Using Unfiltered Images to Perform Standard Filter Band Photometry

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Abstract This paper demonstrates that raw instrumental magnitudes of stars measured from a single unfiltered CCD image can be transformed into standard passband magnitudes. Star fields that have good catalogued photometric magnitudes can be used as a reference to transform unfiltered instrumental magnitudes into a standard system. To demonstrate this, the AAVSO (VSP) M-67 catalogued stars are used. It is shown that, within certain constraints, the standard B, V, Rc, and Ic magnitudes can be accurately determined from unfiltered instrumental magnitudes. For well behaved, well calibrated stars, the transformations to standard magnitudes can be done within a standard deviation of better than 0.021 magnitude. The paper further presents a simple spreadsheet tool to automatically derive the "standard" magnitudes from the raw instrumental magnitudes. This greatly simplifies the task of calculating transformation coefficients, and makes it possible to calibrate a CCD imaging system on an image-by-image basis.

1. Introduction

A variety of differential photometric measurements are made by amateur astronomers, such as: light curves of variable stars, the rotational periods of asteroids, and transit timing of exoplanets. Many projects, however, require photometric measurements referenced to "standard" filter passbands. Due to the added work required and the use of filters that reduce the signal of the image, many amateurs do not attempt to make such measurements.

With the advent of all-sky catalogues such as the Guide Star Catalog (GSC; Space Telescope Science Institute 2001), AAVSO Photometric All-Sky Survey (APASS; Henden *et al.* 2015), Carlsberg Meridian Catalogue 14 (CMC14; Copenhagen University Observatory 2006), and others, nearly any image field will contain a number of cataloged stars having standard magnitudes. As high quality all-sky photometric catalogues become available, single-image transformation of instrumental magnitudes to "standard" systems can become a common practice.

2. Previous work

Henden (2000) presented an experiment using 64 calibrated stars in M67 to determine the practicality of making standard photometric measurements from unfiltered CCD images. Henden has shown that unfiltered images can be used to make some standard photometric measurements. The color response of the camera is determined and used to transform unfiltered instrumental magnitudes to standard magnitudes. The accuracy of the transformation is dependent primarily on obtaining the photometric response of the imaging system and the color index of the target star. He determined the V and R color coefficients for six different CCD sensors. Using these he presented a sample transformation of the unfiltered instrumental magnitude of a star to the standard V magnitude. He demonstrated that by determining the color response of the CCD and the color index of the subject star, the unfiltered instrumental magnitude transformed to the known standard V magnitude of the star within 0.06 magnitude.

Gary (2009) has developed a novel method to do all-sky photometry using unfiltered images. Predetermined zero-point adjustments for his imaging system and the cataloged 2MASS J and K magnitudes of the subject star are used to derive proper transform coefficients to calculate V, R, and r' standard magnitudes.

Dymock and Miles (2009) described a method of determining the V magnitude of an asteroid using differential photometry with the magnitudes of comparison stars selected from the CMC14 catalogue data. They made use of the availability of a large number of suitable CMC14 stars within the data image to make "reasonably accurate magnitude" measurements without resorting to all-sky photometry. This method is basically the same as presented here. Dymock and Miles limited their presentation to "V" magnitudes of asteroids using the CMC14 catalogue as reference. Their procedure, however, is applicable to any other available catalogue and can be used for stars as well as asteroids.

Yoshida (2010) provides a series of conversion coefficients to transform unfiltered instrumental magnitudes of six different CCD chips, as in Henden (2000).

Dunckel (2014) presented a method to obtain calibrated standard magnitudes from measurements of filtered images using APASS magnitudes as reference. This method parallels the procedure presented in this paper, the difference being that Dunckel uses filtered images, while this presentation uses unfiltered images. The results of Dunckel using filtered images, all things being the same, will be more accurate than the use of unfiltered images, but with the disadvantage of signal reduction due to filtering.

The AAVSO Transform Generator (TG; AAVSO 2016) project is a recently developed online tool that allows the easy calibration of a filtered imaging system and the calculation of standard magnitudes of stars imaged by a CCD camera. It is available for use by amateur astronomers. This provides an easy method to generate photometric measurements suitable for AAVSO observing programs.

3. Acquiring instrumental magnitudes

Images of the M-67 star field were made using a 12-inch diameter f/5 Newtonian reflector with an SBIG ST402me CCD camera. The camera was mounted at prime focus. A series of images of M-67 was made in a single night spanning air masses 1.2 to 2.0. The images were 20-second exposures without filter.

Each image was dark- and flat-field calibrated using the AIP4WIN magnitude measurement tool (Berry and Burnell 2005). The stars measured for this exercise were 63 of the 64 Henden (2000) M-67 stars. Star number 56 was out of the image frame and was not measured. The instrumental magnitudes (Imag) of the 63 stars were measured at air masses of 1.2, 1.4, 1.6, and 2.0. To increase the data quality, the instrumental magnitudes of 6 consecutive images were averaged to give the approximate equivalent of 120 seconds of exposure.

AAVSO has expanded and refined the M-67 star chart to over 170 calibrated stars. The current AAVSO VSP star chart magnitudes of the 64 Boulder swri numbers (Henden 2000) M-67 stars were obtained from Myers (2012). The finder chart, Appendix A, identifies these 64 stars with their Boulder swri numbers. Of the original 64 Henden (2000) stars, fifteen have been culled from the current AAVSO-VSP list, leaving 49 Boulder swri calibrated stars. A key correlating the 64 swri numbers to the AAVSO-VSP AUIDs is given in Appendix B (Myers 2016). The measured instrumental magnitudes, and the corresponding AAVSO catalogue magnitudes and AUID numbers for the 48 measured stars are given in Appendix C.

4. Determining the color response of the imaging system

For clarity, catalogued reference magnitudes will be designated using upper case, such as "B" and "V". Calculated standard magnitudes derived from measuring an image are designated using lower case, such as "b" and "v". As a general designation, "F" is used to refer to a catalogue magnitude, and "f" designates a calculated magnitude for a generic passband.

To determine the imaging system's color response, the M-67 catalogued magnitudes (B, V, Rc, Ic) were plotted against the measured unfiltered raw instrumental magnitudes (Imag) of the 48 measured stars. Figure 1 shows the B, V, Rc, Ic magnitudes (y-axis) plotted against the unfiltered raw instrumental magnitudes (x-axis) for air mass 1.2. It is seen that the Rc magnitudes are nearly linear. Figure 2 shows the residuals ("F" – Imag), that is, the cataloged M-67 magnitudes minus the measured instrumental magnitudes (Imag) plotted against the color index (B–V), for these four filter passbands at air mass 1.2. The plotted data demonstrate that the imaging system used is consistent with the Rc filter band. This is good information for the general use of this particular system and replicates the results of Henden (2000).

4.1. Calculating transforms: strategy

Using a photometry processing software, the unfiltered CCD image is measured to obtain the raw instrumental magnitudes (Imag) of the target and comparison stars. The several passband magnitudes of the comparison stars are obtained from a suitable photometric catalogue for stars in the image field: APASS, CMC14, or AAVSO star charts, for example. Finally, using the spreadsheet numerical tool "solver," the transformation coefficients of the imaging system for each filter passband of interest are calculated. The spreadsheet automatically applies the calculated transformation coefficients to the raw instrumental magnitudes of the measured stars, calculating their derived standard magnitudes, "f", for the selected filter band.

The method presented short-cuts the normal photometric procedure which generally requires measuring nearby, out of frame, calibrated reference stars. By using catalogued reference stars within the data image, the reference stars are measured simultaneously with the target star, through the same system, the same atmosphere, and at the same time. This all but eliminates the system and environmental variations of the reference stars with respect to the target star for the image being measured.

4.2. Calculating transforms: calculation equation

The equation used to determine the transformation coefficients is the standard photometric equation. Using the default nomenclature (Boyd 2012), and modified for a generic passband (F), the equation is:

$$f = Imag - (k'_F \times X) - (k''_{F(Ci)} \times X \times Ci) + (T_{F(Ci)} \times Ci) + Z_F. \quad (1)$$

where:

f = Standard magnitude calculated for the "F" filter passband,

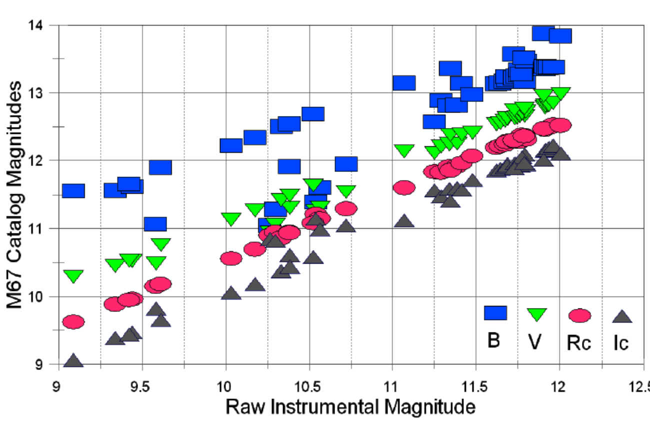

Figure 1. B, V, Rc, Ic magnitudes (y-axis) compared to the unfiltered raw instrumental magnitudes (x-axis) for air mass 1.2.

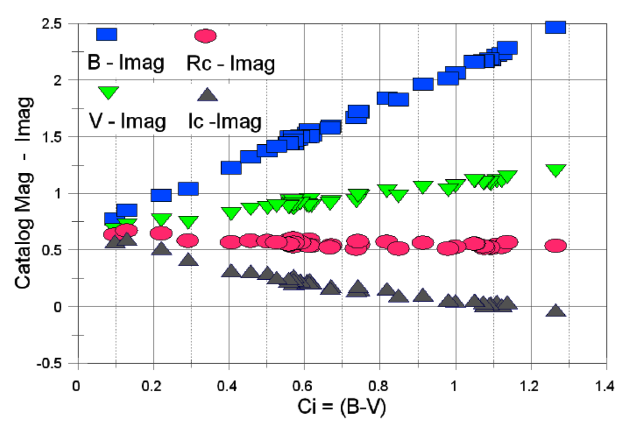

Figure 2. The catalogued M-67 magnitudes minus the measured instrumental magnitudes (Imag) plotted against the color index (B–V), for four filter passbands at air mass 1.2.

Imag = Measured unfiltered raw instrumental magnitude,
k'_F = Atmospheric extinction coefficient at the observatory,
X = Air mass of the image at the observatory when the image was taken,
$k''_{F(Ci)}$ = Second order color extinction coefficient,
Ci = Color index of the measured stars calculated using the reference catalogue, e.g. (B–V)
$T_{F(Ci)}$ = Instrumental transformation coefficient for the color index Ci,
Z_F = Zero point offset of the instrumental magnitude.

It is assumed for the purpose of these calculations that all the stars in a single narrow field image (30 × 30 arc min) have nominally the same air mass and attenuation at elevations above 30 degrees. The users of this procedure should determine the validity of this assumption for their own conditions; see Dunckel (2014, page 109). With this supposition, the values of X, and Z, and the coefficients k' and k" for a given passband are essentially constant for all stars in the subject image. Consolidating constants, the working equation to calculate the derived standard magnitudes in filter band "F" becomes:

$$f = Imag + Ci \times T' + Z' \quad (2)$$

where:

$T' = T_{F(Ci)} - k''_{F(Ci)} \times X$ and
$Z' = Z_F - k'_F \times X$.

It is to be noted that in making these calculations, the transformation coefficients are applicable only to the image from which they were derived. While this procedure does determine the static instrumental constants of the imaging system, these constants are combined with X in both T' and Z' where X is changing with time.

4.3. Calculating transforms: source of data

The data required to make the transformations from instrumental magnitudes to standard magnitudes come from five sources:

1. The star field containing the object of interest is imaged and measured to obtain the raw instrumental magnitudes (Imag) of the target star(s) and the several catalogued reference stars.

2. The standard magnitudes for each of the measured reference stars are extracted from a photometric catalogue for all filter passbands of interest (B, V, Rc, Ic, for example).

3. The color indices (Ci) of each measured star are calculated from the catalogued reference data (Ci = (B–V), for example).

4. The sky and system transformation coefficients (T' and Z') for the image are determined by the spreadsheet.

5. Finally, the color index, Ci, of the target star must be determined. The Ci depends on the nature of the target. For asteroids or comets, Ci may be estimated based on the solar spectrum. Variable stars generally have variable color indices. Each type of star will present a different challenge to obtaining a proper Ci (see Henden 2000, section 3.0, page 40). Appendix E presents a quick method to determine the color index of a star. Note that it is necessary that the color of the target star be within the color response of the imaging camera; see section 6, Conclusions, for an expanded comment.

4.4. Calculating transforms: spreadsheet

For this procedure, Equation 2 is used to calculate the values of the "derived" standard magnitudes of each measured star in the subject image, (b, v, r, i, for example). The "solver" or "optimize" spreadsheet tool will calculate an optimum set of constants that satisfy a given set of boundary conditions. Within the spreadsheet algorithm, the constants T' and Z' are repeatedly changed until the algorithm returns a solution that best meets the boundary conditions. Thus the transformation constants T' and Z' for any given image are directly calculated using the spreadsheet.

The boundary conditions for the calculations are defined in terms of the residual value R', of each measured star, where R' = (F – f); for example, R' = (B–b). The boundary conditions are:

1. The standard deviation of the set of R'(n) for n measured stars is minimized, which sets the color and air mass coefficients.

2. The average of the set of R'(n) values is zero, which sets the zero point adjustment. Using data from the M-67 star field and for the B-filter passband, the spreadsheet appears as in Figure 3.

Two cells are set up to hold the constants T' and Z', {C14, C15}. (These are "fixed" cells and are used in each calculation made in row 10). A third cell is set up to calculate the Standard Deviation of the residuals, StdDev(R'(n)), {C12}, and a fourth cell is set up to calculate the average of the residuals Avg(R'(n)), {C13}. Rows 4 through 7 contain the catalogued standard magnitudes for the several filter bands of interest for each measured star. Row 8 is the color index calculated for each reference star (B–V).

Note that the target star, as shown, does not have cataloged magnitudes; thus, Ci for the target must be determined from another source and inserted at {C8} (see section 4.3, item 5). Row 9 is the raw instrumental magnitudes (Imag) of the measured stars. Row 10 is the derived magnitudes; "b" for the "B" passband being used in this example. Row 11 is the calculated residual for each star, (B–b). The "Solver" insert sets the boundary conditions, which are: 1) minimize the standard deviation of the residuals, and 2) make the average of the residuals equal zero. With the spreadsheet set up, clicking "solve" automatically calculates the image transformation coefficients, T' and Z', and the derived standard magnitude "b" for each star.

The derived magnitudes for an image can be calculated for any filter band. Figure 3 shows the B-filter band calculation. This is determined by using (B–b)n for the values of R'(n). To select the "V" filter band, the R'(n) values used are (V–v)n. A sample spreadsheet is available at: http://users.eoni.com/~garlitzj/Sample_Unfiltered_1.xls .

4.5. Calculating transforms: derived b, v, r, i magnitudes

Using the procedure described, the derived magnitudes (b, v, r, i) for the standard passbands (B, V, Rc, Ic) were calculated for the 48 M-67 stars described in section 2. These 48 reference stars with their corresponding measured unfiltered instrumental

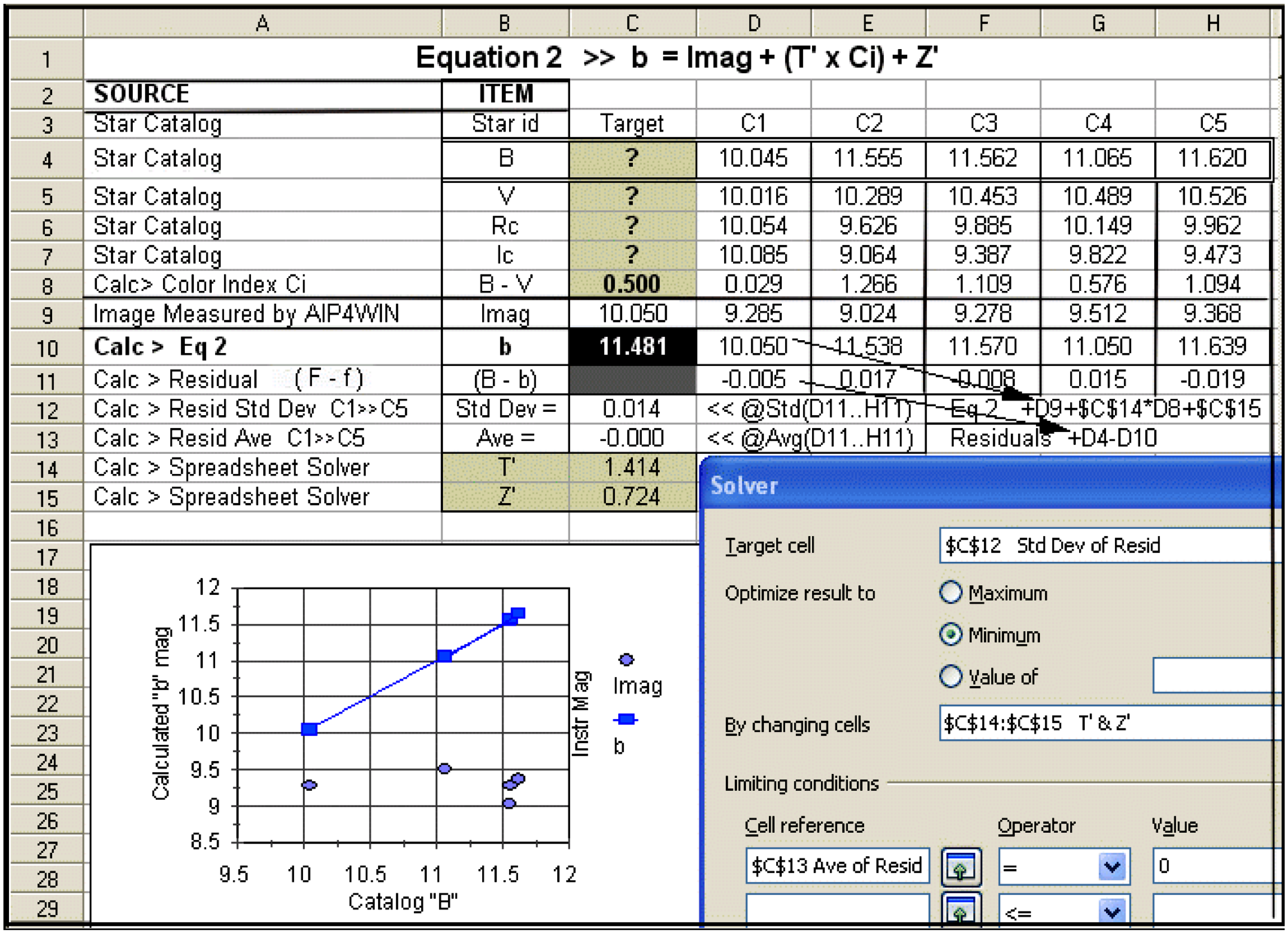

Figure 3. Spreadsheet using data from the M-67 star field and for the B-filter passband.

magnitudes are listed in Appendix C. The derived (b, v, r, i) magnitudes for air masses 1.2, 1.4, 1.6, and 2.0 for each passband (B, V, Rc, Ic) are listed in Appendix D.

Figures 4 and 5 show the raw instrumental magnitudes (Imag) and the "b" and "r" derived magnitudes respectively, plotted against their corresponding catalogued B and Rc magnitudes at air mass 1.2. It is evident from these plots that the calculated magnitudes "b" and "r" are consistent with the catalogued magnitudes B and Rc for these two filter bands. This is especially evident for the B band where the instrumental magnitudes are very widely scattered.

Figures 6 and 7 present the residuals (B–b) and (Rc–r) plotted against their respective color indices (B–V) and (Rc–Ic) at air mass 1.2. The standard deviation of these residuals is 0.016 magnitude for (B–b) and 0.018 magnitude for (Rc–r).

Table 1 presents the transformation coefficients for the B, V, Rc, Ic filter passbands at air masses of 1.2 and 2.0 for the 48 measured M-67 stars. These coefficients were derived from the unfiltered images of M-67 calculated by the spreadsheet using Equation 2. The color indexes used for the calculations were (B–V) and (Rc–Ic) as listed.

5. Assessing the accuracy of the derived magnitudes

For each of the 48 measured stars, the residuals (B–b), (V–v), (Rc–r), and (Ic–i) were calculated at each air mass. Calculating the standard deviation of these residuals gives the results shown in Table 2. For this star field of 48 well calibrated reference stars, the plots in Figures 4, 5, 6, 7, and the standard deviation values in Table 2 demonstrate that standard magnitudes (B, V, Rc, Ic) can be accurately derived from a single unfiltered image. The derived (b, v, r, i) magnitudes are accurate to a standard deviation of 0.021 magnitude or better for air mass 1.2 through 2.0.

The standard deviations of the residuals in Table 2 are comparable to the average of the errors reported for the calibrated AAVSO M-67 stars as shown in Table 3 and listed in Appendix C. This indicates that the quality of the derived magnitudes is comparable to the quality of the reference magnitudes.

6. Conclusions

An imaging system's color response can be readily demonstrated by plotting the measured unfiltered instrumental magnitudes of a star field of well-behaved stars against the catalogued standard magnitudes of those stars (section 3). The imaging system used in the work for this paper is seen to respond very much like an Rc filter. Thus, for this system, the magnitudes derived from the unfiltered instrumental magnitudes

Table 1. Transformation coefficients Z' and T' for B, V, Rc, Ic passbands using 48 M–67 stars.

	Airmass = 1.2				Airmass = 2.0			
Passband and [Ci]	*B [B–V]*	*V [B–V]*	*Rc [B–V]*	*Ic [Rc–Ic]*	*B [B–V]*	*V [B–V]*	*Rc [B–V]*	*Ic [Rc–Ic]*
Z'	0.720	0.720	0.817	0.817	0.264	0.264	0.402	0.376
T'	1.407	0.407	–0.239	–1.239	1.451	0.451	–0.061	–1.135

Table 2. Standard deviations for 48 AAVSO M-67 stars.

Filter Band Residuals	*B (B–b)*	*V (V–v)*	*Rc (Rc–r)*	*Ic (Ic–i)*	*Air Mass*
	0.016	0.016	0.018	0.018	1.2
Standard	0.016	0.016	0.017	0.017	1.4
Deviation	0.018	0.018	0.018	0.019	1.6
	0.020	0.020	0.021	0.021	2.0

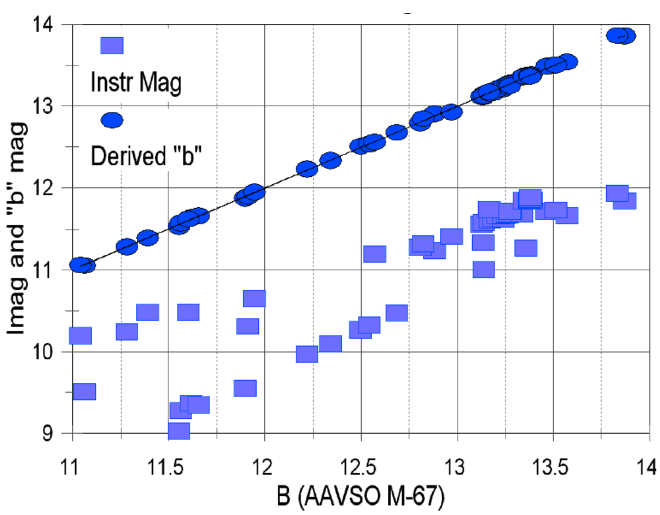

Figure 4. Raw instrumental magnitudes transformed to standard B magnitudes.

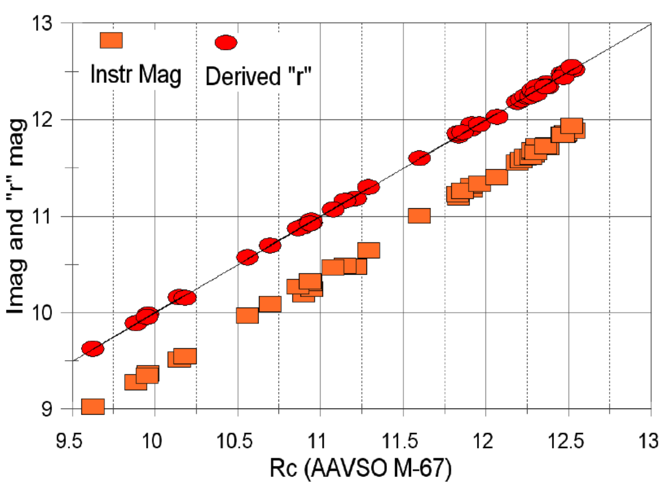

Figure 5. Raw instrumental magnitudes transformed to standard Rc magnitudes.

are similar to making transformations from the Rc passband to the B, V, and Ic passbands.

This paper deals with the B, V, Rc, Ic passbands. It is necessary, then, to recognize the limits in making transformations of unfiltered instrumental magnitudes to these passbands. This procedure works because the imaging system acts as a wide band "filter" over the B, V, Rc, Ic wavelength range. Caution is

Table 3. Average reported errors for 48 AAVSO M-67 stars.

Filter Band	*B*	*V*	*Rc*	*Ic*
Average of Reported Errors Appendix C	0.020	0.017	0.019	0.023

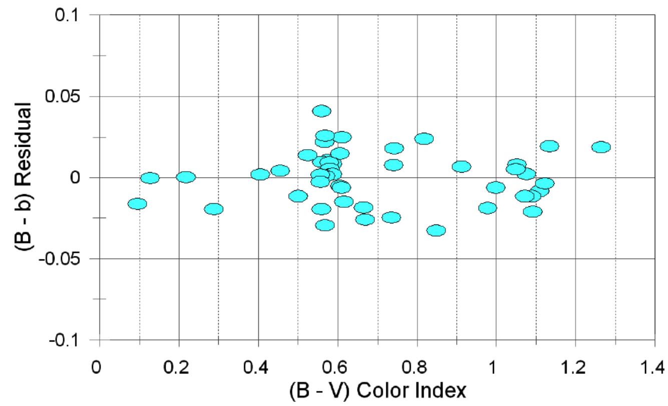

Figure 6. Residuals (B–b) plotted against (B–V) color index; Residual Std Dev = 0.016.

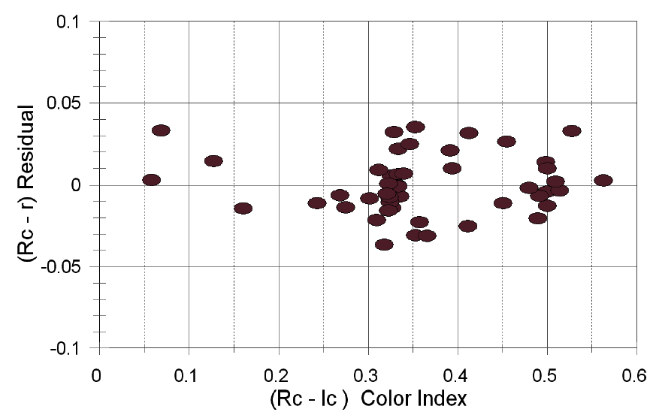

Figure 7. Residuals (Rc–r) plotted against (Rc–Ic) color index; Residual Std Dev = 0.018.

due for stars that are very blue (high UV) or very red (high IR) with spectrums that peak outside of the CCD's nominal "filter" range. In this circumstance, the CCD imaging system will not work as a functional filter.

Figure 8 shows images of the long term variable UX Cyg (Spectral type M4–M6). The target star is not quite as bright as the close-by star in the red image (right), but it is much brighter in the image with no filter (left). This is because the response of the KAF-0402ME CCD chip in the camera peaks at about 6,500 angstroms, but its sensitivity extends well beyond 9,000 angstroms. In Figure 9 the spectrum for an M5v star (Pickles

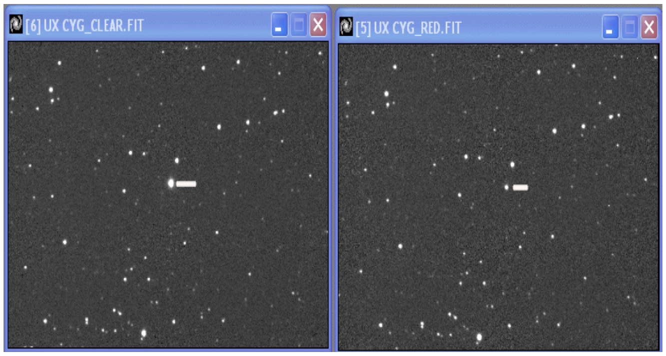

Figure 8. Images of the long term variable UX Cyg (Spectral type M4–M6). The target star is not quite as bright as the close-by star in the red image (right), but it is much brighter in the image with no filter (left). Author's data.

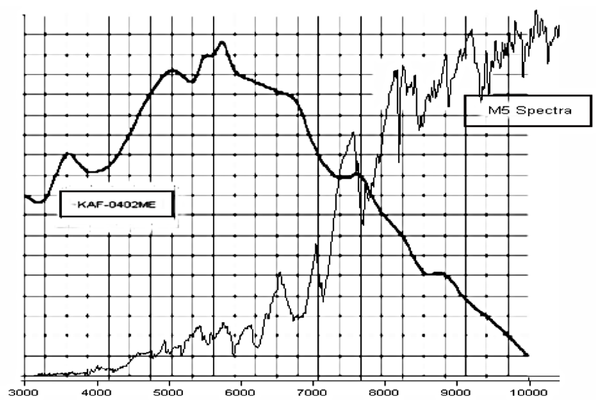

Figure 9. The spectrum for an M5 star shown together with the efficiency curve of the KAF-0402ME camera (Pickles 1998; Diffraction Limited 2015).

1998) is shown together with the efficiency curve of the camera (Diffraction Ltd. 2015). It is evident that the spectram of the star peaks well beyond the camera's IR response. Since the IR light extends beyond the nominal range of the camera's broadband "filter," this star's unfiltered image will not properly transform to the standard B, V, Rc, Ic system.

Noting the cautions for using this method of photometry, it is demonstrated that, for a star field of well-calibrated stars, it is possible to accurately derive standard magnitudes for the B, V, Rc, and Ic filter bands from a single unfiltered image.

While the color indices of the catalogued reference stars in an image field can be determined from the catalogue data, the target star may not have a proper color index. The color index for the target star must be determined in order to calculate its standard magnitudes (section 4.3, item 5).

Setting up a spreadsheet using the "solver" or "optimizer" tool provides a simple and quick method to calculate derived standard magnitudes. A sample spreadsheet can be downloaded from: http://users.eoni.com/~garlitzj/Sample_Unfiltered_1.xls.

This procedure requires that the subject star field has a number of well calibrated catalogued stars. The GSC, APASS, and CMC14 catalogues, as well as star charts prepared for measuring variable stars, are available and suitable for most star fields.

7. Acknowledgements

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I also acknowledge the wealth of work on amateur photometry presented by Bruce Gary which has been an invaluable resource for my adventures into all sky photometry (brucegary.net/DifferentialPhotometry/dp.htm).

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Appendix A: M-67 field with original Boulder swri numbers

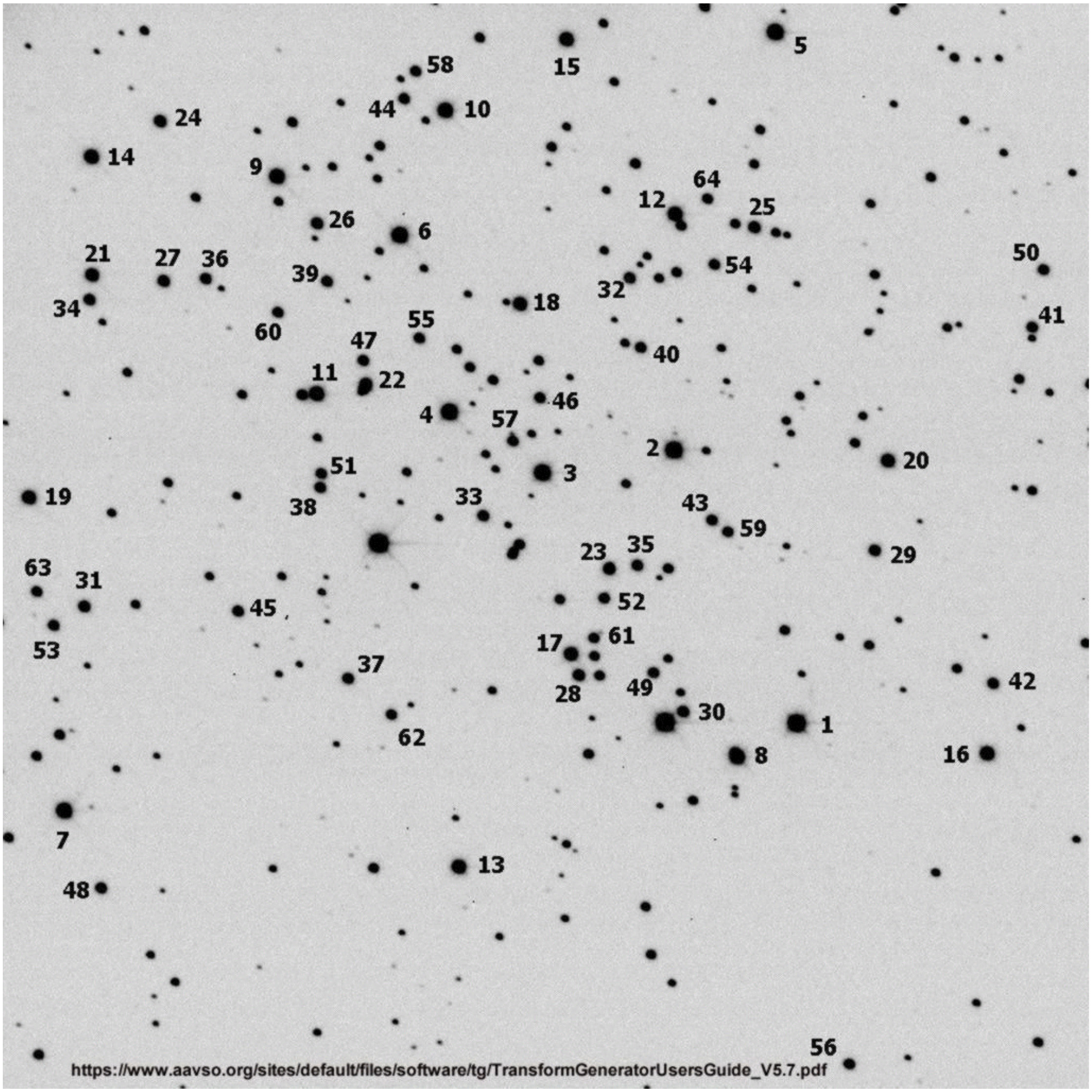

Figure 10. M-67 field with original Boulder swri numbers (AAVSO 2016). Fifteen Boulder swri number stars have been culled by AAVSO from the current VSP data. These are stars 1, 8, 9, 18, 22, 26, 32, 35, 45, 46, 49, 52, 55, 61, 62 (April 2016). Note: Star 56 was out of the author's image frame and was not measured.

Appendix B: Correlation key for M-67

Correlation key for M-67 AAVSO VSP AUID to Boulder swri numbers (Myers 2016). The AAVSO VSP stars labled "000-000-000" are culled from original Henden (2000) M-67 Stars.

swri Number	*AUID*	*swri Number*	*AUID*	*swri Number*	*AUID*	*swri Number*	*AUID*
1	000-000-000	17	000-BLG-899	33	000-BLG-911	49	000-000-000
2	000-BLG-886	18	000-000-000	34	000-BLG-912	50	000-BLG-925
3	000-BLG-887	19	000-BLG-900	35	000-000-000	51	000-BLG-926
4	000-BLG-888	20	000-BLG-901	36	000-BLG-913	52	000-000-000
5	000-BLG-889	21	000-BLG-902	37	000-BLG-914	53	000-BLG-927
6	000-BLG-890	22	000-000-000	38	000-BLG-915	54	000-BLG-928
7	000-BLG-891	23	000-BLG-903	39	000-BLG-916	55	000-000-000
8	000-000-000	24	000-BLG-904	40	000-BLG-917	56	000-BLG-929
9	000-000-000	25	000-BLG-905	42	000-BLG-918	57	000-BLG-930
10	000-BLG-892	26	000-000-000	41	000-BLG-919	58	000-BLG-931
11	000-BLG-893	27	000-BLG-906	43	000-BLG-920	59	000-BLG-932
12	000-BLG-894	28	000-BLG-907	44	000-BLG-921	60	000-BLG-934
13	000-BLG-895	29	000-BLG-908	45	000-000-000	61	000-000-000
14	000-BLG-896	30	000-BLG-909	46	000-000-000	62	000-000-000
15	000-BLG-897	31	000-BLG-910	47	000-BLG-923	63	000-BLG-935
16	000-BLG-898	32	000-000-000	48	000-BLG-924	64	000-BLG-936

Appendix C: Data on M-67 stars

AAVSO M-67 data (April 2016); Boulder swri number Henden (2000). Data taken from VSP Field photometry for EV Cnc; Sequence X16215DHF.

	Measured Instr Magnitudes (average of 6 20-sec exposures)					*Calibrated and Culled AAVSO M-67 Stars*				*Average Errors; vsp*			
Bldr swri	*Airmas 1.2*	*Airmas 1.4*	*Airmas 1.6*	*Airmas 2.0*	*VSP AUID*	*B*	*V*	*Rc*	*Ic*	*0.02 B err*	*0.017 V err*	*0.019 Rc err*	*0.023 Ic err*
1	9.285	9.49	9.71	9.735	—	star culled from swri tlist				—	—	—	—
2	9.024	9.2	9.401	9.412	000-BLG-886	11.553	10.289	9.626	9.063	0.023	0.016	0.021	0.027
3	9.278	9.458	9.656	9.673	000-BLG-887	11.562	10.453	9.886	9.386	0.018	0.014	0.016	0.020
4	9.512	9.696	9.899	9.912	000-BLG-888	11.064	10.489	10.149	9.822	0.016	0.013	0.015	0.021
5	9.368	9.536	9.729	9.748	000-BLG-889	11.617	10.524	9.961	9.471	0.023	0.016	0.020	0.022
6	9.347	9.526	9.722	9.742	000-BLG-890	11.656	10.533	9.952	9.438	0.018	0.012	0.014	0.017
7	9.549	9.732	9.926	9.927	000-BLG-891	11.898	10.763	10.185	9.657	0.019	0.016	0.020	0.023
8	9.986	10.183	10.396	10.408	—	star culled from swri tlist				—	—	—	—
9	10.108	10.298	10.487	10.517	—	star culled from swri tlist				—	—	—	—
10	10.19	10.377	10.59	10.609	000-BLG-892	11.042	10.946	10.902	10.844	0.021	0.019	0.022	0.024
11	10.241	10.428	10.635	10.66	000-BLG-893	11.283	11.064	10.948	10.82	0.019	0.017	0.020	0.024
12	9.968	10.142	10.339	10.353	000-BLG-894	12.221	11.132	10.56	10.059	0.018	0.014	0.017	0.021
13	10.478	10.678	10.894	10.911	000-BLG-895	11.391	11.263	11.215	11.146	0.019	0.016	0.017	0.023
14	10.093	10.268	10.463	10.469	000-BLG-896	12.342	11.266	10.697	10.187	0.016	0.012	0.016	0.020
15	10.31	10.488	10.692	10.709	000-BLG-897	11.911	11.305	10.945	10.609	0.020	0.013	0.018	0.020
16	10.482	10.683	10.903	10.918	000-BLG-898	11.604	11.314	11.149	10.988	0.020	0.017	0.021	0.025
17	10.269	10.454	10.652	10.661	000-BLG-899	12.500	11.427	10.867	10.376	0.017	0.014	0.016	0.020
18	10.396	10.575	10.773	10.787	—	star culled from swri tlist				—	—	—	—
19	10.324	10.506	10.697	10.705	000-BLG-900	12.546	11.494	10.941	10.442	0.016	0.011	0.014	0.017
20	10.644	10.837	11.041	11.059	000-BLG-901	11.949	11.544	11.293	11.050	0.017	0.014	0.017	0.021
21	10.47	10.652	10.844	10.852	000-BLG-902	12.686	11.636	11.081	10.580	0.017	0.012	0.015	0.020
22	10.707	10.895	11.097	11.100	—	star culled from swri tlist				—	—	—	—
23	11.192	11.384	11.593	11.601	000-BLG-903	12.572	12.116	11.835	11.566	0.016	0.013	0.015	0.020
24	11.003	11.174	11.369	11.375	000-BLG-904	13.138	12.138	11.602	11.122	0.016	0.012	0.018	0.021
25	11.232	11.409	11.62	11.627	000-BLG-905	12.883	12.213	11.83	11.477	0.016	0.012	0.014	0.018
26	11.402	11.604	11.804	11.822	—	star culled from swri tlist				—	—	—	—
27	11.273	11.457	11.659	11.664	000-BLG-906	12.808	12.246	11.914	11.588	0.016	0.013	0.016	0.021
28	11.317	11.515	11.723	11.743	000-BLG-907	12.823	12.254	11.917	11.599	0.017	0.015	0.019	0.020
29	11.266	11.451	11.656	11.660	000-BLG-908	13.359	12.38	11.86	11.409	0.016	0.013	0.015	0.021
30	11.337	11.525	11.723	11.738	000-BLG-909	13.136	12.392	11.965	11.571	0.016	0.011	0.015	0.020
31	11.406	11.602	11.799	11.803	000-BLG-910	12.971	12.41	12.069	11.716	0.016	0.013	0.015	0.018
32	11.579	11.765	11.963	11.977	—	star culled from swri tlist				—	—	—	—
33	11.557	11.747	11.947	11.961	000-BLG-911	13.129	12.54	12.194	11.860	0.021	0.018	0.020	0.026
34	11.58	11.758	11.969	11.973	000-BLG-912	13.139	12.56	12.216	11.876	0.022	0.019	0.022	0.024
35	11.516	11.707	11.911	11.916	—	star culled from swri tlist				—	—	—	—
36	11.612	11.789	12.001	12.004	000-BLG-913	13.171	12.589	12.242	11.909	0.022	0.02	0.022	0.024
37	11.635	11.829	12.027	12.039	000-BLG-914	13.191	12.623	12.287	11.953	0.024	0.021	0.022	0.025
38	11.62	11.804	12.001	12.013	000-BLG-915	13.241	12.629	12.272	11.925	0.022	0.02	0.022	0.023
39	11.659	11.842	12.042	12.055	000-BLG-916	13.215	12.633	12.29	11.961	0.022	0.019	0.021	0.023
40	11.664	11.852	12.058	12.074	000-BLG-917	13.246	12.64	12.285	11.96	0.022	0.019	0.021	0.024
41	11.675	11.86	12.06	12.065	000-BLG-918	13.263	12.652	12.299	11.975	0.023	0.019	0.022	0.025
42	11.682	11.885	12.084	12.101	000-BLG-919	13.271	12.653	12.298	11.975	0.021	0.019	0.021	0.024
43	11.738	11.936	12.136	12.153	000-BLG-920	13.166	12.665	12.367	12.092	0.022	0.019	0.021	0.023
44	11.684	11.864	12.064	12.071	000-BLG-921	13.339	12.672	12.285	11.927	0.021	0.019	0.021	0.024
45	11.651	11.835	12.037	12.047	000-BLG-922	star culled from swri tlist				—	—	—	—
46	11.734	11.921	12.118	12.134	—	star culled from swri tlist				—	—	—	—
47	11.716	11.899	12.096	12.119	000-BLG-923	13.280	12.692	12.344	12.01	0.023	0.020	0.023	0.025
48	11.715	11.91	12.11	12.114	000-BLG-924	13.278	12.708	12.378	12.049	0.022	0.019	0.022	0.024
49	11.762	11.952	12.158	12.171	—	star culled from swri tlist				—	—	—	—
50	11.721	11.908	12.096	12.129	000-BLG-925	13.468	12.731	12.311	11.945	0.021	0.019	0.021	0.024
51	11.661	11.853	12.048	12.051	000-BLG-926	13.57	12.752	12.303	11.89	0.023	0.021	0.023	0.025
52	11.796	11.989	12.189	12.210	—	star culled from swri tlist				—	—	—	—
53	11.728	11.925	12.113	12.125	000-BLG-927	13.513	12.772	12.364	11.972	0.022	0.019	0.021	0.022
54	11.847	12.024	12.222	12.246	000-BLG-928	13.349	12.79	12.459	12.149	0.020	0.018	0.02	0.024
55	11.925	11.99	12.199	12.241	—	star culled from swri tlist				—	—	—	—
56	-	-	-	-	000-BLG-929	out of image not measured				—	—	—	—
57	11.847	12.034	12.243	12.259	000-BLG-930	13.386	12.815	12.478	12.155	0.022	0.019	0.022	0.024
58	11.856	12.041	12.236	12.261	000-BLG-931	13.376	12.819	12.481	12.160	0.023	0.019	0.022	0.025
59	11.862	12.06	12.264	12.276	000-BLG-932	13.378	12.821	12.489	12.187	0.023	0.021	0.023	0.025
60	11.891	12.078	12.274	12.291	000-BLG-934	13.380	12.854	12.533	12.221	0.021	0.019	0.021	0.025
61	11.971	12.177	12.38	12.389	—	star culled from swri tlist				—	—	—	—
62	11.792	11.977	12.186	12.186	—	star culled from swri tlist				—	—	—	—
63	11.845	12.031	12.231	12.244	000-BLG-935	13.871	12.958	12.470	12.015	0.024	0.02	0.023	0.025
64	11.938	12.102	12.307	12.317	000-BLG-936	13.835	12.986	12.521	12.109	0.022	0.02	0.022	0.024

Appendix D: Unfiltered instrumental magnitudes transformed to "standard" B, V, Rc, Ic magnitudes

Unfiltered instrumental magnitudes for 48 Calibrated Stars transformed to "standard" B, V, Rc, Ic magnitudes (b, v, r, i) for air mass (X) of 1.2, 1.4, 1.6, and 2.0. "—" in column 2 indicates culled reference star.

						Magnitudes Derived from Unfiltered Image Instrumental Magnitudes (Imag)																			
Bldr	*M-67*	*Reference Magnitudes*				*X=1.2*	*Derived Mags*				*X=1.4*	*Derived Mags*				*X=1.6*	*Derived Mags*				*X=2.0*	*Derived Mags*			
swri	*VSP AUID*	*B*	*V*	*Rc*	*Ic*	*Imag*	*b*	*v*	*r*	*i*	*Imag*	*b*	*v*	*r*	*i*	*Imag*	*b*	*v*	*r*	*i*	*Imag*	*b*	*v*	*r*	*i*
1	—																								
2	000-BLG-886	11.553	10.289	9.626	9.063	9.024	11.534	10.27	9.624	9.061	9.200	11.536	10.272	9.623	9.062	9.401	11.542	10.278	9.630	9.068	9.412	11.543	10.279	9.631	9.069
3	000-BLG-887	11.562	10.453	9.886	9.386	9.278	11.570	10.46	9.890	9.390	9.458	11.573	10.464	9.892	9.393	9.656	11.574	10.465	9.892	9.393	9.673	11.58	10.471	9.898	9.399
4	000-BLG-888	11.064	10.489	10.149	9.822	9.512	11.053	10.478	10.163	9.836	9.696	11.051	10.476	10.173	9.836	9.899	11.048	10.473	10.169	9.834	9.912	11.045	10.470	10.167	9.833
5	000-BLG-889	11.617	10.524	9.961	9.471	9.368	11.638	10.545	9.982	9.492	9.536	11.628	10.535	9.970	9.482	9.729	11.624	10.531	9.966	9.477	9.748	11.632	10.539	9.973	9.485
6	000-BLG-890	11.656	10.533	9.952	9.438	9.347	11.659	10.536	9.955	9.441	9.526	11.662	10.539	9.958	9.444	9.722	11.661	10.538	9.957	9.443	9.742	11.669	10.546	9.9650	9.451
7	000-BLG-891	11.898	10.763	10.185	9.657	9.549	11.879	10.744	10.152	9.624	9.732	11.885	10.750	10.159	9.630	9.926	11.882	10.747	10.157	9.628	9.927	11.872	10.737	10.147	9.619
8	—																								
9	—																								
10	000-BLG-892	11.042	10.946	10.902	10.844	10.19	11.058	10.962	10.899	10.841	10.377	11.050	10.954	10.886	10.832	10.590	11.05	10.954	10.885	10.830	10.609	11.050	10.954	10.885	10.829
11	000-BLG-893	11.283	11.064	10.948	10.820	10.241	11.283	11.064	10.933	10.805	10.428	11.276	11.057	10.925	10.799	10.635	11.273	11.054	10.921	10.794	10.660	11.279	11.060	10.927	10.799
12	000-BLG-894	12.221	11.132	10.560	10.059	9.968	12.233	11.144	10.573	10.072	10.142	12.229	11.140	10.567	10.068	10.339	12.230	11.141	10.568	10.068	10.353	12.233	11.144	10.571	10.072
13	000-BLG-895	11.391	11.263	11.215	11.146	10.478	11.391	11.263	11.182	11.113	10.678	11.397	11.269	11.180	11.117	10.894	11.401	11.273	11.183	11.119	10.911	11.399	11.271	11.181	11.115
14	000-BLG-896	12.342	11.266	10.697	10.187	10.093	12.340	11.264	10.695	10.185	10.268	12.337	11.261	10.692	10.182	10.463	12.335	11.259	10.691	10.181	10.469	12.331	11.255	10.687	10.177
15	000-BLG-897	11.911	11.305	10.945	10.609	10.310	11.896	11.290	10.952	10.616	10.488	11.887	11.281	10.950	10.608	10.692	11.887	11.281	10.950	10.609	10.709	11.889	11.283	10.952	10.612
16	000-BLG-898	11.604	11.314	11.149	10.988	10.482	11.623	11.333	11.164	11.003	10.683	11.632	11.342	11.170	11.011	10.903	11.643	11.353	11.181	11.021	10.918	11.641	11.351	11.178	11.018
17	000-BLG-899	12.500	11.427	10.867	10.376	10.269	12.511	11.438	10.874	10.383	10.454	12.518	11.445	10.876	10.389	10.652	12.520	11.447	10.878	10.390	10.661	12.520	11.447	10.877	10.389
10	—																								
19	000-BLG-900	12.546	11.494	10.941	10.442	10.324	12.538	11.486	10.927	10.428	10.506	12.541	11.489	10.930	10.431	10.697	12.535	11.483	10.924	10.425	10.705	12.532	11.480	10.921	10.423
20	000-BLG-901	11.949	11.544	11.293	11.050	10.644	11.947	11.542	11.304	11.061	10.837	11.950	11.545	11.312	11.065	11.041	11.947	11.542	11.309	11.062	11.059	11.949	11.544	11.311	11.065
21	000-BLG-902	12.686	11.636	11.081	10.580	10.470	12.681	11.631	11.071	10.570	10.652	12.684	11.634	11.073	10.572	10.844	12.680	11.630	11.07	10.569	10.852	12.677	11.627	11.067	10.567
22	—																								
23	000-BLG-903	12.572	12.116	11.835	11.566	11.192	12.568	12.112	11.841	11.572	11.384	12.571	12.115	11.847	11.576	11.593	12.574	12.118	11.850	11.580	11.601	12.567	12.111	11.843	11.572
24	000-BLG-904	13.138	12.138	11.602	11.122	11.003	13.144	12.144	11.604	11.124	11.174	13.135	12.135	11.592	11.114	11.369	13.134	12.134	11.592	11.114	11.375	13.130	12.130	11.588	11.110
25	000-BLG-905	12.883	12.213	11.830	11.477	11.232	12.909	12.239	11.861	11.508	11.409	12.901	12.231	11.853	11.500	11.620	12.910	12.24	11.863	11.509	11.627	12.904	12.234	11.857	11.503
26	—																								
27	000-BLG-906	12.808	12.246	11.914	11.588	11.273	12.799	12.237	11.908	11.582	11.457	12.794	12.232	11.909	11.579	11.659	12.794	12.232	11.909	11.579	11.664	12.785	12.223	11.900	11.571
28	000-BLG-907	12.823	12.254	11.917	11.599	11.317	12.852	12.283	11.954	11.636	11.515	12.862	12.293	11.965	11.646	11.723	12.867	12.298	11.971	11.651	11.743	12.874	12.305	11.977	11.658
29	000-BLG-908	13.359	12.380	11.860	11.409	11.266	13.378	12.399	11.871	11.420	11.451	13.383	12.404	11.867	11.423	11.656	13.392	12.413	11.876	11.431	11.660	13.385	12.406	11.87	11.424
30	000-BLG-909	13.136	12.392	11.965	11.571	11.337	13.118	12.374	11.955	11.561	11.525	13.121	12.377	11.960	11.564	11.723	13.120	12.376	11.959	11.564	11.738	13.123	12.379	11.961	11.566
31	000-BLG-910	12.971	12.410	12.069	11.716	11.406	12.930	12.369	12.034	11.681	11.602	12.938	12.377	12.052	11.690	11.799	12.932	12.371	12.046	11.686	11.803	12.922	12.361	12.037	11.678
32	—																								
33	000-BLG-911	13.129	12.54	12.194	11.860	11.557	13.121	12.532	12.188	11.854	11.747	13.123	12.534	12.192	11.856	11.947	13.121	12.532	12.191	11.855	11.961	13.122	12.533	12.192	11.856
34	000-BLG-912	13.139	12.56	12.216	11.876	11.580	13.130	12.551	12.209	11.869	11.758	13.120	12.541	12.204	11.860	11.969	13.129	12.550	12.213	11.870	11.973	13.119	12.540	12.204	11.861
35	—																								
36	000-BLG-913	13.171	12.589	12.242	11.909	11.612	13.166	12.584	12.242	11.909	11.789	13.155	12.573	12.235	11.899	12.001	13.165	12.583	12.245	11.91	12.004	13.155	12.573	12.235	11.900
37	000-BLG-914	13.191	12.623	12.287	11.953	11.635	13.169	12.601	12.265	11.931	11.829	13.175	12.607	12.275	11.937	12.027	13.171	12.603	12.271	11.934	12.039	13.169	12.601	12.269	11.933
38	000-BLG-915	13.241	12.629	12.272	11.925	11.62	13.216	12.604	12.247	11.900	11.804	13.213	12.601	12.247	11.897	12.001	13.209	12.597	12.243	11.894	12.013	13.208	12.596	12.242	11.893
39	000-BLG-916	13.215	12.633	12.29	11.961	11.659	13.213	12.631	12.29	11.961	11.842	13.209	12.627	12.287	11.957	12.042	13.206	12.624	12.285	11.954	12.055	13.206	12.624	12.285	11.955
40	000-BLG-917	13.246	12.640	12.285	11.960	11.664	13.251	12.645	12.295	11.970	11.852	13.252	12.646	12.294	11.971	12.058	13.256	12.65	12.299	11.975	12.074	13.260	12.654	12.303	11.979
41	000-BLG-918	13.263	12.652	12.299	11.975	11.675	13.269	12.658	12.306	11.982	11.86	13.267	12.656	12.301	11.980	12.06	13.265	12.654	12.300	11.978	12.065	13.258	12.647	12.293	11.971
42	000-BLG-919	13.271	12.653	12.298	11.975	11.682	13.286	12.668	12.314	11.991	11.885	13.302	12.684	12.325	12.006	12.084	13.300	12.682	12.324	12.003	12.101	13.304	12.686	12.328	12.007
43	000-BLG-920	13.166	12.665	12.367	12.092	11.738	13.178	12.677	12.381	12.106	11.936	13.186	12.685	12.386	12.114	12.136	13.183	12.682	12.383	12.110	12.153	13.186	12.685	12.386	12.113
44	000-BLG-921	13.339	12.672	12.285	11.927	11.684	13.357	12.690	12.308	11.950	11.864	13.351	12.684	12.300	11.943	12.064	13.351	12.684	12.301	11.943	12.071	13.345	12.678	12.296	11.938
45	—																								
46	—																								
47	000-BLG-923	13.28	12.692	12.344	12.010	11.716	13.278	12.690	12.345	12.011	11.899	13.274	12.686	12.342	12.007	12.096	13.269	12.681	12.338	12.002	12.119	13.278	12.69	12.347	12.012
48	000-BLG-924	13.278	12.708	12.378	12.049	11.715	13.252	12.682	12.346	12.017	11.910	13.259	12.689	12.354	12.023	12.11	13.256	12.686	12.353	12.022	12.114	13.248	12.678	12.344	12.013
49	—																								
50	000-BLG-925	13.468	12.731	12.311	11.945	11.721	13.493	12.756	12.342	11.976	11.908	13.495	12.758	12.338	11.977	12.096	13.484	12.747	12.328	11.966	12.129	13.505	12.768	12.349	11.986
51	000-BLG-926	13.570	12.752	12.303	11.890	11.661	13.546	12.728	12.271	11.858	11.853	13.555	12.737	12.277	11.866	12.048	13.552	12.734	12.274	11.863	12.051	13.545	12.727	12.267	11.856
52	—																								
53	000-BLG-927	13.513	12.772	12.364	11.972	11.728	13.505	12.764	12.343	11.951	11.925	13.518	12.777	12.355	11.963	12.113	13.506	12.765	12.344	11.952	12.125	13.507	12.766	12.344	11.952
54	000-BLG-928	13.349	12.790	12.459	12.149	11.847	13.369	12.810	12.481	12.171	12.024	13.358	12.799	12.468	12.159	12.222	13.353	12.794	12.464	12.155	12.246	13.364	12.805	12.475	12.166
55	—																								
56	000-BLG-929	Out of Frame Not Measured																							
57	000-BLG-930	13.386	12.815	12.478	12.155	11.847	13.385	12.814	12.477	12.154	12.034	13.385	12.814	12.477	12.154	12.243	13.392	12.821	12.485	12.161	12.259	13.395	12.824	12.487	12.164
58	000-BLG-931	13.376	12.819	12.481	12.160	11.856	13.374	12.817	12.486	12.165	12.041	13.372	12.815	12.485	12.163	12.236	13.365	12.808	12.479	12.156	12.261	13.377	12.82	12.49	12.169
59	000-BLG-932	13.378	12.821	12.489	12.187	11.862	13.381	12.824	12.497	12.195	12.060	13.390	12.833	12.503	12.204	12.264	13.393	12.836	12.506	12.206	12.276	13.391	12.834	12.505	12.204
60	000-BLG-934	13.380	12.854	12.533	12.221	11.891	13.366	12.840	12.524	12.212	12.078	13.365	12.839	12.524	12.210	12.274	13.358	12.832	12.518	12.205	12.291	13.362	12.836	12.522	12.208
61	—																								
62	—																								
63	000-BLG-935	13.871	12.958	12.47	12.015	11.845	13.864	12.951	12.444	11.989	12.031	13.869	12.956	12.444	11.992	12.231	13.873	12.960	12.449	11.996	12.244	13.875	12.962	12.451	11.999
64	000-BLG-936	13.835	12.986	12.521	12.109	11.938	13.868	13.019	12.546	12.134	12.102	13.849	13.000	12.520	12.114	12.307	13.856	13.007	12.528	12.121	12.317	13.856	13.007	12.528	12.121

Appendix E: Determination of target star Ci

It is possible to use two images taken with different filters and the spreadsheet process described above to determine a color index for the target star (Dunckel 2014). Making two different filtered images of the subject star field such as B and V, the color index (B–V) can be calculated. The filtered images are photometrically processed just like the unfiltered images, giving Imag_B and Imag_V. Two spreadsheets are set up using the catalogued magnitudes, one for B and the other for V. The two filtered instrumental magnitude sets are used as the data source (Imag_B) for the B spreadsheet, and (Imag_V) for the V spreadsheet. Using the spreadsheets, the two filtered data sets are each processed using the same "test" value for the color index of the target star at cells {C8}, Figure 3. In one of the spreadsheets, a cell is set to calculate the derived (b–v) value. The value (b) is from the B spreadsheet and (v) from the V spreadsheet at cells {C10}, Figure 3. The same test value (B–V) for the target is placed in each spreadsheet and repeatedly changed until the calculated (b–v) is equal to the test (B–V). Using the calculated (b–v) value as the next "test" (B–V) value, works well and is found to quickly converge to the proper (v–b) = (V– B) value thus giving a Ci = (B–V). Note: the filtered images must be made during the same session and close to the same time as the unfiltered images.

Appendix F: Slope factor—a proposition for discussion

The slope factor, S', is an empirically determined transformation coefficient. In using the spreadsheet model, it was discovered that without a slope coefficient, a linear fit of the derived magnitudes (f) was generally "skewed" to the slope of the reference magnitudes (F). With a slope coefficient S' applied to the instrumental magnitudes (Equation 3), the linear fit of the derived magnitudes better aligns with the reference magnitudes. The standard deviation of the residuals (V–v, for example) is improved as would be expected. Experience has shown that generally the improvement to the standard deviation is from 0.001 to 0.010, depending on the quality of the instrumental magnitudes and the calibration of the reference stars.

Figures 11a and 11b show the effect on the residuals for two different star fields. Figure 11a is for the well calibrated M-67 cataloged stars using a relatively high number of stars (48). This data set is well calibrated and the improvement made by using S' is negligible.

Figure 11b is for the Rubin 152 star field using APASS magnitudes for reference. The transformation for this star field is with fewer stars and the calibration of the stars is of somewhat less quality. The application of the S' factor here is significant. As stated, this is an empirical factor and may or may not suit a given imaging system and or star field.

The "slope" factor is easily calculated. Simply place the factor (S') into Equation 2, thus:

$$f = S' \times \text{Imag} + Ci \times T' + Z'. \quad (3)$$

The spread sheet is modified to have three unknown constants, T', Z', and S'. The calculations within the spreadsheet will then automatically provide the three constants and the derived magnitude values for the selected passband are calculated as before.

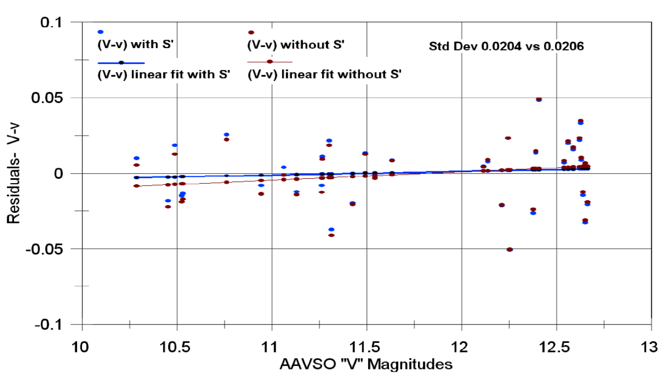

Figure 11a. M-67 catalogued stars using a relatively high number of stars.

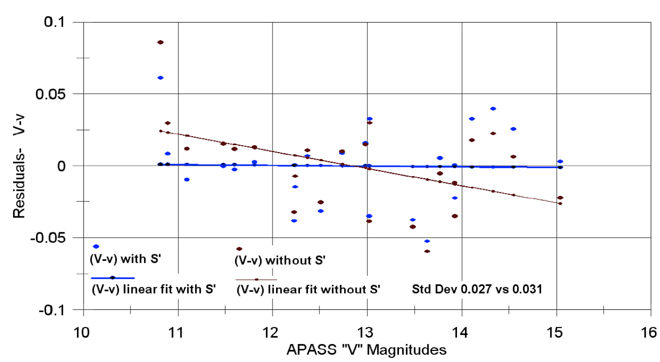

Figure 11b. Rubin 152 star field using APASS magnitudes for reference.