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Report:

Verification of the FORS Absolute Photometry (FAP) Project

VLT-TRE-ESO-13112-5727

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Prepared: S. Moehler, L. Coccato ······ November 12, 2012 ······ Sabine Möhler Coccato Lodovico
Name ······ Date ······ Signature

D. Bramich, W. Freudling ······ November 12, 2012 ······ David Bramich W. F
Name ······ Date ······ Signature

I. Saviane, C. E. García Dabó ······ November 12, 2012 ······ I. Saviane
Name ······ Date ······ Signature

Approved: M. Romaniello ······ 07.12.12 ······ Martino Romaniello
Name ······ Date ······ Signature

Released: M. Romaniello ······ 07.12.12 ······ Martino Romaniello
Name ······ Date ······ Signature

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Issue	Date	Sections Affected	Remarks
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Executive Summary

The FAP Project

One of the goals of the *FORS Absolute Photometry* (FAP) project (see VLT-TRE-ESO-13112-5429) was to produce nightly photometric parameters that can be used to obtain better than 3% photometric accuracy if nights are photometric (and given sufficient science target signal-to-noise). The photometric parameters by themselves, however, are not meant to verify that a night is indeed photometric, i.e. a non-photometric night will not necessarily result in a larger error on the extinction coefficient.

To achieve the required photometric accuracy, changes were made to the procedures to predict at the beginning of a night whether it is photometric or not, to the observing procedure for photometric standards, to the calibration plan, the pipeline, and the way the pipeline is used to compute night parameters. The changes were implemented in routine operations in October 2011.

In this document, we report on our verification whether the desired improvement in photometric accuracy has been achieved by analyzing the data taken in the first 6 months. We found that initially this goal of FAP was not achieved. Several adjustments were necessary to a number of steps in the procedure. After these adjustments, FAP reached its goal stated above: Tests showed that when using the derived photometric parameters to calibrate science frames on a photometric night, the 1σ systematic error is about 2%. The calibration was better than 3% in 97% of all cases we investigated.

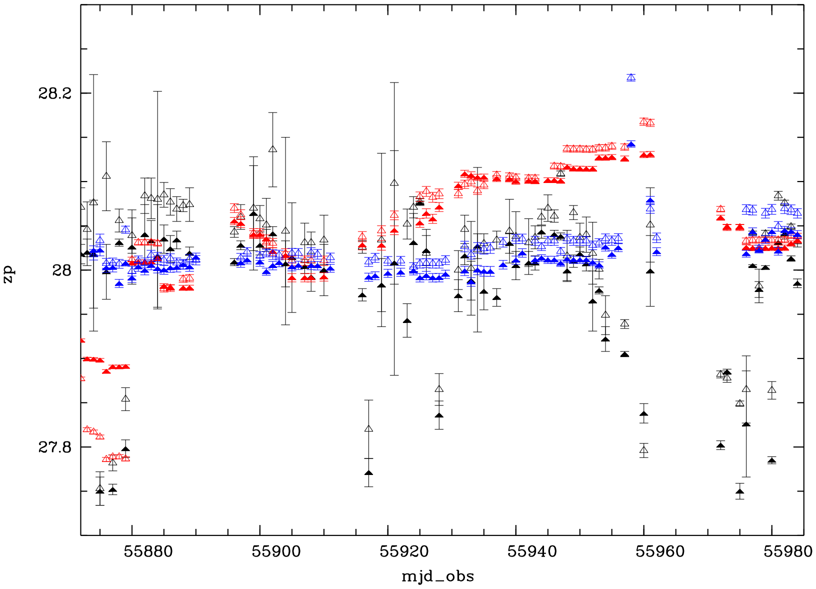

Figure 1: Three estimates of nightly photometric zero-points for FORS. The black points are computed using averaged extinctions as done for quality control. The red points are computed using our photometric model but without the improvements to the pipeline as described in the text. The blue points are our best current estimates. The two detectors in FORS 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.

Verification Results

The main findings of the verification were the following:

- **Calibration Plan** The new calibration plan was put into operations on Oct 24, 2011. It was found that the night observers often did not fully comply with the procedure. After procedures were clarified and better advertised, compliance increased to about 75% of the potentially photometric nights, with the remaining 25% usually used predominantly by other instruments.

- **New Calibration Fields** The newly prepared calibration fields were found to work well most of the time. In particular, they do provide a better coverage of airmass and avoid problems of too few stars in the field at offset positions. To improve the situation for the few sparse fields a newer photometric standard catalogue was introduced.

- **Parameters to perform frame photometry** The pipeline recipe `fors_zeropoint` provided unphysical results in some cases. This problem was solved by adjusting the `SExtractor` parameters used by this recipe.

- **Fit of nightly photometric parameters** It was found that the procedure to determine instrumental zeropoints and nightly extinctions implicitly assumed that there are a sufficient number of photometric nights in any 28 night period. This assumption was removed.

- **Estimate of Quality of Night** The revised photometric calibration plan affects only nights that are judged to be photometric at the beginning of the night. The procedure was found to neglect the case that the zeropoint changes rapidly after a mirror re-coating. This limitation was removed.

Conclusion

In Fig. 1 (p. 3) we show the nightly FORS zero points computed before FAP, after FAP was put in operation, and after changes made during the current verification. The desired photometric accuracy as described above has been achieved.

The number of adjustments needed to achieve this goal was somewhat surprising given the fact that all components had been checked individually before. This project clearly illustrates that the quest for science grade data products goes far beyond correcting pipeline recipes.

The photometric parameters should be monitored closely at least until October 2012 to ensure that the revised procedure works well for the whole year.

Contents

1 Calibration Plan

1.1 New Calibration Plan since October 24, 2011

In document VLT-TRE-ESO-13112-5429 (Issue 1.0) the following new calibration plan was proposed in Sect 5.2 (references in the itemized list below refer to the aforementioned document):

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1. At the beginning of each night for which FORS science observations are required, two standard star images should be obtained in quick succession for each broadband filter (B, V , R and I), such that the difference in airmass between the images is ≥ 0.7 (unless the sky has thin/thick clouds). Necessarily these images will be of different standard star fields, which should be chosen following the recommended Stetson standard star fields listed for different times of year in Section 5.3.
2. If a night is flagged as photometric and science data requiring photometric conditions are to be obtained, then further observations of standard stars should be carried out during the night in order to monitor the continued stability of the conditions. These observations should be carried out with the same filter as the science observations. Observing one standard star field in the middle of the night and another at the end of the night is sufficient. The airmasses of these two fields should be chosen to further sample the previously observed airmass range (e.g. if observations at the beginning of the night were performed at airmasses of 1.1 and 1.9, then the observations in the middle of the night and at the end of the night could be obtained at airmasses of ~ 1.3 and ~ 1.6).
3. Standard star fields should be selected in order to maximise the number of standard stars observed and the range in colour (ideally with $\Delta(B-V)$ and $\Delta(V-R)$ of at least ~ 0.8 mag). The standard star fields listed in Section 5.3 have already been prioritised according to this recommendation.
4. Each observation of the same standard star field should be taken using a different offset and rotation so that over the course of a few months the full set of offsets and rotations specified in the relevant offset file is performed (see Table 1 & Appendix C). This strategy ensures that standard star observations sample the full area of each detector and a full rotation, potentially enabling the calibration of systematic spatially-dependent photometric errors (i.e. static and rotating illumination corrections) in the science object photometry. The set of offsets and rotations to be observed depends on the standard star field in question, since they must be distributed so as to avoid placing very bright stars on the detector and to ensure that a reasonable number of standard stars are present in the images
5. Observations of standard star fields that are close to the Moon should be avoided since the scattered moonlight will reduce the S/N of the photometry and cause unwanted sky gradients in the images. The exact limit on the target-Moon distance should be decided by Paranal.

This calibration plan was put into operations on 2011-10-24 with the list of standard star fields provided in Table 1 (p. 7). These fields have been carefully selected to provide

- the possibility to cover an airmass range of ≥ 0.7 at the beginning of each night in most cases
- standard star magnitudes for all filters

Table 1: Selected standard star fields for new calibration plan

field name	α_{2000}	δ_{2000}
T_Phe	00 30 06.3	−46 28 08.6
L92	00 55 09.7	+00 42 49.9
PG0231	02 33 40.9	+05 19 15.0
L95	03 53 38.7	+00 07 16.7
E3	06 43 13.6	−45 13 28.8
NGC2298	06 48 37.2	−35 58 34.6
L98	06 52 09.3	−00 19 00.3
Ru149	07 24 16.7	−00 32 20.1
Ru152	07 29 56.5	−02 05 42.1
NGC2420	07 38 28.3	+21 34 02.9
NGC2437	07 41 41.0	−14 50 45.8
NGC2818	09 16 22.9	−36 35 20.2
L101	09 56 53.0	−00 19 53.7
LeoI	10 08 55.1	+12 22 37.6
PG1047	10 50 05.3	−00 00 57.4
E5	12 05 13.3	−45 33 56.5
L104	12 42 17.2	−00 31 51.6
PG1323	13 25 45.0	−08 49 59.3
NGC5139	13 26 30.0	−47 10 23.0
IC4499	14 57 50.0	−82 12 00.0
PG1525	15 28 11.0	−07 14 34.2
L107	15 39 32.7	−00 12 32.0
NGC6121	16 24 10.0	−26 35 03.0
PG1633	16 35 12.1	+09 50 59.0
PG1657	16 59 35.5	+07 42 31.0
E7	17 27 20.0	−45 02 28.0
L110	18 42 46.1	+00 07 04.9
NGC6822	19 44 53.0	−14 37 50.0
NGC6940	20 34 32.0	+28 14 50.0
MarkA	20 43 39.6	−10 46 29.0
NGC7006	21 01 15.7	+16 11 26.7
PG2213	22 16 19.1	−00 21 14.1

- as many stars as possible without too high crowding
- the possibility of offset observations to get a better sampling of the illumination pattern without losing too many stars in certain offset positions

1.2 Information Retrieved for Verification

In order to verify the execution of the new calibration plan we retrieved the following information for each night:

- field name, time of observation, filter, and airmass for standard star field observations with binning 2×2 and the SR collimator from the `obs_metadata..fors2` database table
- transparency classification by the weather officer from the night log
- `dp_id` for all night-time on-sky observations of the various instruments using UT1 (FORS2, CRIRES, AMBER, MIDI) from the `obs_metadata..fors2` database table
- frame extinction coefficients from `qc1..fors2_zp_frame` database table

With this information we determined:

- the difference in time and airmass between the first two standard star field observations, the time difference between the first and last standard star field observation, and the maximum airmass difference
- the number of standard star fields observed
- whether the night should have been classified as photometric according to the generous limits specified for the extinction coefficients (0.35, 0.25, 0.20, 0.16 mag/airmass for `b_HIGH`, `v_HIGH`, `R_SPEC`, and `I_BESS`, respectively)
- which fields were observed
- the times during which the various instruments were observing (i.e. if FORS2 was used at all during the night, if it was used at the beginning of the night, etc.)

In order to allow some comparison between data taken with the new calibration plan and older data we performed the same checks for data taken a year before and just before the start of the new calibration plan. The time ranges studied thus are:

1. new calibration plan: 2011-10-25 . . . 2012-01-16 and 2012-01-17 . . . 2012-04-10
2. one year before: 2010-10-24 . . . 2011-01-16
3. just before: 2011-09-01 . . . 2011-10-23

1.3 Checks Performed for Verification

The items checked are:

- How many nights were photometric according to the first extinction measurements and classified `CL`ear or `PH`otometric at the beginning of the night and should thus have triggered the revised calibration plan?
- How many of the nights from the previous selection have the first two standard star field observations with an airmass difference of ≥ 0.7 taken within 36 minutes[1] of each other? If not
  - and the airmass difference was <0.7: were the correct fields observed?
  - and the time difference was >36 minutes: could it be understood why the second field was not observed in time?
- If a night was classified photometric according to the extinction coefficients and FORS2 SCIENCE observations requiring 1PHO were taken, were the other standard star field observation performed?
- How does the airmass coverage of the standard star fields per night compare to a year before and just before the start of the new calibration plan?

1.4 Results

For the time range **2011-10-25 to 2012-01-16** about 55% of the nights with FORS2 observations (35 of 64) were classified `PH|CL` at the beginning. Of those, 33 were photometric according to the rather generous extinction limits provided at
`http://www.pl.eso.org/sci/facilities/paranal/sciops/team_only/MediaWiki/index.php/New_Calplan_Procedures`.
The following discussion refers only to these 33 nights. For 3 nights only one standard star field observation was taken, which was due to CRIRES starting the night. In 6 nights more than 1 hour passed between the first and second observation of standard star fields, which was in 5 nights due to intervening observations of supposedly higher priority.

Of the remaining 24 nights the airmass difference between the first two observations was below 0.7 for 13 nights, which was due to a wrong combination of standard star fields for 8 nights. The remaining 5 nights had correct combinations of standard star fields, but the airmass difference decreased rapidly with time, so that observations taken slightly after the start of the night no longer fulfilled this airmass difference criterion. Unfortunately this problem cannot be solved while keeping other constraints (data in all filters, sufficiently many stars also in offset positions) in mind.

Including those nights where observations of the correct fields did not fulfill the airmass difference criterion we have a total of 16 nights out of 33 possibly photometric nights (48%), where the calibration plan has been fulfilled.

The biggest contribution to this lack of correctly calibrated nights comes from observations of wrong field combinations (8/33 = 24%).

The remaining nights with insufficient calibrations usually present situations not covered in the original phrasing of the calibration plan, namely if FORS2 did not start the night or is observing only for short periods of time. During the period studied here 50% of the time intervals

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[1] The first two standard star observations are usually taken either within this time frame or at much larger time differences of more than 1 hour

Table 2: Observations producing significantly negative extinctions

field	date	filter	airmass	seeing [”]	number of stars	extinction [mag/airmass]
LeoI	2012-01-16	`R_SPEC`	1.306	0.72	118	−0.0403±0.0185
NGC2298	2011-12-07	`I_BESS`	1.022	0.98	110	−0.0543±0.0286
T_Phe	2011-12-04	`R_SPEC`	1.077	0.78	2	−0.2891±0.0683
	2011-12-04	`I_BESS`	1.077	0.78	2	−0.1107±0.0792

during which FORS2 was observing were shorter than 3 hours. Taking one standard star field takes about 10 minutes, so taking two for a time chunk of up to 3 hours takes out more than 10% of the available observing time. We therefore revised the description of the calibration plan (incl. extinction limits) and the use of the `stdsopMain` tool on 2012-02-15 by putting the information about the new calibration plan procedures to the top of the general FORS2 calibration plan page at `http://www.pl.eso.org/sci/facilities/paranal/sciops/team_only/MediaWiki/index.php/FORS_Calibration_Plan`.

The time range **2012-01-17 to 2012-04-10** shows an improved pattern. About 63% of the nights with FORS2 observations (44 of 70) were classified `PH|CL` at the beginning. Only in 1 night (started by CRIRES) no standard star field was observed. Of the remaining 43 nights, 42 were photometric according to the generous extinction limits mentioned above. During 5 nights with significant amounts of CRIRES observations only one standard star field observation was taken. In 4 nights more than 1 hour passed between the first and second observation of standard star fields for unclear reasons. In 14 of the remaining 33 nights the airmass difference between the first two observations was below 0.7, which was in only 2 nights (14%) due to a wrong combination of standard star fields. The remaining 12 nights (86%) had correct combinations of standard star fields.

This leaves us with 31 nights of 42 possibly photometric nights (74%), where the calibration plan has been fulfilled (including those where observations of the correct fields did not fulfill the airmass difference criterion), compared to 48% in the previous time interval.

2 Photometric Parameters from Single Frame Observations

A closer look at the results for the standard star fields revealed that some observations (primarily in the `I_BESS` filter) produced significantly negative extinction values, i.e. outside the error bars, which are unphysical. Observations of the same field at the same time in other (bluer) filters also produced unusually low extinctions, which were not negative, because the extinction in the bluer filters is higher. Table 2 (p. 10) gives information for all the observations yielding negative extinction coefficients for the time 2011-10-24 to 2012-01-16.

Since 2011-11-28, QC has used new photometric coefficients (zeropoints and colour terms). The health check plots at
`http://www.eso.org/observing/dfo/quality/FORS2/reports/HEALTH/trend_report_EXTINCTION_R_HC.html`
(and links to other filters) show a clear jump to lower extinction values at that date for the filters `v_HIGH`, `R_SPEC`, and `I_BESS` due to the new zeropoints. To ensure that the problem of negative extinction values has not been introduced by too bright reference zeropoints we determined the

Table 3: Test fields used to study the effect of varying `SExtractor` parameters

`dp_id`	image FWHM ["]	extinction coefficient [mag/airmass]	airmass	field	filter
`FORS2.2011-11-05T00:02:56.364.fits`	0.83	0.084	1.898	NGC 6940	`R_SPEC`
`FORS2.2011-12-08T06:09:32.351.fits`	0.85	−0.065	1.022	NGC 2298	`I_BESS`
`FORS2.2011-12-08T06:07:53.723.fits`	0.94	0.065	1.022	NGC 2298	`v_HIGH`
`FORS2.2012-01-01T04:21:08.559.fits`	0.47	−0.017	1.026	NGC 2298	`I_BESS`
`FORS2.2012-01-17T08:10:06.673.fits`	0.85	−0.041	1.306	Leo I	`R_SPEC`

zeropoints again from a data set covering August 2011 to January 2012. The resulting zeropoints were in general 0.03 mag fainter than the ones used in the FORS2 pipeline at that time, which does not fully explain the underestimated extinction coefficients. We therefore investigated the `fors_zeropoint` pipeline recipe more closely.

We improved the calculation of the zeropoint and extinction terms per frame by increasing the number of detected standard stars and optimizing the coefficients in the `SExtractor` configuration file used in the `fors_zeropoint` pipeline recipe as described below.

2.1 Update of the Stetson Catalogue of Standard Stars

In December 2011, the September 2007 version of the Stetson catalogue of standard stars was used by the pipeline. A newer version is available (December 2010), which contains the BVRI photometry of a larger number of stars in the fields that are part of the calibration plan. In particular, it increases the detections in the `T_Phe` field from 2–3 per chip to 9–10 per chip; this represents a potential decrease of the noise in the derived photometric parameters by a factor $\sqrt{3}/\sqrt{10} \approx 0.55$.

The December 2010 version of the Stetson catalogue had been implemented for processing by QC on 2012-08-12 and has been included in the pipeline since release 4.9.9.

2.2 Optimizing the `fors.sex` Configuration File

The `fors_zeropoint` recipe within the FORS2 pipeline uses `SExtractor` to detect stars, calculate and subtract the sky background, and perform aperture photometry. The parameters used by `SExtractor` are stored in the `fors.sex` configuration file, distributed with the FORS2 pipeline.

We studied the effects of some of the parameters used by `SExtractor` on the calculated zeropoint and extinction, using a set of five frames producing negative (or very low) extinction coefficients (Table 3).

1. **Aperture size**
   The default aperture diameter used by `SExtractor` is 56 pixels (parameter `PHOT_APERTURES`), which corresponds to 7″ with FORS2 (with the SR collimator). This relatively large default value was chosen to ensure that all the flux from the star is collected, also for observations with bad seeing conditions and bad instrument focusing, and was based on the parameters used by the Landolt catalogues. We used the images listed in Table 3 (p. 11) to test the effect of different aperture sizes on the measurements. The general trend is that the larger the

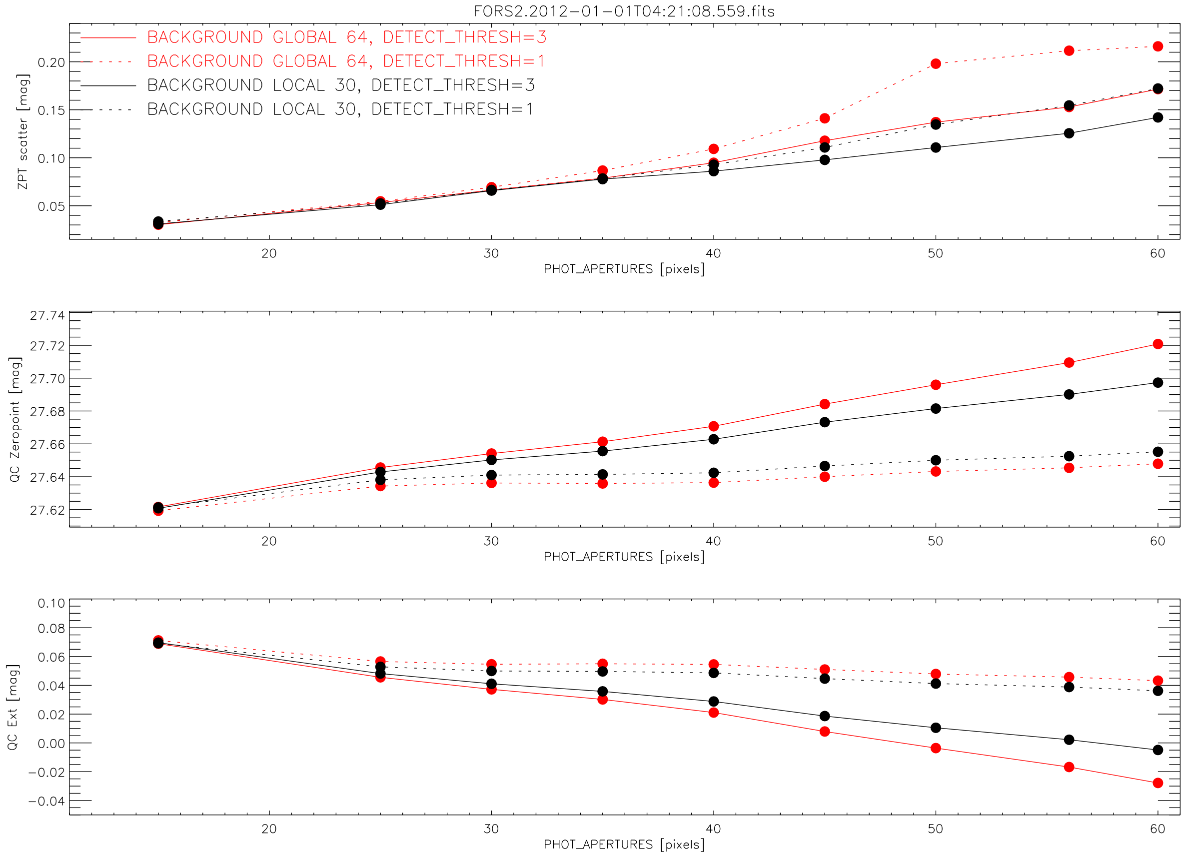

Figure 2: Photometric measurements as a function of aperture size, and `SExtractor` parameters for FORS2.2012-01-01T04:21:08.559 (upper chip, `I_BESS`). Top panel: scatter in the difference between catalogue magnitudes and pipeline magnitude. Central panel: frame zeropoint computed by `fors_zeropoint` (assuming extinction from static calibration files). Bottom panel: extinction coefficient (assuming zeropoint from static calibration files). Red lines correspond to `BACK_PHOTOTYPE=GLOBAL` background subtraction with a size of the background mesh of 64 pixels, black lines correspond to `BACK_PHOTOTYPE=LOCAL` and `BACKPHOTO_THICK=30`. Continuous lines correspond to `DETECT_THRESH=3`, dotted lines correspond to `DETECT_THRESH=1`.

aperture, the fainter the zeropoint determination, and the smaller the extinction coefficient. This suggests that the background level is not properly subtracted. Moreover, we observe an increase in the scatter in the difference between catalogue magnitudes and pipeline magnitudes. This is to be expected since large apertures increase the noise in the measurements, especially in crowded fields, where undetected (and thus uncorrected) sources enter in the aperture. A good compromise between sufficient aperture size to collect all flux and reducing the noise needs to be reached. For most of the images studied an aperture diamter of 40 pixel fulfils this requirement, even though the example shown in Fig. 2 (p. 12) suggests a possible aperture diameter as small as 30 pixels.

This first result clearly indicates where to operate: removal of fainter sources to reduce noise in the measurements (see point 2) and improve the background subtraction (see points 3 and 4).

2. **Detection Threshold**
   The default detection thresholds in `fors.sex` are optimized for bright stars measured with classical aperture photometry, i.e. faint stars inside the aperture do not need to be corrected:

   ```
   DETECT_MINAREA 5 # minimum number of pixels above threshold
   DETECT_THRESH 3 # <sigmas>
   ```

   Reducing both values will ensure that also faint objects are detected and removed when computing aperture photometry, improving the accuracy of the measurements. In fact we see that the scatter in the difference between catalogue magnitudes and pipeline magnitudes is smaller when using `DETECT_THRESH=1` or `DETECT_THRESH=1.5`.

   Moreover, tests show that reducing `DETECT_THRESH` to `1` significantly decreases the measured zeropoints of the test fields and thus increases the measured extinction. However, setting the threshold this low results in correcting positive noise peaks (detected as stars), but leaving negative ones. It also increases the number of supposedly detected stars to a level where the identification in actually sparse fields no longer works. We therefore decide to use 1.5 σ as the detection threshold. Changes in `DETECT_MINAREA` show no effect as long as one stays at values of `3` or more.

3. **Background Size**
   Changing the size of the background grid `BACK_SIZE` from `64` to `100` and `200` pixels, respectively, has no clear effect, nor does a slight increase in the median size `BACK_FILTERSIZE` from `3` to `4`.

4. **Background Type**
   Changing to `BACK_PHOTOTYPE=LOCAL` instead of `GLOBAL` shows a similar effect as reducing the detection threshold. However, the default value for the local sky background annulus is not clear and should therefore be set explicitly via `BACKPHOTO_THICK`. The effect on the measured zeropoints/extinction is largest for the smallest sky background annulus, as expected, as then the difference with respect to the `GLOBAL` mode can be largest because only a very local portion of the sky close to the object is taken into account.

   Tests with various values for the size of the sky background annulus `BACKPHOTO_THICK` show a tendency for smaller zeropoint scatter with `BACKPHOTO_THICK=30` as compared to `BACKPHOTO_THICK=10`.

2.3 Results of the Optimization

The tests detailed in Sections 2.1 and 2.2 suggest to us to adopt the following updates:

- Update of file `stetson_std_BVRI.fits`, from the September 2007 version to the December 2010 version (pipeline version 4.9.9).
- Update the `fors.sex` configuration file with the following new settings (pipeline version 4.9.11, used by QC since 2012-08-12):

  ```
  DETECT_THRESH 1.5
  PHOT_APERTURES 40
  BACK_PHOTOTYPE LOCAL
  BACKPHOTO_THICK 30
  ```

The example shown in Figure 2 supports these conclusions from Sect. 2.1 and 2.2. In the figure, the rms scatter in the individual zeropoints, zeropoint value and extinction coefficient are reported as a function of aperture size, considering different detection thresholds and different background subtractions. On average, the new settings provide the best solution in the sense that the scatter is decreased (i.e. measurements are more precise), the zeropoint and extinction do not increase/decrease with aperture size (i.e. the background and any additional sources are properly subtracted).

Tests show that the identification of stars is sometimes problematic. In a first attempt to increase the number of stars in the catalogue the software should use all standard stars in the field to determine possible shifts, even if they do not have a measurement in the respective filter (DFS11574). This change will then also allow to add astrometric catalogues to increase the numbers of identifiable stars if necessary

3 Photometric Parameters from Multiple Nights

A cronjob for `fors2@dfo26` runs the script `fors_photometry.sh` (current version 2.1) every day. This script collects the products created by the pipeline recipe `fors_zeropoint` from standard star observations for a time range around a date 4 weeks in the past. This time range was set to ensure that only certified products of `fors_zeropoint` are used for the analysis. The original time range was set to ±2 weeks around the given date, without any distinction between photometric and non-photometric nights. The script then calls the pipeline recipe `fors_photometry` to determine a single zeropoint and nightly extinction coefficients from the results of `fors_zeropoint`. The values of the zeropoint and the extinction coefficient for the central night are stored in the database table `qc1..fors2_photometry`. Looking at the results of this routine for data taken with the old calibration plan three disturbing features are evident[2]:

1. a correlation between zeropoint and extinction coefficient (cf. Fig. 3, p. 15)
2. jumps in the zeropoints (cf. Fig. 4, p. 15)
3. negative or extremely high extinction values (cf. Fig. 5, p. 16)

In order to verify if these problems have been solved with the new calibration plan we downloaded the results of the cronjob for the time range 2011-11-07 (first date completely covered by new calibration plan) to 2012-02-28. In addition we downloaded the results obtained one year earlier with the old calibration plan, i.e. 2010-11-07 to 2011-02-28. Within this time interval the mirror of UT1 was re-coated, but this break point has been taken into account within the procedure called by the cron job, i.e. for any date before/after a re-coating only data from before/after the re-coating are used.

Unfortunately it turns out that the results of the old and the new calibration plan are indistinguishable (see Figs. 6, 7, and 8, pp. 16–17), i.e. all problems listed above persisted so far with the new calibration plan.

Triggered by this unsatisfactory result we looked deeper into the data used to derive the zeropoints and nightly extinction coefficients. Earlier tests reported in VLT-TRE-ESO-13112-5429 showed that a minimum number of *photometric nights* needs to be present for `fors_photometry` to provide reasonable results. From here on photometric refers to an independent determination

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[2] Since not all features are present at all times the plots may refer to different time ranges.

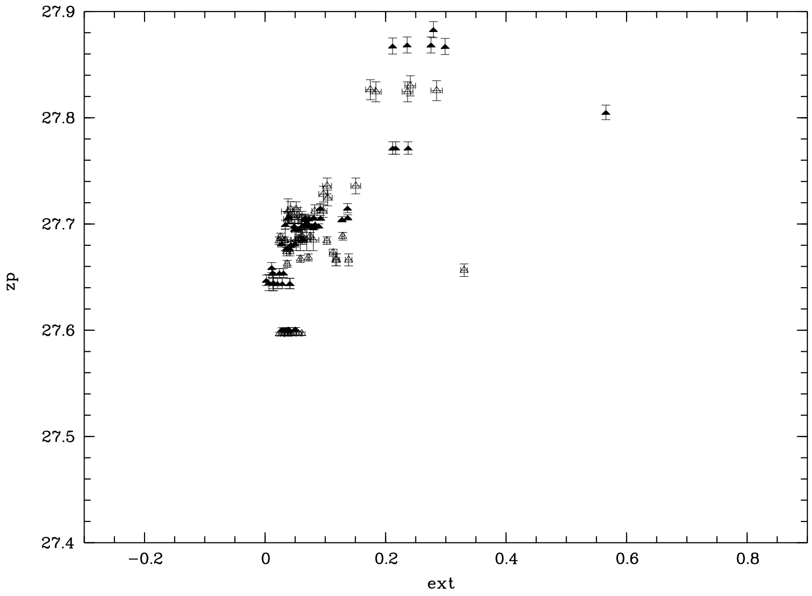

Figure 3: Zeropoints vs. nightly extinctions derived with `fors_photometry` for the time range 2010-11-07 to 2011-02-28 for the `I_BESS` filter. For easy comparison the limits along the y-axis are the same as for Fig. 6 (p. 16). Data from the upper and lower CCD are marked by filled and open triangles, respectively.

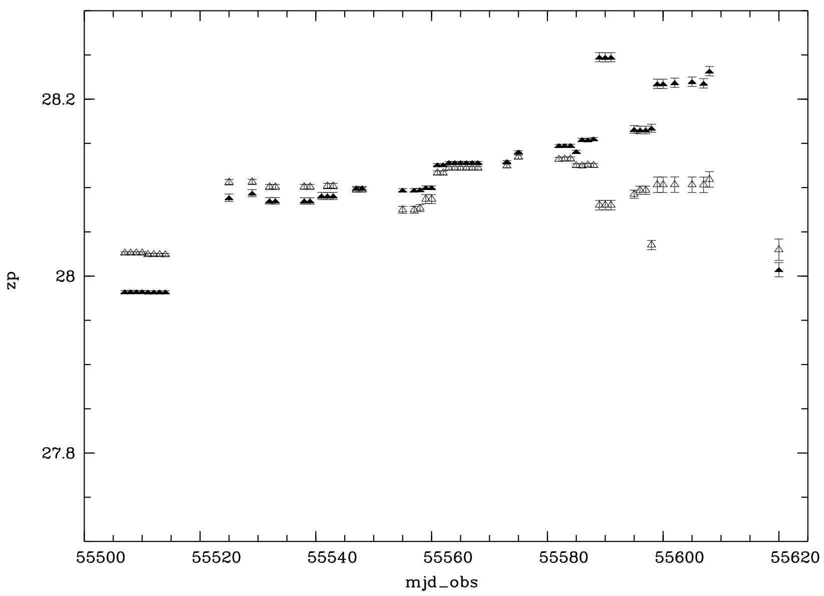

Figure 4: Zeropoints derived with `fors_photometry` vs. `MJD-OBS` for the time range 2010-11-07 to 2011-02-28 for the `b_HIGH` filter. For easy comparison the limits along the y-axis are the same as for Fig. 7 (p. 17). Data from the upper and lower CCD are marked by filled and open triangles, respectively.

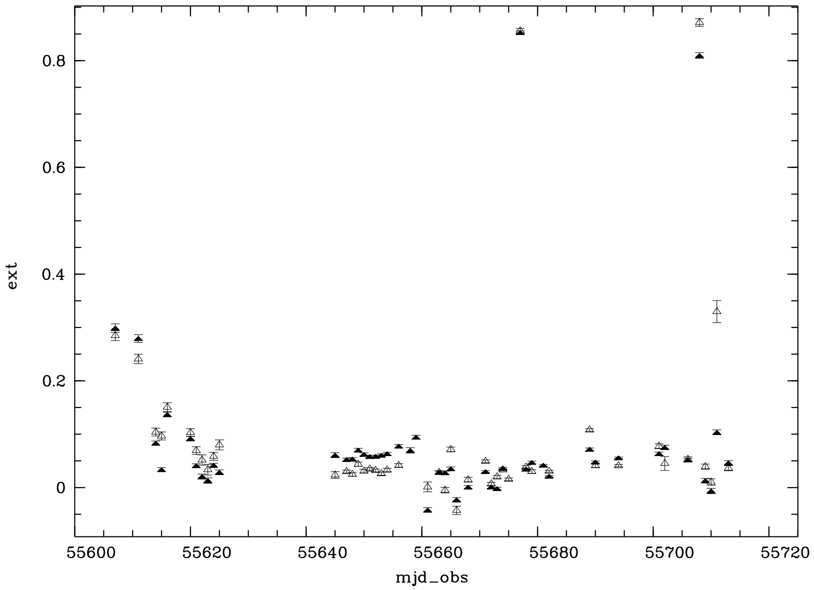

Figure 5: Nightly extinction coefficients derived with `fors_photometry` vs. `MJD-OBS` for the time range 2010-02-14 to 2011-06-08 for the `I_BESS` filter. For easy comparison the limits along the y-axis are the same as for Fig. 8 (p. 17). Data from the upper and lower CCD are marked by filled and open triangles, respectively.

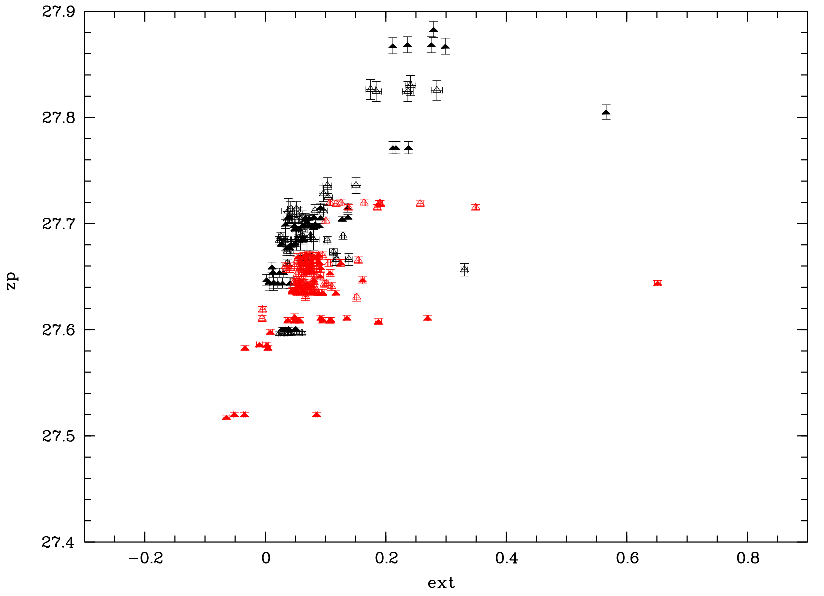

Figure 6: Zeropoints vs. nightly extinctions derived with `fors_photometry` for the `I_BESS` filter for the time ranges 2010-11-07 to 2011-02-28 (black) and 2011-11-07 to 2012-02-28. Data from the upper and lower CCD are marked by filled and open triangles, respectively.

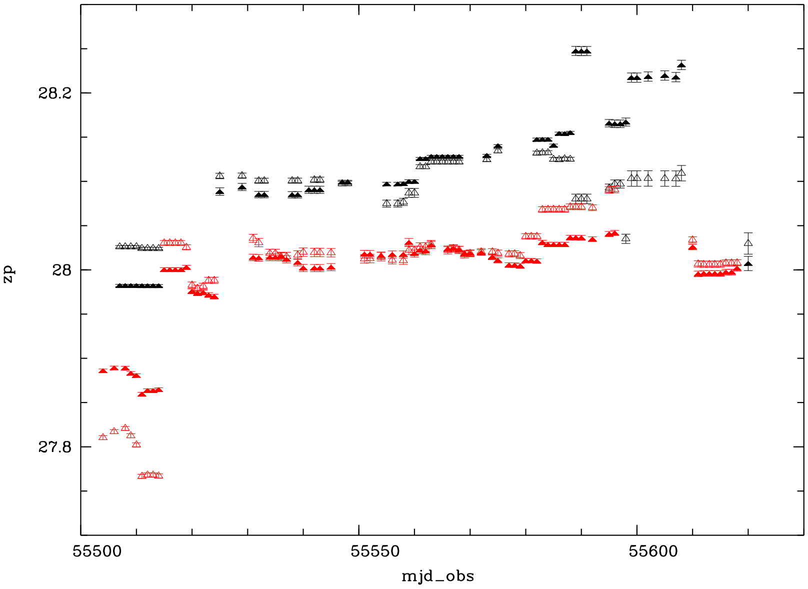

Figure 7: Zeropoints derived with `fors_photometry` vs. `MJD-OBS` for the `b_HIGH` filter for the time ranges 2010-11-07 to 2011-02-28 (black) and 2011-11-07 to 2012-02-28 (shifted by 366 days so as to allow direct comparison). Data from the upper and lower CCD are marked by filled and open triangles, respectively.

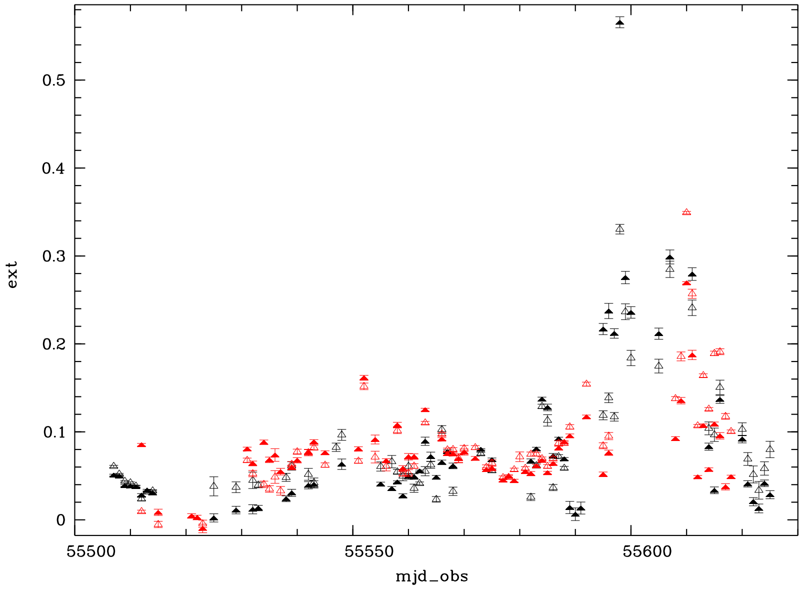

Figure 8: Nightly extinction coefficients derived with `fors_photometry` vs. `MJD-OBS` for the `I_BESS` filter for the time ranges 2010-11-07 to 2011-02-28 (black, different from Fig. 5, p. 16) and 2011-11-07 to 2012-02-28 (shifted by 366 days so as to allow direct comparison). Data from the upper and lower CCD are marked by filled and open triangles, respectively.

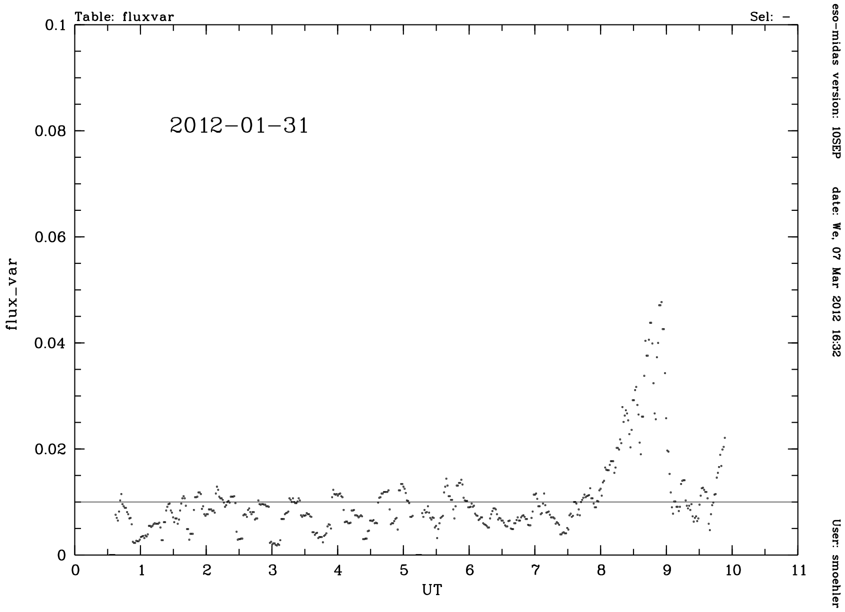

Figure 9: `LOSSAM` data for the night starting on 2012-01-31 (classified as non-photometric).

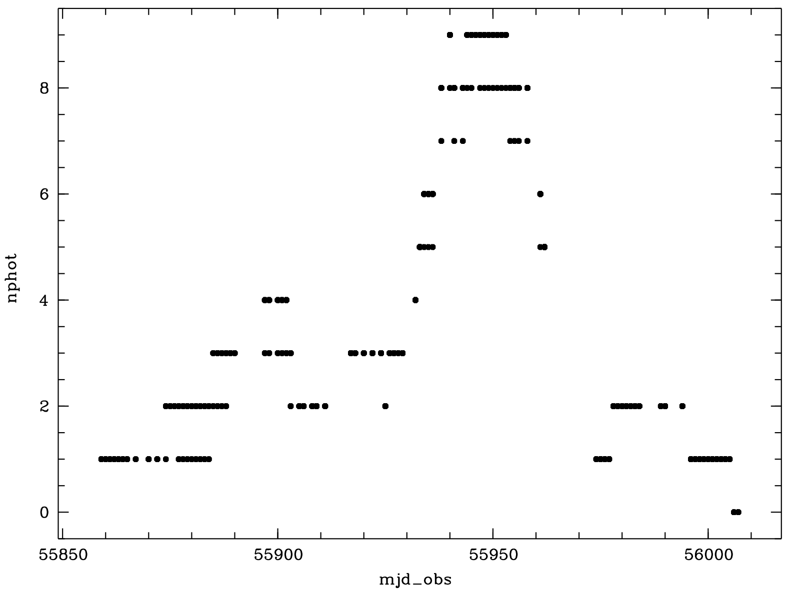

Figure 10: Number of photometric nights within ±14 days around a given date for the time range 2011-11-07 to 2012-02-28

from `Line Of Sight Sky Absorption Monitor (LOSSAM)` measurements. A night is defined as photometric if there are no flux variations above $(0.01{+}1.5\sigma)$ mag, where σ is the rms scatter of the flux measurements for that night. Thus a night is always classified photometric or non-photometric as a whole and not in parts as is often done at the VLT. Fig. 9 (p. 18) shows such a case. The night, for which the `LOSSAM` data are plotted, was classified as photometric from 1:56 UT to 3:36 UT and again from 4:09 UT to 8:27 UT in the nightlog, while it was classified as non-photometric by us.

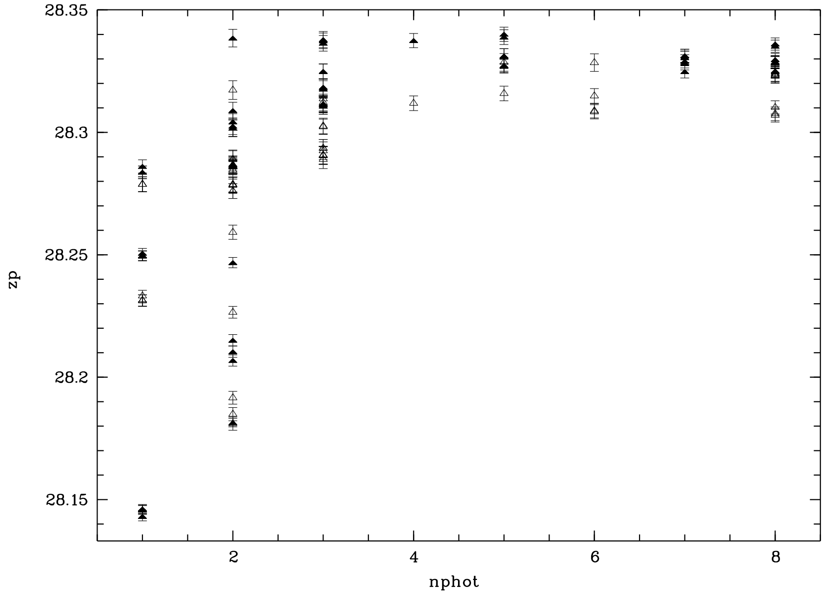

Figure 11: Zeropoints derived with `fors_photometry` vs. number of photometric nights used for their determination for the time range 2011-11-07 to 2012-02-28 and the `R_SPEC` filter. Data from the upper and lower CCD are marked by filled and open triangles, respectively.

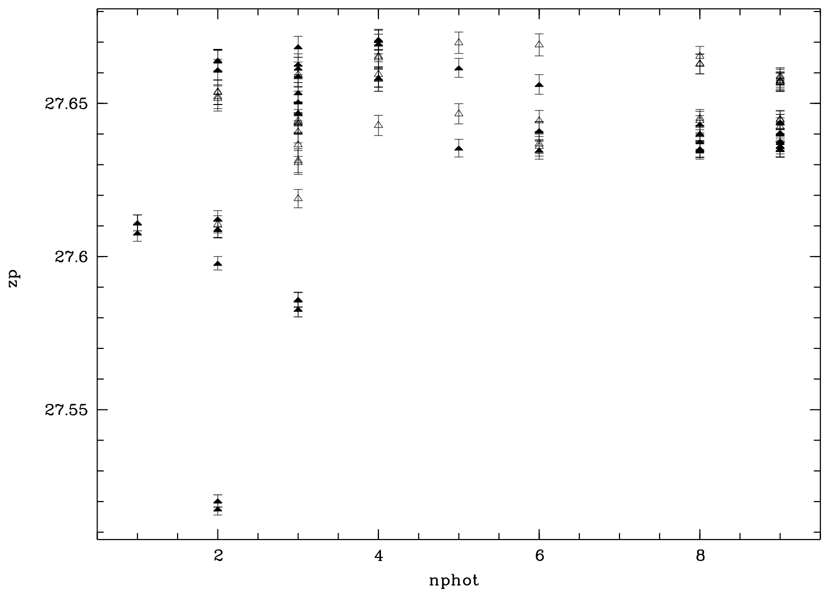

Figure 12: Zeropoints derived with `fors_photometry` vs. number of photometric nights used for their determination for the time range 2011-11-07 to 2012-02-28 and the `I_BESS` filter. Data from the upper and lower CCD are marked by filled and open triangles, respectively.

Fig. 10 (p. 18) shows the number of photometric nights that were used to model a given night. Obviously the number of photometric nights per data point varies strongly. Figs. 11 (p. 19) and 12 (p. 19) show how the stability of derived zeropoints changes with the number of photometric nights.

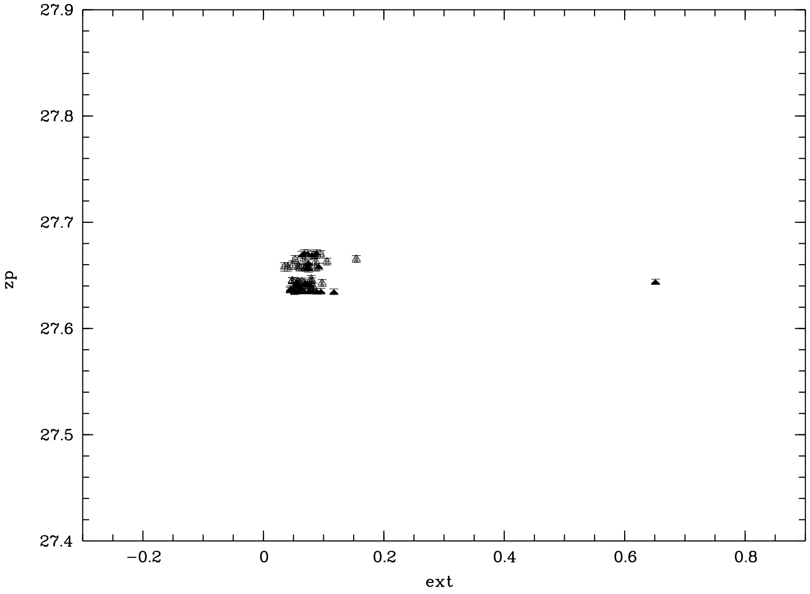

Figure 13: Zeropoints vs. nightly extinctions derived with `fors_photometry` for the `I_BESS` filter for the time range 2011-11-07 to 2012-02-28 for data points including at least 4 photometric nights within +/−14 days around the date considered. Data from the upper and lower CCD are marked by filled and open triangles, respectively. For easy comparison the limits along the y-axis are the same as for Fig. 6 (p. 16).

Figs. 13, 14, and 15 (pp. 20–21) show the same plots as Figs. 6, 7, and 8 (pp. 16–17), but only for data points including at least 4 photometric nights within +/−14 days around the date considered.

We then studied the stabilizing effects of increasing the minimum number of photometric nights as well as the effect of admitting *only* photometric nights (with the possible exception of the "central" night). Leaving out non-photometric nights – as expected – improves the stability of the results. Also requiring 7, 10, and at last 15 photometric nights resulted in a monotonic decrease in the scatter of the derived zeropoints. There is, however, a downside to using a high minimum number of photometric nights. In the case of at least 15 fully photometric nights sometimes a range of more than 120 nights had to be covered to achieve that number. Over such a long time range changes in the zeropoint are very probable, due to either a slow decrease in reflectivity or interventions like mirror cleaning or re-coating. We therefore decided in the end as a compromise to use a minimum of 7 photometric nights. The results for that choice are plotted in Figs. 16, 17, and 18 (pp. 22– 23).

As can be seen in Fig. 17 (p. 22) the derived zeropoints some show significant jumps, usually for nights during which the extinction varied. This is a problem of the procedure, because in the photometric calibration model that we are fitting we *assume* that each night can be characterized by a single extinction coefficient. While this is always true for a night in which a single image is taken (regardless of whether the night is photometric or not), it may not be a valid assumption if the atmospheric transparency varies between images taken on a single night (e.g. because of passing clouds, etc.). In this case, the extinction coefficient that is being fit for that night is serving as an "average" extinction coefficient.

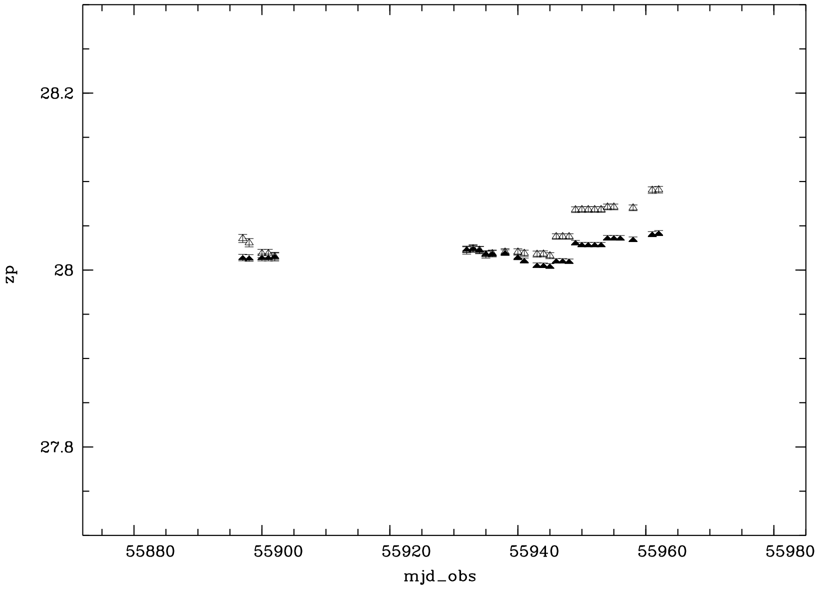

Figure 14: Zeropoints derived with `fors_photometry` vs. `MJD-OBS` for the `b_HIGH` filter for the time range 2011-11-07 to 2012-02-28 for data points including at least 4 photometric nights within +/−14 days around the date considered. Data from the upper and lower CCD are marked by filled and open triangles, respectively. For easy comparison the limits along the y-axis are the same as for Fig. 7 (p. 17).

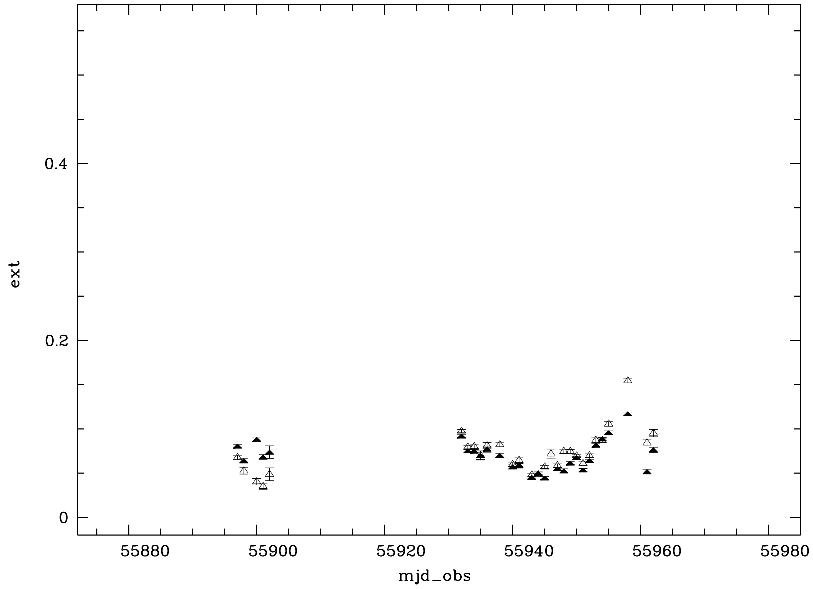

Figure 15: Nightly extinction coefficients derived with `fors_photometry` vs. `MJD-OBS` for the `I_BESS` filter for the time range 2011-11-07 to 2012-02-28 for data points including at least 4 photometric nights within +/−14 days around the date considered. Data from the upper and lower CCD are marked by filled and open triangles, respectively.

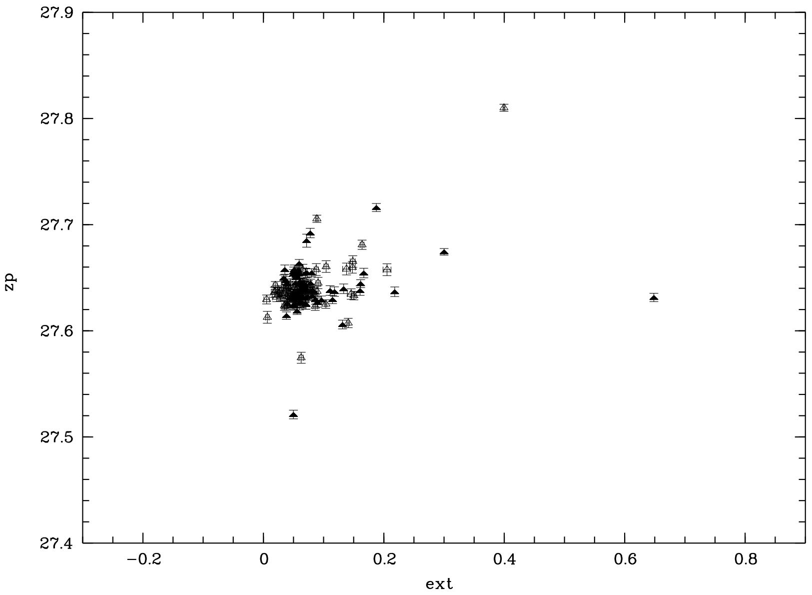

Figure 16: Zeropoints vs. nightly extinctions derived with `fors_photometry` for the `I_BESS` filter for the time range 2011-11-07 to 2012-02-28 with at least 7 photometric nights per data point and new `SExtractor` settings for `fors_zeropoint` (see Fig. 3, p. 15, for QC results). Data from the upper and lower CCD are marked by filled and open triangles, respectively. For easy comparison the limits along the y-axis are the same as for Fig. 6 (p. 16).

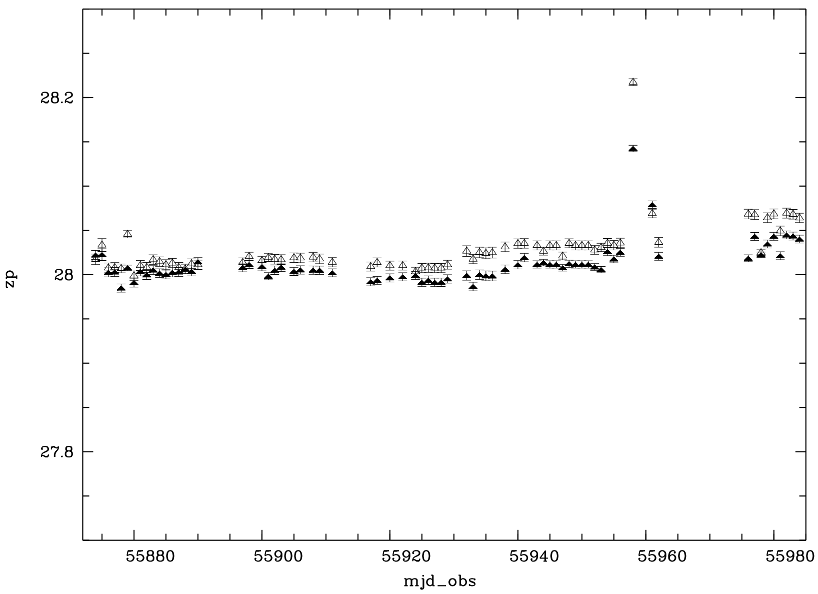

Figure 17: Zeropoints derived with `fors_photometry` vs. `MJD-OBS` for the `b_HIGH` filter for the time range 2011-11-07 to 2012-02-28 with at least 7 photometric nights per data point and new `SExtractor` settings for `fors_zeropoint` (see Fig. 4, p. 15, for QC results). Data from the upper and lower CCD are marked by filled and open triangles, respectively. For easy comparison the limits along the y-axis are the same as for Fig. 7 (p. 17).

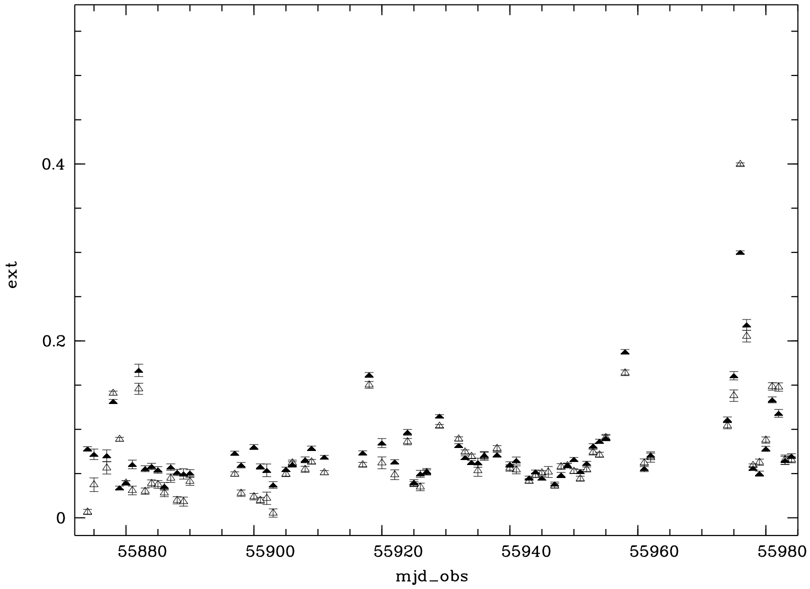

Figure 18: Nightly extinction coefficients derived with `fors_photometry` vs. `MJD-OBS` for the `I_BESS` filter for the time range 2011-11-07 to 2012-02-28 with at least 7 photometric nights per data point and new `SExtractor` settings for `fors_zeropoint` (see Fig. 5, p. 16, for QC results). Data from the upper and lower CCD are marked by filled and open triangles, respectively.

The size of the uncertainty calculated for each extinction coefficient does not depend on the suitability of adopting a single extinction coefficient for each night. The extinction coefficient uncertainties instead solely depend on the uncertainties in the photometric measurements, which will be somewhat larger on nights with overall lower transparency, *and not on their scatter with respect to the fit.* The best way to assess if the adopted photometric model is suitable for any one night is to look at the photometric measurement residuals relative to the photometric model for that night.

The gaps seen in Fig.17 at `MJD-OBS` around 55895, 55915, and 55970 correspond to times when the blue-sensitive CCD was attached to FORS2. The small jumps seen in between might be due to mirror cleanings. Unfortunately we could not find any record of these activities, so that we cannot verify this scenario.

A comparison of earlier results to results from an independent `IDL` script showed that fitting two zeropoints but only one extinction coefficient (per night, for both CCDs) yielded more stable results. With the new settings reported here this effect can no longer be seen (see Fig. 19, p. 24) – instead now the zeropoints derived with separate extinction coefficients are more stable.

We showed above that the selection of photometrically stable nights is essential for the determination of the instrumental zeropoints, because the `fors_photometry` recipe is extremely sensitive to extinction variations during the night as it assumes that every night can be characterized by a single extinction coefficient. This problem could be solved by allowing extinction variations within the recipe. However, such a change would constitute a major re-structuring of the FORS pipeline and currently resources to carry out such a project are not available. Therefore, we decided to test the pragmatic approach of pre-selecting the input data to the `fors_zeropoint` recipe to eliminate data from non-photometric nights. We tested two different methods to do so.

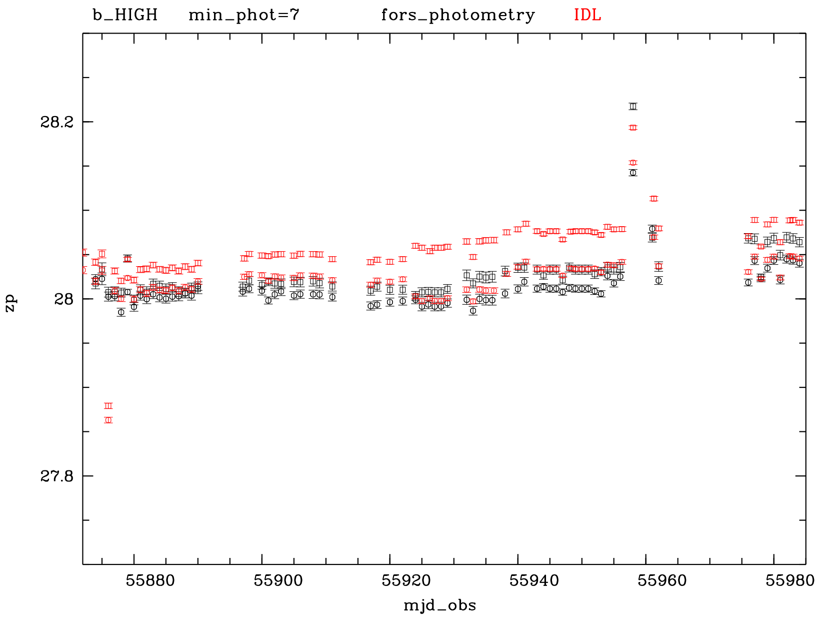

Figure 19: Zeropoints derived with `fors_photometry` vs. `MJD-OBS` for the `b_HIGH` filter for the time range 2011-11-07 to 2012-02-28 with at least 7 photometric nights per data point and new `SExtractor` settings for `fors_zeropoint` (see Fig. 4, p. 15, for QC results). Data from the upper and lower CCD are marked by filled and open triangles, respectively. Red symbols show the results from the `IDL` script, which fits one common extinction coefficient for both chips. For easy comparison the limits along the y-axis are the same as for Fig. 7 (p. 17).

The first approach was to rely on the `LOSSAM` data to determine if a night was fully photometric (see p. 18). However, about 8 months after the start of the new calibration plan we encountered a night for which the `LOSSAM` data stayed below the limit for photometric stability, but the extinction coefficients derived from FORS2 standard star observations showed a large variation during the night (from 0.22 mag/airmass in the `b_HIGH` filter to 0.16 mag/airmass in the `I_BESS` filter). The night log for that night states `‘‘22:00 CL : Clear Sky. Thick Clouds below 25 degrees East and South’’` and the observation with the high extinction was obtained when the standard star field was east by 3.5 hours hour angle, at 23:15UT. So the high extinction is probably caused by some extension of the thick clouds reported in the night log, which went unnoticed by the `LOSSAM` as it does not observe at high airmass. This illustrates again a fundamental limitation of the whole project, namely the determination of the photometric stability for a given night. We had chosen `LOSSAM` data because they cover full nights, while FORS2 standard star images are taken only a few times per night. The fact, however, that the `LOSSAM` data cannot identify non-photometric nights in all cases was confirmed by a recent e-mail from Marc Sarazin stating `‘‘LOSSAM is above all a cloud detector, not an extinction monitor...The plots`[3] `you refer to are generated by a script designed for the commissioning phase 14 years ago and were never intended to be used in operation, thus the 0.01 limit.’’`

We therefore decided to use a different approach, selecting instead stable nights as nights with extinction variations (as measured by FORS2 standard star observations) below 0.06 mag/airmass

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[3] http://www.eso.org/gen-fac/pubs/astclim/forecast/meteo/CIRA/images/repository/lossam/

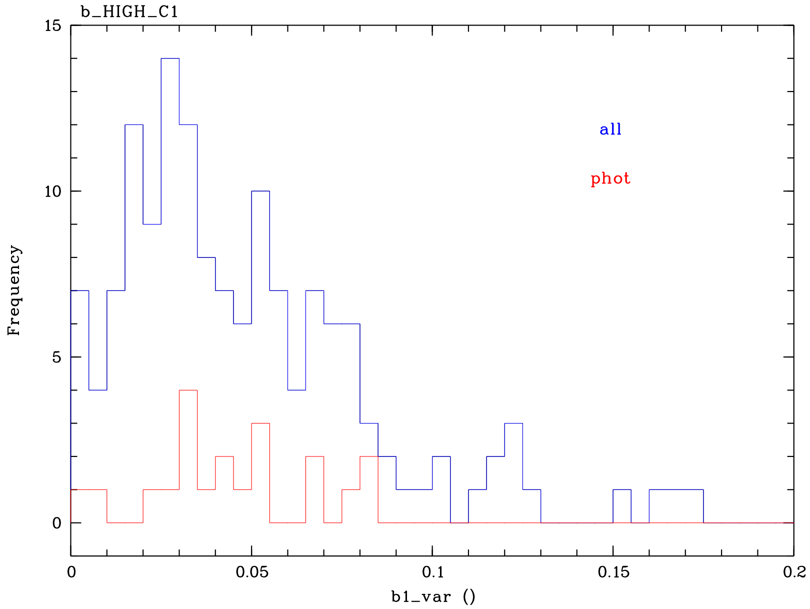

Figure 20: Histogram of the variation of extinction coefficients during a given night for observations with the `b_HIGH` filter and `CCID20-14-5-3`. The extinction coefficients were derived from individual standard star field observations with the pipeline recipe `fors_zeropoint`, assuming an instrumental zeropoint. The blue curve shows the values for all nights with at least 2 measurements since 2011-10-23, the red curve shows the distribution for nights qualified as photometric from `LOSSAM` data.

for `b_HIGH` and 0.05 mag/airmass for the other standard filters. These limits were chosen by looking at the extinction variations observed since 2011-10-23 (see Fig. 20 for a histogram of these variations from observations with the `b_HIGH` filter and `CCID20-14-5-3`).

All histograms showed that the extinction variations observed on supposedly photometric nights (from `LOSSAM` data) covered almost the same range as the majority of all nights. Therefore we used the position of the peak for all nights and multiplied it by 2, assuming a symmetric distribution of variations. Fig. 21 shows the results of the modified filtering of input data to `fors_photometry` for `b_HIGH` observations with `CCID20-14-5-3`.

4 Did FAP reach its goals?

Finally, we carried out some test to determine whether the photometric parameters derived with our procedure are accurate enough to reach the stated goals of FAP to achieve photometric accuracy of 3%. Tests showed that when using the derived photometric parameters to calibrate science frames on a photometric night, the 1σ systematic error is about 2%. The calibration was better than 3% in 97% of all cases we investigated.

5 Estimating the Transparency Conditions at the Telescope

SDP provided two scripts to PSO to facilitate the decision on the photometric quality of a night:

1. **zeroupdate**
   This script retrieves the zeropoints determined by `fors_photometry.sh` from the `qc1..fors2_photometry`

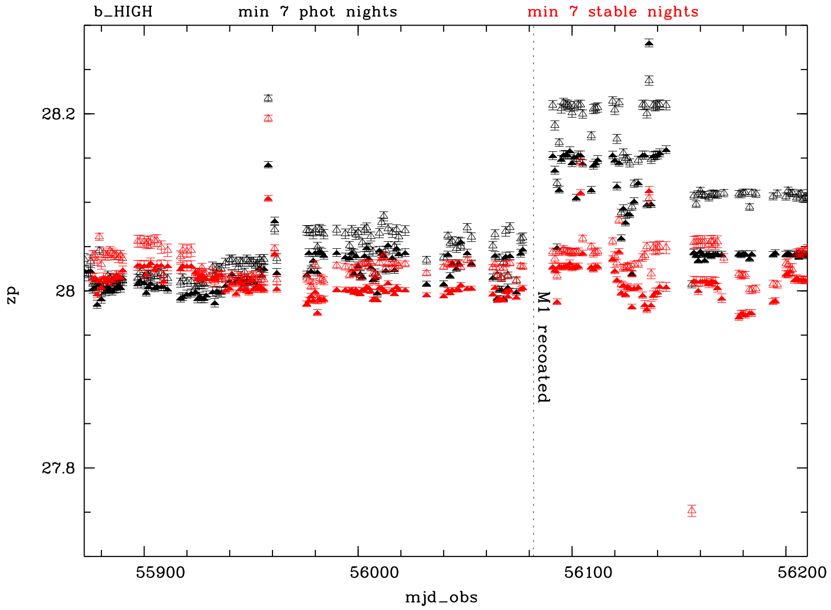

Figure 21: Plot of instrumental zeropoints vs. time since 2011-11-10. The black symbols were derived using at least 7 photometric nights derived from `LOSSAM` data. The red symbols were derived using the new stability criterion (derived from results of `fors_zeropoint`. Data from the upper and lower CCD are marked by filled and open triangles, respectively. The high values for the black points after the re-coating are primarily due to the inclusion of 2012-06-25 as photometric night.

database table and writes them to the `PHOT_TABLE` files used by `fors_zeropoint` to estimate the extinction from a single observation of a standard star field. To reduce the impact of zeropoints from nights with varying extinction the script now uses a median of the last three zeropoints instead of just the last zeropoint.

2. **FORS_ZP**
   This script collects the extinction coefficients written to the pipeline products by `fors_zeropoint` and compares them to pre-defined thresholds. In the first weeks after re-coating the zeropoints retrieved by **zeroupdate** will reflect the situation before the re-coating due to the time delay of 4 weeks (see Sect. 3, p. 14). The script therefore checks if extinction coefficients are below the typical values for photometric nights by more than 0.06 mag. If this is the case a correction of 0.09 mag is applied to the nominal zeropoint (typical offset after re-coating) to the zeropoints in `PHOT_TABLE` and the extinction is rederived. Also a warning is issued that this correction has been applied.

6 Summary of Implemented Changes

- Changes to calibration plan after Oct. 24, 2011: Together with I. Saviane we revised the description of the calibration plan (incl. extinction limits) and the use of the `stdsopMain` tool on 2012-02-15 and clarified the procedure to follow if FORS2 does not start the night

- Changes to pipeline settings

- updated Stetson catalogue to the December 2010 version with pipeline version 4.9.9.
- updated the `fors.sex` configuration file with the following new settings with pipeline version 4.9.11:

  ```
  DETECT_THRESH 1.5
  PHOT_APERTURES 40
  BACK_PHOTOTYPE LOCAL
  BACKPHOTO_THICK 30
  ```

- Changes in scripts/pipeline
  - In order to increase the number of stars in the catalogue used for the determination of a possible shift in the World Coordinate System `fors_zeropoint` should use all standard stars in the field for this determination, even if they do not have a measurement in the respective filter (DFS11574).
  - We modified the selection process for the `fors_photometry.sh` script so that at least 7 stable nights are part of the dataset to be analysed and unstable nights (except the central night) are excluded.
  - We modified the scripts supporting PSO in the decision on the photometric quality of the nights to make them more stable.
  - PSO provides now a list of mirror cleaning dates that is updated daily: `http://www.pl.eso.org/sci/facilities/paranal/instruments/fors/tools/QC_UT1_M1_Cleaning.txt`