distortions. [A. A. Plazas et al. \(2014\)](#) demonstrated that tree rings in DECam produce astrometric displacements of $\sim 0.01\text{--}0.02$ pixels, which are significant for precision astrometry. [G. M. Bernstein et al. \(2017\)](#) implemented tree-ring corrections in the DECam astrometric calibration pipeline and showed that these corrections are essential for achieving sub-milliarcsecond internal astrometric precision.
- **PSF modeling:** Tree-ring-induced centroid and shape variations affect PSF model residuals. [J. Esteves et al. \(2023\)](#) found that tree rings in LSST sensor candidates produce correlated PSF size and shape residuals at the few-percent level, with spatial scales of $\sim 100\text{--}200$ pixels.
- **Weak gravitational lensing:** Cosmic shear measurements require exquisite control of systematic shape and position errors. Uncorrected tree rings can produce spurious convergence and shear signals that mimic lensing effects (Okura 2015). The relationship between flat-field modulation $w(r)$ and spurious lensing quantities is ([A. A. Plazas et al. 2014](#)):

$$\kappa_{\text{sp}}(r) \approx -\frac{1}{2}w(r), \quad \gamma_{\text{sp}}(r) \approx -\frac{1}{2}w(r). \quad (1)$$

For the *LSSTCam* *i*-band detector studied here the flat-field ring amplitude is at the $w \sim 10^{-4}\text{--}10^{-3}$ level (smaller than the $\sim 1\%$ amplitudes seen in some earlier devices), implying spurious shear $\gamma_{\text{sp}} \sim 10^{-4}$; although modest per detector, this is a *fixed-pattern* systematic that does not average down with repeated visits and is therefore relevant to LSST Dark Energy Science Collaboration (DESC) systematic error budgets.

- **Photometry and chromaticity:** Tree rings modulate pixel sensitivity as a function of position and wavelength. Understanding their chromatic properties is essential for multi-band photometric consistency and color-dependent systematics.

Tree rings have been characterized in several astronomical CCD systems. Look up more literature...

[A. A. Plazas et al. \(2014\)](#) presented a detailed study of tree rings in the Dark Energy Camera (DECam), including a formalism for predicting astrometric displacement from flat-field modulation. [G. M. Bernstein et al. \(2017\)](#) implemented tree-ring astrometric corrections in the DECam pipeline. [H.-Y. Park et al. \(2020\)](#) analyzed radial period and amplitude variations in astronomical CCDs. [J. Esteves et al. \(2023\)](#) characterized tree rings in LSST sensor candidates and quantified their impact on PSF metrics.

This paper extends previous studies to the full *LSSTCam* focal plane and provides:

1. focal-plane-wide, multi-band tree-ring characterization for *LSSTCam*,
2. Quantitative azimuthal symmetry tests and polar-coordinate diagnostics,
3. Band-dependent amplitude scaling and phase alignment measurements,
4. Predicted astrometric displacements and spurious lensing signals,
5. Per-detector, per-band radial profile templates with uncertainties and validation metrics for pipeline integration.

[NOTE: Mention general transverse/lateral E-fields paper by Brittney and the conext for this paper that focuses on tree-rings]

The structure of this paper is as follows. Section 2 reviews the physical origin of tree rings and the expected observables. Section 3 describes the flat-field datasets. Section 4 presents our measurement methodology. Sections 5 and 6 show single-detector case studies and focal-plane-wide results. Section 5.2 analyzes band dependence. Section 7 discusses science impacts. Section 8 describes the correction model for pipelines. Section 9 discusses limitations and future work. Section 10 summarizes our findings.

2. PHYSICAL ORIGIN AND EXPECTED OBSERVABLES

2.1. Detector Physics

Tree rings arise from radial variations in dopant concentration during boule growth... The primary observable effects are:

- **Flat-field modulation:** Radial QE variations produce percent-level intensity modulations in flat-field images after illumination gradient removal.
- **Pixel-area modulation:** Electric field variations distort the effective pixel boundaries, leading to apparent position shifts in detected photons.
- **Wavelength dependence:** The depth of charge generation varies with photon wavelength, leading to different sensitivities to dopant variations at different depths. Shorter wavelengths (bluer bands) are absorbed closer to the surface and are more sensitive to near-surface field variations, while longer wavelengths penetrate deeper.

2.2. Relation Among Observables

Following A. A. Plazas et al. (2014), the flat-field fractional modulation $w(r)$ is related to the radial astrometric displacement $f(r)$ by:

$$f(r) = -\frac{1}{r} \int_0^r r' w(r') dr'. \quad (2)$$

This assumes azimuthal symmetry and relates the radial intensity modulation to the radial displacement field. It is the inverse of the flux-conservation (area-distortion)

relation $w = -\nabla \cdot \boldsymbol{\delta}$ for a radial displacement $\boldsymbol{\delta} = f(r) \hat{\mathbf{r}}$; the leading minus sign is the convention of [A. A. Plazas et al. \(2014\)](#) and [J. Esteves et al. \(2023\)](#). After computing $f(r)$, a smooth polynomial or low-frequency trend is subtracted to isolate the oscillatory tree-ring component (the additive constant left by integrating from the smallest sampled radius is absorbed into this trend).

From $f(r) \equiv d(r)$ we obtain the spin-0 (convergence, size) and spin-2 (shear, ellipticity) observables. In general,

$$\kappa(r) = \frac{1}{2} \left(\frac{d d(r)}{dr} + \frac{d(r)}{r} \right), \quad \gamma_{\text{rad}}(r) = \frac{1}{2} \left(\frac{d d(r)}{dr} - \frac{d(r)}{r} \right), \quad (3)$$

and for radii much larger than the displacement scale both reduce to half the flat-field modulation,

$$\kappa(r) \approx -\frac{1}{2}w(r), \quad \gamma_{\text{rad}}(r) \approx -\frac{1}{2}w(r). \quad (4)$$

In the ellipticity convention adopted here, the induced radial ellipticity and fractional PSF-size change are $\delta e_r(r) \approx -w(r)$ and $\delta T/T(r) \approx -w(r)$. The radial spin-2 quantities are rotated into detector Cartesian components using the polar angle ϕ about the ring center,

$$\gamma_1 + i\gamma_2 = \gamma_{\text{rad}}(r) e^{2i\phi}, \quad \delta e_1 + i\delta e_2 = \delta e_r(r) e^{2i\phi}. \quad (5)$$

3. DATA SETS

3.1. Flat-Field Observations

We use two sets of flat-field data.

1. **Deep *i*-band combined flat.** A single high signal-to-noise combined flat per detector, built from **290** individual *i*-band (*i*₃₉) flat exposures taken with the “natural-frequency” (3s_v2) sequencer on 2025-12-28. The exposures are combined with the LSST Science Pipelines flat-generation task, submitted through the Batch Processing Service (BPS) with the input raw collection `LSSTCam/raw/all` and the curated calibration inputs (defects, bias, dark, linearity, gain/PTC, brighter-fatter and flat gradient references) listed in [Appendix A](#). The combining is done at the photon-transfer (PTC) level so that the pixel-to-pixel gain structure is preserved while the per-exposure Poisson noise averages down as $\sqrt{290}$, which is what makes the $\sim 10^{-4}$ tree-ring modulation measurable. Detector 122 (`R30_S12`) is excluded. The resulting combined flats live in the user collection `u/plazas/LSSTCam/calib/none/treerings/flatGen-i.20260319b` and are read directly from the Butler at the USDF; this data set is used for center fitting, radial-profile extraction, and the astrometric/shear predictions. The exact BPS submission script and exposure selection are reproduced verbatim in [Appendix A](#).
2. **Standard calibration flats (all bands).** Standard *LSSTCam* combined calibration flats in the five broad science bands (*g*, *r*, *i*, *z*, *y*) from the `LSSTCam/calib`

collection (one combined flat per band and detector). These are used for the chromaticity analysis, where a single ring center is used across all bands.

3.2. Detector Coverage

Our analysis targets the full *LSSTCam* science focal plane (all 189 science CCDs, both ITL and e2v vendors, excluding guide and wavefront sensors and the anomalous detector 122). In this first draft we demonstrate the end-to-end methodology in detail on a single ITL detector, R02_S02 (detector 11); the identical per-detector pipeline is applied across the focal plane, and those population-level results are presented in Section 6.

3.3. Preprocessing and Masking

All combined flats are preprocessed with a common band-pass operation that isolates the ring-scale structure. Let $F(x, y)$ be the combined flat. We compute

1. **Mild denoising:** a small Gaussian smoothing $F_s = F * G_{\sigma_s}$ with $\sigma_s = 2$ –3 pixels, to suppress pixel-scale noise while preserving the broader ring structure.
2. **Large-scale background:** a broad Gaussian $B = F_s * G_{\sigma_L}$ with $\sigma_L = 100$ pixels, which models the slowly-varying illumination and vignetting.
3. **Fractional residual:** the band-passed image

$$w_{2D}(x, y) = \frac{F_s}{B} - 1, \quad (6)$$

expressing the remaining structure as a fractional deviation from the local background, in which the tree rings stand out at the $\sim 10^{-4}$ – 10^{-3} level.

4. **Outlier masking:** a robust cut flags pixels with $|w_{2D} - \text{median}| > n_\sigma (1.4826 \text{ MAD})$ ($n_\sigma = 5$), removing dust shadows, hot pixels, bad columns and similar defects into a Boolean mask **good**.

A Gaussian kernel has transfer function $\hat{G}(k) = e^{-2\pi^2\sigma^2k^2}$; with $\sigma_s = 2$ pixels the shortest LSSTCam rings ($\lambda \simeq 20$ pixels) are attenuated by $\lesssim 25\%$, and since the same kernel is applied in every band this factor cancels in the chromatic amplitude ratios of Section 5.

By default *masked pixels are not filled or interpolated*: the **good** mask is carried through to every downstream statistic, so flagged pixels are simply excluded from the radial binning rather than being assigned fabricated values. Optional local-median filling of masked pixels is available (for display or for pathological detectors) but is disabled for the science profiles, since filling injects a fixed spatial pattern that, under a moving trial center, can bias the azimuthal average.

Before band-passing we optionally remove residual amplifier-to-amplifier offsets on the Butler flat. LSSTCam reads out through a 2×8 grid of 16 segments, and small gain/level mismatches appear as piecewise-constant steps at the segment boundaries.

We estimate one additive offset per segment from the boundary *discontinuity* — fitting the smooth trend on each side of a boundary and comparing the extrapolations at it, so the illumination slope cancels — and solve all 16 offsets jointly by least squares, gauge-fixed to zero mean (an “ubercal”-style solution). Removing these steps before the large-scale Gaussian background estimate prevents a sharp step from ringing into a σ -neighborhood of pixels and from biasing radial-annulus medians that straddle a boundary; because the correction is a single constant per segment, it cannot create or remove radial ring structure. We monitor detector flatness with amplifier cross-sections (the mean along each amplifier row, clipping 50 pixels from the edges) and with cuts along the two diagonals, and quantify the residual step across each boundary before and after correction.

4. MEASUREMENT METHODOLOGY

4.1. Center Determination

Accurate tree-ring center determination is critical, and it is complicated by the fact that the ring centers usually lie *outside* the physical detector (for R02_S02 the center is near $(-324, 4088)$, i.e. off the lower-left corner), so only a fraction of an annulus is sampled at any radius. We start from the catalog of [H.-Y. Park et al. \(2020\)](#) and optionally refine:

1. Start with an initial guess $(x_{0,\text{init}}, y_{0,\text{init}})$ from the [H.-Y. Park et al. \(2020\)](#) tree-ring center catalog.
2. Optionally refine it (a run-time flag; when disabled the catalog value is used directly). The refinement defines an objective that maximizes the oscillatory power of the azimuthally-averaged radial profile after trend subtraction, and minimizes its negative with Powell’s method within a local box (± 200 pixels), on an image down-sampled by a factor of 2 for speed.

The objective function is

$$\text{Obj}(x_0, y_0) = -\text{RMS}[p(r) - \langle p(r) \rangle_{\text{smooth}}], \quad (7)$$

where $p(r)$ is the median radial profile about the trial center and $\langle p(r) \rangle_{\text{smooth}}$ is a Gaussian-smoothed trend; the true center is the one for which the rings align most coherently in radius, maximizing the trend-subtracted RMS.

We implement three automated fitters that share this radial-coherence idea but differ in the statistic and optimizer, and we compare their results per detector: (i) an *RMS-profile* fit (the trend-subtracted RMS objective above, Powell local search); (ii) an *FFT band-power* fit, which maximizes the Fourier power of the detrended radial profile inside the ring-wavelength band (coarse-to-fine, Powell), and is selective for coherent oscillations; and (iii) an *outer-radius* σ fit, which maximizes the standard deviation of the profile in the outer 75% of radii via a global differential-evolution

search (after [J. Esteves et al. 2023](#)). Hereafter we refer to these as the RMS-profile, FFT band-power, and outer-radius fits. This surface is non-convex and is nearly flat along the chip→center direction (a radial shift of the trial center barely changes the azimuthal average), so a good initial guess is important. For the R02_S02 results below we adopt the catalog center $(x_0, y_0) = (-324.08, 4087.66)$.

4.2. By-Hand Concentric-Center Fit

As an independent cross-check of the automated fitters — and following the approach of [A. A. Plazas et al. \(2014\)](#), who determined DECam tree-ring centers from hand-marked ring points — we also fit the center from points annotated by eye on the rings. The annotator marks N points along several visible rings (spread over as wide an azimuth as possible, since the outer rings and a long azimuthal lever arm constrain the center best). For a trial center $\mathbf{c} = (c_x, c_y)$ we compute each point’s radius $d_i = |\mathbf{x}_i - \mathbf{c}|$, cluster the $\{d_i\}$ into n_{ring} groups with one-dimensional k -means, and take the within-group radial scatter as the objective. We minimize a robust (Huber-loss) version of that scatter,

$$\text{Obj}(\mathbf{c}) = \sum_i \rho_\delta(d_i - \bar{d}_{k(i)}(\mathbf{c})), \quad (8)$$

where $\bar{d}_k$ is the mean radius of ring k and ρ_δ is the Huber function, using a global differential-evolution search followed by Nelder–Mead refinement; the center is allowed to lie outside the detector. Uncertainties on (c_x, c_y) are obtained by bootstrap resampling of the annotated points. Whereas [A. A. Plazas et al. \(2014\)](#) exported the marked points from an external DS9 session, we perform the annotation interactively in the notebook (clicking directly on the band-pass-filtered flat), which is otherwise identical. The band-pass image is used only to make the rings visible for annotation; the center it yields is then used to extract the profile from the unfiltered Butler flat.

Figure 1 shows the hand-marked ring points and the fitted concentric rings for R02_S02.

4.3. Polar Transform Diagnostics

Following [J. Esteves et al. \(2023\)](#), we apply a polar coordinate transformation to validate the fitted center. The image is resampled from Cartesian (x, y) to polar (r, θ) coordinates. A correctly identified center produces horizontal tree-ring lines in (r, θ) space. Misidentified centers result in tilted or disturbed patterns.

4.4. Radial Profile Extraction

We compute the radial profile by binning pixels into annuli of width $\Delta r = 1$ pixel and taking the median intensity in each annulus. The median is robust to outliers and masked pixels. Uncertainties are estimated using the median absolute deviation (MAD):

$$\sigma_{\text{median}} \approx 1.2533 \times \frac{1.4826 \times \text{MAD}}{\sqrt{N}}, \quad (9)$$

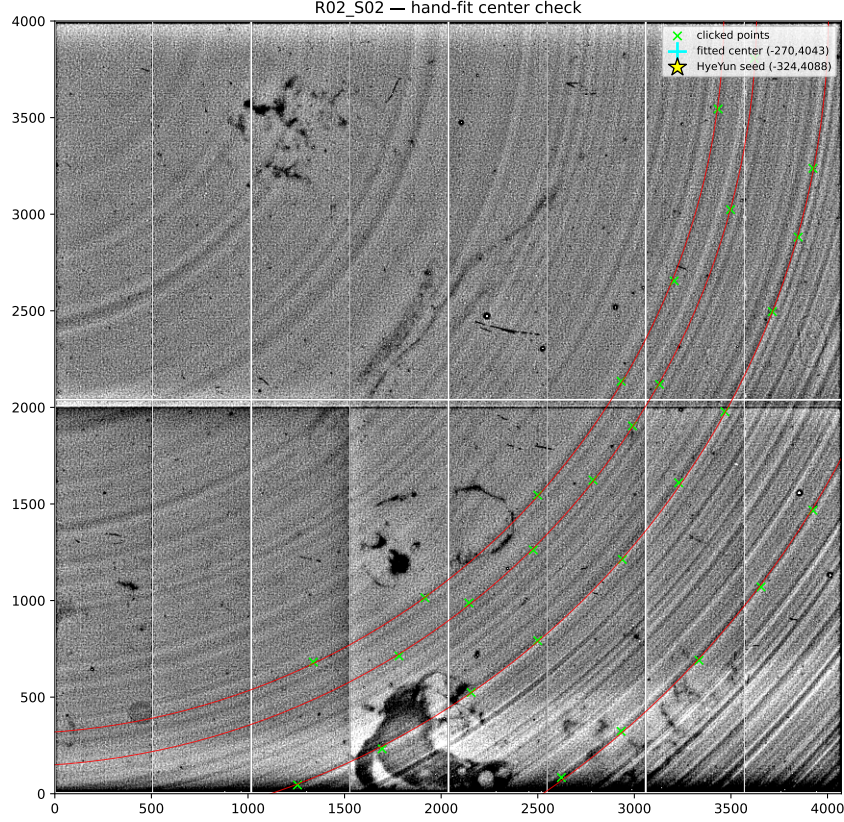


Figure 1. By-hand concentric-center fit for R02_S02: ring points marked interactively on the band-pass-filtered *i*-band flat (green $\times$), the fitted concentric rings (red), the fitted center (cyan $+$), and the [H.-Y. Park et al. \(2020\)](#) catalog seed (yellow star). The resulting center and its comparison with the automated fitters are given in Section 5.1.2.

where N is the number of valid pixels in the annulus.

4.5. Trend Subtraction

We subtract a smooth radial trend using a NaN-aware 1D Gaussian filter ($\sigma = 50$ pixels) to isolate the oscillatory tree-ring signal $w(r) = p(r) - p_{\text{trend}}(r)$. This separates the rings from residual large-scale QE variations left in the azimuthal average.

4.6. Model Subtraction Test and Metrics

As an internal consistency check we reconstruct a 2D ring model $M(x, y)$ by interpolating the 1D trend-subtracted profile $w(r)$ onto the detector at the fitted center, and subtract it from the band-passed image. We quantify the subtraction with (i) the counts-weighted RMS of the 1D ring profile before and after subtraction, (ii) the *suppression factor* $\text{RMS}_{\text{after}}/\text{RMS}_{\text{before}}$, (iii) an approximate reduced chi-square of the residual profile relative to zero, and (iv) the 2D variance ratio of the image before and after subtraction. Because the model is derived from the same image this test is not fully independent, but a large suppression confirms that the center and profile describe the ring pattern well.

4.7. Astrometric Displacement and Its Uncertainty

We integrate Equation 2 numerically (cumulative trapezoid) to obtain the raw displacement profile and then subtract a smooth/polynomial trend to remove the integration's large-scale mode. Propagating the annular profile errors $\sigma_w(r_i)$ through the discrete integral $I(r) = \int_0^r r' w dr'$, and treating radial bins as independent, gives

$$\sigma_I^2(r_k) \approx \sum_{i \leq k} (r_i \sigma_{w_i} \Delta r_i)^2, \quad \sigma_f(r) \approx \frac{\sigma_I(r)}{r}. \quad (10)$$

This is a first-order statistical estimate only; it omits covariance between neighboring bins and systematic uncertainties from the center and from the detrending.

4.8. Derived Observables and 2D Templates

From $w(r)$ and $d(r)$ we form the radial observables $\kappa(r)$, $\gamma_{\text{rad}}(r)$, $\delta T/T(r)$ and $\delta e_r(r)$ (Section 2), and interpolate them back onto the detector to build 2D templates. Scalar quantities map directly; the spin-2 quantities are rotated into Cartesian components with Equation 5. As a detector-level quick look we also estimate the shear two-point correlation $\xi_+(\theta) = \langle \gamma_t \gamma_t \rangle + \langle \gamma_{\times} \gamma_{\times} \rangle$ from the predicted shear map.

5. SINGLE-DETECTOR CASE STUDIES

We present detailed results for four representative detectors:

1. **R02_S02 (ITL)**: A strong tree-ring example with clear radial modulations.
2. **[TBD] (e2v)**: A strong e2v example.
3. **[TBD]**: A weak tree-ring detector.
4. **[TBD]**: A detector with asymmetric or pathological features.

For each case, we show:

- Raw flat-field image
- Filtered (preprocessed) image
- Polar coordinate transform
- Radial profile by band
- Sector profiles (azimuthal symmetry check)
- Dominant period and amplitude versus radius
- Before/after correction comparison

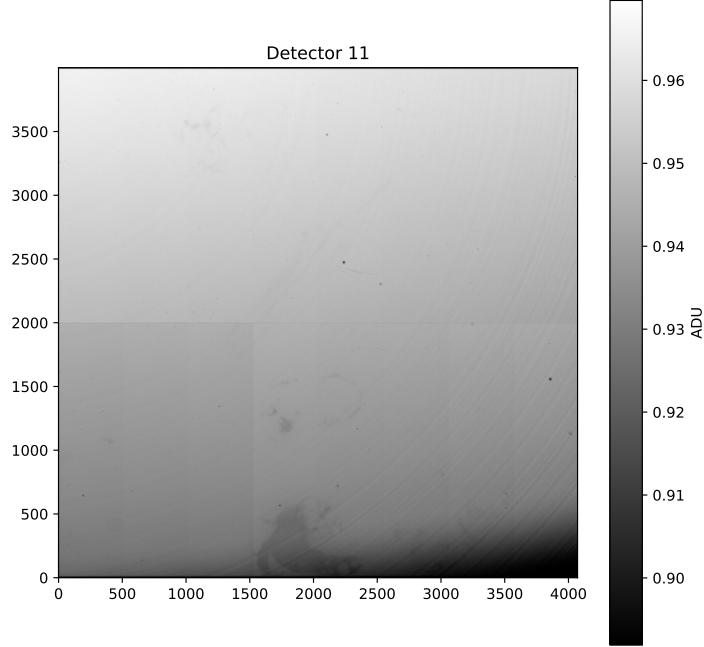


Figure 2. Raw *i*-band combined flat for R02_S02 (detector 11, ITL), built from 290 exposures. Tree rings appear as faint concentric arcs in the lower-right; amplifier boundaries, dust shadows and the illumination gradient are also visible. The ring center lies off the lower-left corner of the device.

5.1. Example: Detector R02_S02 (ITL)

We illustrate the full methodology on detector R02_S02 (LSSTCam detector 11, ITL), using the deep 290-exposure *i*-band combined flat described in Section 3 and the H.-Y. Park et al. (2020) catalog center $(x_0, y_0) = (-324.08, 4087.66)$.

Figure 2 shows the raw combined flat. The tree rings are directly visible as faint concentric arcs curving through the lower-right of the device, centered off the lower-left corner; also visible are the amplifier-segment boundaries (the horizontal mid-line at $y \simeq 2000$ and the vertical segment edges), dust shadows, and the smooth illumination gradient. Figure 3 shows the band-passed image w_{2D} (Section 3), in which the illumination gradient is removed and the ring pattern is greatly enhanced. Figure 4 overlays concentric circles at the adopted center as a visual check that the arcs are indeed concentric about it.

The azimuthally-averaged radial profile (Figure 5) resolves the oscillatory ring signal after the smooth 1D trend is removed. The trend-subtracted amplitude is at the level of a few $\times 10^{-4}$, growing toward the largest radii where the annuli clip only a small corner of the device and are therefore both noisier and affected by residual edge illumination.

The model-subtraction test (Section 4.6; Figures 6 and 7) confirms that the fitted center and profile capture the ring pattern. The counts-weighted RMS of the 1D ring profile drops from $\text{RMS}_{\text{before}} = 2.0 \times 10^{-4}$ to $\text{RMS}_{\text{after}} = 1.7 \times 10^{-5}$, a suppression factor of 0.086 (about 91% of the radial ring power removed, a factor ~ 12). The

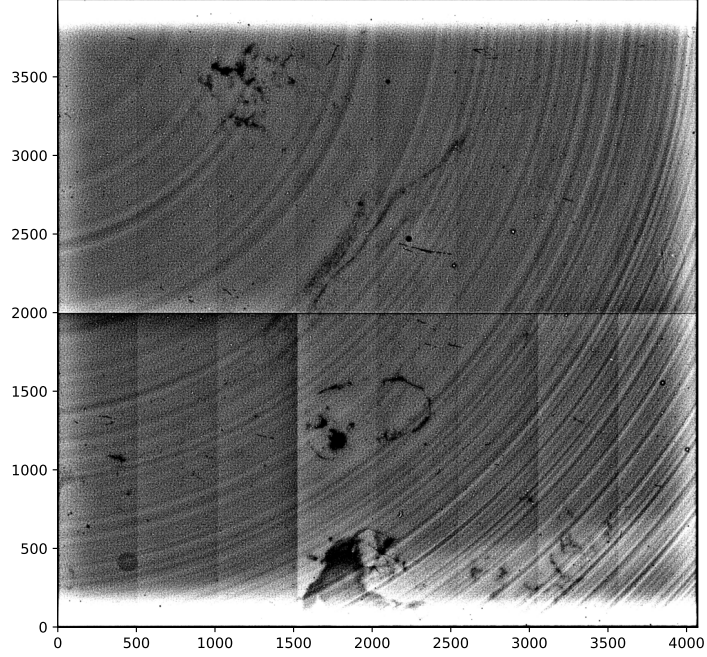


Figure 3. Band-passed (tree-ring-filtered) image $w_{2D} = F_s/B - 1$ of R02_S02. Removing the large-scale illumination model B makes the concentric ring pattern clearly visible.

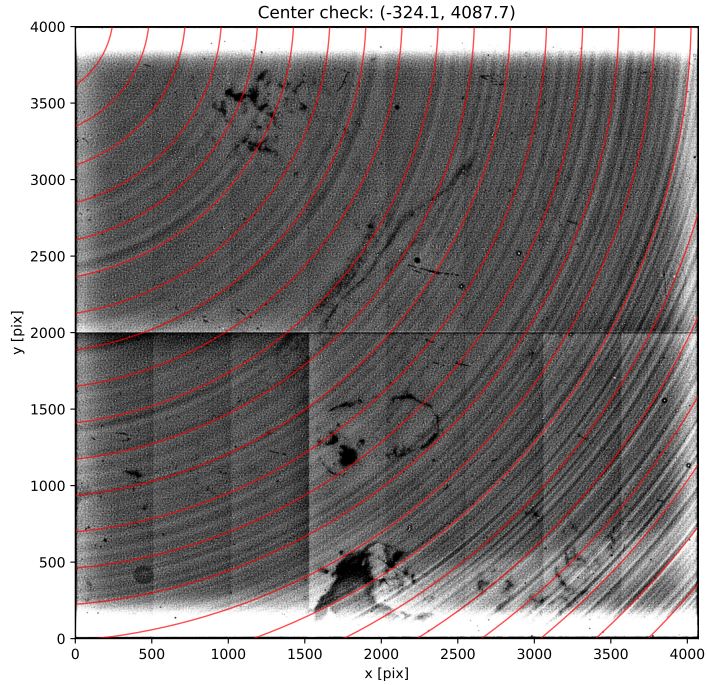


Figure 4. Filtered image with concentric circles drawn at the adopted center $(-324.1, 4087.7)$. The rings track the overlaid circles, confirming the center.

residual reduced chi-square relative to zero is $\chi^2_\nu \simeq 1.13$, indicating that the residual radial signal is close to the level expected from the annular uncertainties. The 2D variance explained is $\simeq 2.6\%$; this is modest only because the total image variance

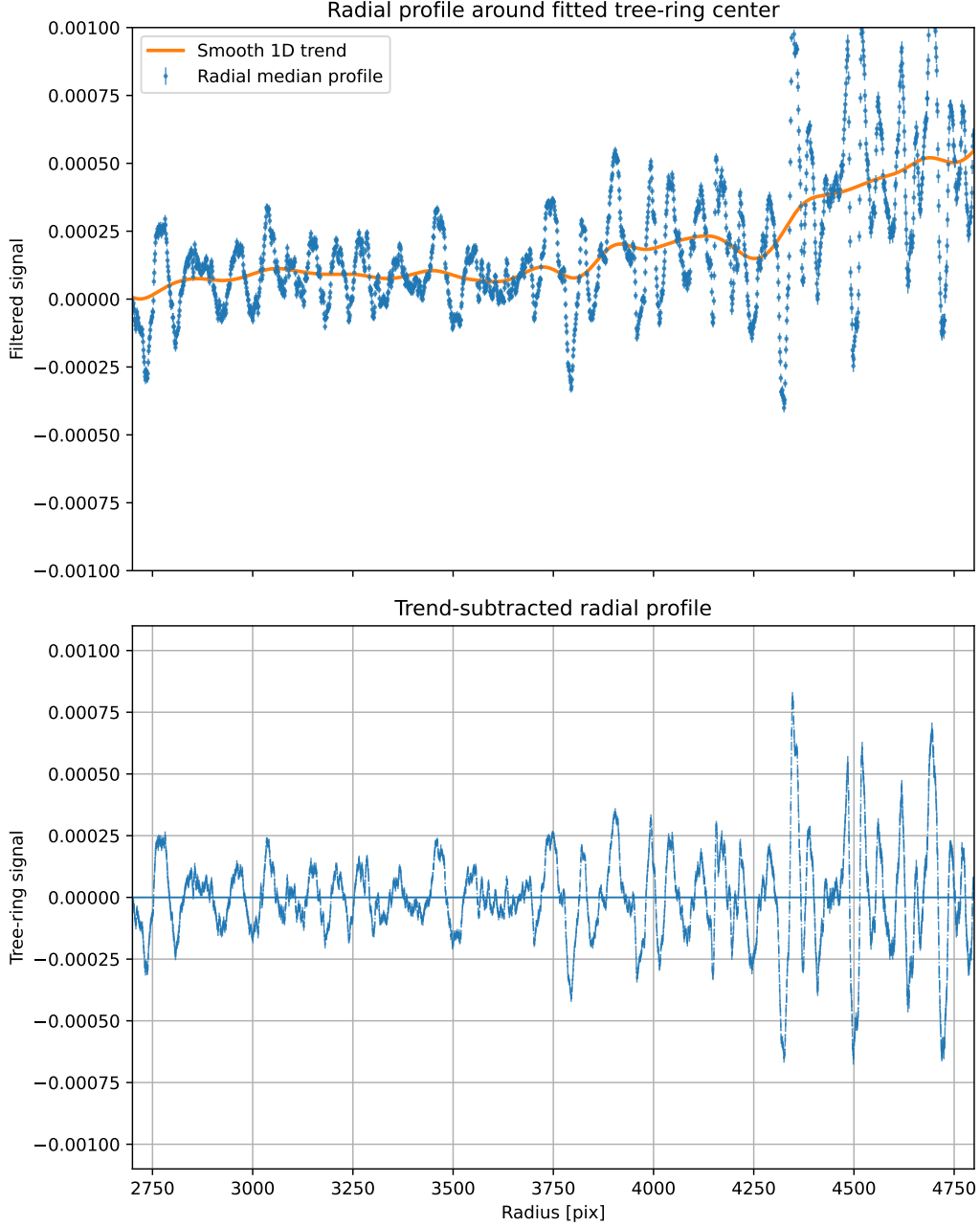


Figure 5. Radial profile of R02_S02 in the i -band. *Top:* annular-median profile $p(r)$ (points with MAD-based error bars) and the smooth trend $p_{\text{trend}}(r)$. *Bottom:* trend-subtracted tree-ring signal $w(r) = p - p_{\text{trend}}$, with amplitude of a few $\times 10^{-4}$. The larger excursions beyond $r \gtrsim 4300$ pixels are dominated by the sparsely-sampled, edge-affected annuli.

is dominated by defects, masking, and residual large-scale structure rather than by rings, so the ring-specific 1D metrics are the informative ones.

5.1.1. Predicted astrometric and lensing observables for R02_S02

Applying Equations 2–5 to the measured i -band profile yields the detector-level tree-ring templates. The predicted radial astrometric displacement (Figure 8) has

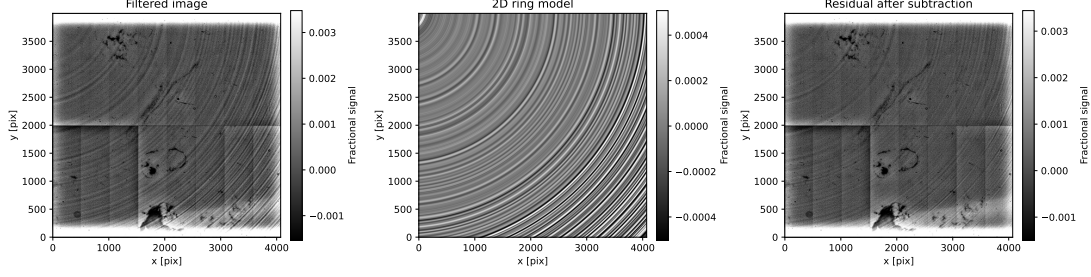


Figure 6. Model-subtraction test for R02_S02. *Left:* band-passed image. *Middle:* 2D ring model built by interpolating the 1D profile $w(r)$ onto the detector at the fitted center. *Right:* residual after subtraction, in which the concentric ring pattern is largely removed (non-ring defects and edge structure remain).

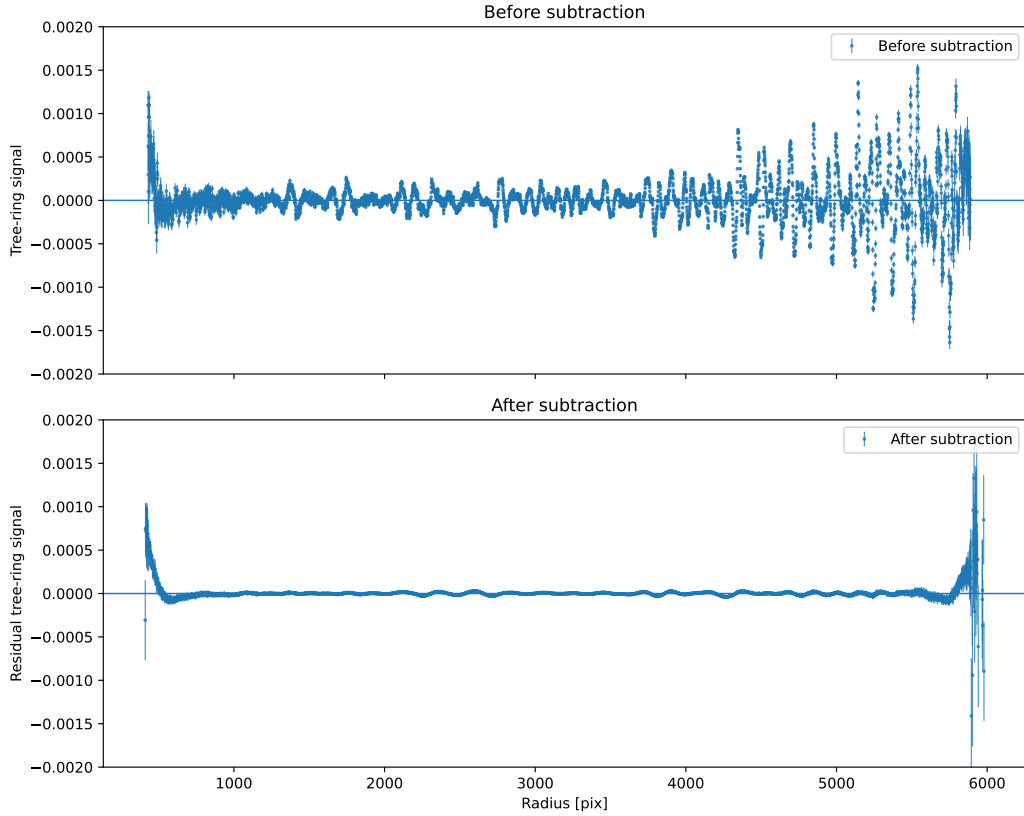


Figure 7. 1D tree-ring profile of R02_S02 before (top) and after (bottom) subtracting the 2D ring model, showing the $\sim 12\times$ reduction in ring amplitude.

a peak amplitude of $|f|_{\max} \simeq 0.025$ pixels, consistent with the ~ 0.01 – 0.02 pixel level found for DECam by A. A. Plazas et al. (2014); over most of the well-sampled area $|f| \lesssim 0.005$ pixels, rising toward the noisy outer edge. Figure 9 shows the corresponding 2D displacement field, and Figure 10 the radial convergence $\kappa(r)$, radial shear $\gamma_{\text{rad}}(r)$ and fractional size change $\delta T/T(r)$. The full set of 2D scalar and spin-2 templates ($\delta T/T$, κ , γ_{rad} , γ_1 , γ_2 , δe_1) is shown in Figure 11; the size template reaches $\delta T/T \sim 1.5 \times 10^{-3}$ and the shear/convergence templates $\sim (3\text{--}4) \times 10^{-4}$, again largest at the device edge. Finally, Figure 12 shows a detector-level quick-look shear two-

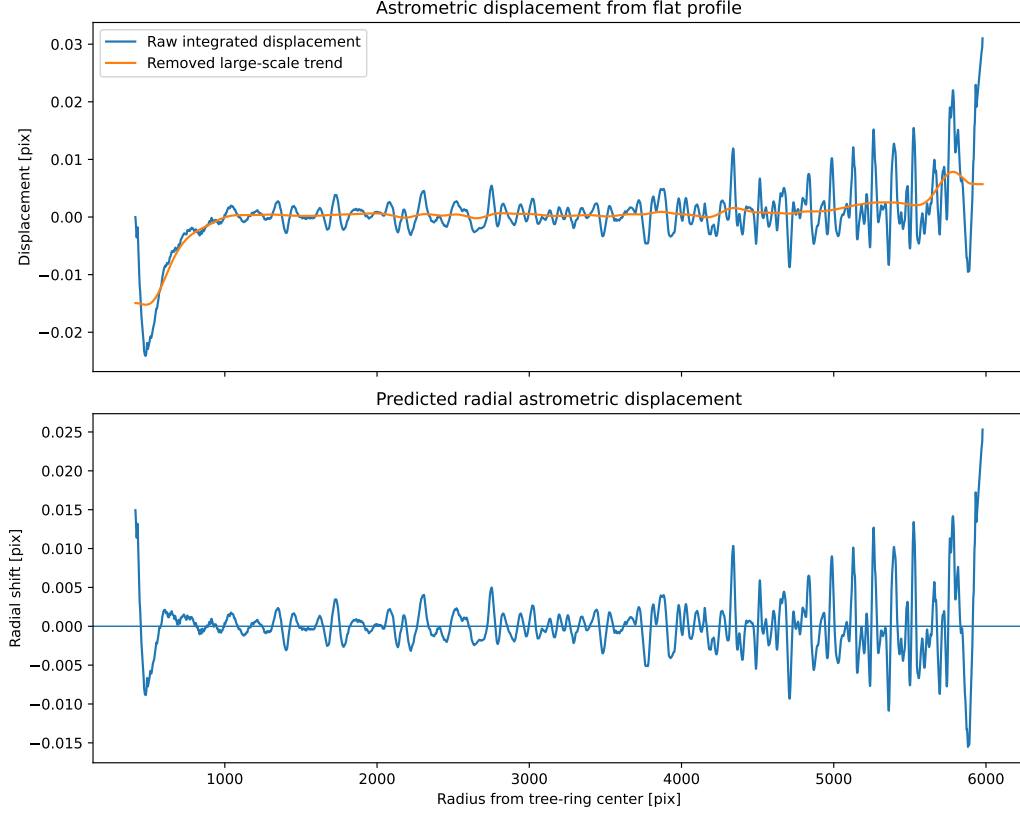


Figure 8. Predicted radial astrometric displacement for R02_S02. *Top:* raw integrated displacement and the removed large-scale trend. *Bottom:* detrended prediction, with peak amplitude $\simeq 0.025$ pixels.

point correlation $\xi_+(\theta)$; it peaks at $\sim 10^{-9}$ on the ring scale (tens of pixels) and falls to $\lesssim 10^{-12}$ by $\theta \sim 2000$ pixels, illustrating how the alternating tangential/radial ring pattern averages down at large separations.

5.1.2. Center comparison across methods

Table 1 compares the R02_S02 center from the three automated fitters (Section 4) against the H.-Y. Park et al. (2020) tree-ring center catalog seed, and the by-hand concentric fit (Section 4.2). The three automated methods scatter by up to 153 pixels: the RMS-profile fit stays closest to the Park+2020 catalog seed ($|\Delta| \simeq 11$ pixels), while the FFT band-power and outer-radius fits move by ~ 82 pixels in nearly opposite directions. This scatter is dominated by the well-known azimuthal-mean degeneracy: the FFT objective’s curvature is effectively flat along the chip→center direction (its along-ridge uncertainty semi-axis is unbounded, with the tightly-constrained axis, $\sigma_\perp \simeq 19$ pixels, perpendicular to it). With a dominant ring wavelength $\lambda \simeq 2 \times 10^2$ pixels here, the amplitude-attenuation criterion (Section 4.2; a center error smears the rings by $\exp[-2\pi^2\sigma_r^2/\lambda^2]$) requires the *perpendicular* component of the center to be known to $\sigma_r \lesssim \lambda/15 \sim 13$ pixels for $< 10\%$ amplitude loss, while the along-ridge component is far less critical.

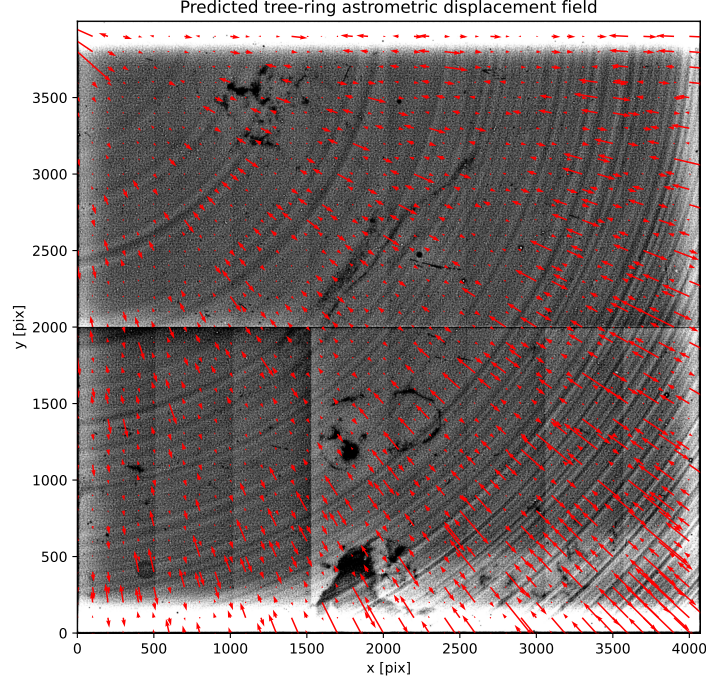


Figure 9. Predicted 2D radial astrometric displacement field $\delta = f(r)\hat{r}$ for R02_S02 (arrows; sub-sampled).

The by-hand concentric fit (Section 4.2; 29 points marked on $n_{\text{ring}} = 4$ rings) yields $(c_x, c_y) = (-270.3, 4043.4)$ pixels, with a small within-ring RMS residual of 6.6 pixels but a large, nearly isotropic bootstrap center uncertainty of $\approx (550, 525)$ pixels. This large uncertainty is itself the key result: annotating an on-chip wedge of rings whose center lies ~ 4000 pixels off the device gives a very short lever arm, so the hand fit — like the FFT fit — is only weakly constraining, especially along the ridge. The hand-fit center lies 51, 65, and 70 pixels from the FFT, RMS, and catalog centers respectively, and 152 pixels from the outer-radius fit; i.e. it is consistent (well within its own uncertainty) with the FFT/RMS/catalog cluster and disfavors the outer-radius solution. Rather than acting as a decisive tie-breaker, the by-hand fit therefore *corroborates* the FFT/RMS/catalog centers and independently confirms that the dominant center systematic for R02_S02 is the along-ridge degeneracy shared by all azimuthal-average methods. Pinning the center substantially better would require rings sampled over a wider azimuth (e.g. combining adjacent detectors) or an independent anchor.

5.1.3. Choosing the center: quality metrics

Because the fitters disagree, we need an objective way to *select* a center. We evaluate several per-center quality metrics and rank the candidate centers by each:

- **Ring-band SNR** (primary): the FFT peak power of the 1-D detrended profile inside the ring-wavelength band divided by the out-of-band noise floor. Higher is better. Because it integrates *coherent* power at the ring wavelength, it averages

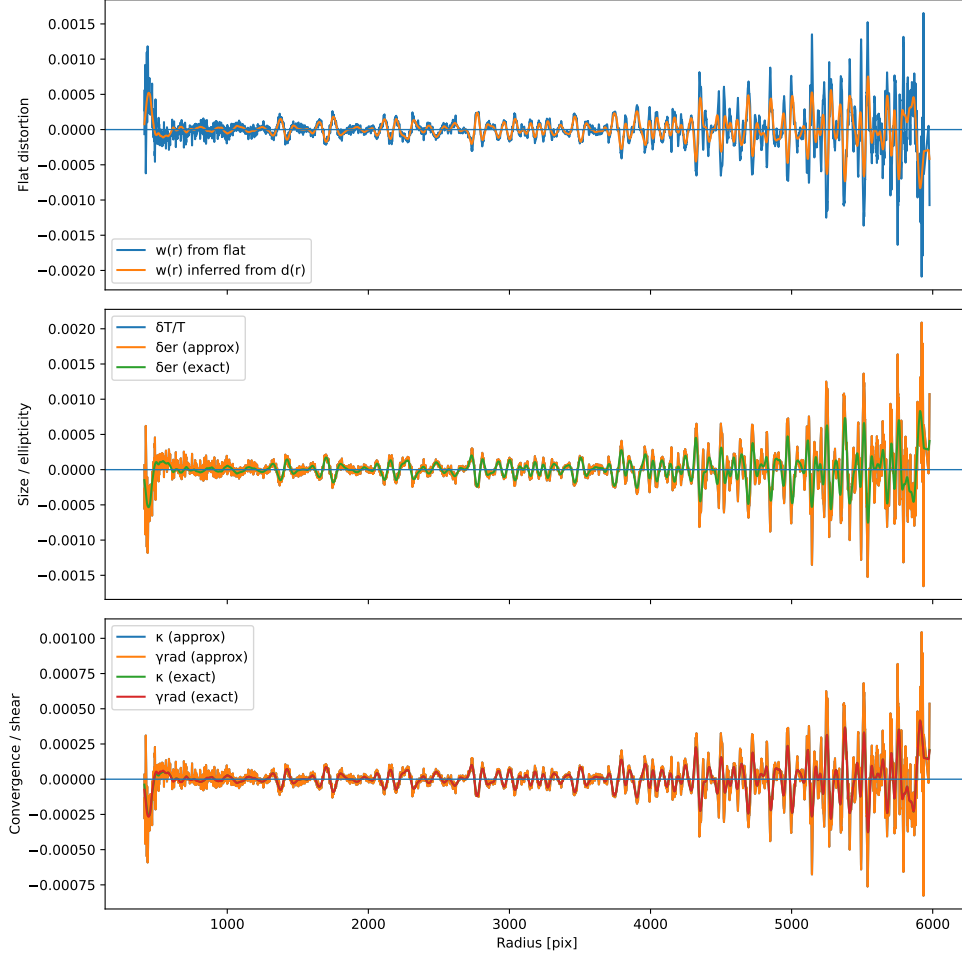


Figure 10. Radial tree-ring observables for R02_S02 derived from $w(r)$: convergence $\kappa(r)$, radial shear $\gamma_{\text{rad}}(r)$, and fractional PSF-size change $\delta T/T(r)$ (Equations 4).

Table 1. Fitted tree-ring center of R02_S02 (det 11, ITL) by method, and offset from the H.-Y. Park et al. (2020) catalog seed.

Method	(c_x, c_y) [pix]	Δ from seed [pix]	$ \Delta $ [pix]
Catalog seed (H.-Y. Park et al. 2020)	(−324.1, 4087.7)	—	—
RMS profile (Powell)	(−313.7, 4091.7)	(+10.4, +4.0)	11.1
FFT band-power (Powell)	(−241.6, 4085.6)	(+82.5, −2.1)	82.5
Outer-radius σ (diff. evolution)	(−382.2, 4146.0)	(−58.1, +58.3)	82.3
By-hand concentric (this work)	(−270.3, 4043.4)	(+53.8, −44.2)	69.6

NOTE—Three-method (automated) spread (max pairwise distance) = 153 pixels; the methods do not agree to the adopted 30 pixel tolerance for this detector. The FFT fit is degenerate along the chip→center direction ($\sigma_{\text{along}} \rightarrow \infty$, $\sigma_{\perp} \simeq 19$ pixels), so most of the scatter is along that (benign) axis. The by-hand concentric fit uses 29 hand-marked points on $n_{\text{ring}} = 4$ rings (RMS ring residual 6.6 pixels); its bootstrap center uncertainty is large and nearly isotropic, $\sigma(c_x, c_y) \approx (550, 525)$ pixels, reflecting the short lever arm of an on-chip wedge of far-off-chip rings.

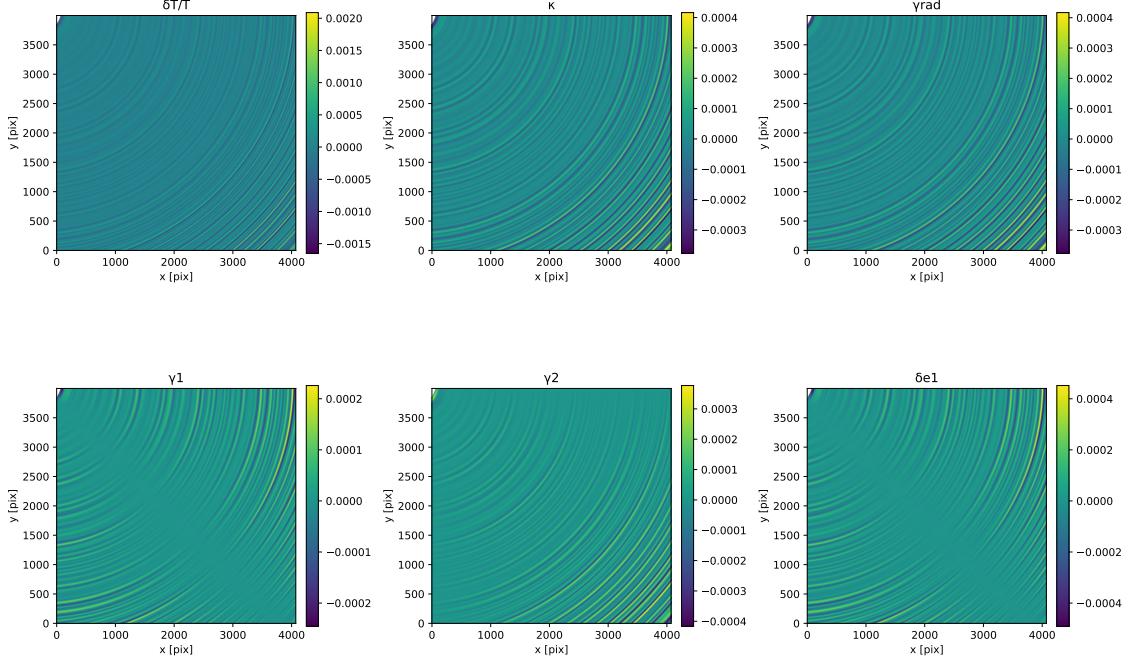


Figure 11. 2D detector templates for R02_S02: fractional size change $\delta T/T$, convergence κ , radial shear γ_{rad} , and Cartesian spin-2 components γ_1 , γ_2 , δe_1 (Equation 5). All share the concentric ring geometry and grow toward the device edge.

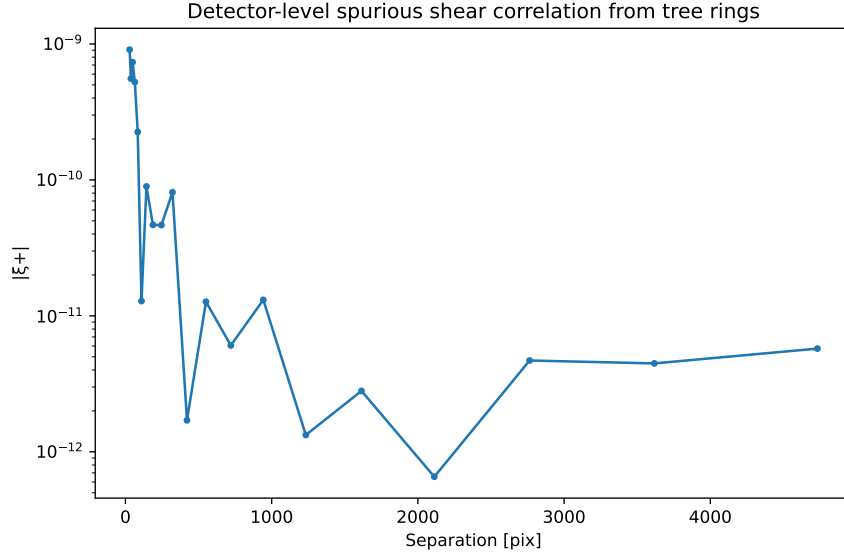


Figure 12. Detector-level quick-look shear two-point correlation $|\xi_+(\theta)|$ predicted from the R02_S02 tree-ring shear template. The signal peaks at $\sim 10^{-9}$ on the ring scale and averages down by $\gtrsim 3$ orders of magnitude by $\theta \sim 2000$ pixels.

down white noise, and on controlled tests it varies by more than an order of magnitude between the true center and centers offset by $\gtrsim 20$ pixels. This is the metric we rank by.

- **Concentricity / polar variance** (secondary): the true center makes each thin annulus lie on a single ring, so the azimuthal (θ) variance of the flat at fixed radius is minimized there. We measure this by binning the background-corrected flat R into (r, θ) cells, averaging within each cell to suppress per-pixel noise, and taking the counts-weighted RMS of the across- θ variance. Lower is better.
- **2-D variance ratio** $\text{var}(R - M)/\text{var}(R)$ from the model-subtraction test.

The ring-band SNR is the robust discriminator. The concentricity and 2-D variance metrics are comparatively weak at *LSSTCam* ITL ring amplitudes: with a ring amplitude of $\sim 10^{-4}$ sitting under a per-pixel flat noise of $\sim 10^{-3}$, the pixel-variance suppression saturates near unity (a noise-floor effect; Section 4.6) and the concentricity metric separates centers only after aggressive cell-averaging — the naive per-annulus scatter is noise-dominated and does not discriminate at all. We therefore rank centers by the ring-band SNR, use the concentricity and variance metrics as consistency checks, and cross-check against the 2-D residual images by eye. Applied across the focal plane this ranking (over the FFT band-power, RMS-profile, outer-radius, catalog, and by-hand centers) yields a recommended working center per detector; the by-hand center of R02_S02 enters this comparison on the same footing as the automated ones.

5.2. Chromaticity of R02_S02

To test the wavelength dependence we load the standard *LSSTCam/calib* combined flats for R02_S02 in the five science bands g, r, i, z, y , preprocess them identically, and extract the radial profile of each about a *single* fixed ring center $(x_0, y_0) = (-305.0, 4092.6)$ (the rings are one physical pattern, so the same center is used for all bands). Figure 13 shows the band flats after filtering, and Figures 14 and 15 overlay the resulting ring profiles $w_b(r)$.

5.2.1. Amplitude Scaling Across Bands

We test whether the profiles share a common radial shape and differ only in amplitude, fitting

$$w_b(r) = A_b w_{\text{ref}}(r), \quad (11)$$

with reference band g . The least-squares estimate over the well-sampled radial range is $A_b = \sum_i w_{\text{ref},i} w_{b,i} / \sum_i w_{\text{ref},i}^2$, with an error from the residual scatter. For R02_S02 we measure the amplitude ordering $A_g > A_r > A_i > A_z > A_y$ (Table 2, Figure 16), exactly the wavelength ordering seen for DECam by A. A. Plazas et al. (2014): shorter (bluer) wavelengths are absorbed nearer the back-illuminated entrance surface and their photo-carriers drift the full sensor thickness through the transverse ring field, producing the largest apparent flat-field amplitude, while redder photons convert closer to the collection gates and show a smaller amplitude. Dividing each profile by its A_b collapses the bands onto a common curve (Figures 17 and 18), confirming a wavelength-independent shape.

Table 2. Chromatic amplitude scaling and phase for R02_S02 (reference band g).

Band	A_b/A_g	Pearson ρ (vs. g)
g	1.0000	1.000
r	0.804 ± 0.010	0.833
i	0.742 ± 0.010	0.806
z	0.650 ± 0.009	0.807
y	0.400 ± 0.012	0.524

NOTE—Cross-correlation with the g -band profile peaks at *zero* lag for all bands (peak ξ of 0.56, 0.63, 0.61, 0.44 for r, i, z, y), confirming phase alignment.

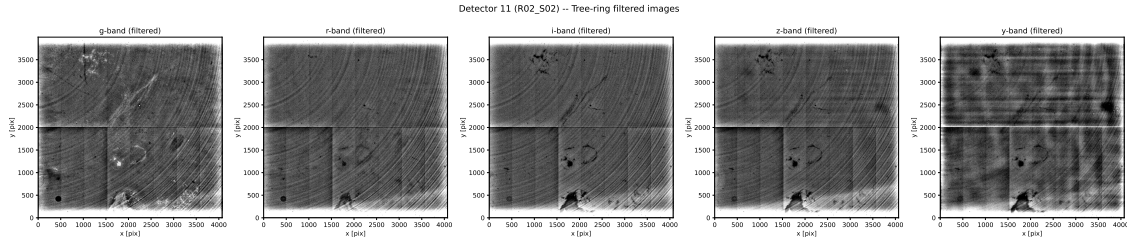


Figure 13. Raw (top) and tree-ring-filtered (bottom) previews of the R02_S02 combined flats in the g, r, i, z, y bands from LSSTCam/calib. The same concentric ring pattern is present in every band.

5.2.2. Phase Alignment

Cross-correlating each band profile against the g -band reference (Figure 19) gives a peak at *zero* lag for every band, with peak correlation 0.56, 0.63, 0.61 and 0.44 for r, i, z, y respectively. The zero-lag peaks, together with the Pearson coefficients in Table 2 ($\rho \simeq 0.81$ –0.83 for r, i, z and $\rho \simeq 0.52$ for the lower-SNR y band), confirm that the tree-ring pattern is in phase across bands and differs essentially only in amplitude. This is consistent with the DECam results of A. A. Plazas et al. (2014) and G. M. Bernstein et al. (2017) and supports a model in which the tree-ring shape is wavelength-independent while its amplitude scales with conversion depth.

6. FULL FOCAL-PLANE CHARACTERIZATION

We analyze all 189 science CCDs and summarize the results using focal-plane heat maps and histograms.

6.1. Measured Quantities

For each detector and band, we measure:

- Fitted tree-ring center (x_0, y_0) and center offset from HyeYun’s catalog
- Tree-ring RMS amplitude (after trend subtraction)

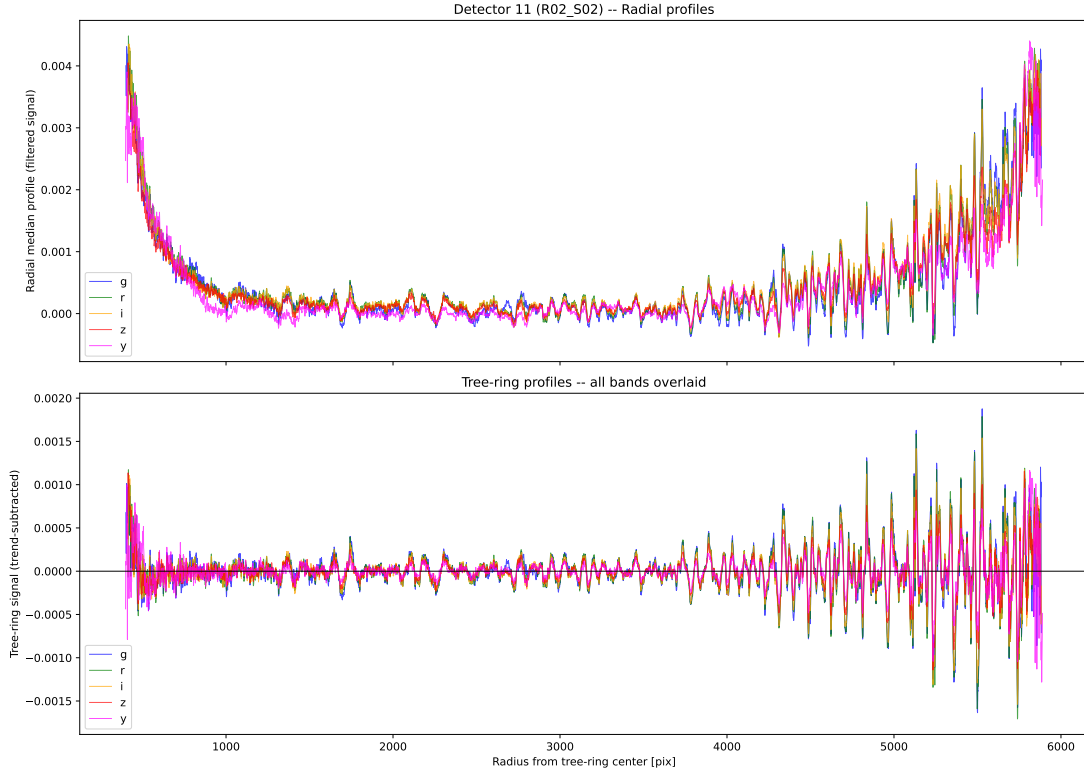


Figure 14. Radial tree-ring profiles of R02_S02 in all five bands (top: raw median profiles; bottom: trend-subtracted). The amplitude decreases from *g* to *y* while the radial pattern stays fixed.

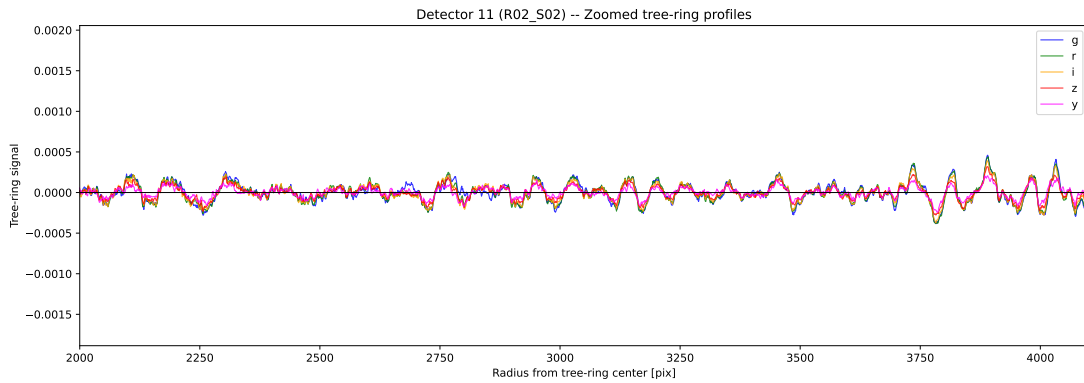


Figure 15. Zoom of the trend-subtracted band profiles of R02_S02, showing the common radial phase across bands.

- Peak-to-peak amplitude in a standard radial range (200–3500 pixels)
- Dominant period at a fiducial radius (2000 pixels)
- Period gradient with radius
- Azimuthal asymmetry metric (sector-to-sector RMS scatter)
- Correction suppression factor (RMS before/after)

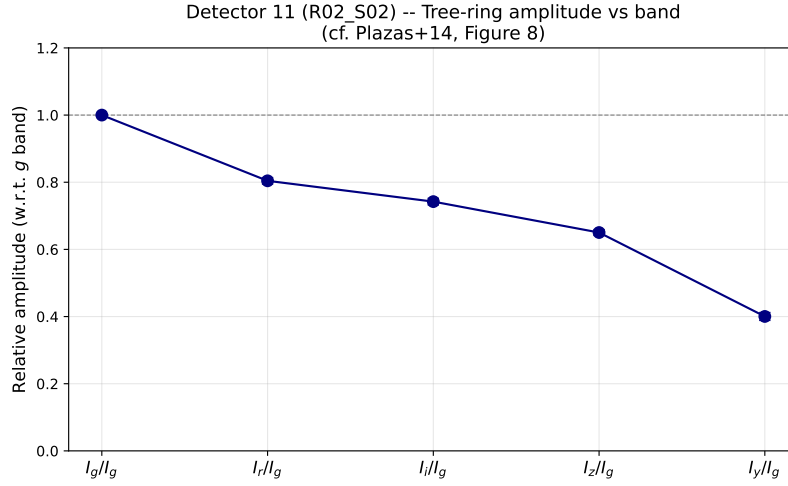


Figure 16. Relative tree-ring amplitude A_b/A_g versus band for R02_S02 (cf. A. A. Plazas et al. 2014, their Fig. 8), showing the monotonic $g > r > i > z > y$ ordering.

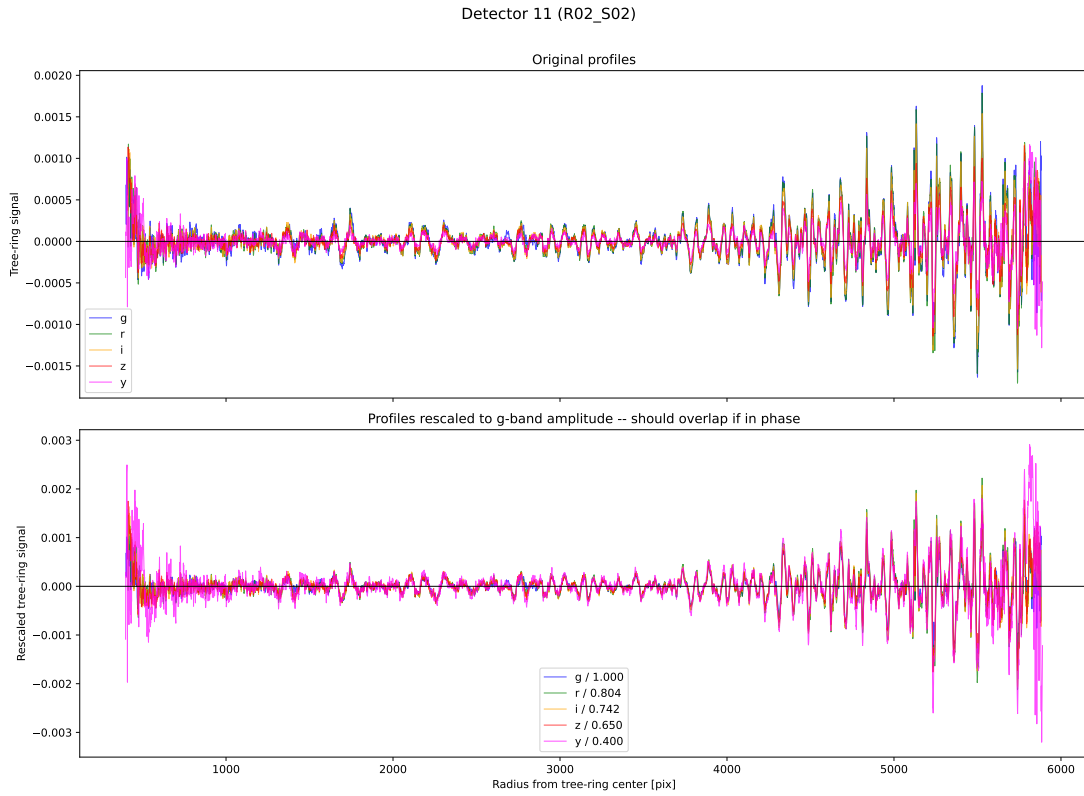


Figure 17. Band profiles of R02_S02 before (top) and after (bottom) dividing by the fitted amplitude A_b . The rescaled profiles collapse onto the g -band curve, confirming a wavelength-independent shape.

- Predicted maximum astrometric displacement
- Predicted spurious shear/convergence amplitude
- Profile reproducibility uncertainty (from jackknife subsets)

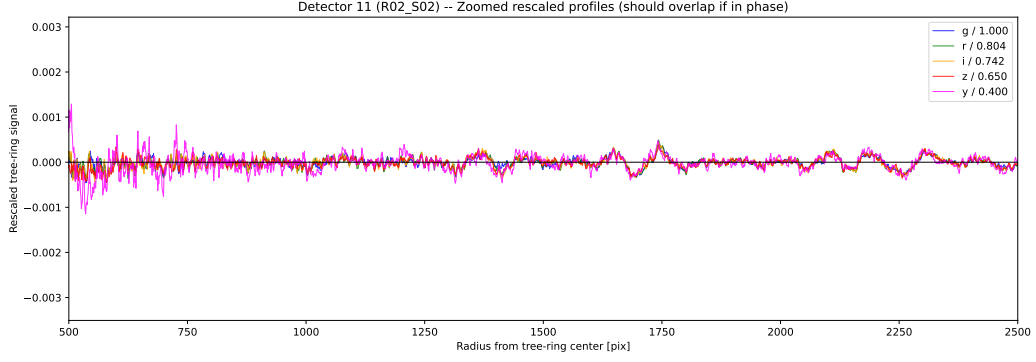


Figure 18. Zoom of the amplitude-rescaled band profiles of R02_S02.

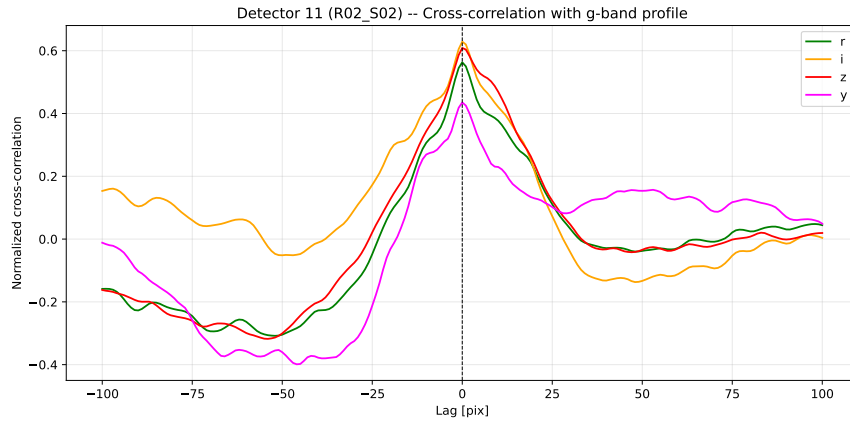


Figure 19. Normalized cross-correlation of each band profile with the g -band profile for R02_S02. All bands peak at zero lag, confirming phase alignment.

- Masked pixel fraction

6.2. Focal-Plane Maps

We present heat maps of:

- Tree-ring RMS amplitude (per band)
- Dominant radial period
- Center offset magnitude
- Azimuthal asymmetry metric
- Correction suppression factor
- Band amplitude ratios (A_g/A_i , A_y/A_i)

6.3. Vendor Comparison

We compare ITL and e2v detectors in histograms of key metrics.

7. SCIENCE IMPACT AND CALIBRATION IMPLICATIONS

7.1. *Astrometric Displacement*

Using Equation 2, the measured *i*-band profile of R02_S02 predicts a peak radial astrometric displacement of $\simeq 0.025$ pixels (Figures 8–9), with $|f| \lesssim 0.005$ pixels over most of the well-sampled area. These values are consistent with A. A. Plazas et al. (2014) for DECam and, while below the LSST single-epoch astrometric requirement (~ 0.05 – 0.1 pixels), they are a coherent, fixed-pattern contribution that is relevant for high-precision relative astrometry and WCS solutions.

7.2. *Spurious Shear and Convergence*

From Equation 4, the ring amplitude $w(r) \sim 10^{-4}$ – 10^{-3} measured for R02_S02 implies spurious convergence and shear $\kappa_{\text{sp}} \approx \gamma_{\text{sp}} \approx w/2 \sim 10^{-4}$ (locally up to $\sim 7 \times 10^{-4}$ near the device edge; Figures 10 and 11). The detector-level quick-look shear correlation (Figure 12) peaks at $|\xi_+| \sim 10^{-9}$ on the ring scale and averages down rapidly with separation. LSST DESC weak-lensing budgets allocate ~ 0.001 – 0.003 to residual systematics (LSST Dark Energy Science Collaboration 2012); the per-detector tree-ring shear is below this level, but because it is a fixed spatial pattern that repeats across all visits of a given detector, it must be modeled and removed rather than assumed to average away.

7.3. *PSF Modeling*

Tree-ring-induced centroid variations introduce position-dependent PSF model residuals. J. Esteves et al. (2023) found PSF size variations of ~ 2 – 3% over tree-ring spatial scales. Correcting tree rings in the flat field should reduce these residuals.

7.4. *Photometric Systematics*

Uncorrected tree rings produce position-dependent photometric errors at the percent level. For time-domain science (e.g., supernovae, variable stars), these errors can mimic or mask intrinsic variability if objects move across tree-ring features.

8. CORRECTION MODEL FOR PIPELINES

1. include astrometric profiles in WCS, include photometric profiles in photometric solution, as for DES. Need to include in LSST Scienc epipelins, referenc E-fields paper.

2 For astrometry, an alternative could be to measure the 2D displavcment field rsiduals empirically, but it might not work so it's good to have the templates too.

9. DISCUSSION

9.1. *Tree Rings Versus Other Sensor Signatures*

Tree rings are not the only fixed-pattern structures in *LSSTCam* CCDs. Other features include:

- Amplifier boundaries and readout artifacts

- Mid-line breaks (significant in some detectors; [J. Esteves et al. 2023](#))
- Residual QE variations (non-azimuthally-symmetric)
- Hardware imprints (e.g., from masks or contamination)
- Diffusion-related effects

9.2. *Limitations of Azimuthal Averaging*

Our 1D radial profile approach assumes perfect azimuthal symmetry. We test this assumption quantitatively using sector profiles and polar transforms (?)

9.3. *Implications for On-Sky Validation*

Validation of tree-ring corrections requires on-sky data:

- **Astrometry:** Compare star positions before/after tree-ring WCS corrections. Internal astrometric scatter should improve.
- **PSF residuals:** Measure PSF model residuals on stars as a function of position. Tree-ring corrections should reduce position-dependent residuals.
- **Weak lensing:** Analyze galaxy shape correlations. Tree-ring corrections should reduce spurious shear patterns.

On-sky validation is beyond the scope of this paper but is planned for future work.

10. CONCLUSION

We have presented the focal-plane-wide, multi-band characterization of tree rings in the LSST Camera. Our key findings are:

1. Tree rings are clearly detected in the deep i -band combined flat of the ITL detector R02_S02, with a trend-subtracted ring amplitude at the $\sim 10^{-4}$ level (RMS $\simeq 2 \times 10^{-4}$ in i , rising to $\sim 10^{-3}$ near the device edge). A 2D ring model built from the 1D profile suppresses $\sim 91\%$ of the radial ring power, validating the fitted center and profile.
2. Tree-ring profiles are highly azimuthally symmetric, with sector-to-sector RMS scatter typically ????? . Polar coordinate diagnostics confirm that fitted centers are accurate.
3. Tree-ring profiles are in phase across the five science bands (g, r, i, z, y ; zero-lag cross-correlation) and differ primarily in amplitude, with ordering $A_g > A_r > A_i > A_z > A_y$ ($A_b/A_g = 1, 0.80, 0.74, 0.65, 0.40$ for R02_S02), consistent with wavelength-dependent conversion depth in the back-illuminated silicon.
4. The measured i -band profile predicts a peak radial astrometric displacement of $\simeq 0.025$ pixels and spurious convergence/shear $\kappa_{\text{sp}} \approx \gamma_{\text{sp}} \sim 10^{-4}$ for this detector — small per visit but coherent and fixed-pattern, and therefore requiring template-based correction.

5. We provide per-detector, per-band radial profile templates, fitted centers, and validation metrics suitable for integration into the LSST Science Pipelines.

ACKNOWLEDGMENTS

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Facility: Rubin

Software: `astropy` ([Astropy Collaboration 2013, 2018](#)), `lsst.afw` ([LSST Science Collaboration et al. 2017](#)), `matplotlib` ([J. D. Hunter 2007](#)), `numpy` ([C. R. Harris et al. 2020](#)), `scipy` ([P. Virtanen et al. 2020](#))

APPENDIX

A. FLAT-FIELD GENERATION AND ANALYSIS CONFIGURATION

For reproducibility we record here the exact inputs used to build the deep *i*-band combined flat and to run the single-detector analysis.

The analysis notebooks read the combined flats directly from the Butler at the USDF with the following configuration:

```
BUTLER_PATH = "/repo/main"
COLLECTIONS = "u/plazas/LSSTCam/calib/none/treerings/flatGen-i.20260319b"
BAND        = "i"
```

The chromaticity analysis instead reads the five-band combined flats from the standard `LSSTCam/calib` collection.

The combined *i*-band flat was produced from 290 individual PTC flat exposures (taken with the `3s_v2` “natural-frequency” sequencer on 2025-12-28) using the LSST Science Pipelines flat-generation pipeline, submitted through the Batch Processing Service (BPS) at the USDF. The submission script is reproduced below; the `SELECTION_FLAT_i` exposure list is abbreviated here (the full set of 290 exposure IDs is preserved with the analysis code).

```
# Generate a combined flat image from i-band PTC flats to study tree rings (2026-02-26)
# Run this at USDF.

# STEP 0: set up the LSST Science Pipelines stack
source /sdf/group/rubin/sw/w_latest/loadLSST.bash
setup lsst_sitcom
```

```

# STEP 1: work from the home directory
cd ${HOME}

# STEP 2: environment / data selection
export USER_CALIB_PREFIX="u/plazas/"
export INSTRUMENT=LSSTCam
export TICKET="none"
export REPO=main
export RAW_COLLECTION=LSSTCam/raw/all
# Curated calibration inputs:
#   LSSTCam/calib/DM-53722: defects, bias, dark, linearity, etc.
#   LSSTCam/calib/DM-52726: flat gradient reference
#   LSSTCam/calib/DM-51599: CBP crosstalk for 3s_v1
#   LSSTCam/calib/DM-51669: curated calibrations
#   LSSTCam/calib/photodiode: photodiode data
export CALIB_COLLECTIONS=LSSTCam/calib/DM-53722,LSSTCam/calib/DM-52726,\
LSSTCam/calib/DM-51599,LSSTCam/calib/DM-51669,LSSTCam/calib/photodiode
export TAG=treerings
export RERUN=20260319b  # bump to "c", "d", ... to rerun

# Flats: 290 i-band PTC flats, 3s_v2 ("natural frequency") sequencer.
# Detector 122 is excluded.
export SELECTION_FLAT_i="instrument='LSSTCam' and detector not in (122) and \
exposure in (2025122800010, 2025122800011, 2025122800012, 2025122800013,
2025122800014, 2025122800015, 2025122800024, 2025122800025,
... # 290 exposure IDs in total (full list with the analysis code)
2025122801080, 2025122801081, 2025122801084, 2025122801085)"

# STEP 3: sanity-check the resolved BPS YAML
cat $CP_PIPE_DIR/bps/templates/bps_flat_i.yaml | envsubst

# STEP 4: submit
bps submit -i ${RAW_COLLECTION},${CALIB_COLLECTIONS} \
$CP_PIPE_DIR/bps/templates/bps_flat_i.yaml

```

The per-exposure Poisson noise averages down as $\sqrt{290}$ in the combine, which is what brings the $\sim 10^{-4}$ tree-ring modulation above the single-flat noise floor.

B. PER-DETECTOR TREE-RING PROFILE TABLES

We provide tabulated radial tree-ring profiles for all detectors and bands. These tables are available online at [DOI TBD] and include:

- Detector ID
- Band
- Fitted center (x_0, y_0)
- Initial center from HyeYun's catalog $(x_{0,\text{init}}, y_{0,\text{init}})$
- Radial coordinate r (pixels)
- Profile amplitude $w(r)$ (fractional units)
- Uncertainty $\sigma_w(r)$

Table 3. Sample Tree-Ring Profile Table

Detector	Band	r (pix)	$w(r)$	σ_w	Mask Frac.	Counts	Flag
R02_S02	i	100.5	0.0012	0.0003	0.02	1245	0
R02_S02	i	101.5	0.0015	0.0003	0.02	1250	0
...	...	...	...	...	...	...	...

NOTE—Full tables for all detectors and bands are available online.

- Mask fraction versus r
- Quality flags

A sample of the table format is shown below.

REFERENCES

- Astropy Collaboration. 2013, *A&A*, 558, A33
- Astropy Collaboration. 2018, *AJ*, 156, 123
- Bernstein, G. M., Armstrong, R., Plazas, A. A., et al. 2017, *PASP*, 129, 074503
- Esteves, J., Snyder, J. A., Saha, A., et al. 2023, in *Proc. SPIE*, Vol. 12711, 127110E
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Nature*, 585, 357
- Hunter, J. D. 2007, *Computing in Science and Engineering*, 9, 90
- Ivezić, Ž., Kahn, S. M., Tyson, J. A., et al. 2019, *ApJ*, 873, 111
- LSST Dark Energy Science Collaboration. 2012, arXiv e-prints
- LSST Science Collaboration, Marshall, P., Anguita, T., et al. 2017, arXiv e-prints
- Park, H.-Y., Baumer, M., Roodman, A., et al. 2020, in *Proc. SPIE*, Vol. 11454, 114542T
- Plazas, A. A., Bernstein, G. M., & Sheldon, E. S. 2014, *PASP*, 126, 750
- Roodman, A., Snyder, J. A., Thayer, J., et al. 2023, in *Proc. SPIE*, Vol. 12711, 1271103
- Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, *Nature Methods*, 17, 261