CCD Transformation Coefficients

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1. Introduction

The usefulness of the AAVSO approach to variable star observing is to combine observations from many observers, in different locations, at varying times, into a composite light curve. Such a light curve would be difficult for any one observer to obtain. Each observation is a very important part of the whole light curve. For this reason, it is imperative that each observer's work correlate with that of other observers and be as accurate as possible. Since each CCD, filter, and telescope combination has a different color response, it is necessary that you transform your data to a Standard System that would represent your data if your match to the Standard System were perfect. Fortunately, if care is taken in the transformations, our composite light curves can be very well defined. The procedure below describes how to determine your Transformation Coefficients which you will use to transform your data before reporting it to headquarters.

2. Why Do You Need Transformation Coefficients?

The Johnson and Cousins UBVRI system is classified as a broadband system. This means the filters have a width on the order of 100 nanometers and the effective wavelength of the filter will depend on the spectral energy distribution of the star. The bandpasses using the Bessell (1990, PASP, 102, 1181) prescription for filters are shown in Figure 1. The number of counts registered for each star in your images will be determined by the light being emitted from the star which is reflected (or refracted) by your telescope and can pass through the filter you are using AND be detected by your CCD chip. Each CCD chip has a slightly different spectral response, even chips of the same type. Figure 2 illustrates some "typical" quantum efficiency curves (Photometrics Ltd, Tucson, AZ) for different CCD chips. Note that the Thomson THX35116 has peak efficiency at about 650 nm, the PM512 at about 700 nm, and the Thomson TH7882 at about 775 nm. This means a star would appear to be relatively redder observed with a TH7882 than with a THX35116 as can be seen in Figure 3. Thus, you need to find out the corrections to be made to transform your data to a standard magnitude system.

As an example, you observe two stars in the same field with V=10.52 with your V filter and obtain the differential magnitude with respect to a third star in the field. If the two 10.52 magnitude stars were different colors, you would obtain two different values for the differential magnitude. In order to transform the differential magnitudes to a Standard System, you need to know two things: the color of the stars and the effect of that color on the differential magnitude you obtained. You have a differential instrumental color $\Delta(v-r)$ and a differential instrumental magnitude Δv. First you need to know how the differential instrumental color relates to the differential true color, and then you need to find how the instrumental differential v relates to the true

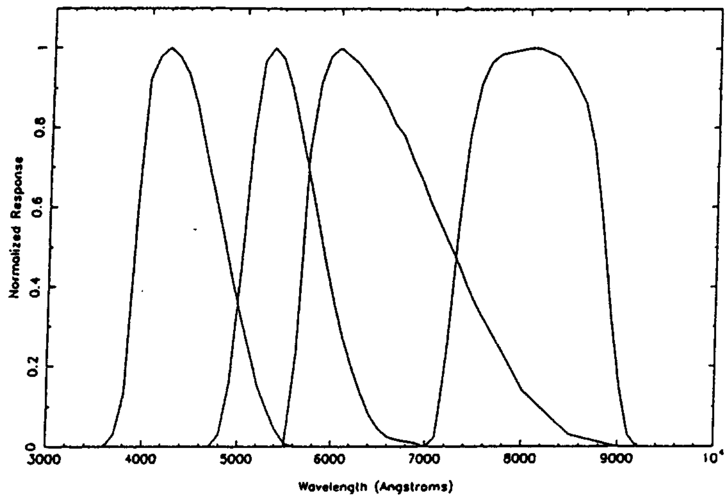


Figure 1
The Bessell BVRI system

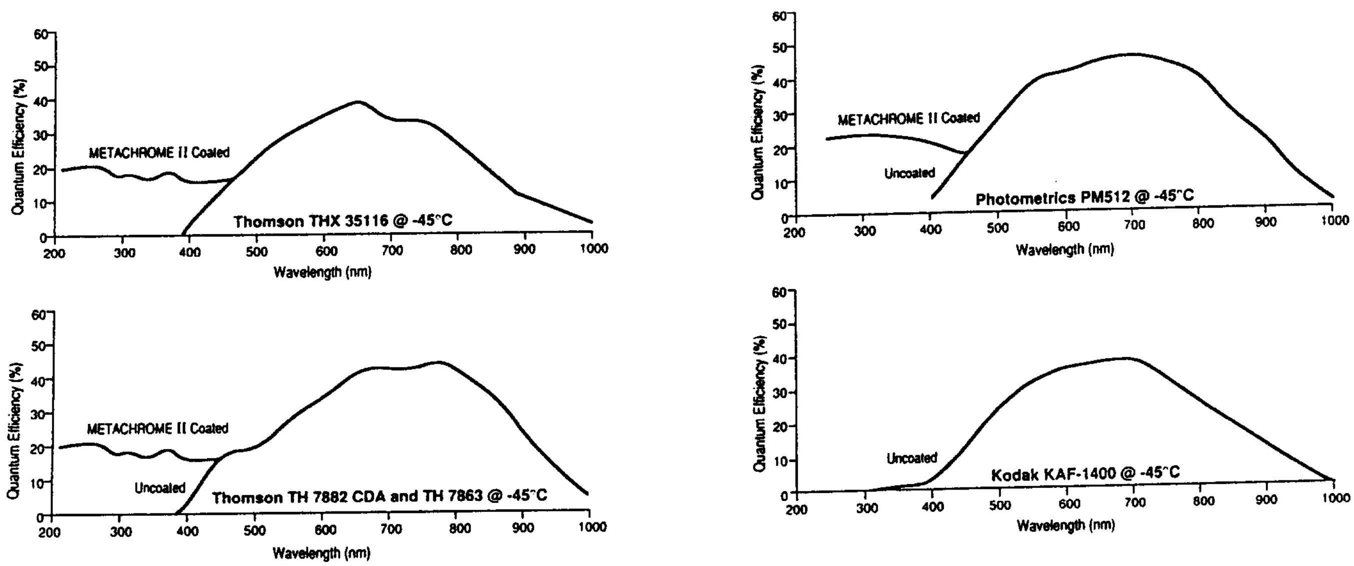
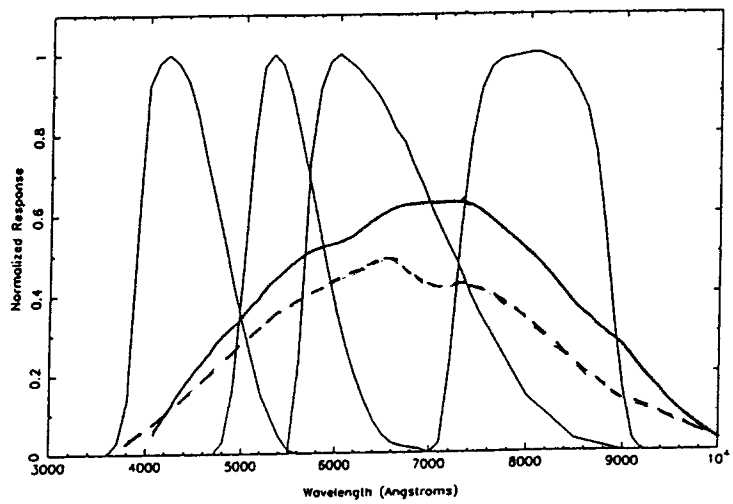


Figure 2
Selected CCD quantum efficiency curves



differential V. Thus, in order to transform your data, you need to observe at least two colors. For example, if you observed with the V and R filters, you could first use T_{vr} to transform the differential instrumental color $\Delta(v-r)$ to a Standard differential color $\Delta(V-R)$. You could then use this Standard differential color and T_v to find the Standard V magnitude of each of your stars. If instead of observing with V and R filters, you usually use R and I, then you will need the transformation coefficients T_{ri} and T_r.

If T_v and T_r are exactly zero, and T_{bv}, T_{vr}, and T_{ri} are exactly 1, then your system matches the Standard System. This is unlikely to be the case; however, the transformation coefficients should be close to the above values. We describe below how to determine your transformation coefficients. How to apply them is described later in the directions for filling out the AAVSO report sheet. The method of determining transformation coefficients described here utilizes differential photometry so that you do not need to have a perfectly photometric night. However, you should repeat your measurements for several clear nights to determine the best values you can. The more observations you make, the more stars you use, and the broader the difference in color of the standard stars, the better you can determine the transformation coefficients. In order to do so, you need to have a standard filter set (with the B and V filters appropriately red-blocked), you must observe through two or more filters (preferably B, V, R, and I), and you need to observe a standard field.

3. Procedures For Determining Transformation Coefficients

We will adopt the "dipper asterism" field in the open cluster M67 as our standard transformation field (RA [1990] $08^h50^m32^s$ Dec [1990] $11°52'24"$) (Figure 4). This field has been well-studied and there are a large number of well-calibrated stars within a small field of view. Each spring, you should observe this field about 10 or 12 times on clear nights and redetermine your transformation coefficients. Since this field is close to 9^h in right ascension, it is not observable during the summer and early fall months. We have provided a couple of fields which you can use if you need to determine transformations at other times of year, but you should check out your results with observations of M67 as soon as you can. Your transformations will change slightly with time, so new values should be determined each year.

Each night you observe your standard field, you should take several images in each of the filters you plan to use for your variable star observations. Try to observe your standard fields when they are high in the sky. Make the exposure long enough so that you have as many counts on your brightest star as your system allows, but be sure you don't saturate it. Process the images in your usual way, subtracting a bias frame and a scaled dark frame from each image and dividing by a bias and dark-corrected flat field for the correct filter. Then do photometry on all the calibration stars.

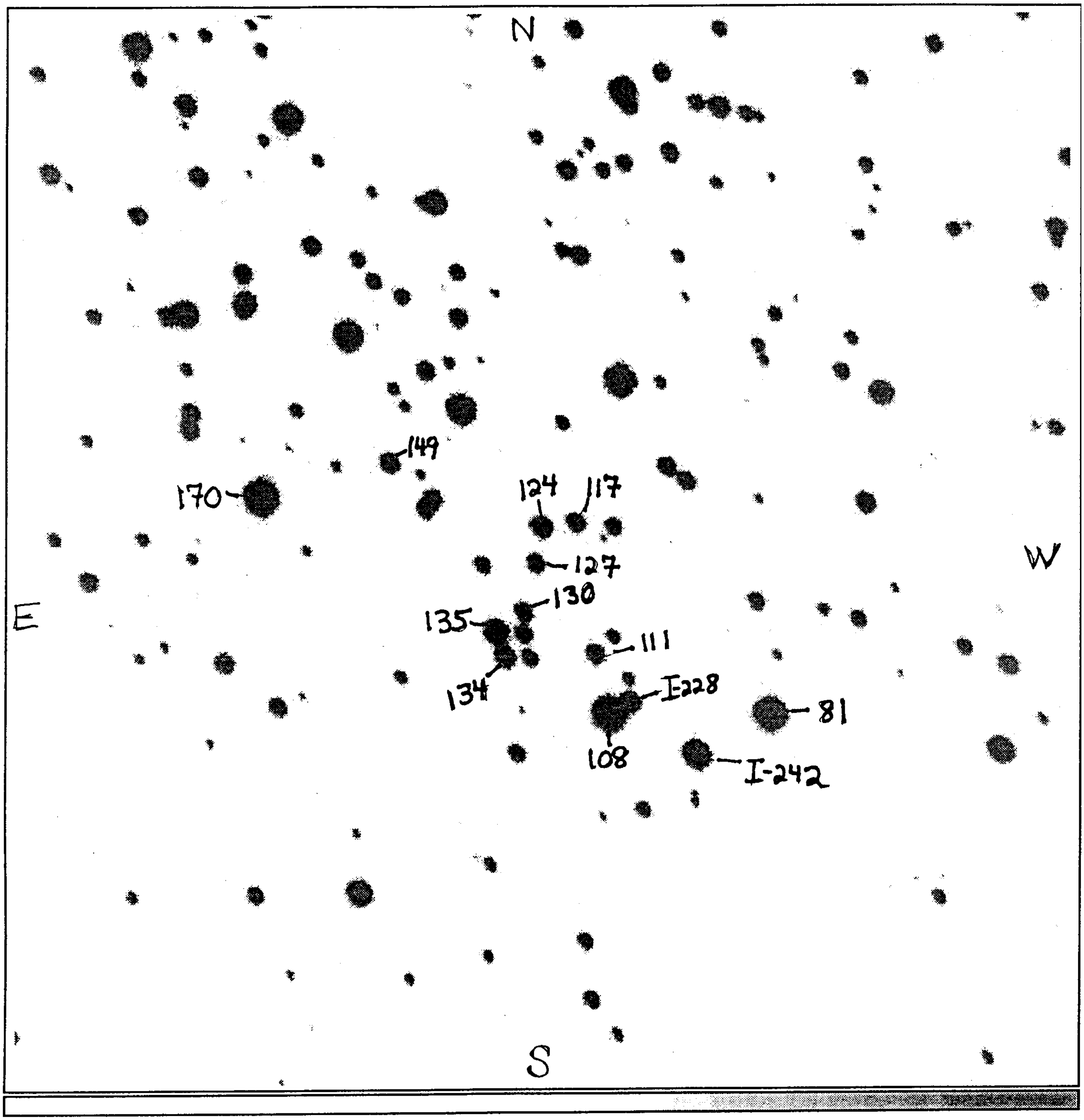


Figure 4
Identification Chart for "dipper asterism" in M67. The field (approximately 9.5 arcmin per side) is centered at RA [1990] $08^h50^m32^s$ Dec [1990] $11^o52'24''$.

You do not need to worry about atmospheric extinction since you will be doing differential photometry, and the program stars and comparisons will be observed at the same air mass.

4. The Equations Used in Transformations

Since we are looking for an accuracy of about 0.1 magnitude, we will describe a method which assumes a linear relationship. A more sophisticated method is described by Da Costa ("Basic Photometry Techniques" in Astronomical CCD Observing and Reduction Techniques, ed. Steve B. Howell, ASP Conference Series, Vol. 23, 1992, p. 90). The basic transformation coefficients (Hardie, in Astronomical Techniques, ed. W. A. Hiltner (U. of Chicago Press), p. 178) can be determined from equations similar to the following:

$$r_0 = r - k_r'X - k_r''(r-i)X$$

$$(r-i)_0 = (r-i) - k_{ri}'X - k_{ri}''(r-i)X$$

where r_0 and $(r-i)_0$ are corrected for atmospheric extinction, and:

$$R = r_0 + T_r\ (R-I) + C_r$$

$$(R-I) = T_{ri}\ (r-i)_0 + C_{ri}$$

The "instrumental magnitudes" are listed with lower case letters and "standard magnitudes" are listed with upper case letters. The air mass is designated by X, and k' and k" are respectively the first order and second order extinction coefficients. The transformation coefficients are given by T_r etc. and the zero point offsets by C_r etc.

Since we will be doing differential photometry, when we calculate the difference between the R values for two different stars, the first order extinction and zero points will drop out as below:

$$\Delta R = \Delta r - k_r''X\Delta(r-i) + T_r\Delta(R-I)$$

$$\Delta(R-I) = T_{ri}\Delta(r-i) - T_{ri}k_{ri}''X\Delta(r-i)$$

where Δ implies the difference between the values for two different stars. We will assume that the second order extinction coefficients are small enough that we can ignore them.

5. The Calculations:

Determine the instrumental colors of b-v, v-r, and r-i for each calibration star from the instrumental values of b, v, r, and i. Then, plot the following graphs:

B - V	b - v	slope is $1/T_{bv}$
V - R	v - r	slope is $1/T_{vr}$
R - I	r - i	slope is $1/T_{ri}$
V - R	V - v	slope is T_v
R - I	R - r	slope is T_r

It is always good practice to actually plot the graphs because you can immediately see whether or not you have a good straight line and if there are any discrepant points which you should check out. If your graph looks good, then find the least square fit to a straight line for each of these five graphs. You can use any calculator with linear regression or a program on your computer. In case you do not have a program, the equation for the slope is:

$$m = \frac{N\Sigma x_i\, y_i - \Sigma x_i \Sigma y_i}{N\Sigma x_i^2 - (\Sigma x_i)^2}$$

Calculate the transformation coefficients from the slope of each line. Note that since we have used the standard magnitudes (known values) for X and the instrumental magnitudes (unknowns) for y, the slope needs to be inverted to determine the values of T_{bv}, T_{vr}, and T_{ri}.

6. Sample Calculations for M67

The following illustrates the calculations for one set of data taken of M67. The finder chart has a field of about 9.5 arcminutes. The table of standard values includes data from Schild (P.A.S.P., **96**, 1021, 1983) for B-V and Joner and Taylor (P.A.S.P., **102**, 1004, 1990) for V-R, R-I, and R.

Standard Values for M67 Stars

Star Num	B-V	V-R	R-I	R
170		0.702	0.625	8.961
149		0.342	0.331	12.208
111		0.328	0.326	12.402
I-228		0.424	0.391	11.978
I-242		0.268	0.265	10.616
81	-0.098	-0.032	-0.036	10.059
108	1.351	0.715	0.636	8.986
130	0.449	0.289	0.291	12.580
134	0.569	0.337	0.332	11.919
135	1.051	0.556	0.497	10.880
127	0.553	0.330	0.321	12.439
124	0.466	0.280	0.280	11.838
117	0.800	0.467	0.434	12.163

Observed Instrumental Magnitudes and Colors for M67

Star Num	b	v	r	i	B-V	b-v	V-R	v-r	R-I	r-i
170	20.539	18.644	17.065	16.625		1.895	0.702	1.579	0.625	0.440
149	22.814	21.543	20.344	20.191		1.271	0.342	1.199	0.331	0.153
111	22.972	21.734	20.541	20.423		1.238	0.328	1.193	0.326	0.118
I-228	22.783	21.387	20.089	19.861		1.396	0.424	1.298	0.391	0.228
I-242	21.085	19.971	18.830	18.753		1.114	0.268	1.141	0.265	0.077
81	19.699	19.036	18.212	18.420	-0.098	0.663	-0.032	0.824	-0.036	-0.208
108	20.611	18.703	17.100	16.651	1.351	1.908	0.715	1.603	0.636	0.449
130	23.037	21.893	20.769	20.684	0.449	1.144	0.289	1.124	0.291	0.085
134	22.494	21.262	20.054	19.919	0.569	1.232	0.337	1.208	0.332	0.135
135	22.097	20.435	18.995	18.684	1.051	1.662	0.556	1.440	0.497	0.311
127	23.001	21.776	20.581	20.447	0.553	1.225	0.330	1.195	0.321	0.134
124	22.278	21.136	19.993	19.904	0.466	1.142	0.280	1.143	0.280	0.089
117	23.062	21.625	20.280	20.030	0.800	1.437	0.467	1.345	0.434	0.250

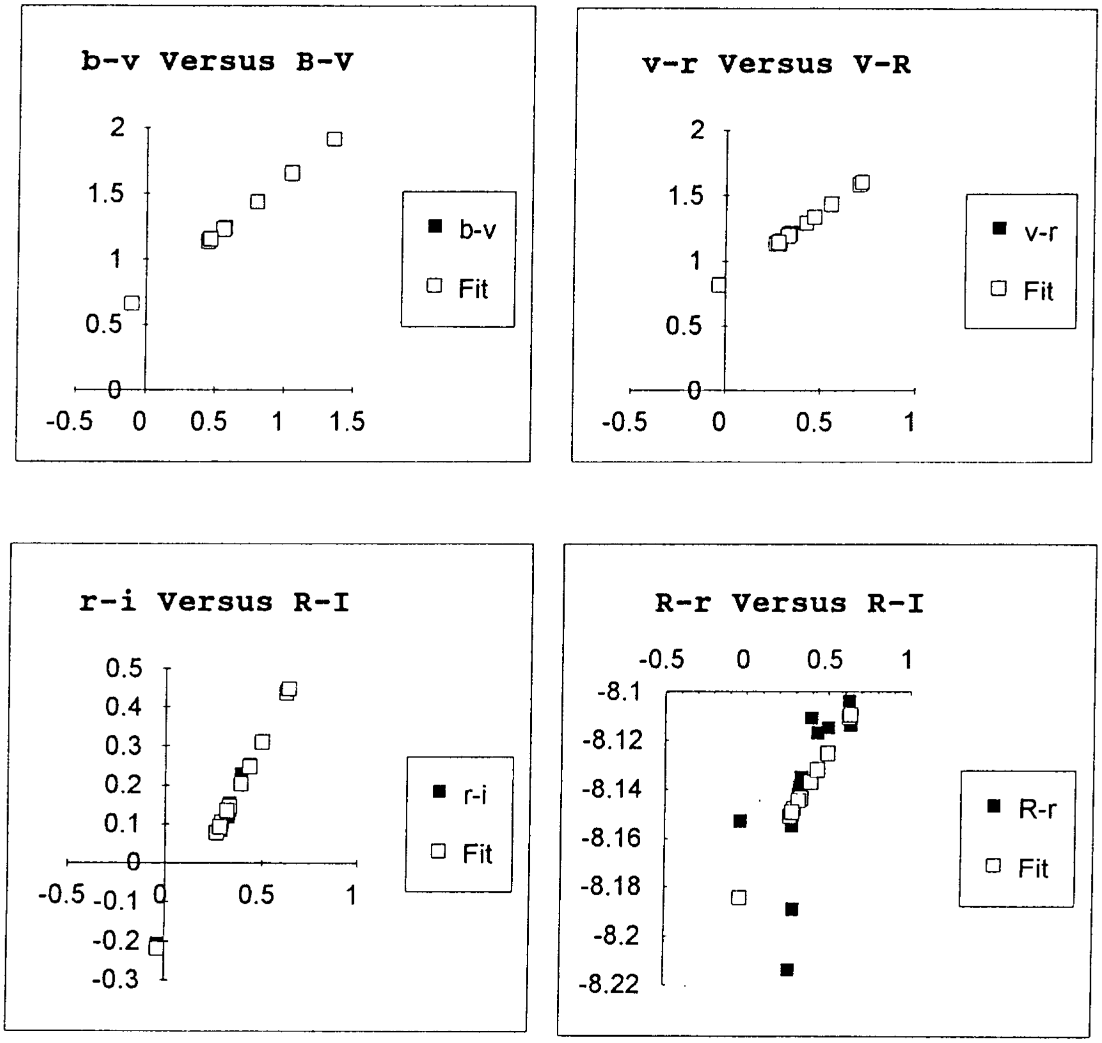


Figure 5
Instrumental versus Standard Magnitudes for M67 Observations

Figure 5 shows the graphs obtained. Analysis of B-V versus b-v yields a slope of 0.862 (0.006). The value of T_{bv} is 1.16 with standard deviation of the fit to the data of 0.007. The slope of V-R versus v-r is 1.047 (0.007). The value of T_{vr} is 0.95 with a standard deviation of 0.011. T_{ri} is 1.01 with a standard deviation of 0.013 from a slope of 0.995 (0.022). T_r is 0.11 with an error in the slope of 0.045 and a standard deviation of the fit of 0.027.

7. Additional fields for Transformation Coefficients from A. U. Landolt 1992, A.J., **104**, 340

PG 1633+099

Star	B-V	V-R	R-I	R
PG1633+099	-0.192	-0.093	-0.116	14.490
PG1633+099A	0.873	0.505	0.511	14.751
PG1633+099B	1.081	0.590	0.502	12.379
PG1633+099C	1.134	0.618	0.523	12.611
PG1633+099D	0.535	0.324	0.327	13.367

The position of PG1633+099B (epoch 2000) is $16^h35^m34^s$ and 09°46'22".

Selected Area 111

Star	B-V	V-R	R-I	R
775	1.738	0.965	0.896	9.779
773	0.206	0.119	0.144	8.844

The position at epoch 2000 for star 775 is $19^h37^m16^s$ in right ascension and +00°12'05".

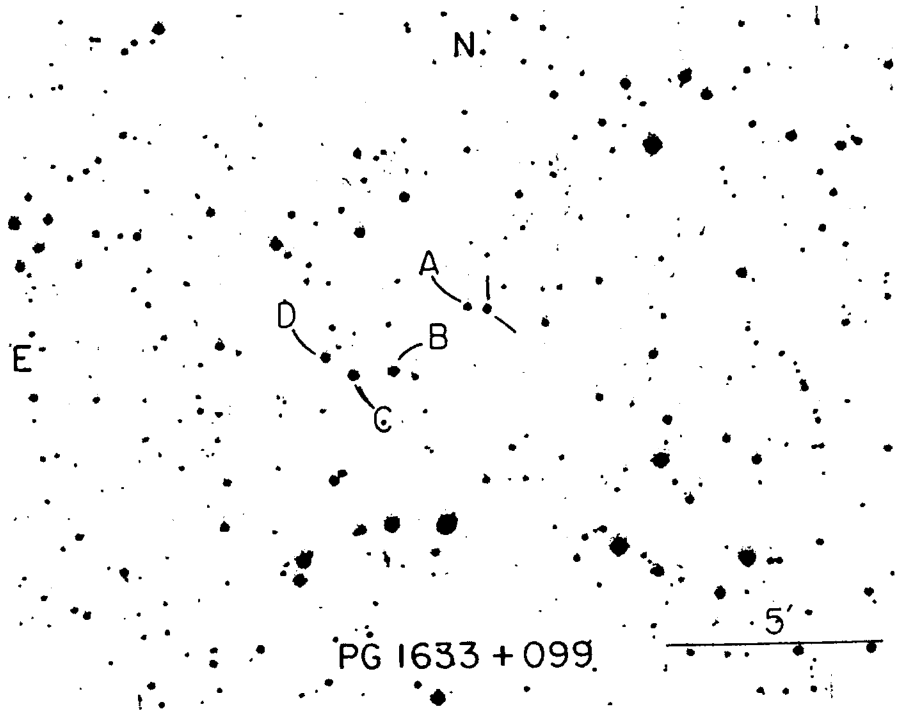


Figure 6
Identification Chart for PG1633+099 at $16^h35^m34^s$ and 09°46′22" (2000).

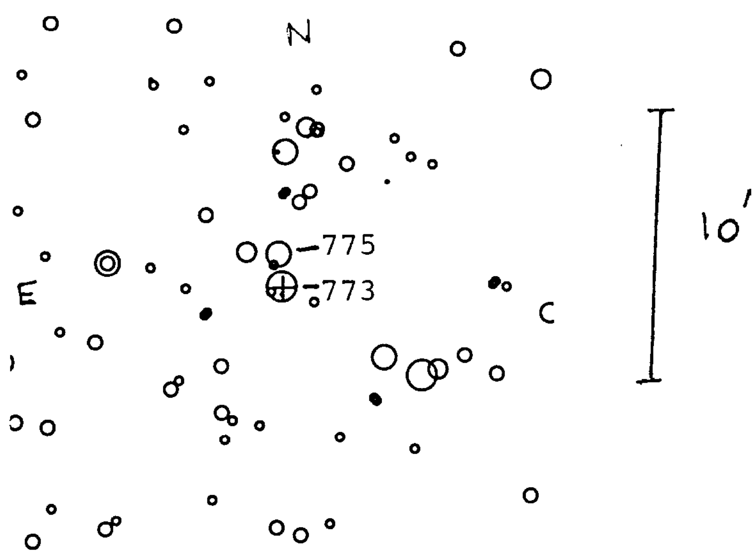


Figure 7
Identification Chart for Selected Area 111-773 and 111-775. The position of 111-775 is $19^h37^m16^s$ +00°12′05" (2000).

Sample Calculation of Transformed Magnitudes

	Instrumental Magnitudes			Standard Magnitudes		
	v	r	i	V	R	I
RR Boo	21.284	18.508	16.974			
Comp 2	19.118	17.599	17.519	9.661	9.046	8.466
Comp 4	22.516	20.999	20.969	13.073	12.522	11.980
Comp 6	23.151	21.625	21.649	13.756	13.154	12.625
RR Boo - Comp 2	2.166	0.909	-0.545			
RR Boo - Comp 4	-1.232	-2.491	-3.995			
RR Boo - Comp 6	-1.867	-3.117	-4.675			

Differential Colors

	v-r	r-i
RR Boo - Comp 2	1.257	1.454
RR Boo - Comp 4	1.259	1.504
RR Boo - Comp 6	1.250	1.558

Assume your transformation coefficients are as follows:

$T_{vr} = 0.95$; $T_{ri} = 1.00$; $T_r = 0.09$ and:

$V-R = T_{vr} * (v-r)$; $R-I = T_{ri} * (r-i)$; and $R = r + T_r * (R-I)$

to transform the instrumental differential colors to standard differential colors:

	Transformed Differential Colors		
	V-R	R-I	R
RR Boo - Comp 2	1.194	1.454	1.040
RR Boo - Comp 4	1.196	1.504	-2.356
RR Boo - Comp 6	1.188	1.558	-2.977

Using $V = (V-R) + R$ and $I = R - (R-I)$ to obtain the transformed differential magnitudes:

	Transformed Differential Magnitudes		
	V	R	I
RR Boo - Comp 2	2.234	1.040	-0.414
RR Boo - Comp 4	-1.160	-2.356	-3.860
RR Boo - Comp 6	-1.789	-2.977	-4.534

Use the standard magnitudes of the comparison stars to obtain the magnitudes of the variable star:

	Magnitudes of RR Boo		
	V	R	I
Based on Comp 2	11.895	10.086	8.052
Based on Comp 4	11.913	10.166	8.120
Based on Comp 6	11.967	10.177	8.090

CCD TRANSFORMATION COEFFICIENTS

Name of Observer: ____

Address: ____

____

I have filled out the AAVSO CCD Observer Registration Form. Below are my transformation coefficients.

$\Delta(B-V) = Tbv * \Delta(b-v)$	Tbv = ________
$\Delta(V-R) = Tvr * \Delta(v-r)$	Tvr = ________
$\Delta(R-I) = Tri * \Delta(r-i)$	Tri = ________
$\Delta R = r + Tr * \Delta(R-I)$	Tr = ________
$\Delta V = v + Tv + \Delta(V-R)$	Tv = ________

Date______________________________

Please complete and return this form to:

AAVSO CCD Committee
AAVSO Headquarters
25 Birch Street
Cambridge, MA 02138
USA