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TESTS OF BROADBAND PHOTOMETRIC CONSISTENCY FOR STANDARD STARS, THE HYADES, AND M67

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ABSTRACT

New South African Astronomical Observatory (SAAO) $BV(RI)_C$ measurements of 19 Hyades stars and 11 M67 stars are reported. The zero points of the new color indices conform closely to those of SAAO data reported in a previous paper. In addition, the new M67 measurements of $(V-R)_C$ and $(R-I)_C$ are compared to data published previously by Taylor, Joner, and Jeffery. The results support conclusions drawn by those authors that the scale factors of their data are correct and that a scale factor problem exists in measurements published by Montgomery, Marshall, and Janes. The new values of $B-V$ are used with *Tycho* data in tests of extant Hyades and M67 measurements and of the accuracy of the SAAO $B-V$ system. A problem encountered previously with the Hyades $B-V$ zero point is resolved, and an extant Hyades relation between $B-V$ and $(R-I)_C$ is re-zeroed. A satisfactory zero point is also obtained for M67, and published photomultiplier values of $B-V$ are reduced to that zero point, averaged, and tabulated. It is found that the zero point of $B-V$ data published by Sandquist is satisfactory. However, tests of $B-V$ measurements made by Montgomery et al. suggest that those data are not on a single zero point. Finally, the scale factor of the E region $B-V$ system is found to be satisfactory, but a well-supported interim conclusion is drawn that E region values of $B-V$ should be corrected by about −9 mmag. It is suggested that this conclusion be tested by using instrumental systems that have not yet contributed to the testing process.

Key words: methods: statistical – open clusters and associations: individual (M67, Hyades) – stars: fundamental parameters – techniques: photometric

1. INTRODUCTION

It has been known for some time that when published bodies of broadband photometry are compared, disturbing inconsistencies can be found. This problem has appeared repeatedly when systems of standard stars are tested (see for example, Oja 1994; Menzies & Marang 1996). In addition, it has appeared when measurements of cluster stars are collected from diverse sources (see especially Table 3 of Stetson et al. 2004). As a result, theorists who wish to analyze cluster data may be constrained to discuss their accuracy at length before making even tentative choices among them (see for example, Section 2.2 of VandenBerg & Stetson 2004).

Partly because they are so persistent, problems like these are arguably the most significant challenges that photometrists face. Fortunately, it is possible to overcome them in at least three ways. For *BV* photometry specifically, one may appeal to the *Tycho* B_T, V_T system (Perryman et al. 1997). This system is likely to be uniform over the entire sky, and it can be transformed with confidence to a useful version of *BV* photometry (see Section 4). By applying this system, one can escape obstacles such as azimuthal extinction variation and photomultiplier flexure that can hamper ground-based photometry.

A second possibility is to compare groups of stars by measuring them on the same nights with a single instrumental system. As far as we know, the earliest published examples of this procedure appear in Sturch (1972, 1973). Useful results may be obtained from either straightforward "Sturch exercises" or from overlapping sets of such exercises.

A third possibility is to apply measurements made with an unusually stable instrumental system. This procedure is suitable for both *BV* data and Cousins *RI* photometry. In particular, it has been adopted recently in the first paper in this series (Joner et al. 2006, hereafter Paper I). Using a dedicated *BVRI* system at the South African Astronomical Observatory (SAAO), the authors made new measurements of the Hyades and then compared them to previously published photometry.

In this paper, we follow up on the analysis performed in Paper I. Using further SAAO photometry of the Hyades and new SAAO photometry of M67, we investigate four problems. One of these concerns the character of extant $V(RI)_C$ photometry for M67. In this case, we augment a discussion given recently by Taylor et al. (2008). A second problem concerns the zero point of Hyades $B-V$ photometry, and it was discussed but not solved in Paper I. The third problem concerns the zero point of M67 $B-V$ photometry, and the fourth is the overall relationship of the SAAO and Johnson $B-V$ systems.

The structure of this paper is as follows. A brief description of reduction procedures appears in Section 2, and the new data are also presented there. Statistical procedures and photometric transformations are described briefly in Sections 3 and 4, respectively. In Section 5, the M67 and Hyades *VRI* measurements are compared with previously published data. $B-V$ analyses appear in Section 6 (for field stars and the Hyades) and Section 8 (for M67). Section 7 resolves a problem posed by the zero-point status of photometry by Johnson and his collaborators, while Section 9 explores a problem posed by the conclusions drawn in Section 6. The paper concludes in Section 10 with a review of results.

2. REDUCTION PROCEDURES AND RESULTS

As in Paper I, measurements were made with the 0.5 m telescope and modular photometer at the SAAO Sutherland station. The Hyades were observed from 2006 October through 2007 January, while M67 was observed from 2006 January through 2007 April. The adopted reduction procedures have been described in Section 2 of Paper I, so only a few comments about them will be made here. We first note that substantial nonlinear corrections were not applied to the data because very blue

Table 1
New SAAO $BV(RI)_C$ Data for the Hyades

vB[a]	HIP	GSC[b]	V^c	$B-V^c$	$V-R^c$	$R-I^c$	$V-I^c$	n^d
7[e]	18327	01253–00868	8.996(3.2)[f]	0.906(3.7)	0.490(2.0)	0.426(2.0)	0.916(2.8)	6
64[g]	20741	01265–00241	8.106(6.6)	0.677(4.7)	0.362(2.5)	0.341(4.2)	0.703(2.8)	4
66[g]	20826	00676–00062	7.503(2.3)	0.562(6.6)	0.315(2.0)	0.295(4.1)	0.608(4.5)	3
89[g]	21137	01265–01173	6.008(2.5)	0.333(3.4)	0.199(1.8)	0.192(2.1)	0.391(1.3)	4
109	21741	01830–01358	9.390(5.5)	0.823(5.3)	0.431(6.1)	0.395(3.3)	0.825(7.8)	4
173	20485	01264–00902	10.464(4.3)	1.242(2.8)	0.735(3.0)	0.622(1.7)	1.357(3.0)	6
174[g]	20563	01269–01212	9.980(5.0)	1.069(3.3)	0.598(2.5)	0.504(1.9)	1.101(2.3)	4
175[g]	...	01269–00128	10.275(2.5)	1.035(2.3)	0.584(2.0)	0.487(1.5)	1.071(2.7)	3
176[g]	20679	...	9.015(1.5)	0.946(3.0)	0.526(1.9)	0.455(2.0)	0.981(0.3)	3
181[h]	...	...	10.318(9.0)	1.168(2.5)	0.676(2.8)	0.575(2.4)	1.252(3.0)	3
183[g]	...	01266–00944	9.649(1.8)	0.928(5.0)	0.503(2.0)	0.437(4.9)	0.940(3.5)	5
229	19263	01250–00414	9.907(4.4)	1.034(1.8)	0.575(1.9)	0.485(2.9)	1.060(4.2)	6
231	19207	01250–00004	10.465(3.5)	1.192(3.3)[i]	0.695(3.3)	0.583(3.0)	1.278(1.3)	5
253	20086	01268–00707	9.989(4.7)	1.119(1.7)	0.655(1.9)	0.612(1.0)	1.267(2.1)	4
262	20527	00680–00889	10.872(4.5)	1.299(8.4)[i]	0.774(2.2)	0.665(5.5)	1.439(3.3)	4
291	21261	01274–01346	10.687(5.2)	1.233(8.4)[i]	0.721(3.1)	0.596(2.7)	1.317(4.9)	5
311	21723	00690–00945	10.020(10.0)	1.092(8.5)	0.621(8.0)	0.516(3.0)	1.137(5.0)	2
324	...	01279–02259	9.823(4.5)	1.071(3.6)	0.602(3.2)	0.508(1.5)	1.110(4.6)	5
...	19808[j]	00675–00186	10.675(2.7)	1.239(9.2)[i]	0.733(2.3)	0.637(2.9)	1.370(2.1)	4
σ_0[k]	...	...	0.009	0.008	0.006	0.006	0.008	...

Notes.
[a] This is the van Beuren (1952) number.
[b] This is the number from the *Hubble Guide Star Catalog.*
[c] Entries in parentheses are standard deviations in millimags derived from the scatter for each individual set of measurements. The $B-V$ data are on the SAAO (not the Johnson et al. 1966) zero point. Values of V and $V-R$ are on the Cousins (not the Landolt) system. (For a transformation between the two systems, see Equation (5) of Taylor & Joner 1996).
[d] Number of measurements.
[e] Judging from the new V datum and its counterpart in Table 2 of Paper I, this star is variable in V with a range of about 32 mmag.
[f] This datum has been derived from five measurements.
[g] Measurements in Paper I and/or this paper suggest that this star may vary in V.
[h] This star is HD 285805.
[i] For these measurements, $\sigma_0 = 15.8$ mmag.
[j] This star is vA 68.
[k] The quoted values of σ_0 are rms errors in millimags. Each value has been derived from at least 79 measurements.

and very red stars were avoided. In the SAAO reduction procedure, the largest of these corrections range from 20 to 60 mmag (in absolute value). For the G and K dwarfs considered in Paper I, however, such corrections did not exceed 2 mmag. Here, despite the fact that measurements of the B star F 81 (see Johnson & Sandage 1955) are included, the corresponding upper limit to the corrections is only 6 mmag.

It should also be noted that (as in Paper I) the adopted extinction coefficients for each night were tested by comparing measurements of standard stars made near the zenith with measurements made at air masses of at least 1.5. That practice was deemed to be adequate for observing M67 and the Hyades because at Sutherland both clusters culminate at about 1.4 air masses. Finally, there was continued reliance on the stability of derived transformation coefficients during intervals of several months. Encouraging support for the success of these policies is offered by the close agreement between the zero points of the new data and those of the Paper I data (see Section 5 and entry 1 of Section 6).

The new data (for 19 Hyades stars and 11 M67 stars) are given in Tables 1 and 2, respectively. The M67 data are limited to stars with $V < 11.5$ because of the size of the telescope used.[3] It should be noted that Table 2 includes measurements of S1082 = ES Cnc, a triple system and eclipsing binary (see Van den Berg et al. 2001 and Sandquist et al. 2003) whose status was noted only after it had been included in our list of program stars. Results of individual measurements of ES Cnc are given in Table 3.

[3] Here and below, data quoted in magnitudes are stated without units. If millimags are used instead, that unit is always stated.

3. STATISTICAL PROCEDURES

Two statistical procedures used in Paper I are also applied here. One (a χ^2 differencing algorithm) is used to compare the zero points of data vectors. The other is a two-error least-squares algorithm that is used to derive linear relations between photometric data vectors. This algorithm yields values of $s \equiv 100(S-1)$, with S being a slope.

Most of the pertinent details about these procedures are given in the Appendix to Paper I. However, that source does not include an algorithm for identifying wild points that can appear when either of the two adopted procedures is applied. Wild points are detected by applying Thompson t tests, and the results are then interpreted by using false-discovery rate (FDR). The Thompson t test is the second statistical tool described in Section 6.2 of Taylor (2000). A convenient summary of FDR appears in Section 3 of Miller et al. (2001).

Other statistical procedures applied here include (1) the basic Student's t test, (2) the F (variance-ratio) test, (3) a

Table 2
New SAAO $BV(RI)_C$ Data for M67

F[a]	Sanders[b]	V[c]	$B-V$[c]	$V-R$[c]	$R-I$[c]	$V-I$[c]	n[d]
55	752	11.316(3.9)	0.299(2.6)	0.165(1.8)	0.170(3.5)[e]	0.332(5.7)	17
81	977	10.017(3.2)	−0.071(1.9)	−0.030(1.1)	−0.031(2.7)	−0.067(2.1)	18
105	1016	10.282(5.6)	1.262(3.1)	0.645(1.1)	0.572(3.0)	1.217(4.4)	15
131[f]	1082	...[f]	0.426(3.3)	0.250(2.2)	0.256(3.7)	0.505(5.3)	5
136	1072	11.284(2.6)	0.645(4.1)	0.359(1.7)	0.344(2.6)	0.702(3.5)	16
141	1010	10.459(6.9)	1.117(4.7)	0.559(2.6)	0.501(3.2)	1.060(3.8)	4
151	1084	10.481(5.0)	1.103(2.0)	0.552(1.5)	0.498(2.1)	1.050(2.9)	15
153	968	11.265(2.9)	0.124(2.3)	0.052(1.9)	0.054(6.1)	0.106(6.8)	16
170	1250	9.645(4.0)	1.350(2.4)[g]	0.693(1.2)	0.611(2.5)	1.304(2.3)	15
223	1316	10.522(4.6)	1.116(2.2)[e]	0.563(1.4)	0.504(2.9)	1.068(3.8)	13
266	1479	10.491(4.6)	1.112(2.5)[e]	0.553(2.6)	0.499(2.5)	1.052(4.1)	14

Notes. None of the tabulated data have been corrected for reddening.
[a] This is the Fagerholm (1906) number and also the WEBDA number.
[b] This is the Sanders (1977) number.
[c] Entries in parentheses are standard deviations in millimags derived from the scatter for each individual set of measurements. The $B-V$ data are on the SAAO (not the Johnson et al. 1966) zero point. Values of $V-R$ are on the Cousins (not the Landolt) system. (For a transformation between the two systems, see Equation (5) of Taylor & Joner 1996.)
[d] Number of measurements.
[e] One wild point has been deleted, leaving $n-1$ contributing data.
[f] This star is ES Cnc (Sandquist et al. 2003). See Appendix for individual measurements.
[g] Two wild points have been deleted, leaving 13 contributing data.

Table 3
New SAAO $BV(RI)_C$ Data for ES Cnc

HJD[a]	Phase[b]	V	$B-V$	$V-R$[c]	$R-I$	$V-I$
120.04922	0.094	11.206	0.421	0.255	0.269	0.524
128.51353	0.021	11.253	0.416	0.250	0.255	0.505
129.51890	0.962	11.237	0.428	0.249	0.247	0.496
154.38413	0.249	11.157	0.429	0.252	0.255	0.507
212.27027	0.459	11.185	0.435	0.242	0.252	0.494

Notes. None of the tabulated data have been corrected for reddening.
[a] Add 2,454,000 to the listed dates.
[b] Phases have been calculated from the ephemeris of van den Berg et al. (2001).
[c] Values of $V-R$ are on the Cousins (not the Landolt) system. (For a transformation between the two systems, see Equation (5) of Taylor & Joner 1996.)

data-comparison algorithm, and (4) the unequal-variance t test. The first and second of these procedures are basic algorithms described in numerous statistics texts. The third procedure is the third statistical tool described in Section 6.2 of Taylor (2000). The fourth procedure is illustrated in the notes to Table 3 of Taylor (1992).

To grasp the results from the tests, it is useful to take note of some definitions. For an isolated test, let C be the derived confidence level and $p \equiv 1 - C$ be the false-alarm probability (or, to be more exact, the probability of Type I error). Because the meaning of C can be hard to visualize if it differs from zero by a small amount, values of $P \equiv -\log_{10}(20p)$ are stated instead. Note that $P = 0$ if C is exactly 95% and that positive values of P imply that $C > 95\%$.

For each test performed in this paper, a value of P is calculated. Each calculation includes an allowance for the number N of contributing data, so values of P based on small values of N are not less reliable than those based on large values of N. The results of the tests are stated in ways that depend on their outcomes. If $P < 0$, its value is not given, and a note is instead made that a null result has been obtained. This outcome is often stated by noting that a statistic that does not differ from zero at the 2σ level has been obtained. If $P > 0$, its meaning must be assessed by applying FDR because multiple tests are performed (see Section 2 of Miller et al. 2001). The only values of P given below are those that turn out to be significant with an *overall* confidence level of at least 95%.

4. PHOTOMETRIC TRANSFORMATIONS

Turning to photometric transformations, we note that two of them are applied below. One is the following relation between Strömgren photometry and $B-V$:

$$B - V = 1.520(b - y) + 0.604m_1 - 0.105 + 0.005E(B - V). \tag{1}$$

This relation is applied to photometry from overlapping Sturch exercises (Taylor & Joner 1992; Joner & Taylor 1997). All quantities in the relation are stated in magnitudes, and $B-V$, $b-y$, and m_1 are not corrected for reddening. The relation is valid if $0.05 \leqslant B - V \leqslant 0.70$. Its original version is from Cousins (1987), but its zero point has been rederived by using $B-V$ values from Johnson et al. (1966, hereafter JMIW). In addition, the reddening term has been included by using reddening coefficients from the Asiago database.[4]

Especially because an m_1 term is included in Equation (1), values of $B-V$ derived by using that equation may be sensitive to metallicity differences. However, metallicity corrections are neglected here because the metallicities of the program stars are very similar. For field stars, the mean value of [Fe/H] is -0.041 ± 0.013 dex (Taylor & Croxall 2005). For the Hyades and M67, the values of [Fe/H] are 0.103 ± 0.008 dex and -0.009 ± 0.009 dex, respectively (see Table 11 of Taylor & Joner 2005 and Table 8 of Taylor 2007, respectively).

The other relation applied here is used to transform *Tycho* photometry to values of $B-V$. One way to do this is to adopt a

[4] See http://ulisse.pd.astro.it/Astro/ADPS

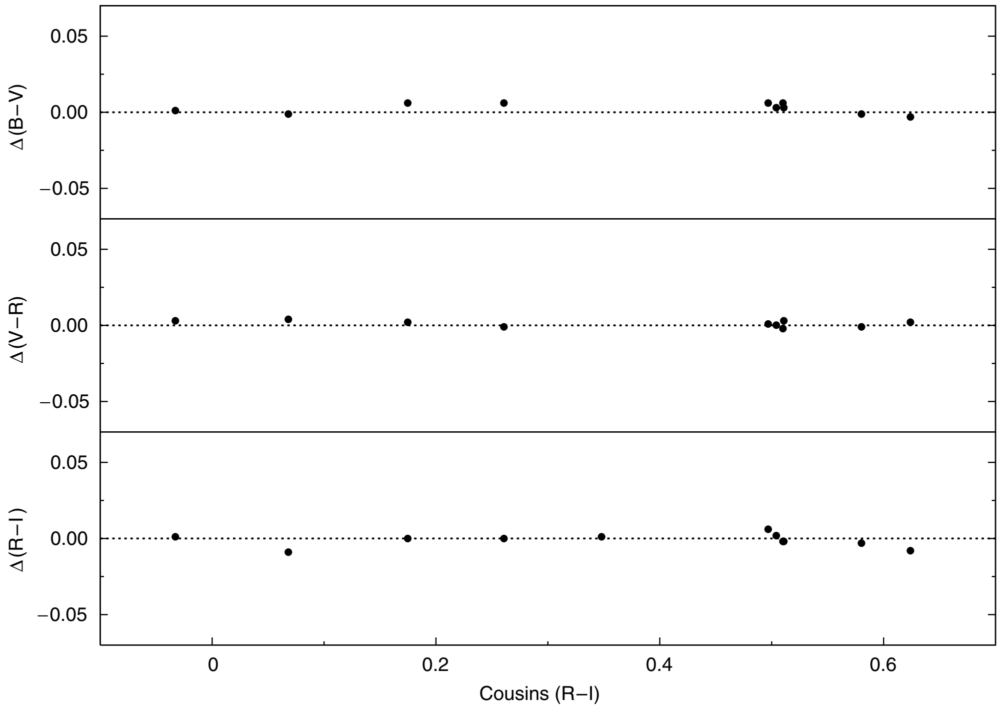

Figure 1. In the upper panel, M67 $B-V$ residuals (in the sense "SAAO minus interim consensus") are plotted against $(R-I)_C$. In the middle and lower panels, M67 $(V-R)_C$ and $(R-I)_C$ residuals (in the sense "SAAO minus Taylor et al. 2008") are plotted against $(R-I)_C$.

linear transformation given by Perryman et al. (1997). However, we instead adopt a nonlinear transformation to the SAAO system given in Table 2 of Bessell (2000). That algorithm is based on data for more than 600 stars, and its shape appears to be quite adequate over a wide color range (see Figure 4 in Bessell's paper). Its zero point will be tested as the analysis proceeds.

In accordance with a recommendation by Taylor & Joner (2006), we briefly review some possible systematic effects on output data from these transformations. Bessell's relation is applied only to stars that are unlikely to be reddened, while Equation (1) is applied only to stars with $E(B-V) < 0.05$. The effects of Balmer-line variation on results from Equation (1) are limited by applying the equation only to data for AF V stars. CN effects on results from Bessell's transformation are limited by applying the transformation to data for G and K giants, but not to data for dwarfs later than G2 (which appear to be missing from the *Tycho* catalog in any event). No corrections for the effects of binarity are made because the passbands of the original and the transformed data are reasonably close to each other in wavelength space (see notably Figure 5 in Bessell's paper). No corrections for rotational effects are made because they appear to be negligible (see Sections 4.2 and 4.3 of Taylor 2008).

5. ANALYSIS OF THE $(V-R)_C$ AND $(R-I)_C$ MEASUREMENTS

The first data to be considered here are *VRI* results for the Hyades. Those data can be used to improve on an existing transformation between $(V-K)_J$ and $(R-I)_C$ (see the Appendix). In addition, the 19 Hyades stars measured include eight with measurements reported in Paper I, so a consistency check between the new data and those of Paper I can be performed. The formal $(V-R)_C$ and $(R-I)_C$ corrections required to put the new data on the Paper I zero points turn out to be 0.0 ± 1.6 and 0.2 ± 1.6 mmag, respectively. Clearly, the zero points for the two data sets agree closely.

The M67 measurements are considered next. Here, the topic of interest is the relationship between the new SAAO data and a set of databases considered by Taylor et al. (2008). In Sections 5.3 and 6 of their paper, those authors discussed the relationship between a new M67 database they had presented, extant results from Montgomery et al. (1993) and other sources, and the SAAO data given in this paper. Using those results, Taylor et al. showed that the zero points of their newly presented data are acceptably close to the zero points of the E region standards. However, they also performed a scale factor analysis that did not include a comparison between their new data and the SAAO measurements. That omission is significant because for all results they considered except those of Montgomery et al., s could not be distinguished from zero at 95% confidence. When the Montgomery et al. data were compared to their own data set, s was found to be 2.7 ± 1.1, and the hypothesis that $s = 0$ was rejected with $P = 0.55$. Clearly, one would like to be as certain as possible about the source of this problem.

The procedure adopted here is to compare the scale factors of the SAAO data with those of the data presented by Taylor et al. Residuals derived from that comparison are plotted against values of $(R-I)_C$ in the lower two panels of Figure 1. Note that for both $(V-R)_C$ (middle panel) and $(R-I)_C$ (lower panel), the lines of residuals are essentially flat and display only small amounts of scatter. Small and precise values of s are therefore expected, and in fact s is found to be -0.37 ± 0.23 for $(V-R)_C$ and 0.0 ± 0.65 for $(R-I)_C$. Since neither value of s differs from zero by at least twice its standard error, we conclude with some confidence that the measurements published by Taylor et al. (2008) have the same scale factor as the SAAO data. Presumably that scale factor is correct, and the scale factor problem described above can be attributed to the Montgomery et al. (1993) data.

Table 4
$B - V$ Tests: Hyades and Field Stars

Entry	Stars	Extrinsic Source	Extrinsic Index	Tested Source	Tested Index	$\Delta(B-V)$ (mmag)	P[a]
1	Hyades	SAAO (Paper I)	$B-V$	SAAO (Table 1)	$B-V$	-1.5 ± 2.2	...
2	Hyades	SAAO (Paper I)	$B-V$	JK55[b]	$B-V$	8.1 ± 1.3	>4.7
3	Hyades	SAAO (*Tycho*)	$B_T - V_T$	SAAO (Paper I)	$B-V$	0.2 ± 1.6	...
4	Field	JMIW_1[c,d]	$B-V$	SAAO (*Tycho*)	$B_T - V_T$	-9.4 ± 1.5	>4.7
5	Field	JMIW_2[c,e]	$B-V$	SAAO (*Tycho*)	$B_T - V_T$	-8.4 ± 1.6	>4.7
6	Field	JMIW_2[c,f]	$B-V$	SAAO (*Tycho*)	$B_T - V_T$	-10.1 ± 2.6	2.0
7[g]	Both	JMIW_1[c]	$B-V$	JK55[b]	$B-V$	$* -1.3 \pm 2.0 *$	...
8	Hyades	TJ92[h]	$b-y, m_1$	JK55[b]	$B-V$	$* -5.8 \pm 2.8 *$	...
9	Hyades	J63, S73[i]	$B-V$	JK55[b]	$B-V$	$* -4.9 \pm 2.3 *$	...
10	Both	...[j]	...	JK55[b]	$B-V$	-3.5 ± 1.3	0.7

Notes. The entries in the penultimate column are differences in the sense (extrinsic source minus tested source). The standard errors quoted in that column include allowances for accidental errors introduced by reduction and transformation relations when such allowances are required.
[a] Values of P are quoted if the overall significance level (see Miller et al. 2001) is >95%.
[b] The source paper is Johnson & Knuckles (1955).
[c] The source paper is JMIW (Johnson et al. 1966).
[d] This sample is drawn from AF V and GK III stars with $V > 2$ and 9 or more measurements by JMIW. Johnson & Harris (1954) standards make up 69% of the sample.
[e] This sample is drawn from AF V and GK III stars with $V > 2$ and 6 or more measurements by Johnson et al. Johnson & Harris (1954) standards make up 31% of the sample.
[f] This sample is drawn from the list of unreddened B III–V stars in Table 10 of Taylor (2008) with $V > 2$. Johnson & Harris (1954) standards make up 29% of the sample.
[g] In this entry, the sum of entries 2 and 4 is given.
[h] The source paper is Taylor & Joner (1992).
[i] Standards given by Johnson (1963) are compared to the Hyades by Sturch (1973).
[j] This entry is a weighted average of the three entries just above it.

6. A $B - V$ ANALYSIS FOR FIELD STARS AND THE HYADES

We now direct our attention to $B - V$ measurements of field standard stars and Hyades stars. A numerical result for each step in the resulting analysis is given in Table 4. Supplementary details (including some not discussed below) appear in the table's footnotes. The steps in the analysis are as follows.

Entry 1. This entry is included to show that the SAAO instrumental system is as stable in $B - V$ as it is in $(V - R)_C$ and $(R - I)_C$.

Entry 2. In Section 4.3 of Paper I, the Hyades measurements reported in that paper are compared with the data of Johnson & Knuckles (1955). A disquieting offset found through this comparison is shown in Table 4.

Entry 3. Because the Hyades lie well to the north of the E region standards, the offset might be produced by an effect in the SAAO instrumental system that varies with declination. To test this possibility, the Paper I Hyades data are compared with transformed *Tycho* photometry. Both of these data sets have been reduced to the E region system, but this was done using ground-based photometry for the first data set and satellite photometry for the second. As a result, a comparison of the two data sets yields a consistency test.

Note that according to entry 3, no detectable zero-point offset is found. This test is reasonably stringent: the 2σ limit obtained from entry 3 is 3.2 mmag, so an offset with an absolute value larger than this would have been detected with $P \geqslant 0$. Unless coincidence is at work (see Section 9), it appears that systematic effects do not influence either the Bessell calibration or SAAO photometry at the few-millimag level.

Entries 4–6. Another possible explanation of entry 2 is a zero-point offset in the SAAO system itself. This hypothesis is tested by comparing JMIW values of $B - V$ to transformed *Tycho* data for field standard stars. The samples for entries 4 and 5 include data for AF V and GK III stars, with the number of JMIW measurements being $\geqslant 9$ for entry 4 and $\geqslant 6$ for entry 5. In contrast to those entries, entry 6 is derived from luminosity class IV–V stars with $B - V < 0.04$. Note that despite their diverse sources, the three entries are all decisively nonzero and agree well with each other.

Given this result, one naturally asks whether a scale factor difference or a nonlinear relation between the SAAO and JMIW standards can be found. The first step in testing for such problems is to plot differences between these two data sets against $B - V$ (see Figure 2). Note that if data that produce positive residuals for two red stars are omitted, the resulting line of residuals is nearly horizontal and has little or no perceptible curvature. This result is reassuring because possible curvature has previously appeared in a corresponding set of residuals (see Figure 2b of Menzies & Marang 1996). Calculated values of s turn out to be 0.0 ± 0.2 with data for the two red stars included and -0.3 ± 0.2 if those data are excluded. We therefore conclude that no scale factor difference is detected.

Entry 7. Entry 4 is now selected for further use because it is based on data for a higher percentage of original *UBV* standards than entries 5 and 6 (see footnote "b" of Table 4). Assume, for the sake of argument, that entry 4 is applied to all values of $B - V$ for SAAO standards. This procedure leaves entries 1 and 3 unaffected because in each case both sets of contributing data are adjusted by the same amount. However, entry 2 is altered because in this case SAAO data comprise only one of the two sets of contributing photometry. By adding entry 4 to entry 2, one obtains the revised formal correction to the Johnson & Knuckles (1955) data that is listed as entry 7 of Table 4.

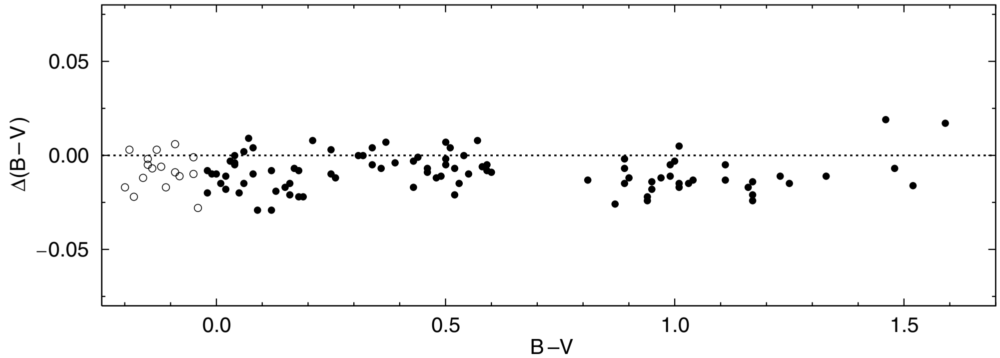

Figure 2. For field stars, $B - V$ residuals (in the sense "JMIW minus transformed *Tycho* data") are plotted against values of $B - V$. Data that contribute to entries 5 and 6 in Table 4 are represented by the filled and open circles, respectively. The two lines of residuals have been adjusted to reflect their average zero point.

Entries 8 and 9. These entries are counterparts to entry 7, but are not based on SAAO and *Tycho* data. Entry 8 is derived from Strömgren photometry, while entry 9 is based on measurements of Hyades stars and Johnson standards made on the same nights with a single *UBV* instrumental system (see Sturch 1973).[5] Note that these two entries disagree with entry 2; this problem was noted in Paper I, but no explanation was advanced there. Now, with entry 2 replaced by entry 7, one has three offsets that appear to agree despite being from independent sources (compare the three entries flagged with asterisks in the last column of Table 4). This assessment is confirmed by applying the χ^2 algorithm mentioned in Section 3.

Entry 10. The weighted mean of entries 7–9 turns out to differ from zero with $P = 0.66$. Using that mean value, an extant relation between $B - V$ and $(R - I)_C$ for single Hyades dwarfs may be re-zeroed (see Equation 1 of Taylor 1994). Let

$$B - V = \sum_{i=0}^{3} C_i r^i, \tag{2}$$

with $r \equiv (R - I)_C$. For the re-zeroed relation,

$$[C_0, C_1] = [(0.244 \pm 0.001), (-1.13 \pm 0.41)] \tag{3}$$

and

$$[C_2, C_3] = [(9.53 \pm 1.45), (-7.89 \pm 1.61)]. \tag{4}$$

This relation holds if $0.11 \leqslant (R - I)_C \leqslant 0.50$. It is recommended for use in color–magnitude analysis of the Hyades when values of $B - V$ are considered.

7. A COMMENT ON JOHNSON PHOTOMETRY

Since data published by Johnson and his collaborators define the *UBV* system, readers may wonder whether applying the entry 10 correction to some of that photometry is a meaningful operation. This issue can be resolved by noting that in the 1950s *UBV* cluster photometry was commonly performed in two steps: (1) cluster measurements were referred to one or more local standards and (2) those standards were then tied into the standard system. This procedure was adopted by Johnson & Knuckles (1955) in particular. Because some zero-point uncertainty is inevitably incurred in the second of these steps, cluster photometry from sources such as Johnson & Knuckles does not have the definitive zero points of field star photometry from sources such as JMIW.

When local standards were used, probable errors were stated for the zero points determined in the second step. By adopting a probable error from Table 1a of Johnson & Knuckles (1955) and converting it to a $\pm 2\sigma$ interval, one finds that interval is about ± 12 mmag for Hyades values of $B - V$.[6] This result shows at once that an adjustment of the Johnson & Knuckles data by -3.5 mmag is well within the expected range of possibilities. Especially because Menzies & Marang (1996) have also made use of data based on 1950s zero-point procedure, we suggest that zero-point practice as described in source papers be checked before data from that epoch are used. This procedure is easy to apply if probable errors for zero points are given in separate tables in the source papers. Johnson & Knuckles adopt that practice, and it appears to have been used consistently in cluster papers by Johnson and his collaborators.

8. A $B - V$ ANALYSIS FOR M67

Numerical results for an M67 analysis are given in Table 5, with supplementary details again appearing in footnotes. The steps in this analysis are as follows.

Entries 1–4. These entries concern a "consensus" database for M67 giants assembled by Taylor (2007) and cited in Table 11 of that paper. The contributing data are initially from Eggen & Sandage (1964), Coleman (1982), Janes & Smith (1984), and Sanders (1989), and are solely from photomultiplier measurements.

Entry 1. Attention is focused first on the Sturch (1973) data. That author measured stars in M67 as well as the Hyades stars and field standard stars noted above. Entry 1 shows that the Sturch and Coleman (hereafter S–C) data have indistinguishable zero points.[7]

Entries 2 and 3. Entry 2 is an offset between the S–C data and the Sanders (1989) measurements, while entry 3 is a corresponding offset for the data of Eggen & Sandage (1964). The offsets are applied before data from the two sources tested are included in the consensus database.

Entry 4. For measurements published by Janes & Smith (1984), the offset from the Sanders (1989) data is

[5] Data from Sturch (1972) are not used because at least some of those data are superseded in Sturch (1973).

[6] Because it is no longer standard practice to quote probable errors, we note that they can be converted to standard errors by dividing them by a factor of 0.68. This factor can be obtained readily from tables of integrals under the Gaussian.

[7] Though the Sturch data are used to establish a zero point for the consensus database, they are not ultimately included in that database because most of them are derived from a single measurement per star.

Table 5
$B-V$ Tests: M67

Entry	$B-V$ Range[a]	Extrinsic Source	Extrinsic Index	Tested Source	Tested Index	$\Delta(B-V)$ (mmag)	P[b]
1	>0.85	Coleman (1982)	$B-V$	Sturch (1973)	$B-V$	-3.3 ± 4.5	...
2	>0.62	SC[c]	$B-V$	Sanders (1989)[d]	$B-V$	-14.9 ± 4.3	1.3
3	>0.55	SC[c]	$B-V$	ES64[e]	$B-V$	-10.8 ± 2.8	1.9
4	>0.90	JS84[f]	$B-V$	Sanders (1989)[d]	$B-V$	-19.6 ± 6.4	0.7
5	−0.1, 1.1	Corrected SAAO[g]	$B-V$	Consensus[h]	$B-V$	$+2.3 \pm 2.4$	...
6	>0.85	Consensus[h]	$B-V$	MMJ[i]	$B-V$	-4.2 ± 2.2	...
7	>0.94	Consensus[h]	$B-V$	MMJ[j]	$B-V$	-25.4 ± 7.0	1.3
8	>0.60	SC[c]	$B-V$	Sandquist (2004)	$B-V$	$+3.6 \pm 3.5$	...
9	0.5, 0.7	NTC, JT97[k]	$b-y, m_1$	Sandquist (2004)	$B-V$	-4.7 ± 3.6	...
10	⩾0.4	...[l]	...	Sandquist (2004)	$B-V$	$+2.3 \pm 2.4$	...

Notes. The entries in the last column are differences in the sense (extrinsic source minus tested source). The standard errors quoted in that column include allowances for accidental errors introduced by reduction and transformation relations.
[a] Entries in this column are in magnitudes.
[b] Values of P are quoted if the overall significance level (see Miller et al. 2001) is >95%.
[c] "SC" refers to data from Sturch (1973) and Coleman (1982) that are combined without a zero-point adjustment.
[d] For the range $B-V<0.62$, the formal correction to the Sanders data calculated using data from Eggen & Sandage (1964) and Sturch (1973) is $+8.0 \pm 4.2$ mmag. That correction and the one listed in the table above differ with $P = 1.2$.
[e] "ES64" refers to Eggen & Sandage (1964). For stars with $0.4 \leqslant B-V \leqslant 0.75$, the formal correction to the ES64 data calculated using Strömgren photometry is -20.3 ± 2.9 mmag. That correction and the one listed in the table differ with $P = 0.4$.
[f] "JS84" refers to Janes & Smith (1984).
[g] This entry is based on data from Table 2 that have been corrected by −9 mmag (see entry 4 of Table 4).
[h] This entry refers to combined data from Janes & Smith (1984), Coleman (1982), Eggen & Sandage (1964), and Sanders (1989). The adopted zero-point adjustments to these data are (in order) 0, 0, −11, and −15 mmag, with the last correction applying only at $B-V>0.6$ mag. Sanders data from outside this range are not used. After entry 5, corrected SAAO data are added to the database.
[i] "MMJ" refers to data from Montgomery et al. (1993) for sample 1 stars (listed in Table 1 of Eggen & Sandage 1964).
[j] "MMJ" refers to data from Montgomery et al. (1993) for sample 2 stars (not listed in Table 1 of Eggen & Sandage 1964).
[k] "NTC" refers to transformed Strömgren data from Table I of Nissen et al. (1987). "JT97" refers to transformed Strömgren data from Table 3 of Joner & Taylor (1997). Both sets of data are on a zero point established by Taylor & Joner (1992). The transformation applied to these data is Equation (1). The assumed value of $E(B-V)$ for M67 is 41 ± 4 mmag (see Taylor 2007).
[l] This entry results from averaging entries 8 and 9.

indistinguishable from the offset obtained for the S–C data (compare entries 4 and 2). Judging from this result, the zero point of the Janes & Smith data and that of the S–C data are effectively identical. The Janes & Smith data are therefore included in the consensus database without a zero-point adjustment.

Entry 5. The consensus database is now compared with SAAO data from Table 2. The latter are adopted after a zero-point adjustment derived above (see entry 3 of Table 4) is applied. The resulting null offset implies that the zero points of the adjusted SAAO data and the S–C data are indistinguishable. Judging from a flat row of residuals in the uppermost panel of Figure 1, it appears that the scale factors are also indistinguishable. The latter deduction is confirmed by a calculated value of s (0.06 ± 0.23).

Entries 6 and 7. The re-zeroed SAAO data are included in the consensus database, and the resulting data (for G and K giants only) are given in Table 6. Those data are then differenced from the measurements of Montgomery et al. (1993), and the residuals are used to test the zero points of the Montgomery et al. data. Before being tested, the residuals are divided into two groups. For a group that will be called "sample 1" here, the parent stars are listed in Table 1 of Eggen & Sandage (1964). For "sample 2," the parent stars are not listed in that table.

This exercise does not separate the parent stars into two groups with mutually exclusive locations in the color–magnitude array of M67. For that reason, the adopted partitioning may appear at first to be ad hoc. Nevertheless, one finds that the two samples yield contrasting results. Both their net scatter and their mean offset from zero appear to differ (compare the filled circles plotted for sample 1 in Figure 3 with the open circles plotted there for sample 2). Statistical testing supports both of these

Table 6
Consensus Photomultiplier $B-V$ Values for M67

WEBDA	Sanders	$B-V$ (mag)[a]	WEBDA	Sanders	$B-V$ (mag)[a]
37	794	0.969(9.6)	231	1254	1.045(4.1)
84	1074	1.099(5.6)	244	1237	0.935(4.1)
105	1016	1.253(2.5)	266	1479	1.102(2.2)
108	978	1.365(4.1)	286	1592	1.080(9.6)
135	989	1.052(5.1)	305	721	1.058(9.6)
141	1010	1.107(3.5)	2152	1402	1.122(7.9)
143	1040	0.868(4.8)	3035	1293	1.019(6.1)
151	1084	1.093(2.8)	4169	494	1.068(6.8)
164	1279	1.109(4.8)	4202	488	1.532(5.1)
170	1250	1.342(2.1)	6470	364	1.293(5.6)
193	1305	1.004(9.6)	6474	676	1.200(7.9)
217	1288	1.069(6.1)	6495	1135	1.440(9.6)
218	1277	1.045(6.1)	6513	1533	1.233(7.9)
223	1316	1.107(2.0)	6514	1553	1.625(7.9)
224	1221	1.115(4.3)	6515	1557	1.265(7.9)

Notes. None of the listed data have been corrected for reddening.
[a] The data in parentheses are standard errors in millimags.

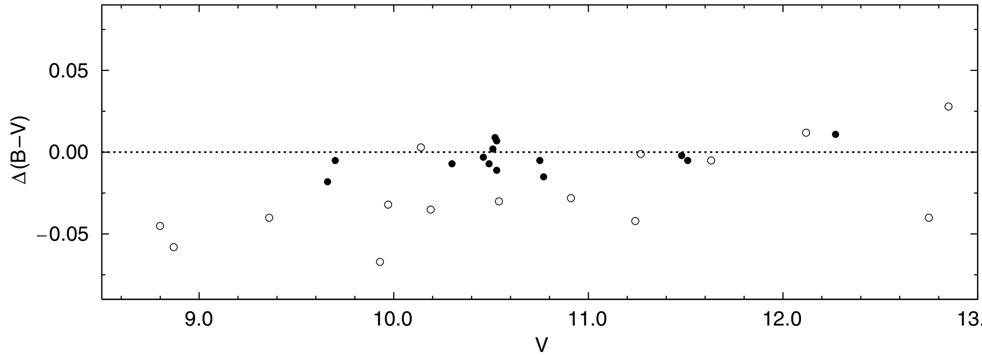

Figure 3. For M67, $B - V$ residuals are plotted against V for the data of Montgomery et al. (1993). The adopted values of V are from Eggen & Sandage (1964), Janes & Smith (1984), Sandquist (2004), and Taylor et al. (2008). The filled and open circles represent data for sample 1 and sample 2 stars, respectively.

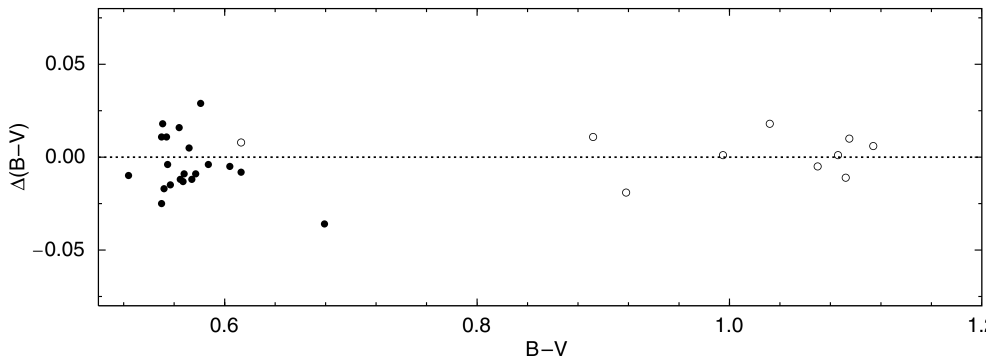

Figure 4. For M67, $B - V$ residuals are plotted against $B - V$ for the data of Sandquist (2004). The open circles are plotted if the comparison data are from Sturch (1973) and Coleman (1982; see Table 5 and the discussion of its entry 8 in Section 8). The filled circles are plotted if the comparison data are from Nissen et al. (1987) and Joner & Taylor (1997; see Table 5 and the discussion of its entries 9 and 10 in Section 8).

assessments. For sample 1, the mean residual does not differ detectably from zero (see entry 6 in Table 5). For sample 2, a firmly significant difference is found (see entry 7 in Table 5). In addition, the root mean square (rms) scatter of the residuals is found to be 7 mmag for sample 1 and 25 mmag for sample 2. Using a variance-ratio test, one finds that these two results differ with $P > 2.7$.[8]

These are some of the more unusual statistical results we have seen. Partly because those results appear to be reasonably decisive as well, we perform no further tests of the Montgomery et al. (1993) data. Instead, we suggest that those data, like the V and $(V - I)_C$ measurements of Montgomery et al., should not be used in color–magnitude or color–color analysis. Additional support for this suggestion is offered by the data of Sandquist (2004), which will be considered below. Sandquist finds that there is an overall offset of about 8 ± 1 mmag between his values of $B - V$ and those of Montgomery et al.[9] (The character of the $(V - I)_C$ data of Montgomery et al. is discussed in Sections 5 and 6 of Taylor et al. 2008. A detection of a positional effect in the V data of Montgomery et al. is documented in Table 1 of Taylor et al.)

Entry 8. Attention is now directed to the Sandquist (2004) data. First, a comparison is made between those data and the S–C results, which can now be regarded as a proxy for the re-zeroed SAAO data (recall entry 5). The resulting residuals are plotted as open circles in Figure 4. Judging from that figure, the mean residual is effectively zero. This initial estimate is supported by the result of the statistical test reported for entry 8.

Entry 9. Here, the zero point of the Sandquist (2004) results is compared with that of transformed Strömgren data for stars on and near the vertical subgiant branch in M67. Once again, no nonzero mean offset is detected in either Figure 4 (note the filled circles) or by a statistical test.

Entry 10. Note that the mean residuals given in entries 8 and 9 agree. This is especially encouraging because the two means have been derived for color intervals that are largely complementary (see the appropriate entries in the second column of Table 5). Entry 10 includes an overall mean residual that has been derived from the two accordant means by using inverse-variance weighting. To interpret that mean value, we adopt a 2σ limit as before and conclude that no offset as large as 4.8 mmag is detected in the Sandquist (2004) data. Those data (and the entries in Table 6) are therefore recommended for use in color–magnitude and color–color analysis as a substitute for the measurements of Montgomery et al. (1993).

9. THE SAAO $B - V$ OFFSET: A KNOTTY PROBLEM CONSIDERED

So far, the $B - V$ analysis has not revealed any serious problems. In particular, the results of adopting the zero-point offset derived for the SAAO system in Section 6 have been satisfactory. Now, however, we acknowledge that our analysis

[8] It should be noted that the apparent contrast between the residuals plotted in Figure 3 is not completely sustained by statistical testing. Despite appearances, the slopes of the two sets of residuals cannot be distinguished at 95% confidence.

[9] In his Figure 5, Sandquist presents a graphical comparison of his M67 $B - V$ data with those of Montgomery et al. We assume that an rms error is included in the offset quoted in the figure by Sandquist (-8 ± 11 mmag). The required standard error of the mean follows from the appearance in Sandquist's plot of data for an estimated 100 stars or more.

does not include the results of two previous comparisons between the Johnson and SAAO systems. Cousins (1984) performs such a comparison by measuring a number of the Johnson & Harris (1954) standard stars. Menzies & Marang (1996) report data on the SAAO system for stars in IC 4665 that have been measured by Johnson (1954) and other authors.[10]

Before zero-point offsets from measurements by Cousins (1984) and Menzies & Marang (1996) are calculated, the photometric literature for IC 4665 is examined. This is done to identify published data sets that (1) have reasonably high precision, (2) include at least 10 stars, and (3) have been standardized using Johnson standards. It is found that only measurements made by Hogg & Kron (1955) and Johnson (1954) satisfy these conditions. For a reason that will become clear shortly, only Johnson's data are used.

When a value of $\Delta(B-V)$ like those in Tables 4 and 5 is calculated for Johnson's (1954) data, the result is as follows:

$$\Delta(B-V) = 1 \pm 6\,\text{mmag}. \tag{5}$$

The standard error in this equation is dominated by zero-point uncertainty of the sort described in Section 7. Adopting measurements from Hogg & Kron (1955) would not improve Equation (5) because their data have been reduced to the Johnson (1954) zero point. Apparently, the measurements of Menzies & Marang (1996) cannot be used to perform a satisfactory zero-point test.

When the Cousins (1984) data are considered instead, one finds that

$$\Delta(B-V) = -0.8 \pm 1.2\,\text{mmag}. \tag{6}$$

A useful way to evaluate this result is to compare it to the corresponding entries in Table 4 with the highest available precision. On this basis, entries 4 and 5 in Table 4 are selected. Using an unequal-variance *t* test (see Section 3), it is found that Equation (6) differs from those entries with $P > 2.70$. This high level of significance underscores an important contrast: the analysis in Section 6 yields a nonzero correction to the SAAO standards, but the Cousins (1984) data do not.

This is a problem that is not to be solved by making any merely facile choice. Given the care with which Cousins established the *UBV* system for the E region standards (see for example, Cousins 1973), Equation (6) would be accepted without hesitation if additional pertinent data were not available. Since such data are available, however, we shall try to make the best decision about the problem that the evidence permits.

An essential starting point is the deduction that at least one SAAO photometer suffers from a declination effect in $B-V$. Admittedly, this is not a welcome idea. Although declination effects in *V* are quite conceivable (see Section 3.1 of Menzies & Marang 1996), a declination effect in a color index is both new to our experience and a troubling hint of possible problems in other photometric venues.[11] Nevertheless, we accept the verdict and try to decide which of the SAAO photometers is more likely to be the source of the problem.

For the sake of argument, we begin by assuming that the declination effect is in the photometer that is currently being used at SAAO. The results of this assumption are as follows.

1. Given the null offset in entry 3 of Table 4, there must also be a declination effect in the *Tycho* photometry. Note that it is difficult to imagine how such an effect could be produced. In particular, instrument flexure is ruled out by the fact that the *Tycho* measurements were made in free fall.
2. The declination effects in the *Tycho* photometry and SAAO photometry of the present epoch must be very similar despite the fact that the *Tycho* and SAAO instrumental systems are completely independent. Such a coincidence, though conceivable, seems unlikely.

Next, we assume instead that the declination effect is in the photometer used by Cousins (1984). Now the results are as follows.

1. There is no need to suppose that the *Tycho* photometry harbors systematic effects.
2. In addition, there is no need to conclude that such effects are produced by the current SAAO photometer. For this reason, the agreement displayed in entry 3 of Table 4 receives a natural explanation.
3. Cousins (1984) notes that the photometer he used to test the E region photometry is the one used to establish *UBV* photometry for the E region standards. One therefore concludes that the declination effect was not detected because it appears in both sets of measurements. Note that as a result there is no need to attribute any problem to the careful observing and reduction procedures that Cousins employed.

Since the second option is clearly the more palatable of the two, we adopt it. However, it seems unwise to regard it as definitive, so we instead describe it as a well-supported interim choice that should be tested further. This should be done by taking note of point 3, which is a useful reminder that accuracy tests should be based on data from at least two independent instrumental systems. Pertinent measurements that include Johnson standards with a photometer that has not contributed to the discussion so far would be especially welcome.

10. SUMMARY

New SAAO $BV(RI)_C$ measurements of cluster stars are presented, with data being reported for 11 stars in M67 and 19 Hyades stars. Because measurements for eight of those stars were reported in Paper I, it is possible to test the zero-point consistency of the new and previously published data. It is found that the zero points of the new color indices conform closely to those obtained in Paper I. In addition, the new M67 measurements of $(V-R)_C$ and $(R-I)_C$ are compared to data published by Taylor et al. (2008). The accuracy of the scale factor of those data is supported by the new results. For this reason, the new data reinforce a conclusion drawn by Taylor et al. that a scale factor problem is present in the $(V-I)_C$ measurements of Montgomery et al. (1993).

The new values of $B-V$ participate in an analysis of Hyades and M67 data and the accuracy of the SAAO $B-V$ system. A problem with the Hyades $B-V$ zero point posed in Paper I is resolved, and an extant Hyades relation between $B-V$ and $(R-I)_C$ is re-zeroed. A satisfactory zero point is also obtained

[10] Taken at face value, a third comparison (see Section 4 of Koen et al. 2002) suggests that the SAAO zero point should be corrected by about +22 mag. However, this comparison is based solely on M dwarfs, and it appears that extant $B-V$ photometry of such stars has a zero-point jitter of about 10 mmag (see Section 3 of Koen et al. 2002). In addition, the cited comparison depends partly on *Tycho* photometry and partly on ground-based photometry (again see Section 4 of Koen et al. 2002). We therefore suggest that (1) $B-V$ photometry of M dwarfs should not be used to test the SAAO zero point and (2) the correct zero point for such photometry should ultimately be the subject of further discussion.

[11] Fortunately, there is good reason to conclude that such problems do not affect commonly used sets of Cousins *VRI* colors (see Table 3 and Sections 5–7 of Taylor & Joner 1996).

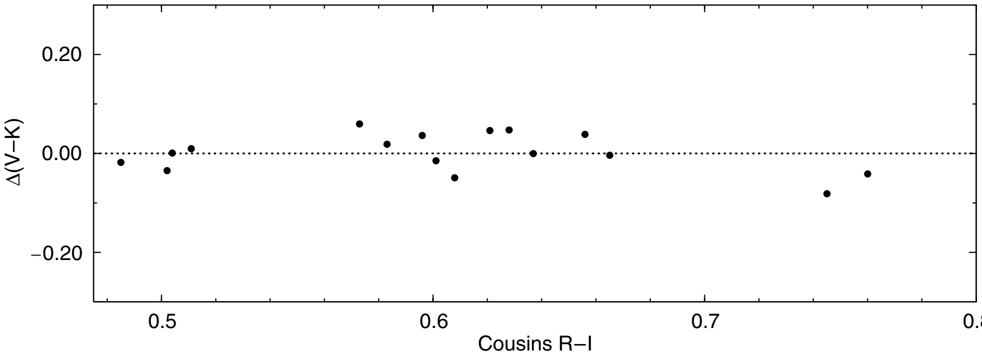

Figure 5. $(V - K)_J$ residuals from equations (A1) and (A2) are plotted against $(R - I)_C$.

for M67, and photomultiplier values of $B - V$ for evolved M67 stars are reduced to that zero point (if necessary), averaged, and tabulated. The zero point of $B - V$ data published by Sandquist (2004) turns out to be satisfactory. However, tests of $B - V$ measurements made by Montgomery et al. suggest that those data are not on a single zero point. Finally, the scale factor of the E region system is found to be satisfactory, but a well-supported interim conclusion is drawn that E region values of $B - V$ should be corrected by about −9 mmag. It is suggested that this conclusion be tested by measuring Johnson standards and by using instrumental systems that have not yet contributed to the testing process.

As in Paper I, we gratefully acknowledge SAAO for granting telescope time on such a well-established observing system. We also thank Lisa Joner for reading the manuscript carefully and Dr. D. Kilkenny for providing data reductions for the paper and a careful evaluation of its reasoning. The WEBDA database (operated at the Institute for Astronomy at the University of Vienna), the SIMBAD database (operated at Centre de Données Astronomiques de Strasbourg, Strasbourg, France), the General Catalogue of Photometric Data (Mermilliod et al. 1997), the Asiago Database of Photometric Systems (Moro & Munari 2000), and the Smithsonian/NASA ADS listings have all contributed to this investigation, and we thank the operators of these Web sites with alacrity. Finally, we note with thanks that page charges for both Paper I and this paper have been generously underwritten by the College of Physical and Mathematical Sciences and the Physics and Astronomy Department of Brigham Young University.

APPENDIX

AN UPDATED TRANSFORMATION BETWEEN $(V - K)_J$ AND $(R - I)_C$

Taylor & Joner (2006) have published a transformation between $(V - K)_J$ and $(R - I)_C$. The transformation consists of three relations that apply in disjoint intervals in $(R - I)_C$. Taylor & Joner note that the reddest of these relations is based on data that fall well short of being uniformly distributed in color. This problem can be partially solved by adding data for vA 68 and vB 229, 231, 262, 291, and 324 to the original data set and then recalculating the relation. The result may be expressed as follows: if

$$(V - K)_J = C_0 + C_1(R - I)_C, \tag{A1}$$

then

$$[C_0, C_1] = [(0.551 \pm 0.077), (3.80 \pm 0.13)] \quad \text{if} \quad (R - I)_C \geqslant 0.495. \tag{A2}$$

A plot of $(V - K)_J$ residuals against $(R - I)_C$ is given in Figure 5. While the color coverage of the revised relation has been improved, one can see that further data will ultimately be required at $(R - I)_C \sim 0.55$ and $(R - I)_C \sim 0.70$. Meanwhile, readers who want to use the full relation are invited to consult Table 4 of Taylor & Joner (2006) while substituting the above relation for entry 8 in that table.

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