Correcting spatial gradients:

The case of Wide Field Imager photometry

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We present a method to significantly reduce large-scale photometric variations seriously affecting imaging data from the Wide Field Imager (WFI). The primary source for these gradients is non-uniform illumination, which cannot be corrected by standard flatfielding techniques. Comparison of our observations with well-calibrated multi-colour photometry from the SDSS enabled us to characterize and quantify these variations and finally to model them using a second-order polynomial. Application of the model to our observations and an independent dataset consistently reduced the large-scale gradients and thus provides a generally valid and simple tool for improving WFI photometry.

Any astronomical imaging system is affected by intrinsic and external effects, which limit the quality of the resulting data. In this vein, modern CCDs exhibit, e.g., small-scale variations in quantum efficiency. However, such intrinsic shortcomings are generally corrected during the flatfielding process. Yet several large-scale effects may vary with time and pointing and are more difficult to treat. For instance, stray light can hardly be avoided in complex optical instruments, leading to a non-uniform illumination of both flatfield and science exposures.

ESO's Wide Field Imager (WFI) has repeatedly been reported to exhibit significant large-scale spatial gradients in photometry across each of its eight individual CCD chips and particularly over the entire mosaic's field of view (e.g., Manfroid et al. 2001).

An assessment of presence and magnitude of such variations requires the comparison of a well-sampled observational dataset against a photometrically calibrated standard sample. Since the general method of taking exposures of a small number of standard stars (e.g., Landolt fields) on each of the single CCDs is rather time consuming, it is much more efficient to calibrate observational data against well-defined datasets with comparable or even larger spatial coverage.

For the purpose of the present work, we benefited from the fact that all of our observed fields coincide with the area surveyed by the Sloan Digital Sky Survey (SDSS, Stoughton et al. 2002, Abazajian et al. 2003). The high accuracy and homogeneity of the multi-colour photometry from the SDSS and its general availability enabled us for the first time to directly calibrate WFI photometry against a dense grid of local quasi-standard stars and thus to thoroughly correct the emerging large-scale gradients on the science frames. For a detailed technical description of our method the reader is referred to Koch et al. (2004).

Primary data

In an imaging run in May 2001 we used the WFI to target three different fields in and around the globular cluster Palomar 5. These data aim at analyzing the luminosity function in the cluster and its tidal tails (Odenkirchen et al. 2001, 2003) and are subject to a subsequent paper (Koch et al. in prep., Koch 2003). For the purpose of this instrumental note, the exact location of the fields is irrelevant, as long as there is an overlap with the SDSS and the regions are not exceedingly highly crowded.

Observations were carried out both in the *V* and *R* filter, where each field was exposed five times (900s for the *V*-, 600s in the case of the *R*-band). Single exposures were dithered against each other to cover the gaps between adjacent CCD chips. The observations were performed under good conditions, with the seeing ranging from 0.7″ to 1.1″, and an average airmass of 1.2.

For a description of the standard reduction steps we refer the reader to Koch et al. (2004); for the time being it should suffice to say that all steps were carried out for each of the CCD chips separately. For our case of twilight flatfield corrections this means that a mean value for each chip was determined to normalize the flatfield to unity, hence preserving the gain differences between individual CCDs. Finally, aperture photometry was carried out using DoPHOT.

Photometric gradients

Since the observed fields in Palomar 5 coincide with the equatorial stripe of the SDSS, we matched the stars on each single WFI exposure by position against the SDSS database. Constraining the magnitude range to 16.3 mag $< r <$ 21.7 mag[1] in order to avoid saturated objects and larger photometric errors, this procedure yielded approximately 200 common objects per CCD chip, filter and field.

In the next step, linear transformations of the kind $R = R(r,g,i)$ and $V = V(g,r)$ were used to compare our instrumental WFI magnitudes *V* and *R* to the quasi-standard photometric *ugriz*-system of the SDSS.

The residuals e of the transformation for the case of the *R*-filter are shown in Figure 1 (top left) versus vertical position on the CCD. In this plot the distribution of residuals is not flat across the camera or on the CCDs, but instead the gaps and parabolic gradients appear distinctly. The overall

[1]Lowercase letters denote SDSS magnitudes (Smith et al. 2002)

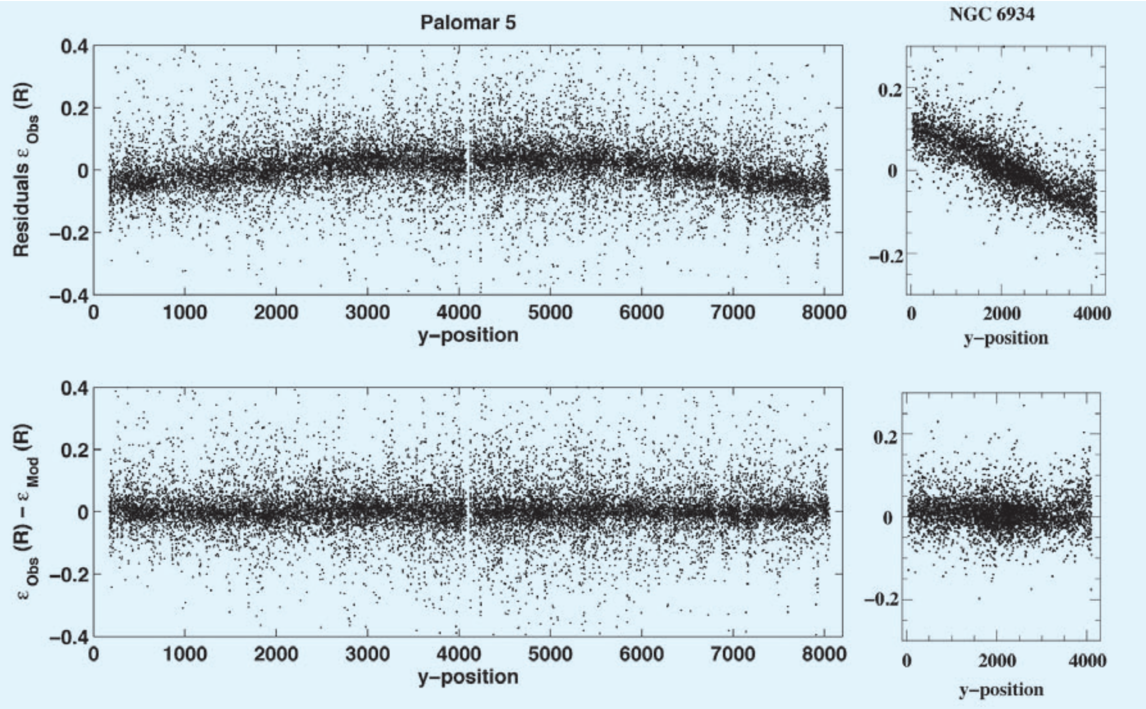


Figure 1: Top left panel: Residuals ε (in mag) of the transformation between WFI and SDSS magnitudes for the case of the *R*-filter. The coordinate system is such that the origin is at the bottom left corner of the camera, the axes (in pixels) increasing from bottom to top (y) and left to right (x). The bottom right panel shows the residuals after the calibration model (eq. 1) was subtracted. The right panels display similar results for independent data for the globular cluster NGC 6934.

observational scatter of these residuals is approximately 0.08 mag on each chip and the zeropoint differences reach values of 0.19 mag. Likewise there is a similarly strong variation with x-position and also for the *V*-filter.

A model for the gradients

The output data from all exposures on each chip were now combined to build an extensive dataset with excellent spatial sampling. Thus the number of stars to be used in the subsequent analysis amounts to ca. 2200 per CCD, or 17754 for the whole camera mosaic.

Judging from the shape of the curves in Fig. 1, a low-order polynomial appears to be suited to model the variation of residuals with position (x,y) on each CCD. Hence we performed a weighted least squares fit of a function

$$\varepsilon(x,y) = Ax^2 + By^2 + Cxy + Dx + Ey + F \quad (1)$$

to the observed residuals.

The actual values for the model coefficients *A*-*F* can be found at http://www.astro.unibas.ch/~koch/#WFI and also in Koch et al. (2004).

To estimate the pure global properties of the overall variations, we then removed the intensity level offsets that were introduced by the individual flatfielding of each chip. This was achieved by calculating a mean value of the residuals and adjusting it to fit each adjacent CCD. These additive additional zeropoints are of the same order of magnitude as the fit constants *F* in eq. (1).

Figure 2 displays contour maps of the final offset-corrected model map according to eq. (1). The resulting photometric variations reach peak-to-valley amplitudes of 0.19 mag both in *V* and *R*.

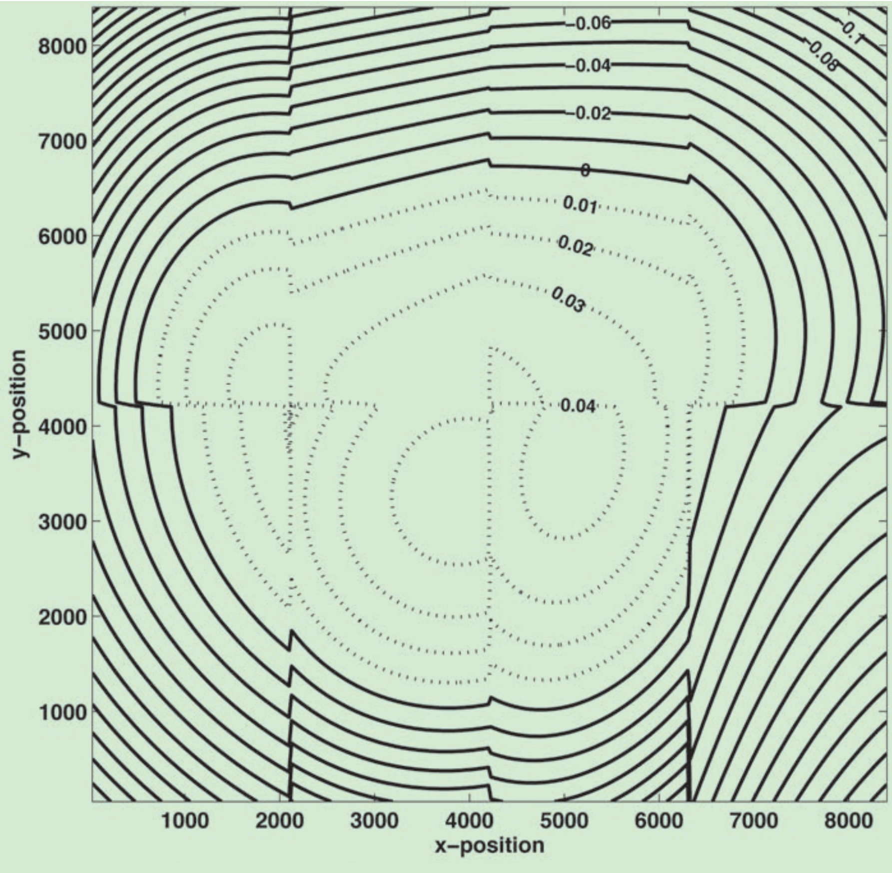
Apart from the overall similar appearance of the maps for the *V* and *R* filters, we point out that the *V*-band residuals show a more central concentration than those on the *R* map. An additional difference is the salient feature on the two leftmost CCDs in the case of the *V* map: there is a band of higher brightness along the vertical axis. This well-known problem arises from stray light due to bright stars that are reflected from the tracker CCD (located left of the camera) onto the science mosaic.

In the final step, the model correction terms were subtracted from the observed residuals. The resulting post-fit residuals are plotted in the bottom left panel of Fig. 1. As an essential outcome, there is a considerable flattening of the large-scale structure, suggesting that our correction method is a successful tool for significantly reducing gradients. Moreover, after the subtraction, the overall scatter was reduced to 0.06 mag. One should note that the *V*-correction, though not shown here, shows similarly good results in terms of reduced scatter and gradients (cf. Koch et al. 2004). Yet there are still some slight variations remaining, in particular at the very edges, where our model was extrapolated instead of being determined in the fit.

Independent test by complementary data

In order to ensure that our correction coefficients are not limited to correcting only our own data, from which they were calculated, but also are suited to calibrate datasets from different runs, we applied it to photometric data of the globular cluster NGC 6934. These observations were obtained at La Silla in September 2000, also both in *V* and *R*. Contrary to the processing of our Pal 5 data, the flatfielding here was performed on the entire camera simultaneously, thus normalizing all CCDs of the entire mosaic to a common gain. This way, initial zeropoint offsets between single chips are removed when dividing by the flatfield.

The photometric gradients from this analysis are shown in the right panel of Fig. 2: The upper right plot displays the difference of stars measured on the lower CCD panel (chips #54 to #57) and those of the same stars located on the upper CCD panel (#50 to #53) of an exposure dithered by one chip size in y-direction (~16′). Also in this case there is a strong spatial dependence of the photometry to be seen. After subtraction of our calibration terms both the overall scatter and gradients were visibly reduced (bottom right panel of Fig. 2). Here, the r.m.s.



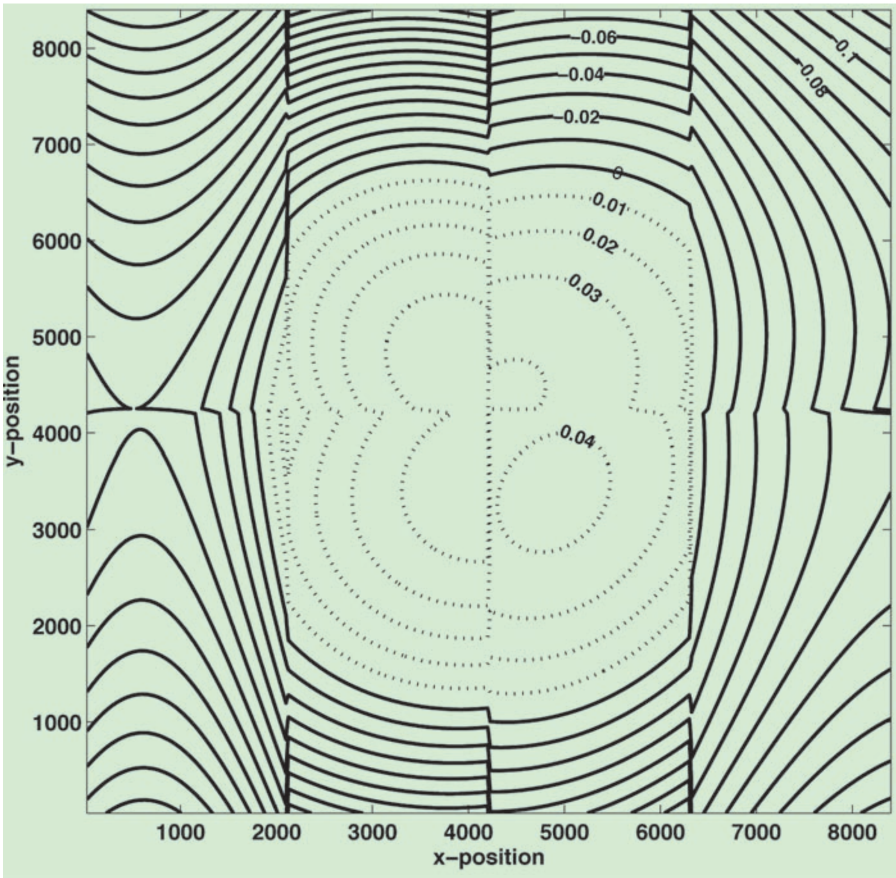


Figure 2: Best-fit second-order calibration map after removal of the mean offsets that arose from different flatfield scale factors. The map for the R-band is on the left, the right panel shows the correction map for the V filter. Contours are separated by 0.01 mag. Near the centre of the camera, stars are measured fainter than near the edge.

scatter diminuished from 0.07 mag to 0.04 mag.

Benefits and caveats of the model

Previous attempts have been made to calibrate WFI photometry, each pursuing different methods. Among these are the use of superflats, the construction of calibration maps via exposures that are shifted with respect to each other, or determining the calibration by means of "standard" stars (Landolt, Stetson or others) observed on each of the CCD chips. All these methods have their individual advantages and disadvantages. The most common drawbacks are, however, that the number of standard stars is generally small and/or the required number of exposures is large, making these calibration methods rather time consuming.

Considering the entirely separate observations and reductions of the NGC 6934 dataset, it is encouraging that our devised method yields such a good result in terms of strongly reduced gradients. This is a reliable indication that it can be generally applied to other WFI datasets to correct for these common large-scale variations. One should note, however, that it can only be considered as generally valid if there is no significant change in the optical setup of the telescope. In this vein, the coefficients cannot, e.g., correct data from the last quarter of 2002, where a major baffle re-engineering was performed at the 2.2 m telescope.

Yet, we encourage WFI users to apply our coefficients to their respective datasets, or, in turn, benefit from excellent databases provided by the publicly available multicolour driftscan surveys like the SDSS to pursue similar calibrations to correct large-scale illumination effects.

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