The Photometric and Astrometric Properties of DECam as Enablers of Precision Science

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DES Calibration Scientist

DECam Community Science Workshop 2018
Tucson, Arizona
21 May 2018
The Photometric and Astrometric Calibration of DECam using DES and BLISS as Examples

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Background
Blanco + DECam
Dark Energy Camera Parts (2008-2012)

Credit: H.T. Diehl
Instrumental Effects

- CCD effects
- Amplifier effects
- Gain measurement
  - Linearities and non-linearities


Slide credit: William Wester
Ancillary Hardware

DECaL system

Marshall et al. 2013

GPS monitor
(to measure PWV)

Credit: Rick Kessler
The Dark Energy Survey (DES)

5-year survey in *grizY*

¼ of southern sky (c. 5000 sq deg)

Credit: Josh Frieman
Astrometry
DES Astrometry

SCAMP

• **SCAMP astrometric software (E. Bertin)**
  • Current DES Data Management/Community Pipeline
  • UCAC4: Science Verification through Year 3 processing; DES DR1
  • 2MASS: Year 4 processing & Year 5 processing(?)
  • Gaia DR2: Year 5 processing(?) and beyond
DES DR1 Astrometry

**SCAMP**

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<tr>
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<th>r</th>
<th>i</th>
<th>z</th>
<th>Y</th>
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<td>42</td>
<td>36</td>
<td>37</td>
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Single-epoch Astrometric Repeatability (total distance, mas)

Coadd Astrometric Precision (total distance, mas)

30 (internal); 151 (vs. Gaia)

Astrometric residual vs Gaia ($G \sim 16$ stars) in arcsecs

Median = 0.151 ''

DES DR1 vs. Gaia DR1

DES Astrometry

wcsFIT

* wcsFIT (G. Bernstein et al 2017)
  - DECam starflats (taken ~ 4x per year)
  - Gaia DR1 used to stabilize low-order behavior of solutions (soon: DR2)

Astrometric model includes:

- Tree ring distortions (template)
- Serial register edge distortions (template)
- Optics (polynomial)
- Lateral color
- CCD linear shifts
- Exposure linear shifts
- Differential chromatic refraction

wcsFit refinements to DES Year 4 and beyond…
DES Astrometry

**wcsFIT**

- Mean astrometric error of all detections in g,r,i for starflat epoch 20150204 vs. position on focal plane.

- Distortion field is multiplied by 50,000 to match red scale bar.

- **RMS**: 2.4 milli-arcsec!

Bernstein et al 2017
DECam CCDs move a few microns on thermal cycling...

Change in CCD orientations after focal plane cooling event.

Credit: Gary Bernstein
DES Astrometry

wcsFIT

• Some un-modelled distortions…

Credit: Gary Bernstein
DES Astrometry

• Some un-modelled static distortions?…

Credit: Gary Bernstein
Photometry
1. **Internal**: 2% rms on scales of $0.05^\circ$ - $4^\circ$.
   
   Goals: 1% rms and/or over $160^\circ$ in RA, $30^\circ$ in DEC.
   
   → angular galaxy clustering

2. **Absolute Color**: 0.5% ($g-r$, $r-i$, $i-z$); 1% ($z-Y$).
   
   “Between-filters” calibration.
   
   Photometry as a “low-res. spectrum”
   
   → photo-z’s, SNe k-corrections

3. **Absolute Flux**: 0.5% in $i$-band.
   
   Relative to standard star BD$+17^\circ$4708, C26202
   
   Zeropointing the overall filter system.
   
   → comparison with other surveys (esp. for SNe)
DES Photometry: SV, Y1, (Y3)

**Photometric Global Calibration Module (PGCM)**

- Observe nightly standards to create a sparse gridwork of tertiary standards.
- Use overlapping exposures to tie DES photometry to tertiary network.

For DES Year 1, each part of the covered footprint had 3-4 overlapping exposures in each band.
Internal Photometric Reproducibility (overlapping CCDs): c. 3 mmag

DES Photometry: SV, Y1, (Y3)

Photometric Uniformity (APASS/2MASS comparison): ~20 mmag (~2%)

**Stellar Locus Regression (SLR)**

- Match the observations against the stellar locus.
- "Top of the Milky Way" as opposed to “Top of the Atmosphere”
- Colors good to ~1%.
- Could be affected by variations in stellar populations.

High et al. (2009)
DES Photometry: DR1 (& Y3, Y4, Y5)

**FGCM**

- **Forward Global Calibration Method (FGCM)**
  - Burke et al. 2018, AJ, 155, 41
  - Take all the inputs and build and exposure-by-exposure model of the camera response + atmosphere prior to iterative fits of stars.

### Diagram

- **DECal Scans**
- **MODTRAN Atm. Models**
- **Barometric Pressure Measurements**
- **GPS monitor**
- **PWV**

**Note:**
- Millions of stars observed 2+ times in griz under photometric conditions
**Forward Global Calibration Module (FGCM)**

- Burke et al. 2018, AJ, 155, 41
- Take all the inputs and build and exposure-by-exposure model of the camera response + atmosphere prior to iterative fits of stars.

**Y3 Annual Processing Results**

- 8.7 million *griz* cal stars
- 6.2 million Y cal stars
- 3.2 million CCD image ZPs
- Fit residuals: 6-7 mmag rms
- Estimated uniformity over the DES footprint of <7mmag rms (compared to Gaia DR1) (even better for Y4 annual processing -- see next slides)
DES Photometry: DR1 (& Y3, Y4, Y5)

• Offset map (G - r) for Gaia DR1
• Uniform with RMS of 5.1 mmag

Credit: Eli Rykoff
DES Photometry: DR1 (& Y3, Y4, Y5)

• Offset map (G - r) for Gaia DR2
• Uniform with RMS of 3.8 mmag

Credit: Eli Rykoff
DES Photometry: DR1 (& Y3, Y4, Y5) FGCM

(Y4 processing)

DES r-band and Gaia DR2

- Now with a simple reddening correction
- RMS is 3.5 mmag

Credit: Eli Rykoff
FGCM Absolute Calibration
(also relevant to other calibration methods)

- Three CALSPEC standards in DES footprint. Only one is a faint standard. FGCM has absolute scale set to C26202.
- DES DR1: 3-5 mmag uncertainty, relative to C26202.
- Multi-year program of identifying white dwarf candidates (~100), obtaining spectra, and performing model fits giving synthetic spectra.

Synthetic photometry can be compared with observed mags.

Representative SOAR-4m Spectra

DA WD atm. model fits
(P.-E. Tremblay)
(Also using G. Narayan’s WDmodel)
BLISS
Blanco Imaging of the Southern Sky (BLISS; PI: Marcelle Soares-Santos)

- DES, Public DECam, and BLISS data as of c. Early 2017

- Public DECam data supplemented with new observations to cover Southern sky to $|b| = 10^\circ$ in griz.

- Processed with DES pipeline at Fermilab.

- Science:
  - Templates for Optical Counterparts to LIGO/Virgo events
  - Dwarf Galaxy searches
  - Planet 9 searches

Credit: Alex Drlica-Wagner
Blanco Imaging of the Southern Sky (BLISS; PI: Marcelle Soares-Santos)

Public, non-DES exposures processed (current status)

Photometric calibration via “expCalib”
expCalib: On-the-fly nightly calibration and zeropoint estimation

Sahar Allam (Fermilab)

What is expCalib?

- Quick zero point estimate for single epoch exposures.
- Useful for on-the-fly calibration.
- Can easily identify ZP gradient over an exposure.
- Currently uses APASS/2MASS transformed to DES \{u,g,r,i,z,Y\}
- Future: use Gaia DR2 or Gaia + APASS/2MASS/Galex hybrid for transformed DECam \u{g},VR,r,i,z?
- ZP outlier rejection for each exposure via scikilearn Local Outlier Factor (LOF**)
- Estimated ZPs for the following programs:- DES, DES-SNe, DES-CalSpec, DES-TMO, DECam Engineering, DES-GW, IceCube, BLISS, MagLiteS, BLINK, and others.

**http://www.dbs.ifl.lmu.de/Publikationen/Papers/LOF.pdf
Miscellanea
DECam Filters: Normalization Factors

DES DR1 Standard Passbands

Synthetic photometry:
\[ m = -2.5 \log \frac{\int d(\log \nu)f_{\nu}S_{\nu}}{\int d(\log \nu)S_{\nu}} - 48.60, \]

Exposure Time Calculations:
\[ N_* = A t \int \frac{\lambda}{hc} f_{\lambda} S_{\lambda} d\lambda \]

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<th>synthetic count rate [e-/sec]</th>
<th>observed count rate [e-/sec]</th>
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<td>i</td>
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<td>z</td>
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<td>457</td>
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<tr>
<td>Y</td>
<td>299.87</td>
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</tbody>
</table>

Scaling Factor
(= obs./synthetic) [dimensionless]
- 0.557
- 0.585
- 0.590
- 0.587
- 0.624

Multiply by these scaling factors (Preliminary!)
DECam Filters: Out-of-Band Leaks

- DECal is not precise enough to measure out-of-band leaks below the $\sim 10^{-4}$ level.
- During the January and March 2018 DECam engineering runs, the Texas A&M team observed bright stars through double filters, trying all possible combinations.
- Evidence for out-of-band leakage in u-band and either g- or i-band.
- Detailed analysis is still in progress.
There’s a lot more that can be done with aTmCam!
(e.g., perhaps estimating hourly DECam ugriz extinction coefficients from aTmCam mags?)
DECam Calibrations Enabling Science
Stellar Streams in Milky Way Halo
(Nora Shipp et al. 2018, arXiv:1801.03097)

See Nora’s talk this afternoon!
Extra Slides
Milky Way Structure
(Regions of high star density)
• CCD focal plane is housed in a vacuum vessel (the imager) which is supported by the barrel.

• LN2 is pumped from the telescope floor to a heat exchanger in the imager: cools the CCDs to -100°C.

• CCD readout electronic crates are mounted to the outside of the Imager and are actively cooled.

• Filter changer (8 filter capacity) and shutter form one mechanical unit.

• Hexapod provides focus and lateral alignment capability for the corrector-imager system.

• Barrel supports the lenses and imager.

• DECam weighs about 4 tons (load limit is ~ 6 tons).
DECam CCDs

- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.264”) pixel size
- 12 2kx2k guide and focus chips (hexapod)
- Excellent red sensitivity
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels

DECam / Mosaic II QE comparison
1. **Internal (local):** 15 mas rms
   - Mapping of centroids of bright stars between a (deeper) coadd and its overlapping single-epoch (SE) images.
   - shape measurements on SE images; template image subtraction

2. **Relative Between-Band:** 100 mas
   - A limit on the effects of differential chromatic refraction within each passband.
   - deblending between bands; aperture photometry colors

3. **Absolute:** 100 mas rms
   - How well the DES astrometric system is tied to an external reference frame.
   - co-addition without degrading image quality
   - cross-ids with other catalogs
   - spectroscopic follow-up (particularly for SNe)
From the Scientific Requirements Document
(sciReq-9.86, 10 June 2010)

**R-10** For each of the $grizY$ bandpasses of the wide-area survey, the fluctuations in the spatially varying systematic component of the magnitude error in the final co-added catalog must be smaller than 2% rms over scales from 0.05 to 4 degrees.

**Internal (Relative) Calibration**

$$m_i = -2.5 \log\left(\frac{f_1}{f_2}\right) + C$$

**Absolute Color Calibration**

$$m_i - m_z = -2.5 \log\left(\frac{f_i}{f_z}\right) + z_{piz}$$

**Absolute Flux Calibration**

$$m_i = -2.5 \log(f_i) + z_p$$

**System Response**

**R-11** The color zeropoints between the survey fiducial bandpasses ($g-r$, $r-i$, $i-z$) must be known to 0.5% rms. The $z-Y$ color zeropoint shall be known to 1% rms.

**R-12** The $i$-band magnitude zeropoint relative to BD+17, and therefore the AB system, must be known to 0.5% rms.

**R-13** The system response curves (CCD + filter + lenses + mirror + atmosphere at 1.2 airmasses) must be known with sufficient precision that the synthesized $grizY$ magnitudes of any astronomical object with a calibrated spectrum agree with the measured magnitudes to within 2%. When averaged over 100 calibrating objects randomly distributed over the focal plane, the residuals in magnitudes due to uncertain system response curves should be < 0.5% rms.

**G-4** A goal of the survey is to achieve **R-10** at the enhanced level of 1% for the final co-added catalog.

**G-5** A goal of the survey is to achieve **R-10** over 160 degrees of Right Ascension and 30 degrees of Declination.
R-14 The absolute sky position of bright stars in both the individual images and the coadded image should be measured to an rms of $\leq 100$ mas on all scales. Absolute positions will be reported in the J2000 system.

In order to reject cosmic rays and achieve efficient photometric calibration, the survey must average together (coadd) a number of images to reach the necessary depths for the dark energy science objectives. In order for this averaging process to not degrade the PSF for photometric purposes, the images of the objects must be aligned to better than a third of a pixel, 0.1", which is R-14’s requirement of 100 mas. Spectroscopic followup of the Supernova survey also requires positions accurate to 0.1". R-14 is thus a global astrometry requirement to be verified using published astrometric catalogs.

R-15 The centroid of the images of the same star in adjacent passbands of the coadd should agree to within 100 mas, over the range of airmasses allowed by the survey.

The rationale for R-15 is that relative astrometry of 100 mas is needed for deblending and that it also minimizes systematic errors in aperture photometry colors. The issue here

R-16 The rms of the centroids of each bright star in a set of all overlapping exposures that contain it should be no larger than 15 mas. The position measured in a coadd image must be mapped to the corresponding position in the overlapping input images with an accuracy of 15 mas or better. This requirement is for each bandpass individually.

Requirement R-16 derives from the use of the co-add images to determine the centroids of stellar and galaxy intensity distributions, which are then used for shape measurements on single exposures. It is inherently a very local requirement. This Note that this is a requirement on systematic error and not on centroid accuracy. R-16 is the astrometric requirement most relevant to the SN survey. This also an internal
What is expCalib?

- Quick zero point estimate for single epoch exposures.
- Useful for on-the-fly calibration.
- Can easily identify ZP gradient over an exposure.
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- ZP outlier rejection for each exposure via scikilearn Local Outlier Factor (LOF**)
- Estimated ZP for the following programs:- DES, DES-SNe, CalSpec, DECam Engineering, DES-GW, IceCube, BLISS, MagLiteS, BLINK, and others

**http://www.dbs.ifi.lmu.de/Publikationen/Papers/LOF.pdf
Y4A1_FINALCUT vs. APASS/2MASS

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expCalib

Y4N1 (Aug 2016-Feb 2017):
Effective ZP\(_{\text{exp}}\) vs. time

Credit: Sahar Allam
expCalib

Y4N1 (Aug 2016-Feb 2017): internal error in CCD zeropoints using APASS/2MASS

Credit: Sahar Allam