Correction of Field Rotator-Induced Flat-Field Systematics—
A Case Study Using Archived VLT-FORS Data

SABINE MOEHLER, WOLFRAM FREUDLING, PALLE MÖLLER, FERDINANDO PATAT, AND GERO RUPPRECHT
European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany; smoehler@eso.org, wfreudli@eso.org, pmoller@eso.org, fpatat@eso.org, grupprec@eso.org
AND
KIERAN O’BRIEN
European Southern Observatory, Casilla 19001, Santiago 19, Chile

ABSTRACT. ESO’s two FOcal Reducer and low-dispersion Spectrographs (FORS) are the primary optical imaging instruments for the VLT. They are not direct-imaging instruments, as there are several optical elements in the light path. In particular, both instruments are attached to a field rotator. Obtaining truly photometric data with such instruments presents a significant challenge. In this article, we investigate in detail twilight flats taken with the FORS instruments. We find that a large fraction of the structure seen in these flat fields rotates with the field rotator. We discuss in detail the methods we use to determine the cause of this effect. The effect was tracked down to be caused by the Linear Atmospheric Dispersion Corrector (LADC). The results are thus of special interest for designers of instruments with LADCs and developers of calibration plans and pipelines for such instruments. The methods described here to find and correct it, however, are of interest also for other instruments using a field rotator. If not properly corrected, this structure in the flat field may degrade the photometric accuracy of imaging observations taken with the FORS instruments by adding a systematic error of up to 4% for broadband filters. We discuss several strategies to obtain photometric images in the presence of rotating flat-field pattern.

Online material: color figures

1. INTRODUCTION

Systematic differences between flat-field images, i.e., high count level CCD exposures of a smooth/diffuse source, and the actual system efficiency at any position of the CCD ultimately set a limit for the photometric accuracy of an imaging instrument unless they are accurately determined and corrected for. This correction process is known as “illumination correction” and is especially important for focal reducer type instruments due to their numerous internal reflections that redistribute diffuse light, an effect sometimes referred to as “sky concentration” (see, for instance, Andersen et al. 1995; Koch et al. 2003).

The two optical focal reducer instruments FORS1 and FORS2 have been in operation at the ESO VLT since 1999 April 1, and 2000 April 1, respectively. During this time a large database of calibration data has been accumulated. In an effort to improve the overall photometric accuracy that we offer to ESO users, we are in the process of defining a procedure to determine and correct for systematics such as sky concentration (Möller et al. 2005; Freudling et al. 2007a, 2007b).

In the course of this work we have found an effect that has previously not been described in the literature. The effect is seen as twilight image features which rotate along with the field rotator position and therefore clearly are created inside the telescope/instrument system. The effect might not be limited to the two FORS instruments, but affect other instruments mounted on telescopes with field rotators. Due to our vast database covering about one decade of systematically obtained and documented calibration data we are able to investigate and quantify the features.

The paper is organized in the following way. In § 2, we describe the selection and processing of the data used in this investigation. In § 3, we describe how we isolated the rotating part of the flat fields and investigate the properties and origin of this structure. Finally, in § 4, we discuss the impact of our finding on photometry and strategies for dealing with this effect.

2. DATA

The current calibration plan for the FORS instruments specifies that twilight flat fields have to be taken within seven nights of a science observation with a given setup. Usually about 4–6 frames are taken, mostly during evening twilight, but sometimes also during morning twilight. Hereafter, we refer to these individual images as “twilight flats.” In order to
TABLE 1
COMBINATIONS OF TELESCOPE AND FORS

| Instrument | Unit Telescope | Start       | End          | Time Range Used          | Event                        | Number of Frames |
|------------|----------------|-------------|--------------|--------------------------|------------------------------|-----------------|
| FORS1      | UT1-Antu       | 1999 Apr 01 | 2001 Jul 31  | 1999 Apr 13...1999 Sep 14 | 2000 Oct 13...2001 Feb 25    | 1999 Oct 25 FORS1 maintenance |
|            |                |             |              |                          | 2001 Mar 25 mirror recoating | 137             |
|            | UT3-Melipal    | 2001 Aug 02 | 2002 Oct 19  | 2001 Sep 12...2002 Sep 08 | 2002 Oct 19 move from UT3 to UT1 | 266             |
|            | UT1-Antu       | 2002 Oct 22 | 2004 May 30  | 2002 Dec 06...2004 Mar 25 | 2004 Jun 04 move from UT1 to UT2 | 234             |
|            | UT2-Kueyen     | 2004 Jun 06 | 2009 Mar 31  | 2004 Sep 01...2005 Dec 29 | 2006 Jan 27 FORS1 maintenance | 247             |
|            |                |             |              |                          | 2006 Dec 01 mirror recoating | 201             |
|            |                |             |              |                          | 2007 Apr 01 new CCD mosaic   | 46/106/134/127/129/141 |
|            |                | 2007 Oct 09 | 2008 Apr 11  | 2007 Sep 24 FORS1 mainten ance | 132                |
|            |                | 2008 Apr 11 | b_HIGH replaces | B_BESS as standard filter |                 |
| FORS2      | UT2-Kueyen     | 2000 Mar 25 | 2001 Jun 01  | 2000 Mar 30...2000 Dec 03 | 2000 Dec 08 FORS2 maintenance | 155             |
|            | UT4-Yepun      | 2001 Jun 05 | 2004 May 29  | 2001 Dec 22...2001 May 26 | 2001 Jun 02 move from UT2 to UT1 | 125             |
|            |                |             |              | 2001 Jun 11...2002 Mar 21 | 2002 Mar 29 new CCD mosaic   | 199             |
|            |                |             |              | 2002 Apr 07...2003 Oct 04 | 2004 May 31 move from UT4 to UT1 | 289             |
|            |                |             |              | 2004 Jul 09...2005 Nov 30 | 2005 Dec 15 mirror recoating | 256             |
|            |                | 2006 Jun 01 | 2007 Jul 01  | 2006 Jun 01...2007 Jul 01 | 2007 Jul 02 mirror recoating | 154             |
|            |                | 2007 Oct 01 | 2008 Nov 01  | 2007 Oct 01...2008 Nov 01 | 2008 Nov 06 mirror recoating | 187             |
|            |                |             |              |                          |                              |                 |

eliminate the contributions of field stars on the jittered sequence of flat fields, the frames are combined using a median rather than a simple average. Before combining the individual frames, the master bias is subtracted and each frame is normalized with the median of its flux. The resulting master flats are used for the pipeline processing of the images and also by most users of FORS data.

We used the individual twilight flats to investigate the properties of flat fields taken with the FORS instruments. For that purpose, we retrieved data from the ESO archive observed between 1999 April 1 and 2008 April 11, for FORS1, and between 2000 May 1 and 2008 November 1, for FORS2. Within these time intervals, the FORS instruments and the telescopes they were attached to went through several maintenance intervals and/or upgrades, and the instruments were moved to different Unit Telescopes (UTs) of the VLT. In order to assess the stability of the twilight flats, we took care to combine only twilight flats taken between such interventions. The periods we considered are detailed in Table 1. In addition to the archive data from the calibration plan, we obtained a specifically designed sequence of twilight flats for FORS1 with the O II +44 filter between 2007 August 31 and September 4. This filter is an interference filter centered at 372 nm. These observations are the only ones explicitly taken to analyze the rotating feature, and the rotator angle was changed in roughly 10° steps.

Before investigating the flat fields in more detail, we prepared them in the following way. First, each individual image was bias corrected using the prescan region only and normalized with the median of its flux (hereafter flux-normalized twilight flat). The single CCDs of the FORS instruments were read out via four ports in standard imaging mode, which yields different gains for the four quadrants (see the FORS manual1 for more details). In these cases the median was determined from the region from 100,100 (lower left corner) to 900,900 (upper right corner), covering the first quadrant of the CCD. For the CCD mosaics we first combined the 2 frames corresponding to one exposure and extracted the illuminated part. Within the illuminated part the flux was determined for the region 500,900 (lower left corner) to 800,1500 (upper right corner).

A cursory inspection of the flux-normalized flat fields shows that individual flats differ by as much as 5% in amplitude. At the same time, there is a stable component that is similar for all twilight flats for a given time range between interventions. This stable component emerges when the median of those twilight flats is computed and is often dominated by sky concentration (see Fig. 1). In Figure 2, the shape of the pattern is shown for the broadband and the narrowband filter we used. The figure shows cuts through the medians for the Bessel $U$, $B$, $V$, $R$, and $I$ filters and the O II narrowband filter. The overall shape and amplitude is similar for all filters, and the total amplitude is on the order of 3 to 5%.

In order to investigate the changing component of the twilight flats, we divided each flat by the median flux-normalized twilight flat for the corresponding filter (hereafter, flat-fielded twilight flat). This removes any structure of the flat field that is stable and fixed relative to the detector.

1 At http://www.eso.org/sci/facilities/paranal/instruments/fors/doc/.
3. CHANGING COMPONENT OF TWILIGHT FLATS

3.1. Rotating Pattern

Inspection of the flat-fielded twilight flats revealed that some of the remaining structures seem to change their position between flat fields taken in the same night. This observation immediately rules out that these features are caused by spatial sensitivity variations on the detector, or vignetting on structures which are physically fixed relative to the detector. Instead, at least some of the variations in the flat fields must be caused by moving parts within the telescope or FORS instrument. The alt/az mounting of the VLT UT telescopes causes field rotation, which is compensated by rotating the instrument accordingly. Fixed components along the light path (e.g., the Linear Atmospheric Dispersion Corrector or the M3) will therefore rotate with respect to the detector of the instrument. To test whether the flat-field structures are related to the field rotation, we compared twilight flats taken with different rotator angles.

In order to investigate the exact relation between the orientation of structures in the twilight flats and that of the field rotator, we took a set of twilight images with a maximum of 5 images per 5° interval in rotator angle. These were then counterrotated with the angle of the field rotator multiplied with a factor $\epsilon$ between 0 and 2. Then we computed the median of these counterrotated flat-fielded twilight flats and measured the amplitude of the structures as the difference between the ninety-ninth and first percentiles. Only pixels within a centered circle with a diameter equal to the dimension of the image were used for that purpose. The amplitudes as a function of the rotation factor $\epsilon$ are shown in Figure 3. It can be seen that the amplitudes of structures peak when the derotation angle is exactly identical to the rotator angle. We therefore use rotations with the opposite of the exact rotator angle to isolate the rotating pattern (hereafter, RP).

We applied this procedure to the data sets described in Table 1. We compared the structures in the resulting image with the median of the same frames, but rotated by a random rotation angle. One example of such a comparison is shown in Figure 4. The amplitude of structures in the median of the counterrotated flat-fielded frames is typically between about 0.6% and 2.0%, whereas no structure can be recognized in the median of randomly rotated flat-fielded frames.

So far, we have identified two components of the flat fields: one is the pattern fixed relative to the detector, and the other one is the RP. An interesting question is on what scales the RP becomes relevant, and whether all structure in the flat field which is not fixed to the detector can be attributed to the RP. To investigate this, we computed the power spectrum within the central circle of the isolated RP, and divided it by the power spectrum of the same region in the randomly rotated average. The result is shown as crosses (+) in Figure 5. It can be seen that the range of scales present in the RP is from about 0.6% and 2.0%, whereas no structure can be recognized in the median of randomly rotated flat-fielded frames.

At intermediate scales between 30 and 300 pixels, the amplitude of the RP is small compared to other structures in the flat field.
To illustrate this more clearly, we removed the RP from the individual flat-fielded flats with rotator angles between 135° and 145° after rotating it in place, and then computed the average. The power spectra of the RP-corrected average flat-fielded flat are shown as squares in Figure 5. It can be seen that most of the power at scales larger than 300 pixels can be removed when correcting the isolated RP at the correct rotator angle.

3.2. Rotating Pattern for Different Filters

The next question we wish to address is whether the shape and amplitude of the RP depend on the filter. We therefore isolated the RP with the method described in § 3.1 for all filters within the periods that include a sufficient number of narrowband observations. In Figure 6, we show the RPs for one of these periods. It is clearly seen that the amplitude as well as the shape of the structure vary smoothly with wavelength for the broadband filters. The amplitudes for different filters are listed Table 2, and the variation in amplitude are illustrated in Figure 7. The amplitudes are about 1.8% for the narrowband filter, and below 1.5% for the broadband filters. This trend has to be considered when searching for the cause of the RP (see § 4.1).

This larger amplitude of the RP seen in the narrowband filters means that more photons were detected in the RP relative to photons detected in the underlying twilight image. One possible way to explain this is that while the underlying image only detects photons within the passbands of the narrowband filters, within the central circle on the images, and divided by the power spectrum of the randomly rotated average. See the electronic edition of the PASP for a color version of this figure.
the RP is made up of photons which do not pass through the filter and therefore has the full bandwidth of unfiltered twilight. This explanation implies a correlation of the amplitude with the fraction of photons that pass through the filter. Such an effect has been reported by Fynbo et al. (1999) for narrowband observations at the NOT telescope. This fraction of sky photons that pass through a filter can be computed from the width of the filter bandpass, the mean transmission of the filter, the mean CCD efficiency over the bandpass, the relative brightness of the twilight sky within the bandpass, and the total sky brightness and exposure time. To estimate this number, we used the twilight sky brightness at different bandpasses from Patat et al. (2006), and the filter and CCD characteristics for FORS, which are available on the World Wide Web.²

We then computed the ratio $r$ of the number of photons available outside the filter to the number of photons detected after passing through the filter as

$$r = \frac{\int N_p(\lambda) f(\lambda) \, d\lambda}{\int N_p(\lambda) \, d\lambda},$$

(1)

where $N_p(\lambda)$ is the detected photon rate as a function of wavelength, and $f(\lambda)$ is the filter throughput curve. The photon rate was computed from

![Fig. 6.—Comparison of flat-fielded twilight flat fields rotated to rotator angle 0 for the broadband filters $UBVRI$ and the narrowband filter O II observed with FORS1 at UT2 from 2007 Apr 01 to 2007 Sep 24. All images are displayed with cuts of 0.995 and 1.005. See text for further detail.](image)

![Fig. 7.—Amplitudes of the rotating pattern as a function of the wavelength range of the filters for the time ranges listed in Table 2. The FWHM filter width is shown for each filter. FORS1/2 data are marked by dotted lines and solid lines, respectively.](image)

² At http://www.eso.org/sci/facilities/paranal/instruments/fors/inst/.
\[ N_p(\lambda) = S(\lambda) \cdot R_{\text{CCD}}(\lambda), \]  

(2)

where \( S(\lambda) \) is the twilight sky brightness expressed in photons per wavelength, and \( R_{\text{CCD}}(\lambda) \) is the response of the CCD.

In Figure 8, we plot the measured amplitude of the RP versus the fraction of sky photons that pass through the filter. It can be seen that there is some trend in the sense that when only a small fraction of the photons pass through the filter, the amplitudes tend to be higher. However, the large scatter make this test inclusive. In § 4, we will discuss a more sensitive test to determine whether the RP is likely to be caused by scattering.

3.3. Stability of Rotating Pattern

The finding that some of the structures in twilight flats rotate with the rotator angle has significant impact on the photometry with either of the FORS instruments. To correct for this effect, it is important to know how stable this pattern is with time. Both instruments have been moved between the telescopes which comprise the four unit VLT. Both FORSs use Linear Atmospheric Dispersion Correctors (LADCs; Avila et al. 1997), which are fixed to the telescope and mounted in front of the instrument. The two existing LADCs, LADC-A and LADC-B, have also been switched between the two FORSs once (2004 June). The different combinations of LADCs, telescopes, and instruments can be used to search for correlations between the RP and the use of those optical components. We used the

\[ B \] Bessell filter (B_BESS in the FORS filter system) for this investigation. While the amplitude of the signal is stronger in the \[ U \] Bessell filter, there are many more twilight flats observed for the \[ B \] Bessell, so we can achieve a more homogeneous angle distribution and a better signal-to-noise ratio. In Figures 9–12, the rotating structures are shown for different periods when the FORS instruments were mounted at the VLT units UT1 to UT4. The amplitudes of the structures are listed in Table 3, together with the combination of instrument, UT, and LADC used in each case.

Inspection of the figures shows that the general structures frequently but not always change when any changes were made to the instrument. In most cases, these changes involve removing the instrument from the field rotator and remounting it.

![Figure 8](image1.png)

**Fig. 8.**—Amplitudes of rotating pattern as a function of the fraction of sky photons that pass through the filter. Different symbols are used for the two periods listed in Table 2. FORS1/2 data are distinguished by open and filled symbols, respectively.

![Figure 9](image2.png)

**Fig. 9.**—Comparison of flat-fielded B_BESS twilight flat fields rotated to rotator angle 0 observed at UT1. Data on the left are from FORS1 (1999 Apr 13 to 1999 Sep 14, 2000 Aug 01 to 2001 Feb 25, and 2002 Dec 06 to 2004 Mar 25 from top to bottom). Data on the right are from FORS2 (2004 Jun 09 to 2005 Nov 30, 2006 Jun 01 to 2007 Jul 01, 2007 Oct 01 to 2008 Nov 01 from top to bottom). All images are displayed with cuts of 0.995 and 1.005.
Slight changes in the optical alignment might therefore explain these differences. The overall shape of the RP seems to be more strongly correlated with the LADC than with either the UT or the instrument used. Structures observed with FORS1 and FORS2 look similar when the LADC-A was used at UT2, UT3, or UT4. At UT1 with LADC-A (Fig. 9), both FORSs show a gradient of increasing flux from the lower left corner to the upper right corner for data observed after 1999. The amplitude of this effect increased when the LADC was switched from FORS1 to FORS2 (cf. Table 3). On the other hand, for UT2 and UT4 in combination with LADC-B (Figs. 10 and 12) one can see the same features, a slanted “1” in FORS1 data observed between 2004 July and 2006 December and in FORS2 data observed between 2000 December and 2001 May (UT2) and between 2001 June and 2003 October (UT4). A similar feature can be observed in the newest FORS1 data (since 2007 April), although the “1” appears to be flipped and rotated. The feature is not present in the earliest FORS2 data at UT2, which look more similar to the FORS1 data from UT3 (Fig. 11) and show a slope similar to the UT1 data, albeit with some variation in the low flux region.

3.4. Contamination of the LADC

Under normal circumstances, the LADC is not accessible unless the FORS instrument is dismounted. After we identified the LADC as a possible cause for the RP, we visually inspected LADC-B, which has been decommissioned with FORS1 on 2009 March 31. Figure 13 shows a picture of the lower prism illuminated with a flash light. Comparing the smudges seen in this picture to the structures visible in Figures 6, 10, and 12 suggests that the LADC is responsible for a major part of these structures.

4. IMPLICATIONS FOR PHOTOMETRY

4.1. RP and Photometric Zero-Point Variations

The observed RP raises the question of how accurate relative photometry can be obtained from FORS images. The obvious question is whether the RP is a faithful representation of throughput variations across the detector, or whether it is an
additive defect in the flat fields that should be removed. To address this issue, we analyzed a set of dithered $R$-band observations of Stetson standard fields (Freudling et al. 2007a). Correlating the measured magnitudes of stars with features of the RP can determine whether the RP is additive or multiplicative, and thereby decide on the appropriate correction procedure.

The details of data taking and reduction are given in Freudling et al. (2007a, 2007b, 2007c). Here, we only give a brief summary. In total, 30 images of the field were taken on a 5 × 5 grid covering a total area of about 12′ × 12′, including several rotations of the field. We removed any structure larger than 100 pixels from the master flat, and the resulting master flat was used to flat-field all the images. We then measured instrumental aperture magnitudes for any star that is included on at least two of the images. In total, there are about 10,000 measured magnitudes of 900 unique stars. The measured magnitudes were then used to fit a model of the illumination pattern, relative magnitude zero points of the stars, and a zero point for each image. The model for the illumination pattern was a two-dimensional third-order polynomial. The scales that can be fitted with such a model are too large to remove any possible sensitivity variations on the scales of the RP. We computed the residuals from the fit $\Delta m = m - m_{\text{rel}} - m_i - i(x, y)$, where $m$ are the measured instrumental magnitudes, $m_{\text{rel}}$ are the relative magnitudes of the stars, $m_i$ the relative zero points of the images, and $i(x, y)$ is the model of the illumination pattern.

We then plotted these residuals with the corresponding pixel value of the normalized flat fields taken with the same rotator angle as the stellar images. The results are shown in left panel of Figure 14. It can be seen that there is a correlation between the two quantities in the sense that measured magnitudes of the same stars are brighter when they are in areas where the RP is bright, and fainter where the RP is faint. A line with a slope of $-1$ in Figure 14 shows the expected relation if the RP directly represents sensitivity variations across the detector. The reduced $\chi^2$ from this line is 1.45. This suggests that the RP is indeed a valid part of the flat field, i.e., the pattern is multiplicative and is directly related to the photometry.

In order to evaluate the significance of this result, we repeated the described procedure with the positions of the stars on the detector randomly drawn. In this case, we do not expect any relation between the residuals and the values on the RP. Residuals from fitting a line with a slope $-1$ therefore will be large, and this can be detected by a large values for $\chi^2$. For each realization, we computed the $\chi^2$ of the fit in the same

![Figure 13](image)

**Figure 13.** Lower prism of LADC-B illuminated by a flashlight; photograph taken on 2009 Jun 29.
way as we did with the original data. The distribution of $\chi^2$ for 10,000 realizations is shown in the right panel of Figure 14. Only in about 0.2% of all realizations was the $\chi^2$ as low as for the original data. As an additional test, we repeated the procedure with the original data, but the RP rotated by 90°. Again, there was no correlation between the residuals and the RP. We therefore conclude that at least for the R_BESS filter we tested, the RP presents a sensitivity variation across the detectors.

However, as discussed in § 3.2, we also see evidence for a scattered component which shows up relatively strongly for narrowband filters. Therefore, the RP for the narrowband filters might include both multiplicative and additive components.

### 4.2. Data Reduction Strategy

One consequence of the findings discussed here is that the RP will significantly affect the master flats unless the rotator angles are carefully controlled. Applying a flat field that includes the RP to imaging data with a different rotator angle will introduce shifts of the photometric zero point with amplitudes twice as large as the RP, i.e., up to almost 4% across the inner circle on the detector for broadband filters. There are several conceivable strategies to address this problem. The first is to try to isolate the RP as we have described, rotate it to the rotator angle of each individual twilight flat, and correct the master flats. The disadvantage of this approach is that it is not applicable to the corners of the detectors where the RP cannot be isolated. The second strategy is to remove any structure in the twilight flats on the scale of the structures seen in the RP (see Fig. 5), and then determine the larger scale illumination correction through independent observations. The disadvantage of this approach is that it is difficult to determine the illumination correction with sufficient spatial resolution. Finally, one could address the RP matching the orientation of flat fields to the corresponding science images. For reasons of efficiency, the implementation of such a strategy requires one to restrict the orientation of science data to the small number of selected rotator angles for which flat fields are available. We consider this solution to be the best strategy.

We also recommend this strategy of searching for twilight flats with rotator angles close to those of the science data to users, who already have FORS data or retrieve them from the archive. They must, however, avoid mixing data across interventions. If there are no flat fields in the given time range with a rotator angle similar to that of the science data, the next best solution is to construct a master twilight flat by combining twilight observations with a large range of rotator angles to smear out the RP.

---

Fig. 14.—Left panel: Magnitude residuals as a function of pixel value of the RP. Data points are the averaged magnitude residuals for a given level of the RP, error bars are the $1\sigma$ uncertainties of the mean. Solid line is the fit of a line with a slope of $-1$ to the data points. Reduced $\chi^2$ of the fit is 1.45. Right panel: Distribution of reduced $\chi^2$ for 10,000 fits to residuals vs. pixel values of the RP. The P of the stars were randomly assigned for each each of the fits. Arrow marks the $\chi^2$ of the original data as shown in the left panel.
5. SUMMARY AND CONCLUSIONS

Using archived calibration data from more than 8 yr, we have shown that the master twilight flats regularly produced from FORS observations include structures that are not related to sensitivity variations across the detector. Part of this is caused by field illumination effects, which can be corrected using standard field illumination correction (for details, see Freudling et al. 2007a), but in addition we find a pattern that rotates with the setting of the field rotator. This pattern is stable in the absence of instrument interventions, but occasionally changes when work on the instrument has been performed.

Obviously the source of this additional pattern must be either partly or completely external to the instrument itself in order to be able to follow the field rotator. Possible candidates were therefore the guide probe or structures inside or on the M3 tower, e.g., reflections off some structure related to the M3 mirror or to the LADC. Alternatively the effect may be caused directly by transmission variations in the optical surfaces of the LADC itself. Since the method by which one would correct for the effect is very different for reflections (additive effect) or transmission variations (multiplicative), we have deemed it important to determine its source.

Data taken through a narrowband filter suggested at first that reflections were the main cause, but data taken through a second narrowband filter did not strongly support this suspicion. There is evidence that the rotating patterns followed the LADCs when they moved between the two instruments. Further a direct inspection of one of the LADCs, which has now been dismounted and decommissioned, showed a structure on its coating that well resembles the pattern seen in the flat fields. A last test finally showed that comparison to photometric stellar data confirmed that the pattern is multiplicative, i.e., consistent with transmission variations. Having thus identified the cause we conclude that if it is left uncorrected, in the worst case it could cause systematic errors of up to 4% in the photometry. Future photometric observations with the FORS2 instrument will have to take this newly discovered feature into account in order to remove or minimize its impact. Several options for corrective action exist and are described in this article in § 4.2.

One might well expect that a similar detailed analysis of archived calibration data from other long-term stable instrument/telescope configurations on alt/az mounted telescopes would produce similar results, in particular if these also include LADCs (e.g., LRIS on Keck). We recommend that such analysis should be performed on all instruments used for photometry as part of the general health check and trending analysis when sufficient calibration data are available. Such effects could be stronger or weaker on other instruments than were found here, and they could be both additive and multiplicative as described above. In this article we have provided a detailed description of how such an analysis is best performed, how one may best determine the source of such effects, and how one may correct for them.

We thank Hans Dekker, Martino Romaniello, and Andreas Kaufer for valuable discussions. We highly appreciate the help of the staff on Paranal in locating and examining the LADC-B.

REFERENCES

Avila, G., Rupprecht, G., & Beckers, J. 1997, in Proc. SPIE 2871, Optical Telescopes of Today and Tomorrow, ed. A., Ardeberg, 1135
Andersen, M. I., Freyhammer, L., & Storm, J. 1995, in Calibrating and Understanding HST and ESO Instruments, ed. Benvenuti, Piero, Garching: ESO, 87
Freudling, W., Romaniello, M., Patat, F., Møller, P., Jehin, E., & O’Brien, K. 2007a, ASP Conf. Ser. 364, The Future of Photometric, Spectrophotometric and Polarimetric Standardization, ed. C. Sterken, 113
Freudling, W., Møller, P., & Patat, F., et al. 2007b, The 2007 ESO Instrument Calibration Workshop, ed. Kaufer, A., & Kerber, F. (New York: Springer) 25

———. 2007c, Messenger, 128, p. 13

Fynbo, J. U., Møller, P., & Warren, S. J. 1999, MNRAS, 305, 849

Koch, A., Odenkirchen, M., Grebel, E. K., & Caldwell, J. A. R. 2003, Astron. Nachr. Suppl., 324, 95

Møller, P., Järvinen, A., & Rupprecht, G., et al. 2005, FORS: An assessment of obtainable photometric accuracy and outline for strategy for improvement, VLT-TRE-ESO-13100-3808

Patat, F., Ugolnikov, O. S., & Postylyakov, O. V. 2006, A&A, 455, 395

2010 PASP, 122:93–102