FORS1 is getting Blue: New Blue Optimised Detectors and High Throughput Filters

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Ground-based observations in the ultraviolet part of the electromagnetic spectrum are notoriously difficult owing to absorption of the atmosphere, of optical elements and the poorer efficiency of detectors. Now that CCD detectors with excellent UV response and cosmetic quality have become available, it was time to optimise FORS1 for imaging, low-resolution spectroscopic and polarimetric observations in the blue-UV. As a bonus, a new set of broadband filters with very high transmission and carefully defined filter bands were installed.

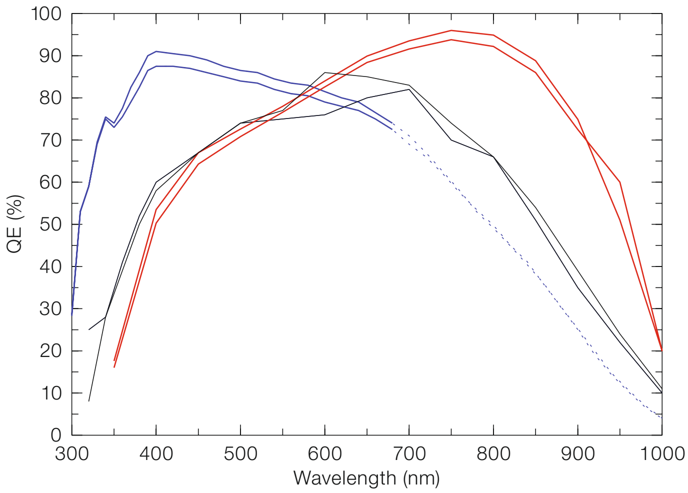

Figure 1: Comparison of the CCD efficiencies of FORS1 and FORS2 before and after the respective upgrades. Black: Tektronix CCDs; Red: FORS2 MIT CCDs; Blue: FORS1 E2V CCDs. The dotted part indicates the range affected by fringing (see text).

FORS – A brief history

FORS1 and FORS2 are two of the first-generation VLT instruments that were built by an external consortium (Landessternwarte Heidelberg, Universitätssternwarte München and Universitätssternwarte Göttingen, all in Germany). FORS1 was the first of the scientific facility instruments and saw first light at the Cassegrain focus of VLT-ANTU, on 15 September 1998 (Appenzeller et al. 1998). FORS2 followed in 2000 on VLT-Kueyen. The FORSes also served on Melipal and Yepun; currently they are installed again on Antu (FORS2) and Kueyen (FORS1). They are amongst the most scientifically productive instruments of the VLT: more than 750 refereed papers have been published to date with both FORSes. Many of these papers have achieved high scientific impact factors as indicated by nearly 20 000 citations.

Soon after it entered regular science operations, FORS2 received a major upgrade when its original 2k × 2k Tektronix detector was replaced (effective April 2002) by a mosaic of two red-optimised MIT/LL CCDs. Further upgrades included several prototype volume-phased holographic grisms (VPHG) that greatly boosted its scientific productivity. We intended to follow this highly successful example by adding similar capabilities to FORS1. The first stage in this process was the addition of the 1200 B VPHG that opened new opportunities for stellar and extragalactic observations by doubling the spectral resolution at very high grism throughput.

The upgrade

Following the purchase of the VPH grisms and the success of the new red detector mosaic of FORS2, it was clear that an upgrade of FORS1 with a blue-sensitive new mosaic would be a good complement to FORS2. The prospect of having the same detector format for both instruments was another strong driver: it allows essentially the same control and data-reduction software to be used with FORS1 and FORS2. When the hardware and the resources to carry out the upgrade became available, we seized the opportunity.

The Garching Optical Detector Team (ODT) prepared the hardware part of the upgrade, a pair of E2V blue-sensitive chips. ODT was in particular responsible for the selection and characterisation of the CCDs, the mounting and adjustment of the mosaic and the preparation of the detector control system (FIERA). The CCDs are named "Marlene", formerly the detector in the UVES blue arm, and "Norma III", one of the CCDs from the batch procured for OmegaCAM. The choice was motivated by a dramatic increase in the quantum efficiency of these two chips in the blue-UV compared to that of the existing Tektronix CCD, as can be seen in Figure 1.

The significant boost in the quantum efficiency of these CCDs has been achieved by subjecting them to a treatment of soaking in synthetic air, combined with UV light flashing. The precise physics of this effect is not known, however, the effect is reproducible and sufficiently long-lived so that it can be applied to an instrument in regular science operations. For a description of the process see Baade et al. (2005). Additional reasons for choosing these new detectors are that they can be read out much faster and have a lower read-out noise level, which is crucially important for dark-time spectroscopy and narrow-band imaging in the blue and UV. Finally the cosmetic quality of these detectors is far superior to that of the generation of the Tektronix detector used up to now with FORS1.

The properties of the new CCD mosaic are: 4096 by 4096 pixels, 15 µm square, binned 2 × 2 by default. The pixel scale is 0.25″ per (binned) pixel and the inter-chip gap width is 12.2″. The read-out noise as measured during the commissioning is about three electrons.

Strong support came from the Garching Integration and Cryo-Vacuum Department that prepared the cryostat and the various mechanical pieces required for the upgrade. An important part of the upgrade was the adaptation of the various pieces of software affected by the upgrade: Observation Software (OS), templates and the Observer Support Software (OSS) tool FIMS. These upgrades were done by members of the Paranal software department who greatly benefited from the fact that FORS2 already uses a similar mosaic and similar control software. Finally, the Exposure Time Calculator (ETC) and data-reduction pipeline had to be adapted and tested.

Installation and Commissioning was a joint enterprise of theParanal Science Operation Team and the Garching Instrumentation Division (see Figure 2). After two commissioning runs the upgraded system was certified in early April 2007 ready for science operations. This is the reason why the upgrade was only announced in the Call for Proposals (CfP) for Period 80. It would however have been hard to justify mothballing an excellent CCD system for six months and continuing operations with an old, inferior one. So it was decided to go already into P79 with the upgraded system and adjust the schedule where necessary at short notice in coordination with the PI's.

We also ordered a set of dichroic high throughput filters for the *U*, *B*, *V* and *g* bands to take further advantage of the new blue sensitivity of the mosaic. We specified a very high transmission, very carefully chosen central wavelengths and full width half maximum values so that the photometric flux can be nicely transferred to Vega magnitudes with standard stars selected from Landolt (1992). Colour corrections are typically smaller than 0.1 magnitudes. The resulting filter set (together with the already existing R_SPECIAL, I_BESS and z_GUNN filters) either matches the Bessel (1990) definition of the UBVRI or the Sloan Digital Sky Survey (SDSS; Fukugita et al. 1996) *ugriz* systems. The latter system has achieved great acceptance in the scientific community due to the large impact of the SDSS. Figures 3 and 4 compare the old FORS1/2 filters with the new ones, the latter manufactured by Asahi (Japan). Note that u_HIGH, b_HIGH, v_HIGH and R_BESS filters are only offered with FORS1 and the R_SPECIAL filter only with FORS2.

The new "HIGH" filters are available with FORS1 since April 2007 in Visitor Mode only, because they were not yet ready and characterised when the CfP for Period 79 went out in September 2006.

Figure 2: Old (left) meets new (right) – the two detector systems side by side on their dedicated carriages next to FORS1 in the enclosure of Kueyen.

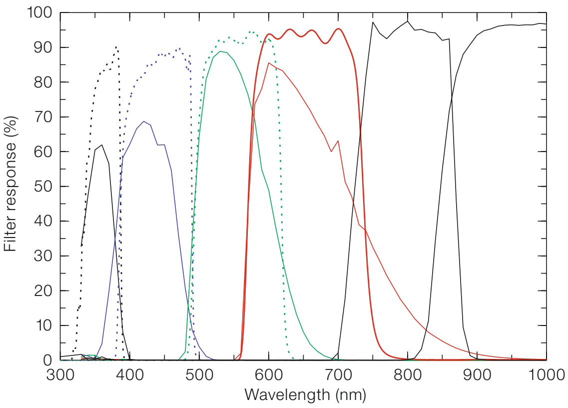

Figure 3: Transmission curves of the old (continuous lines) and new (dotted lines) FORS filters as measured in the ESO Optics Lab for Bessel *UBVRI* and *z*. The thin and thick red lines indicate the FORS1 R_BESS and the FORS2 R_SPECIAL filter, respectively.

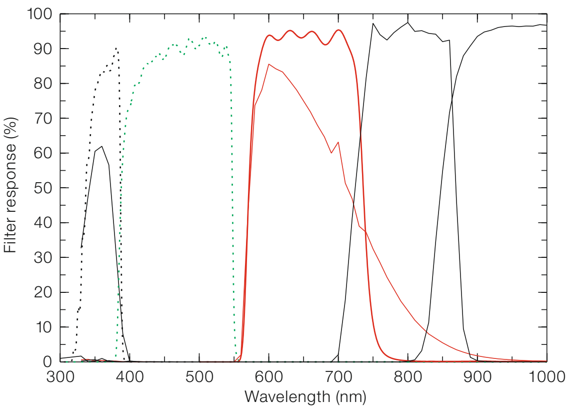

Figure 4: Transmission curves of the old (continuous lines) and new (dotted lines) FORS filters as measured in the ESO Optics Lab for SDSS *ugriz* filters. The thin and thick red lines indicate the FORS1 R_BESS and the FORS2 R_SPECIAL filters, respectively. The [OI] line at 557.7 nm falls exactly in the gap between *g* and *R*.

Let the game begin …

The new detector system saw its first sky light on 30 January 2007. During a first commissioning run lasting three nights we performed a thorough characterisation of the quantum efficiency, not only of the detectors but also of the new filters. Observations of numerous photometric and spectrophotometric standard stars proved that our expectations, based on the laboratory data, were correct. The new detector alone gave an improvement of 0.8 and 0.4 magnitudes in *U* and *B*, respectively, and the performance dropped (as expected) only slightly in the *I*-band. Using, in addition, the new high throughput filters resulted in a spectacular gain of 1.3 mag. in *U* and 0.8 and 0.3 mag. in *B* and *V*.

The response given here has been calculated from the photometric zero points measured during the first commissioning run, according to the following strategy. First we calculated the Vega flux, integrated over the filter curves. From the Vega flux we calculated the zero points for 100 % instrument and telescope throughput in magnitudes (27.41, 29.12, 29.21, 29.18, 28.78 in UBVRI and 27.93, 29.47, 29.33 and 29.90 in the ubvg filters, respectively) for incoming photons/sec at the 8-m aperture of the VLT (see Table 1). The overall instrument response can then be easily derived from the measured photometric zero points at zero airmass. Similarly the Vega zero points at 100 % response were calculated for the VIMOS *UBVRI* filters (27.93, 29.37, 28.96, 29.05 and 28.91 mag.) and for the FORS2 R_SPECIAL filter (29.33 mag.). The response is then given in units of detected electrons per incoming photon including the telescope, the FORS longitudinal Atmospheric Dispersion Corrector (ADC), the instrument optics and detector response, but not the filter transmission. This response is given in parentheses in Table 1 and demonstrates the high performance of FORS1, FORS2 and VIMOS in all filters.

In addition the new *g*-band filter opens a new observation window. It collects the flux from the astronomical targets over a wide wavelength range were the night sky is very dark and the atmospheric transmission is high (390 nm to 550 nm).

A second commissioning run (five nights in March/April 2007) finally verified the functioning of the system in all supported observing modes (imaging, long-slit and multi-object spectroscopy, imaging and spectropolarimetry).

Filter	FORS1 TEK	FORS1 e2v	FORS2 MIT	VIMOS e2v
U	25.20 (0.13)	26.53 (0.28)	n/a	26.5 (0.27)
B	27.70 (0.27)	28.48 (0.40)	27.70 (0.27)	28.20 (0.34)
g	n/a	28.89 (0.39)	n/a	n/a
V	28.05 (0.34)	28.33 (0.39)	28.10 (0.39)	27.90 (0.38)
R	28.00 (0.34)	27.96 (0.33)	28.40 (0.42)	27.90 (0.35)
I	27.15 (0.22)	26.99 (0.19)	27.70 (0.37)	27.0 (0.17)

Table 1: Zero points and instrument response for FORS1, FORS2 and VIMOS. Note that the VIMOS *U*-filter red cut-off is at 395 nm while it is at 385 nm for FORS1. Similar differences exist also for the other filters; therefore zero points do not allow a direct comparison of the absolute instrument response. The instrument response in detected electrons per incoming photon after eliminating the effect of the different filter sets is given in parentheses.

… even with some adverse effects

There is however a significant price to pay for high quantum efficiency in the blue-UV: the fringe pattern at near-infrared wavelengths, beyond approximately 700 nm, increases significantly as compared to the old (somewhat thicker) Tektronix detector and the spatial frequency of the fringes also increases strongly. The fringing has a heavy impact on high signal-to-noise observations.

For imaging observations the fringes will remain at high amplitude in the sky background, on account of its OH emission-line spectrum, after flat fielding with the solar spectrum twilight flat fields. The sky background with fringes is best subtracted by obtaining an averaged sky image cleaned from astronomical sources, scaled to the sky level of the individual exposures. More commonly observers obtain “super flats” from the night sky airglow images observed in a jitter sequence. While this method leads to a more pleasing image with a flat sky background, it strongly compromises the photometric accuracy, which better matches a continuous or solar-type spectrum than the OH airglow spectrum.

In spectroscopy, flat fields obtained with continuous light calibration lamps can, at least partly, correct the fringes. In theory the light that is detected by every pixel has the same wavelength for targets, sky and flat field lamps. The correction should therefore be possible. In practice, however, the slightly different light path of the calibration light as compared to the telescope optical path, together with the small flexure of the FORS instrument, prevents perfect fringe correction using flat field spectra. In first tests, we obtained signal-to-noise ratios of up to 15 at wavelengths greater than 700 nm (see Figure 5).

Many scientific projects with FORS1 are focused on detecting extremely faint objects at very low signal-to-noise ratios or will concentrate on the shorter wavelength range after the blue optimisation. To demonstrate the performance of FORS1, Figure 6 shows a spectrum of a $z = 2.42$ quasar of $g = 20.4$ magnitudes which was obtained in only 15 minutes of integration time.

In both imaging and spectroscopy it is mandatory to apply jitter and nodding techniques to obtain good sky subtraction. The fringes however will not be corrected in the extracted spectra of science targets and standard stars by the nod-

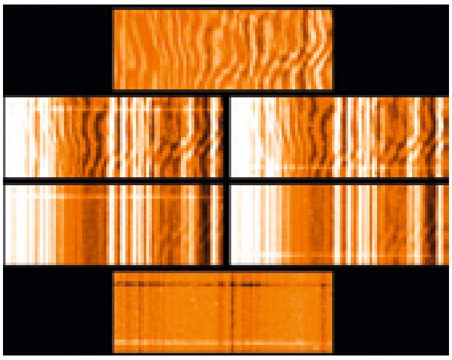

Figure 5: A demonstration of fringe correction with the new FORS1 detector. The top panel shows part of a spectroscopic (master) screen flat. The next two panels show parts of two bias-subtracted sections from 1200 s spectra taken with an offset along the slit (positions A (left), and B (right)). The two panels below show the same parts of the spectra, now divided by the master flat (top). Fringes are only partly corrected by the continuous light screen flat fields. The difference image of these two exposures (bottom) still contains significant sky background flux. A better result could be achieved using a sequence of four exposures (A-B-B-A).

ding technique. More details on this topic will be available on the FORS web pages. It should be noted that FORS2 has extraordinarily low fringe amplitude with its red-optimised MIT detector combined with the very low flexure it shares with its twin, FORS1. Users with strong requirements on fringe correction are therefore encouraged to choose FORS2.

In summary, the successful blue upgrade of FORS1 leads to a very promising complement to FORS2 that will further enhance the scientific productivity of this efficient and reliable pair of instruments.

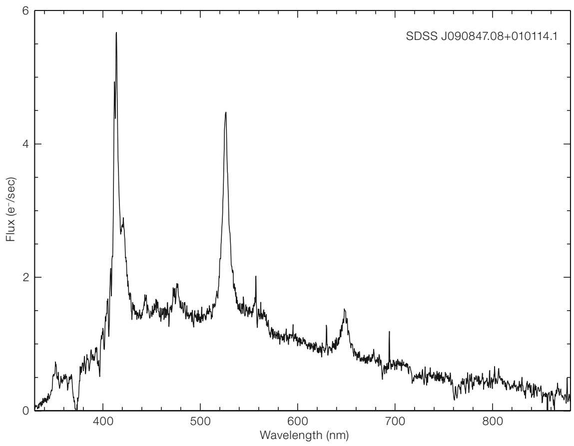

Figure 6: Extracted, airmass-corrected spectrum of the quasar SDSS J090847.08+010114.1 (20.4 mag in *g*-band, z = 2.42). Note that the spectrum (exposed for 15 minutes during dark time without order separation filter) is also shown in the red and near-infrared spectral range where the fringes are strongest. The strongest three emission lines (from left to right) are the hydrogen Lyman alpha line, C IV and C III] lines.

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VLT FORS1 image of the bubble nebula N76 around the hot binary star AB7 in the Small Magellanic Cloud, based on three exposures through narrowband filters isolating doubly ionised helium (He II, in blue), doubly ionised oxygen ([O III], in green) and singly ionised hydrogen (H-alpha, in red). The image measures 400 by 400 arcseconds and north is up and east to the left. The binary system AB7 (the bright stellar image in the centre of the nebula) consists of one evolved massive Wolf-Rayet star and a companion O-type star. The very high temperature of the stars is responsible for the centred He II nebula (blue region enclosed within the yellower ring). To the north-east, just outside the nebula, a small network of green filaments is visible, a remnant of an earlier supernova explosion. See ESO PR 08/03 for more details.