Stellar Photometry With DSLR: Benchmark of Two Color Correction Techniques Toward Johnson's VJ and Tycho VT

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Abstract DSLRs are now routinely used for measuring the V magnitude of stars through their G channel output. This requires a transformation to Johnson V, using a correction based on the catalogue (B–V) color indices of the stars. This paper reviews the responses of the involved passbands and proposes an alternate solution using a synthetic filter made by combining the three RGB DSLR channels. The assessment of the two techniques through experimentation being uncertain, we have chosen to use a computer simulation instead. This simulation combines the measured spectral responses of the DSLR channels, the atmospheric reddening, and star spectra from the Pickles library.

1. Introduction

The recent ε Aurigae campaign (thanks to AAVSO's Citizen Sky, hereafter "CS") has been a great opportunity to experiment with the DSLR's (Digital Single Lens Reflex) photometry capabilities. We have had to observe under very different conditions, sometimes near zenith, but also at very low elevation and high airmass, during the conjunction period that was an important phase of the eclipse. The typical CS DSLR observer works with a standard DSLR equipped with a regular lens and mounted on a photo tripod. The author's lens is a 200 mm, *f*/4, but most people use shorter focal length, typically 70mm, *f*/2.8. Accurate photometry is achievable down to magnitude 6 with this configuration. Less accurate data can be gathered down to magnitude 8. Ideally, an observation made every few days (when weather permitted) was needed to obtain good coverage of the phenomenon over two years. For an amateur this is possible only near home, most of the time under urban sky conditions, with typically 15 to 20 minutes of observation. This also means under an extinction much worse than any professional observatory would encounter. Not only was neutral extinction a problem, but also reddening at high airmass was making things more complex (unusual for professional observers). A specific observing method and data processing technique has been devised by the Citizen Sky's DSLR team to fit all such conditions. It is known at CS as the "intermediate spreadsheet" method (hereafter "CSIS") and can be found on the CS website (AAVSO Citizen Sky 2009).

A simpler method is also used by CS people when observations are done below airmass 1.5. It is known as the "beginner spreadsheet." It involves only the color corrections and not the differential extinction across the DSLR field-of-view.

2. Present work

Initially, the author used the tools and publications provided by C. Buil on his website (Buil 2012), his book (Buil 1991), and the tutorials from Citizen Sky (AAVSO Citizen Sky 2009), but soon developed his own software pipeline to make the operations more productive and to experiment with various techniques including a synthetic Johnson V filter.

The goal was to better extract useful data from observations under the poor ε Aur conjunction conditions. Another aim was to push the DSLR to perform at its best in bright star photometry.

The DSLR itself has G- and B-color filters which do not match the standard Cousins-Johnson B and V passbands (hereafter BJ and VJ). The DSLR R channel is too far from the Cousins Rc to be faithfully transformed. A specific transformation and extinction correction technique has been devised to take care of both the G passband and the CS amateur context (Henden and Kaitchuck 1982; Kloppenborg and Pearson 2011). This CSIS technique is based on the catalogue (B–V) and V-magnitude of a star "ensemble" that determines the related correction coefficients.

In the CSIS the differential neutral extinction is determined through a mapping of the magnitude deviations of stars of a large ensemble distributed in the DSLR field-of-view (FOV). To do this, the fully "color corrected" instrumental magnitude of the stars is then compared to the catalogue magnitude of the stars. The resulting magnitude differences that are a function of the differential airmass determine the neutral extinction gradient across the FOV.

Statistics have been extracted from the ε Aur observations and critical cases have been identified in this CSIS technique. The single-equation system (Equation 5) used by the CSIS has some drawbacks depending on the distribution of stars. To overcome that issue the author soon considered a color correction technique independent of the catalogue data using an RGB synthetic filter equivalent to VJ or VT (hereafter "VSF"). It is implemented by combining the three RGB channel signals of the DSLR. The first experiments showed interesting possibilities but it was obvious that an accurate assessment of these techniques was difficult to achieve through observations. Then it was decided to use a computer simulation for that study.

Several options of processing of the neutral part of the extinction in the VSF technique remain under study. The author plans to address it in a future paper based on the best option.

By the way, the present paper addresses only the color aspect of both the CSIS and the author's VSF technique. For such study only the DSLR response and the slope of the atmosphere transmission curve are used in a differential photometry scheme where all stars are at the same airmass.

Carrying out such a simulation needed a library of stellar spectra. The Pickles library (Pickles 1998) has been found to meet the need with its 131 stars from O to M, at all luminosities and several levels of abundance. Other inspiring sources have been the many papers from Bessell: in "UBVRI passbands" (Bessell 1990) he analyzed the issues of various filter implementations used under several photometric systems. The paper includes a synthetic magnitude calculation using the Vilnius spectra library. The approach is very similar to what is reported in this paper. His last paper has an interesting appendix pointing out some issues of such broad passbands (Bessell and Murphy 2011).

The paper from (Tokunaga and Vacca 2005), the photometry introduction of (Romanishin 2006), and a study of the calibration of Tycho-2 and Johnson systems (Apellániz 2006) have also been very informative.

Another important source for the DSLR application is the Hipparcos mission (Perryman *et al.* 1997). Looking at the various system passbands revealed that the Tycho VT passband is comparable to the DSLR green response. In addition the *Tycho-2* catalogue (Høg *et al.* 2000) catalogue is a uniform, very accurate, and reasonably precise reference. This opened a new possibility that will be analyzed hereafter and compared to Johnson VJ using both the CSIS and the VSF techniques.

At this point the author would like to discuss the accuracy of the catalogues compared to what can be obtained through DSLR photometry techniques. Such techniques, based on mapping of magnitude differences, are very sensitive to the catalogue errors. Fortunately, DSLRs have a large FOV that allows one to work with a large ensemble of stars (50 to 100 stars accessible in a 6×4 degree field). This averages both catalogue errors and the imperfect color distribution in the FOV. At a 1000 signal-to-noise ratio the DSLR provides results reproducible within a few millimagnitudes. Most catalogues have larger uncertainties, and from catalogue to catalogue such uncertainties are often much larger; this could affect the determination of both the color transformation coefficient and the differential neutral extinction with the CSIS (as it is based on a mapping of it from an ensemble of stars).

3. Color Passband: DSLR's RGB versus Johnson's VJ and Tycho-2 VT

The DSLR R,G,B channel responses are shown in Figure 1. They have been obtained from a clear day, sunlight observation using a slit and grating mounted in front of the DSLR lens, then corrected from the standard ASTM sun spectrum at 1.5 airmass (ASTM International 2008) and the RGB balance of the grating. It is to be noted that DSLR curves are the responses of the filter stack (R, G, B, IR, and UV cut) plus the sensor and the lens. The linear RAW output of the DSLR has been used; that excludes any processing from the DSLR—in particular, any gamma application or any transformation to sRGB or other color profile. The DSLR was a standard Canon 450D with a CMOS sensor, 14 bits, equipped with a Nikkor 85 mm lens. Its IR and other filter stack has not been modified.

In the UBVRI (and other) photometric systems (Bessell 1990), magnitudes are calculated from the photon-count from photometric chains of several passbands. Figure 2 shows the Johnson V (hereafter "VJ") passband and its relationship with the DSLR G channel. The version used as reference in this study is the one recommended in the Pickles (Pickles 1998) spectra library. This version is very similar to the one recommended by the CDS. They are used in a number of publications, but other versions also exist (Bessell and Murphy 2011).

Figure 3 shows the relationship between the *Tycho-2* VT passband definition (Apellániz 2006) and the DSLR G channel response curve.

Other DSLR color channels responses could be seen at the website of C. Buil (Buil 2012). They are very similar. Apparently, there are no large differences between recent DSLR or DSC (digital still cameras; large differences may be found in older cameras).

The color filter array of the DSLR is of the Bayer type (Bayer 1975) with a square RG/GB arrangement. That means the G signal is obtained from two sub-pixels instead of only one for R and B. In addition, as shown in Figure 1, the transmission of the red filter is much lower than G and B. As a result the SNR of the G channel is much higher than the B and, in particular, the R channel. The RAW resulting color balance is more or less CIE (Commission Internationale de l'Eclairage) typical (Green *et al.* 2002). In most common usage (sRGB and Jpeg output) the RGB levels are realigned to 1, 1, 1. Then the representation is non-linear (0.45 gamma) coded on 8 bits and to some color profile like sRGB. This study uses only the linear RAW output of R, $G=(G_1+G_2)/2$ and B data (said ADUs, proportional to photon-count, hereafter all photo-count data are denoted as "*G*", italicized uppercase, and magnitudes as "*Gm*").

The instrumental magnitude, *Gm,* is usually calculated with the equation (Equation 3) from the DSLR G-channel output, *G,* then transformed to VJ *Gtm* using Equation 4. If we compare the G response to the VJ response (Figure 2), there is a large common surface between them both, but also significant differences.

The blue side roll-off is the largest significant difference. The centroid of the G response is at 530 nm and the VJ one at 542 nm. But the blue roll-off of the G response is shifted 26 nm to the blue compared to the steep roll-off of the VJ curve. In addition there is a blue leak at the foot of the curve between 450 and 400 nm.

On the red side the difference is less important and opposite: missing red instead of too much blue. The red side G roll-off is shifted to the blue by about 5 nm. Figure 3 shows the Tycho VT passband which is much more similar to the G channel. The centroids positions are different by only 2 nm. The resulting color correction between both should be minimal. We will also study that case as it offers a real opportunity for DSLR photometry.

4. Atmosphere transmission

The bandwidths of all DSLR-involved passbands are not small. Besides the impact of the mean extinction at the centroid, the passband's internal color balance is affected by the atmosphere transmission variation as a function of the wavelength (essentially the slope of this function). The result is the product of both: the camera response S(λ) and the atmosphere transmission T(λ). This more-or-less moves the resulting centroid to the red. The atmosphere affects all passbands including the references, Johnson's VJ, and Tycho VT. The atmosphere attenuates the short wavelengths more than the long ones. This is shown in Figure 5, extracted from the Moon's solar irradiance table (Desvignes 1991). That effect is weighted by the length of the light path in the atmosphere known as the airmass number (*AM*), after the Beer-Lambert-Bouguer equation:

$$T(\lambda, AM) = e^{-\varepsilon(\lambda)\, AM} \quad (1)$$

Where the airmass *AM* is a function of the star zenithal distance z (or elevation $h = 90 - z$), and $\varepsilon(\lambda)$ is the extinction coefficient. In the Desvignes table $\varepsilon = 0.23$ at $\lambda = 550$ nm. It could also be extracted from the solar irradiance at AM0 and AM1.5 from the ASTM standard (ASTM International 2008). The solar energy standards better fit our urban amateur sky conditions than the data from professional observatories.

$$M = 1/\cos(z)$$
$$AM = M - 0.0018167 \times (M-1) - 0.002875 \times (M-1)^2 - 0.0008083 \times (M-1)^3 \quad (2)$$

Where M is the airmass in a planar homogeneous atmosphere model (valid down to 10 degrees elevation), and *AM* the corrected airmass after the Hardie's approximation (valid down to 5 degrees elevation) (Ilovaisky 2006). These equations are not used in the simulation where the input of the transmission table is directly *AM*.

In the following simulation only the chromatic part of the extinction is used and studied (the transmission slope). The neutral part of it and its differential effect in the DSLR FOV is eliminated by the differential photometry and the fact all stars are set at the same airmass in this simulation.

5. CSIS color transformation from the DSLR *Gm*, instrumental magnitudes, to *Gtm*, VJ, or VT magnitudes

The CSIS color transformation (Henden 2000) is a linear interpolation between the color indices of the stars, the target one and at least two reference stars (an "ensemble" being better). The color index is the magnitude difference between two passbands like $(B_3 - V)$. (Pickles 1998; B3 denotes a specific

Johnson B filter adopted for the Pickles spectra. It is not far from the filter recommended by the CDS.) The magnitude difference from a third passband is linearly interpolated from the known color indices. The interpolation coefficient "k_D" is expected to be specific to a given DSLR. A similar term shall also account for the reddening due to the chromatic part of the atmospheric extinction "k_K". It shall be readjusted for each star field as a function of its distance angle to the zenith. Within 40 degrees of the zenith it accounts for about 2 millimagnitudes only within the usual ±0.7 (B–V) range, then it could be ignored. At airmass 1.5 ~ 4 the impact shall be taken into account (3 ~ 30 millimagnitudes).

$$Gm = m_0 - 2.5 \log (G / G_0) \tag{3}$$

$$Gtm_i = Gm_i + zp + k_D (B_3 - V)_i + k_K (B_3 - V)_i + k_N X_i \tag{4}$$

Gm is the instrumental magnitude from the *G* and G_0 photon-count issued from the green channel of the DSLR respectively for a target star and a comparison star. $(B_3 - V)$ is the catalogue color index of the star (*i*). *Gtm* is the transformed magnitude of the star. *zp* is the zero-point, the magnitude constant from the instrument. In a given observation k_D and k_K can't be separated when solving the equation system (Equation 5) and shall be replaced by $k_C = k_D + k_K$. In the DSLR FOV, X_i is the differential airmass of the star (*i*) from the reference star or ensemble.

In the simulation reported in this paper G_0 is the photon-count of an A0V star of magnitude $m_0 = 0$ and $(B_3 - V) \sim 0$ resulting in $zp \sim 0$. Then all stars of the FOV being set at the same airmass, all $X_i = 0$ and k_N are not applicable.

From actual observations, the coefficients for a given DSLR and a given FOV are determined from the catalogue values $(B_3 - V)$ and *Vjm* of several reference stars and their measured *Gm* values (or hereinafter *BT – VT* and *VTm* in the case of Tycho-2).

$$Vjm_i = Gm_i + zp + k_c (B_3 - V)_i + k_N X_i \tag{5}$$

Applying the relation Equation 5 to the observation of more than three stars (*i*) forms an overdetermined equation system that is solved using the least square error algorithm. This method is used to determine *zp*, k_C, and k_N from this ensemble of stars. Only k_C is used in the reported simulation.

Characterizing the DSLR k_D through observations instead of through simulation is tricky. Such observations should be made under very good sky conditions, near the zenith, using well-documented, stable stars of a matching (B – V) range, at high SNR (>300), and repeated several times. The extinction should be independently checked using the Bouguer's line method (Ilovaisky 2006). If the resulting extinction parameters are far from standard and/or irregular as a function of the star's elevation, the sky conditions should be considered inadequate for a calibration.

6. Definition of a DSLR "VSF" synthetic filter delivering a VJ- or VT-like magnitude

From the analysis of the wavelength response of the DSLR channels we can define another technique to emulate a Johnson VJ chain. The wavelength difference between the blue leak and the B response centroids, and similarly for the red, leads one to think that a compensation would be possible in the form of a synthetic filter combining the RGB channels:

$$Gc = G + a\,R - b\,B \tag{6}$$

$$Gcm = -2.5 \log (Gc \,/\, G_0) \tag{7}$$

Where *G,R,B* are the photon-count (or ADUs) from the DSLR raw output, *Gc* and G_0 are the respective photon-counts of a target star and the A0V comparison star ($m = 0$, $B-V \sim 0$), both VSF-filtered, and *Gcm* is the corrected magnitude of the target.

In the following simulation the *a* and *b* coefficients are optimized from the RGB outputs of the DSLR *G,R,B,* and the standard filter output, *Vj,* of the Pickles stars spectra (all photon-count; or *VT* in the case of *Tycho-2*). This optimization of (*a,b*) across the HR diagram is done by solving the overdetermined equation system formed from the relation (Equation 8) using the ensemble of stars (*i*).

$$Vj_i = k\,(G_i + a\,R_i - b\,B_i) \tag{8}$$

It is not recommended to apply Equation 8 to data obtained from observations. The various errors due to the observational conditions and the catalogue uncertainties can have a significant impact on the (*a,b*) coefficients. Such errors can unbalance the corrections from the B and R channels. This could result in a good correction for a given star set but one that is not optimal across the overall (B–V) range. It's better to use the coefficients determined from the RGB passbands.

The way (*a,b*) works can be understood as controlling the centroid and the bandwidth of the VSF. When (*a,b*) vary in opposite directions they control the bandwidth, otherwise they shift the centroid of the VSF.

This *G,R,B* combination results in a synthetic filter (VSF) which has a response similar to VJ (or VT) in the visible domain. The VSF passband shape is not exactly the same as VJ but responds similarly to the spectrum continuum (Figure 18). The VSF response to specific features of the spectra, like Balmer's lines of blue stars or molecular bands of the red ones, could differ (Figure 4). A first check has been made using the black body spectrum at various star temperatures with excellent results (within one millimagnitude).

The proposed VSF technique has also been extensively tested on the star field of the ε Aur campaign with excellent results. Under good sky conditions the standard deviation within an ensemble of five stars (*B–V* from –0.18 to 1.22) and their catalogue values was often as low as a couple of millimagnitudes. But that field had no spectrum-critical star. Next, there are few reference stars of various types having VJ magnitudes known with high accuracy in a single field of 5 ~ 15 degrees (DSLR FOV). It has been judged easier, more accurate, and informative to assess this technique through a computer simulation using the coherent Pickles spectra library and the measured RGB responses of the DSLR.

In the CSIS transformation the chromatic part of the extinction is included in k_C, and we see that it shall be set before the determination of the differential neutral extinction in the DSLR FOV.

This can be achieved with the VSF technique by adapting the color balance of the synthetic filter. This is just making the (*a,b*) coefficients adaptive to a measure of the atmospheric reddening (Equation 9). The B_c / G_c ratio of the B,G outputs of the DSLR is an excellent measure of it. It is very stable during an observation and looks much more reliable than any single channel output.

$$a = a_0 + a_1\, B_c / G_c \qquad b = b_0 + b_1\, B_c / G_c \tag{9}$$

The B_c / G_c ratio used is that of a reference star in the FOV or of an ensemble centered on the (B–V) range. This atmospheric reddening correction should not be confused with the main filter synthesis operated by Equation 6. It produces only a limited centroid shift of the synthetic filter that compensates for the reddening, and a first order link to (*a,b*) has been found accurate enough for the Canon 450D. A second order could be needed for some older DSLRs having a large blue leak into the G channel.

7. Pickles spectra library

The Pickles library includes 131 spectra of stars with $(B_3 - V)$ from –0.38 to 1.816 and O5 to M10 spectral types. All luminosity classes I to V are represented. The spectra comprise wavelengths 1150 Å to 25000 Å at a resolution of about 500 $(\Delta\lambda / \lambda)$. The library has been constructed by combining the data from sixteen other libraries with a dedicated combination and verification methodology. Details may be found in Pickles (1998).

For the purpose of the DSLR simulation the range from 350 nm to 750 nm has been extracted from the original data (Figure 4). The library provides calibrated spectra in energy density per Ångstrom; then the flux has to be converted to photon-count. The original normalization at 5556 Å of the spectra has been readjusted for normalizing the output of the VJ (or VT) passband to zero magnitude at zero airmass for all stars. This makes the assumption the VJ magnitudes are defined on top of the atmosphere after the Johnson definition (Bessell 1990).

Most stars of M spectral type show large color transformation errors. This is due to their spectrum having large absorption molecular bands resulting in their $(B_3 - V)$ colors no longer reflecting the black-body flux and predicting the correct flux correction to VJ. For M stars, a magnitude correction based on the (V–Rc) color is more appropriate (Rc is not accessible to DSLR except if IR cut and IR dye filters are removed). M stars have been processed separately and 110 O-to-K stars remain in the main analysis.

The ninth star of the library of A0V spectral type has been used as the comparison star (G_0 photon-count) in the magnitude computations. Its VJ (VT) magnitude has been set to zero but the color index determined by its spectrum is 0.015. This induces some few millimagnitudes global shift of the end result.

8. Computer simulation of the DSLR outputs and color processing

The simulation is just the software implementation of Equation 10 to each system passband of that study:

$$G_{ADU} = k\,Np = \frac{k}{hc}\int_{\lambda} \lambda\, F_{\lambda}(\lambda)\, T(\lambda, Am)\, S(\lambda)\, d\lambda \qquad (10)$$

where G is any of RGB channel outputs of the DSLR, k is the sensitivity (or calibration factor) in ADU/photon, and Np is the photon-count. The spectral energy distribution, F(λ), of the Pickles spectra is transformed in the photon-count as $\lambda\, F_{\lambda}(\lambda) / hc$.

$S(\lambda)$ is the overall photonic camera response and $T(\lambda, Am)$ is the atmosphere transmission.

$S(\lambda)$ is successively set to the response of the five passbands VJ, VT, R, G, B, the collecting area being arbitrarily set at 1 cm^2.

In this process the software computes G_{ADU} of all stars at airmass zero and normalizes $F_{\lambda}(\lambda)$ to put all star magnitudes *Vjm* or *VTm* to zero at this level using the reference passbands VJ or VT. Then B_3jm or *BTm* and the related color indexes are computed for checking against the original library values.

Next the G_{ADU} of all stars are re-evaluated at each targeted airmass from the normalized $F_{\lambda}(\lambda)$, the atmosphere transmission $T(\lambda, Am)$, and the passband response $S(\lambda)$. The results after integration are the new *Vj* or *VT* and *R, G, B* photon-counts.

The last phase is to compute the end results of both techniques from the photon-counts using Equations 3–4 and 6–7. The results are the final magnitudes *Vjm* (the reference, or *VTm*), *Gtm*, *Gcm* (the corrected results).

Here we should bring to mind that all stars are at the same airmass under evaluation. No differential neutral extinction is involved in the result. These results are the deviations due to the combined camera passbands and the atmospheric reddening, depending on the star's color. They are graphically shown below.

In a first pass the software is also used to compute only *R,G,B* and calibrate the coefficients k_C, a, and b using Equations 5 and 8.

All that computing chain, up to Equation 3 or Equation 7, uses the notion of transmission and photon-count instead of the logarithmic processing usual in astronomy. This is needed as the VSF technique is additive at the photon-count level and cannot be processed using logs.

This simulation has been implemented in the APL language and performed under a Dyalog APL system.

9. Benchmark results

9.1. Airmass 1 instrumental results under both VJ and VT systems

Johnson System—Figure 6 shows the respective instrumental magnitude deviations at airmass 1 of the Johnson VJ passband, *Vjm*, and the DSLR green channel, *Gm*. *Vjm* was normalized to 0 at airmass 0. The deviations are more or less a linear function of $(B_3 - V)$. The peak-to-peak deviation for *Gm* is about 260 mmg across the color index range of 2.2 magnitudes. The slope is roughly 0.118. This $Gm\,(B_3 - V)$ curve is what we shall use to transform to Johnson VJ.

There is a set of outliers above $(B_3 - V) = 1.1$ magnitude. Those are the M stars, which are bluer than the K stars, although they are cooler, due to large molecular absorption bands in their spectra. Their effective temperature is much lower than expected from their color index defined by the BJ and VJ passbands. In the following they are excluded from the main analysis. This issue has been denoted in the Hipparcos and Tycho report (Perryman *et al.* 1997) and the authors recommend not to transform the M star magnitudes (like Tycho, we can only work with B and V, as the DSLR R is too far from Rc).

The *Vjm* Johnson output itself shows a small deviation at airmass 1 due to the star color—about 10 millimagnitudes across the range. This is small but would need a linear correction when precise photometry is required.

Tycho System—Figure 7 shows the comparative deviations of the Tycho VT passband *VTm* and the DSLR green channel *Gm*, without correction, at airmass 1. *VTm* is normalized to 0 at airmass 0. The *VTm* deviation at airmass 1 is somewhat larger (19 millimagnitudes) than *Vjm*. This is due to the larger and bluer VT passband. The response of the DSLR green channel shows a much smaller deviation than under the Johnson system (23 millimagnitudes peak-to-peak instead of 260). This confirms the analysis (section 3) made from the response curves and their centroids. The outliers are the M stars and a few K stars as seen in the VJ plot (Figure 6), but with a smaller scatter.

This confirmation is important, showing the *Tycho-2* catalogue should be the reference for DSLR photometry. This catalogue is accurate in the magnitude range accessible without a telescope and provides well-quantified uncertainties.

9.2. Airmass 1 to 4 and both VJ and VT passbands

Figures 8 and 9, respectively, show the responses of the Johnson VJ and Tycho VT passbands at airmasses 0, 1, and 4. They show the strong impact of the atmospheric reddening even on such standard filters. At airmass 4, the peak-to-peak errors are, respectively, 40 and 65 millimagnitudes for *Vjm* and *VTm*. The airmass color shift needs a compensation for the standard passbands.

The following sections compare the CSIS and VSF deviations at airmass 1 and 4 under VJ and VT.

9.3. Johnson's VJ—airmass 1 and 4—CSIS and VSF techniques

Figures 10 to 13 show the deviations of *Gtm* and *Gcm* for the 110 stars of type O-to-K.

CSIS—The CSIS transformation result, *Gtm* (Figures 10 and 12) has been optimized with respectively k_C = 0.135 and 0.098 for airmass 1 and 4. This 0.135 value is in good agreement with the one typically used, at zenith, for our ε Aur observations.

The deviation pattern is similar at both airmasses and forms two lines from a maximum around 5 millimagnitudes at $(B_3 - V)$ = 0.33 and a range of 20 millimagnitudes. Using slightly different coefficients for the color index ranges –0.4 ~ 0.33 and 0.33 ~ 1.8 (two different slopes) would improve it. This should reduce the error range to about 8 millimagnitudes except a few outliers. Those outliers are K-type stars that show some problems similar to the M types. On the blue side there are one B3I and one F5I outlier without clear reason to deviate, although the additional violet flux in supergiants is suspected to be the cause.

VSF—The VSF result, *Gcm* (Figures 11 and 13) has been optimized with, respectively, (a = 0.284, b = 0.224) and (a = 0.149, b = 0.244) for airmass 1 and 4. This is just the experimental value for b, and a somewhat higher value for a. But the red correction coefficient has a large variability depending on the experimental conditions due to its weak effect. a equal to or above 0.284 is not uncommon.

The airmass 1 deviation pattern differs from *Gtm* with a well contained section above $(B_3 - V)$ = 0.3 within 7 millimagnitudes and no K outlier. At airmass 1 the section below 0.3 shows more dispersed results (within 15 millimagnitudes) of the OBA stars.

The pattern at airmass 4 is reduced to a 12 millimagnitude range but has the same shape as airmass 1. Both are better contained than *Gtm*, the result of the CSIS transformation.

9.4. Tycho VT—airmass 1 and 4—CSIS and VSF techniques

Figures 14 to 17 show the deviations of *Gtm* and *Gcm* for the 110 stars of type O-to-K.

CSIS—The CSIS transformation result, *Gtm* (Figures 14 and 15), has been optimized with, respectively, k_C = 0.009 and –0.019 for airmass 1 and 4. This 0.009 is well in agreement with the value typically used, at zenith, in another massive survey experiment based on *Tycho-2*.

The pattern of the deviations at airmass 1 is more or less similar to that of VJ but with a reduced amplitude of 10 millimagnitudes excluding the usual outliers. The pivot point has moved about $(B_3 - V) = 0.8$. The outliers also show a reduced deviation.

The overall improvement from the VJ system is more than a factor two. At airmass 4, the pattern amplitude is further reduced, but dominated by the outliers.

VSF—The VSF result, *Gcm* (Figures 16 and 17) has been optimized with, respectively, ($a = –0.085$, $b = 0.073$) and ($a = –0.136$, $b = 0.030$) for airmass 1 and 4.

The deviation patterns at airmass 1 and 4 are nearly identical showing the lowest amplitude of all about 8 millimagnitudes (excluding some outliers). As in the VJ system, using VSF, the late K stars are no problem and the dispersions are not clearly linked to any specific spectral type. At that level of a couple of millimagnitudes it is very possible we are seeing limitations due to the library.

10. Discussion of the simulation results

The accuracy of the simulation results depends upon three items: the spectra library, the passband responses, and the atmosphere extinction model. The last is just a standard model, and the observations clearly show large deviations from such a model. The B_c/G_c ratio dependency to the airmass is usually stable and the neutral extinction much more variable. This is the result of the variability of the high aerosol content of our urban skies. Such a neutral component has no impact and any slope change of $T(\lambda, Am)$ is a color balance difference that would just affect the correction coefficients, not the end error level shown by the simulation (the chromatic and differential neutral corrections are independent in the VSF technique).

The next point is the DSLR response curve accuracy. The passbands have been tested by comparing the simulated RGB outputs with the physical RGB outputs of the DSLR and have been found to be within a couple of percent and corrected. The response curves have been measured using three different reference light sources and found similar. The differences impacted the correction coefficient by less than 2%.

The spectral features: lines, bands, but also some small differences in large bands of the continuum, are expected to be the reason for the star-to-star deviations seen in the simulation results. Then we have a standard deviation from Pickles (hereafter SD) at each wavelength that ranks from 5% to 0.5%. But we don't know the correlation from one wavelength to the next that could form such small "bumps" of the continuum (a few percent) over a bandwidth large enough to interact with the roll-off of the DSLR passbands. In the hypothesis, where we propagate those SDs without any correlation, we will get a worse SD of 3 millimagnitudes at the end which seems somewhat optimistic with regards to the simulation results. Then, if we take the worst case possible correlation, we will get a deviation of 50 millimagnitudes which is obviously far too large and unlikely. This aspect would need a deeper study of the library construction, which combines a variable number of original spectra depending the wavelength and the star spectral type. There are cases based on a few data only. Anyhow, the Pickles library is an excellent resource and the best of those tested by the author for this work.

The VSF technique has been extensively used during the ε Aur campaign with good results (reports can be found under PROC at Citizen Sky and the AAVSO). It permits us to achieve a fully VJ color response of the DSLR independently from the differential neutral extinction correction (and other error sources). This avoids possible contamination from other factors that exists with the CSIS transformation. This CSIS issue depends on the star color distribution and their position in the field of view. The VSF technique is also independent of the catalogues after its calibration is set.

The VSF technique has been very effective when we had to observe ε Aur at low elevation during the conjunction. It is also very helpful in cases of color change of a variable. This has been recently the case of ζ Aur, for which interesting results have been gathered.

A further improvement of the DSLR photometry will be to use the *Tycho-2* catalogue as a primary reduction reference. The DSLR instrumental color correction is very low under this photometric system; only the high airmass chromatic effect is significant. This shall further improve the accuracy of both color and neutral extinction corrections thanks to the better uniformity and accuracy of this catalogue. If a Johnson's *Vjm* is needed the end result can be converted using the Tycho recommended methods (Perryman *et al.* 1997). A more detailed table of corrections as a function of BT–VT is provided in (Bessell 2000).

11. Conclusion

It is possible to achieve a color correction of the instrumental magnitudes of a DSLR to Vj or VT, within ±5 millimagnitudes, with both the CSIS transformation and the VSF technique. The CSIS transformation would need some refinement (second order coefficient, or two slopes) to achieve it across a wide B–V range under the Johnson system. The color and airmass of the reference stars used in the CSIS should be well-balanced and bracket the target stars in all aspects.

M-star magnitudes are not well-transformable from the DSLR passbands, with possible errors as large as 60 millimagnitudes. Some late K stars could also deviate by 20 millimagnitudes after the CSIS transformation. The luminosity and the abundance of the stars seem not to be significant factors of deviation.

The VSF technique provides the best accuracy, and is independent of the catalogue (B–V), of the differential neutral extinction and other various error sources. It shows no specific error for the K stars and generally works better with red stars. Using it under the *Tycho-2* system provides a further improvement, reducing the color related errors and also providing a more uniform reference for determining the differential neutral extinction in the field of view of the DSLR.

12. Acknowledgements

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Table 1. CSIS and VSF coefficients to the VJ and VT photometric systems.*

AM	$G_{c\ mean}$	$B_c/G_{c\ mean}$	VJ/k_c	*VJ/a*	*VJ/b*	VT/k_c	*VT/a*	*VT/b*
0	1027	0.805	0.145	0.340	0.217	0.020	–0.064	0.089
1	800	0.750	0.135	0.284	0.224	0.009	–0.085	0.073
2	624	0.701	0.125	0.235	0.231	–0.002	–0.103	0.058
3	488	0.656	0.110	0.190	0.238	–0.012	–0.121	0.045
4	382	0.616	0.098	0.149	0.244	–0.019	–0.136	0.030

**Table 1 shows the various coefficients used in the simulation at various airmasses. "$G_{c\ mean}$" and "$B_c/G_{c\ mean}$" are the mean output intensities of the DSLR channels for the O-to-K spectra "ensemble" (or of a F6V star). The extinction coefficient used is ε = 0.23 at 550 nm. The B_c/G_c ratio is used to measure the atmospheric reddening as a function of the airmass, AM. $G_{c\ mean}$ results from the atmosphere transmission for the G channel after the Moon's model (Desvignes 1991). "k_c", "a", and "b" are the correction coefficients defined in sections 3 and 4, applied to both Johnson and Tycho standards. The values at AM0 are the correction coefficients of the DSLR G channel passband alone, normally invariant.*

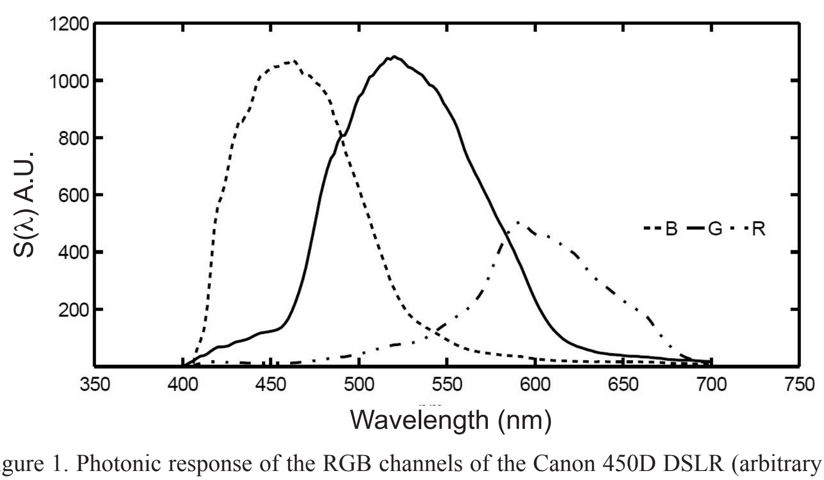

Figure 1. Photonic response of the RGB channels of the Canon 450D DSLR (arbitrary units proportional to S(λ) of equation 10).

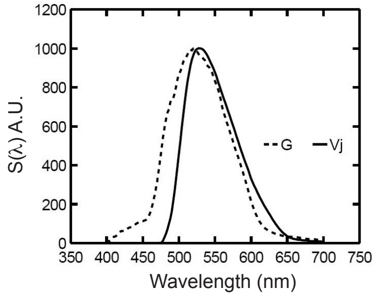

Figure 2. Photonic response of the Johnson VJ passband compared to the DSLR green (G).

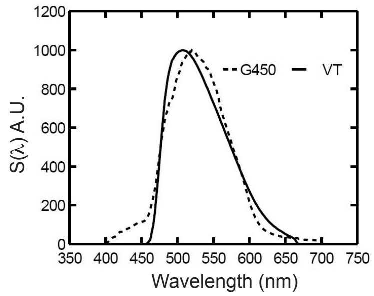

Figure 3. Photonic response of the Tycho VT passband compared to the DSLR green (G).

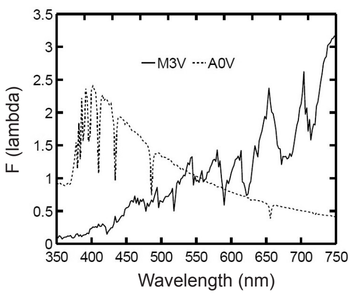

Figure 4. Pickles library (Pickles 1998), samples of M3V and A0V stars of the 131 spectra normalized at 555.6 nm. Spectra are in energy density per wavelength (nm).

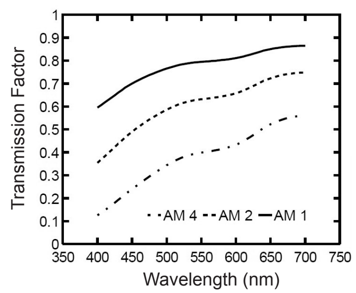

Figure 5. Transmission factor of the atmosphere at airmasses 1, 2, and 4, computed from the solar energy density (Desvignes 1991). The extinction coefficient is 0.23 at 550 nm.

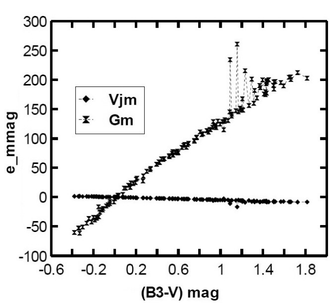

Figure 6. Johnson's Vjm and DSLR Gm magnitude deviation, without correction, at airmass 1 under the Johnson's system. Vjm is normalized at airmass 0.The Gm errors are 11 times those of Figure 7.

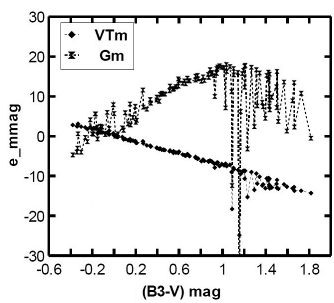

Figure 7. Tycho VTm and DSLR Gm magnitude deviation, without correction, at airmass 1 under the Tycho system. VTm is normalized at airmass 0. The outliers are M stars and a couple of K stars.

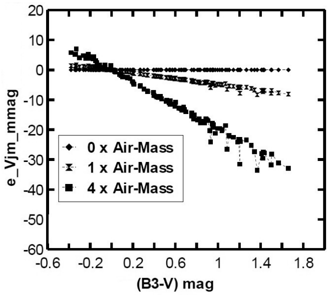

Figure 8. e_Vjm magnitude deviation of the VJ passband at airmass 0, 1, and 4, under the VJ photometric system. The results shown are those of the 110 O-to-K spectra of the library.

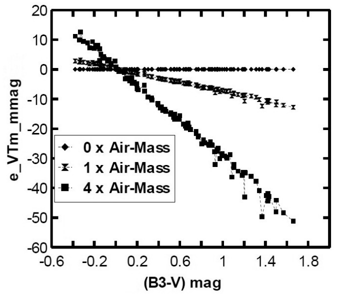

Figure 9. e_VTm magnitude deviation of the VT passband at airmass 0, 1, and 4, under the VT photometric system. The results shown are those of the 110 O-to-K spectra of the library.

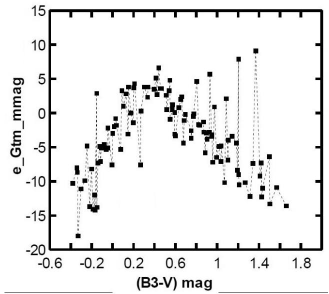

Figure 10. e_Gtm deviation of the CSIS transformation of the Gm DSLR channel to Johnson's Vjm at airmass 1.

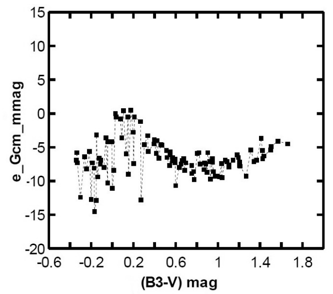

Figure 11. e_Gcm deviation of the VSF filter of the DSLR against Johnson's Vjm at airmass 1.

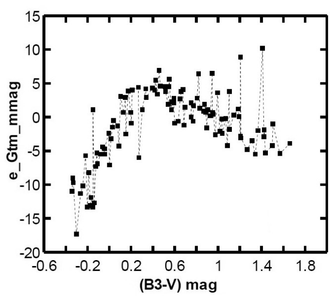

Figure 12. e_Gtm deviation of the CSIS transformation of the Gm DSLR channel to Johnson's Vjm at airmass 4.

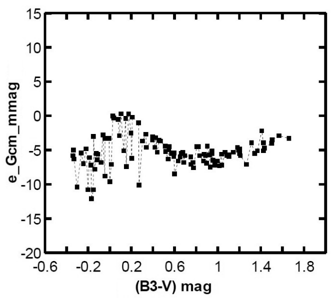

Figure 13. e_Gcm deviation of the VSF filter of the DSLR against Johnson's Vjm at airmass 4.

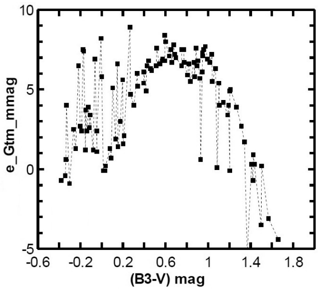

Figure 14. e_Gtm deviation of the CSIS transformation of the Gm DSLR channel to Tycho VTm at airmass 1.

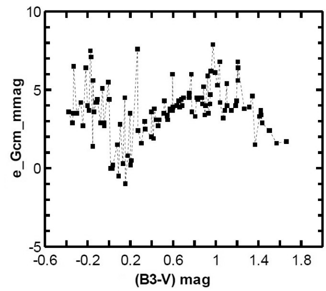

Figure 15. e_Gcm deviation of the VSF filter of the DSLR against Tycho VTm at airmass 1.

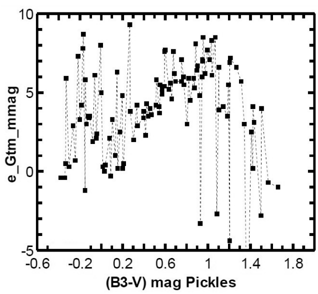

Figure 16. e_Gtm deviation of the CSIS transformation of the Gm DSLR channel to Tycho VTm at airmass 4. Outliers are few K stars.

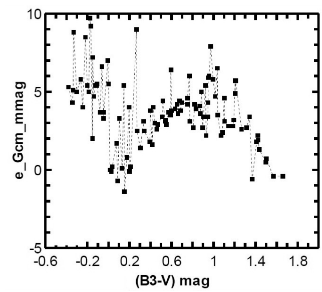

Figure 17. e_Gcm deviation of the VSF filter of the DSLR against Tycho VTm at

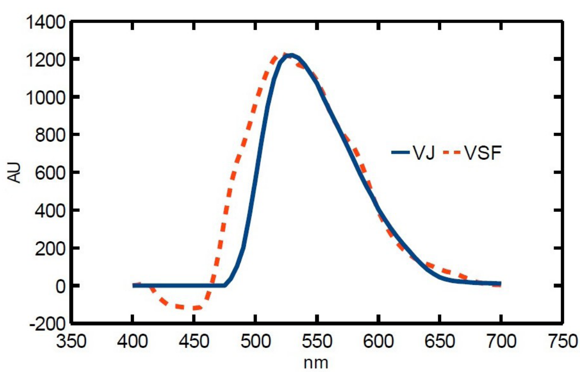

Figure 18. Response of the synthetic filter for a correction to VJ at airmass 0. This correspond to the correction of the DSLR alone. The DSLR R and B outputs are combined to G weighted with the coefficients "a" and "–b" from Table 1 (a = 0.34; b = 0.217). The resulting centroids of the two passbands keep within 1 nm in the –0.4~1.8 (B_3–V) range. The negative section in the blue provides a compensation of the residual excess of the blue roll-off of the VSF. It works like a complementary transformation.