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Transformations from Pan-STARRS1 and UBV Filters into ZTF Filters

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INTRODUCTION

The Zwicky Transient Facility (ZTF) is an optical time-domain survey that has been operating on the 48-inch Samuel Oschin Telescope at Palomar Observatory since March 2018 (Bellm et al. 2018). ZTF surveys the visible Northern sky every few nights in ZTF g-band and r-band, as well as an i-band filter used only for partnership observations and thus absent from this analysis. Transformations between the photometric systems of ZTF, Pan-STARRS1 (PS1) (Chambers et al. 2016), and Johnson-Morgan-Cousins (UBV) (Johnson et al. 1966) are essential for extending both the time-baseline and wavelength coverage of ZTF catalogs with information from other catalogs. We use cross-matching catalogs and simple stellar population (SSP) synthesis models to derive photometric transformations from PS1 and UBV to ZTF.

PAN-STARRS1 TO ZTF PHOTOMETRIC CONVERSIONS

We selected g-band and r-band photometric catalogs from ZTF observations at random locations throughout the sky. These stars were cross-matched to PS1 mean magnitudes in the DR1 catalog. Saturated stars and stars with significant noise were removed from the sample by applying a cut of 12 mag $< m_{\rm PS} <$ 19 mag for each band. We also removed any sources with bad PS1 photometry in any filter. We calculated a linear fit to the difference of each ZTF filter to it's corresponding PS1 filter as compared to the star's PS1 g minus r color. We find

$$m_{\rm ZTF,g} - m_{\rm PS,g} = 0.055(m_{\rm PS,g} - m_{\rm PS,r}) - 0.012$$
$$m_{\rm ZTF,r} - m_{\rm PS,r} = -0.087(m_{\rm PS,g} - m_{\rm PS,r}) - 0.0035.$$

To estimate the error of our method, we re-sampled the sky and calculated the difference between the ZTF magnitude calculated from our transformation and the star's magnitude as recorded in the ZTF catalog. We measure the difference between ZTF magnitudes transformed from PS1 and true ZTF magnitudes for stars with 12 mag $< m_{\rm PS} <$ 19 mag to be

$$\sigma_{\rm PS\text{-}TO\text{-}ZTF,\ g} = 0.114 \text{ mag}$$
$$\sigma_{\rm PS\text{-}TO\text{-}ZTF,\ r} = 0.063 \text{ mag}.$$

Because we are able to use a large number of stars, the formal uncertainties on the fit parameters are negligible, though systematic effects in the surveys' photometric calibrations or through-puts may lead to slight variations over the sky. The left subplot in Figure 1 shows our sample and the linear fit that well captures the trend in the data. Note that this is a transformation from PS1 to ZTF apparent magnitudes.

UBV TO ZTF PHOTOMETRIC CONVERSIONS

`PyPopStar` (Hosek submitted) is a python package that generates single-age, single-metallicity populations from user specified initial mass functions, stellar evolution models, and stellar atmospheres. `PyPopStar` contains transmission curves for all UBV filters, as well as ZTF g-band and r-band filters as a result of this work, and produces photometric observations of stars in a synthetic cluster. We produced clusters with

- Initial Mass Function: Kroupa 2001 ($0.08M_\odot < M_* < 120M_\odot$)
- Cluster Mass: $10^5 M_\odot$
- Age: 8×10^9 years
- Metallicity: [M/H] = 0
- Evolution: MIST v1.2 (Choi et al. 2016)

- Atmospheres: ATLAS9 (Castelli & Kurucz 2003),
  PHOENIXv16 (Husser et al. 2013), BARAFFE (Baraffe et al. 2015)
- Reddening Law: Damineli et al. 2016
- Extinction: 0.0 mag $< A_{\rm Ks} <$ 1.0 mag

We chose a grid of extinctions from 0.0 mag $< A_{\rm Ks} <$ 1.0 mag, which corresponds to a $\rm A_V \lesssim 10$ mag, in order to fully explore high extinctions found throughout the Galactic plane and towards the Galactic bulge. After executing these simulations, we extracted the UBV (B, V, R) and ZTF (g, r) absolute magnitudes for stars in the resulting clusters. This photometry was placed onto a 2-D plane of $m_{\rm UBV,B} - m_{\rm UBV,V}$ versus $m_{\rm UBV,V} - m_{\rm UBV,R}$ resulting in stars separating without significant overlap. We calculated the difference between the ZTF magnitude and a selected UBV magnitude for each star: $m_{\rm ZTF,r} - m_{\rm UBV,R}$ and $m_{\rm ZTF,g} - m_{\rm UBV,V}$. The choice to calculate the offset of $m_{\rm ZTF,g} - m_{\rm UBV,V}$ instead of the perhaps more intuitive $m_{\rm ZTF,g} - m_{\rm UBV,B}$, avoiding interpolation artifacts. A linear interpolation was fit to the UBV photometry in this 2-D plane, calculated separately for each of the ZTF filters. We applied a nearest extrapolation to points that fell outside the convex hull of our data but within the range of $0 < m_{\rm UBV,V} - m_{\rm UBV,R} < 6$ and $0 < m_{\rm UBV,B} - m_{\rm UBV,V} < 6$. We believe the region outside of the convex hull of our data to be largely un-physical but chose to extrapolate into this region to provide approximate solutions.

We estimate the error of our method by randomly sampling the transformation via bootstrap sampling. We generated new synthetic clusters with both UBV and ZTF photometry at different extinctions and compared the ZTF magnitude predicted by our method against artificial photometry measured by `PyPopStar`. The resulting spread in our magnitude differences came out to be

$$\sigma_{\rm UBV\text{-}TO\text{-}ZTF,\ g} = 0.023 \text{ mag}$$
$$\sigma_{\rm UBV\text{-}TO\text{-}ZTF,\ r} = 0.020 \text{ mag.}$$

Any star with a measured $m_{\rm UBV,B}$, $m_{\rm UBV,V}$, $m_{\rm UBV,R}$ magnitude can be placed on these planes, producing a ZTF g-band and r-band magnitude with relatively small errors. These planes, along with a set of `python` functions that executes the UBV to ZTF transformations, can be found at https://portal.nersc.gov/project/uLens/ZTF_Photometric_Transformations. Note that this is a transformation from UBV to ZTF absolute magnitudes.

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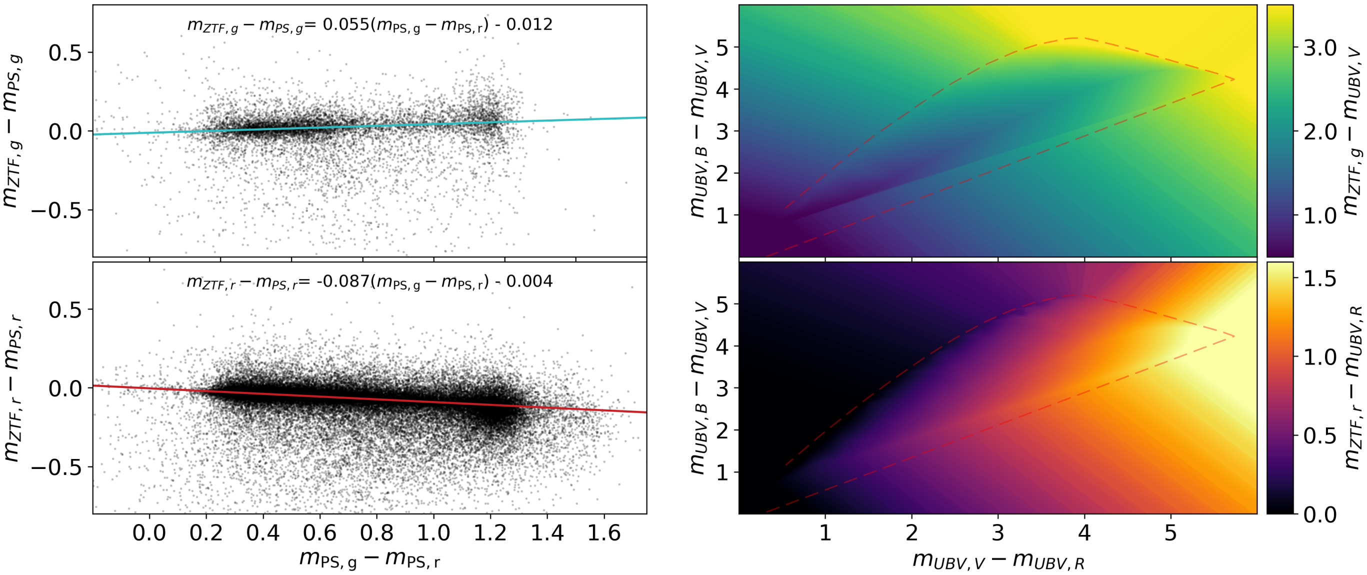

Figure 1. Results for transforming from the PS1 and UBV photometric systems to ZTF filters. The PS1 to ZTF transformation (left) is derived from cross-matching stars observed on ZTF, limiting the sample to only stars with $12 < m_{\mathrm{PS,g/r}} < 19$, and correlating the difference in ZTF and PS1 magnitude with the PS1 color. ZTF observations for these fits were drawn from random dates and sky locations. The UBV to ZTF transformation (right) shows a 2-D color relationship derived from simple stellar population synthesis models. Applying a linear interpolation to photometry of synthetic clusters with varying amounts of extinction produce these relationships. Points outside of the convex hull (dashed red) of our synthetic data are extrapolated and occupy largely un-physical regions. Functions for executing a photometric transformation with these 2-D planes can be found at https://portal.nersc.gov/project/uLens/ZTF_Photometric_Transformations.

REFERENCES

Baraffe, I., Homeier, D., Allard, F., & Chabrier, G. 2015, Astronomy & Astrophysics, 577, A42. https://doi.org/10.1051/0004-6361/201425481

Bellm, E. C., Kulkarni, S. R., Graham, M. J., et al. 2018, Publications of the Astronomical Society of the Pacific, 131, 018002. https://doi.org/10.1088%2F1538-3873%2Faaecbe

Castelli, F., & Kurucz, R. L. 2003, in IAU Symposium, Vol. 210, Modelling of Stellar Atmospheres, ed. N. Piskunov, W. W. Weiss, & D. F. Gray, A20

Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv e-prints, arXiv:1612.05560

Choi, J., Dotter, A., Conroy, C., et al. 2016, The Astrophysical Journal, 823, 102. https://doi.org/10.3847/0004-637x/823/2/102

Damineli, A., Almeida, L. A., Blum, R. D., et al. 2016, Monthly Notices of the Royal Astronomical Society, 463, 2653. https://doi.org/10.1093/mnras/stw2122

Hosek, M. submitted, https://github.com/astropy/PyPopStar

Husser, T.-O., von Berg, S. W., Dreizler, S., et al. 2013, Astronomy & Astrophysics, 553, A6. https://doi.org/10.1051/0004-6361/201219058

Johnson, H., Mitchell, R., Iriarte, B., & Wisniewski, W. 1966, Communications of the Lunar and Planetary Laboratory,, 4, 99

Kroupa, P. 2001, Monthly Notices of the Royal Astronomical Society, 322, 231. https://doi.org/10.1046/j.1365-8711.2001.04022.x