THE M67 UNFILTERED PHOTOMETRY EXPERIMENT

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Abstract

An experiment has been conducted over the past year to see how far from a standard filter an unfiltered CCD's response lies, whether it is possible to transform such unfiltered data into the standard system, and how much limiting magnitude is lost by using a standard filter.

1. Introduction

At a Minor Planet Workshop held at Lowell in 1999, several participants asked whether they really needed to use a filter when doing asteroid photometry. This has always been an intriguing question: can an unfiltered CCD be used as if you just had a very wide standard filter? Certainly, one can transform a measurement taken with a Johnson R filter into an equivalent measurement in the Cousins R system, or from the Tycho Bt/Vt system into Johnson B and V. Usually, there are limits based on the color of the object being measured and how far from the alternative system the current filter lies. You can do this theoretically if you know the transmission at every wavelength of every element in the optical path, as well as the spectral response of the CCD. However, in practice, it is difficult to ensure that all CCDs of a given type are manufactured identically, or that focal reducer A gives the same results as focal reducer B.

Members of the minor planet mail list, as well as those from the aavso-discussion and ccd mail lists, were asked to take an unfiltered exposure with their CCD and telescope of the old open cluster M67 to answer this question. M67 is an ideal candidate. It is well-placed for northern observers. It has a wide range of star color, yet most of its stars are bright enough to be well-exposed with normal amateur equipment. At the same time, the cluster is not too large to fit the field of view of a typical CCD, nor so small that crowding prevents good photometry. This cluster has been observed by a number of professionals, and the quality of the published photometry is at the Landolt level.

A master UBVRI photometry file for M67 has been created by the author (see ftp://ftp.nofs.navy.mil/pub/outgoing/aah/m67/m67-data.txt), based on a dozen photometric nights. The photometry extends from V=10 to V=17 with less than one percent mean errors in all magnitudes and colors. This file has been compared with photometry by Montgomery *et al.* (1993), with negligible differences. The field covered by the master photometry file is shown in Figure 1, and represents the field center for the experiment participants.

By comparing the unfiltered instrumental magnitudes to standard Johnson V and Cousins R magnitudes for M67 stars, one can determine transformation equations to V and R and see how well one can reproduce those standard magnitudes.

2. Observations

Approximately 45 observers submitted unfiltered observations of M67. These were taken with a wide variety of telescopes, CCDs, cameras, and observing conditions. They are fairly representative of the equipment used by most amateurs, though the number of observations with a particular setup is too small to give good statistical results. Instead, qualitative answers will be given in this paper. The full summary table for all observers can be found at ftp://ftp.nofs.navy.mil/pub/outgoing/aah/m67/summary.txt .

For each observation, the participant was asked to limit the exposure time so that bright stars were not saturated. Each CCD frame was to be dark-subtracted and flat-fielded. The FITS formatted images were then uploaded to the USNO Flagstaff Station anonymous ftp server. From there, the images were first examined to determine full-width-half-maximum (fwhm) of the stellar profiles ("seeing") and the sky background and noise. These parameters were used in DAOPHOT to find all objects in the image. These objects were further measured with aperture photometry, and a subset was selected to form a mean point-spread-function (psf) profile for the image. This psf was used in the ALLSTAR function of DAOPHOT to obtain final photometry of every object on the frame. Once the photometry and centroid of every object was obtained,

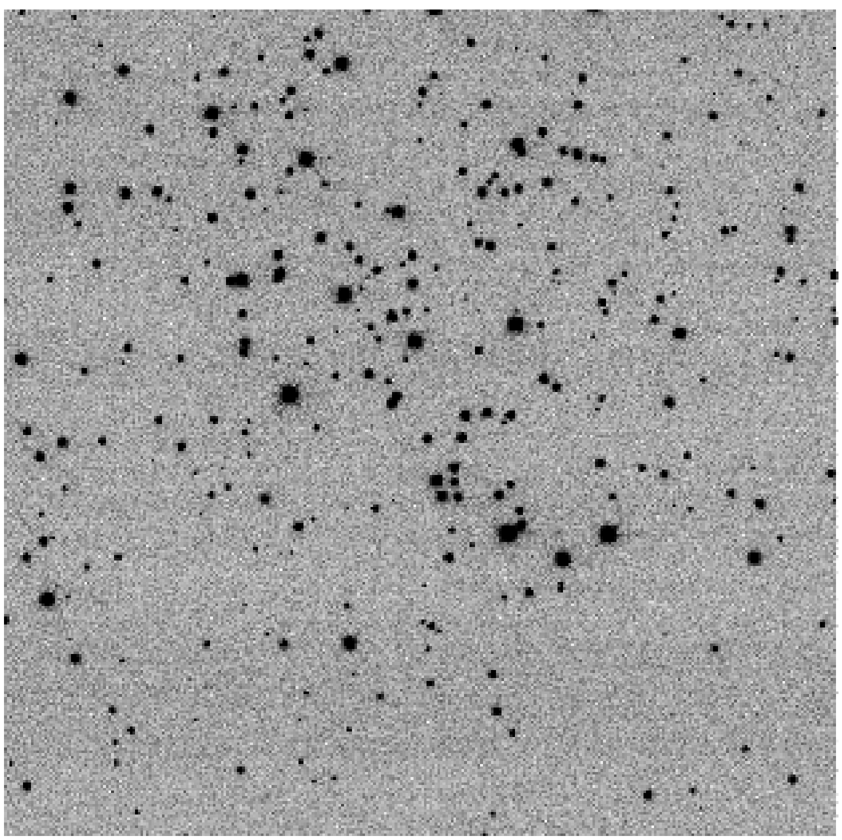

Figure 1. CCDV image of M67, north up and east left. Field of view is 11 x 11 arcmin.

astrometry using *USNO-A2.0* was performed to find linear plate constants for the frame and create RA,DEC for every object on the image. The final output of this processing was thus the coordinates and accurate psf magnitudes for all objects.

A program was written to match all input coordinates/magnitudes to the appropriate master photometry file star. This matched list is the basis for all further reductions. For each matched pair, the differences (V-inst) and (R-inst) were calculated, and tabulated along with (B-V) and (V-I) for each reference star. These four quantities were then used in linear least squares solutions to the equations

$$(V\text{-inst}) = a(v) + b(v) * (B\text{-}V) \tag{1}$$

$$(R\text{-inst}) = a(r) + b(r) * (V\text{-}I) \tag{2}$$

where a(x) is the zero point between the instrumental system and the standard magnitude, and is irrelevant since it is just a constant for all stars in the frame. The important quantity is b(x), the slope of the relationship, showing whether there is a systematic trend with color between the two systems. The color index [(B-V) or (V-I)] is not very important, but was selected to bracket the magnitude that is to be fit. However, the fitted slopes are specific to the color index that is used.

Taking the V equation as an example, if b(v) is positive, then as you use redder stars, the difference between V and the instrumental magnitude becomes larger, which means the instrumental magnitude is brighter than the true magnitude. This result indicates that the instrumental system peak response wavelength is redder than V. Likewise, if b(v) were negative, then this means the instrumental magnitude of a red star is fainter than for V, and the peak system response is blueward of V. By this means, you can see whether a particular CCD has a similar response to either V or R, is between the two filters, or lies outside either filter peak.

3. Analysis

Wayne Brown (2000) has a nice plot showing the spectral response of various CCDs. The plot is reproduced in Figure 2. Note that the response of any CCD is quite broad, ranging from at least 400nm to 900nm. From this plot, three types of responses are expected: CCDs with V-like response (Sony interline), CCDs with R-like response (most front-illuminated devices), and those that fall between (such as the Kodak blue-enhanced CCDs or back-illuminated CCDs).

A typical set of plots showing the residuals between (V-inst) and (R-inst) for a KAF0400E is shown in Figures 3 and 4. Note that (V-inst) vs. (B-V) shows a positive slope, whereas (R-inst) *vs.* (V-I) shows a negative slope. This indicates that the response of a blue-enhanced CCD lies somewhere between V and R, in accordance with the anticipated results based on Figure 2.

Other CCDs generate different plots. The types of CCDs used by the participants yield the typical results shown in Table 1, where participants whose systems deviated by more than two sigma from the mean or who had an unusual setup (an IR blocker, for example) have been removed from the calculation.

Riess *et al.* (1999) approach this problem from the theoretical direction, using the published response curves from the CCD vendors to establish transformations from the unfiltered instrumental system to Johnson V. Their transformation equation to V is identical in form to our (V-inst) equation, with transformation coefficients of 0.40 for a TC245 equivalent chip, and 0.33 for a SITe chip. Within the estimated errors of Riess *et al.*, these coefficients agree with the coefficients in Table 1.

What does this table mean? Those observers with unfiltered CCDs of the KAF and TC245 (cookbook) types should assume their CCDs are similar to R-band

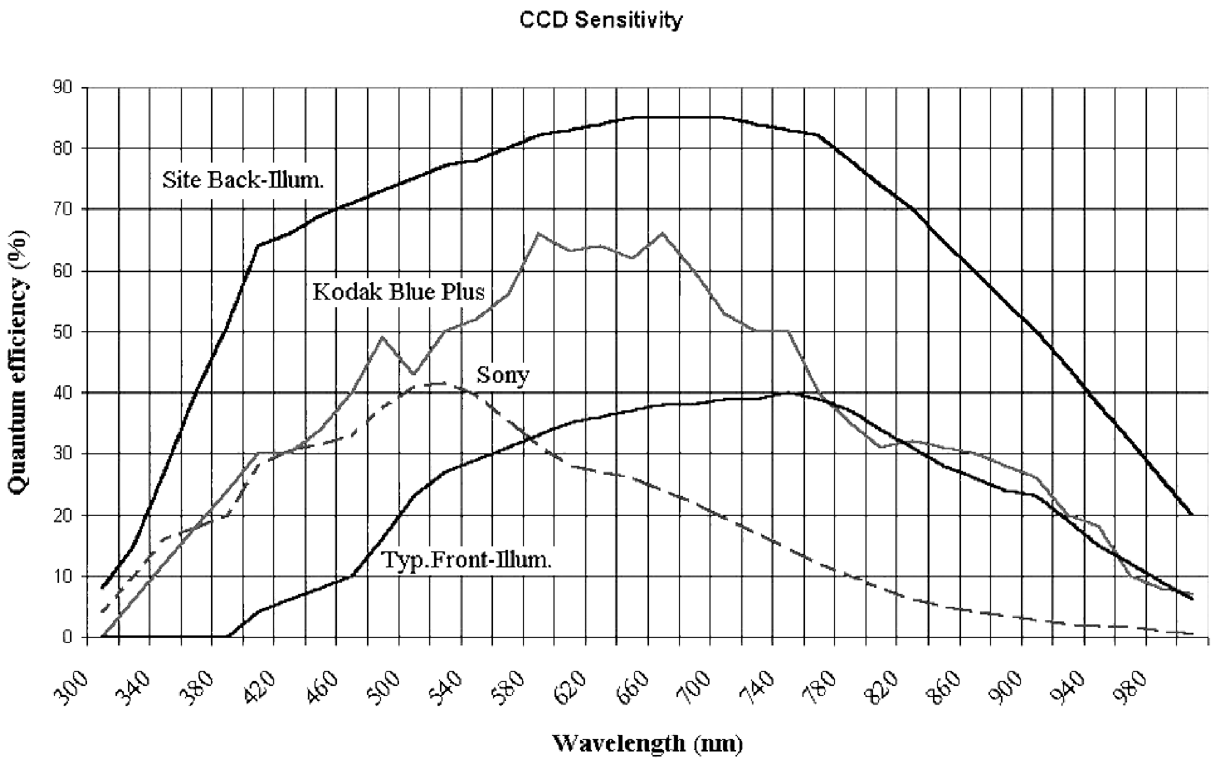

Figure 2. Sensitivity *vs.* wavelength curve for various CCD types (Apogee, Inc.; Brown 2000).

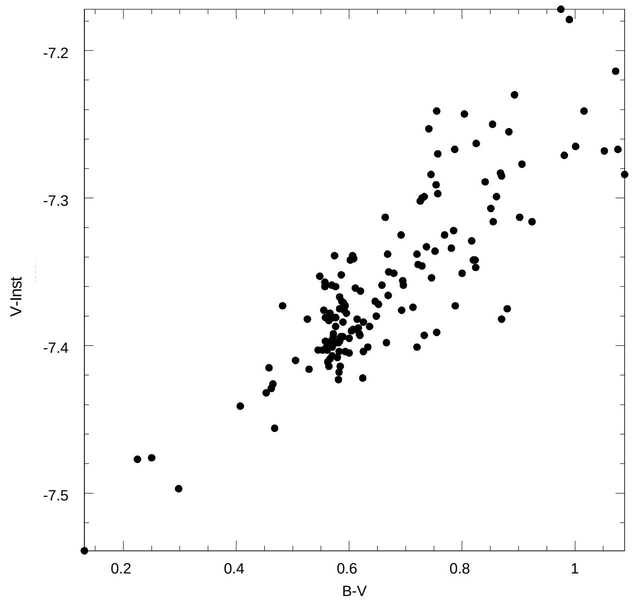

Figure 3. V-magnitude residuals *vs.* color for a KAF0400E CCD.

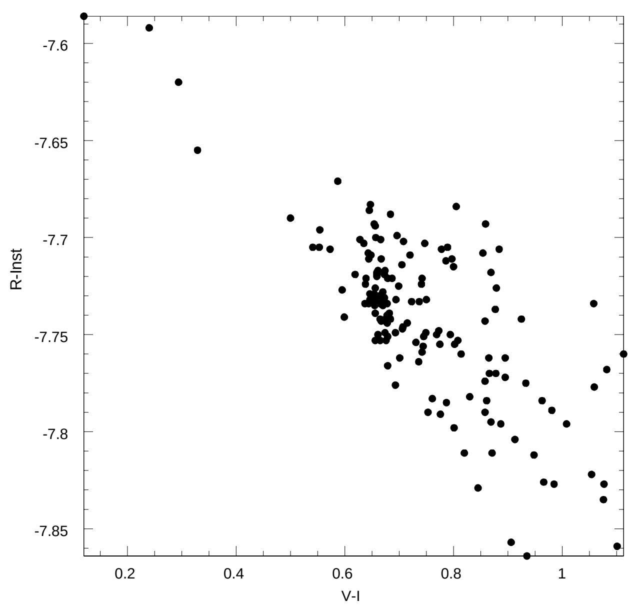

Figure 4. R-magnitude residuals *vs.* color for a KAF0400E CCD.

Table 1. Slopes for CCD types.

CCD	b(v)	b(r)
SITe back-illuminated	0.2600	-0.2716
KAF-E	0.3602	-0.1541
KAF	0.5174	0.0005
Sony	-0.0606	-0.6256
TI TC245	0.4292	-0.1021
TI TC241 (VP)	0.2905	-0.2510

photometry, and use R-band magnitudes when setting their zero points in a field. They should report their results as CCDR (if the AAVSO will accept such a system). Likewise, observers with Sony interline chips should assume their CCDs are similar to V-band photometry, and use V-band magnitudes when setting their zero points in a field. All other CCD types should transform their results into either V or R using the slopes given above.

Unfortunately, to transform an instrumental magnitude into a standard magnitude means that you have to know the intrinsic color of the program object. In some cases, this is known, such as an eclipsing binary that does not undergo large color change through its cycle. On the other hand, cataclysmic variables are often very different in color between outburst and quiescent phases, and pulsating variables typically become bluer (hotter) as they rise to maximum light. For these stars, not transforming your data will result in systematic errors that cannot be corrected by a simple zero point adjustment. For still other observations, you have no idea what the color of the object might be. Another complication is if the object's spectral energy distribution is not similar to a black body. For instance, if the object has emission lines or strong molecular absorption lines, then only systems with the same bandpass will reproduce the same magnitudes and colors; you will not be able to transform accurately.

You can reduce the problem with systematic errors by using comparison stars that closely match in color the program object. An example of the improvement possible by transformation is given in Figures 5 and 6. Figure 5 is the raw comparison between unfiltered instrumental magnitudes from a KAF0400E and the standard R system. Figure 6 is a comparison in which the instrumental magnitudes have been transformed onto the standard system. You can see that the scatter has been dramatically decreased.

3.1. Limiting Magnitude

So, why not use a V or an R filter instead of observing unfiltered? Certainly, there is cost involved (though standard filters are in the US$60 range for most cameras; see chetschu@concentric.net for example), and some complexity (either a threaded filter in the system, a filter slide, or filter wheel). You might think that adding a filter will cut down on the throughput of your system and therefore prevent you from going as deep. Another part of the experiment was for observers to take identical exposures of M67, one through an R filter and one unfiltered. These frames have been processed with DAOPHOT to see what the effect of a typical R filter is on the limiting magnitude. A list of the results from the two-frame test is given in Table 2. This table indicates that the impact can range from almost zero to about a magnitude, depending on the CCD and the quality of the R filter.

Another option is to do "light filtering." This means using a Wratten 12 (yellow) filter to move the spectral response towards the red, or an IR blocker to move the spectral response towards the blue. These methods do work, and will give you wide-R and wide-V response, respectively, at very little loss in throughput. You should at least consider this option when making photometric measurements.

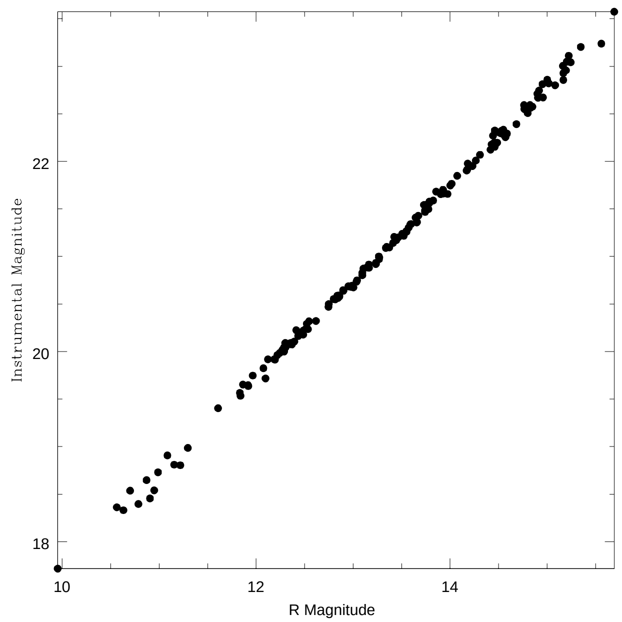

Figure 5. Instrumental unfiltered KAF0400E magnitude *vs*. Cousins R-magnitude for M67.

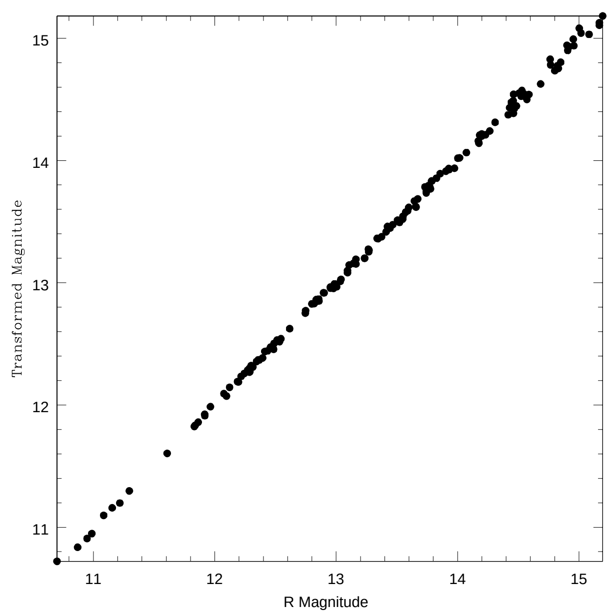

Figure 6. Instrumental unfiltered KAF0400E magnitude transformed onto the standard Cousins R system *vs*. Cousins R-magnitude for M67.

Table 2. Filtered vs. Unfiltered Limiting Magnitude.

CCD	*unfiltered*	*R-band*
SITe	17.5	17.2
SITe	18.6	18.4
TC245	17.1	16.3
TC245	18.2	17.0
KAF0400E	17.4	16.5

4. Transformation Example

Here is an example of the use of the slopes from Table 1: determining the true V-magnitude of a program star from its instrumental unfiltered magnitude plus knowledge of its true (B-V) color. Assume that you use a Kodak KAF 0400 to measure the instrumental magnitudes of the program star and three comparison stars given in Table 3; the standard V and (B-V) colors for the program star and its comparisons are also given in Table 3.

Table 3. Raw Data for Example.

Star	*inst*	*V*	*B-V*
Var	19.133	??	1.072
compA	20.534	12.623	0.572
compB	20.452	12.540	0.591
compC	20.053	12.119	0.458

First, find the zero point for this particular frame:

$$(V\text{-}inst) = a(v) + b(v)*(B\text{-}V)$$

or

$$a(v) = (V\text{-}inst) - b(v)*(B\text{-}V)$$

CompA: a(v) = (12.623-20.534) - 0.5174*(0.572) = -8.207
CompB: a(v) = (12.540-20.452) - 0.5174*(0.591) = -8.218
CompC: a(v) = (12.119-20.053) - 0.5174*(0.458) = -8.171
AVERAGE a(v) = -8.199

Then, using the known (B-V) color of your program star, you can convert the instrumental value into a standard V magnitude:

$$\begin{aligned} V &= inst + a(v) + b(v)\ (B\text{-}V) \\ &= 19.133 - 8.199 + 0.5174\ (1.072) \\ &= 11.489 \end{aligned}$$

There can be some error in this transformation (stars are not nice smooth blackbodies, and also these slopes are the average of several datasets, and an individual slope may be different), but at least this gets you close. In this case, the true V magnitude of the program star was 11.433, reasonably close to the calculated value from this exercise. If you had just used the V magnitudes of the comparison stars without any color term, you would have gotten:

$$V = a(v) + \text{inst} \tag{3}$$
$$a(v) = V\text{-inst}$$

CompA: $a(v) = (12.623\text{-}20.534) = -7.911$
CompB: $a(v) = (12.540\text{-}20.452) = -7.912$
CompC: $a(v) = (12.119\text{-}20.053) = -7.934$
AVERAGE: $a(v) = -7.919$

$$V = -7.919 + 19.133$$
$$V = 11.214$$

This value is considerably different than the true value, and reflects the systematics of the blind approach.

5. Conclusions

Different CCDs have different response curves. You cannot blindly assume that a CCD has an R-like response as has been quoted in some publications. If the CCD does not behave like a wide-V or a wide-R, then there will be systematic shifts in derived magnitudes depending on the color of the observed object, and these shifts may make combination of results from different observatories difficult.

You can remove some of the systematics if you (a) use the closest filter to your CCD response, and (b) transform the results onto the standard system if you know the basic color of the program object and its comparison stars.

6. Acknowledgement

This paper would not have been possible without the data provided by dozens of amateurs. Please keep up the good work!

References

Brown, W. (Apogee Inc.) 2000, http://www.apogee-ccd.com/apspecs.html#QECurves
Montgomery, K. A., Marschall, L. A., and Janes, K. A. 1993, *Astron. J.* **106**, 181.
Riess, A. G., *et al.* 1999, *Astron. J.* **118**, 2675.