Transverse electric fields’ effects in the Dark Energy Camera CCDs

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ABSTRACT: Spurious electric fields transverse to the surface of thick CCDs displace the photogenerated charges, effectively modifying the pixel area and producing noticeable signals in astrometric and photometric measurements. We use data from the science verification period of the Dark Energy Survey (DES) to characterize these effects in the Dark Energy Camera (DECam) CCDs, where the transverse fields manifest as concentric rings (impurity gradients or “tree rings”) and bright stripes near the boundaries of the detectors (“edge distortions”) with relative amplitudes of about 1% and 10%, respectively. Using flat-field images, we derive templates in the five DES photometric bands (grizY) for the tree rings and the edge distortions as a function of their position on each DECam detector. Comparison of the astrometric and photometric residuals confirms their nature as pixel-size variations. The templates are directly incorporated into the derivation of photometric and astrometric residuals.

The results presented in these proceedings are a partial report of analysis performed before the workshop “Precision Astronomy with Fully depleted CDDs” at Brookhaven National Laboratory. Additional work is underway, and the final results and analysis will be published elsewhere (Plazas, Bernstein & Sheldon 2014, in prep.).

KEYWORDS: Image processing; Data Processing; Data analysis

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1 Introduction

1.1 The Dark Energy Survey and the Dark Energy Camera

The Dark Energy Survey is a multi band (grizY) photometric survey of 5000 sq deg of the Southern sky whose main scientific goal is to constrain the dark energy equation of state, $w$, to about 2–3% of statistical precision. Four independent probes — weak lensing, galaxy cluster counts, baryon acoustic oscillations, and type Ia supernovae — will be combined under this single experiment. A 570 megapixel camera, the Dark Energy Camera (DECam), was built and commissioned (Oct. 2012) on the 4 m Blanco telescope in the Cerro Tololo Interamerican Observatory in La Serena, Chile. After commissioning, DES underwent a science verification period (Nov. 2012–Feb. 2013) to assess the quality of the images, and the first season (out of five) began on August 31, 2013.

The focal plane of DECam is composed of 62 2k by 4k CCDs, plus 12 more 2k by 2k CCDs for focus and guiding. These devices are fully depleted (high-resistivity), thick (about 250$\mu$m) CCDs, built by DALSA\(^1\) and Lawrence Berkley National Laboratory. The pixel size of the devices is 15$\mu$m, with a plate scale of about 0\arcsec27, generating a field of view of 3 sq-deg.

\(^1\)http://www.teledynedalsa.com/corp/.

1 Impact on astrometry and photometry

2.1 Photometric signatures

2.2 Astrometric signatures

3 Improving the astrometric and photometric solutions using templates from dome flats

4 Summary and conclusion
Figure 1. Master dome flat images from one of the DECam CCDs in the g band. Each one is normalized to 1, and the gray scale represents deviations of approximately ±1% from this value, with lighter shades representing enhanced brightness (the black strip surrounding the CCD is an 15 pixels-wide area of zero flux, masked during the making of the master flats). The “tree rings” can be seen in the first two images. The contrast difference between the left and right sides are due to gain differences in the two readout amplifiers of the detector. The last image shows the effect of the distorted electric field at the edge (bright stripes) and that of the lattice stresses due to double-sided tape (upper right corner).

1.2 Structures in flat-field images: “tree rings” (impurity gradients), edge distortions, and “tape bumps” (lattice stresses)

Dome flats are taken daily as part of standard DES operations to be used during the usual data reduction and calibration process. A single, reduced master dome flat\(^2\) per CCD and photometric band is then created by the DES Data Management pipelines. When analyzed in detail, structures can be identified in the flat-field images. The most visually striking features in the flats are concentric circles, commonly known as “tree rings” (see figure 1). Their origin lies in circularly symmetric differences in impurity gradients that result when using the floating zone method in the fabrication of high-resistivity silicon wafers (see figure 5 in ref. [5]). The second important effect seen in the dome flats of the DECam devices is an increase in brightness near the four detector edges, likely due to the presence of guard rings around the edges of the pixel array (see contribution by C. Stubbs). Within the DES collaboration, this is known as the “glowing-edge” effect, although it should be noticed that a similar feature has been measured in LSST devices, but with an opposite sign (i.e., a reduction in brightness is seen closer to the edge). Therefore, we will refer to this effect more generally as the edge-distortion effect. Finally, three small (about 50 by 50 pix) deformations on each side of the CCD can be seen. These features arise from physical stresses on the silicon lattice due to pieces of double-sided tape between the CCD and its mount. The current plan in DES is to mask these regions during processing, and therefore we will discuss only the tree-rings and edge-distortions hereafter.

\(^2\)A master dome flat is the median of the best dome-flat exposures of each night, reduced, and normalized to 1.
Flat field images can generally be used to infer variations in the properties of pixels on a CCD (pixel response non-uniformities, PRNU). These variations may arise from intrinsic changes in pixel sensitivity (or quantum efficiency), or pixel area variations. Therefore, it is not clear a priori whether the effects mentioned above are due to one or the other. Since the main purpose of dividing the scientific images by a flat field frame is to account for the sensitivity differences across the pixel array, dividing by a flat field image that contains effects other than sensitivity variations will introduce systematics errors in the data. Thus, it is important to characterize the nature of these effects.

Data taken with DECam during the DES science verification period show correlations between the effects of transverse electric fields and astrometric displacements (see next section and figure 4). This strongly supports the interpretation that they are due to charge redistribution between neighboring pixels caused by the presence of spurious electric fields transverse to the optical axis of the device, and not just quantum efficiency variations.

2 Impact on astrometry and photometry

By examining the residuals in the astrometric and photometric solutions, we can identify patterns that remain due to the effects of the transverse electric fields. We use dithered exposures of star fields (≈ 20), in which each star is recorded at different parts of the detector. This is known as the star flat data (see ref. [6]).

The input images are divided by the dome flats, and then large-aperture stellar photometry is performed. A “star-flat” photometric correction model is produced by varying the parameters of the model to minimize the disagreement between magnitudes of the multiple measurements of each star. This model is allowed to have low-order polynomial variation across each CCD, plus an exposure-dependent offset and linear slope across the full array. Every measurement of every star has a residual of its star-flat corrected magnitude to the mean magnitude of all measurements of that star.

In the case of the astrometric models, we solve for the parameters of the geometric distortion model (the map between pixel coordinates and sky coordinates, \( \Omega(x,y) \)) by forcing agreement between positions of a give star in different exposures, and then calculating the astrometric residuals with respect to the mean position of the star.

The DES science requirements demand an astrometric accuracy < 15 mas of objects in different exposures, and a relative photometry of 2%. If the tree rings and edge distortion effects are not taken into account, coherent systematic errors comparable to and even larger than specified levels will remain in both the astrometric and photometric residuals.

2.1 Photometric signatures

In figures 2 and 3 we show the correlations of photometric residuals and the signatures from the edge distortion and tree rings effects as measured by the dome flats, respectively. Figure 2 plots the mean residual to the photometric model as a function of distance from one of the edges of a particular DECam CCD. In the case of the edge distortions, while the stacked profiles and stacked magnitude residuals agree within the measurement errors, the individual profiles do not present an
Figure 2. Stacked photometric residuals (stars) and stacked dome-flat signal (dots) as a function of distance of the bottom of the detectors, in 8-pixels sized bins. The stack is over all DECam CCDs and all g band data. The images were divided by the dome-flat frames. The residuals are largely driven by this division.

The images were divided by the dome-flat frames. The residuals are largely driven by this division. On the other hand, the magnitude residuals seem to fully trace the rings signal as measured in the dome flat images, as can be seen in figure 3.

The residuals are calculated after dividing by the dome-flat images, and the photometric model for these data do not include terms to track the edge distortions and the tree rings. Hence, the correlations between the dome-flat signals and the photometric residuals indicate that the tree-rings and edge distortion features are not tracing pixel-sensitivity variations.

2.2 Astrometric signatures

Figure 4 shows the map of astrometric residuals as a function of CCD position of a particular device, stacked over all exposures in all photometric bands. Correlations with the tree-ring patterns from the dome flat images are readily apparent. After identifying the center of the rings in each device, we can create a radial profile of the tree rings’ signal as a function of distance from that center. In an analogous way, we create profiles of the astrometric signatures as a function of the distance to each edge (see figure 5). The amplitude of the astrometric signal in the case of the rings is about 0.5 pixels (≈ 13 mas) to 0.1 pixels (≈ 26 mas); for the edge distortion, the amplitude is also approximately 0.05–0.1 pixels.\(^3\) We also note that there is a wavelength dependence in both cases.

\(^3\)The relative amplitude of the edge distortion can be of 10% or more as the distance to the edges diminishes. However, the master dome-flats we used in our analysis have a masked region of 15 pixels from the edge, and the astrometric and photometric solutions mask regions of 30 pixels within the CCDs boundaries.
Figure 3. Mean amplitude of tree rings as measured on the dome flats compared to means of photometric residuals in bins of tree ring values from DES data. The aperture or each object was adjusted and measured with the SExtractor (see ref. [7]) parameter \texttt{MAG\_AUTO}. On average, the data trace the dotted line, which has a slope of $2.5\ln(10) \approx 1.085$, indicating a positive correlation between the two quantities. The damping at large tree-ring values is likely due the smoothing of the sharpest rings due to the finite size of the stellar images. When using fitting photometry (SExtractor parameter \texttt{MAG\_PSF}), there is an offset of $\approx 2\times$ because both the flux and the size of the stars are different in the rings, so the PSF fitter (not knowing about either) calculates an erroneous value for the total flux.

3 Improving the astrometric and photometric solutions using templates from dome flats

We would like to characterize these structures in the residuals by using the information from the dome flats. For that purpose, we measure templates of the edge distortion as a function of the distance from each of the four edges. In the case of the tree rings, we identify their centers in each one of the DECam devices, and plot their amplitude in the flats as a function of distance to these centers. We do this for each one of the five DES photometric bands ($grizY$), and the wavelength dependence is more apparent (see figure 6). In general, we would expect to measure a larger amplitude towards the blue part of the spectrum because the absorption length in silicon implies that photons with shorter wavelength interact, on average, closer to the back, incident side of the CCD. Thus, photo-generated holes from blue light would be subject to the effect of transverse electric fields for a longer time, displacing the centroid of the charge packet farther away from where it would have hit if the transverse field did not exist. The ring profiles seem to follow this model, and each profile seems to differ by the other only by a multiplicative factor. In the case of the edge distortions the wavelength dependence is not a simple scaling, suggesting that a more complicated electric field model might be needed to account for the observations at the
Figure 4. Astrometric residuals in the ‘x’ and ‘y’ directions plotted as a vector field for a particular DECam device. The median magnitude across the whole chip is 5.65 mas, with an rms of 5.35 mas. Correlations with the structures of the dome flats are seen.

To improve the photometric solutions, we include in the optimization process functional terms proportional to the measured templates from the dome flats, leaving their amplitudes as free parameters.

For the astrometric solutions, we would like to utilize the photometric signal in the dome flats again because it has a higher signal-to-noise (S/N) ratio than in the pixel area map from the finite number of stars useful for the astrometric solutions. Below we show how the signal in the dome flats and the signal measured by the astrometric residual map are related to each other. We begin by pointing out that the number of photons per unit area in the pixels is proportional to the intensity of the incident light, which is uniform on small scales in a flat-field image. Photon number conservation therefore translates as sky-area conservation in the flat-field signals.

In the case of the tree rings the astrometric errors can be modeled as a function of radius from the ring center \( f(r) \) that represents the displacement of photons hitting a position \( r \) to photons detected at \( r' \approx r + f(r) \). The dome flat images include the effect of the variable pixel area across the field, and therefore measure their effective area, \( A' \). The oscillatory tree-ring pattern measured in the dome flat images can be written as \( w(r) \). This function is the azimuthally averaged tree-ring signal from the dome flats, normalized to 1, and filtered with a high-pass filter. It is related to the Jacobian determinant of the coordinate transformation between this effective area and the unperturbed area \( A \) by:

\[
1 + w(r) = \left| \frac{dA'}{dA} \right| = \left| \frac{r'dr'd\theta'}{rdrd\theta} \right| \approx \left| \frac{(r+f)(dr+dr\partial_r f)}{rdr} \right| 
\]  

(3.1)
The last expression of eq. (3.1) is valid to first order in $f(r)$, and we have used $r' = r + f(r)$ to calculate the partial radial derivatives. Solving for $f(r)$ as a function of $w(r)$, we have (discarding second order terms):

$$f(r) = \frac{1}{r} \int rw(r)dr \quad (3.2)$$

Equation (3.2) allows us to use the ring patterns measured from the dome flats to predict the radial component\(^4\) of the astrometric error induced by the tree rings. Figure 7 shows how the predicted astrometric function $f(r)$ (after removing large-scale modes introduced by the integration process) correlate to the measured radial component of the astrometric residuals from the star flats (stacked in all $grizY$ filters to generate more S/N). The astrometric predictions for each DECam CCD can now be tabulated and incorporated into the astrometric solution fitting process.

For the glowing edges, an analogous equation in cartesian coordinates should apply ($f(x) = \int w(x)dx$). However, data show disagreements with this prediction, suggesting that more complicated physical mechanisms might be present at the edge of the devices. We are currently investigating this behavior.

\(^4\)The orthogonal component is consistent with zero.
4 Summary and conclusion

We analyzed the effects of parasitic electric fields transverse to the surface of DEcam CCDs on astrophysical measurements (photometry and astrometry). In particular, we studied the electric fields generated by circularly symmetric impurity gradients in the silicon wafer (giving origin to structures visually similar to tree rings), and distorted fields at the four edges of the detectors (“edge-distortion” effect). These structures are visible in the dome flat images used by the data calibration pipelines. We used data from the science verification period of the Dark Energy Survey to show how these instrumental features imprint a residual signal on astrometric measurements, indicating that they are consequence of charge redistribution among the different pixels of the CCD. The effective pixel area is modified too, leaving residual correlations in photometric measurements in addition to the astrometric residuals. We showed how measurements of templates of the amplitudes of the rings and the edge distortions from the dome flats can be used to improve the accuracy of the photometric measurements.

The final analysis of this work will be published in Plazas, Bernstein & Sheldon 2014 (in prep.).

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Figure 7. Measured astrometric residuals, binned as a function of radial distance from the tree rings’ center for a particular detector. The prediction derived from the photometric signal of the dome flats (eq. (3.2)) correlates with the measured tree-ring astrometric residuals from the star flats.

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