Sloan Digital Sky Survey Photometric Calibration Revisited

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Abstract. The Sloan Digital Sky Survey calibration is revisited to obtain the most accurate photometric calibration. A small but significant error is found in the flat-fielding of the Photometric telescope used for calibration. Two SDSS star catalogs are compared and the average difference in magnitude as a function of right ascension and declination exhibits small systematic errors in relative calibration. The photometric transformation from the SDSS Photometric Telescope to the 2.5 m telescope is recomputed and compared to synthetic magnitudes computed from measured filter bandpasses.

1. Introduction

Recent measurements of cosmological parameters using Type Ia supernovae have identified photometric calibration as an important source of uncertainty (Connolly 2011). Type Ia supernovae show a dispersion on the Hubble diagram of around 0.15 magnitudes, and, consequently, an individual supernova measures the distance modulus to about 15%. However, when the distance moduli of hundreds of SN are averaged, systematic errors in the photometric calibration can be important at the level of 1% when the errors are common to all the supernovae.

The Sloan Digital Sky Survey (SDSS) (York et al. 2000) calibration was reviewed with an eye towards obtaining the most accurate calibration possible prior to the publication of the supernova light curve data (Frieman et al. 2008). The SDSS supernova survey photometry (Holtzman et al. 2008) is calibrated using a reference star catalog (Ivezic et al. 2007). Any errors in the stellar magnitudes result in zeropoint errors for the SN photometry.

The SDSS calibration strategy for the SDSS 2.5 m telescope has been outlined in Stoughton et al. (2002). A small telescope called the Photometric Telescope (PT) was used to obtain a nightly photometric calibration and to measure"secondary patche" distributed throughout the SDSS observing footprint, which served to transfer the the PT calibration to the 2.5 m telescope. The analysis of PT data is described by Tucker et al. (2010).

The flat-fielding of the SDSS camera is greatly simplified because imaging data is obtained using drift scanning, where each point on the sky is sampled by each CCD row, so that the effective response is averaged over all rows. The original method for flat-fielding the 2.5 m telescope images based on sky levels proved to be problematic, and a new procedure that determined relative zeropoints using the stellar locus was adopted[1].

[1]See http://www.sdss.org/dr7/algorithms/flatfield.html

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The stellar locus technique was also applied to the the SDSS object catalogs from all the observations of the equatorial stripe, where SDSS SN were observed, resulting in a precise stellar catalog (Ivezic et al. 2007) that I will call the Coadd catalog. But the stellar locus can adjust only the color as a function of CCD column; the overall "gray" scale is unconstrained. Ivezic et al. (2007) relied on the calibration provided by the PT to set the overall scale, and any errors in PT flat-fielding are transferred to the 2.5 meter telescope as a common error in all the filters.

A separate effort (Padmanabhan et al. 2008) sought to calibrate the SDSS survey with special crossing scans that scanned the sky in directions that were approximately perpendicular to the normal direction. The observation of stars in different camera columns allowed a flat-fielding technique, sometimes known as Ubercal, that did not rely on the PT. Each filter was calibrated separately and did not rely on the stellar locus or other assumptions about the objects being observed. This technique was used for the SDSS Data Release 8 (Aihara et al. 2011). A star catalog was extracted from DR8 and will be referred to as the DR8 catalog. The DR8 catalog is based on a single observation of each star, and is consequently less precise than the Coadd catalog. In addition, typical SDSS observing takes place at low airmass, making it difficult to determine the atmospheric extinction for the SDSS 2.5 m data alone, requiring some additional constraints.

2. PT flat fields

There are some overlapping PT observations that can be used to check for deviations from a uniform response. The data sample consists of 13 observations that overlapped 50% in declination. The analysis involved matching stars in the overlapping pointings and computing the difference in magnitude. The differences in magnitude measure the difference in response of the focal plane between a given column and another one that is half way across the CCD. If the response is uniform all the differences would be zero.

The average differences in magnitudes are shown in Figure 1 for three of the SDSS filters: *u*, *g*, and *z* as a function of degrees from the center of the focal plane in 0.055 degree wide bins. Also shown is a straight line fit to the data. The plots only show the data that is well-measured (the uncertainty of the difference is less than 0.05) and any matches that differ by more 0.2 magnitudes are excluded from consideration. The bin values are the unweighted average of all the stars and the error is determined from the variance.

The results shown in Figure 1 only give the difference in response between the two halves of the PT. Determining the actual response requires additional data or assumptions. If I assume that the response function is a polynomial over the entire CCD, then the assumed linear form of the fits implies a quadratic form for the flat-field as shown in the lower right-hand panel in Figure 1. The data for the different filters is similar so the polynomial curve is drawn using the average of the *g*, *r*, and *i*-band data.

The Coadd catalog is built by using the stellar locus to adjust the colors to give a consistent stellar locus as a function of declination, but relies on the PT calibration for *r*-band. Since the response of the PT is not flat over the PT focal plane, the Coadd could be expected to exhibit a modulation pattern that repeats every 0.6 degrees because of the flat-fielding error in the PT. However, the assumption of a polynomial response is not necessarily justified. For example, there could be a discontinuity in the flat-field between the two sides of the CCD, whcih are read out by different amplifiers.

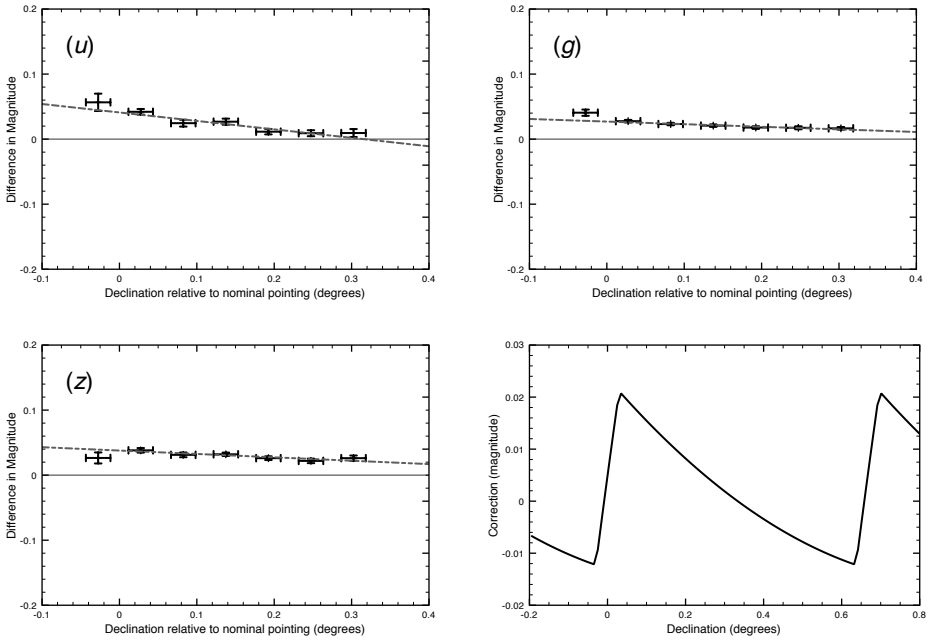

Figure 1. Comparison of secondary patch stars in overlapping frames. The results of the differences between left and right half of the CCD is shown for each of the five filters, and the response inferred as described in the text is shown at bottom right.

3. Comparison of the Coadd Catalog and SDSS DR8

There is more than one version of the Coadd catalog. This analysis uses version 2.4, the version that was used in the SDSS SN processing. The Coadd catalog consists of 681301 stars. The catalog contains 2767 duplicate entries (right ascension and declination within 10^{-6} degrees). The DR8 catalog consists of 3128672 stars. The number of objects common to the two catalogs is 650617.

The published (Ivezic et al. 2007) Coadd catalog is version 2.6. The use of the earlier, unpublished version of the catalog was inadvertent, and there are significant differences between the catalogs in the number of stars they contain and the photometry. One difference is that there is no correction for the differences in the filter response as measured by Doi (2010) for the different camera columns. This is probably an advantage because the DR8 catalog, which I use to cross-calibrate the Coadd catalog, also does not include these corrections.

The left-hand panel of Figure 2 shows the difference in the two catalogs as a function of right ascension for g and z bands. A clear trend is seen in the data that is approximately linear in right ascension, and the data are fit to straight lines whose parameters are shown in Table 1. Given the significant trend in the differences, the question arises as to which catalog is more nearly correct. The SDSS Ubercal procedure (Padmanabhan et al. 2008) assumes the extinction to be of the form $k(t) = k_0 + \frac{dk}{dt}t$ where k_0 and dk/dt are constants and t is the time of observation. The assumed mean values and dispersion of dk/dt are taken from Padmanabhan et al. (2008), converted into mmag/degree and shown in the last two columns of Table 1, assuming an airmass of 1.2, a typical airmass

for observation. The slopes of the differences between the Coadd and DR8 catalogs are similar to the values assumed by Ubercal, but not identical.

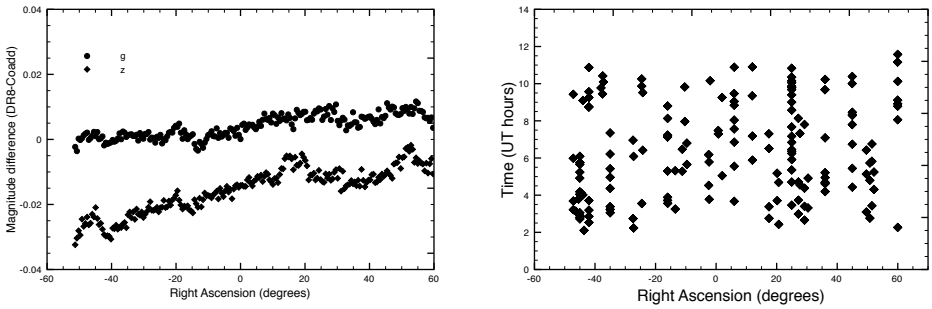

Figure 2. The difference in magnitude (DR8-Coadd) for the g and z filters is shown as a function of right ascension (left). The times of observation of the PT fields is shown as a function right ascension (right).

Table 1. Trend line fits to the average difference in the Coadd adn DR8 catalogs as a function of right ascension

Filter	slope (mmag/°)	offset (mmag)	χ^2	DR8 dk/dt (mmag/°)	DR8 $\sigma(dk/dt)$ (mmag/°)
u	0.142	3.1	2566	0.096	0.200
g	0.082	3.7	3777	0.056	0.136
r	0.075	-3.4	4113	0.080	0.136
i	0.087	-6.6	4665	0.096	0.120
z	0.199	-16.7	8109	0.176	0.136

The calibration (Tucker et al. 2010) that was used for SDSS data production does not include any time-dependent terms although occasionally different photometric solutions were used for different time intervals during the night. The PT calibration is imprinted on the SDSS 2.5m data through the secondary patches. Thus, we would expect a calibration error in the SDSS catalog data because of the time variation would depend on the time of the PT observations but not on the time of the 2.5m telescope observations. The secondary PT patches, however, were taken throughout the night at more-or-less random times as shown in right-hand panel of Figure 2, which shows the observing time versus RA for the 178 secondary patches that were used to process the SDSS 2.5 m data.

Given the number of patches and their distribution in time of observation, it seems unlikely that an error in the Coadd would be the source of the slopes shown in Table 1. We therefore choose to remove the linear trend by using the parameters shown in Table 1 to adjust the DR8 data to bring it into agreement with the Coadd. There are trends in the data shown in Figure 2 that are not well fit by the straight-line approximation. This is not too surprising, since we expect there to be at least some error in the calibration of the various secondary patches. We are primarily interested in the flat-fielding as a function of declination, and the correction in RA has little effect on the flat-fielding except that

the dispersion is reduced by removing the difference in slope. As a consequence, it didn't seem like trying to fit a more complicated function to the difference as a function of RA would be of any value.

The Coadd catalog, however, is expected to be in error in declination because of the errors in the PT flat-field. The entire length of equatorial stripe was used for the calibration of the Coadd by DR8 (after removing the slope in right ascension from DR8). The average difference in magnitude in bins of declination is shown in Figure 3 for *r* and *z* bands. The statistical uncertainties are smaller than the size of the symbols used to plot the data. A smooth curve was fit to the data and is superimposed on the graph. The pattern in *r* is similar to that in *z* but not identical. There is a hint of a pattern that repeats every 0.6 degrees as would be expected from a PT flat-fielding error, but the PT flat-fielding error is at best one factor in the differences.

In Figure 4, I split the same data into 4 different ranges in RA for the *u*, *g*, *r*, and *z* filters. The data is still binned but is represented by lines joining the points for a clearer presentation. There are similarities in the patterns among different filters, but there are also substantial differences between the bluer filters (*u* and *g*) and the redder ones (*r* and *z*). The differences in magnitudes are seen consistently in the 4 independent data sets, which suggests that there are residual flat-fielding errors in the catalogs. There is a variation, however, for some CCD's, notably for $0.0 < \delta < 0.2$ and $-0.2 < \delta < 0.0$. The source of the variation is unknown, but the DR8 catalog is based on a single observation. Since the Ubercal redetermines the zeropoint for each observation and the DR8 catalog is a composite of many different nights of observation, it is possible that the variations are driven by zeropoint errors on different nights.

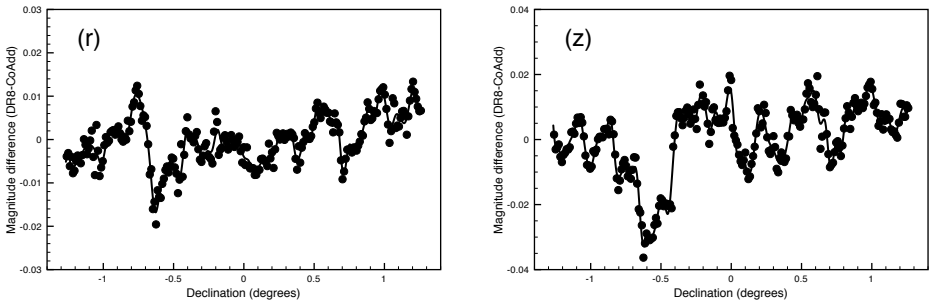

Figure 3. Comparison of average differences in magnitude between DR8 and the Coadd catalogs as a function of declination.

4. SDSS filters

Understanding the SDSS photometric system when measuring objects with diverse spectra (like supernovae) requires a precise measurement of the telescope response as a function of wavelength. The SDSS filters measured by Doi (2010) are shown in Figure 5. Figure 5 also shows the calculated response of the PT telescope based on filter measurements obtained from Doi and estimates of the telescope and camera throughput. While the PT filters were intended to be the same as the 2.5 m telescope, the bandpasses are different, as discussed in more detail in Doi (2010). These response curves are considered to be indicative of the actual PT response, but their accuracy is uncertain.

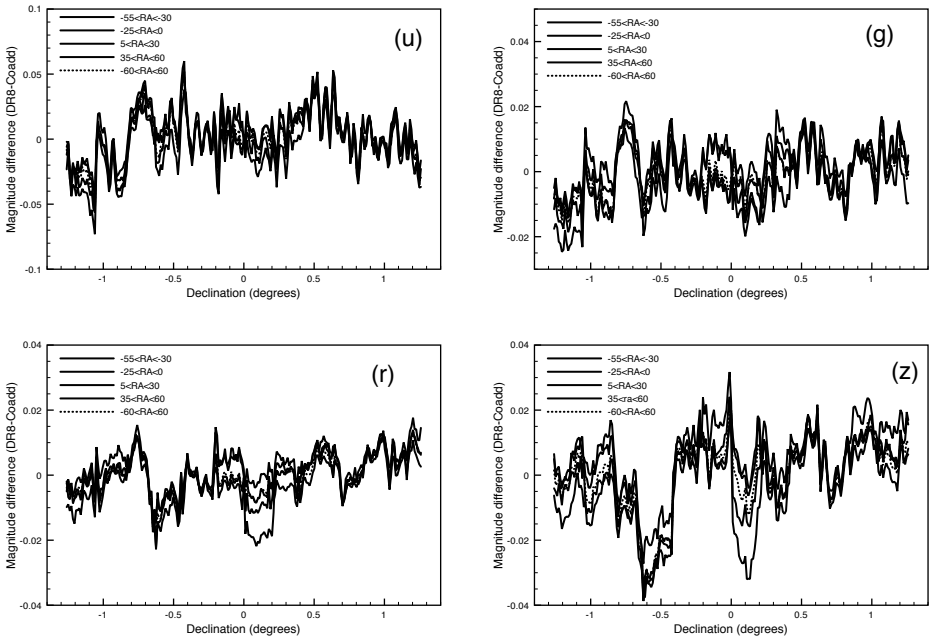

Figure 4. Comparison of average differences in magnitude between DR8 and Coadd catalogs as a function of declination for 4 separate ranges in right ascension.

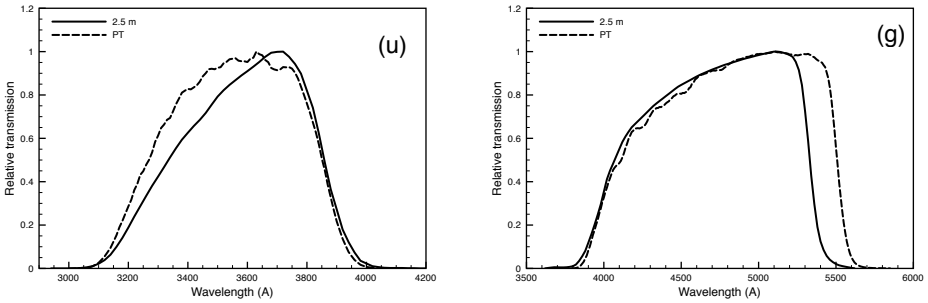

Figure 5. The measured SDSS filter responses for *u* and *g* bands are shown. The curves' normalization is arbitrary: all curves are chosen to have a peak response of 1. The 2.5 m telescope response is taken from Doi (2010) while the PT response curve is calculated using data from Doi.

We can test the consistency of the PT filter curves with the color transformations derived by matching stars between the 2.5 m telescope and the PT. Figure 6 shows the expected color magnitude relationship based on the filter curves shown in Figure 5 and a library of stellar spectra (Gunn & Stryker 1983). The line shows the empirically measured relationship; the offset of the line is arbitrary.

Curiously, the the color term for *u*-band is nearly zero, despite the differences shown in Figure 5. The synthetic magnitudes in *r* band do not agree well with the empirically measured color term, but there is at least qualitative agreement in all the filter bands. The SDSS filter shapes include a model of atmospheric extinction from

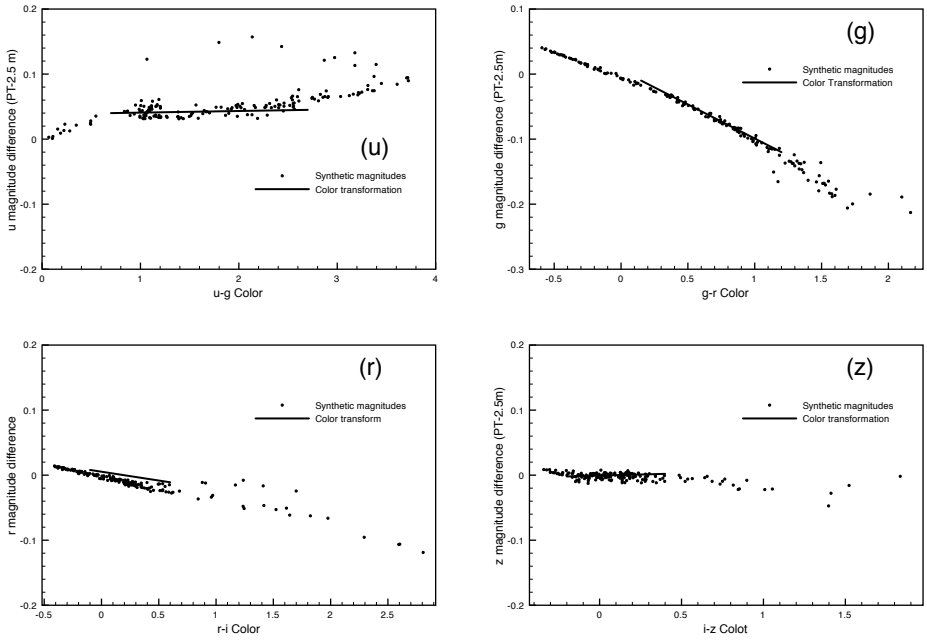

Figure 6. The expected magnitude difference between the PT and 2.5 m telescope based on the response functions (Figure 5) and stellar spectra is show versus color (points). The line shows the empirically measured color transformation.

1.2 airmasses. This convention reduces the need for second order extinction corrections (since observations are made in the range of 1 to 2 airmasses). However, an inaccurate atmospheric transmission model would result in inaccurate synthetic magnitudes.

The change in filter bandpasses with time is of significant interest, especially for the 2.5 m telescope *u*-band filter that was measured to change between the measurement in 2001 and the measurement in 2004. The data from the PT patches separate well into three groups: before 2001, 2001-2004, and after 2004. The color terms relating PT magnitudes to 2.5 m magnitudes for each era of observation relative to the standard terms are calculated and displayed in Table 2. Since the 2.5 m catalog is not similarly divided into time intervals, this test is only a measure of the stability of the PT filters. The calculated color terms are small and in most cases consistent with zero, meaning that there is no evidence for changes in the response of the PT filters over time. These results suggest that changes in response, if any, took place soon after installation.

5. Conclusions

The SDSS survey has set new standards for photometric accuracy in ground-based imaging surveys. However, there are several lessons that can be extracted to improve the photometric calibration of future surveys. Some lessons are:

- Star-flats (measuring the same stars at different positions on the focal plane) are an essential tool to get a uniform camera response.

Table 2. 2.5 m to PT Color Terms by Season

Filter	before 2001	2001-2004	after 2004
b terms			
u	0.0178 ± 0.0124	−0.0036 ± 0.0054	0.0052 ± 0.0072
g	0.0076 ± 0.0055	−0.0114 ± 0.0023	0.0067 ± 0.0033
r	−0.0068 ± 0.0090	−0.0003 ± 0.0035	−0.0015 ± 0.0049
i	−0.0212 ± 0.0096	−0.0142 ± 0.0038	−0.0177 ± 0.0054
z	−0.0465 ± 0.0206	−0.0391 ± 0.0088	0.0010 ± 0.0121
a terms			
u	−0.0005 ± 0.0029	−0.0034 ± 0.0014	−0.0008 ± 0.0019
g	−0.0053 ± 0.0010	−0.0019 ± 0.0004	−0.0015 ± 0.0006
r	−0.0035 ± 0.0008	−0.0017 ± 0.0004	−0.0028 ± 0.0005
i	−0.0078 ± 0.0010	0.0007 ± 0.0004	−0.0032 ± 0.0006
z	−0.0155 ± 0.0018	−0.0061 ± 0.0008	−0.0085 ± 0.0011

- Characterizing the change in atmospheric transmission over the course of a single night is important in obtaining 1% photometry.
- Frequent, accurate filter measurements are necessary for a fully-specified photometric system.
- Redundant calibration techniques and standards are the key to understanding systematic errors.

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