Photometric Cross-Calibration of the SDSS Stripe 82 Standard Stars catalogue with Gaia EDR3, and Comparison with Pan-STARRS1, DES, CFIS and GALEX catalogues

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1 INTRODUCTION

Modern multi-band photometric sky surveys aim to deliver measurements uniform at or better than the 1% (0.01 mag) level, to enable cosmological and other high-precision measurements (e.g., the Vera C. Rubin Observatory Legacy Survey of Space and Time, Ivezić et al. 2019). Photometric data are usually calibrated using sets of standard stars whose brightness is known from previous work. One of the largest catalogues with sub-percent measurement precision and optical multi-band $ugriz$ photometry was constructed by averaging multi-epoch data for about a million stars collected by the Sloan Digital Sky Survey (SDSS, York et al. 2000) in a 300 deg$^2$ region known as SDSS Stripe 82 (Ivezić et al. 2007, hereafter I007). The SDSS $ugriz$ photometric system is now in use at many observatories worldwide and the I007 catalog has been used both for calibration and testing of other surveys.

After completion of the I007 catalog, SDSS obtained additional imaging data, about 2-3 times more measurements per star depending on its sky position within Stripe 82. This increased number of data points results in averaged photometry with 1.4-1.7 times smaller random errors (precision) than in the original catalogue (and about three times as small as for individual SDSS runs). In addition, the availability of photometric data from recent wide-field surveys such as the Dark Energy Survey (DES, Dark Energy Survey Collaboration et al. 2016), Pan-STARRS (PS1, Kaiser et al. 2010) and Gaia (Gaia Collaboration et al. 2018), enables a much more detailed and robust cross-calibration, including correcting for residual photometric zeropoint errors in SDSS flat-fielding. For example, Betoule et al. (2013) reported a saw-tooth pattern in photometric residuals between the SDSS and the Supernova Legacy Survey (SNLS) catalogues, as a function of Declination (see their Fig. 23). Such a pattern is most likely due to errors in SDSS zeropoint calibration because of the flat-field correction of Stripe 82 being only a function of Declination (due to drift-scanning in R.A. direction). Given that systematic errors in other catalogues are much smaller (Gaia), or are expected to display different spatial patterns (DES and PS1), it is likely that a cross-comparison of several catalogues can result in significant improvements. These are the main reasons that motivated our decision to construct an updated version of the I007 catalog.

We describe datasets used in our analysis in §2, and the construc-
tion of the new catalogue and its analysis in §3. Our results are summarized and discussed in §4.

2 DATASETS

2.1 SDSS Stripe 82 Imaging Data

In the SDSS survey, Stripe 82 is a contiguous, 300 deg$^2$ equatorial region, which stretches between $-60^\circ \leq RA \leq 60^\circ$ [20h to 4h], and $-1.266^\circ \leq Dec \leq 1.266^\circ$. Following the initial, concerted effort by the SDSS collaboration between 2001 and 2008 to map this region repeatedly to a forecast imaging depth, $r \leq 22$, several other surveys in various wavebands have also targeted this same patch of sky to provide a rich multi-wavelength dataset suitable for a variety of investigations. SDSS observations have also continued in this region (e.g., the SDSS-II search for supernovae, Frieman et al. 2008), resulting in an imaging depth greater than what was initially planned.

Data from the SDSS imaging camera (Gunn et al. 1998) were collected in drift-scan mode. The images which correspond to the same sky location in each of the five photometric bandpasses (these five images are collected over ~5 minutes, with an exposure time of 54 seconds for each band) are grouped together for simultaneous processing as a field. A field is defined as a 36 second (1361 rows) stretch of drift-scanning data from a single column of CCDs (sometimes called a scan line; for more details, see I007 and references therein).

2.1.1 The 2007 SDSS Standard Star catalogue

The SDSS standard star catalogue, I007 (version 2.6) was constructed by averaging multiple SDSS photometric observations (at least four per band, with a median of 10) in the ugriz system. The catalogue includes 1.01 million non-variable stars. The measurements for individual sources have random photometric errors below 0.01 mag for stars brighter than 19.5, 20.5, 20.5, 20, and 18.5 in ugriz, respectively (about twice as good as for individual SDSS runs). Several independent tests of the internal consistency suggested that the spatial variation of photometric zero points is not larger than ~0.01 mag (RMS).

2.1.2 Post-2007 SDSS data

In this work, we used the SDSS Data Release 15 (DR15) as available in April 2019 (Blanton et al. 2017). In DR15, the Stripe 82 region is covered by 118 runs, which include 32,292 fields, each with observations in the five ugriz SDSS filters. Using our programmatic query tool, we obtained the processed data for all these runs from the DR15 public database. In the database, the data are presented as individual FITS tables, named photObj_<run>_<camcol>_<field>.fits. From each fits table, we extracted photometric and astrometric quantities, time of observation, and several ancillary data for all the objects into a formatted master file for further processing.

The objects in each of these data files were then matched with the standard stars in the I007 catalogue using their mean sky positions (R.A. and Declination) and a matching radius of 0.5 arcsec. For matching, only deblended objects ($nchild=0$), lying between rows $64 < objc_rowc \leq 1425$ in each field, were selected to avoid poor photometry due to blending or lying close to edges of the CCD. From these matched objects, only those with photometric error <0.1 mag were selected to compute photometric zeropoint offsets between the I007 catalogue and DR15. These offsets were obtained independently for all runs and fields, in all five filters, and applied to bring our DR15 based catalogue to the same photometric scale as the I007 catalogue – in essence, we have re-calibrated photometry for all Stripe 82 runs in DR15 using the I007 catalogue. In addition, the MJD and fractional MJD of observation were computed using the median of the TAI values (the GPS time reported by the SDSS Apache Point Observatory) for these matched objects. In the final step, the photometric, astrometric and other details for each of these matched standard stars were written to independent (one per star) light curve files. Further processing of these light curves is described in Section 3.1.

The final dataset, consisting of all the light curves in the five ugriz filters for the 1,006,849 standard stars in the I007 catalogue resulted in ~20 GB of tabular data. To make file search and access fast, the data were chunked into sub-directories, each spanning 1 deg in RA, and 0.1 deg in Dec (a “poor-man’s” two-dimensional tree structure). These light curve data files can be made available as a single tarball by emailing the contact author.

2.2 Gaia Early Data Release 3 Data

For our primary astrometric and photometric cross calibration we use the Gaia Early Data Release 3 (EDR3) catalogue. Gaia is a European Space Agency (ESA) mission designed to map over a billion stars in the Milky Way and the local group in three dimensions, providing accurate proper motion and radial velocity measurements. Gaia Collaboration et al. (2016) provide a detailed overview of the Gaia mission (spacecraft, instruments, survey and measurement principles, and operations), while technical details for specific topics relevant to our work may be found in the following citations: pre-processing and source-list creation (Fabricius et al. 2016), astrometric solution (Lindegren et al. 2018), processing the photometric data (Riello et al. 2018), photometric content and validation (Evans et al. 2018), and full catalogue validation (Arenou et al. 2018). A detailed description of Gaia data products may be found in Gaia Collaboration et al. (2018). Here we summarize only the pertinent details.

EDR3 includes astrometry, photometry, radial velocities, and information on astrophysical parameters and variability, for approximately 1.8 billion sources. This dataset is based on the first 34 months of the mission and includes celestial positions and the apparent brightness in the broad-band G ($G_{Gaia}$ hereafter) for sources brighter than $G_{Gaia}$~21. This data release also contains two additional broad-band magnitudes, the BP (330–680 nm) and RP (630–1050 nm). Gaia EDR3 photometry is generally superior to ground-based photometry for sources with sufficient signal-to-noise ratio, and we use it to derive zeropoint corrections for SDSS photometry, as described in Section 3.2.

2.3 Dark Energy Survey (DES) Data

The Dark Energy Survey (DES; Dark Energy Survey Collaboration et al. 2016) is an imaging survey of the Southern Galactic Cap in 5 filter passbands (grizYDES) that was conducted from 2013 to 2019.
with the 570 mega-pixel Dark Energy Camera (DECam; Honscheid & DePoy 2008; Flaugher et al. 2015) on the Victor M. Blanco 4-m telescope at the Cerro Tololo Interamerican Observatory.

For this paper, we made use of the DES Data Release 1 (DES DR1: Morganson et al. 2018, Abbott et al. 2018) public data set, which is based on the first 3 years of DES observations. The DES DR1 object catalogue consists of ~400 million objects to a depth of 24.33, 24.08, 23.44, 22.69, 21.44 mag in grizYDE5 bands (S/N = 10σ). The DES DR1’s photometric calibration is uniform at the sub-percent level (RMS) for each of the five filter passbands over the entirety of the survey footprint. Its astrometric precision is quoted to be 151 milli-arcsec (RMS). We downloaded DES DR1 data via the NOAO Data Lab Table Access Protocol (TAP) service, selecting stars in the general area of the SDSS Stripe 82 region of the DES footprint. For the purposes of our analysis, we downloaded from the co-added catalogue, the weighted mean PSF magnitude (WAVG_MAG_PSF) and magnitude error (WAVG_MAGERR_PSF) as well as the number of observations that went into the weighted catalogue-coad weighted mean PSF magnitude (N_EPOCHS) in each filter band for each downloaded DES star. In total, 3,585,229 stars were downloaded in the region (RA > 270° or < 105°; DEC = −3.5° to +3.5°), of which 619,741 were matched to our SDSS catalogue using a match radius of 0.5 arcsec.

2.4 Pan-STARRS (PS1) Data

The Panoramic Survey Telescope And Rapid Response System, Telescope 1 (Pan-STARRS-1, or PS1), commissioned in 2010, is the first of four planned 1.8m telescopes, designed to map three quarters of the entire sky visible from Hawaii (Kaiser et al. 2010). This panchromatic, synoptic survey, called the 3σ Steradian Survey was carried out in five bands, grizYp1, with limiting magnitudes of 23.3, 23.2, 23.1, 22.3, and 21.4 mag. Chambers et al. (2016) provide full details about the PS1 observatory, the surveys being carried out, and the database and data products (Flewelling et al. 2020).

Here we used the 2019 data release PS1-DR2 from MAST. The catalogue overlapping the Stripe 82 region contains over 7 million point sources taken from the stacked 3σ Steradian Survey. From the large set of measured and derived quantities available for these objects, we downloaded grizYp1 PSF photometry and various quality flags. For this region, the mean positional uncertainties are 12 and 11 milli-arcsec in the RA and Dec directions. Based on this positional precision and that of our SDSS standard stars catalogue, we compared both catalogues using a matching radius of 0.5 arcsec. The resulting matched catalogue used in our analysis presented in §3.4 contains 909,000 objects. Taking the r band as being representative, the mean number of visits used to obtain the mean PSF magnitudes for these matched stars is 14 visits.

2.5 Canada-France Imaging Survey (CFIS) Data

The Canada-France Imaging Survey (CFIS) (Ibata et al. 2017) is a large observing program being carried out at the Canada-France-Hawaii Telescope (CFHT) to map the northern sky in the MegaCam u and r bands. With a broad range of science goals, including providing ground-based optical photometry to complement the Euclid space mission, CFIS aims to cover 10,000 deg² in the u band to a depth of 24.4 mag. For our analysis, we were provided the u band data which overlaps the Stripe 82 footprint from the CFIS Data Release 2 (DR2, January 2020). In this region, CFIS data are available only for Declination > +0.45 degree, thus covering only about a quarter of the Stripe 82 survey footprint.

The available CFIS DR2-Stripe 82 catalogue contains close to 965,000 sources, of which ~315,000 matched within a link radius of 0.5 arcsec with stars in our SDSS standard stars catalogue. The astrometry over the complete CFIS survey region has been calibrated against Gaia DR2. The residuals of the astrometric solution are typically 10 mas. From the matched objects, we select only bright stars, r ≤ 20 mag, with colours 1 ≤ (u − g)SDSS ≤ 2.1, following Ibata et al. (2017). This colour-magnitude cut yields 150,114 stars, which are used in the comparison described in §3.5.

2.6 GALEX Data

The Galaxy Evolution Explorer (GALEX) all-sky survey catalogue in the NUV (1771-2831 Å) and FUV (1344-1786 Å) bands provides a unique photometric dataset to crosscheck the u-band of a multiband survey such as the SDSS. Processed and calibrated archival data from the eight year, All-sky Imaging (AIS) and Medium depth Imaging (MIS) surveys are available at MAST. Due to the failure of the FUV detector midway through the survey, the available imaging depth in this band is shallower by nearly 1 ABmag than the NUV depth of 20.8 ABmag in the AIS. Overall, the source number count in the FUV is, on average, only a tenth of that in the NUV. Given these limitations in the FUV survey, we extracted only sources in the NUV catalogue corresponding to the Stripe 82 footprint.

Bianchi et al. (2017) provide full details of the GALEX survey, and we summarize only the NUV details, which are pertinent to our analysis here. The coverage over the survey region led to total exposure times of ~150s in the AIS, and ~1500s in the MIS. The corresponding NUV survey depths are 20.8 and 22.7 ABmag in the two surveys respectively. Objects in the Stripe 82 region were extracted and matched with our SDSS DR15 catalogue, described in §2.1.2 using a matching aperture radius of 3″, which corresponds to the matching radius used internally by GALEX to match their NUV and FUV sources. The GALEX catalogues do not list the RA, Dec positional errors for their sources, and we found their listed sky positions generally carry a greater uncertainty than the other catalogues used in this work.

Our matched GALEX catalogue consists of 150,945 NUV sources in the Stripe 82 footprint for which we obtained aperture magnitudes and uncertainties, as well as various fitted geometric measures for each of them. The astrometry has greater uncertainty than that of SDSS, with mean positional uncertainties of 1″ RMS. We also note that there is an overall mean shift in GALEX astrometry relative to that of the SDSS by ~0.1 arcsec in RA, and ~0.3 arcsec in Dec; our GALEX-SDSS positional offset results are comparable to what others have reported in the past (Aguerros et al. 2005; Morrissey et al.)
After accounting for proper motions, the positions agree at the level published in the Gaia EDR3 catalogue (see the left panel in Figure 2). Between the SDSS-Gaia positional differences and proper motions need to be accounted for; indeed, we find a very strong correlation. Astrometric epochs are sufficiently different that stellar proper motions are accurate to better than 0.1 arcsec per coordinate (RMS). Naively, one would positionally match the SDSS and Gaia EDR3 catalogue, as shown in this work. The variation of photometric zeropoints with position on the sky in the I007 catalog (see their eq. 4) was constrained using a combination of stellar colours (the principal axes in colour-colour diagrams, for details see Ivezic et al. 2004) and a standard star network (Smith et al. 2002; Tucker et al. 2006). It is likely that residual errors in zeropoint calibration (e.g., a saw-tooth pattern as a function of Declination, which was reported by Betoule et al. 2013; see their Fig. 23) could be further minimized using uniformly calibrated space-based zeropoint calibration (e.g., a saw-tooth pattern as a function of Dec). Similarly, use Gaia’s BP-RP colour to derive zeropoint corrections for the ugri bands, relative to the r band. Given a large number of matched stars (~ 400,000), and a large number of colour combinations, we do not attempt to derive analytic fits for synthetic magnitudes and colours but instead use narrow colour bins of 0.05 mag, and linearly interpolate between the bins. We have verified that even sixth-order polynomial fits do not provide better results than this simple numerical approach. For example, we had to use two piece-wise polynomial fits to be able to fit the \( G_{Gaia} - r \) vs. \( g - i \) relation with residuals smaller than 0.01 mag separately for 0.0 < \( g - i \) < 2.0 and 2.0 < \( g - i \) < 3.4 (\( g - i \approx 2.0 \) approximately corresponds to M0 MK spectral type. These fit residuals are dominated by systematic errors, mainly the inability of even the sixth order polynomial to follow all the variations at the millimag level).

### 3.3.2 Gaia-based photometric zeropoint corrections

Gaia EDR3 reported \( G_{Gaia} \) magnitudes, which approximately span the SDSS griz bandpasses, and BP and RP magnitudes, which approximately correspond to the blue and red halves of the \( G_{Gaia} \) bandpass. We first use \( G_{Gaia} \) data to derive “grey” zeropoint corrections (applied to all five SDSS bands), and then use the BP-RP colour to derive zeropoint corrections for the ugri bands, relative to the r band.

The best fit polynomial coefficients for both colour ranges are listed in Table 1 and the fit is shown by the green solid line in Figure 3. The variation of G magnitude residuals, \( \Delta G \), with \( G_{Gaia} \) (see Figure 4) shows an overall gradient of ~ 10 millimag from bright (G=16) to faint (G=20) end. A comparison of the SDSS catalogue with Pan-STARRS and DES catalogues (see Section 3.4 and Figures 14 and 16) strongly suggests that the origin of this discrepancy is a magnitude-dependent bias in Gaia’s \( G_{Gaia} \) photometry, rather than a problem with the SDSS catalogue (offsets between the SDSS and DES photometry, are < 2 millimag at \( G_{Gaia} \approx 20 \), and < 5 millimag when compared to Pan-STARRS).

Given these two features, we limit the calibration sample to the 16 < \( G_{Gaia} \) < 19.5 magnitude range. We further restrict calibration

\[
G_{Gaia} - r = \sum_{k=0}^{k=6} a_k (g - i)^k, \tag{1}
\]

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Given these two features, we limit the calibration sample to the 16 < \( G_{Gaia} \) < 19.5 magnitude range. We further restrict calibration

\[
\sigma_G = 0.741 \times (q_{25} - q_{75}), \text{ where } q_{25} \text{ and } q_{75} \text{ are the 25% and 75% quantiles, and the normalization factor } 0.741 \text{ assures that } \sigma_G \text{ is equal to the standard deviation for a normal (Gaussian) distribution.}
\]
Figure 1. (Left) A comparison of the number of observational epochs for matched stars in the new standard star catalogue (SSC) v4.2 versus the I007 catalog. (Right) A comparison of the median formal $r$ band photometric uncertainties of matched objects in the v4.2 versus I007 catalog, as a function of their mean $r$ magnitudes.

Figure 2. (Left) The R.A. difference between SDSS and Gaia vs. R.A. proper motion reported by Gaia EDR3. The solid line shows the median difference in bins of proper motion and the dashed lines mark the $\pm \sigma_G$ envelope around the medians, where $\sigma_G$ is the robust standard deviation. The density of the distribution (in dex) is indicated by the colour bar, and the overplotted contours represent 1, 2 and 3 dex. (Right) The R.A. difference after correcting using the best-fit R.A. difference vs. proper motion curve, as a function of the SDSS $r$ magnitude. Overplotted contours represent 1, 2 and 3 dex. The residual differences are dominated by systematic errors in SDSS astrometry at the level of $\sim$28 milliarcsec (note that there is no increase with magnitude). In an analogous plot for Declination, the residuals are similar.

Table 1. The best-fit coefficients for eq. 1.

| Colour range   | $a_0$   | $a_1$   | $a_2$   | $a_3$   | $a_4$   | $a_5$   | $a_6$   |
|----------------|---------|---------|---------|---------|---------|---------|---------|
| $0.0 < g - i < 2.0$ | -0.0307 | -0.0885 | 0.6632  | -1.0179 | 0.7262  | -0.2547 | 0.0337  |
| $2.0 < g - i < 3.4$ | 9.6488  | -8.4115 | -7.9834 | 13.757  | -7.0973 | 1.5993  | -0.1351 |

stars to the $0.4 < (g - i)_{SDSS} < 3.0$ colour range (approximately A0 to M5 spectral range), yielding a sample of $\sim 372,000$ stars (see Figure 5 for the $G_{Gaia}$ vs. $(g - i)$ colour-magnitude diagram). The behaviour of the median G magnitude residuals per R.A. and Declination bin are shown in the left and right panels respectively of Figure 6.

Except for a few degrees long region at the edge of Stripe 82 (R.A.$>$55 deg), the SDSS photometric zeropoints are remarkably stable with respect to R.A.; the scatter is only 3.5 millimag. On the other hand, there are clear deviations in the Declination direction, which clearly map to the 12 scanning strips that fill Stripe 82. We note that discrepancies never exceed 0.01 mag (with a scatter of 6.2 millimag), which was the reported accuracy of the I007 catalog. Thanks to a large number of stars in the sample, and well calibrated Gaia’s photometric zeropoints across the sky, we can now constrain SDSS zeropoints with a precision of about 1 millimag per 0.01 degree wide Declination bin.

The residuals shown in the left and right panels of Figures 6 are applied as “grey” zeropoint corrections to $ugriz$ magnitudes, as functions of R.A. and Declination, to all 991,472 stars in the catalogue.

In the next re-calibration step, we derive synthetic $u - r$, $g - r$, $r - i$
and \(r - z\) colours from Gaia’s BP-RP colour, using the same binning procedure as we used above for the \(G_{Gaia} - r\) vs. \(g - i\) variation (see Figure 7). An example of colour residuals is shown in Figure 8. The median residuals per R.A. and Declination bins are then used as zeropoint corrections for the \(ugiz\) bands. We required that the median offsets for all stars are vanishing and thus photometry in the new catalogue is on the same AB scale as the old catalogue (for related discussion, see Section 3.7). The robust standard deviation for all zeropoint corrections is listed in Table 2.

The largest corrections were derived for the \(u\) band. Given that Gaia’s BP-RP colour does not strongly constrain the \(u\) band flux, we used the CFIS catalogue (see Section 2.5) as an independent cross check. We verified that zeropoint errors in the SDSS catalogue implied by Gaia and CFIS data agree at the level a few millimags in Declination direction, but found larger inconsistencies of \(\sim 0.01-0.02\) mag for R.A. bins. For this reason, we only applied the \(u\) band correction as a function of Declination was validated with the CFIS data (see Section 3.5).

### 3.2.3 Validation of recalibration

By construction, the new v4.2 catalogue should not show appreciable zeropoint residuals when binned by R.A. and Declination. We have verified this expectation for all colours used in the recalibration. For illustration, Figure 9 shows such a test for the \(g - r\) colour, with binned median scatter of the order 1 millimag.

### 3.3 Comparison of the SDSS I007 catalog and the v4.2 catalogue

The v2.6 (“old”) SDSS Standard Star I007 catalog has been extensively used (e.g., Frieman et al. 2008), and here we briefly analyze differences between the v4.2 (“new”) and v2.6 magnitudes to inform future users about the consistency of the catalogues. In our analysis,
**Figure 6.** (Left) The R.A. variation of the residuals between Gaia’s G magnitude from EDR3, \(G_{Gaia}\), and synthetic G magnitude values, \(G_{SDSS}\), generated using SDSS \(gri\) photometry. The colour map illustrates the distribution of ~372,000 matched stars within \(16 < G_{Gaia} < 19.5\) and \(0.4 < g - i < 3.0\). The two solid lines represent the median values ± uncertainty of the median for 1 degree wide R.A. bins. The short-dashed lines show the median values ± the robust standard deviation for each bin. The horizontal solid and long-dashed lines at zero and ±0.01 mag, respectively, are added to guide the eye. The mean of the two solid lines is the grey correction, as a function of R.A., applied to the SDSS \(u gri\) magnitudes. The standard deviation for the applied correction is 3.2 millimag. **Note:** The stripe of missing data seen at R.A. ~ -37 deg is due to the presence of the globular cluster, M2. The resulting high stellar density region was masked off during data processing. (Right) Analogous to the left panel, except that here results are shown for 0.01 degree wide Declination bins. The 12 clearly visible regions correspond to two SDSS scans (in R.A. direction) and six CCD columns in the SDSS camera. The standard deviation for the applied correction is 6.5 millimag, with a maximum absolute value of ~0.01 mag.

**Figure 7.** Analogous to Figure 3, except that the correlations between SDSS colours and Gaia’s BP-RP colour are shown.
we first compare the magnitudes of individual stars in the v2.6 and v4.2 catalogues, and bin the differences by R.A., Declination and magnitude.

On average, both catalogue versions are on the same magnitude scale (the median $ugriz$ magnitude differences for all stars are zero by construction). There are no systematic offsets when binned by magnitude, as illustrated in Figure 10. The most obvious differences appear when magnitude differences are binned by Declination. An example is shown in Figure 11, where the periodicity of residuals corresponds to the size of the field-of-view of the SDSS Photometric Telescope (Tucker et al. 2006). The standard deviation for median values per bin is 6.8 millimag, with extreme values of about 0.01 mag. It is likely that systematic errors in the photometry of the calibration star network were propagated through “flat-field corrections” discussed by I007 to the v2.6 catalogue. We note that these errors, now found thanks to the Gaia catalogue, are well within the claimed photometric accuracy by both I007 and Smith et al. (2002). The standard deviation for the median values per bin for the five bands and both coordinates is listed in Table 3.

Given the quality of the Gaia photometry, there should be no doubt that SDSS $ugriz$ photometry reported in the new v4.2 catalogue is superior to the old v2.6 catalogue. Nevertheless, we perform additional tests, based on the position of the stellar locus in the $g - r$ vs. $u - g$, $r - i$ vs. $g - r$ and $i - z$ vs. $r - i$ colour-colour diagrams (Ivezić et al. 2004). The tests are based on the second principal colour for the blue part of the stellar locus, whose median should not deviate from zero by construction. Figure 12 compares the behaviour of the $w$

![Figure 8](image.png)

Figure 8. Analogous to Figure 6 (Right), except that here residuals correspond to differences between the SDSS $r - i$ colour and a synthetic $r - i$ colour generated using Gaia’s $BP - RP$ colour. Note the signature of SDSS camera columns at the level of a few millimagms. The standard deviation for the binned medians is 3.2 millimag (for other bands, please see Table 2).

Table 3. The robust standard deviation for magnitude differences between the v2.6 (old) and v4.2 (new) catalogues (in millimag).

| Band | RMS for R.A. | RMS for Dec |
|------|--------------|-------------|
| $u$  | 2.0$^{+4}$   | 25.5        |
| $g$  | 4.0          | 9.7         |
| $r$  | 1.7          | 7.1         |
| $i$  | 4.1          | 6.5         |
| $z$  | 7.5          | 8.4         |

Notes: (a) For the $u$ band, the scatter in the R.A. direction is due to more observations in v4.2 than in v2.6, rather than the zeropoint correction.

we first compare the magnitudes of individual stars in the v2.6 and v4.2 catalogues, and bin the differences by R.A., Declination and magnitude.

On average, both catalogue versions are on the same magnitude scale (the median $ugriz$ magnitude differences for all stars are zero by construction). There are no systematic offsets when binned by magnitude, as illustrated in Figure 10. The most obvious differences appear when magnitude differences are binned by Declination. An example is shown in Figure 11, where the periodicity of residuals corresponds to the size of the field-of-view of the SDSS Photometric Telescope (Tucker et al. 2006). The standard deviation for median values per bin is 6.8 millimag, with extreme values of about 0.01 mag. It is likely that systematic errors in the photometry of the calibration star network were propagated through “flat-field corrections” discussed by I007 to the v2.6 catalogue. We note that these errors, now found thanks to the Gaia catalogue, are well within the claimed photometric accuracy by both I007 and Smith et al. (2002). The standard deviation for the median values per bin for the five bands and both coordinates is listed in Table 3.

Given the quality of the Gaia photometry, there should be no doubt that SDSS $ugriz$ photometry reported in the new v4.2 catalogue is superior to the old v2.6 catalogue. Nevertheless, we perform additional tests, based on the position of the stellar locus in the $g - r$ vs. $u - g$, $r - i$ vs. $g - r$ and $i - z$ vs. $r - i$ colour-colour diagrams (Ivezić et al. 2004). The tests are based on the second principal colour for the blue part of the stellar locus, whose median should not deviate from zero by construction. Figure 12 compares the behaviour of the $w$

![Table 4](image.png)

Table 4. The robust standard deviation for the binned median magnitude differences between the new v4.2 SDSS catalogue, and DES and Pan-STARRS1 catalogues (in millimag).

| Band | DES R.A. | DES Dec. | PS1 R.A. | PS1 Dec. |
|------|----------|----------|----------|----------|
| $g$  | 4.8      | 2.0      | 3.3      | 1.6      |
| $r$  | 3.3      | 0.9      | 2.1      | 0.9      |
| $i$  | 5.9      | 1.4      | 2.2      | 1.0      |
| $z$  | 12.1     | 3.6      | 5.1      | 2.3      |

3.4 Comparison of the new v4.2 SDSS catalogue with DES and Pan-STARRS catalogues

The quality of photometric zeropoint calibration for the new SDSS catalogue can be conveniently tested with the DES (see Section 2.3) and Pan-STARRS (see Section 2.4) catalogues. Both catalogues list $griz$ photometry of sufficient precision for essentially all stars from Stripe 82. Their photometric calibration procedures are expected to result in different spatial patterns and thus a cross-comparison with the v4.2 catalogue may reveal any residual problems with the zeropoint calibration. They are also deeper than the Gaia EDR3 catalogue and can thus provide further clues about the ~0.01 mag residual $Gmag$ gradient (bright-to-faint end bias) illustrated in Figure 4.

Our comparison of the magnitude differences binned in the R.A. and Declination directions are illustrated in Figures 14 and 15 respectively, and the corresponding robust standard deviations for binned median magnitude differences are listed in Table 4. This multi-survey comparison indicates that the spatial variation of photometric zero points in the updated SDSS catalogue is well below 0.01 mag (RMS), with typical values of 3–7 millimag in the R.A. direction and 1–2 millimag in the Declination direction (excluding the $z$-band where these values are higher). Note the implied DES $z$ band zeropoint errors as a function of R.A. of up to 0.02 mag (see the bottom left panel in Figure 14), although a similar trend in the corresponding Pan-STARRS plot (bottom right panel in Figure 14) indicates that the SDSS catalogue, calibrated using Gaia EDR3, may be at least partially responsible for the observed differences.

The variation of the residual magnitude differences with magnitude (see Figure 16 for DES results) is typically flat to within ~3.4 millimag for both DES and Pan-STARRS. This much smaller gradient than the one observed for Gaia (~20 millimag) implies a likely problem (a bias between bright and faint ends) with the Gaia EDR3 photometry. The largest discrepancy of about 2 millimag/mag is observed for the Pan-STARRS $r$ band, while the gradient is limited to <1 millimag when compared to the DES $r$ band.

For a comparison of DES DR1 and Gaia DR2 calibrations, see e.g., Fig. 9 of Abbott et al. (2018).
Figure 9. (Left) Analogous to Figure 6, except that here residuals between the SDSS $g - r$ colour from the v4.2 catalogue and a synthetic $g - r$ colour generated using Gaia’s $BP - RP$ colour are shown. The binned median scatter is 1.6 millimag. (Right) The SDSS $g - r$ residuals are shown as a function of Declination. The binned median scatter is 0.8 millimag.

Figure 10. The differences between $r$ band magnitudes listed in the v2.6 and v4.2 SDSS Standard Star catalogues, shown as a function of the $r$ band magnitude. The scatter of median values per bin is 1.7 millimag. The scatter of individual values is ~0.01 mag for $r < 20$, and is due to more data in the new catalogue.

3.5 Comparison of the new v4.2 SDSS catalogue and $u$ band data from the CFIS catalogue

The comparison of the new SDSS catalogue with the DES and Pan-STARRS catalogues in the previous section did not include the $u$ band. To assess the quality of $u$ band zeropoint calibration, we use the CFIS catalogue (see Section 2.5). The CFIS $u$ band photometry was calibrated using a combination of the SDSS, Pan-STARRS and GALEX UV data. Even given that we recalibrated the new SDSS catalogue using Gaia data, it should not matter for this comparison that SDSS data were used in the calibration of the CFIS catalogue. Nevertheless, this should be kept in mind while interpreting the results presented in this section. We also note that the transmission curve of the MegaCam $u$ band filter used for the CFIS survey differs from that of the SDSS $u$ band filter. However, this does not lead to any noticeable differences in the magnitude comparisons between the two catalogues presented here.

A comparison for about 150,000 sufficiently bright stars, $r < 20$, with colours matching the main sequence, $1.0 < u - g < 2.1$, is illustrated in Figure 17. The binned median scatter for the Declination direction is 5.7 millimag with systematic differences of up to 0.01 mag. The constraints in the R.A. direction are noisier, with residuals appearing about twice as large as in the Declination direction. These residuals compare favourably to the results of the analysis by Ibata et al. (2017), who showed that some SDSS runs in Data Release 13 have $u$-band zeropoint errors as large as 0.1 mag.

3.6 Comparison of the new v4.2 SDSS catalogue and transformed NUV data from the GALEX catalogue

We also use the NUV magnitudes from GALEX (see Section 2.6) to provide an independent check on the SDSS $u$-band magnitudes, following the zeropoint corrections with Gaia photometry described
in §3.2. For this we derive the following GALEX to SDSS u transformation equation:

$$
\begin{align*}
    u_{\text{ext}} &= NUV - 0.990 \times (NUV - g) + 0.014 \times (NUV - g)^2 \\
    & \quad - 0.407 \times (g - i) + 0.797 \times (g - i)^2 + 0.835 \\
    & \quad + T \times [-1.346 \times (E(B-V) - 0.15) \\
    & \quad + 3.400 \times (E(B-V) - 0.15)^2]
\end{align*}
$$

where $NUV$ refers to GALEX, and $g$ and $i$ are SDSS magnitudes. $T$ is a step function in the value of the interstellar reddening, $E(B-V)$, from the Schlegel et al. (1998) reddening map:

$$
T = \begin{cases} 
0 & E(B-V) \leq 0.15 \\
1 & 0.15 < E(B-V) < 0.3 
\end{cases}
$$

This transformation relation, which is suitable for stars with $0.5 < (u-g)_{SDSS} < 2.0$, $0.2 < (g-r)_{SDSS} < 0.8$, $0.3 < (g-i)_{SDSS} < 1.0$, and $E(B-V) < 0.3$, has a per star RMS of $\sigma = 0.061$ mag (the relatively high RMS is due in part to the relatively high RMS in the GALEX $NUV$ magnitudes). This relation converts the GALEX $NUV$ magnitudes into very reasonable approximations of the SDSS $u$-band. To refine these approximations, we then applied the same sort of numerical transformation that was used for the SDSS to Gaia transformation in Figure 3; this improved the overall per star RMS to $\sigma = 0.055$, with most of the improvement occurring for the bluest, $(u-g)_{SDSS} \lesssim 1.0$, and the reddest, $(u-g)_{SDSS} \gtrsim 1.0$ stars in our sample.

Despite the relatively noisy results, we can make several conclusions based upon the binned data consisting of 89,722 matches between the v4.2 SDSS catalogue and the GALEX catalogue. First, in Figure 18, we show the difference between the SDSS-measured and GALEX-predicted $u_{SDSS}$ vs. SDSS $u_{SDSS}$ for the 80,053 matches that lie within the colour and $E(B-V)$ cuts used for the initial transformation equation (Eq. 1). Although the relation, even when binned like here, is noisy, there is clearly a noticeable trend in the residuals vs. SDSS $u$. As with the comparison with Gaia (Fig 4), we expect that this magnitude dependence is associated with the GALEX photometry rather than with SDSS. Second, in Figure 19 (Left), we plot this magnitude difference vs. RA along SDSS Stripe 82. Here, in addition to the cuts used for Figure 18, we also apply a cut of $u_{SDSS} \leq 20.0$, to avoid the worst deviations seen in that figure; this results in a sample of 69,783 matches. We do note some small but significant large-scale trends with RA, at the 9.5 millimag level (RMS). Third and finally, in Figure 19 (Right), we plot this magnitude difference vs. DEC across SDSS Stripe82 using the same sample of 69,783 matches used for Figure 19 (Left). Unlike for the CFIS comparison in the previous section (see, e.g., Fig. 17), the GALEX comparison covers the full DEC range of Stripe 82. Overall, aside of a possible slight gradient, there appear to be no strong large-scale trends. The hints of smaller scale, $\sim 0.4^\circ$ variations – roughly on the scale of a SDSS camera column – seen in the CFIS comparison (Fig. 17), however, are not seen here, perhaps due to the relative “noisiness” of the GALEX comparison.
3.7 Offsets from AB magnitude scale

We estimate offsets from the AB magnitude scale using synthetic photometry derived from the spectra of three DA white dwarfs observed by HST (see Table 5): GD50 (specifically, the calibrated spectrum file gd50_004.fits) from the HST CalSpec database of spectrophotometric standard stars (Bohlin et al. 2014)\(^{10}\), and SDSSJ 232941.32+001107.8 and SDSSJ 010322.19-002047.7 from Narayan et al. (2019) (the flux-calibrated modeled spectrum files were provided by G. Narayan, private communication). These three spectrophotometric calibrators are particularly useful for our purposes since they are faint enough not to be saturated in the SDSS photometry (r ≈ 14) and they lie within the SDSS Stripe 82 footprint, making direct comparison to the SDSS measurements relatively simple. Synthetic AB magnitudes for these three DA white dwarfs were derived via numerical integration of Equation 8 of Fukugita et al. (1996), which serves to define broad-band AB magnitudes. This equation requires not only a well-calibrated spectrum, but also the well-calibrated bandpass response curves for the photometric system in question. Here, we make use of the SDSS bandpass response curves from Table 4 of Doi et al. (2010). Our results for the synthetic SDSS AB magnitudes for these three stars can be found in Table 5. The errors on these synthetic AB magnitudes are expected to be ~5–10 millimag (statistical) and ~10 millimag (systematic) (e.g., Bohlin et al. 2014).

Table 6 presents the numerical summary of the comparison between SDSS magnitudes and HST-based synthetic magnitudes for the three white dwarfs. We used unweighted mean because formal uncertainties for SDSS photometry are subdominant to systematic errors in the HST-based synthetic magnitudes, estimated to be ~0.01 mag. Uncertainties of the mean offsets were computed from the observed scatter of the three values. In the riz bands we detect significant (~3σ) deviations, ranging from 0.012 mag to 0.033 mag, while in the u and g bands we can only place upper limits (at 2σ: 0.038 mag and 0.028 mag, respectively).

4 DISCUSSION AND CONCLUSIONS

To enable further progress in cosmological and other high-precision photometric measurements, modern multi-band photometric sky surveys aim to deliver measurements internally consistent to at least the 1% (0.01 mag) level. Over the last decade a number of such large-scale surveys approached, and often surpassed this photometric accuracy requirement. For ground-based surveys, which are affected by variable atmospheric effects and hardware responses to changes in local environment (e.g. temperature), significant improvements are achieved by averaging multiple observations.

In this paper, we have described the construction, calibration and...
Figure 14. A comparison of the magnitude differences between the SDSS v4.2 catalogue and DES (left) and Pan-STARRS (right) catalogues, for the $riz$ bands binned by R.A.

Table 5. Synthetic SDSS magnitudes for three WD dwarfs with HST photometry.

| Name           | R.A.           | Dec.     | u       | g   | r    | i    | z       |
|----------------|----------------|----------|---------|-----|------|------|---------|
| GD50           | 57.2091083     |          |         | 13.409 | 13.784 | 14.295 | 14.655 |
| SDSSJ 232941.32+001107.8 | 352.42231875 | 0.185500 | 18.154 | 18.145 | 18.566 | 19.042 |
| SDSSJ 010322.19-002047.7 | 15.8424625     | -0.346592 | 18.627 | 19.057 | 19.558 | 19.923 | 20.258 |

Notes: (a) Sourced from Bohlin et al. (2014) and Narayan et al. (2019).
(b) The CalSpec spectrum stopped at about 9000 Å and thus did not cover all of SDSS z band.

MNRAS 000, 1–17 (2021)
Figure 15. Analogous to Figure 14, except that the magnitude differences are binned by Declination.

Table 6. AB offsets implied by three WD dwarfs with HST synthetic photometry\(^{41}\).

|        | \(\Delta u\) | \(\Delta g\) | \(\Delta r\) | \(\Delta i\) | \(\Delta z\) |
|--------|----------------|----------------|----------------|----------------|----------------|
| mean   | -              | -              | 0.015          | 0.016          | 0.035          |
| \(\sigma_{\text{mean}}\) | 0.019          | 0.014          | 0.004          | 0.004          | 0.011          |

Notes: (a) Offsets are defined as additive corrections to SDSS photometry to place it on AB scale (in mag). Listed values are unweighted mean and its uncertainty.
Figure 16. A comparison of the magnitude differences between the SDSS v4.2 catalogue and the DES catalogue, for the $r$ and $i$ bands. Note the very small gradient of the median residuals between the bright and faint ends: about 3-4 millimag and thus much smaller than ~20 millimag when compared to the Gaia G magnitude (see Figure 4).

Figure 17. Analogous to Figure 6 (Right), except that here residuals between the SDSS $u$ band magnitudes and $u$ band magnitudes from the CFIS catalogue (corrected for small colour terms, ~ 0.05 mag, as a function of the $u-g$ colour), for ~150,000 matched stars with $1.0 < u-g < 2.1$ and $r < 20$ are shown. The binned median scatter is 5.7 millimag. Note that the CFIS data are available only for Declination > +0.45 degree.

Figure 18. Analogous to Figure 4, except that here the residuals between the SDSS $u$ band magnitudes and predicted $u$ band magnitudes transformed from the GALEX catalogue are shown. The individual star scatter is 54.5 millimag (dot-dashed lines); the binned median scatter is 24.5 millimag (solid grey lines).

uncertainties is < 5 millimag for the $gri$ bands, and < 10 millimag for the $u$ and $z$ bands.

Various catalogue cross-comparisons have revealed minor problems with all the analyzed catalogues. For example, we detected DES $z$ band zero-point errors of up to 0.01-0.02 mag, as a function of R.A., and demonstrated that the Gaia EDR3 G magnitude, $G_{Gaia}$ has an overall gradient of ~0.01mag from the bright to faint end (16 $\leq G_{Gaia} \leq 19$), and therefore appears too faint by about 0.02 mag at $G_{Gaia} \sim 20$.

We constrained offsets from the absolute AB magnitude scale using three white dwarfs with the HST CalSpec absolute photometry data. In the $riz$ bands we measured significant (> 3\sigma) deviations, ranging from 0.015 mag to 0.035 mag (see Table 6), while in the $u$ and $g$ bands we only placed upper limits (at 2\sigma: 0.038 mag and 0.028 mag, respectively). These constraints on absolute AB magnitude scale could be improved by increasing the number of such calibrators.

Thanks to its high stellar density, about 1 star per square arcmin, and demonstrated sub-percent internal photometric precision, this catalogue is a good resource for both calibrating and testing other surveys. In particular, it will enable high-precision photometric testing of data collected during the commissioning phase of the Vera C. Rubin Observatory Legacy Survey of Space and Time.
Figure 19. (Left) Analogous to Figure 6 (Left), except that here residuals between the SDSS $u$ band magnitudes and predicted $u$ band magnitudes transformed from the GALEX catalogue are shown. Unlike in Figure 18, we exclude matches for which SDSS $u > 20.0$. The individual star scatter is 52.9 millimag (dot-dashed lines); the binned median scatter is 5.0 millimag (solid grey lines). (Right) Analogous to Figure 6 (Right), except that here the residuals between the SDSS $u$ band magnitudes and predicted $u$ band magnitudes transformed from the GALEX catalogue are shown. Unlike in Figure 18, we exclude matches for which SDSS $u > 20.0$. The individual star scatter is 52.9 millimag (dot-dashed lines); the binned median scatter is 5.0 millimag (solid grey lines).

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DATA AVAILABILITY

The public data described here may be obtained from the following websites:

- **SDSS-IV, DR15:**
  - www.sdss.org
  - https://dr15.sdss.org/sas/dr15/eboss/photoObj/
- **Gaia EDR3:**
  - https://www.cosmos.esa.int/web/gaia/earlydr3
- **DES DR1:**
  - http://datalab.noao.edu
- **MAST:**
  - https://dx.doi.org/10.17909/T9RP4V

The catalogues generated as part of this work may be accessed at the following links:

- **New SDSS standard star catalogue, version 4.2:**
  - http://faculty.washington.edu/ivezic/sdss/catalogs/stripe82.html
- **Old SDSS standard star catalogue, I007 (version 2.6):**
  - http://faculty.washington.edu/ivezic/sdss/catalogs/stripe82.html

SOFTWARE CITATIONS

- Numpy (Harris et al. 2020)
- Scipy (Virtanen et al. 2020)
- Astropy (Astropy Collaboration et al. 2013, 2018)
- Pandas (McKinney 2010)
- AstroML (VanderPlas et al. 2012)
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