Astron. Astrophys. 333, 673–677 (1998)

ASTRONOMY
AND
ASTROPHYSICS

Research Note

On the systematic accuracy of the equatorial UBV standards*

T. Oja[1] **and D.W. Evans**[2]

[1] Astronomical Observatory, Box 515, S-751 20 Uppsala, Sweden
[2] Royal Greenwich Observatory, Madingley Road, Cambridge CB3 0EZ, UK

Received 22 September 1997 / Accepted 20 January 1998

Abstract. Using photometric data from the TYCHO experiment of the HIPPARCOS mission the discrepancies in $B-V$ between the different series of measurement of the equatorial UBV standards have been studied. Corrections to the data by Landolt (1983) and Menzies et al. (1991) have been derived.

Key words: techniques: photometric – stars: fundamental parameters

1. Introduction

The discrepancies between the different series of UBVRI photometry of the equatorial standards (Landolt 1983; Wall et al. 1989; Menzies et al. 1991) are most alarming, especially so in $B-V$ where they amount to 0.02 mag. at maximum, while the mean errors of measurement for single stars are of the order of a few thousandths of a magnitude. This north-south discrepancy has been pointed out by Menzies et al. (1991) and by Oja (1994, 1995). Oja (1994) remeasured a sample of the equatorial standards together with a large number of stars in the list defining the UBV system (Johnson 1952, 1955), and concluded that Landolt's $B-V$ system very probably reproduced the original $B-V$ system better than the SAAO system, but the result was not quite conclusive.

The completion of the HIPPARCOS mission has made available a set of photometric data that contains stars all over the sky that should not be affected by systematic errors depending on declination, since all the data have been collected with the same instrumentation above the earth's atmosphere. The systematic differences between the different series of standards can thus be studied again using these independent data.

2. The data

The intercomparison of the different sets of (ground-based) UBV photometry was made via the HIPPARCOS satellite TYCHO magnitudes V_T and B_T (ESA, 1997) for stars contained in the HIPPARCOS Input Catalogue (Turon et al. 1992). Three sets of UBV photometry were compared with the TYCHO data, viz.

(i) those by Johnson (1955) supplemented with the data by Oja (1996) assumed to define the UBV system,
(ii) the equatorial standards measured by Landolt (1983), and
(iii) the southern hemisphere standards in the E and F regions and in the Magellanic clouds (Menzies et al. 1989).

At a later stage also data from the Geneva photometry were included in the discussion (Rufener 1988).

Standard errors are used throughout this paper.

3. Discussion

3.1. Comparison between the TYCHO magnitudes and the UBV standards

As a first step the relation between V and V_T, and between $B-V$ and B_T-V_T was established using only the UBV data given by Johnson (1955) and Oja (1996) in order to make sure that the relations derived really apply to the original UBV system.

It was at once obvious that the very brightest stars deviate considerably from the fainter ones (probably due to systematic errors in the TYCHO data), so all stars brighter than $V=2.2$ or $B=2.2$ were excluded from the discussion. After omitting supergiants, late-type dwarfs redder than $B-V=1.0$ and heavily reddened stars ($E_{B-V}>0.2$), in order to avoid ambiguous relations, the relation for the V magnitude becomes

$$\begin{aligned} V = V_T \;+\; & .004 - .115(B_T-V_T) + .008(B_T-V_T)^2 \\ & \pm\ .001 \pm .003 \qquad\qquad \pm\ .002 \end{aligned} \tag{1}$$

This relation is very close to Eq. [1.3.33] of the Hipparcos and Tycho Catalogues (ESA, 1997, Vol. 1).

For $B-V$ a reddening line was first derived from all O and B0-B1 stars. The result is

$$\begin{aligned} B-V \;=\; & 1.024(B_T-V_T) + .036 \\ & \pm .006 \qquad\qquad \pm\ .003. \end{aligned} \tag{2}$$

The relation for unreddened stars is obviously non-linear, see Fig. 1. (See also ESA, 1997, Vol. 1, Fig. 1.3.5 and Eqs. 1.3.24–1.3.32.) A relation was derived valid for main-sequence stars

* based on observations made with the ESA Hipparcos satellite.
Correspondence to: T. Oja

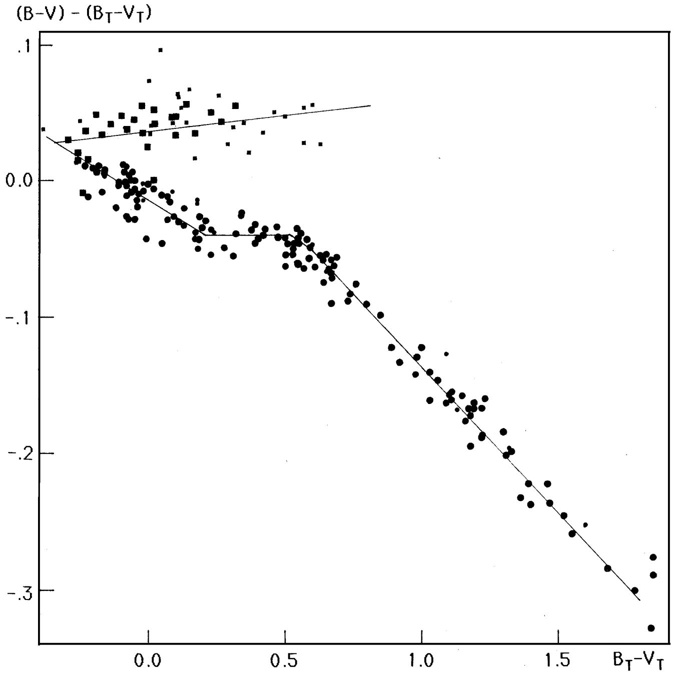

Fig. 1. The relation between Johnson's $B-V$ and the TYCHO colour $(B_T - V_T)$. Squares designate stars of spectral types $\mathrm{O}-\mathrm{B1}$ of all reddenings, circles unreddened stars of later spectral types. Small symbols: lower accuracy (mean error of the colour difference $> .02$).

bluer than $B-V = 1.0$ and all giants (except the reddest ones, $B_T - V_T > 1.8$) using different linear relations in different intervals of colour; the relation is drawn in Fig. 1. The TYCHO data for all stars were reduced to V and $B-V$ taking into account an excess term corresponding to Eq. (2), and weights were calculated in accordance with the mean errors of the TYCHO data. Known variables, supergiants of spectral type A0 and later, and late-type dwarfs redder than $B-V = 1.0$ were omitted from all discussions. The quality of the transformation can be seen from Table 1, where all the differences are in the sense reduced TYCHO *minus* Johnson. The reduced TYCHO photometry is systematically on the Johnson system to within a few thousandths of a magnitude.

The differences between the Johnson system and the transformed TYCHO system were also studied as a function of declination, since a systematic error depending on declination in Johnson's data could easily cause systematic differences between the northern and southern UBV systems. Table 2 lists the result of that comparison (TYCHO *minus* Johnson). Though there are a few rather large deviations in some declination zones, there is no general trend, and the stars south of Decl. $+30°$ (i.e. stars easily available to southern observers) do not deviate significantly from the stars north of that declination. A systematic error depending on declination in Johnson's data is thus no explanation for the north-south discrepancy.

Table 1. Differences between transformed TYCHO data and UBV standard values.

Interv. of $B-V$	Diff(V)	Diff($B-V$)
$-.3,\ -.2$	$-.002 \pm .002$	$+.008 \pm .002$
$-.2,\ -.1$	$-.005 \pm .003$	$+.002 \pm .001$
$-.1,\ \pm.0$	$+.001 \pm .002$	$\pm.000 \pm .001$
$\pm.0,\ +.1$	$-.001 \pm .002$	$+.001 \pm .001$
$+.1,\ +.2$	$+.001 \pm .002$	$-.002 \pm .001$
$+.2,\ +.3$	$+.002 \pm .003$	$+.002 \pm .002$
$+.3,\ +.4$	$+.005 \pm .003$	$-.005 \pm .002$
$+.4,\ +.5$	$+.003 \pm .003$	$+.008 \pm .002$
$+.5,\ +.6$	$+.001 \pm .002$	$+.002 \pm .002$
$+.6,\ +.7$	$-.001 \pm .004$	$+.001 \pm .002$
$+.7,\ +.8$	$-.008 \pm .005$	$+.002 \pm .004$
$+.8,\ +.9$	$-.001 \pm .003$	$-.001 \pm .003$
$+.9,\ +1.0$	$-.005 \pm .003$	$-.003 \pm .002$
$+1.0,\ +1.1$	$+.001 \pm .002$	$-.002 \pm .002$
$+1.1,\ +1.2$	$-.001 \pm .004$	$+.005 \pm .002$
$+1.2,\ +1.3$	$-.002 \pm .004$	$-.002 \pm .003$
$+1.3,\ +1.4$	$-.005 \pm .009$	$-.013 \pm .016$
$+1.4,\ +1.5$	$-.002 \pm .005$	$+.009 \pm .005$
$+1.5,\ +1.6$	$+.005 \pm .003$	$-.019 \pm .004$
$-.3,\ +1.6$	$\pm.000 \pm .001$	$+.001 \pm .0005$

Table 2. Differences between transformed TYCHO data and UBV standard values as a function of Declination.

Interv. of Decl.	Diff(V)	Diff($B-V$)
$90°, 60°$	$+.001 \pm .002$	$\pm.000 \pm .002$
$60°, 50°$	$-.001 \pm .002$	$+.001 \pm .001$
$50°, 40°$	$+.002 \pm .003$	$+.004 \pm .002$
$40°, 30°$	$+.002 \pm .002$	$-.003 \pm .001$
$30°, 20°$	$+.001 \pm .002$	$+.004 \pm .001$
$20°, 10°$	$-.004 \pm .002$	$+.003 \pm .001$
$10°, 0°$	$\pm.000 \pm .002$	$-.003 \pm .001$
$0°, -10°$	$-.003 \pm .003$	$+.001 \pm .002$
$-10°, -20°$	$-.018 \pm .009$	$+.006 \pm .003$
$30°, -20°$	$-.001 \pm .001$	$+.001 \pm .001$

Table 3. Differences between the transformed TYCHO data and the Landolt data.

Interv. of $B-V$	$\Delta(V)$	$\Delta(B-V)$
$-.3,\ \pm.0$	$-.010 \pm .005$	$-.002 \pm .003$
$+.0,\ +.3$	$+.016 \pm .008$	$-.018 \pm .004$
$+.3,\ +.5$	$+.002 \pm .011$	$-.005 \pm .007$
$+.5,\ +.7$	$+.001 \pm .011$	$+.004 \pm .007$
$+.7,\ +.9$	$-.004 \pm .012$	$-.007 \pm .009$
$+.9,\ +1.1$	$-.006 \pm .008$	$-.008 \pm .007$
$+1.1,\ +1.2$	$\pm.000 \pm .010$	$-.004 \pm .009$
$+1.2,\ +1.5$	$-.010 \pm .009$	$-.011 \pm .009$
$-.3,\ +1.5$	$-.003 \pm .003$	$-.007 \pm .002$

3.2. The Landolt system

There are 64 stars in common between the transformed TYCHO list and Landolt's list (1983). Most of these stars are quite faint, especially so in blue light, so the individual accuracy of the TYCHO data is rather low. The differences in the sense TY-

Table 4. Differences between the transformed TYCHO data and the SAAO data.

Interv. of $B-V$	ΔV	$\Delta(B-V)$
$-.3,\ -.2$	$-.002 \pm .009$	$-.001 \pm .007$
$-,2,\ -.1$	$-.001 \pm .002$	$\pm.000 \pm .002$
$-.1,\ \pm.0$	$-.001 \pm .002$	$-.008 \pm .001$
$\pm.0,\ +.1$	$+.002 \pm .003$	$-.010 \pm .002$
$+.1,\ +.2$	$+.002 \pm .002$	$-.017 \pm .002$
$+.2,\ +.3$	$+.007 \pm .003$	$-.013 \pm .002$
$+.3,\ +.4$	$+.008 \pm .002$	$-.016 \pm .002$
$+.4,\ +.5$	$+.004 \pm .002$	$-.007 \pm .002$
$+.5,\ +.6$	$+.001 \pm .002$	$-.004 \pm .002$
$+.6,\ +.7$	$-.001 \pm .004$	$-.010 \pm .004$
$+.7,\ +.8$	$-.025 \pm .010$	$+.005 \pm .010$
$+.8,\ +.9$	$-.007 \pm .004$	$-.015 \pm .004$
$+.9,\ +1.0$	$-.008 \pm .002$	$-.016 \pm .002$
$+1.0,\ +1.1$	$-.010 \pm .002$	$-.011 \pm .002$
$+1.1,\ +1.2$	$-.009 \pm .003$	$-.015 \pm .004$
$+1.2,\ +1.3$	$-.011 \pm .003$	$-.009 \pm .004$
$+1.3,\ +1.4$	$-.010 \pm .009$	$-.002 \pm .008$
$+1.4,\ +1.5$	$-.007 \pm .003$	$-.010 \pm .004$
$-.3,\ +1.5$	$-.001 \pm .001$	$-.010 \pm .001$
$-.1,\ +.4,\ E(B-V) < .1$		$-.012 \pm .001$
$-.1,\ +.4,\ E(B-V) > .1$		$-.013 + .003$

CHO *minus* Landolt are presented in Table 3. Assuming linear relations the result is

$$\Delta V = -.003 + .000(B-V) \pm.004 \pm .005 \tag{3}$$

$$\Delta(B-V) = -.006 - .003(B-V) \pm.002 \pm .004 \tag{4}$$

The deviations are barely significant, but the difference in $B-V$ in the interval $0.0 < B-V < 0.3$ is large. Apart from stars in that interval, the Landolt system is quite close to the Johnson system as far as can be judged from the present data and in accordance with the result by Oja (1994).

3.3. The SAAO system

There are 409 stars in common between the TYCHO data and the list of standards by Menzies et al. (1989) and many of them are quite bright, so the differences between these two systems can be established with much higher significance than in the case of the Landolt equatorial stars. The result is presented in Table 4.

As to V, a linear regression results in

$$\Delta V = +.003 - .008(B-V) \pm.001 \pm .001. \tag{5}$$

There seem to be, however, deviations from linearity amounting to several thousandths of a magnitude. They may be explained partly by omitted higher-order terms in the transformation between V_T and V, but that does not explain the trend for red stars.

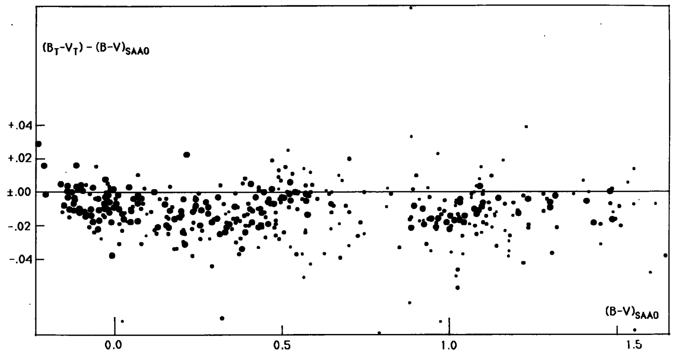

Fig. 2. The difference between $B-V$ derived from the TYCHO colour and $B-V$ measured at the SAAO as a function of colour. Larger dots carry higher weight.

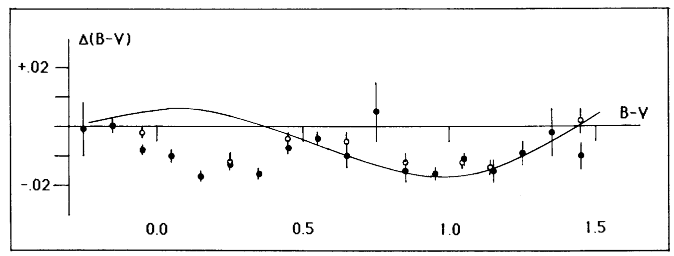

Fig. 3. The difference between the $B-V$ measured at the SAAO and other deteraminations (in the sense other source minus SAAO): the TYCHO data (filled circles), Oja (1994, open circles), Landolt (1983, full line). All error bars denote mean errors.

Thus, very probably the SAAO standard V magnitudes are affected by a colour equation approximately obeying Eq. (5).

The situation for $B-V$ is shown in Table 4 and Figs. 2 and 3. The SAAO $B-V$ values are on an average systematically $.010 \pm .001$ mag. redder than the transformed TYCHO colours. The full line in Fig. 3 shows the difference between Landolt's data and the SAAO data for the equatorial standards according to Menzies' (1991) Fig. 2b. The difference between Landolt and SAAO is practically identical with the difference between the transformed TYCHO data and the SAAO data for stars redder than about $B-V = .4$, so for these stars the SAAO measurements (of the standard stars in the E- and F-regions and in the Magellanic Clouds as well as the equatorial standards) suffer from a systematic error, while Landolt's data are very closely on the original Johnson system. This probably also holds for the very bluest stars ($B-V < -.1$). This conclusion is supported by the direct comparison between the Johnson system and the equatorial standards by Oja (1994, Fig. 3).

However, in the interval $-.1 < B-V < .4$ the situation is more complicated. If the transformed TYCHO data are systematically correct then the southern primary standards are too red by about .01; if Landolt's data are correct then the SAAO equatorial standards are too *blue* by about $.005$. The few stars in this interval of colour in Oja (1994) indicate both series of equatorial standards to be slightly too red. There are a few possibilities to explain the discrepancies

(i) the transformed TYCHO colours are too blue by more than 0.01 mag; this is far beyond the errors of the differences between Johnson and transformed TYCHO (Table 1) and indeed very unlikely;

(ii) the SAAO primary standards are not on the same system as the SAAO equatorial standards; systematic errors of the order of magnitude of more than 0.01 mag should, however, have been obvious during the reductions, but this possibility cannot completely be ruled out, as the colour distribution of the standards actually used is not known;

(iii) Landolt's data as well as the SAAO data are too red, the SAAO data slightly less than Landolt's. This would mean that Landolt's $B-V$ values are systematically about 0.015–0.020 too red, the SAAO colours about 0.012 too red. Such systematic errors seem indeed a priori improbable, but they are not impossible. As a matter of fact, $\Delta(B-V) = -.018 \pm .004$ for Landolt's data (Table 3) in the interval $.0 < B-V < .3$ as deduced from the TYCHO comparison. The direct comparison with Oja (1994) gives $\Delta(B-V) = -.010$ in the same interval for the two unreddened stars (even $-.016$ if the two additional slightly reddened stars are included in the comparison).

(iv) Perhaps some part of the explanation could be found in insufficient reddening corrections. Amongst the stars available from the southern hemisphere for the transformation of an instrumental system to standard UBV (Johnson 1955) there are few heavily reddened stars, the majority of those being located at high northern declination. It is therefore difficult to derive accurate reddening lines for an observer in the south. Most reddened O and B stars are located in this interval of colour, so differences between different sets of data may arise from different proportions of reddened and unreddened stars combined with erroneous (or neglected) excess terms in the transformation equations. Neither Landolt (1981) nor Menzies et al. (1991) mention the colour-excess terms of the transformation equations, while this effect was properly taken into account above when transforming the TYCHO data to $B-V$. However, the number of reddened stars amongst the southern standards is small and does not influence the result significantly, nor do these stars deviate from the unreddened ones (see Table 4). This also holds true for the equatorial standards; a study of the differences between Landolt and SAAO as a function of colour excess shows no significant correlation with colour excess, so excess terms are not the explanation of the discrepancies.

4. Comparison with the Geneva photometry

In order to investigate further the discrepancies in $B-V$ found above for A and F stars the extensive body of photometric data collected by the Geneva observers (Rufener, 1988) was used. The Geneva system suffers from some systematic errors running with right ascension and declination (Pel, 1991), but if the errors are just zero-point errors, a comparison between the F stars and the late-type giants in the north and south separately could still yield independent results.

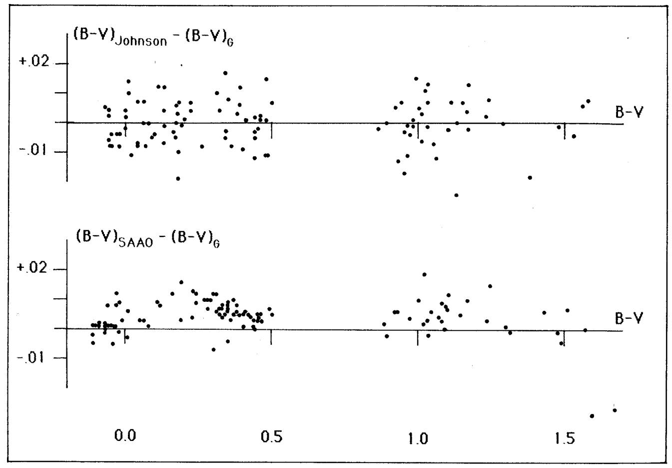

Fig. 4. The difference between Johnson's $B-V$ and the $B-V$ calculated from the Geneva photometry (upper half) and between the $B-V$ measured at the SAAO and the $B-V$ calculated from the Geneva photometry (lower half).

At first linear relations were derived between $B-V$ and the Geneva colours V and $(B2-V1)$. Using the Johnson standards and a few more stars included by Oja (1996) the result, valid in the colour interval $-0.1 < B-V < 0.5$, is

$$\begin{aligned}(B-V)_1 &= 0.787 - 0.826V \\ &\quad \pm.003 \ \pm.004 \\ (B-V)_2 &= 0.179 + 1.194(B2-V1) \\ &\quad \pm.002 \ \pm.010\end{aligned} \tag{6}$$

The dispersions are 0.008 and 0.012 respectively. A combined weighted $B-V$ value was calculated according to

$$(B-V)_{\rm G} = [(B-V)_1 + 0.4(B-V)_2]/1.4. \tag{7}$$

In order to check the north-south inconsistency within the Geneva photometry (obviously present at least for the colour $B2-V1$, see Pel, 1991), the same procedure was applied to late-type giants, for which the difference between Johnson and Menzies et al. is well established. For these stars the result is

$$\begin{aligned}(B-V)_1 &= 0.776 - 0.759V \\ &\quad \pm.003 \ \pm.005\end{aligned} \tag{8}$$

$$\begin{aligned}(B-V)_2 &= 0.234 + 1.136(B2-V1) \\ &\quad \pm.010 \ \pm.013\end{aligned} \tag{9}$$

the dispersions being 0.009 and 0.014 respectively. A weighted mean was again calculated according to Eq. (7). In Fig. 4 the difference $(B-V)_{\rm SAAO}$ and $(B-V)_{\rm G}$ is plotted as a function of colour. If the Geneva system is homogeneous then the SAAO colours are too red for the early-type stars as well as for the late-type giants, but not as much as the direct comparison between TYCHO and SAAO indicates (Table 4 and the open circles in Fig. 3). However, the error of the SAAO giants being

Table 5. Corrections to the measurements of $B-V$ at the SAAO (Menzies et al. 1989, 1991) and by Landolt (1983)

	Correction to the SAAO $B-V$ from					Corr. to
$B-V$	TYCHO	Geneva	Oja	Landolt	Smoothed	Landolt
$-.25$	$-.001 \pm .007$					
$-.15$	$\pm.000 \pm .002$				$\pm.000$	$\pm.000$
$-.05$	$-.008 \pm .001$	$-.009 \pm .001$	$-.002 \pm .002$		$-.006$	$-.011$
$.05$	$-.010 \pm .002$	$-.010 \pm .002$			$-.011$	$-.017$
$.15$	$-.017 \pm .002$	$-.016 \pm .002$			$-.014$	$-.020$
$.25$	$-.013 \pm .002$	$-.014 \pm .001$	$-.012 \pm .003$		$-.014$	$-.018$
$.35$	$-.016 \pm .002$	$-.013 \pm .001$			$-.013$	$-.013$
$.45$	$-.007 \pm .002$	$-.011 \pm .001$	$-.004 \pm .002$	$-.003$	$-.007$	$-.004$
$.55$	$-.004 \pm .002$			$-.006$	$-.005$	$\pm.000$
$.65$	$-.010 \pm .004$		$-.005 \pm .003$	$-.009$	$-.008$	
$.75$	$+.005 \pm .010$			$-.013$	$-.011$	
$.85$	$-.015 \pm .004$		$-.012 \pm .003$	$-.016$	$-.014$	
$.95$	$-.016 \pm .002$	$-.011 \pm .003$		$-.016$	$-.014$	
1.05	$-.011 \pm .002$	$-.012 \pm .001$	$-.012 \pm .002$	$-.016$	$-.014$	
1.15	$-.015 \pm .004$	$-.015 \pm .003$	$-.014 \pm .002$	$-.014$	$-.014$	
1.25	$-.009 \pm .004$	$-.016 \pm .003$		$-.010$	$-.011$	
1.35	$-.002 \pm .008$	$-.007 \pm .003$		$-.005$	$-.006$	
1.45	$-.010 \pm .004$	$-.007 \pm .003$	$+.002 \pm .004$	$+.001$	$\pm.000$	

well established from the comparisons with TYCHO, Landolt (Menzies 1991), and Oja (1994) the difference between TYCHO and Geneva as demonstrated by Fig. 4 has most probably to be interpreted as a general north-south transfer zero-point error in the Geneva photometry amounting to $-.007\pm.001$ (north *minus* south) in $(B-V)_{\rm G}$. Assuming this to be true, corrections to the SAAO $B-V$ colours were derived from Fig. 4. The resulting corrections to the SAAO measurements of $B-V$ from

(i) the direct comparison with TYCHO (this paper, Table 4),
(ii) the comparison with the Geneva photometry,
(iii) the direct comparison by Oja (1994),
(iv) the comparison with Landolt (Menzies et al. 1991, Fig. 2b)

are presented in Table 5, which also contains smoothed values as well as a correction to Landolt's equatorial standards in the colour interval $-0.2 < B-V < +0.5$ derived from those smoothed values in combination with Menzies et al.'s Fig. 2b.

5. Conclusion

Combining all the evidences from the comparisons between the Johnson (1952, 1955) UBV standards, the three series of measurements of the equatorial standards by Landolt (1983), the SAAO observers (Menzies et al. 1991, Wall et al. 1989), and Oja (1994), the measurements of the southern standards at the SAAO (Menzies et al. 1989), the TYCHO measurements and the Geneva photometry (Rufener 1988), it has been shown that

(i) the SAAO measurements of $B-V$, of the E- and F-region and Magellanic Cloud standards as well as of the equatorial standards, are generally slightly too red and should be corrected by Table 5, column 6 in order to bring them to the original Johnson system;
(ii) Landolt's measurements of $B-V$ of the equatorial standards are on the original Johnson system with the exception of the colour interval $-0.2 < B-V < 0.5$ where they are too red and should be corrected by Table 5, column 7.

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