VARIABLE STAR ASTRONOMY WITH A CCD WIDE-ANGLE LENS SYSTEM

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Abstract

A system for performing CCD photometry employing an ST6 attached to a 2-inch f/3.6 lens is described. The system's advantages and problem areas are discussed, its performance is described based on over 4500 CCD images of eclipsing binary stars, and its prospects for photometry on more than one variable per image are explored.

1. Introduction

I have been observing eclipsing binary stars (EBs) on and off since 1967 as part of the AAVSO Eclipsing Binary Program aimed at monitoring times of minima. Much of this work has been done visually with a 6-inch reflector. Recently, I have adopted new equipment and methods. As a result, my productivity per time invested has roughly doubled, both the quality of my data and my capabilities have improved, and I simply enjoy observational astronomy more.

For the last year I have used an ST6 CCD camera (made by the Santa Barbara Instrument Group) attached to a 2-inch f/3.6 lens. During that time I have made over 4500 differential V magnitude (VAR-COMP) photometric measures of some 170 eclipsing binaries, and timed about 135 minima. With this setup, I can observe eclipsing binaries down to about as faint as I can visually with my 6-inch reflector: V magnitude = 12.5 or so. With brighter stars, I can gather data I would never have a chance of recording visually with any telescope, such as eclipses of very small amplitude, which I routinely record. In this regard, see Figures 1 and 2 for CC Cas and DM Del, for which the *General Catalogue of Variable Stars* (GCVS) (Kholopov *et al.* 1985) gives amplitude of variations (DM Del secondary minimum) in the 0.15- to 0.25-magnitude range. Also, with my setup, stars that are difficult to monitor visually are easier to handle, as Figures 3 and 4 illustrate. Here the GCVS amplitudes are at the 0.6- to 0.7-magnitude level, EE Peg being 7th magnitude at maximum, BL And, 11th magnitude. The visual data shown for EE Peg were never reported, since I had such little confidence in their validity. Visually, I never saw BL And undergo an eclipse, because the GCVS position (and my chart) was so poor that I was watching the wrong star!

Let me emphasize that my goal with this setup is not to make highly accurate photometric measurements on a few stars. Rather, I am going after hundreds of eclipsing binary stars in an effort to measure their V magnitudes much more precisely than can be done visually.

2. The setup—description, advantages, problems

I have mounted a 2-inch lens and an 11 x 60 mm finder on a small motor-driven equatorial mount. The whole setup sits on an upstairs deck easily accessible from the adjoining bedroom in my house. My observing sessions begin outside, with removing the plastic cover that shelters the mount, attaching the CCD, and plugging in the cable and motor drive. Inside, the other end of the cable stays connected to the CCD's CPU unit, which likewise stays connected to the 486 computer at my desk. After booting and instructing that the CCD head be cooled (typically to 40°C below ambient temperature),

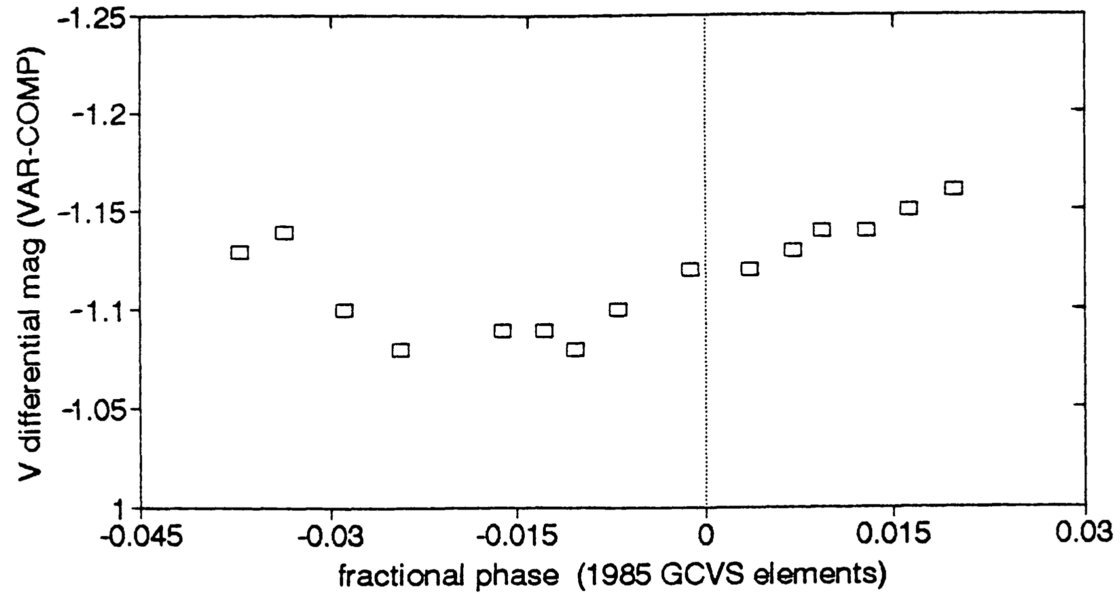

Figure 1. Primary minimum of CC Cas (COMP = SAO 23896). Based on the author's 1996 CCD photometry with 2" f/3.6 lens, V differential magnitude is plotted vs. (heliocentric) fractional phase. CC Cas's primary eclipse variation is given as 7.06 to 7.30 V magnitude in the GCVS, and as 7.59 to 7.74 magnitude (pg) in the *Rocznik Ephemerides*. □ = March 1–2, 1996.

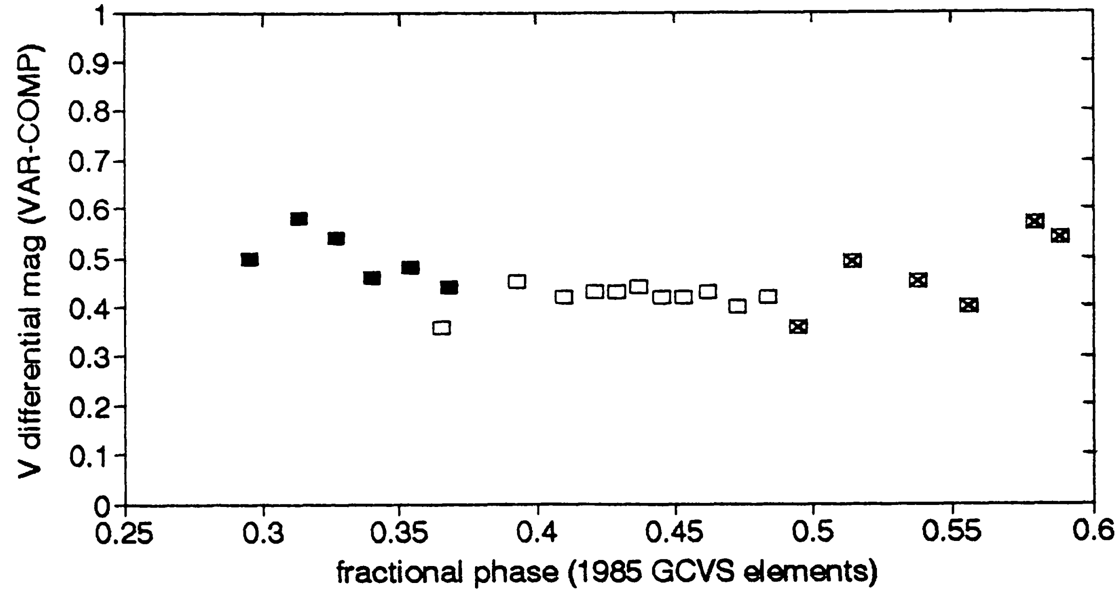

Figure 2. Secondary minimum of DM Del (COMP = SAO 106358). Based on the author's 1995 CCD photometry with 2" f/3.6 lens, V differential magnitude is plotted vs. (heliocentric) fractional phase. DM Del's secondary eclipse variation is given as 8.58 to 8.80 V magnitude in the GCVS. □ = July 19–20, 1995; ■ = July 24–25, 1995; ☒ = August 27–28, 1995.

I am back outside using setting circles to point to an eclipsing binary star of interest. Typically, less than 10 minutes elapses between going out to remove the cover and identifying the star on the computer screen inside.

CCDs are notorious for their small field of view. For example, with the ST6 on my 16-inch f/4.5 reflector, the field is but 0.275° x 0.206° (this is big by some standards!). Finding objects in this tiny window can take a frustratingly long time. With the wide

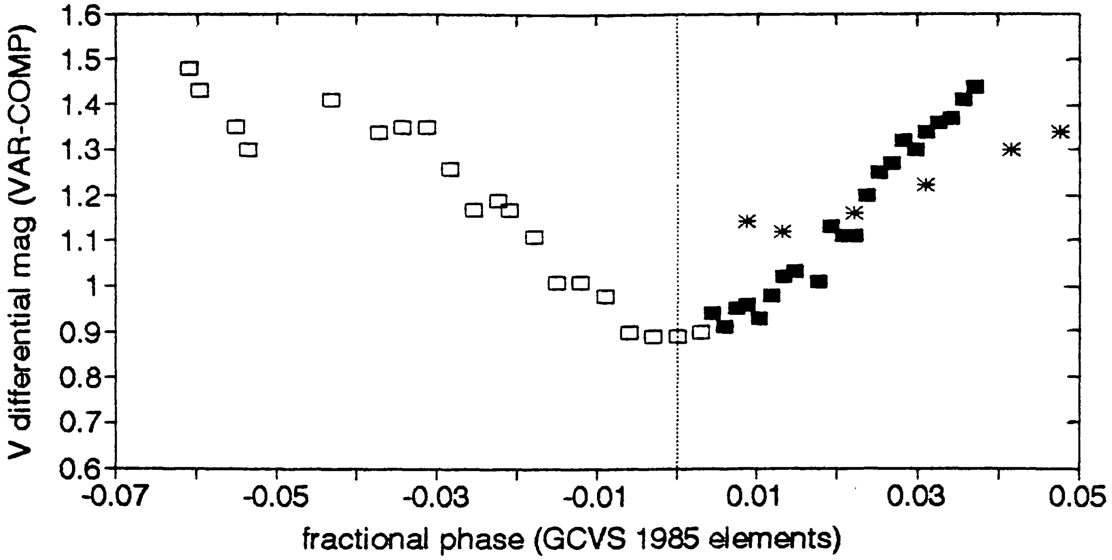

Figure 3. Primary minimum of EE Peg (COMP = SAO 126961). Based on the author's 1995 CCD photometry with 2" f/3.6 lens, V differential magnitude is plotted vs. (heliocentric) fractional phase. EE Peg's primary eclipse variation is given as 6.93 to 7.51 V magnitude in the GCVS. His 1992 visual estimates are included for comparison purposes. ■ = July 6–7, 1995 (CCD); □ = August 17–18, 1995 (CCD); ⧆ = September 22–23, 1992 (visual).

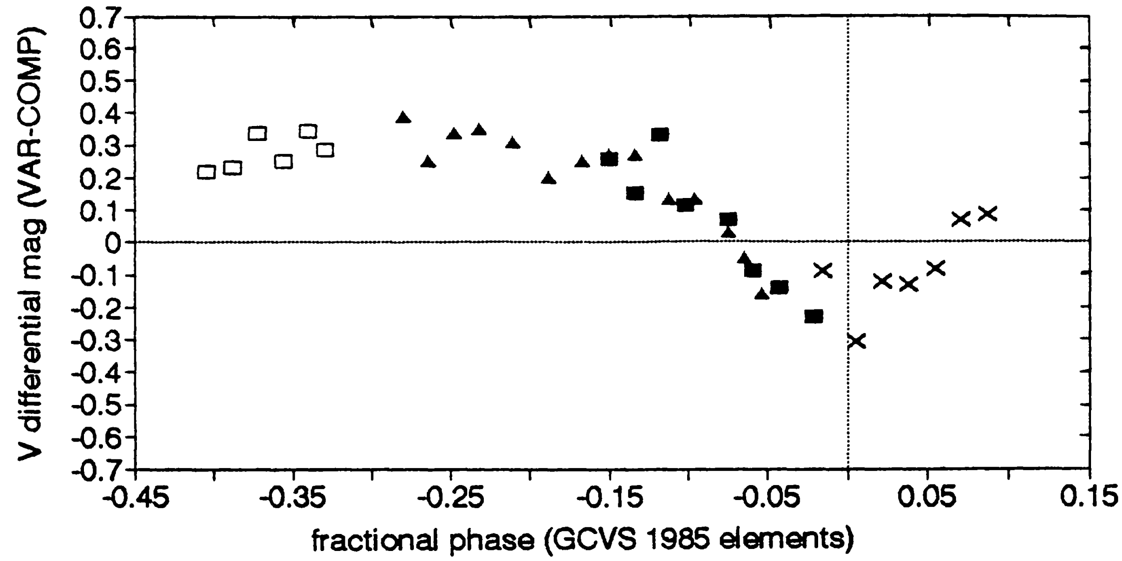

Figure 4. Primary minimum of BL And (COMP = GSC reg3635 star 1121). Based on the author's 1995 CCD photometry with 2" f/3.6 lens, V differential magnitude is plotted vs. (heliocentric) fractional phase for the eclipsing binary BL And. Its primary eclipse variation is given as 11.0 to 11.74 (photographic) magnitude in the GCVS. ■ = October 10–11, 1995; ▲= October 15–16, 1995; □ = October 17–18, 1995, ⊠ = October 18–19, 1995.

angle, short focus lens setup, this is no longer a problem. In fact, it provides such convenience that the mere thought of either using the CCD on the big scope or returning to visual observing is painful. Consider these advantages:

a. Ease of finding objects. The lens' short 7.2-inch focal length gives a large field of view: 2.75° x 2.06°—a window 100 times bigger than the CCD / 16-inch setup! Also, finding objects on a computer screen while sitting inside sure beats looking through an eyepiece.

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b. Capability of gathering data on more than one variable per image. The large field of view means that often I record two or more variables on a single CCD image. (See section 5).

c. Ease of tracking. With typical 20-second exposures and the large field, demands on tracking accuracy and polar alignment are minimal.

d. Capability of unattended operation. Often, I point to an EB star, instruct that an image be taken, say, every 6 minutes, and return three hours later—with 30 images waiting for me on the hard drive!

e. Separating the data gathering and data reduction. When I am tired or have other things to do at night, I can wait and reduce the data the next morning, when I am well rested and working efficiently at my desktop computer.

f. Minimizing the time spent outdoors in cold weather. I sometimes spend less than 10 minutes outside, but get a whole evening's worth of data. (The computer's location inside my house also protects it from the cold.)

g. Minimal weight. Even with an UBVRI filter wheel attached, the load on the mount is small, thus eliminating the typical balancing or tracking problems that I have experienced with the CCD/filter wheel attached to larger telescopes.

While this setup has advantages, it also presents the following problems:

a. The limited light gathered by the 2-inch aperture hardly optimizes signal-to-noise ratio (S/N).

b. With an image spanning a significantly large part of the sky, factors which could safely be considered constant across the field in conventional CCD differential photometry must be considered as potentially variable. Thus, differential atmospheric extinction and non-uniform sky background become important possible sources of error.

c. The non-uniform sky background problem also complicates flat fielding, which is typically done to correct for variations in pixel sensitivity over the chip (including dust on the filter, etc.), and to overcome vignetting. While flat fielding corrections are ultimately made using software routines, the process can begin with taking images of a non-dark sky. Unfortunately, taking sky flats does not work with the short focus lens. Given its large field, how does one get uniform sky brightness (to one part in a thousand) over the entire image?

d. The mere 7.2-inch focal length makes the pixel size large, specifically 26.4 by 30.5 seconds of arc, and this can lead to field star contamination problems. In crowded fields, stars can blend together. I cannot observe a variable unless there is one minute of arc separating it from a nearby star of non-negligible brightness. With eclipsing binaries, this has not limited me much. Still, I have to use care when the variable or comparison stars have bright neighbors in adjoining pixels. The ST6 software's photometric routines allow for sampling boxes of from 3 x 3 pixels up to 11 x 11 pixels. I use that smallest size for anything fainter than 7th magnitude or so. In very crowded fields, I pay attention to intensities in individual pixels.

Finally, there are the usual CCD photometry concerns about finding appropriate comparison (COMP) and check stars, temperature regulation, variations in sky brightness, spurious counts due to cosmic rays, selection of software aperture, CCD intrapixel effects and read noise, etc. Having identified problems, I shall now discuss them.

3. Photometry: Overcoming problems, assessing precision

I was warned that accurate photometry with small, short focus lenses would be difficult to do, and I have certainly experienced difficulties. Early on, it became obvious that photometry of faint stars would require adding individual images to improve signal-to-noise ratio. It took a while to realize the importance of the proximity of the variable (VAR) and the comparison star (COMP) with respect to minimizing differential atmospheric extinction, non-uniform sky background, and other errors. The former source of error becomes quite significant if VAR and COMP are more than one degree apart; the latter is significant at even smaller separations. Initial flat fielding efforts, first using sky flats, then by imaging a screen uniformly illuminated by an incandescent lamp, actually degraded photometric precision! Proper flat fielding technique (see Massey and Jacoby 1992) employs a quartz lamp or lamps, and takes time, both in taking flats and in reducing data. I soon learned that I could reduce two images without flat fielding in the time it would take to reduce one with those corrections.

Weighing these problems against successes and my goals, I have lowered my expectations with regard to the quality of data this system can generate, while expecting more in terms of quantity. With these lowered expectations, I have given up flat fielding (at least for now). Since this is recommended where greater than a ±5% level of photometric precision is desired, at first it must seem that I am limiting precision to around 0.05 magnitude. But instead of flat fielding, I average at least two separate images (typically taken 4 to 8 minutes apart). Given less than perfect tracking, this averaging partly compensates for errors due to variations in pixel sensitivity while helping overcome other problems (see below). I also simply throw out the occasional image where dust has apparently blocked light—something flat fielding would catch. (Around 1 in 25 images are thrown out for this reason.)

What precision characterizes my data? Following Howell, Mitchell, and Warnock (1988), I have calculated the variance in COMP - CHECK (per their equation 1) from CCD images associated with data for numerous eclipsing binaries. Assuming comparison and check stars are constant, I attribute variances to instrumental and other sources, take the square root, and call the result $\sigma_{C\text{-}K}$. The results appear in Table 1. There, average standard deviations are calculated for bright, moderate, and faint stars. Note values in the 0.02 to 0.04 magnitude range, with smaller values associated with brighter stars. Are these representative of the precision of my EB data, i.e., what Howell, *et al.* call $\sigma_{V\text{-}C}$(INST)? I believe my VAR-COMP data are typically slightly better than Table 1 COMP - CHECK standard deviations would imply. I say this simply because VAR and COMP are nearly always closer together and often better matched in brightness than COMP and CHECK, but I have not calculated any scaling factors (see Howell *et al.*, equations (3) and (13)) to support this belief.

When care is taken to minimize other possible sources of error, I believe the largest contributors to $\sigma_{V\text{-}C}$(INST) errors are introduced by 1) failure to make flat fielding corrections properly, 2) S/N factors, given photon (Poisson) statistics, and 3) field star contamination problems. For bright stars, errors of the first type are believed most important, while those in the second category can be shown to be insignificant. In Figure 1, each image for 7th magnitude CC Cas had about 13,500 signal counts, times 2 images averaged, giving 27,000 counts. If, as a first approximation, we assume

$$S/N = S^{0.5} \tag{1}$$

and

$$\sigma = 1/(S/N) \tag{2}$$

the calculated S/N of 164 corresponds to $\sigma = 0.006$ magnitude. For faint stars, such as 11th magnitude BL And in Figure 4, these S/N errors are more important. Repeating the above calculation (admittedly (1) is not as good an approximation!) with 725 signal counts per image, times 3 images averaged, giving 2175 counts, yields S/N = 46.7 and $\sigma = 0.021$ magnitude. Note how the averaging of multiple images approach builds signal counts and improves signal-to-noise ratio. This approach also addresses field star contamination concerns.

The field star contamination problem can limit photometric accuracy. Using the 3 x 3 pixel box and given the large pixels, (perhaps unseen) field stars around the variable or comparison star may end up being part of the measurement. For differential photometry this would not be a problem if the same field stars (assumed to be nonvariable) were always included. When working with faint stars, however, there is no way to insure this. To illustrate the problem, imagine the signal from an 11th magnitude comparison star is 725 counts and an unseen 14th magnitude field star in the same measuring box gives 45 counts. If this field star is sometimes in the box and sometimes out, due to position changes in the software aperture and/or seeing-introduced image shifts, the measured count might ideally range from 725 to 770. This leads to uncertainty of an unacceptably large 0.065 magnitude.

How can this uncertainty be reduced? The averaging-multiple-images approach spreads out the field star contamination problem and minimizes its effect through sampling of different pixels and averaging. In fact, due to potential field star contamination problems, instead of relying on one image of 60 seconds' exposure (as building S/N concerns alone might dictate), I will take, individually measure VAR-COMP, and then average results for 3 images each of 20 seconds' exposure. This multiple-images approach also lessens demands on tracking accuracy. How many images I average depends on the brightness of the variable and sky conditions. Typically, I might follow these guidelines: brighter than magnitude 8.0, 2 images; magnitude 8.0–10.0, 2 or 3 images; magnitude 10.0–12.0, 3 or more images.

4. Additional tips

Finally, some other things I have learned about CCD photometry with this small-aperture, large-field setup include:

a. If a COMP very nearby and nearly identical in brightness to VAR cannot be selected, one brighter rather than fainter is preferable. (This preference follows from photon statistics concerns.)

b. In skies brightened by moonlight or light pollution, non-uniform sky background-related problems make having COMP and VAR close together especially important. This is also important if flat fielding is not done, given typical variations in CCD sensitivity with pixel location (after "hot pixels" are suppressed).

c. One must watch out for supposed variations in VAR-COMP that actually occur as the sky brightens over an observing run (i.e., moonrise) or darkens (i.e., twilight fades). The latter may explain the initial large scatter in the light curve in Figure 3. Poor temperature regulation on a hot August night and inappropriate flat fielding "corrections" (which also plague Figure 2 data) are suspects as well!

d. One must cool the CCD as much as ambient temperature and power requirements permit. Faint star photometry on hot, humid nights—when I cannot cool below -16° C—is more difficult than on cooler nights when I am running at -30°C or below.

e. Short focal length/large pixel size has limited me to reporting differential V magnitudes. So, although I use standard V and other filters (Bessell-Cousins system, designed for CCDs), I have not yet transformed magnitudes to the standard system. Why not?—with the short focal length, the stars in the M67 field often used to do this are too close together to measure reliably.

5. Maximizing the efficiency of gathering variable star data

The wide field of the setup I have described makes it possible sometimes to capture more than one variable on a single CCD image. On several occasions I have thus monitored either two EB stars or one EB and one RR Lyr-type variable. This works best when the time interval needed between observations is similar and when the phases of each variable are such that interesting portions of the light curve present themselves simultaneously. Targeting an EB star near primary minimum and a nearby short period RR Lyr variable works well, since observations of the latter can be started at any time. With two or more eclipsing binaries in the same field, waiting for concurrent primary eclipses may not be practical. However, if one of the eclipsing binaries is a shorter period

EW eclipsing binary system (in which secondary minimum is about as deep as the primary), planning observations at the time of primary minimum of the longer period EB makes taking data for the other EB worthwhile as well. Of course several EB systems have interesting light curves outside of primary eclipse: secondary eclipses are too often neglected, out-of-eclipse RS CVn system variations need study, certain systems show intrinsic variations (Cook 1993), etc.

How many such possibilities, i.e., eclipsing binaries and/or RR Lyrs that are close enough together, exist? Counting only systems brighter than V = 12.3 at maximum and within 2.2° of each other as listed in the GCVS, I found that of the 94 AAVSO EB program stars, 47 had other EB or RR Lyr stars appropriate for such simultaneous observation. Surveying 165 RR Lyr stars from one ephemerides listing (Rocznik 1985) revealed that 39 had EB stars nearby suitable for such monitoring.

In the future, when big CCD chips that give wide fields (with larger aperture, longer focal length telescopes) are available at reasonable prices, the number of stars that present themselves for such simultaneous imaging will increase as the magnitude limit is extended due to greater light gathering power.

6. Acknowledgements

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Table 1. Standard deviations in COMP - CHECK, σ_{C-K} (from measured V instrumental magnitudes).

Eclipsing Binary star field	Ave. Mag. of COMP & CHECK stars	Number of images combined to yield data point	Total number of images	σ_{C-K} standard deviation (V mags)
AR Lac	5.6	2	14	0.021
AH Cep	7.0	2	28	0.015
GT Cep	7.8	2	17	0.041
ER Vul	8.0	2	25	0.016
Average standard deviation, where COMP, CHECK bright (mag. 5 to 8)				= 0.023
IU Aur	8.5	2	21	0.016
EK Cep	8.5	2	28	0.019
KW Per	8.5	2	34	0.033
RX Ari	8.6	3	33	0.046
DM Del	9.4	2	13	0.042
Average standard deviation, where COMP, CHECK moderate (mag. 8 to 10)				= 0.031
VZ Cep	10.2	3	16	0.018
IT Per	10.5	3	36	0.050
AA And	11	3	18	0.050
BT Vul	12	6	18	0.055
Average standard deviation, where COMP, CHECK faint (mag. 10 to 12)				= 0.043