WHAT PHOTOMETRIC PRECISION CAN I ACHIEVE?

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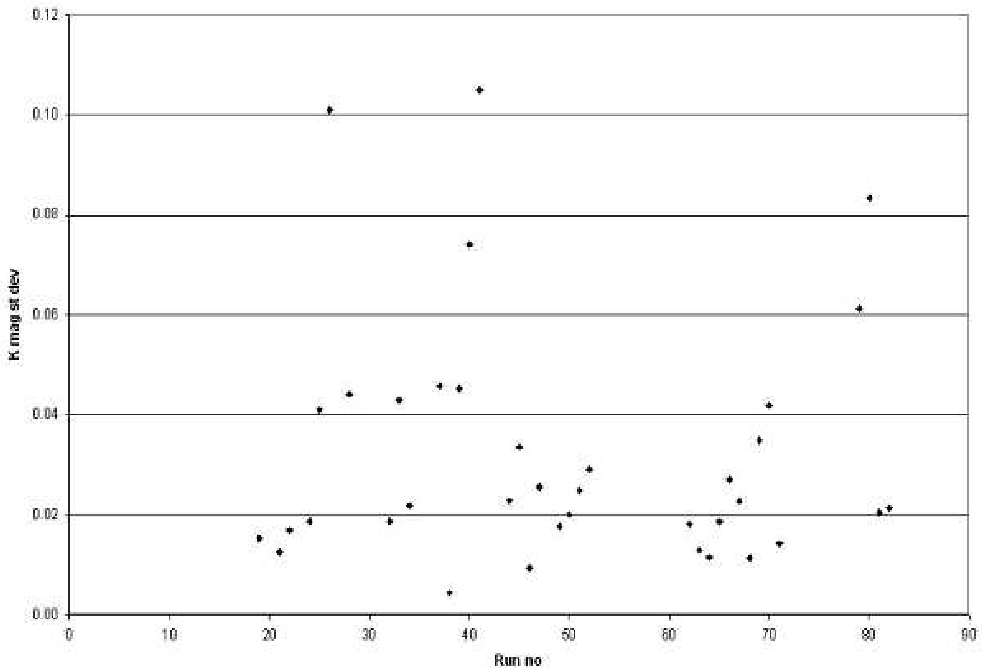
If you start using a CCD camera to carry out photometry on variable stars, this is a question that sooner or later you will ask yourself. Prompted by discussions at the recent VSS meeting at Northampton, I decided to investigate the precision I've been able to achieve in time-series differential photometry measurements on variable stars over the past couple of years. I use a 250mm f/3.6 Newtonian reflector with a Starlight Express HX516 CCD camera, and, for wide field photometry, I use the HX516 with a 35mm focal length SLR camera lens. I normally attach a V-band filter in a custom-made holder to the front of the camera for variable star measurements, and I analyse the data using the multi-image photometry routine in AIP4WIN. 37 observing runs formed the basis for this analysis. Runs on objects other than variable stars are not included.

I based my assessment of achieved photometric precision on measurements of the magnitude of the check star (K) in each of these runs. The differential magnitude of the K star relative to the comparison star (C) should be constant over a run. The variation of the measured differential magnitude of K relative to C over a run therefore gives a measure of the photometric precision achieved in that run. I calculated the standard deviation of the measured differential K magnitude (hereafter just called the K standard deviation) for each run, and Fig 1 shows this for all the runs analysed.

Fig 1: Distribution of K standard deviation over all 37 runs



About a year ago, after run 44, I replaced the original parallel port interface for the HX516 with a USB interface. Results following the change seem to be better and more consistent, though this could be due at least in part, to a learning effect, as I became more proficient at taking and analysing data. To concentrate on the quality of the results I'm getting now, I've restricted the rest of this analysis to the 21 variable star runs carried out since I changed over to the USB interface.

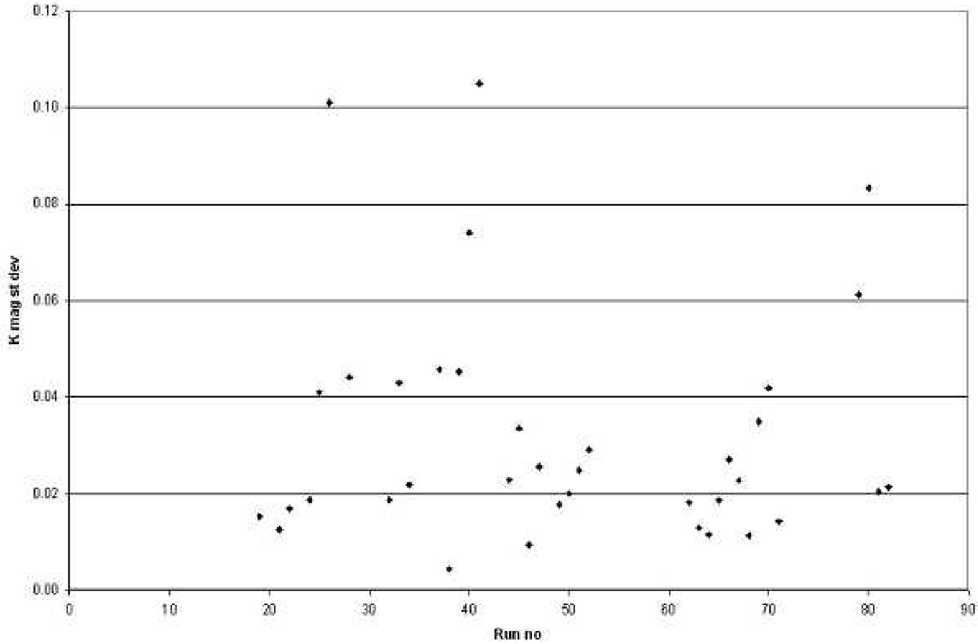


Fig 2: K standard deviation vs mean K magnitude for USB-based runs only

Figure 2 shows the distribution of the K standard deviation against the mean K magnitude for all the USB-based runs. The magnitudes of the K stars that were used ranged from 10.8 to 14.4. There is a slight trend of increasing standard deviation (=decreasing precision) at fainter magnitudes. However, this is not a large effect, presumably because I normally increase exposure times when measuring fainter stars to maximise the count rate, and maintain as high precision as possible. Increasing exposure times also increases my sensitivity to tracking errors, which potentially increases the scatter in the magnitude estimates, so this may be a contributing factor to the trend. For increasingly fainter stars, the counts obtained within reasonable exposure times will reduce, and the achievable precision will decrease more rapidly.

A major factor affecting the precision achieved is the photometric quality of the night sky. To assess this for each run, I looked at the variation of the calculated V, C and K instrumental magnitudes over the run. If these were essentially flat (apart from the effect of real stellar variation and possibly changing altitude) as in Figure 3 (overleaf), then I classified the night as good. In other circumstances as in Figure 4 (overleaf), I called it poor.

The distribution of K standard deviation for the 12 good nights is shown in Figure 5 and for the 9 poor nights in Figure 6.

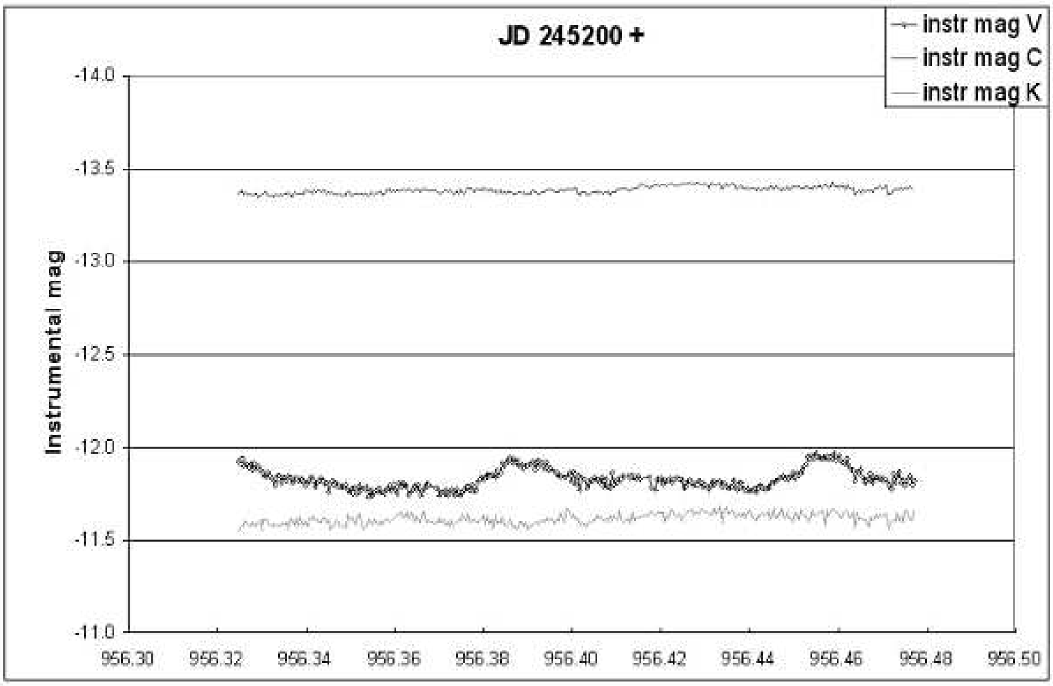


Fig 3: A good night

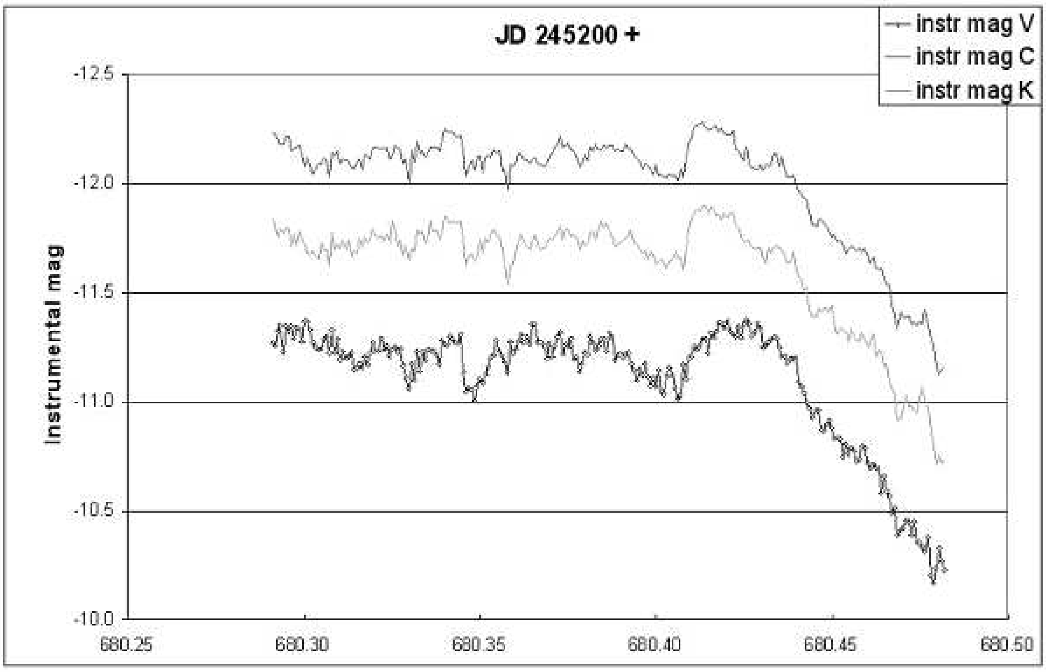


Fig 4: A poor night

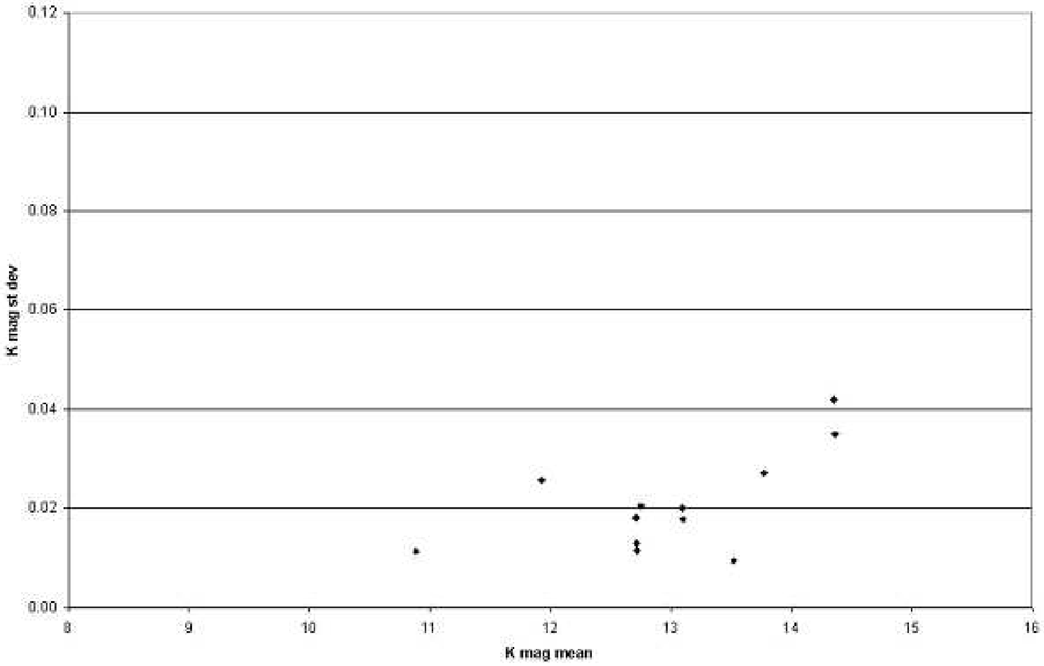


Fig 5: K standard deviation on good nights

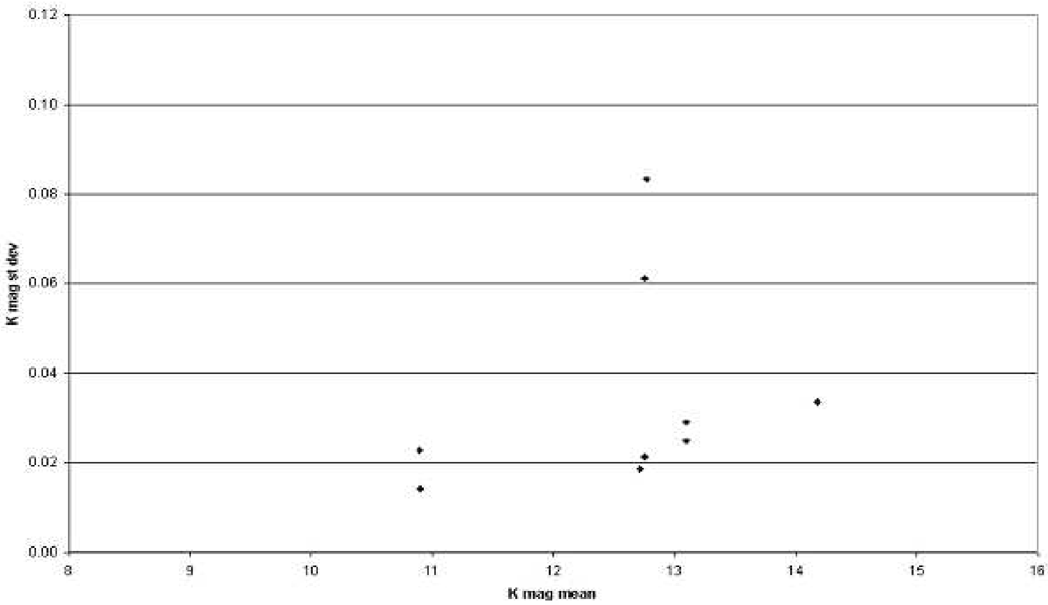


Fig 6: K standard deviation on poor nights

For good nights the average K standard deviation, which I am adopting as a measure of the precision achieved, is 0.021 magnitude, and for poor nights it is 0.034 magnitude. It's interesting to observe that there is only one run with a precision smaller than 0.01 magnitude. Although in theory, it should be possible to achieve precision better than this if the ADU counts are high enough, in practice this is rarely achieved, as it would require both the K and C stars to be comparable in brightness, and the exposure to be set so they both had the maximum possible peak count (subject of course to avoiding saturation and any effects of anti-blooming). Circumstances are rarely this cooperative.

I've also analysed 12 runs of one field taken at intervals throughout this period using a 35mm focal length camera lens set to f/4 attached to the HX516. The magnitude of the K star in these runs is 7.2. The average K standard deviation for these runs is 0.040 magnitude, somewhat larger than when using the telescope. These were all good nights.

The conclusion I draw from this analysis is that, on good nights, I can carry out time-series differential photometry using a 250mm telescope and CCD camera with an average precision of about 0.021 magnitudes, while on poor nights this drops to 0.034 magnitudes. These results span a magnitude range from 10.8 to 14.4. With a 35mm camera lens and CCD, the average precision is 0.040 magnitudes at magnitude 7. Precision better than 0.01 magnitude with this equipment is not realistically achievable. I hope this exercise will encourage others starting out in CCD photometry to investigate the precision they are able to achieve as this is helpful in deciding what projects to attempt.

Addendum

A separate but related question is whether it is possible to make a reliable estimate of the precision of an individual photometric measurement. I have, for over a year, been calculating a value for the error on my measured instrumental V, C and K star magnitudes in each image using the error formula given by Steve Howell in his book *Handbook of CCD Astronomy*. This incorporates Poisson errors on the star and sky ADU counts, the measurement aperture pixel counts, and various instrumental parameters. Adding the errors on the K and C star magnitudes in quadrature gives the calculated error on the K-C differential magnitude for each image in a run. Using the data I had now gathered together, I thought it would be interesting to compare this calculated error for the K star with the standard deviation of the measured magnitude of K used in the analysis described above. I therefore computed the mean calculated error for the K differential magnitude for each run and compared this with the standard deviation of the measured K magnitude for the same run.

Figure 7 shows the mean calculated error for the K magnitude from Howell's formula, plotted against the standard deviation of the measured K magnitude for each of the USB-based runs. Also plotted is a linear fit to the data. The parameters of this linear fit indicate that the two error values are related by a simple scale factor with the calculated error being about 84% of the measured error. The distribution of the residuals of the calculated errors from the linear fit has a standard deviation of 0.003 magnitude, indicating that the linear fit represents the data quite well. Although obtained for the K star, this relationship between the calculated and measured errors should be true for all stars measured in these images, at least within the magnitude range covered here.

This leads me to the conclusion that I can make a reasonable estimate of the error in the

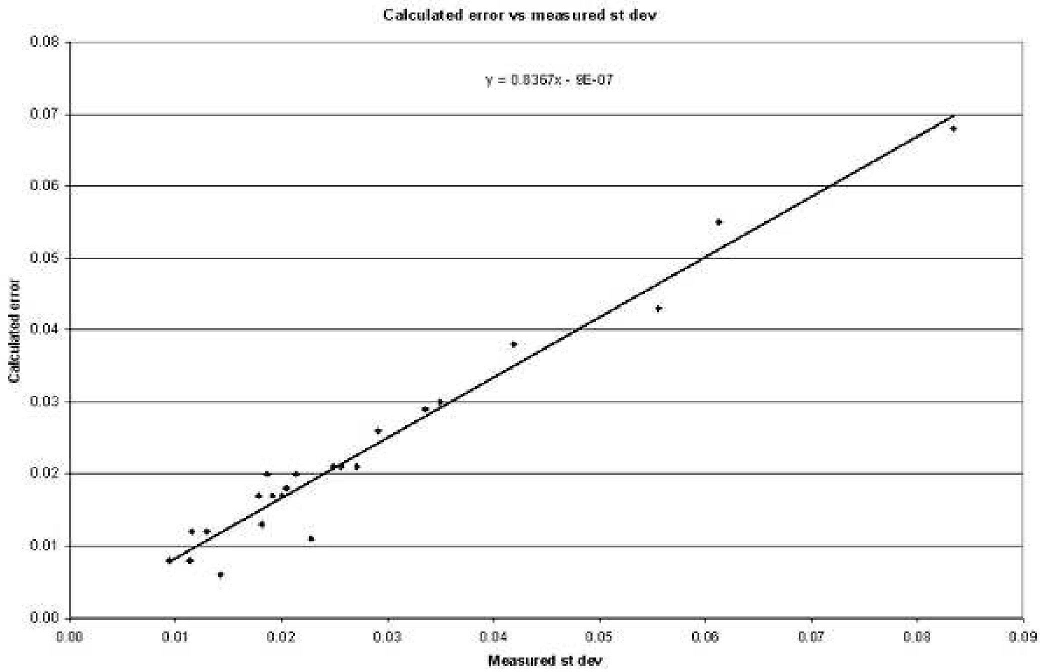


Fig 7: Calculated error vs standard deviation of measured K magnitude

photometric measurement of the magnitude of any star in an image by calculating the error using Howell's formula and multiplying it by a factor 1.2.

Howell S. B., Handbook of CCD Astronomy, pp 53-58, Cambridge University Press (2000)