Assessment of Systematic Chromatic Errors that Impact Sub-1% Photometric Precision in Large-Area Sky Surveys

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Abstract

The science goals for many current and future ground-based large-area sky surveys, such as the Dark Energy Survey (DES) and the Large Synoptic Survey Telescope, require calibration of broadband photometry that is stable in time and uniform over the sky to 1% precision or better. Photometric calibrations in past and current surveys have achieved photometric precision of 1%-2% by using overlapping observations. However, this technique only considers the relative field-to-field photometric zeropoint offset, which is independent of the source color. In reality, variations in the wavelength dependence of the atmospheric transmission and the instrumental throughput can also induce systematic errors that depend on source colors (or source SEDs). In this work, we examine such systematic errors using DES observation as an example. We simulate the systematic errors for several science cases (stars, SNe, and galaxies), when the atmospheric transmission and instrumental throughput deviate from a standard one. The wavelength-dependent variations can be caused by the change of airmass in each exposure, the change of the precipitable water vapor and aerosol in the atmosphere over time, and the non-uniformity of instrumental throughput over the focal plane. We compare simulated results with actual DES data and show such errors could be corrected to < 5mmag (0.5%) if the atmospheric transmission and instrumental throughput are measured.

Variations in the wavelength dependence of the **system response** can induce **systematic errors** that depend on source colors or source SEDs.

- System Response $\phi_b(\lambda)$
  - Atmospheric Transmission $\phi^{atm}(\lambda, alt, az, t)$
    - Airmass
    - Aerosol
    - Precipitable Water Vapor (PWV)
    - Ozone
    - Barometric Pressure
  - Instrumental Throughput $\phi_b^{inst}(\lambda, x, y, t)$
    - Mirrors
    - Camera lens
    - Filters
    - Detector

Define a Fiducial/Standard System Response

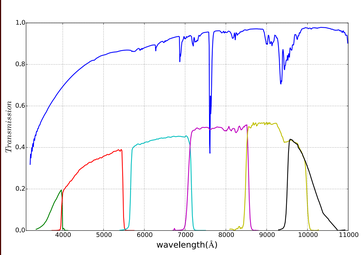

Figure 1. The fiducial atmospheric transmission model at CTIO and the fiducial instrumental throughput of DES-ugrizY filter bandpasses from DECal scan.*

*DECal: a spectrophotometric calibration system for Dark Energy Camera (DECam)

We compute the synthetic systematic errors when the system response deviates from a standard system response.

- **Errors caused by the variations in barometric pressure and ozone are tiny.**
- **Errors from the variation of other components: 1% or more.**

EXAMPLES

Variation in airmass (1.2 → 1.8), Main Sequence stars (O5V-M6V)

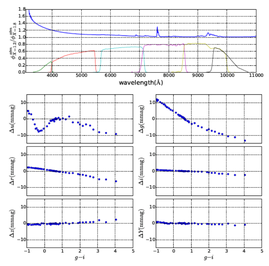

Figure 2. Top panel: Ratio of the atmospheric transmissions at airmass 1.2 & 1.8, with DES ugrizY-band as reference. Bottom panel: Synthetic errors on O5V-M6V stars (Pickle 1992) introduced by this airmass change, as a function of g-i color.

Uncorrected: > 1% errors in g-band, for O stars and M stars!

Variation in precipitable water vapor (3 mm → 10 mm), SN Ia over redshift z=0 to z=1.

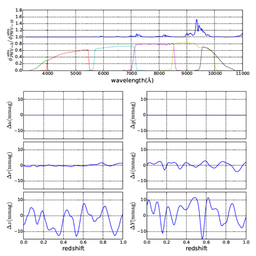

Figure 3. Top panel: The ratio of the atmospheric transmission at PWV 3 mm & PWV = 10 mm.
Bottom panel: Systematic errors on SN Ia (SN2011fe; Pereira et al. 2013) due to the change in PWV, as a function of redshift.

Uncorrected: > 1% errors in zY-band, redshift dependent!

Variation in instrumental throughput: shift 20 Å towards longer wavelength, elliptical galaxies over redshift z=0 to z=2.

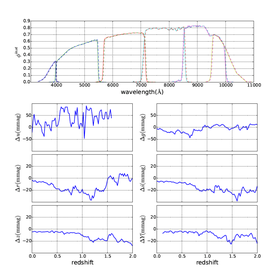

Figure 4. Top panel: Solid lines -- standard instrumental throughput for DES ugrizY-band. Dashed lines -- new instrumental throughput with 20 Å shift.
Bottom panel: Systematic errors in elliptical galaxies (Kinney et al. 1996) introduced by this 20 Å shift, as a function of redshift.

Uncorrected: > 1% errors when Balmer jump redshifting into grizY-band.

Summary of errors on a M6V star

Table 1: Synthetic systematic errors on a M6V star with respect to a G2V star.

Component	Standard	Change to	Systematic Errors (mmag)					
			u	g	r	i	z	Y
Pressure	$P_0 = 779$ hpa	$P_0 = 789$ hpa	-0.2	-0.4	-0.08	-0.06	0.04	-0.02
Aerosol	$AOD_{550} = 0.02, \alpha = 1$	$AOD_{550} = 0.20, \alpha = 1$	-3	-11	-6	-4	-1	-0.2
	$AOD_{550} = 0.02, \alpha = 1$	$AOD_{550} = 0.20, \alpha = 0.5$	-1	-5	-3	-2	-0.8	-0.1
PWV	PWV = 3 mm	PWV = 10 mm	0	0	3	-0.6	+10	-3
Ozone	Ozone = 270 DU	Ozone = 230 DU	0	-0.7	0.9	0.1	0	0
Airmass	$X = 1.2$	$X = 1.8$	-9	-13	-6	-2	+2	-0.8
Instrument	Standard	shift 20Å	-24	-15	-16	-19	-10	-5

Errors on SN Ia and galaxies are even larger!!

We use the actual **calibrated DES data** to show that such systematic errors **do exist** and **are able to be corrected to 2-3 mmag**, if the variation of the atmospheric transmission and instrumental throughput are well measured.

EXAMPLES

Comparing observations of the same stars observed at same (left) and different (right) PWV.

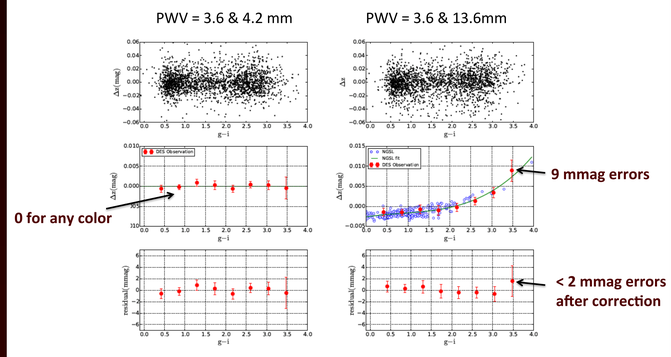

Figure 5. Top panels: Δz from two exposures on different nights, (left) similar PWV (right) different PWV. Each black dot is a Δz from one star.
Middle panels: Divide these stars into 8 bins and calculate the average of Δz in each bin, shown as the red filled circles. Green line is a third-order polynomial fit to the theoretical calculations using the the stellar spectra from Next Generation Spectral Library (NGSL), shown as the blue open circles.
Bottom panels: Residuals after corrections with theoretical calculation from the middle panels; residuals < 2 mmag for any color.

Comparing observations of the same stars observed in different annuli of the DECam focal plane.

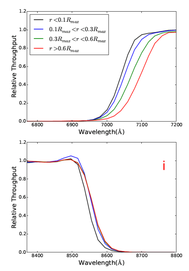

Figure 6. Relative throughput for 4 annuli from DECal scan around cut-on (cut-off) wavelength in the top (bottom) panel. The throughput is normalize at 7700 Å. There is about a 60 Å shift at the cut-on wavelength from the center of the focal plane to the edge of the focal plane.

Region 1: 0 – 0.1 R_{max}
Region 2: 0.1 – 0.3 R_{max}
Region 3: 0.3 – 0.6 R_{max}
Region 4: 0.6 – 1 R_{max}.
R_{max} is the maximum radius of the DECam focal plane.

Lines are from theoretical calculation, not fits to the data!

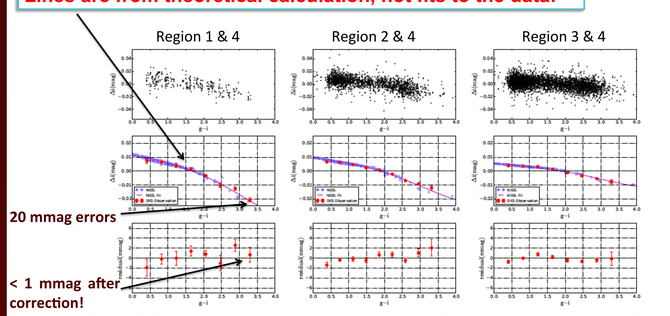

Figure 7. Top panels: Δi of the same stars observed in Region 1 & 4 (left), Region 2 & 4 (middle) and Region 3 & 4 (right).
Middle panels: Divide these stars into 8 bins and calculate the average of Δi in each bin, shown as the red filled circles. Purple line is a fourth-order polynomial fit to the theoretical calculations using the stellar spectra from NGSL, shown as the blue open circles.
Bottom panels: Residuals after corrections with theoretical calculations from the middle panels; residuals < 3 mmag for any color.

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GMT

HETDEX Hobby-Eberly Telescope Dark Energy Experiment — Illuminating the Darkness

LSST Large Synoptic Survey Telescope

DARK ENERGY SURVEY

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