CALIBRATION OF HIPPARCOS LONG PERIOD VARIABLE STAR FIELDS USING MULTI-COLOR CCD OBSERVATIONS

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Abstract

The first set of 4-color AAVSO CCD finder charts has been prepared using the 0.9-m telescope at Kitt Peak National Observatory in Arizona. The stars selected were northern long period variable stars observed with the Hipparcos astrometric satellite, since multicolor photometry was needed on these stars to calibrate and reduce the photometric and astrometric data obtained by the satellite. We describe the criteria in choosing the stars for which to prepare CCD finder charts, the observation process, and the reduction of the CCD data to obtain 4-color CCD magnitude sequences to use in the creation of AAVSO finder charts.

1. Introduction

The American Association of Variable Stars Observers (AAVSO) has been providing ground-based observations of variable stars for the scheduling and correlation of multicolor observations with satellites, one of which was the Hipparcos (High Precision Parallax Collecting Satellite) astrometric satellite. During its mission between August 1989 and August 1993, Hipparcos obtained parallax and proper motion observations on 118,000 stars. In order to allocate satellite observing time for each star, it was necessary to know the brightness within an accuracy of one magnitude. There were 245 large amplitude long period variable stars in the Hipparcos observing program for which prediction of their brightness was needed during satellite observing times. The AAVSO provided data support before and during the mission for these predictions. Over 1 million AAVSO observations, submitted by observers from around the world over 25 years, were used to predict the brightness of these stars. These predictions were then checked against approximately

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70,000 incoming observations per year on these stars throughout the mission to make sure that the predicted magnitudes agreed with the observed behavior of each of the stars.

Along with the astrometric data, Hipparcos also obtained valuable photometric data. The Hipparcos magnitude is a function of the color index (B - V) in cases where (B - V) ≤ 1.50, and a function of (R - I) for cases where (B - V) ≥ 1.50 (Grenon 1985a, 1985b).

There are a limited number of individual measurements, particularly in the R and I bands, for the long period variable stars. Requests were made to the AAVSO by the Hipparcos Photometric Team Leader (Grenon 1992) and the Variable Star Coordinator (Mennessier) to provide (B, V, R, I) Charged Couple Device (CCD) observations on as many northern Hipparcos long period variables as possible, where these 4-color observations could be used in the final reduction of the photometric and the astrometric data.

As CCDs have become more and more affordable and available, an increasing number of amateur astronomers and small colleges are purchasing CCDs and requesting useful scientific projects from the AAVSO. These observers could provide the much-needed 4-color photometric data for Hipparcos. However, well-calibrated, four-color CCD comparison stars are needed for the fields of the Hipparcos long period variables in order to obtain the multicolor magnitudes. While AAVSO charts with visual and/or photoelectric V magnitudes exist for these stars, B, R, and I magnitudes are generally not available.

Thus, in the autumn of 1992, we submitted a proposal for observing time at Kitt Peak National Observatory to obtain 4-color CCD comparison star magnitudes in the fields of about 30 Hipparcos long period variables. These comparison stars could then be used by AAVSO observers and small college faculty and students to make CCD observations of these stars.

All of the Hipparcos variables have corresponding AAVSO finder charts that are used by visual observers who provided data for the Hipparcos satellite. Whenever possible the comparison stars close to the variable were chosen as CCD comparison stars. Since there is excellent coverage on most of the stars by the visual observers, these stars will also act as test stars for comparing visual and CCD observations, and determining the degree of agreement between the two techniques.

2. The Observations

We were scheduled for six bright-time nights with the 0.9-m telescope at Kitt Peak National Observatory for the nights of February 2 - 7, 1993. We had two clear nights, two partly cloudy nights, one very cloudy night, and one rainy night.

We used the central 1024 X 1024 pixels of the 2048 x 2048-pixel CCD camera with a gain of 10.5. The image size was about 11.5 arc-minutes with an image scale of 0.68"/pixel.

Each afternoon, we took 15 bias frames and six dome flat fields in each of the filters B, V, R, and I. For calibration, each night we took several images of the "dipper" asterism in M67 (NGC 2682) at different air masses and at least one Landolt standard field. These were interspersed between our object fields. We observed 17 variable star fields and for each field we took a minimum of three images in each filter, but for most fields we took several images of various exposure times to get good statistics on both bright and faint comparison stars.

3. CCD Data Reduction

The data reduction steps used for this project were the following:

1. Standard 2-D CCD image data reduction.

This reduction consists of bias and flat field corrections. These were done in the standard way and the reader is referred to articles in the *ASP Conference Series Book,* Vol 23.

2. 2-D aperture photometry.

In this step we calculated the instrumental magnitudes and, using standard star observations, the final stellar magnitudes placed on (in this case) the Johnson UBVRI system.

Two-dimensional aperture photometry is a fancy-sounding term for a computer-directed method by which all the counts within a star are accumulated, the background (sky) value is estimated, and the final sky-subtracted star counts are turned into an instrumental magnitude. There are a number of schemes used for this procedure, but the most popular method is to place a circular aperture around the star, with a larger circular annulus, centered on the star, used to gather background information. The sum within the star aperture minus the sky contribution within that same aperture yields the stellar sum. The usual equational form for magnitude (i.e., m (inst) = -2.5 log (star counts) - Constant), is then used to convert from counts to magnitude units. Keep in mind that to this point we have only determined an instrumental magnitude. We must do some more work to reach our final objective of placing our magnitudes in a standard system.

For this project we chose to use two sets of standard stars, those in the cluster M67 (Schild 1983, 1985; Joner and Taylor 1990) and some Landolt stars (Landolt 1992). These stars, which have magnitudes defined in the standard system, were observed for the purpose of finding the correct transformation equations to use to go from instrumental magnitudes to magnitudes on the Johnson system. Remember that observations of standard stars are necessary and critical in order to get your program star magnitudes onto a system that everyone else uses. Setting up even a few stars as standards is a painstaking process, and the reader is referred to a very interesting paper on the subject by Tug *et al.* (1977).

Now, just a brief word on the philosophy of picking standard stars. There is a lot of art to photometry, and the use of standard stars is no exception. For example, which M67 stars do we use? All of them? Only one? If we used them all we would have a larger data set to observe and reduce. If we used only one we would have large errors and no consistency checks. So we traded off, picking a nice set with well determined magnitudes (colors) and easy to handle within our observing program. As for the Landolt stars, why use them at all? After all, we had enough from M67 alone. Using the few Landolt stars allowed us to keep an eye on the M67 stars just to make sure they were as they were supposed to be.

From the stars listed in the references above for M67, we used 11 stars in or very near the "dipper" asterism. These 11 stars all had well-determined magnitudes in all four colors (BVRI) and were easily able to fit within one CCD frame. Three frames in each color were normally taken, allowing for errors to appear within any particular star in any particular frame (especially cosmic ray hits). Since we already knew the real magnitudes for these 11 stars, after our determination of their instrumental magnitudes we could plot the two quantities against each other. They should be related by an almost linear relation, i.e., the fainter stars should have lower counts. Figure 1 is an example of such a plot for the B filter. Similar plots were made for the other three colors. The spread seen in the vertical direction in this figure is due to the fact that these plots were made before any corrections for airmass were made. Notice how linear the relation is. That is a good sign. We then used these data to determine our transformation equations.

Determination of transformations at times can border on a black art. Generally, however, there are well studied, typical forms of equations that work quite well. The basic method is to start with one of these forms and iterate (either by computer or by varying the equational form, or both) until you are happy with the results. While there are no rules as to when to quit, Occam's razor is not a well-used tool for nothing. As an example, we started with the equational form below:

$$V\ (real) = v1 + V(inst) + v2 * X(v), \qquad (1)$$

where V (real) is the <u>real</u> V magnitude and the final answer we want, v1 and v2 are constants to be determined, V (inst) is the instrumental magnitude determined from 2-D photometry, and X(v) is the airmass of the given V observation.

Figure 2 shows the results using this equation. The crosses are data, and the boxes are the fit. We expect that for good fits, the calculated magnitude will equal what we observed, that is, the instrumental magnitude, and the results do look good. However, we are trying to obtain as accurate results as possible, so we looked at the relation in Figure 2 in a different way.

Figure 3 shows the residuals for the best fit relation to the data in Figure 2. There is indeed a problem, as the residuals show two bad effects:

1. The overall residuals (i.e., errors) are large, and
2. Measurements at the bright end are too bright while those at the faint end are in general too faint.

We tried a different (actually more typical) form for the transformation equation:

$$V\ (real) = v1 + v2 * V\ (inst) + v3 * X\ (v) + v4\ [B\ (inst) - V\ (inst)] \qquad (2)$$

We have added two new terms: one for the color term and one for a slope or curvature term to 'correct' the non-linear V (real) - V (inst) relation. Our general fit looked to the eye much like that of Figure 2. However, Figure 4 shows the new and improved residual plot. Notice the much smaller overall residuals and the disappearance of the trend described above. (Note: when one reaches this point, a few minutes of admiration and savoring are in order!) Similar equations were used for the remaining three colors and are summarized in Table 1.

Table 1. Transformation equations.

$$V_R = v1 + v2 \times v_I + v3 \times x_v + v4 \times (b_I - v_I)$$

$$B_R = b1 + b2 \times BB + b3 \times x_b + b4 \times (b_I - v_I)$$

$$R_R = r1 + r2 \times RR + r3 \times x_r + r4 \times (v_I - r_I)$$

$$I_R = i1 + i2 \times II + i3 \times x_i + i4 \times (v_I - i_I)$$

where $BB = v_I + (b_I - v_I)$
$RR = v_I - (v_I - r_I)$
$II = v_I - (v_I - i_I)$

While the M67 stars spanned a fairly large range in both magnitude (≈9-13) and color and were each observed many times so that the magnitude error was small for each, the Landolt stars we chose did not. (Remember, we chose to use some Landolt standard stars just as a check, not as our primary standard stars to use.) The Landolt stars were in a field such that four could be imaged at once (SA104-366). This field is roughly centered on a spiral galaxy, the fuzzy arms of which unfortunately lead to some contamination in the photometry of the stars, the faint ones in particular.

Landolt's stars were observed photoelectrically, while the M67 stars used above were CCD magnitudes. One quickly learns that all observational techniques will convert to a standard system with slightly different transformation equations, which generally means that trends occur when different measures of the same stars are compared. Figure 5 shows such an example. Here we have plotted the magnitudes determined by Landolt on the x-axis against those which we determined for his stars when we used the M67 transformation equations. If the magnitudes of the Landolt stars matched exactly those we determined, the data would all fall on the straight line. What we see however, is a trend away from the line at fainter magnitudes. This was quite worrisome at first as it might have been an indication of some problem. However, all can be reconciled by the fact that the fainter Landolt stars had only 1-2 measures, thus large 1 sigma errors in the true magnitude value. Also, the fuzz of the galaxy is likely to have caused even more error (in the direction of the trend) for the fainter measures due to the lack of proper background subtraction (as they were photoelectric magnitudes).

Which magnitudes are correct? Why don't they agree perfectly? Does this mean that CCDs are better than photomultiplier tubes (PMT)? Neither, because, and no. What it does mean is that calculation of and understanding of errors is CRUCIAL!! In principle (and shown to be true in practice), magnitudes determined by any correct method will agree.

Once we were satisfied with our transformations equations, we applied them to our program stars. These stars, after all, are what we really wanted to know about. An item of note here is that the 11 stars in M67 that we used did not cover the entire magnitude range or color range spanned by our program stars. This is usually the case and is yet another one of those difficult crosses we astronomers have to bear.

Table 2 gives an example of the final data sets we have obtained, this one for the star RR Boo. Figure 6 shows the end product we are after in this program, an AAVSO CCD chart giving four-color data for stars near the variable. Generally, we try to use any AAVSO comparison stars which fall within the CCD frame and list in the table the previously known magnitude (usually photovisual) which is roughly equal to the V bandpass. We note that for fainter stars there appears to be some difference between AAVSO magnitudes and the CCD (V) magnitudes.

Table 2. Final variable star data set.

RR Boo							
Star	*AAVSO*	*B*	B_{err}	*n*	*V*	V_{err}	*n*
RR Boo = 1	8.3-13.9	15.503	0.013	3	13.946	0.013	3
2	9.7	10.872	(0.002)	1	9.661	(0.002)	1
3	10.4	11.046	(0.002)	1	10.678	(0.003)	1
4	13.2	14.131	0.006	3	13.073	0.007	3
5	13.5	13.859	0.005	3	13.130	0.007	3
6	14.1	14.776	0.008	3	13.756	0.011	3

Table 2 continued.

Star	*AAVSO*	*R*	R_{err}	*n*	*I*	I_{err}	*n*
RR Boo = 1	8.3-13.9	11.578	0.004	3	9.135	0.002	3
2	9.7	9.046	0.001	2	8.466	0.001	3
3	10.4	10.424	0.003	2	10.143	0.003	3
4	13.2	12.522	0.009	3	11.980	0.009	3
5	13.5	12.753	0.010	3	12.358	0.010	3
6	14.1	13.154	0.012	3	12.625	0.014	3

Using the reduction technique described above, we have prepared 4-color AAVSO CCD charts for the following six Hipparcos long period variable stars: 0215+58 S Per, 0549+20a U Ori, 0707+14 VX Gem, 1048+14 W Leo, 1242+04 RU Vir, and 1443+39 RR Boo. In addition, we have prepared charts for two new long period variables, 1009+73 DH Dra and 1048+72 VX UMa. We are working on the photometry of the remaining eleven stars to determine if there may be more fields for which the photometry is satisfactory to prepare more CCD finder charts. The AAVSO CCD finder charts may be obtained free of charge from AAVSO Headquarters by anyone interested in contributing CCD observations to the AAVSO International Database.

4. Acknowledgement

We sincerely thank the Kitt Peak National Observatory for granting us the telescope time to obtain CCD comparison star magnitudes of long period variable stars. We also thank the night assistants at Kitt Peak for their help during our run. J.A.M. gratefully acknowledges NASA grant NAGW-1493 which provided partial financial support for this project.

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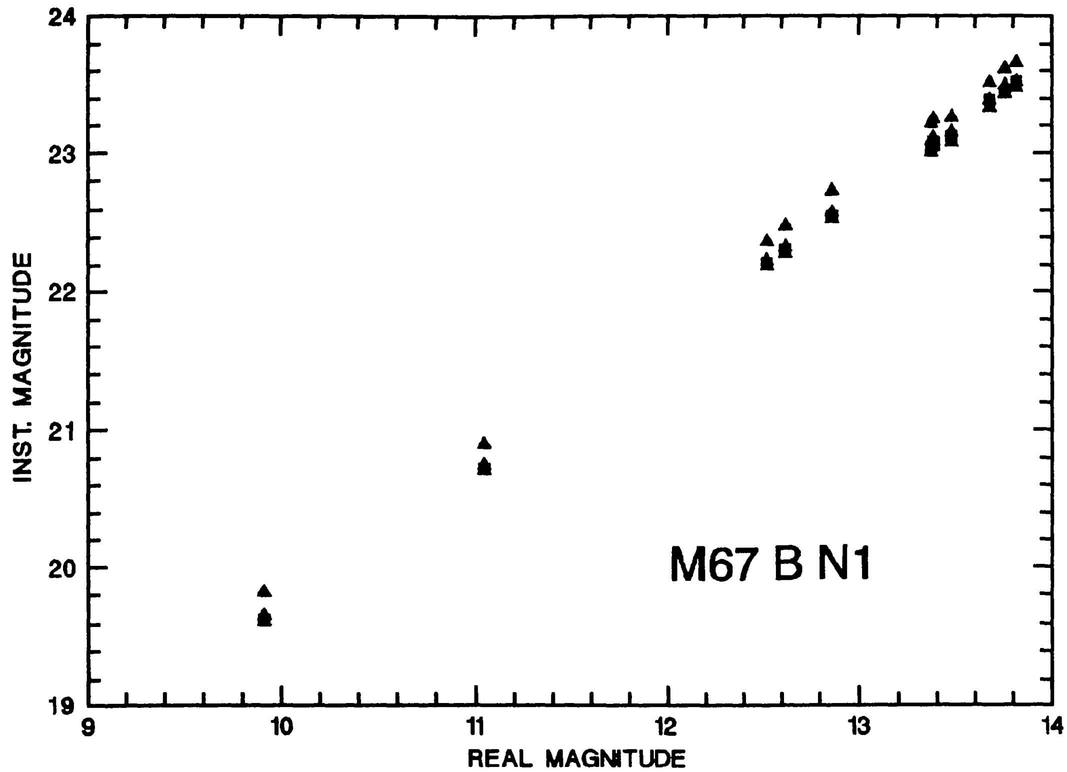


Figure 1. Real versus instrumental magnitudes are plotted for the B filter. The spread in the vertical direction is due to the fact that the plot was made before any corrections for airmass were made. The linearity of the relation is a good sign.

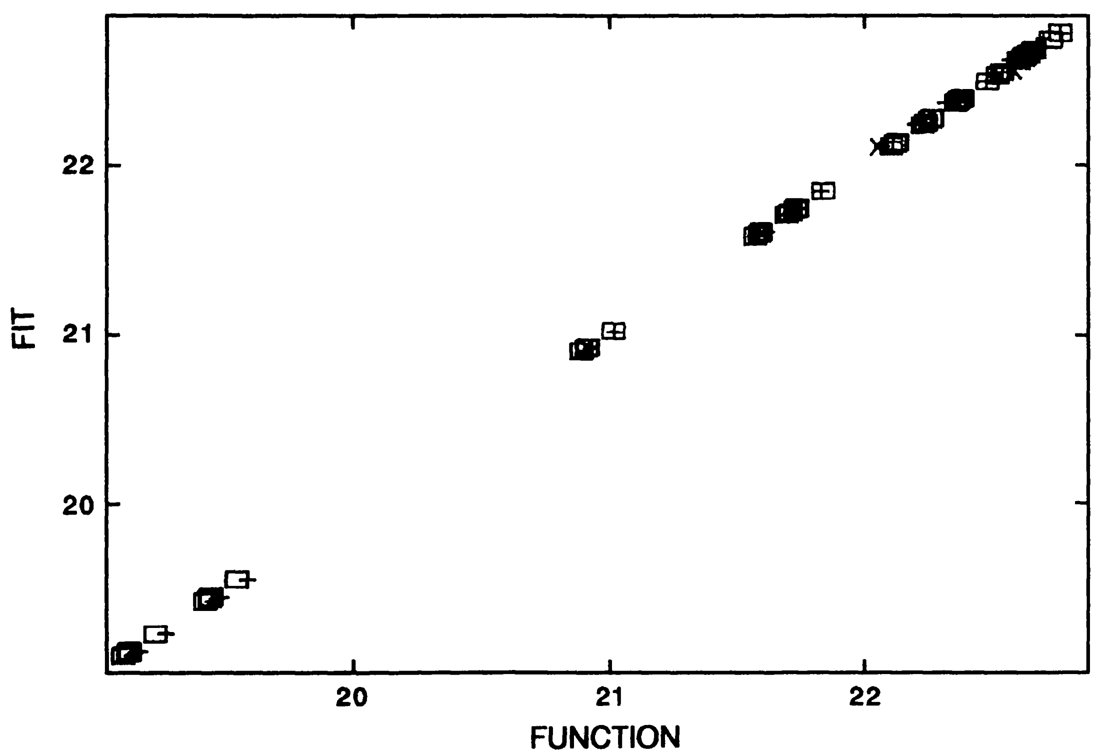


Figure 2. Determination of transformations, using equation 1. Crosses are data, and boxes are the fit.

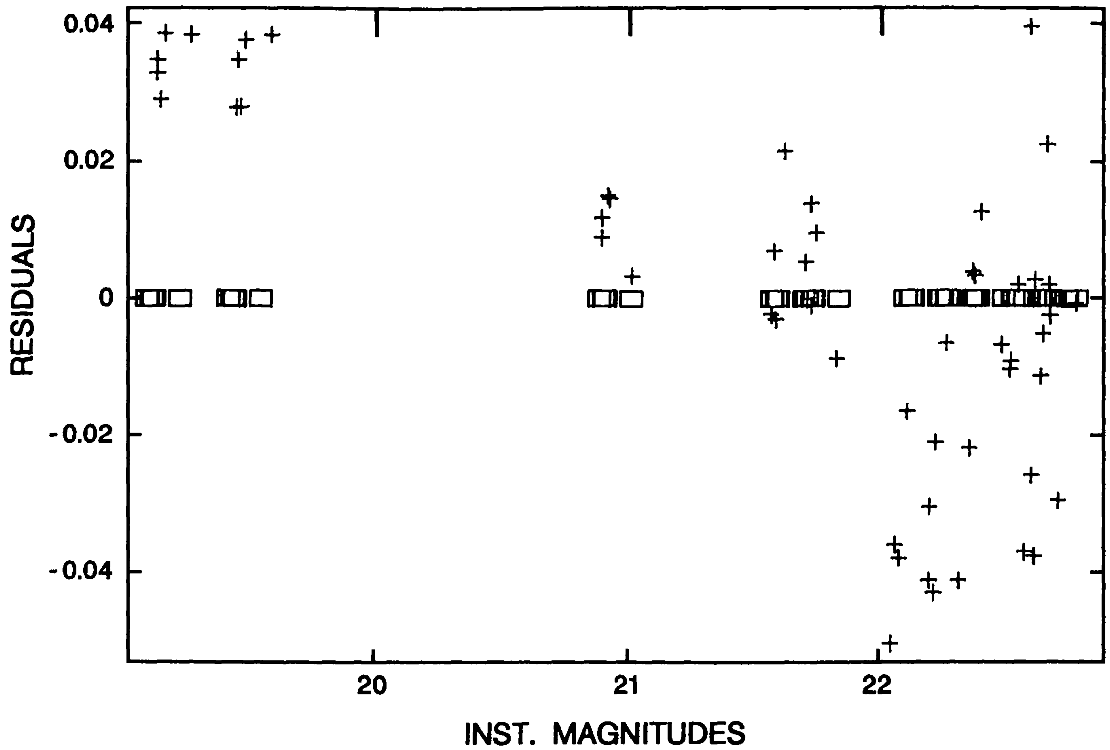


Figure 3. The residuals (magnitudes) for the best fit relation to the data in Figure 2.

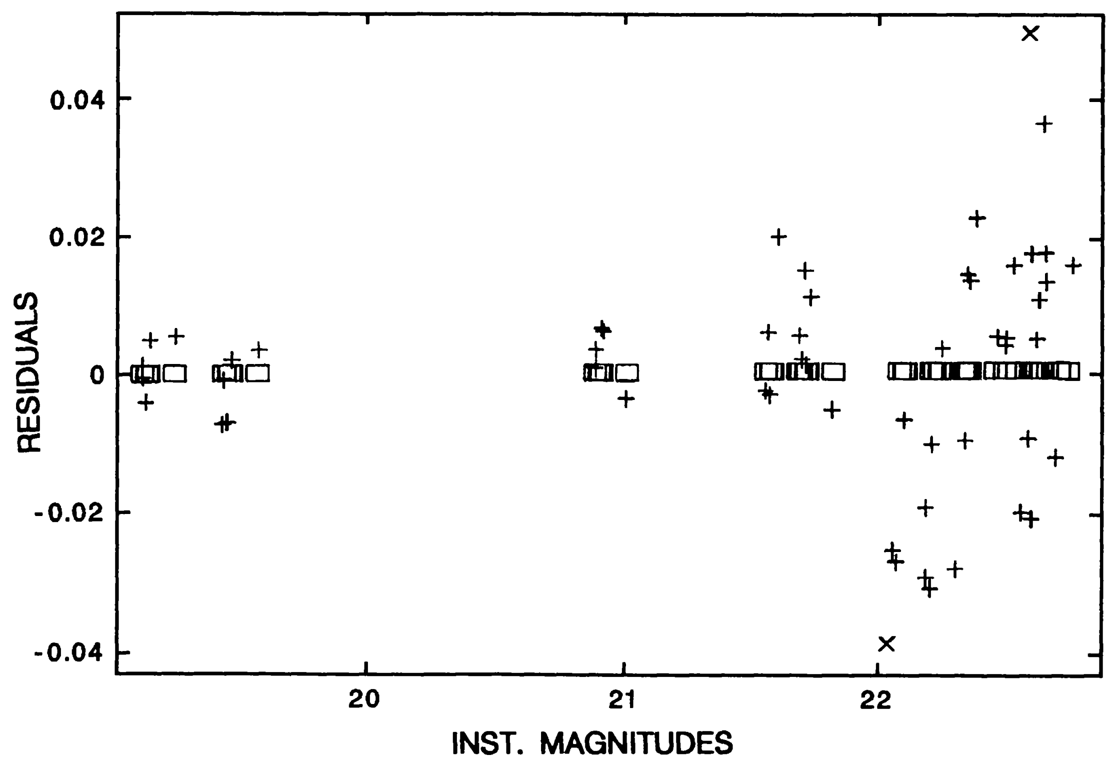


Figure 4. Residuals (magnitudes) computed from a different (actually more typical) form for the transformation equation (equation 2), with two new terms added: one for the color term and one for a slope or curvature term. Notice the much smaller overall residuals and the disappearance of the trend described in the text.

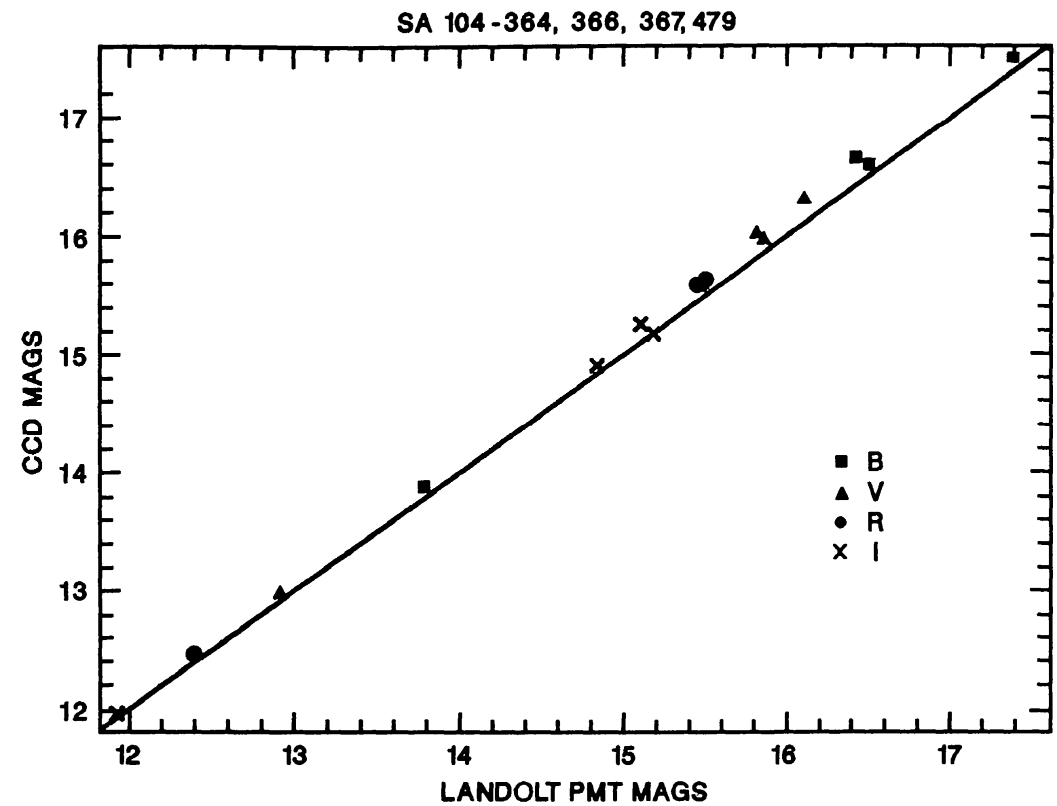


Figure 5. This figure shows the trend observed between our CCD-determined magnitudes (using the M67 transformation equations) and those determined photoelectrically by Landolt for four Landolt standard stars.

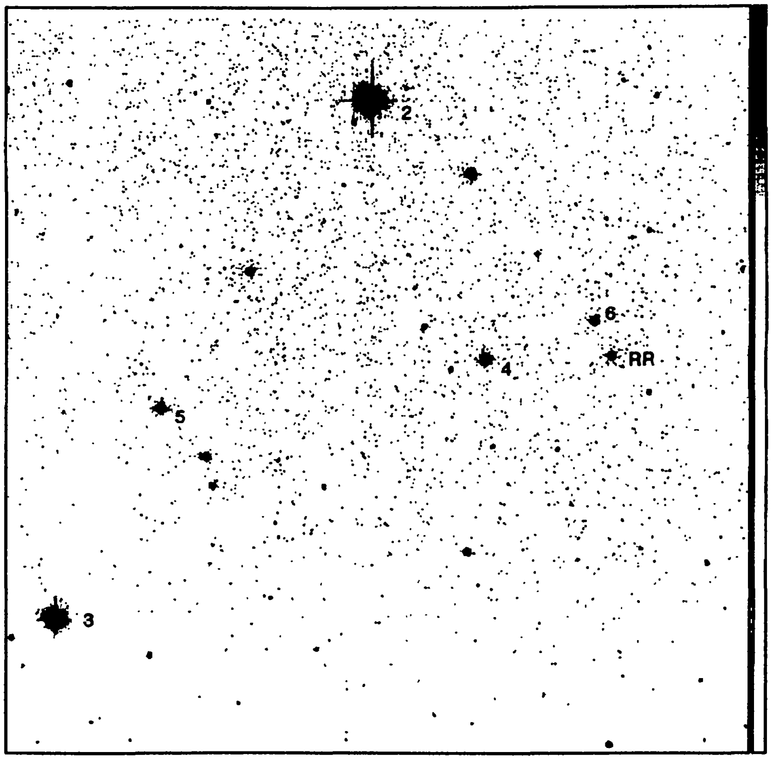
S

1443+39 (f) **RR Boo (Bootis)** AAVSO CCD Chart 5/93 5" = 1mm

Magn. - <8.8-12.7>
Period - $194^{d}.70$
Type - Mira
Spec. - M2e - M6e

(1900) $14^{h}\ 43^{m}\ 11^{s}$ $+39^{\circ}\ 44'.1$
(2000) $14^{h}\ 47^{m}\ 05^{s}$ $+39^{\circ}\ 19'.0$

W E



Star	B	V	R	I
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3	11.046	10.678	10.424	10.143
4	14.131	13.073	12.522	11.980
5	13.859	13.130	12.753	12.358
6	14.776	13.756	13.154	12.625

Drawn by: CES & RAL
From: Kitt Peak National Obs'y CCD(V) Image, S. Howell, J. Mattei & P. Benson
Sequence: CCD, S. Howell, J. Mattei & P. Benson

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Figure 6. An example of the end product we are after in this program, an AAVSO CCD chart giving four-color data for stars near the variable, in this case RR Boo.