Contrib. Astron. Obs. Skalnaté Pleso **35**, 35 – 44, (2005)

Photometry of the variable stars using CCD detectors

I. Photometric reduction.

Š. Parimucha[1], M. Vaňko[2]

[1] *Institute of Physics, Faculty of Natural Sciences, University of P.J. Šafárik, 040 01 Košice, The Slovak Republic (E-mail: parimuch@ta3.sk)*

[2] *Astronomical Institute of the Slovak Academy of Sciences 059 60 Tatranská Lomnica, The Slovak Republic, (E-mail: vanko@ta3.sk)*

Received: December 6, 2004; Accepted: February 11, 2005

Abstract. We discuss photometric calibration techniques of the CCD images using bias, dark and flat-field frames. Description and properties of the individual calibration images are given. Procedures for creating of high-precision master calibration frames are described.

Key words: photometry – CCD

1. Introduction

It is no doubt that CCD (*Charge-Coupled Device*) detectors have revolutionized astronomy and allowed observers to perform more precise photometric and/or astrometric observations, detect fainter objects and obtain data with higher signal to noise S/N ratios. CCDs are the most applayed detectors in the modern astronomical research. They are usually used to produce direct astronomical images (simple pictures of a region of the sky), which are subsequently analyzed.

The CCD was invented in 1969 by W.S. Boyle and G.E. Smith (Boyle & Smith, 1970) in the Bell Laboratory. They were investigating techniques for possible use in a "picture-phone", and were not directly interested in astronomical detectors. Indeed, most of the applications of CCDs are not astronomical. CCDs were first used in astronomy in 1976 when J. Janesick and B. Smith obtained images of Jupiter, Saturn and Uranus using a CCD detector attached to the 61-inch telescope on Mt. Bigelow in Arizona. CCD detectors were rapidly adopted in observational astronomy in the 1980's. The progress in technology in the last decade permits to create detectors with large arrays (with up to 10^9 individual pixels), which are sensitive in arbitrary passbands (from UV to infrared) and with high-speed electronics for data reading and storage. CCDs are now widespread, they are easily the most popular imaging devices used in astronomical research.

It is not the aim of this paper to describe a technical construction of the CCD chips and cameras and their properties. A detailed description of these equipments could be found in e.g., Sterken & Manfroid (1992), Martinez & Klotz (1998), Howell (2000) or in technical documentations of the specific cameras.

For our purpose, we will deem that CCD detectors are 2-D arrays, one face of which is sensitive to light. This array consists of n columns and m rows of the individual light detectors, called *pixels*. Pixels can collect incident photons and change them with some efficiency to electrons of which certain amount is transferred by camera electronics to the so called ADUs (Analog to Digital Units). These values are read from the camera to obtain a CCD image, which is stored in computer's memory for other analysis.

The great advantage of CCD detectors is their high quantum efficiency (see e.g., Howell, 2000), which enables us to use not only big telescopes in major observatories, but also small amateur's ones (with diameters up to 1m) for unique data collecting. This opens up many new opportunities in the astronomical research, e.g., a long-term monitoring of variable stars, search for new variable stars, search for novae and supernovae eruptions in other galaxies, search for Near Earth Asteroids and their photometry and astrometry, and many others.

CCD photometry is one of the opportunities where also small telescopes could be used for serious data mining (see e.g., Pribulla et al. 2003). High-precision photometric observations can be obtained in two different ways. The first one is using single or multichannel photoelectric photometers (see e.g., Henden & Kaitchuck, 1982, Sterken & Manfroid, 1992) and the second one by using CCD detectors. Observations and a data reduction are different in the both cases. A detailed comparison of advantages and drawbacks between single and multichannel photoelectric and CCD observations was given by e.g., Kjeldsen & Frandsen (1992).

Let us to summarize benefits of the photometry with CCD detectors as follows:

- all object are observed by the same detector and through the same filter
- photometry is performed in a small region of the sky, where atmospheric conditions are the same for all objects in the image and no corrections for atmospheric extinction have to be performed
- more than one or two comparison stars can be used at once
- sky background can be estimated directly near measured stars and contributions from other sources could be eliminated
- it is not very sensitive for small seeing variations, nor small tracking errors of the telescope and mechanical construction of the instrument (like e.g., the aperture diameter in a photomultiplier)

On the other hand, CCD photometry is very sensitive to a correct photometric calibration (see below). CCD detectors are also not good for the fast photometry with integration times less than one second because of relatively high noise. Some problems could originate from a rather small field of view of the camera, where sometimes not enough useful comparison stars could be found. The problem arise when comparison stars have significantly different colors than the studied one. In this case, we have to use a second order correction for atmospheric extinction, which complicates the straightforward reduction.

The main aim of this series of papers is to describe photometry using CCD detectors, image reduction and optimal photometry techniques for high signal to noise S/N measurements. This first paper deal with the photometric reduction of CCD images, which is essential for precise photometric results with a low noise level.

2. Calibration images

The image obtained by a CCD camera is affected by a number of instrumental effects, which must be corrected before reasonable results can be obtained. The image which is not yet corrected will be called a *raw image*. The raw image contains not only information about the object of interest, but also a contribution from the residual electrons in the individual pixels, electrons introduced by readout noise and thermally generated electrons. Sensitivity of the particular pixels could vary over the chip array and any nonuniformity affects measured intensities.

To obtain precise photometric results from CCD images, we have to perform so called *photometric reduction* of all used raw images. The process of standard CCD image reduction is based on the use of the set of three calibration images: the bias (or offset) frame, dark frame and flat-field frame. Their properties are described in the following sections.

2.1. Types of the calibration images

- **Bias frame** - the frame is exposed with an exposure time of zero seconds or with minimal time which is enabled by the camera. The shutter of the camera is closed during this exposure. The purpose of the bias frame is to determine the underlying noise level of each raw image. This noise is caused by precharge on CCD pixels and also by the readout noise of the camera.
- **Dark frame** - the frame is exposed with the closed shutter, usually with the same exposure time as the raw image. The dark frame measures the thermal noise (also called the dark, or thermal current) on the CCD chip during the exposure. The dark frame can also give information about bad or *hot* pixels on CCD chip (see Section 4) as well as an estimate of the cosmic rays strikes at the observing site.
- **Flat-field frame** - the frame is used for a correction of the pixel to pixel response variations as well as any nonuniform illumination of the CCD detector. Flat-field frames could be obtained by illumination of the CCD chip by constant and uniform light (e.g expose of the twilight sky, dome or projector

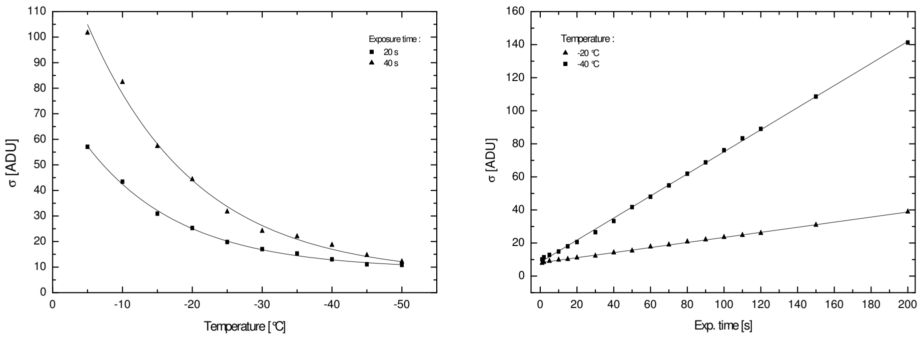

Figure 1. Temperature (top) and time (bottom) dependency of the dark frame standard error σ. Detailed description see in text.

lamp, see section 2.2.3) to provide a high S/N image. Flat-field frames are needed for each instrumental setup as well as for each color or wavelength region.

2.2. Properties of the calibration images

2.2.1. Bias frames

The precharge values on the CCD chip determined by the bias level should be constant within 1-2 % throughout all the pixels in the array of the CCD chip. This variations should remain also constant with time. The bias level is mainly affected by the construction of the readout electronics of the CCD camera, as well as by the properties of the chip material.

2.2.2. Dark frames

The dark frame determines the level of the thermal noise of the camera. It is affected by the properties of the chip material and by the dimensions of the individual pixels. If the dimension of the pixel is larger, the thermal noise is large too. Its level can be decreased by cooling of the CCD chip.

To assess temperature dependency of the dark current, we have obtained a set of test dark frames by the SBIG ST-10MXE camera mounted in the Newton focus of the 0.5m reflector at Stará Lesná Observatory of the Slovak Academy of Sciences (Pribulla & Chochol, 2003). For each temperature we have constructed a master dark frame (see section 2.3) and then calculated an average value of the all pixels and determined its standard deviation σ. Fig. 1 (left) shows the temperature dependency of the standard deviations of the dark frames for two different exposure times. It is clearly seen that the thermal noise decreases exponentially and for lower temperatures it is negligible and pixels values of the

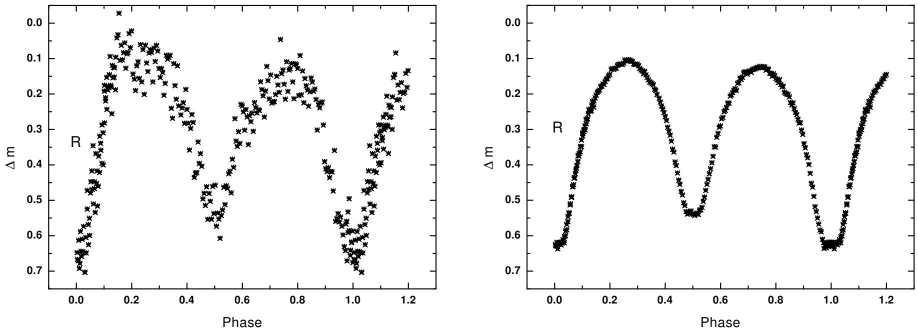

Figure 2. Resulting R light curve (FU Dra, Vaňko 2004) from images not corrected by flat-field (top) and after correction (bottom). Detailed description see in text.

dark frame are close to the bias level. Fig. 1 (right) shows a time dependency of the dark current for two different temperatures. The standard deviations σ were estimated by the same procedure as in the previous case. Dark current of the CCD chip linearly increases with time. Because of presented linearity of the dark current, dark frames for longer or shorter exposure times could be obtained by a simple scaling.

The dark frames also provide an estimate of the cosmic rays or strikes at the observing site. Cosmic ray strikes or events are caused in most cases by the background terrestrial radiation. When a cosmic ray particle hits a CCD chip, it increases charge in a pixel. Cosmic strikes are random events. To eliminate them, one has to use a master dark image (see Section 2.3).

2.2.3. Flat-field frames

Because of limitation of the current technology and the manufacturing process, the perfect CCD chips are not allowed. The sensitivity of the pixels vary slightly by few percent across a CCD chip. This pixel to pixel sensitivity variations also change with the wavelength of incident light.

This variations could be eliminated by flat-field frames. Flat-field frames are most important for a photometric reduction. Their importance is illustrated in Fig. 2. Left panel shows the resulting light curve in the R passband of the contact binary FU Dra before correction by flat-field frame. Relatively large scatter is visible. It is caused by a small drift of the stars on the image because of inaccuracy of the telescope mount. The stars are measured on different positions on the image and so different relative brightness is obtained because of pixel to pixel sensitivity. The right panel in Fig. 2 shows the light curve obtained from the same images after correction by flat field. The quality of the observations increased rapidly. More details about particular observations of this system can be found in Vaňko (2004).

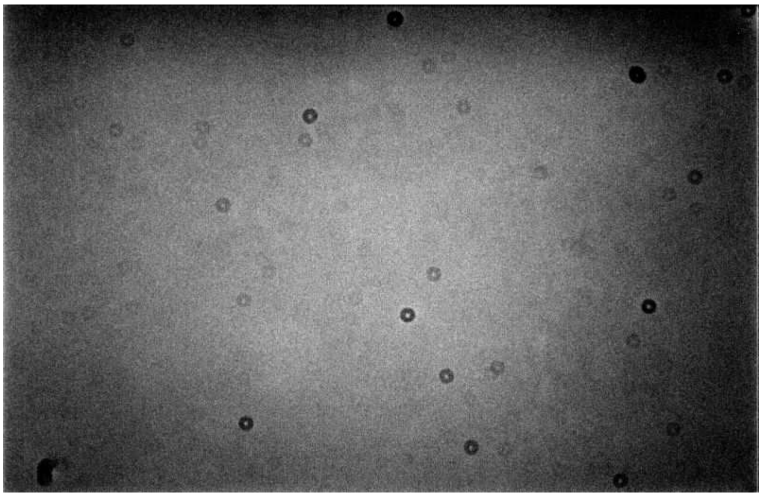

Figure 3. A typical master flat field frame. It also demonstrates other effect which could be corrected, such as dust particles and vignetting (see text).

A typical master flat field in R filter is shown in Fig. 3. It was obtained by the same instrument and procedures as dark frames in section 2.2.2.

The flat fielding procedure also corrects for several other effects: (i) dust particles on the CCD chip and filters, which are manifested by dark ring features on the image and they are the same on all exposures with the same filter, but obviously differ from filter to filter, and can differ from time to time, (ii) vignetting, the dimming of objects observed towards the edge of the telescope's field of view. It is caused by various out of focus obstructions in the light path, such as the support for the secondary mirror.

To obtain high quality flat field, one has to illuminate a CCD chip by uniform light. The source of uniform light could be: (i) the telescope dome, illuminated by a bright continuum source free of emission lines or (ii) the sky during twilight, when it is relatively bright. The flat fields in the dome can be taken in unlimited numbers during the day, rather than during twilight when one has not enough time. But they have two disadvantages. The first one is due to a different angle of the scattered incident light from the dome and the light from the sky. It doesn't affect pixel to pixel sensitivity variations but could affect vignetting and the shape of the dust grains images. The second problem arises from a different color of the light source and the color of the twilight sky. This is important for observations made in broad band filters (typically $UBVRI$). The sky flat fields are exposed during twilights close after sunset or before sunrise. The sky has to be brighter than stars and faint enough to saturate the detector. The optimal time depends on the telescope configuration as well as on used filters and spectral response of the CCD detector. It is necessary to turn off the mount of the telescope because of stars images on the frames.

To create flat field as good as possible one can combine flat fields obtained in the dome and the sky flat fields. The first correct pixel to pixel sensitivity and the second are useful for vignetting.

2.3. Master calibration images

In practice, if we want to perform photometric reduction of the large set of raw CCD images, we have to create so called *master* calibration images. They could be created by average, or better by median of a large number of calibration images (more than ~ 50)

$$l_c(x,y) = \text{med } L_c(x,y), \tag{1}$$

where $L_c(x,y)$ is the set of the individual calibration images (bias, dark or flat-field) and $l_c(x,y)$ is the resulting master calibration image (bias, dark or flat-field). This images are used in subsequent photometric reduction (see Section 3) .

Median calculation of the calibrations frames can eliminate cosmic ray hits or changes caused by instability of the exposure time, and it can eliminate stars images on particular flat fields as well.

3. Photometric reduction of the CCD images

Let us denote the total intensity $I(x,y,t,T)$ (in ADUs) of the raw image measured at the pixel with coordinates (x,y) with exposure time t and temperature of the CCD chip T. The individual contributions to the total intensity $I(x,y,t,T)$ on the CCD frame are shown in Fig. 4. It could generally be written

$$I(x,y,t,T) = b(x,y,T) + d(x,y,t,T) + i(x,y,t,T)f(x,y,t_f,T), \tag{2}$$

where $b(x,y,T)$ is the intensity of the bias image, $d(x,y,t,T)$ is the intensity introduced by the dark current, $i(x,y,t,T)$ is the real intensity of the object at the pixel (x,y) and $f(x,y,t_f,T)$ is the response factor from the flat-field, which was obtained with the exposure time t_f.

As one can see from equation (2), all intensities are depended on temperature T. As it was mentioned in Section 2.2.2, the thermal noise exponentially decreases, so it is useful to cool down a CCD chip to as low temperature as it is possible. To eliminate severity of the reduction process, it is convenient to take all images with the same temperature.

Since we are looking to extract $i(x,y,t,T)$ quantity from the raw image, the relation (2) becomes (ignoring temperature dependency)

$$i(x,y,t) = \frac{I(x,y,t) - b(x,y) - d(x,y,t)}{f(x,y,t_f)}. \tag{3}$$

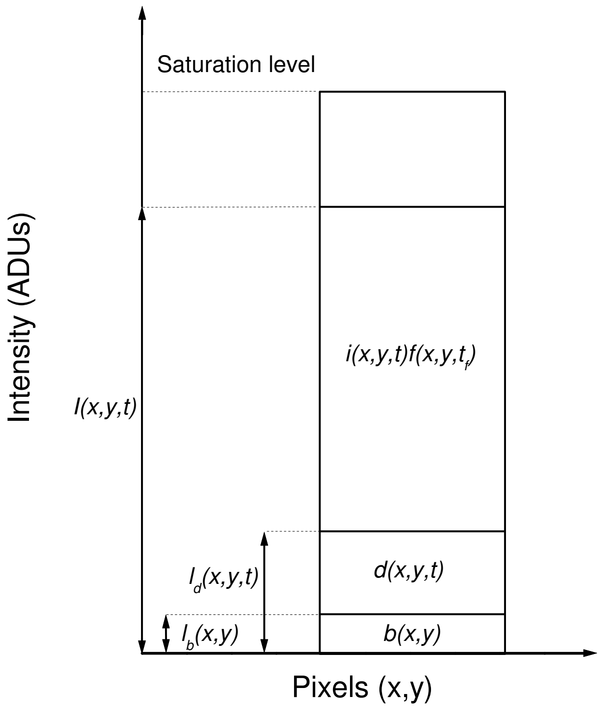

Figure 4. The contributions to the total intensity $I(x, y, t, T)$ on CCD frame. For a description of used terms see the text.

From the bias image, we have directly intensity value $l_b(x, y) = b(x, y)$. But intensity measured from the dark frame $l_d(x, y, t)$ contains also the bias value, so $l_d(x, y, t) = l_b(x, y) + d(x, y, t)$ (see Fig. 4).

If we want to know the response factor $f(x, y, t_f, T)$ of the CCD detector, we have to illuminate it by constant and uniform light (see Section 2.2.3). Then from equation (2) we have for the intensity of the flat-field l_f

$$l_f(x, y, t_f) = b(x, y) + d(x, y, t_f) + f(x, y, t_f) \times \text{const.} \tag{4}$$

If we take flat-field with an exposure time sufficiently short, we can ignore thermal contribution $d(x, y, t_f)$ and we can rewrite equation (3) as:

$$i(x, y, t) = \frac{I(x, y, t) - l_d(x, y, t)}{l_f(x, y, t_f) - l_b(x, y)} \times \text{const.} \tag{5}$$

This relation describes photometric reduction of the one individual CCD frame. In reduction process, we have to in the first step create master calibration images (see Section 2.3). From the raw frame we have to subtract the master dark frame and the resulting frame we have to divide by the master flat field, from which we have subtracted master bias frame.

4. Cosmetic corrections

Cosmetic corrections are often neglected in photometric reduction of raw images. But cosmetic effects, like bad pixels, hot pixels, or dead columns, can strongly affect correct flux estimates.

Bad pixels are individual pixels which are not sensitive to incident photons. On the other hand, hot pixels are individual pixels with a high dark current. The dead columns are columns on a CCD array which are not sensitive to incident light. The bad and hot pixels as well as dead columns, are persistent and occur at fixed positions on a CCD detector. They can be eliminated by estimation of the correct pixels values from surrounding pixels on the same image. This could be done by the average or median of optional number of pixels around the hot one, the best of all surrounding 8 pixels.

The accurate positions of bad and/or hot pixels could be found from dark frames. We can also create a special reduction image with the position of all bad pixels.

5. Conclusion

This paper is the first one in a series of papers which deal with photometry of variable stars obtained using CCD detectors. It describes photometric reduction techniques necessary for precise photometric results.

Photometric reduction of the CCD frames is done through the set of calibration images. It was pointed out that the most important calibration image is a flat field frame. It aligns nonuniform sensitivity of the pixels and corrects effects caused by nonuniform illumination and dust particles on the detector. These changes are color dependent, so it is necessary to create flat field for each filter in use. The best flat fields could be produced by a combination of the sky and dome flat fields. The former are useful for correction of the vignetting and the latter for pixel to pixel sensitivity.

The level of the thermal noise is eliminated by dark frames. During a reduction process one has to use a dark frame with the same exposure time as a reduced image. Because of presented linearity of CCD detectors, it is possible to create one long-exposure master dark frame. This could be used for reduction of the images with different exposure times by simple scaling to used exposure time.

Acknowledgements. This work was supported by VEGA Grant 4014 of the Slovak Academy of Sciences, grant APVT 20-014402 and grant No. VVGS/005/2004/F of University of P. J. Šafárik. The authors would like to thank Dr. Pribulla for suggestive comments and D. Božik for assistance during necessary observations.

References

Boyle, W.S., Smith G.E.: 1970, *Bell Syst. Tech. J.* **49**, 587

Henden, A.A., Kaitchuck, R.H.: 1982, *Astronomical Photometry*, Van Nostrand Reinhold Company, New York

Howell, S.B.: 2000, *Handbook of CCD Astronomy*, Cambridge University Press, Cambridge

Kjeldsen, H., Frandsen, S.: 1992, *Publ. Astron. Soc. Pac.* **104**, 413

Martinez, P., Klotz, A.: 1998, *A Practical Guide to CCD Astronomy*, Cambridge University Press, Cambridge

Pribulla, T., Chochol, D.: 2003, *Baltic Astronomy* **12**, 555

Pribulla, T, Parimucha, Š., Chochol, D., Vaňko, M.: 2003, *Inf. Bull. Variable Stars* **5414**

Sterken, C., Manfroid, J.: 1992, *Astronomical Photometry - A Guide*, Kluwer Academic Publishers, Dordrecht

Vaňko, M.: 2004, *PhD Thesis*, (in Slovak)