# FGCM in 2019: With Great Power Comes Great Systematics





Large Synoptic Survey Telescope

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LSST Project/DESC Calibrations Workshop July 10<sup>th</sup>, 2019



DARK ENERGY SURVEY

## **Previous Talks**

- "Survey Uniformity and Atmosphere Modeling with Forward Global Calibration": <u>https://indico.in2p3.fr/event/17361/</u> contributions/62539/attachments/48345/61033/fgcm\_des\_and\_lsst.pdf, <u>https://indico.in2p3.fr/event/17361/contributions/62539/attachments/</u> 48345/61032/fgcm\_des\_and\_gaia.pdf
- "Updates on Survey Uniformity with FGCM...and a bit about reddening": <a href="https://indico.in2p3.fr/event/17773/contributions/65630/attachments/50041/63812/FGCM\_des\_updates\_october.pdf">https://indico.in2p3.fr/event/17773/contributions/65630/attachments/50041/63812/FGCM\_des\_updates\_october.pdf</a>
- "The Chromatic Effects of Mirror Degradation": https:// confluence.slac.stanford.edu/download/attachments/199823421/ desc\_pc\_chromatic\_mirror.pdf? version=1&modificationDate=1554414875000&api=v2
- "Updates on Mirror Chromaticity": https:// confluence.slac.stanford.edu/download/attachments/199823421/ chromatic\_effects\_update.pdf? version=1&modificationDate=1561729445000&api=v2

### Outline

- FGCM in a Nutshell
- Highlights of improvements
- Uncovering Systematics
  - Persistent flat-field errors
  - Persistent background estimation errors
  - Persistent chromatic errors
  - Astrophysics and comparisons to Gaia

## FGCM in a Nutshell

- The "Forward Global Calibration Method"
  - Solve the global calibration problem with a physical model of the atmosphere + instrument
  - Picking up on Stubbs & Tonry (2006)
  - Requires instrument throughput measurements
- Given a set of atmospheric parameters at any given time (under photometric conditions) we can predict the atmospheric extinction as a function of wavelength
  - Also need to know object SED (see e.g., Li+16)
- Once we know the atmospheric extinction, can predict fluxes of all the objects in an exposure

# Advantages of FGCM

- Forward model approach always leads to physically possible solutions
  - Allows physically-motivated non-linearities with airmass
  - No gray terms in the model means no runaway solutions
- Uses full range of star colors increase the s/n and this is useful information!
- Instrumental transmission variations, plus possible evolution of passbands is properly incorporated
- Works best with more overlap in time and space (like übercal), and multiple bands per night is very useful

# The Atmosphere Model

- Atmospheric transmission can be described with a small number of parameters
- Precipitable water vapor (PWV)
- Aerosol Optical Depth (AOD)  $\tau$  and  $\alpha$

 $\tau(\lambda) = \tau_{7750} \times (\lambda/7750 \,\text{\AA})^{-\alpha}$  $S_{\tau}(\lambda) = e^{X\tau(\lambda)}$ 

- Ozone (O3)
- Given zenith distance and barometric pressure, compute Rayleigh and O2 using MODTRAN

#### **Atmosphere Constituents**

• The FGCM standard atmosphere for DES:



#### Fit Parameters

- PWV varies quadratically through the night
- A single-constituent aerosol, with optical depth  $\tau_{7750}$  that varies linearly through the night, and single  $\alpha$  per night
- A single value for Ozone each night
- Plus airmass and site-monitored barometric pressure

## Instrumental Passband

- Instrumental effects (filter variations, anti-reflective coating differences, CCD QE differences) are as big or bigger than atmospheric effects
- Require (at least) CCD-by-CCD scans
  - For DES from the "DECal" system
  - For LSST from the CBP

## Filters + CCDs for DES

- From the DECal monochromatic scans
  - g band especially variable from chip to chip



#### Improvements and Upgrades

- Modeling the flux errors (rather than trusting the nominal quoted errors)
- Mirror chromaticity variations
- Better fits via bug fixes

#### Six Years of DES

- Residual chromatic error between red and blue stars
- There is a long term trend; is this the mirror? Yes!



# **Testing PWV**

- For the first 4 years of DES, we mostly have GPS PWV measurements (not used in the FGCM fit)
- There is a good correlation per exposure.



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- For the first 4 years of DES, we mostly have GPS PWV measurements (not used in the FGCM fit)
- There is a better correlation per exposure with the "retrieved" PWV
- This is estimated by the relative shift of red/blue stars on each z-band image (the "Lupton Dream")
- I am currently using this only for testing



## In the LSST Stack

- Now "fgcmcal" works with reference stars, if available
  - Helpful but not required for disconnected surveys like HSC
- fgcmcal support for running on a single tract is in progress, will be done in August
  - Full multi-band support
  - Requires reference stars

#### Datasets

- DES data:
  - Six years of DES (full survey) "Y6A1"
  - All results preliminary
- HSC data:
  - Three years of HSC survey
  - Using "s18a" calexps (input into PDR2): Aihara et al.: <u>https://arxiv.org/abs/1905.12221</u>
  - See <u>https://jira.lsstcorp.org/secure/attachment/38150/</u> <u>hsc\_s18a\_FGCM.pdf</u> for full results

## **Background Residuals**

- Follow Bernstein star flat paper, Figure 3
- Stack all DECam CCDs, rotate N CCDs by 180°



# **Background Residuals**

- Very red photons go through the CCD and bounce off the backplane
- Why isn't this taken care of in the flat field?
  - The flat field was created with a very red LED that is much, much redder than any stellar SED
  - This residual is then implanted into the images





## **Background Residuals**

- Follow Bernstein star flat paper, Figure 3
- Stack all DECam CCDs, rotate N CCDs by 180°



- Stack all HSC PDR2 (S18a) CCDs in the g-band
- Some interesting features for bright stars



- Stack all HSC PDR2 (S18a) CCDs in the g-band
- Some interesting features for bright stars (column bins)



- Stack all HSC PDR2 (S18a) CCDs in the g-band
- Some interesting-er features for faint stars (column bins)



- Background pedestal issues affect faint objects more than bright objects
  - More on modeling this systematic in a bit...
- This photometric residual has been traced to amp-to-amp offsets in HSC (not corrected by flat field)
  - The way the sky model is computed turns this into "ramps"
  - I am investigating the origin of these amp-to-amp offsets, see <u>https://jira.lsstcorp.org/browse/DM-20303</u>

- Stack all HSC PDR2 (S18a) CCDs in the y-band
- Some interesting features for bright stars



- Stack all HSC PDR2 (S18a) CCDs in the y-band
- Some interesting features for bright stars (column bins)



## **Chromatic Residuals**

- Looking at the difference of the "mean exposure residual" for red and blue stars separately is a powerful way of looking for chromatic problems
- Any gray corrections will cancel out
- This plot shows the first check of mirror chromaticity in DES, prior to any atmospheric model fits, and using the loosest of quality cuts



## With the PSF

- There is a residual chromatic error correlated with PSF size
  - Primarily in g-band, at the 1-2 mmag level
- Why?
- PSF size is chromatic
  - Red stars are smaller than blue
  - See Meyers & Burchat
- But this shift itself depends on PSF
  - Larger PSF means atmosphere is dominant term



# DECam Instrument (g)



- Units are chromatic shift from blue to red stars
- Residuals are due to varying QE (typically AR coating in g band)



## HSC Instrument (g)



- Units are chromatic shift from blue to red stars
- Residuals are due to varying QE (typically AR coating in g band)



### Gaia G and DES

- Synthesize Gaia G using (weighted) g+r+i+z
- Consistency at 2.1 mmag, most Galaxy is gone
  - But not all...



#### Something, Something, Galaxy

• Here is a map of the star density in the DES footprint



#### Something, Something, Galaxy

Here is a map of the star density of very blue (0.3 < g-i < 0.6) stars in the DES footprint</li>



#### Something, Something, Galaxy

• The offset in the map is correlated with the bluest stars, toward the Galactic center, but not the anti-center...



## Very Blue Stars??

• DES does not cover the u-band part of Gaia G-band...



### HSC and Gaia DR2

- Train a "color correction" from HSC-r to Gaia G using a simple random forest.
- Bin matched stars (G<20) in nside=128 pixels
- Take the median G G<sub>pred</sub>(r) bias in each pixel
- Uniformity rms is 2.1 mmag (that's good!)



## HSC to Gaia DR2

- Same as previous plot, except this was a calibration run without any PS1 reference stars
- We still get 3 mmag rms uniformity in the r-band.
  - Enough observations of deep fields to tie the wide fields together!



## **Background Pedestals**

- What is the effect of an additive background offset on the photometry?
  - Assume we have a background offset,  $\boldsymbol{\varepsilon}$

• 
$$m = -2.5 \log_{10}(f + \varepsilon)$$

• 
$$m = -2.5 \log_{10}(f(1 + \frac{\varepsilon}{f}))$$

• 
$$m = -2.5 \log_{10} f - 2.5 \log_{10} (1 + \frac{\varepsilon}{f})$$

• Assuming  $\varepsilon$  is small, we have

• 
$$m \approx -2.5 \log_{10} f - \frac{2.5}{\ln(10)} \frac{\varepsilon}{f}$$

## **Background Pedestals**

• Using this equation:

$$m \approx -2.5 \log_{10} f - \frac{2.5}{\ln(10)} \frac{\varepsilon}{f}$$

• We can see that:

• 
$$m_{\text{obs}} - m_{\text{true}} = \left(\frac{2.5}{\ln 10} 10^{m_{\text{true}}/2.5}\right)\varepsilon + E_{\text{gray}}$$

 So if we know m<sub>true</sub> for every star, we can fit a linear equation to a set of stars and determine the sky pedestal (allowing for a calibration offset / gray correction)

#### Gaia Background Estimation

• Evans++2018 shows vs SDSS evidence for a global Gaia background pedestal

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Observe similar feature compared to DES



#### Gaia Background Estimation

- We can fit the pedestal locally
  - Gaia scan patterns are clearly visible



#### **DES Background Estimation?**

- Epsilon seems to be correlated with number of stars in region
- We have evidence from fake star insertion -2 that there is a DES background -3 estimation issue -4 correlated with star density
- Could also be an issue in Gaia
- Is there a way of figuring this out without fakes?



# Coming Work

- LSST stack "fgcmcal" support for tract-based work
- More systematics testing
  - Leave out 1 year at a time
- Investigate instrumental tweaks
  - Similar to mirror chromaticity model

#### **Extra Slides**

### Gaia BP and DES g



#### Gaia BP and DES r



#### Gaia RP and DES i



#### Gaia RP and DES z

