# On the Photometric Calibration of FORS2 and the Sloan Digital Sky Survey

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**An accurate absolute calibration of photometric data to place them on a standard magnitude scale is very important for many science goals. Absolute calibration requires the observation of photometric standard stars and analysis of the observations with an appropriate photometric model including all relevant effects. In the FORS Absolute Photometry (FAP) project, we have developed a standard star observing strategy and modelling procedure that enables calibration of science target photometry to better than 3% accuracy on photometrically stable nights given sufficient signal-to-noise. In the application of this photometric modelling to large photometric databases, we have investigated the Sloan Digital Sky Survey (SDSS) and found systematic trends in the published photometric data. The amplitudes of these trends are similar to the reported typical precision (~ 1% and ~ 2%) of the SDSS photometry in the *griz*- and *u*-bands, respectively.**

## The general photometric calibration problem

Calibration of science target photometry consists of fitting an appropriate photometric model (e.g., zero-point, extinction and colour coefficients, etc.) to the calibration data (standard star observations) and then using the photometric model parameters to derive the photometric corrections that should be applied to the science observations. Sometimes it is convenient to split the calibration problem into an absolute calibration (i.e. knowledge of fluxes in physical units such as J $m^{-2}$ $s^{-1}$) and a relative calibration (where all observations are calibrated to the same instrumental flux scale). This splitting is necessary since an accurate absolute calibration is substantially more challenging to achieve than a precise relative calibration due to the inherent difficulties in minimising the systematic uncertainties between the spectral energy distribution of appropriate (and usually very bright) photometric standards and the natural photometric system of the observations.

## FORS2 photometry

With the Very Large Telescope (VLT) FORS2 instrument, we aim to provide the user with the possibility, given sufficient science target signal-to-noise (S/N), of performing an absolute calibration of their photometry to an accuracy of better than 3% on photometrically stable nights. This is a challenging problem both in terms of collecting appropriate standard star observations as well as with regards to modelling the standard star photometry.

The photometric model should not only account for a photometric zero-point, nightly extinction coefficients and colour terms to convert from the standard filter wavebands to the instrumental wavebands, but should also potentially include terms to model the static and rotating residual flatfield patterns (Freudling et al., 2007; Moehler et al., 2010). The latter effect was found to be caused by the linear atmospheric dispersion compensator (LADC) and was worst for the LADC used with the now retired FORS1 instrument. The LADC used with FORS2, however, shows mainly a gradient (of amplitude 1.5% peak-to-valley) instead of a complicated pattern. The necessity for a photometric model to account for all these effects leads to requirements for non-trivial modelling software. Furthermore, the standard star observations need to be designed to provide plenty of photometric measurements over sufficient ranges in airmass, time, colour, spatial coordinates and rotator angles during photometrically stable nights.

## Simulated FORS2 observations

To understand how to provide calibrations that allow better than 3% absolute photometric accuracy with FORS2, we performed extensive simulations and modelling of standard star observations in order to identify the minimum requirements for a certain photometric precision. To each simulation realisation, we fitted a photometric model that analyses a large number of nights of data simultaneously. For this purpose, we developed a general IDL program[1] to perform photometric modelling, including both absolute and relative photometric calibrations. This software allows the user to fit any linear photometric model (i.e. any sum of photometric terms) to a set of magnitude measurements. The main results from our modelling of the simulated data are the following:

1) To achieve ~ 1% precision for the photometric zero-point, two standard star images per night should be obtained at airmasses of ~ 1.1 and 1.8, ensuring a range in airmass of ~ 0.6–0.7, and at least 18 photometric nights should be included in the photometric model to be fitted. This result is based on the assumption that the extinction coefficient is stable for the time period over which the standard star images are observed on any one night.
2) Observations coupled with modelling that satisfies the constraints described above should enable the atmospheric extinction coefficient to be determined to a precision of ~ 6–8%.
3) The FAP project goal, to allow the user to reach an absolute photometric accuracy of 3% during photometric nights, may be achieved by following the constraints described above, which lead to the ability to reach absolute photometric accuracies of 1.4–1.8% (given sufficient science target S/N).
4) Once two standard star images at airmasses of ~ 1.1 and 1.8 have been obtained, further images at intermediate airmasses have little impact on the precision of the monitoring of the photometric zero-point and the extinction coefficient for the night in question, but will be needed to monitor the photometric stability of the night.

Comparing the requirements defined by these simulations to the calibration plan we found that:

a) The standard star fields for each month did not provide calibrating stars with a sufficiently wide and homogeneous range of colours.
b) The calibration plan needs to include standard star observations at both

high and low airmass to allow a correct judgement of the photometric quality at the start of the night (as opposed to an observation of just one standard star field near zenith).

c) In order to judge the photometric quality based on a single observation, the extinction derived assuming a well-determined instrumental zero-point should be used, as opposed to deriving a zero-point from an average extinction (which shows a correlation with airmass if the true extinction differs from the average extinction).

## New calibration plan

Triggered by these findings, we changed the FORS2 imaging calibration plan. At the beginning of every night without visible clouds, one standard star field near zenith is observed. If the extinction coefficient derived from this observation (using the latest best estimate of the zero-point) is consistent with the extinction coefficient limits for a photometric night, then a second standard star field at high airmass is observed immediately afterwards to verify the stability of the extinction coefficient. If both observations yield the same extinction coefficient, then the night is declared to be photometric. If science data requiring photometric conditions are observed in service mode, then additional standard stars have to be taken at the middle and at the end of the night to allow monitoring of the photometric stability of the night.

The standard star fields are observed with offsets in position and rotation angle to allow the presence of static and rotating residual flatfield patterns to be investigated. After problems experienced with some of the Stetson standard star fields (Stetson, 2000) due to a lack of stars, we carefully selected a new set of Stetson fields that primarily satisfy the airmass constraints in the new calibration plan, and that are further optimised for the number of standard stars that are observed along with the colour range that is achieved.

The new FORS2 calibration plan (including the new standard star fields) was put into operation on 24 October 2011, and compliance was carefully monitored. The new calibration plan is now followed in about 75 % of the nights where it is applicable (i.e. potentially photometric nights). Most of the potentially photometric nights during which it is not fully followed are nights in which FORS2 is used for only part of the night.

## Fit of photometric model for FORS2

With the new calibration plan in place, a sufficiently large dataset is routinely collected to fit our photometric model. The FORS2 pipeline provides two recipes for that purpose, called fors_zeropoint and fors_photometry. The former identifies standard stars with catalogued magnitudes in each frame, and performs aperture photometry. The latter fits our model to the data of several nights, and computes, in addition to a number of nuisance parameters (*viz*. model parameters which need fitting but whose values we are not interested in, which in this case are the true instrumental object magnitudes), a single zero-point for these nights and an extinction coefficient for each night.

To obtain reliable results, several improvements had to be made to the recipes, the parameters to run those recipes, and the data distributed with the recipes[2]. Specifically, the following changes were made:

1) We found that the automatic identification of standard stars by the FORS2 pipeline recipe fors_zeropoint was not robust, sometimes resulting in misidentifications that can cause incorrect extinction coefficients to be derived. We replaced the original pattern-matching algorithm used in this recipe with a robust algorithm that identifies the shift between the standard stars in the catalogue and the detected objects in the image by building up a histogram of all possible shifts between the standard stars and the detected objects and finding the histogram peak (which is very pronounced for ≥ 4 standard stars in the field). Although this algorithm can only cope with very small rotations (≤ 0.3 deg), this is not a problem because rotations in the FORS2 world coordinate system (WCS) are extremely rare.
2) Up until December 2011, the September 2007 version of the Stetson catalogue of standard stars was used by the FORS2 pipeline. A newer version is available (December 2010[3]) which contains *BVRI* photometry of a larger number of stars in fields that are part of the calibration plan and increases the coverage in very sparse fields by up to a factor of three. Hence we adopted this newer standard star catalogue.
3) The FORS2 pipeline recipe fors_zeropoint uses SExtractor (Bertin & Arnouts, 1996) to perform the background subtraction and measure the standard star flux. The settings used as default values were optimised for the Landolt catalogue (Landolt, 1992) that was originally used and which contains a few bright, isolated stars, whose catalogued magnitudes were measured with classical aperture photometry. The detection threshold in fors_zeropoint was therefore set rather high and a global background subtraction was used. The aperture size was set to 14 arcseconds in diameter, corresponding to the aperture used by Landolt.
The Stetson catalogue, on the other hand, reports magnitudes derived using adaptive aperture photometry, i.e. the aperture size increases until it encounters the next star. In addition, many of the Stetson fields are quite densely populated, so that a global approximation of the background is problematic. The higher star density also makes it advisable to lower the detection threshold to enable SExtractor to also correct for stars detected inside the aperture. We therefore lowered the detection threshold in fors_zeropoint from 3 $\sigma$ to 1.5 $\sigma$ and decreased the aperture size to 10 arcseconds in diameter. In addition we switched from global to local background fitting. These changes reduced the scatter in the derived photometric zero-points from individual stars within one image by more than a factor of two on average.

We experimented with the number of nights needed to obtain reliable fits of our model. We found that a minimum of seven fully photometric nights were needed. We therefore adopted the following procedure to collect the data for each model fit. For each night, we chose a range of dates that is large enough to include at least seven fully photometric nights around that night. During periods with few fully photometric nights, this means that a date range of up to 60 nights needed to be included in the analysis. The number of seven photometric nights is a compromise between the increase in accuracy with an increasing number of photometric nights and temporal resolution of the parameters. In Figure 1 we show a comparison between the results of a fit that used a fixed window of 28 nights, not including the above pipeline improvements, and a fit using the current procedure. It can be seen that the zero-points change by less than about 5 % over a range of 100 nights.

We believe that the photometric parameters obtained with the procedure as outlined above are accurate enough to photometrically calibrate science data if a night is photometric. However, the user should be aware that the new calibration plan is not sufficient in itself for establishing that a night is photometric. There is a finite risk that a non-photometric night has not been recognised as such by the classification performed at Paranal. It is therefore advisable, that for science observations requiring photometric conditions, the user requests further standard star observations during the night. A procedure to submit standard star observing blocks without having to specify which standard star field is to be observed is currently under preparation. Another tool to judge the quality of a given night is the MeteoMonitor tool[4]. This tool should be consulted if the data of any given night are to be used for photometry.

## SDSS photometry

Our modelling of historical FORS2 photometric data revealed subtle effects, such as a rotating illumination pattern that can be corrected to improve the photometric accuracy. This raises the question of whether other large photometric datasets suffer from biases that can be revealed, modelled and corrected with our methodology. Arguably the most productive wide-field multi-waveband survey is the Sloan Digital Sky Survey (SDSS).

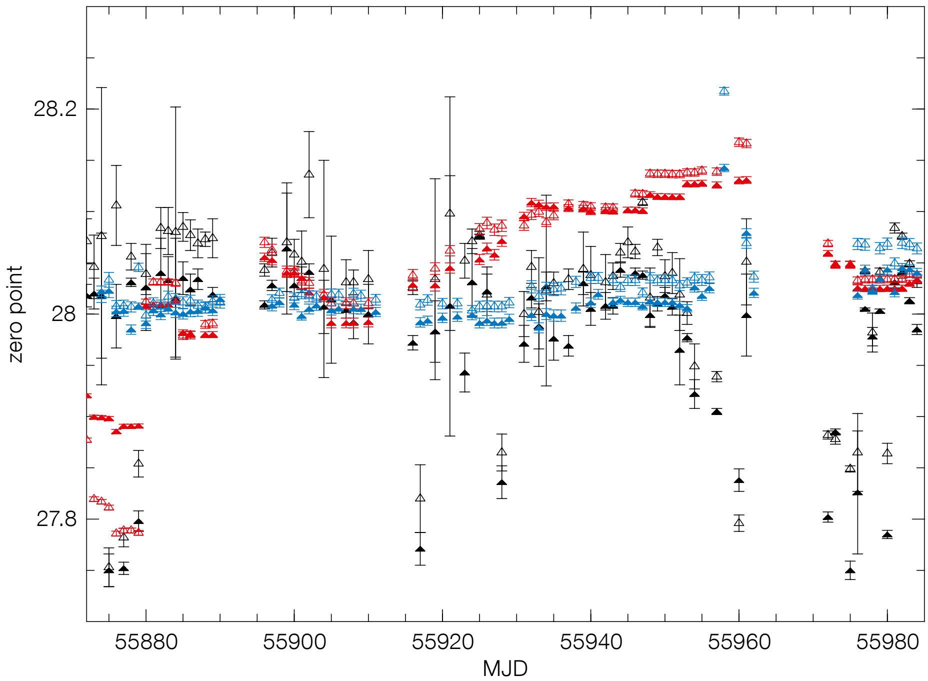


**Figure 1.** Three estimates of nightly photometric zero-points for FORS2 over 100 nights. The black points are computed using averaged extinctions as done for quality control. The red points are computed using our photometric model but without the improvements to the pipeline as described in the text. The blue points are our best current estimates. The two detectors in FORS2 are distinguished by open and filled points. It can be seen that by fitting a photometric model, zero-points can be obtained with an accuracy of a few percent. The fairly stable difference in zero-point between the two chips is clearly visible.

The large size of the SDSS survey makes it challenging to search for biases. Since our software is capable of handling such a large dataset, we decided to use it for an investigation of the SDSS photometry.

The SDSS (York et al., 2000) provides photometry (including widely used aperture and point spread function [PSF] magnitudes) in the *ugriz*-bands for objects down to ~ 22.5 mag and covering ~ 14555 square degrees. Padmanabhan et al. (2008) developed a photometric calibration model for SDSS data, similar to the model that we developed for FORS2, but with many more (~ 2000) calibration parameters of interest and ~ $10^7$ nuisance parameters to be solved for, that results in a relative photometric calibration that is good to ~ 1 % in the *griz*-bands (~ 2 % in the *u*-band).

The repeat observations from the SDSS allow us to test our photometric modelling procedures using a dataset that includes many objects with unknown true magnitudes. So we decided to apply our methodology to investigate any systematic trends that might still be present in the SDSS photometric data after the Padmanabhan calibration effort. To this end, we downloaded all of the SDSS photometric data down to 19 mag in each waveband and analysed the repeat observations that satisfy certain quality constraints. We considered the aperture (7.43 arcseconds) and PSF magnitude measurements, and we looked for trends as a function of image and observation properties, such as detector column and row, PSF full width at half maximum (FWHM), sub-pixel coordinates, etc.

In the upper panel of Figure 2, we show how measured *u*-band aperture magnitudes systematically change as a function of PSF FWHM for a single detector in the SDSS camera, and we note that the changes increase in amplitude for fainter objects. Similar trends are found in the other bands and they are strongest in the *z*-band. We find that the trends range from ~ 7–15 millimag in each band for objects brighter than 16 mag, to

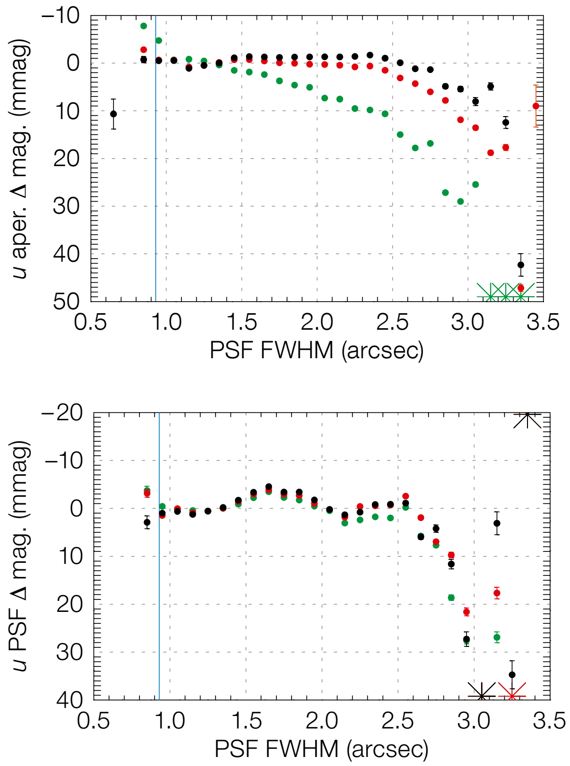


Figure 2. Upper: Systematic trends in the *u*-band aperture magnitude measurements as a function of PSF FWHM and object brightness for one of the detectors in the SDSS camera. The black, red and green points correspond to aperture magnitude measurements brighter than 16 mag, in the range 16–18 mag and fainter than 18 mag, respectively. Asterisks represent magnitude offsets that fall outside of the plot range. Lower: Same as the upper panel for the *u*-band PSF magnitude measurements from the same detector in the SDSS camera. In both plots the vertical blue line represents the critical sampling for the SDSS camera.

~ 30–60 millimag and ~ 100–170 millimag, in the *ugri*- and *z*-bands, respectively, for objects fainter than 18 mag.

In the lower panel of Figure 2, we present a similar plot for the *u*-band PSF magnitudes for the same detector in the SDSS camera. The systematic trends for the PSF magnitudes as a function of PSF FWHM are similar in amplitude to those for the aperture magnitudes but they are also more complicated and seem to "oscillate" as the PSF FWHM increases (the *ug*-bands show the clearest examples).

The full details of our analysis of the SDSS data are presented in Bramich & Freudling (2012) where we also investigate systematic trends as a function of other parameters such as subpixel coordinates, and we speculate as to the causes of some of the trends that we have found.

## Acknowledgements

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## Links

[1] The IDL photometric modelling program is available from dbramich@eso.org on request
[2] All improvements to the pipeline recipes are available in version 4.9.11 of the FORS pipeline at: www.eso.org/sci/software/pipelines/fors/fors-pipe-recipes.hmtl
[3] New version of the Stetson photometric catalogue: http://www2.cadc-ccda.hia-iha.nrc-cn
[4] Paranal MeteoMonitor: http://archive.eso.org/asm/ambient-server

ESO/Manu Mejías

Colour image of the young open cluster NGC 371 in the Small Magellanic Cloud obtained with FORS1. Images in three emission lines – two of helium (He I 5876 Å and He II 4686 Å) and one of hydrogen (Hα) – were combined and emphasise the extended Hα emission produced by ionising photons from the hot O and B type stars in the cluster. See eso1111 for more details.