Calibrated *griz* Magnitudes of Tycho Stars: All-Sky Photometric Calibration Using Bright Stars

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ABSTRACT. Photometric calibration to ∼5% level is frequently needed at arbitrary celestial location. However, existing all-sky astronomical catalogs do not reach this accuracy, and time consuming photometric calibration procedures are required. I fitted the Hipparcos B_T and V_T magnitudes, along with the 2MASS J, H, and K magnitudes of Tycho-2–catalog stars with stellar spectral templates. From the best-fit spectral template derived for each star, I calculated its synthetic SDSS $griz$ magnitudes and constructed an all-sky catalog of $griz$ magnitudes of bright stars ($V \lesssim 12$). Testing this method on SDSS photometric-telescope observations, I find that the photometric accuracy, for a single star, is usually about 0.12, 0.12, 0.10, and 0.08 mag (1 σ), for the g, r, i, and z-bands, respectively. However, by using ∼10 such stars, the typical errors per calibrated field (systematic + statistical) can be reduced to about 0.04, 0.03, 0.02, and 0.02 mag, in the g, r, i, and z-bands, respectively. Therefore, in cases for which several calibration stars can be observed in the field of view of an instrument, accurate photometric calibration is possible.

Online material: color figure, table

1. INTRODUCTION

Often in astronomical research, absolute photometric accuracy better than 10% is required. In many cases, the method of choice is to observe photometric standards (e.g., Landolt 1992). However, this requires photometric observing conditions and additional observations. The Sloan Digital Sky Survey (SDSS; York et al. 2000) provides an excellent photometric calibration in $ugriz$ bands, with accuracy better than 2% (Adelman-McCarthy et al. 2008). However, this is available only for about a quarter of the sky. Other all-sky visible-light catalogs, like the USNO-B1 (Monet et al. 2003) and the U.S. Naval Observatory CCD astrograph catalog (Zacharias et al. 2004) provide relatively poor photometric accuracy. The magnitudes of individual stars in these catalogs are accurate to about 0.3 mag, and even with a large number of stars there is still a considerable field-to-field systematic error.

In this paper, I calculate the SDSS $griz$ magnitudes of Tycho-2 stars over the entire sky. In case $\gtrsim 10$ of these stars are visible in a camera field of view, these stars can be used to calibrate photometrically an astronomical image to an accuracy of better than 0.04 mag. The only overhead is that, typically, a shorter exposure in which the Tycho-2–catalog stars will not be saturated is required.

2. CONSTRUCTION OF THE CATALOG

From the Tycho-2 catalog (Hog et al. 2000), I selected all stars with $B_T < 13$ mag and $V_T < 12$ mag. This choice was made in order to remove stars with magnitude uncertainties $\gtrsim 0.1$ mag. I cross-correlated this list with the 2MASS catalog (Skrutskie et al. 2006), and selected only stars that have a single 2MASS match within 6″. The final list contains 1,560,980 stars. Next, I fitted the Tycho-2 and 2MASS magnitudes of these stars with synthetic photometry, in the $B_T V_T JHK$ bands, of 131 stellar spectral templates (Pickles 1998). The synthetic photometry was calculated using the code of Poznanski et al. (2002). For each star I preformed two types of fits: (i) a χ^2 fit; (ii) a least square, of residuals, fit ignoring the Tycho-2 and 2MASS photometric errors. I note that the spectral templates were not corrected for Galactic extinction.

A table (see the online edition of the PASP for this table) listing the 1.56 million stars, along with their coordinates, observed $B_T V_T JHK$ magnitudes, fitted $griz$ magnitudes for both kinds of fits, and the corresponding root-mean-square (rms) and χ^2, is available in the electronic version of this paper and via the VizieR service.[2] In Table 1 I describe the content of this table. The third column in the catalog is a flag indicating if the star is recommended for use as a standard star (i.e., Flag = 1). These stars satisfy all of the following criteria: $J > 6$ mag and $H > 6$ mag and $K > 6$ mag;

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[2] The VizieR Service can be found online at http://webviz.u-strasbg.fr/viz-bin/VizieR.

TABLE 1

Header description for the catalog of SDSS magnitudes of Tycho-2 stars

Column	Explanations	Units
1	Right Ascension J2000.0	deg
2	Declination J2000.0	deg
3	Flag for good standards[a]	
4	B_T magnitude	mag
5	B_T magnitude error	mag
6	V_T magnitude	mag
7	V_T magnitude error	mag
8	J magnitude	mag
9	J magnitude error	mag
10	H magnitude	mag
11	H magnitude error	mag
12	K magnitude	mag
13	K magnitude error	mag
14	Best rms-fit template[b]	
15	rms for the best rms-fit template	mag
16	rms-fit g-band magnitude[c]	mag
17	rms-fit r-band magnitude[d]	mag
18	rms-fit i-band magnitude[e]	mag
19	rms-fit z-band magnitude[f]	mag
20	Best χ^2-fit template[b]	
21	χ^2 for the best χ^2-fit template (d.o.f.=4)	
22	χ^2-fit g-band magnitude[g]	
23	χ^2-fit r-band magnitude[h]	
24	χ^2-fit i-band magnitude[i]	
25	χ^2-fit z-band magnitude[j]	

Note.—List of columns in the $griz$ synthetic magnitudes catalog of Tycho-2 stars. The catalog is available from the electronic version of this paper and from the VizieR service.

[a] Flag indicating if the star is a good standard, i.e., $J > 6$ mag and $H > 6$ mag and $K > 6$ mag and err(BT) < 0.15 mag and err(VT) < 0.15 mag and minimum rms < 0.15 mag.

[b] Template names adopted from the stellar spectra catalog of Pickles (1998).

[c] A 0.06 mag was already added to this column.

[d] A 0.04 mag was already added to this column.

[e] A 0.03 mag was already added to this column.

[f] A 0.03 mag was already added to this column.

[g] A 0.07 mag was already added to this column.

[h] A 0.04 mag was already added to this column.

[i] A 0.04 mag was already added to this column.

[j] A 0.03 mag was already added to this column.

error(B_T) < 0.15 mag; error(V_T) < 0.15 mag; and rms of the best rms-fit template smaller than 0.15 mag. There are 993,428 stars with Flag = 1.

The constructed catalog star density as a function of Galactic latitude is shown in Figure 1. For Flag = 1 stars, the sky density ranges from 55 deg^{-2} at the Galactic plane to about 10 deg^{-2} at the Galactic poles.

3. DISCUSSION

In order to test the accuracy of the derived synthetic magnitudes, I constructed a catalog of all the photometric measurements available from the SDSS photometric-telescope "secondary patches" fields[3] (Tucker et al. 2006). From this catalog I selected all the nonsaturated stars brighter than 12th magnitude in both the g- and r-bands. Davenport et al. (2007) analyzed the systematic offset between the SDSS magnitude system and the SDSS photometric-telescope bands. They found that the magnitudes of very red stars are different in the two systems. Using the transformations given by Davenport et al. (2007), I converted all the SDSS photometric-telescope magnitudes to the SDSS system.

Next I cross-correlated this list with the catalog of $griz$ synthetic magnitudes presented in § 2, and selected stars that have JHK magnitudes fainter than 6 (i.e., not saturated); B_T and V_T magnitude errors smaller than 0.15; and rms of the best rms-fit template of less than 0.15 mag. For each of the 3714 stars satisfying these criteria, I compared the corrected magnitudes (i.e., Davenport et al. 2007) as measured by the SDSS photometric telescope with its best-fit synthetic magnitude. In Figure 2, I show histograms of the fitted synthetic magnitudes minus the SDSS magnitudes for the $griz$-bands. The median value, along with half the range containing 68% of the stars, are indicated in each panel. The upper row is for the best-fit magnitude by minimizing the rms, while the lower row is for the χ^2 fit. This plot suggests that the χ^2 fit is marginally better. Therefore, it should be preferred over the rms fit. In all the bands there are small offsets, listed in Figure 2, between the SDSS photometric-telescope magnitudes and the derived synthetic magnitudes. The magnitudes in the catalog (Table 1) are corrected for these small offsets. I note that I repeated this test using 42 SDSS photometric standards[4] (Smith et al. 2002) and found similar results.

The field of view of large-format cameras may contain only several suitable Tycho-2 stars (see Fig. 1). To estimate the uncertainty in magnitude calibration when using several stars, I have carried out the following simulations: I randomly selected N stars, for any N between 2 and 100, out of the 3714 SDSS standard stars that I used for the comparison of the derived magnitudes with the actual SDSS magnitudes. For each set of randomly selected N stars, I calculated the median of differences between the χ^2-fitted synthetic magnitudes and the SDSS magnitudes. Next, I repeated this procedure 10,000 times (for each N), and calculated the standard deviation of the 10,000 median of differences. In Figure 3 I show the standard deviation of the distribution of the median of differences between the synthetic magnitudes and the measured SDSS magnitudes, as a function of N. The plot suggests that, for example, by using five stars the errors in photometry reduce to 0.07, 0.04, 0.03, and 0.03 mag in the g, r, i and z-bands, respectively. When using 10 stars the errors reduce to about 0.04, 0.03, 0.02, and 0.02 mag in the

[3] These SDSS photometric measurements are available from http://das.sdss .org/PT/.

[4] The electronic version is available from http://home.fnal.gov/~dtucker/ugriz/ tab08.dat.
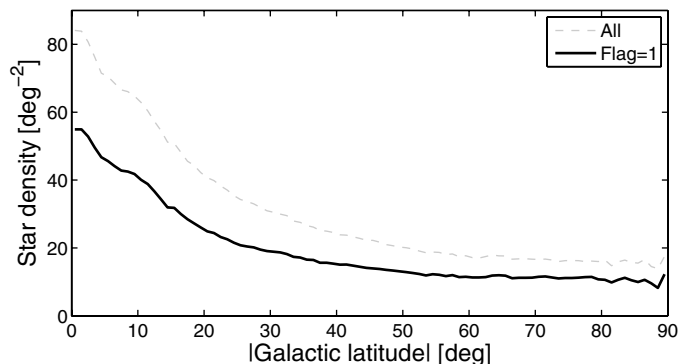
FIG. 1.—Star density in the constructed catalog, as a function of Galactic latitude. The gray dashed line shows all 1.56 million stars, while the black line shows the 993,428 stars for which Flag = 1 (i.e., good for photometric calibration).

g, r, i and z-bands, respectively. In order to remove outliers it is important to use the median of differences (i.e., and not mean of differences).

To summarize, I suggest an alternative method for photometric calibration that may work to accuracy of about a few percent. This method relies on selected stars in the Tycho-2 catalog for which I fitted spectral templates to their $B_T V_T J H K$ magnitudes. Two major limitation of this method is that several Tycho-2 stars are needed in the field of view, and that
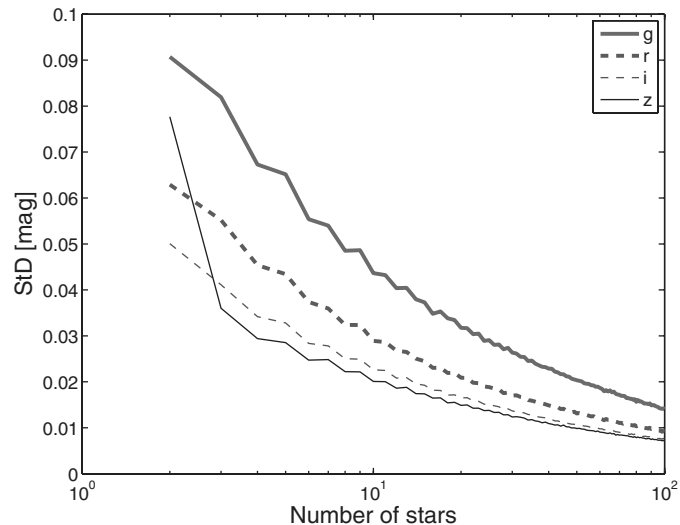

FIG. 3.—Expected error in photometric calibration as a function of the number of stars used in the calibration process (see text). The thick solid line, thick dashed line, thin dashed line, and thin solid line are for the g, r, i, and z-bands, respectively. See the electronic edition of the PASP for a color version of this figure.

shorter exposures, in which these stars are not saturated, are required. Given the catalog star density as a function of Galactic latitude (Fig. 1), this method is applicable for instruments with large field of view or for low Galactic latitude observations.
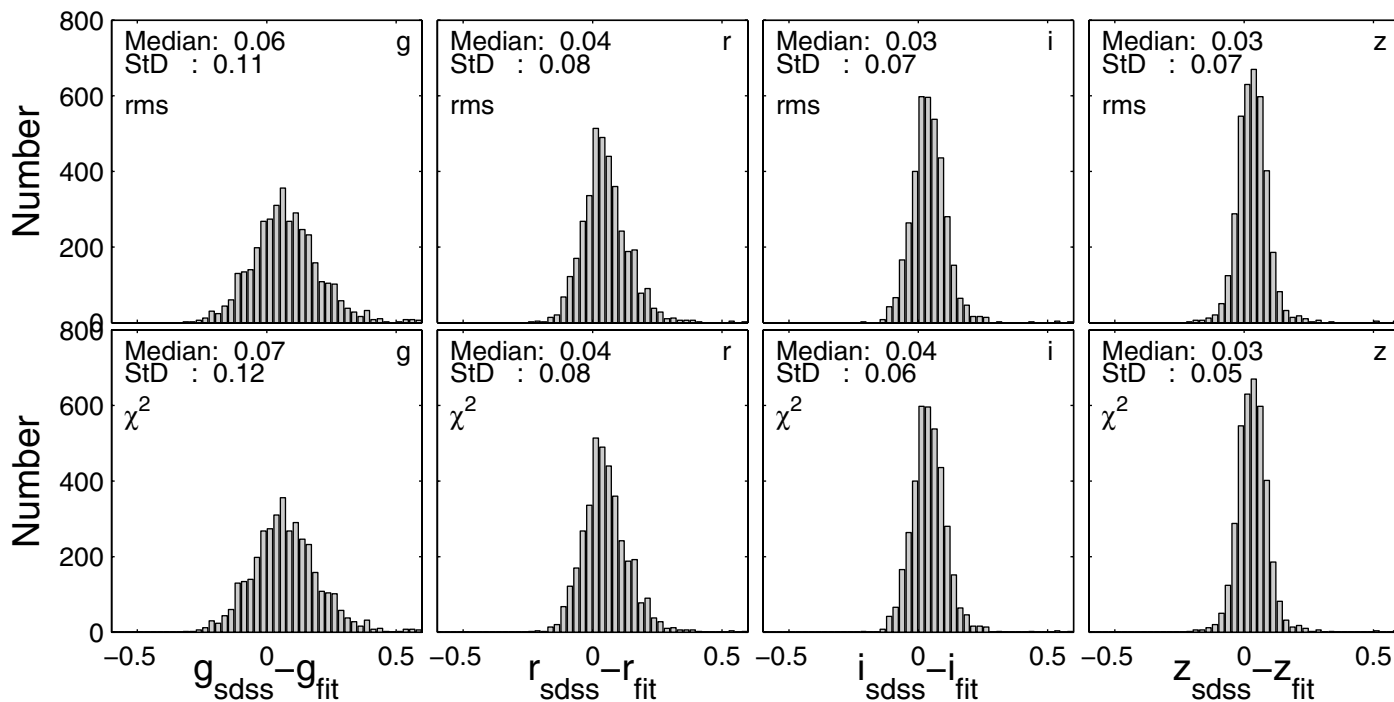

FIG. 2.—Histograms of the actual SDSS magnitude minus the best-fit magnitude for a set of 3714 stars for which magnitude was measured by the SDSS photometric telescope. The histograms are shown for the g, r, i, and z-bands (from left to right), respectively. The upper row is for the best-fit magnitude obtained by minimizing the rms, while the lower row is for the χ^2 fit, which is somewhat better. The median value is the median of the histogram, while "StD" is half of the range containing 68% of the values in the histogram (rather than the usual definition).

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