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Differential CCD photometry Using Multiple Comparison Stars

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Abstract

This paper describes a method of performing differential CCD photometry using multiple comparison stars. The instrumental magnitudes of the comparison stars (obtained for example using AIP4WIN v2) are used to compute a weighted mean zero point for each image. The contributions of individual comparison stars are weighted according to their errors. The zero point and its error are then used to derive magnitudes and error estimates for a target object and for each of the comparison stars in the image. Variants of the method may be used for filtered and unfiltered data and for using whatever information is available about the comparison stars. Examples are given of the results of these analyses. Potential advantages of using multiple comparison stars include reduced errors on derived magnitudes compared with using a single comparison star, detection of inaccuracies in comparison star magnitudes, and recognition of variability in comparison stars.

1. Overview of the Method

The principle of the method is straightforward. We use multiple comparison stars to produce a weighted mean value for the zero point of each image. This zero point is then used to calculate a derived magnitude for the target object and for each comparison star in the image. We will assume in what follows that the target object is a variable star although it need not be.

We make the following assumptions: that there is a comparison star sequence available for the field which provides magnitudes and errors for each comparison star in one or more standard filter passbands; that each image has been measured using a program such as AIP4WIN v2 which provides instrumental magnitudes with error estimates for the variable and comparison stars; that transformation coefficients for the relevant filters and their errors have been measured in a calibration procedure; and that we are working with typical telescopic fields of less than 0.5º at altitudes above 30º.

2. Case 1

We will first consider the case where we have standard V- and I-band comparison star magnitudes and errors available in the sequence and we are able to make measurements through standard V- and I-band photometric filters. The conventional formula for the V magnitude for a star transformed to the standard photometric system (see for example [1]) is

$$V = v + T_{VI} * (V-I) + K^1_V * X + K^2_{VI} * X * (V-I) + Z^0_{VI}$$

where

- V is the standard V magnitude of the star (from the comparison star sequence)
- I is the standard I magnitude of the star (from the comparison star sequence)
- v is the observed instrumental magnitude in the V-band (from AIP4WIN v2)
- T_{VI} is a transformation coefficient defined as the gradient of V-v vs V-I
- X is the airmass of the star
- K^1_V is the 1st order atmospheric extinction coefficient in the V-band
- K^2_{VI} is the 2nd order atmospheric extinction coefficient for the (V-I) colour index
- Z^0_{VI} is the V-band exo-atmospheric zero point with respect to the (V-I) colour index

Because we are using differential photometry in small telescopic fields at an airmass below 2, we will make the approximation that the 1st and 2nd order atmospheric extinction terms are the same for all stars in the image and we will absorb them into a single endo-atmospheric zero point term for the image. The inaccuracy in doing this under these conditions is normally less than 0.5% but rises towards the blue end of the spectrum, so this approximation should be reviewed for validity when observing with larger fields or at a larger airmass, particularly with a B filter.

The above formula for the transformed V magnitude can then be written as

$$V = v + T_{VI} * (V-I) + Z_{VI}$$

where

Z_{VI} is the V-band endo-atmospheric zero point with respect to the (V-I) colour index

A similar formula gives the standard I magnitude

$$I = i + T_{IV} * (V-I) + Z_{IV}$$

where

i is the observed instrumental magnitude in the I-band (from AIP4WIN v2)
T_{IV} is a transformation coefficient defined as the gradient of I-i vs V-I
Z_{IV} is the I-band endo-atmospheric zero point with respect to the (V-I) colour index

Suppose we have n comparison stars for each of which V and I are known from the comparison star sequence. For the j^{th} comparison star we have

$$V_j = v_j + T_{VI} * (V-I)_j + Z_{VI_j}$$

Hence

$$Z_{VI_j} = V_j – v_j – T_{VI} * (V-I)_j$$

$$\sigma Z_{VI_j}^2 = \sigma V_j^2 + \sigma v_j^2 + T_{VI}^2 * (\sigma V_j^2 + \sigma I_j^2) + \sigma T_{VI}^2 * (V-I)_j^2$$

where

σZ_{VI_j} is the standard deviation of Z_{VI_j}
σV_j is the standard deviation of V_j (from the comparison star sequence)
σI_j is the standard deviation of I_j (from the comparison star sequence)
σv_j is the standard deviation of v_j (from AIP4WIN v2)
σT_{VI} is the standard deviation of T_{VI} (from the calibration procedure)

We calculate weights according to the generic formula

$$w_j = 1 / \sigma_j^2$$

so we take the weight of Z_{VI_j} as

$$wZ_{VI_j} = 1 / \sigma Z_{VI_j}^2$$

Thus comparison stars with larger standard deviations contribute with less weight to the analysis. If we represent the weighted mean and weighted standard deviation in the mean (standard error) of Z_{VI} for the image as $\langle Z_{VI} \rangle$ and $\sigma\langle Z_{VI} \rangle$ respectively, we can calculate these as

$$\langle Z_{VI} \rangle = \Sigma_j (wZ_{VI_j} * Z_{VI_j}) / \Sigma_j wZ_{VI_j}$$

$$\sigma\langle Z_{VI} \rangle^2 = \Sigma_j (wZ_{VI_j} * (Z_{VI_j} – \langle Z_{VI} \rangle)^2) / ((n-1) * \Sigma_j wZ_{VI_j})$$

We can then use the weighted mean and weighted standard error of Z_{VI} for the image to derive a transformed V magnitude and its error for any object in the image, including the variable and each of the comparison stars, using

$$V_j = v_j + T_{VI} * (V-I)_j + \langle Z_{VI} \rangle$$

$$\sigma V_j^2 = \sigma v_j^2 + T_{VI}^2 * (\sigma V_j^2 + \sigma I_j^2) + \sigma T_{VI}^2 * (V-I)_j^2 + \sigma\langle Z_{VI} \rangle^2$$

The same procedure is used to derive transformed I magnitudes and errors

$$I_j = i_j + T_{IV} * (V-I)_j + \langle Z_{IV} \rangle$$

$$\sigma I_j^2 = \sigma i_j^2 + T_{IV}^2 * (\sigma V_j^2 + \sigma I_j^2) + \sigma T_{IV}^2 * (V-I)_j^2 + \sigma\langle Z_{IV} \rangle^2$$

where

σi_j is the standard deviation of i_j (from AIP4WIN v2)
σT_{IV} is the standard deviation of T_{IV} (from the calibration procedure)
$\langle Z_{IV} \rangle$ is the weighted mean of Z_{IV} (calculated as for Z_{VI} above)
$\sigma\langle Z_{IV} \rangle$ is the weighted standard error of Z_{IV} (calculated as for Z_{VI} above)

This is clearly an iterative process as V and I appear on both sides of the equation but it is straightforward to implement such an iterative process in a spreadsheet. Experience shows it usually converges after a small number of iterations.

3. Case 2

This is similar to Case 1 in that the same standard V and I magnitudes and filters are available. However we rewrite the formulae for the transformed V and I magnitudes in terms of (v-i) rather than (V-I) as follows.

$V = v + T'_{VI} * (v-i) + Z'_{VI}$

$I = i + T'_{IV} * (v-i) + Z'_{IV}$

where

T'_{VI} is a transformation coefficient defined as the gradient of V-v vs v-i
Z'_{VI} is the V-band endo-atmospheric zero point with respect to the (v-i) colour index
T'_{IV} is a transformation coefficient defined as the gradient of I-i vs v-i
Z'_{IV} is the I-band endo-atmospheric zero point with respect to the (v-i) colour index

Some manipulation will show that

$T'_{VI} = T_{VI} / (1 – T_{VI} + T_{IV})$
$Z'_{VI} = Z_{VI} + (T_{VI} * (Z_{VI} – Z_{IV}) / (1 – T_{VI} + T_{IV}))$
$T'_{IV} = T_{IV} / (1 – T_{VI} + T_{IV})$
$Z'_{IV} = Z_{IV} + (T_{IV} * (Z_{VI} – Z_{IV}) / (1 – T_{VI} + T_{IV}))$

The formulae for Z'_{VI_j} and its standard deviation $\sigma Z'_{VI_j}$ are

$Z'_{VI_j} = V_j – v_j – T'_{VI} * (v-i)_j$

$\sigma Z'_{VI_j}{}^2 = \sigma V_j{}^2 + \sigma v_j{}^2 + T'_{VI}{}^2 * (\sigma v_j{}^2 + \sigma i_j{}^2) + \sigma T'_{VI}{}^2 * (v-i)_j{}^2$

As before, we can then derive transformed V magnitudes and errors

$V_j = v_j + T'_{VI} * (v-i)_j + <Z'_{VI}>$

$\sigma V_j{}^2 = \sigma v_j{}^2 + T'_{VI}{}^2 * (\sigma v_j{}^2 + \sigma i_j{}^2) + \sigma T'_{VI}{}^2 * (v-i)_j{}^2 + \sigma <Z'_{VI}>^2$

where the weighted mean and weighted standard error for Z'_{VI} are given by

$<Z'_{VI}> = \Sigma_j (wZ'_{VI_j} * Z'_{VI_j}) / \Sigma_j wZ'_{VI_j}$

$\sigma <Z'_{VI}>^2 = \Sigma_j (wZ'_{VI_j} * (Z'_{VI_j} – <Z'_{VI}>)^2) / ((n-1) * \Sigma_j wZ'_{VI_j})$

The corresponding formulae for the transformed I magnitudes and errors are

$I_j = i_j + T'_{IV} * (v-i)_j + <Z'_{IV}>$

$\sigma I_j{}^2 = \sigma i_j{}^2 + T'_{IV}{}^2 * (\sigma v_j{}^2 + \sigma i_j{}^2) + \sigma T'_{IV}{}^2 * (v-i)_j{}^2 + \sigma <Z'_{IV}>^2$

This solution does not require iteration as the results are obtained directly in terms of measured and calculated quantities.

4. Case 3

In this case we have standard V magnitudes and (V-I) colour indices and their errors available in the sequence and we can measure using V- and I-band filters. The transformed V magnitude and its error are derived in the same way as in Case 2. We can manipulate the equations for V and I given in Case 2 to get the following formula which will enable us to calculate the transformed (V-I) colour index directly.

$(V-I) = T'_{V-I} * (v-i) + Z'_{V-I}$

where

T'_{V-I} is a transformation coefficient defined as the gradient of V-I vs v-i
Z'_{V-I} is the endo-atmospheric zero point for the (v-i) colour index

and it can be shown that

$T'_{V-I} = 1 / (1 – T_{VI} + T_{IV})$
$Z'_{V-I} = (Z_{VI} – Z_{IV}) / (1 – T_{VI} + T_{IV}))$

The formulae for Z'_{V-I_j} and its standard deviation $\sigma Z'_{V-I_j}$ are

$Z'_{V-I_j} = (V – I)_j – T'_{V-I} * (v-i)_j$

$\sigma Z'_{V-I_j}{}^2 = \sigma(V - I)_j{}^2 + T'_{V-I}{}^2 * (\sigma v_j{}^2 + \sigma i_j{}^2) + \sigma T'_{V-I}{}^2 * (v-i)_j{}^2$

We then calculate the transformed (V-I) colour indices and their errors as

$(V-I)_j = T'_{V-I} * (v-i)_j + <Z'_{V-I}>$

$\sigma(V-I)_j{}^2 = T'_{V-I}{}^2 * (\sigma v_j{}^2 + \sigma i_j{}^2) + \sigma T'_{V-I}{}^2 * (v-i)_j{}^2 + \sigma <Z'_{V-I}>^2$

where the weighted mean and weighted standard error for Z'_{V-I} are given by

$\langle Z'_{V-I} \rangle = \Sigma_j (wZ'_{V-I_j} * Z'_{V-I_j}) / \Sigma_j wZ'_{V-I_j}$

$\sigma\langle Z'_{V-I} \rangle^2 = \Sigma_j (wZ'_{V-I_j} * (Z'_{V-I_j} - \langle Z'_{V-I} \rangle)^2) / ((n-1) * \Sigma_j wZ'_{V-I_j})$

5. Case 4

Here we have V magnitudes and errors but no colour information available in the comparison star sequence and we are able to make measurements through V- and I-band filters. We can derive the transformed V magnitude and its error as in Case 2.

6. Case 5

In this case we only have V magnitudes and errors available for stars in the sequence and we are only able to measure with a V-band filter so we are not able to transform our magnitude to the standard system. We can express the untransformed V magnitude as

$V = v + Z_V$

where

Z_V is the V-band endo-atmospheric zero point

so

$Z_{V_j} = V_j - v_j$

$\sigma Z_{V_j}^2 = \sigma V_j^2 + \sigma v_j^2$

The untransformed V magnitudes and errors are then

$V_j = v_j + \langle Z_V \rangle$

$\sigma V_j^2 = \sigma v_j^2 + \sigma\langle Z_V \rangle^2$

where

$\langle Z_V \rangle = \Sigma_j (wZ_{V_j} * Z_{V_j}) / \Sigma_j wZ_{V_j}$

$\sigma\langle Z_V \rangle^2 = \Sigma_j (wZ_{V_j} * (Z_{V_j} - \langle Z_V \rangle)^2) / ((n-1) * \Sigma_j wZ_{V_j})$

7. Case 6

In this case we have V magnitudes and errors from the sequence but we make our measurements without a filter or with a clear (C) filter. We can then only derive an untransformed C magnitude which is not in the standard system. Similarly to Case 5, we use the formula

$V = c + Z_C$

where

- V is the standard V magnitude (from the sequence)
- c is the unfiltered instrumental magnitude (from AIP4WIN v2)
- Z_C is the unfiltered endo-atmospheric zero point

As before, we have

$Z_{C_j} = V_j - c_j$

$\sigma Z_{C_j}^2 = \sigma V_j^2 + \sigma c_j^2$

where

σc_j is the standard deviation of c_j (from AIP4WIN v2)

The untransformed C magnitudes and errors are then

$C_j = c_j + \langle Z_C \rangle$

$\sigma C_j^2 = \sigma c_j^2 + \sigma\langle Z_C \rangle^2$

where

$\langle Z_C \rangle = \Sigma_j (wZ_{C_j} * Z_{C_j}) / \Sigma_j wZ_{C_j}$

$\sigma\langle Z_C \rangle^2 = \Sigma_j (wZ_{C_j} * (Z_{C_j} - \langle Z_C \rangle)^2) / ((n-1) * \Sigma_j wZ_{C_j})$.

8. Transformation Coefficients and Filters

Note that only two independent transformation coefficients are required in all of the above cases. The others can be computed from these two, although they could of course be measured directly. This would be a good check for consistency.

The descriptions have been given in terms of V and I filters. We leave it as an exercise for the reader to develop analogous formulae for other filters.

9. Errors

The errors calculated using the above formulae take account of the following sources of uncertainty:

a) errors in the measured instrumental magnitudes due to statistical uncertainty in the ADU counts plus various noise and background sources inherent in the imaging, readout and measurement processes (these are incorporated in the error provided by AIP4WIN v2);

b) errors in the standard magnitudes of the comparison stars which are usually also given in the sequence, otherwise they have to be estimated;

c) errors in the transformation coefficients which should be known from the calibration process.

10. Advantages of Using Multiple Comparison Stars

Using multiple comparison stars has several potential advantages over using a single comparison star. The random variations which occur in measurements of a single comparison star tend to be smoothed out when measurements of several stars are combined giving smaller errors in the derived magnitudes. Variability in comparison stars can easily be recognised and they can be omitted from the zero point calculation. Inaccuracies in the magnitudes of comparison stars given in the sequence can be identified as these usually lead to a large mean standard error in the zero point over the run. A small zero point error, on the other hand, is a good indication of internal consistency between the comparison star magnitudes.

A large standard error on the zero point for a single image usually indicates there was something wrong with that image, caused for example by an aircraft trail or a cosmic ray. Variation in the zero point during a run is a good indication of changing atmospheric conditions since deteriorating conditions will tend to reduce the zero point. As a rule of thumb, images are usually discarded where the zero point is more than about one magnitude lower than the average highest level.

11. Implementation

These formulae have been programmed into a series of spreadsheets. These take the output from the multiple image ensemble photometry routine in AIP4WIN v2 which contains instrumental magnitudes and errors for each measured star and they calculate derived magnitudes with error estimates. They produce plots which show the variation of the derived magnitudes and errors and the mean image zero point and its error over the run. They also calculate the airmass for each image and generate results in the format required to report to the BAAVSS, AAVSO and the CBA. The BAAVSS now archives measured instrumental magnitudes and errors of the variable and all comparison stars used in the analysis to enable reanalysis at a future date.

The following examples use data obtained with a 0.35m SCT operating at f/5.2 and an SXV-H9 CCD camera.

12. Example 1

Figures 1 and 2 show the transformed V and I magnitudes respectively for the variable and 5 comparison stars in a 4hr run of 15sec exposures using V and I filters on VY Aqr on 7 October 2006. Figure 3 shows the variation in the mean V and I image zero points during the run as the conditions changed with occasional breaks due to clouds. Table 1 lists the V and I magnitudes and errors given in the sequence for the 5 comparison stars and their mean derived V and I magnitudes and errors over the run. These results are calculated using the formulae in Case 1. It also shows the standard deviation of the derived magnitudes over the run labelled "V (or I) mag std dev" as a comparison with the calculated error. The comparison stars used in the zero point analysis are indicated. Given the larger error for star 138, this was not included in the analysis but its magnitude was calculated using the derived zero point. Table 2 shows the same data analysed according to Case 2.

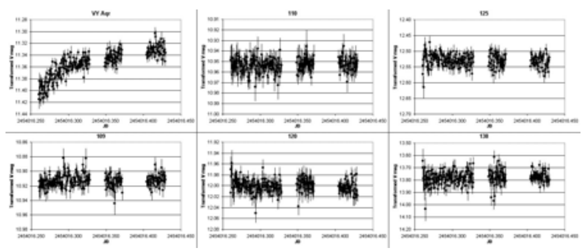

Figure 1: Transformed variable and comparison star V magnitudes

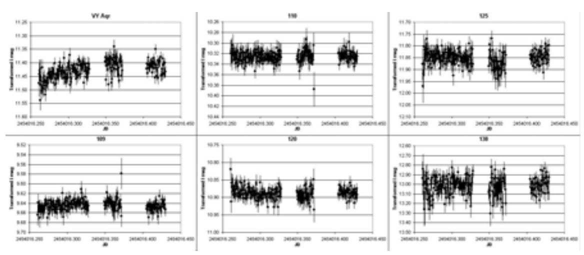

Figure 2: Transformed variable and comparison star I magnitudes

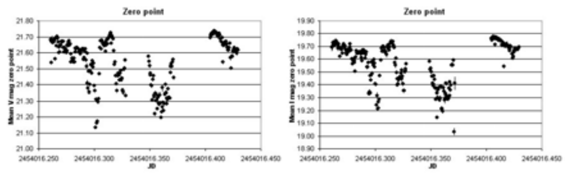

Figure 3: Mean V and I image zero points during a run

ID	V mag sequence	V error sequence	V mag derived	V error derived	V mag std dev	Used in analysis?
109	10.910	0.010	10.913	0.008	0.008	Y
110	10.957	0.010	10.953	0.008	0.007	Y
120	12.001	0.012	12.001	0.013	0.012	Y
125	12.526	0.015	12.530	0.019	0.020	Y
138	13.767	0.020	13.781	0.052	0.055	N
ID	I mag sequence	I error sequence	I mag derived	I error derived	I mag std dev	Used in analysis?
109	9.638	0.010	9.644	0.012	0.010	Y
110	10.336	0.010	10.326	0.013	0.010	Y
120	10.884	0.010	10.888	0.018	0.016	Y
125	11.843	0.010	11.852	0.033	0.031	Y
138	12.972	0.015	13.019	0.088	0.090	N

Table 1: Comparison star sequence and derived V and I magnitudes from Case 1

ID	V mag sequence	V error sequence	V mag derived	V error derived	V mag std dev	Used in analysis?
109	10.910	0.010	10.913	0.008	0.008	Y
110	10.957	0.010	10.953	0.009	0.007	Y
120	12.001	0.012	12.001	0.013	0.012	Y
125	12.526	0.015	12.529	0.019	0.019	Y
138	13.767	0.020	13.781	0.052	0.054	N
ID	I mag sequence	I error sequence	I mag derived	I error derived	I mag std dev	Used in analysis?
109	9.638	0.010	9.643	0.011	0.010	Y
110	10.336	0.010	10.325	0.015	0.011	Y
120	10.884	0.010	10.887	0.018	0.017	Y
125	11.843	0.010	11.851	0.034	0.033	Y
138	12.972	0.015	13.018	0.089	0.094	N

Table 2: Comparison star sequence and derived V and I magnitudes from Case 2

13. Example 2

Figures 4 and 5 show the transformed V and V-I magnitudes respectively for the variable and 5 comparison stars in a 5hr run of 60sec exposures using V and I filters on the variable 1RXS J224342.3+305526 (aka Bernhard 02) on 25 November 2005. Figure 6 shows the mean V and V-I image zero points. Table 3 lists the V magnitudes and errors given in the sequence for the 5 comparison stars together with estimated V-I values obtained from the quoted B-V values using a transformation based on Landolt stars. It also shows the mean derived V and V-I magnitudes and errors over the run for the comparison stars calculated using the formulae in Case 3, together with the standard deviation of the derived magnitudes over the run labelled "V (or V-I) mag std dev" as a comparison with the calculated error. The comparison stars used in the zero point analysis are indicated. Given the possible variability of star 153 and the larger errors on star 161, these were not included in the analysis.

It can be seen that, in this particular example, the calculated errors are considerably larger than the standard deviations of the derived magnitudes. This is because the standard V magnitudes given in the sequence were based on a single night of observation and therefore have larger scatter about their true values, and the V-I magnitudes were estimated. In consequence, the zero point errors are larger and this feeds through into the calculated errors. This correctly reflects the fact that the actual errors are somewhat larger than the standard deviations of the magnitudes might suggest due to the larger uncertainty in the sequence magnitudes.

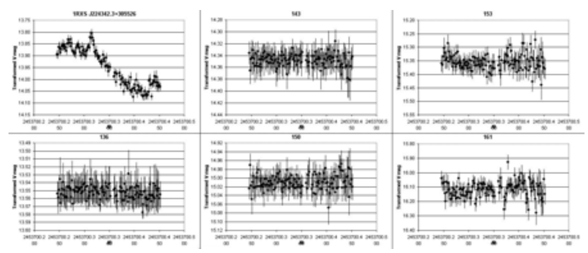

Figure 4: Transformed variable and comparison star V magnitudes

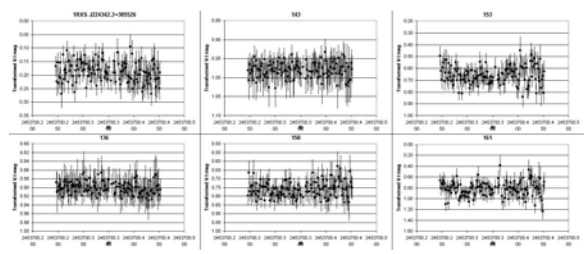

Figure 5: Transformed variable and comparison star V-I magnitudes

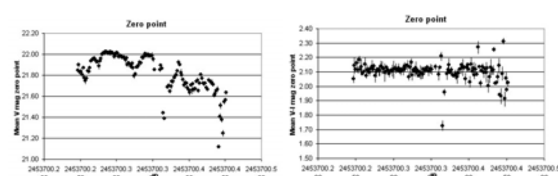

Figure 6: Mean V and V-I image zero points during a run

ID	V mag sequence	V error sequence	V mag derived	V error derived	V mag std dev	Used in analysis?
136	13.576	0.020	13.552	0.018	0.008	Y
143	14.329	0.020	14.348	0.021	0.011	Y
150	14.993	0.020	15.010	0.028	0.017	Y
153	15.325	0.030	15.355	0.034	0.028	N
161	16.070	0.040	16.118	0.059	0.053	N
ID	V-I mag sequence	V-I error sequence	V-I mag derived	V-I error derived	V-I mag std dev	Used in analysis?
136	0.917	0.050	0.901	0.030	0.017	Y
143	0.944	0.050	0.981	0.038	0.020	Y
150	0.793	0.050	0.761	0.062	0.041	Y
153	0.708	0.050	0.655	0.085	0.075	N
161	0.805	0.050	0.820	0.144	0.137	N

Table 3: Comparison star sequence and derived V and V-I magnitudes from Case 3

14. Example 3

Figures 7 and 8 show the untransformed V magnitudes and mean V zero point from a 6hr run of 15sec exposures using a V filter on V2362 Cyg on 1 November 2006. Table 4 lists similar V magnitude information to that given in Table 3. For information, it also includes V-I magnitudes from the sequence which were not used in the analysis. Given the variability of star D and the significantly different colours of stars F and G, these were not included in the analysis. These results are an example of Case 5.

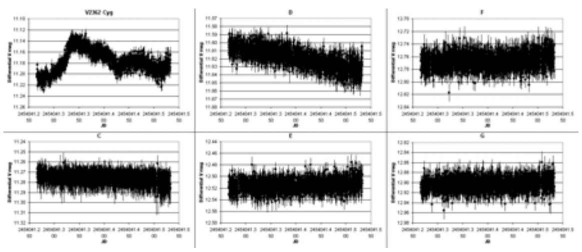

Figure 7: Untransformed variable and comparison star V magnitudes

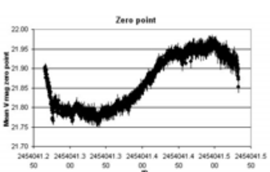

Figure 8: Mean V image zero point during a run

ID	V mag sequence	V error sequence	V-I sequence	V mag derived	V error derived	V mag std dev	Used in analysis?
C	11.270	0.010	0.340	11.270	0.007	0.003	Y
D	11.630	0.010	0.450	11.614	0.007	0.012	N
E	12.510	0.020	0.650	12.510	0.011	0.010	Y
F	12.790	0.020	1.580	12.761	0.013	0.014	N
G	12.910	0.020	1.750	12.898	0.014	0.014	N

Table 4: Comparison star sequence and derived V magnitudes from Case 5

15. Example 4

Figures 9 and 10 and Table 5 show untransformed results for a 6hr unfiltered (Clear) run of 20sec exposures on DW Cnc on 6 February 2007. For information, Table 5 also includes B-V magnitudes from the sequence which were not used in the analysis. Star 145 and 149 were not used in the analysis because of their different colours. This is an example of Case 6.

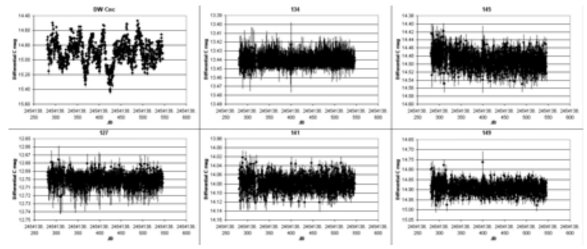

Figure 9: Untransformed variable and comparison star C magnitudes

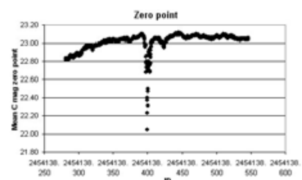

Figure 10: Mean C image zero point during a run

ID	V mag sequence	V error sequence	B-V sequence	C mag derived	C error derived	C mag std dev	Used in analysis?
127	12.695	0.014	0.464	12.700	0.007	0.007	Y
134	13.443	0.008	0.525	13.441	0.010	0.006	Y
141	14.080	0.011	0.529	14.079	0.014	0.012	Y
145	14.546	0.013	0.916	14.490	0.019	0.020	N
149	14.912	0.009	0.737	14.892	0.026	0.026	N

Table 5: Comparison star sequence and derived C magnitudes from Case 6

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17. References

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