DESI Commissioning Instrument Throughput Analysis

1 Background Information

The Dark Energy Spectroscopic Instrument (DESI) Commissioning Instrument (CI) was an imager used to preliminarily verify key functionality of the Mayall telescope at Kitt Peak National Observatory as outfitted with its newly installed DESI corrector, including the tracking, guiding, pointing model, polar axis alignment, hexapod motion, throughput, focusing, and image quality. The CI was equipped with five commercial SBIG STXL-6303e cameras and 22 illuminated fiducials, and matched the mass and moment of the full DESI focal plane system that will be used throughout the upcoming five-year spectroscopic survey.

On-sky observing with the CI began on the evening of 2019 April 1 following CI installation at Kitt Peak the week prior. This marked the first on-sky observing with the Mayall telescope since 2018 February. The final on-sky CI observing occurred during the morning of 2019 June 3. Thus, the nights of on-sky CI campaign data acquisition spanned from 20190401 to 20190602 (inclusive), where these labels correspond to the calendar date (Kitt Peak local time) at the start of the night. There was an approximately 1.5 week 'pause' in the CI on-sky observing which lasted from 20190506 to 20190515 (inclusive), to move the corrector in z by approximately 9 mm and thereby center the best focus very close to the hexapod neutral z position.

Each CI camera contains a 3072 pixel $\times$ 2048 pixel detector, with square pixels 9μm on a side. Although all CI pixels are physically square, they can subtend non-square regions on-sky due to the directionally-dependent DESI corrector platescale, and also subtend different solid angles as a function of radius from the field of view center. The approximate CI platescale is $\sim$0.13$''$/pixel. Figure 1 of DESI-5228 shows a schematic of the CI camera layout within the focal plane (see DESI-3347 for more such details). Critically, one of the CI cameras ("CIC") is in the center of the focal plane, and therefore has provided the only opportunity for on-axis imaging through the DESI corrector. The outlying four CI cameras ("CIE", "CIN", "CIS" and "CIW") are separated from CIC along the sky E, N, S, W cardinal directions by an on-sky angular radius of $\sim$94 arcminutes. These outer four CI cameras are meant to help understand the astrometry, vignetting, image quality, and so forth at the very edge of the wide DESI field of view, and to mimic the guide-focus-alignment cameras (GFAs) included in the DESI focal plate assembly, although the GFAs will not be SBIG STXL-6303e devices like those of the CI. The CI cameras all observe through a narrow Astrodon r' filter transmitting in the wavelength range 560 nm $\lesssim \lambda \lesssim$ 700 nm[1].

Other information closely related to that presented in this document can be found in Ross et al. (2019; DESI-3624), DESI-3516, DESI-3358, DESI-3347,

[1] `https://astrodon.com/products/astrodon-photometrics-sloan-filters/`

DESI-4790, DESI-5228 and the CI CCD data sheet[2].

2 Camera Labeling

One important cautionary note to keep in mind is that prior to 20190402, four out of the five CI camera labels were "swapped" within the raw metadata relative to their sky locations. Throughout this document, we refer to each camera by its sky location[3]. For data up to and including 20190401, the camera labeled "CIE" was actually CIW, the camera labeled "CIW" was actually CIE, the camera labeled "CIN" was actually CIC, and the camera labeled "CIC" was actually CIN. This label swapping is summarized in Table 1 of DESI-5228. CIS was always labeled correctly. Starting on 20190402, the labels in the raw metadata were corrected so that they matched the sky locations of all five cameras.

3 Mayall Primary Mirror Aperture Mask

During science observations, the Mayall primary mirror typically has a "aperture mask" mask installed around its edges, to block collection of light from the outermost portion of the mirror, which is not figured with the same fidelity as the more interior regions. However, at the start of the DESI CI observing campaign, the aperture mask had not yet been installed. This compromised the image quality of early CI observations, but also provides an opportunity to quantitatively assess the cost/benefit trade-offs associated with the decision of whether to install or not install the aperture mask during DESI science observations. The benefit of leaving the aperture mask off is that some small amount of additional light could potentially be gathered within the $\sim 1.5''$ DESI fiber diameter. The downside is that the PSF wings are more poorly behaved without the aperture mask in place, raising concerns about e.g., additional contamination of faint objects by light from bright sources in the same field.

The CI run started without the aperture mask, then the aperture mask was eventually installed during the day on 2019 April 9 and left in place from then on.

4 Throughput Prediction

Prior to the CI run I made a detailed prediction for the CI throughput as a function of wavelength, as well as the closely related CI zeropoint. All code and auxiliary data used in this calculation can be found online in a publicly accessible GitHub repository[4].

[2] https://www.onsemi.com/pub/Collateral/KAF-6303-D.PDF

[3] The four outlying cameras would be labeled differently if the labels were based on geographic location, so it is important to clarify that our labels refer to sky location.

[4] https://github.com/ameisner/ci_throughput

The zeropoint prediction I made used a mirror area which assumed that the aperture mask was installed.

The ultimate result was that at airmass = 1, the CI zeropoint should be 26.56 for a source with total detected flux of 1 electron per second.

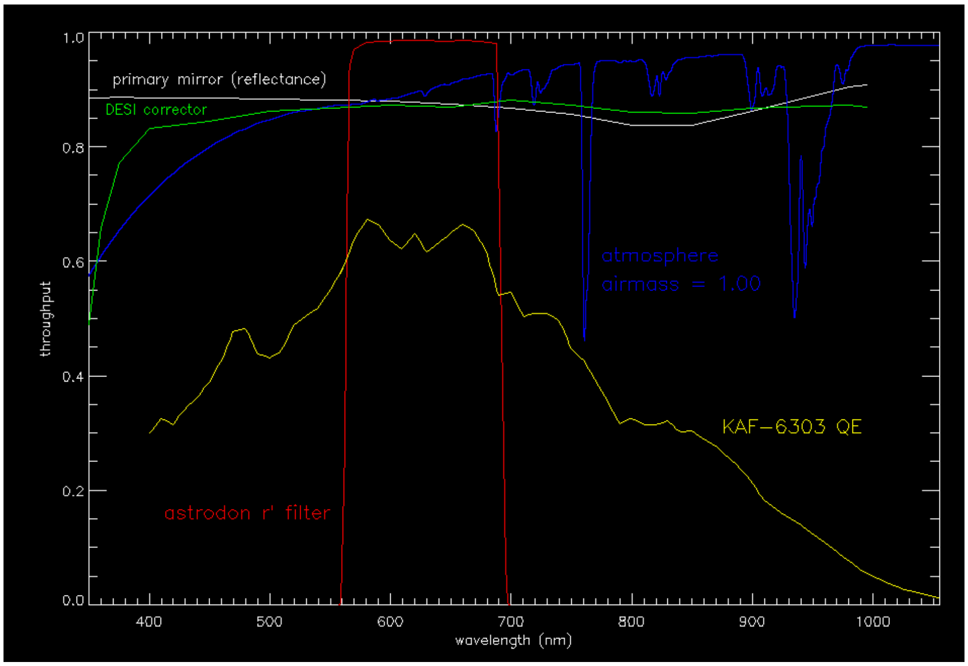

Figure 1: Effects of the atmosphere (airmass = 1), primary mirror reflectance, DESI corrector, astrodon r' filter, and CI CCD QE on CI throughput.

5 Throughput without Aperture Mask Installed

The 20190406 desi-nightlog observing report ([desi-nightlog 2]) stated that conditions were photometric during the later parts of the night ("We also tried to make sure to get good data for the throughput measurements since conditions were good."). Several images from that time period (including EXPID = 4486) listed "image without aperture mask" in the PROGRAM keyword, with high star density and good image quality. So I assumed that these were images meant to be used for checking the throughput. I analyzed aperture photometry of 100 stars with $14.3 < r_{ps1} < 17$ in the CIC image of EXPID = 4486. I used CIC because we don't yet have flat fields and that limitation would be more problematic for the outlying chips given the vignetting. I created a PSF model and used the PSF model to make an aperture correction to total flux in ADU. Then I converted these total fluxes to e-/second using an assumed gain of 1.64 e-/ADU and EXPTIME = 15 seconds. I find a median offset between

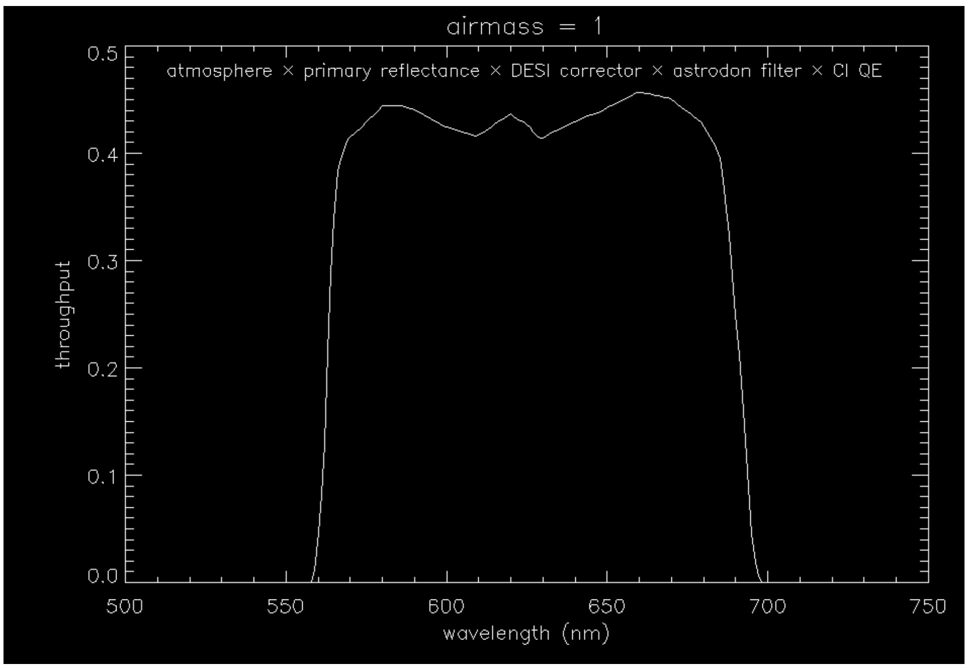

Figure 2: Predicted CI throughput accounting for the effects of the atmosphere (airmass = 1), primary mirror reflectance, DESI corrector, astrodon r' filter, and CI CCD QE.

instrumental magnitudes (-2.5*log10[total detected e-/s]) and r_ps1 of 26.509 mags. The AIRMASS keyword of this observation was 1.59, for which I calculate a predicted zeropoint of r = 26.485 AB for a source with total flux of 1 detected electron per second. This prediction assumes the mirror area from DESI-347-v15. Taken at face value, this would indicate to me that we're going an extra 0.024 mag deeper than nominal thanks to the extra mirror area without the aperture mask. However, in reality I don't think this current zero point estimate is accurate at that level:

- it's not clear to me that we know the CIC gain at the percent level, especially given the camera label swapping we discovered on the first night.
- I'm completely ignoring any corrections needed from the PS1 system to the DESI CI system.
- I'm assuming the PS1 mags are not dereddened. A_r $\sim$ 1.2 in this field, so the correspondence between predicted and measured zeropoints would go from excellent to horrible if the PS1 mags turned out to actually be dereddened. I'm also assuming r_ps1 is AB.
- I've only looked at 100 stars in one image, and don't know how perfectly photometric conditions were.
- it would be better to do this analysis once we have some understanding of the flat field.
- I wouldn't really trust my aperture correction at the 1% level. I've attached a few plots illustrating different portions of this analysis.

6 Throughput with Aperture Mask Installed

- only CIC analyzed
- observed on 20190406 in photometric conditions according to the observing log (without aperture mask in place)
- same field was observed again by Arjun on 20190417 in photometric conditions (with aperture mask in place)
- in both cases (20190406 and 20190417) the seeing was reasonably good
- very nearly the exact same airmass ($\sim$1.59) of observations on both nights
- low galactic latitude $(l_{gal}, b_{gal}) \approx (5^\circ, 10^\circ)$
- exposures within a single night are aligned to within $\sim 1''$.
- pointings of exposure sets on the two different nights are offset by $\sim 0.5'$

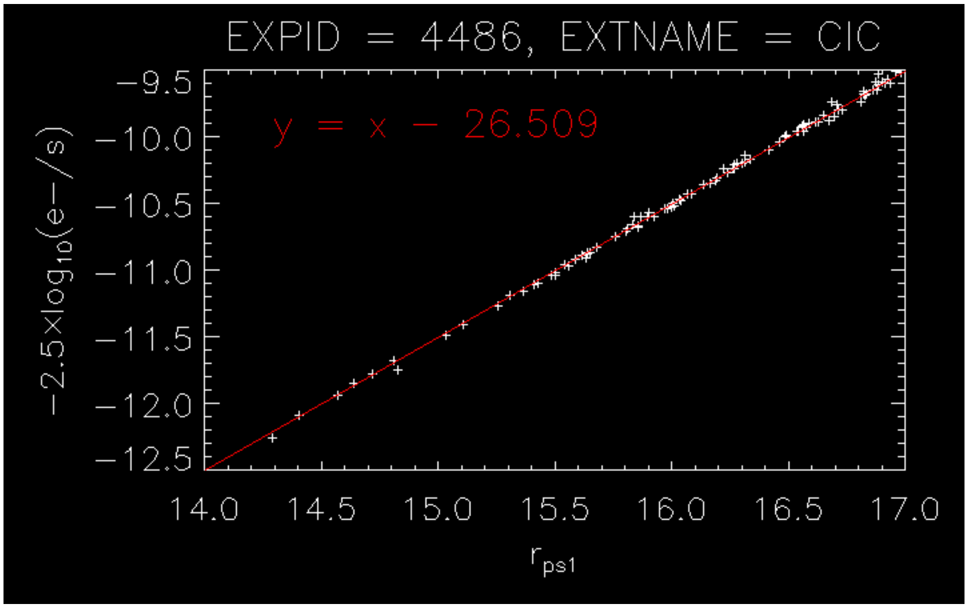

Figure 3: EXPID = 4486, EXTNAME = CIC zeropoint analysis summary.

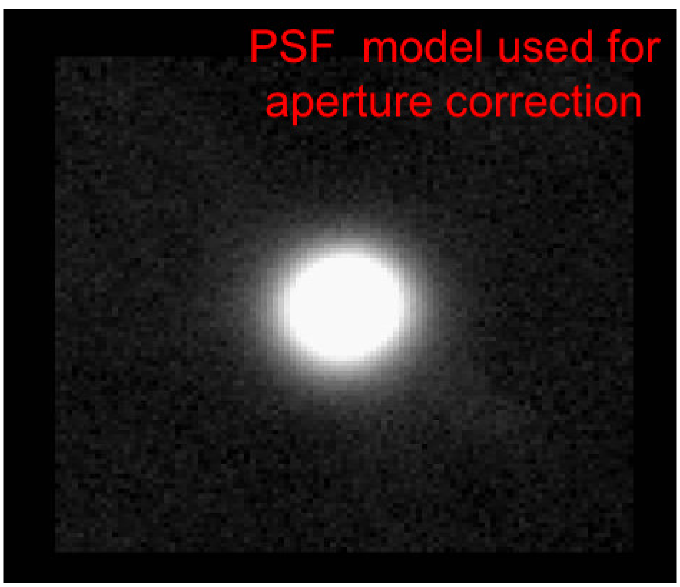

Figure 4: EXPID = 4486, EXTNAME = CIC PSF used for aperture correction when performing the zeropoint/throughput analysis of this exposure.

NIGHT	EXPID	EXPTIME (s)	AIRMASS	ZP_{meas} (AB)	ZP_{pred} (AB)	gain ($e-$/ADU)	n_{stars}	α_{bore} (°)	δ_{bore} (°)
20190406	4486	15	1.591	26.553 ± 0.002	26.4851	1.710	98	259.9794	−19.0949
20190406	4487	10	1.590	26.549 ± 0.003	26.4852	1.710	99	259.9794	−19.0950
20190406	4488	10	1.590	26.557 ± 0.004	26.4852	1.710	99	259.9794	−19.0950
20190417	7577	10	1.590	26.449 ± 0.007	26.4852	1.710	103	259.9726	−19.0908
20190417	7578	15	1.590	26.448 ± 0.006	26.4852	1.710	103	259.9726	−19.0908
20190417	7579	30	1.590	26.446 ± 0.005	26.4853	1.710	103	259.9726	−19.0909
20190417	7580	60	1.590	26.460 ± 0.006	26.4853	1.710	103	259.9726	−19.0909
20190417	7581	120	1.589	26.464 ± 0.007	26.4853	1.710	103	259.9726	−19.0910

Table 1: Note that the measured zero points reported in this table count all light within a 50 pixel = $6.67''$ radius.

- about 100 CIC stars per exposure contribute to the zero point determination
- magnitude range of the stars analyzed is roughly $14 < r_{ps1} < 17$
- zero point measurement uses gain of 1.71 $e-$/ADU which I measured from my 'gain low dome' calibration screen sequences (for a full discussion see companion document DESI-5228, in particular §8 and Table 7).
- gain measurements based on calibration screen data taken in early april and late may agree very well for CIC, both giving 1.71 $e-$/ADU, so there is not a clear basis for worrying about gain variation over time during the CI run.
- the predicted zero point values are all nearly identical because they all use the mirror area from DESI-347-v15
- The reason the predicted zero points are very slightly different is because these predictions use the very slightly different airmass values when calculating the atmospheric transmission.
- The predicted zero point using the DESI-347-v15 mirror area falls in between the zero points with and without the aperture mask
- The zero points with and without aperture mask are different by 0.0996 mag on average, in the sense that with the aperture mask less light is detected for a given source (which makes sense). this 0.0996 mag value just directly compares the zero points, since accounting for the tiny differences in airmass would make a negligible difference
- The aforementioned 0.0996 mag translates to 9.6% more light gained by removing the aperture mask (although much of this increase may come from light far from the centroid). This is a larger differential than suggested by David Schlegel's estimate of ∼6% (from [desi-commiss 1084]).
- The radius used for the aperture correction is 50 pixels = $6.67''$, which is very large relative to the $\sim 1''$ FWHM.
- α_{bore} and δ_{bore} are the coordinates of the center of CIC in each exposure, according to my astrometric recalibrations based on to Gaia DR2. They are equinox 2000.
- PS1 matches (and r_{ps1} mags) come from `/project/projectdirs/cosmo/work/gaia/chunks-ps1-gaia` files. To the best of my understanding, these files include only stars, but it would nevertheless be good to further confirm the provenance of these files. In any case, since this analysis uses only relatively bright objects in a field that is just ∼11.5 degrees from the Galactic center, it seems highly implausible that we are suffering from significant contamination by extended galaxies.

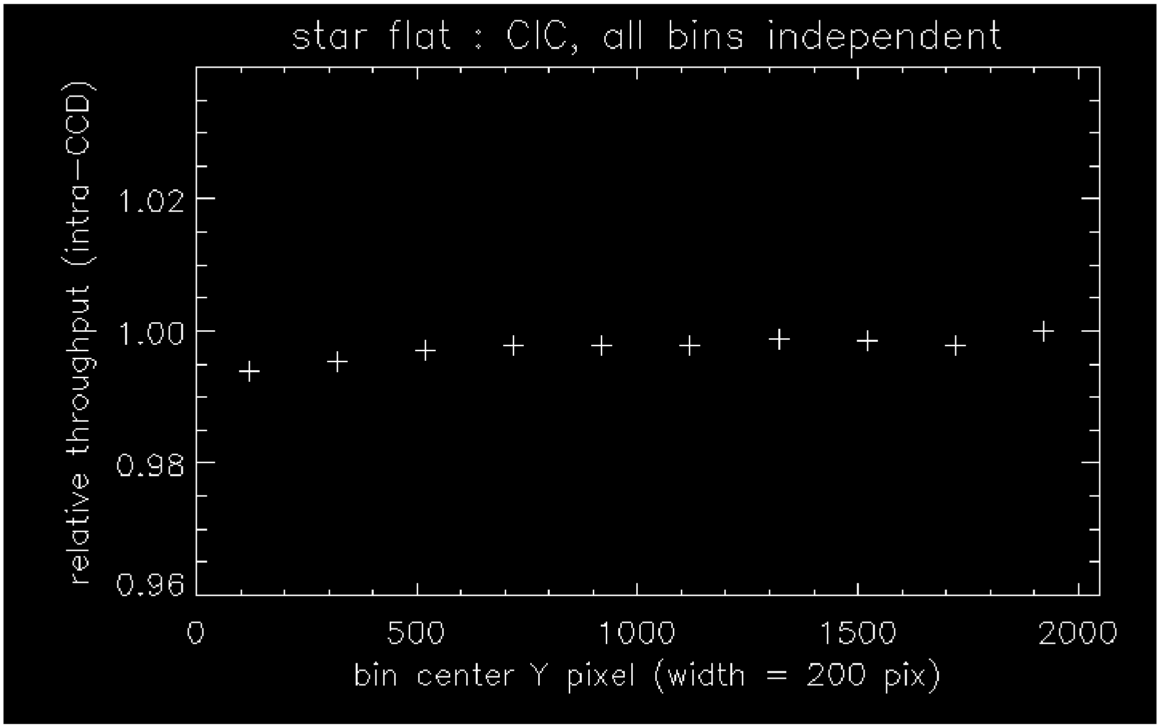

Figure 5: CIC starflat.

7 Flatfield/Vignetting

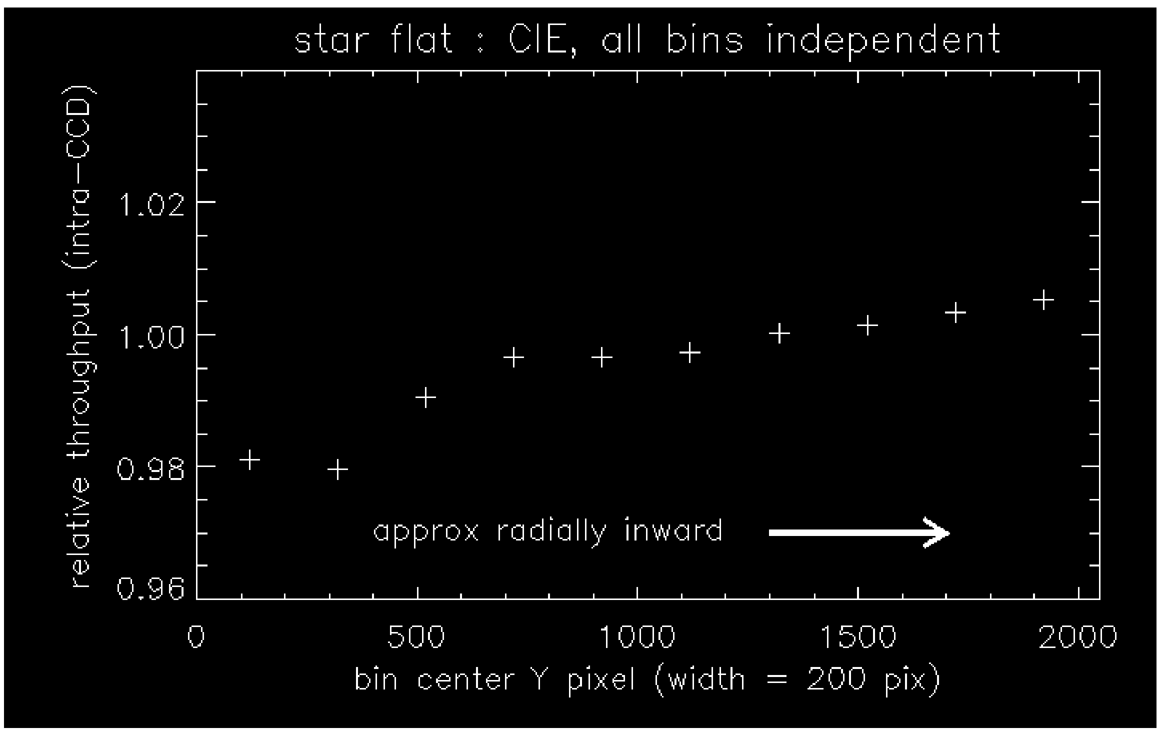

Figure 6: CIE starflat.

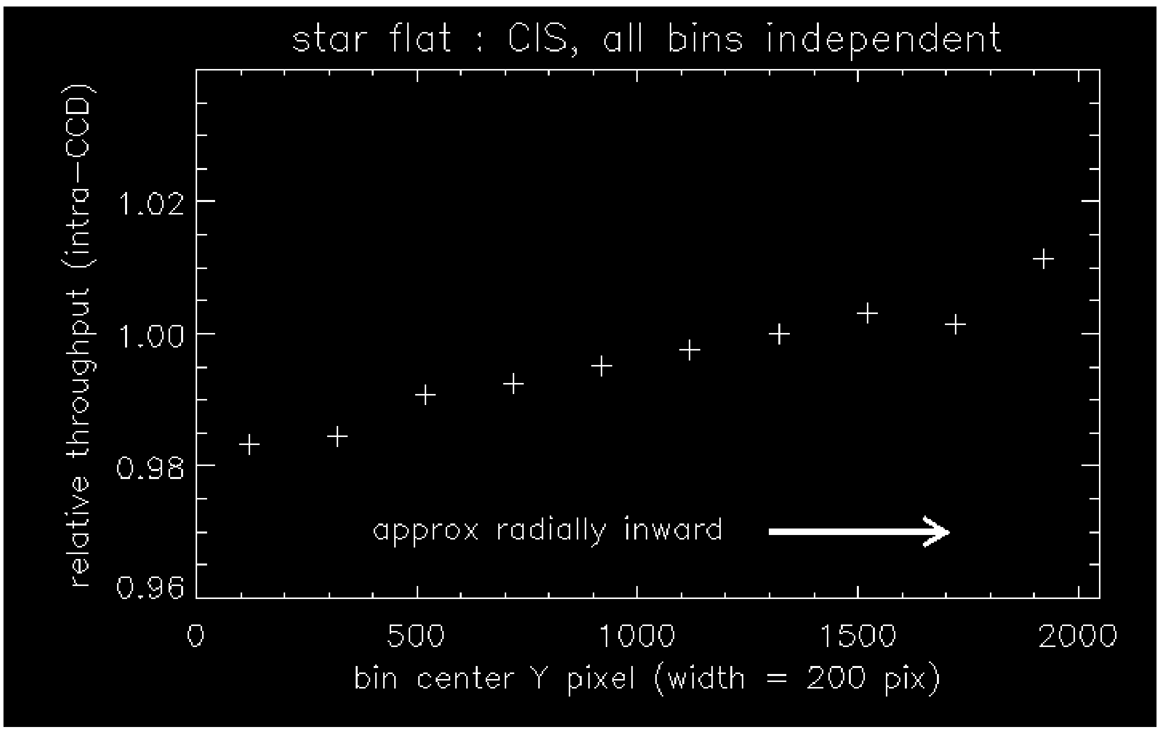

Figure 7: CIS starflat.

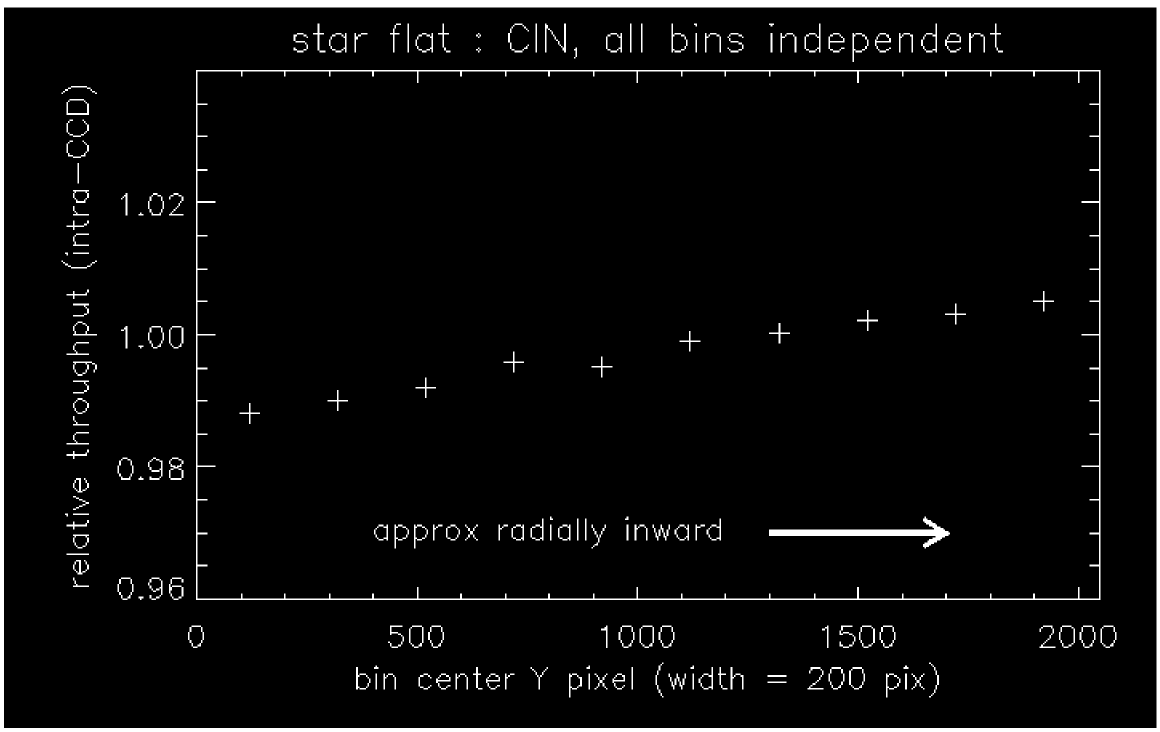

Figure 8: CIN starflat.

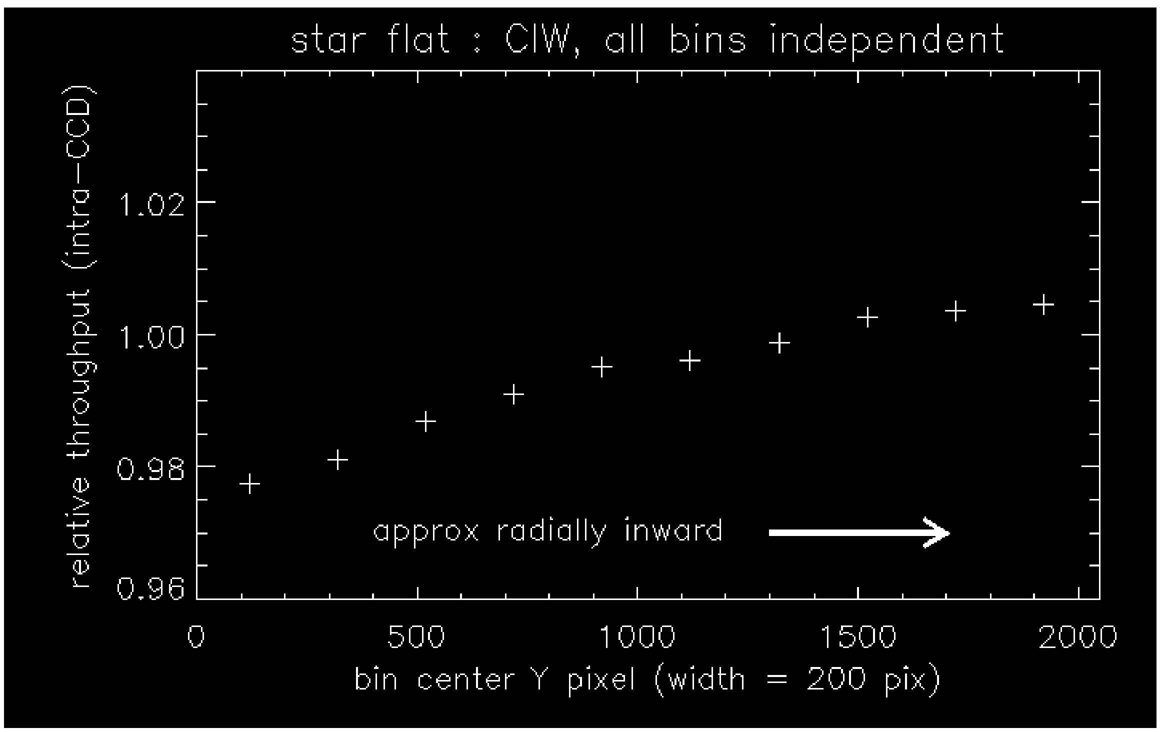

Figure 9: CIW starflat.

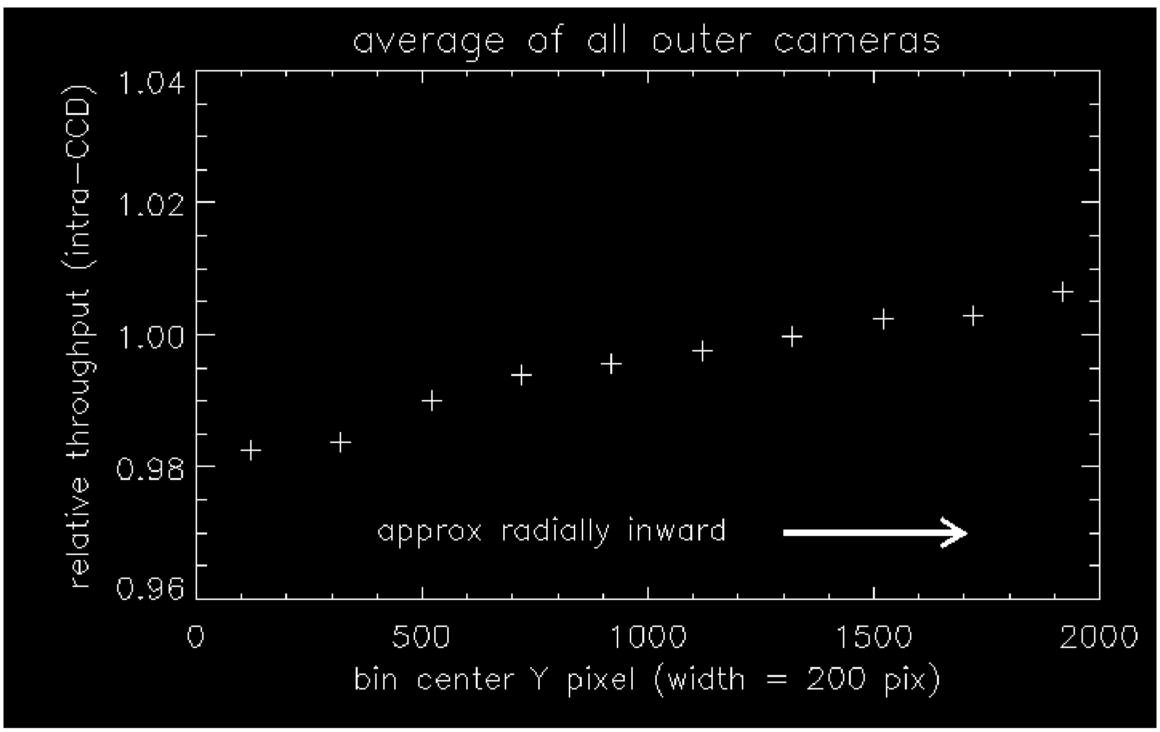

Figure 10: Average starflat for four outlying CI cameras (CIE, CIN, CIS, CIW).