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Correction of Systematic Errors in Differential Photometry

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Abstract. A common cause of errors in CCD differential photometry is an improper calibration of the array. The importance of these errors is evaluated for different cameras with fields between 3 and 30 arcminutes. The usual superflat illumination corrections based on night sky exposures are often found to be unsatisfactory. "Photometric superflats" based on stellar measurements are more reliable and should be used instead.

1. Introduction

Differential photometry performed within a single CCD field can lead to very good accuracy. However, the imperfect nature of the flat-field calibrations results in spatially dependent errors which show up as zeropoint shifts, or time variations if the stars are not centered on the same pixels in every frame. Depending on the centering procedure, the resulting errors may thus seem to be either random or systematic, space or time dependent.

The same problems arise in non-differential photometry but they are more difficult to detect because the exposures are generally isolated, and there are additional sources of error. Moreover, the calibration errors partly cancel out when computing colour indices, so colour diagrams are largely unaffected.

2. Superflat Correction of Data

An example of space-dependent calibration errors combined with poor centering is shown in Figure 1, where the differential V photometry for three stars in a single field is plotted as a function of the position on the detector. The observations were made with the University of Bochum 0.6 m telescope at ESO providing a field of $3\farcm2 \times 4\farcm8$.

Clearly, the stars suffer from large space-dependent errors that can be traced to the flat-field calibration. As a consequence, some stars exhibit large time variations (see the light curve of star b in Figure 2). These variations are quite different from star to star. It is difficult for the observer to detect a systematic pattern and, hence, to suspect an instrumental effect.

Dithered observations bring the opportunity to correct the errors. Given a sufficiently large number of stars, diagrams similar to the upper ones of Figure 1 can yield a rough estimate of the 2D illumination correction. A more efficient procedure has been described by Manfroid (1995, 1996). Several improvements have been brought, making the method more robust. Independent fields, hence

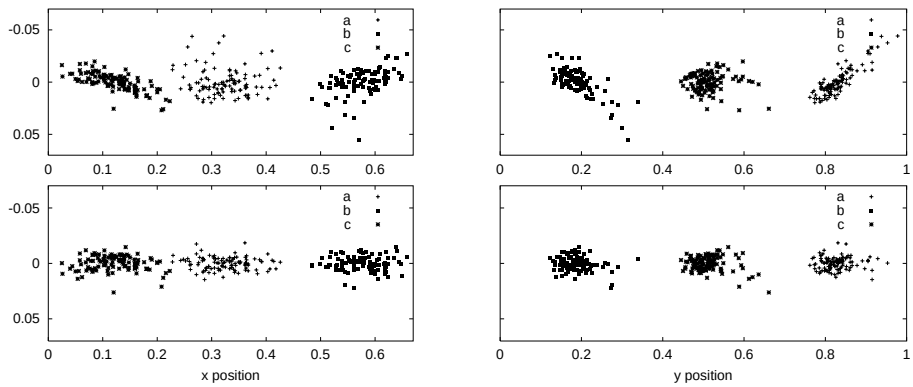

Figure 1. Differential V photometry as a function of the position on the CCD for three stars in a field observed with the University of Bochum 0.6m telescope at the ESO La Silla observatory. The reference is computed from the median of the other stars in the frame. The upper panel shows uncorrected data, i.e., only submitted to the usual flat-field calibration. The stars are brightest towards the edges of the CCD. The lower panel shows data corrected with a proper photometric calibration.

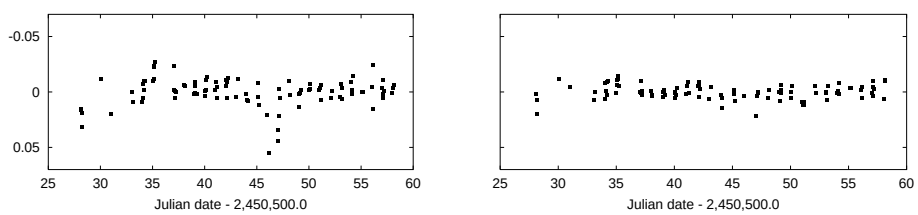

Figure 2. Time variations of star b of Figure 1 before and after calibration.

groups of nights, can be treated at once. A first-order correction of the extinction is included. This is necessary at high air masses and/or in the case of wide field cameras.

The procedure yields a purely photometric calibration which shall be called hereafter the "photometric superflat". It has exactly the same purpose as the superflat obtained from a median of night sky frames.

The photometric superflat has been computed for the Bochum data, by analyzing 67 stars and 106 frames. The data have then been submitted to this illumination correction. The new light curve of star b no longer shows spurious large-amplitude variations (Figure 2, right).

Profiles of the photometric and night-sky superflats for the Bochum telescope data are shown in the first panel of Figure 3. They give opposite results. Obviously, the night-sky superflat technique degrades the data. Without superflat correction, the stars at the edge of the CCD are too bright by about 0.05 mag relative to the stars close to the center, while the sky background shows an opposite pattern. With the night-sky superflat, the sky background is forced to

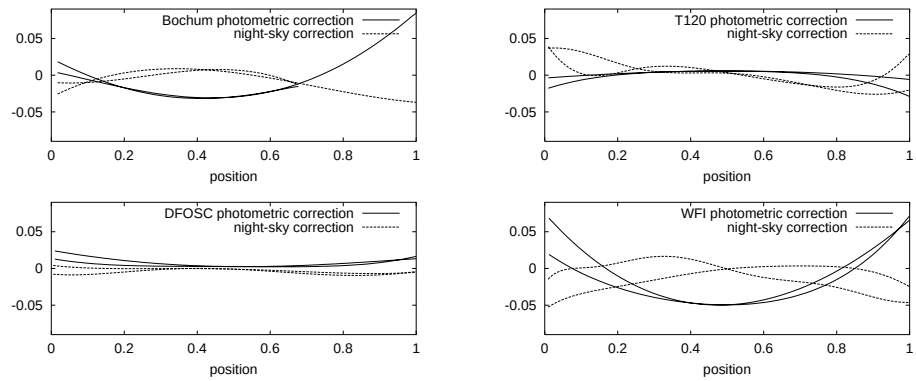

Figure 3. Central profiles (in RA and declination) of both superflat corrections relative to the observations obtained at various telescopes (in magnitude units). The photometric superflats were computed as 4th-order 2D polynomials. The two corrections yield contradictory results, i.e., the sky superflat increases the calibration errors.

be uniform, but the brightness of the outer stars is further enhanced relative to that of the central stars. The correct photometric calibration of the Bochum data gives an *uneven background,* which is brighter by about 0.10 mag at the center. The quality of the calibration can not be judged from the uniformity of the sky background.

Similar conclusions are obtained for other telescopes (Figure 3): the Haute Provence Observatory T120 telescope (field 12′), the ESO 1.54m telescope with the DFOSC camera (13′) and the ESO 2.2m with the WFI mosaic (32′). DFOSC shows the smallest errors, followed by the T120 telescope. The night sky superflat correction mainly corrupts the northern and southern edges of the field at the T120 telescope.

Figure 4 shows the residuals for hundreds of stars observed in I and V with the WFI, plotted along the CCD columns. Data reduced with (i) dome flats only, (ii) dome + night sky superflats and (iii) dome + photometric superflats are compared. Again, the night-sky superflats are seen to degrade the results, in accordance with the calibrations shown in Figure 3. Differential data computed between widely separated stars can show errors of up to about 0.1 mag when a night-sky superflat correction is applied. In the same conditions, CM diagrams over wide fields would show an instrumental effect (increased dispersion) of the same order of magnitude.

Despite its wide field, most of the area of the WFI mosaic can be calibrated within 0.01 mag using a relatively smooth correction (the very edges (40″) must be excluded because of sharp variations). However, when a better accuracy is needed, a higher-order analytic function is needed (see Figure 4, rightmost lower panel in V).

Larger errors were noticed at the 4.2m WHT telescope at La Palma, with a CCD camera using narrow band filters (see Royer et al. 1998). The central stars were too faint by more than 0.20 mag. Such large variations probably had their origin in the design of the camera: unfiltered *white*light reached the detector. In

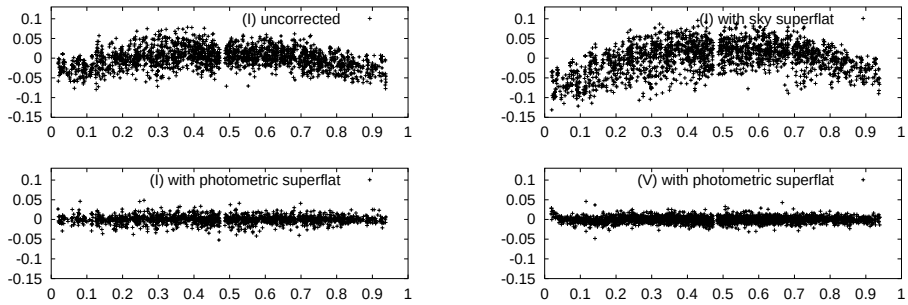

Figure 4. Observed deviations from the average I magnitude as a function of the (relative) row number for the WFI mosaic. The exposures have been calibrated using dome flat fields. Without further corrections (upper left panel) the rms scatter is 0.024 mag. In the upper right panel, a night-sky superflat correction has been included—obviously degrading the data (0.036 mag rms). In the lower left panel, a photometric superflat is used instead, and the deviations are much lower (0.009 mag rms). The plots combine data relative to 2000 I band observations of 400 stars measured on 34 exposures, in 7 distinct fields. Photometrically corrected data for the V band are shown in the lower right panel. The rms is lower than in I (0.007) and it can still be improved by using higher-order functions.

such a case, the high-frequency component of the original flat-field calibration is wrong. The photometric superflat calibration can only correct the large-scale variations.

3. Discussion

The large magnitude of the errors discussed here should be a cause of concern, in differential and non-differential photometry. The background of astronomical images includes an important, non-uniform, component of unfocused (scattered or reflected) light and should not be used to provide the long-wavelength component of the flat-field calibration. In particular, the illumination correction based on median sky frames appears to be quite unreliable. Comparison (Figure 4) of photometrically corrected data and data processed in a more conventional manner shows that a much better calibration can be achieved simply through the use of appropriate software. Additional effects such as geometric distortion are simultaneously corrected. Moreover, the use of this method relaxes the constraint on the flat field acquisition.

References

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