The X-shooter Imaging Mode

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X-shooter is a three-arm multi-wavelength (~ 300–2500 nm) medium resolution spectrograph installed on the VLT's Unit Telescope 3. From April 2014, a complementary imaging mode is offered to the astronomical community. This new observing mode uses the acquisition and guiding camera facility equipped with a set of Johnson and SDSS filters and gives the option of complementing the spectroscopic data with multi-band images and photometry. The main characteristics of the X-shooter imaging mode, an outline of its calibration and a few examples of scientific applications are presented.

Motivation for a limited imaging mode

Right from the design phase, there has been the intention to offer a complementary imaging mode for X-shooter, utilising its acquisition and guiding camera (AGCCD, see Sørensen et al. [2004]), in addition to its spectroscopic capabilities. Since X-shooter remains primarily a set of spectrographs (see Vernet et al., 2011), the imaging mode of X-shooter was not developed, commissioned or offered to the community until Period 93 (P93). Nevertheless, the AGCCD is provided with a set of Johnson and Sloan Digital Sky Survey (SDSS) filters. The images taken with the AGCCD are often used by the community to complement spectroscopic data with multi-band photometry. Typical uses of the AGCCD images are the flux calibration of spectra or the study of variability in transient objects such as gamma-ray bursts, exoplanets or variable stars. Following the growing interest by the community, it was decided to offer an imaging mode for X-shooter starting from Period 93 (April 2014).

Main characteristics, calibration plan and stability

The detector of the AGCCD is an E2V CCD with a peak sensitivity at 580 nm. The field of view is about 1.5 by 1.5 arcminutes and the pixel scale is about 0.17 arcseconds. Only the fast unbinned readout mode is offered in order to minimise overheads. However, the data quality is preserved by using a new gain that allows a relatively low readout noise and noise structure. This gain will help to avoid saturation of bright objects as well, while the bias value also becomes lower than in previous periods. Finally, the non-linearity is lower than 1 % over most of the dynamic range. Details (gain, readout noise [RON], dark and bias levels, etc) of the AGCCD are summarised in the Table 1. In Table 2, the list of filters and their fringing amplitudes are presented. The zero points at Unit Telescope 2 (UT2), where X-shooter was previously placed, and later on at UT3, its current location, are provided in Table 2. Their small variation corresponds to differences in the optical quality of the two telescopes.

Stability and accuracy

A study of the detector stability and performance was performed using daytime calibrations and photometric standard star observations. In Figure 1 we show the variability of the AGCCD bias and readout noise levels over a period of 52 days. The root mean square (RMS) of the bias level variability is 0.33 % while for the RON it is 0.56 %.

The short-term photometric stability was monitored over 1 hour using the spectrophotometric standard star GD71. The 1σ standard deviations in the *B*- and *V*-bands are 0.006 mag for both bands. Archival data of the standard star EG274 were used to check the long-term stability of the *V* magnitude over 500 days. In Figure 2, we show the variability of the *V* magnitude of EG274 with time (blue points). Only images obtained with photometric transparency (as determined by other Paranal instruments), with a seeing better than 1.3 arcseconds and not too early in twilight, when the sky background varies quickly, were employed for these monitoring observations. However, about 95 % of the observations were performed in twilight, with an unavoidable negative impact on the stability of the magnitudes. We performed aperture photometry on the images with an aperture radius of about 1.5 arcseconds using Sextractor (Bertin & Arnouts, 1996).

Table 1. Main AGCCD detector characteristics.

Detector type	E2V CCD57-10IE	Quantum efficiency	82 % at 580 nm, 50 % at 380 and 820 nm
Pixel scale (arcsecond/pixel) since P92 at UT3	0.1744 ± 0.0016	Field of view (arcminutes)	1.5 × 1.5
Gain (e-/ Analogue-to-Digital Unit [ADU])	1.29 ± 0.02	Readout noise (RMS in e-)	4.14 ± 0.08
Saturation (ADU)	65 535	Readout mode, binning, and overheads	Fast, binning 1 × 1, total time = 1.12 s
Dark current level (e-/pixel/s)	0.97	Bias level (ADU)	1688 ± 5.5
Non-linearity (ADU)	< 1 % at 10 000 and 50 000		

Table 2. Filters and zeropoints.

List of filters	*U,B,V,R,I, u′,g′,r′,i′,z′*	Position angles	9999 = parallactic (default) or other
Fringing amplitude (peak to peak)	Filter-dependent, 3 % in *I, z′*		
Zeropoints U/B/V/R/I ± 0.10 mag at UT3 (P92 onward)	24.83 / 27.91 / 27.83 / 27.74 / 27.36	Old zeropoints U/B/V/R/I ± 0.10 mag at UT2 (until P91)	24.95 / 27.74 / 27.63 / 27.83 / 27.49

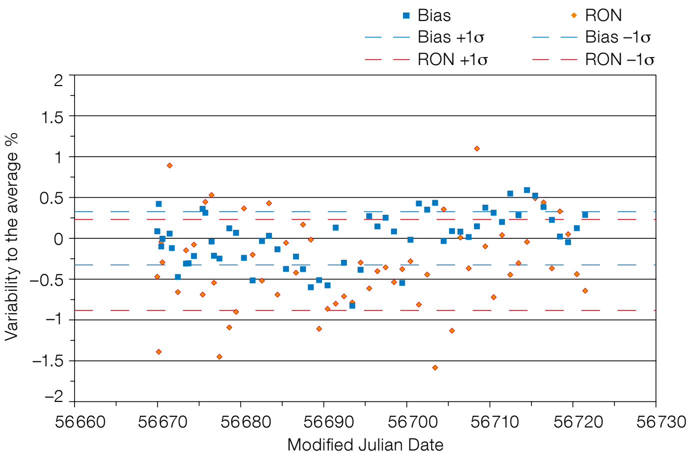


Figure 1. X-shooter AGCCD variability (or relative difference) in the bias level (blue squares) and RON level (orange diamonds) in % from the average with time are plotted. For each of the curves the ± 1σ spread is shown.

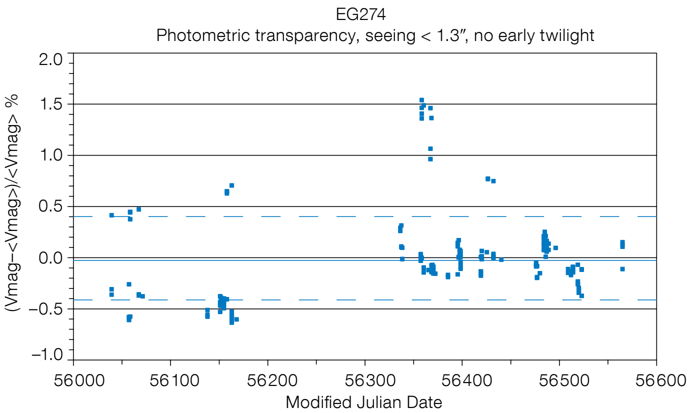
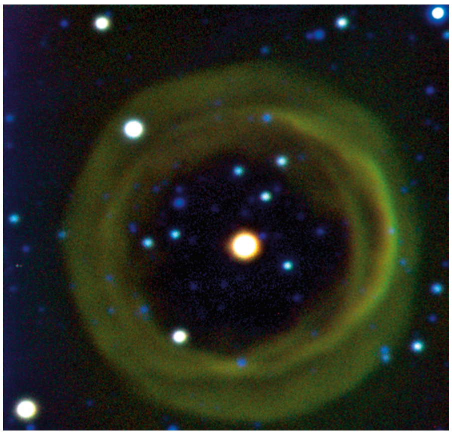


Figure 2. AGCCD photometric variability (%) for the *V* magnitude of the star EG274. Only points observed under photometric transparency, seeing < 1.3 arcseconds and with maximum Sun altitude of −10° were retained. The average and 1σ limits are shown.

Despite the non-ideal observing conditions, the average deviation appears to be stable (RMS of 0.42 % over 1.4 years).

Astrometric measurements show a standard deviation of 0.1 arcseconds. Distortion maps are also available. The astrometric system of X-shooter was calibrated using Two Micron All Sky Survey (2MASS) coordinates for standard star fields.



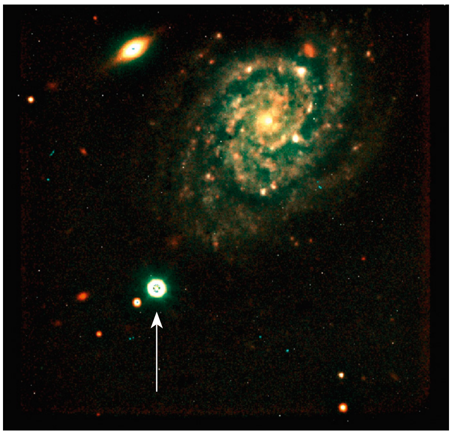


Figure 3. Examples of complementary scientific observations with the X-shooter AGCCD.
Left: The planetary nebula Shapley 1 from *BVI* filter images, taken with GenericOffsets and exposure times of 60, 45 and 30 s respectively.
Right: The galaxy NGC 7259 with SN2009ip indicated. For this image, *VRI* filter observations with 60-second stare observations were combined.

Calibration plan and templates

Several calibration and science templates were created to perform biases (ten are taken daily), darks (3 × 10 s monthly, or on request), detector linearity measurements (taken on a monthly basis), twilight flat-fields and optical distortion measurements. Twilight flat-fields (ten per filter, taken monthly) are preferred because the optical configuration of the instrument, optimised for the spectrographs, leads to only partial light coverage of the AGCCD and therefore to non-uniform illumination of the detector.

For science observations, the user has the choice between stare (XSHOOTER_img) and generic offset (XSHOOTER_img_GenericOffset) templates. The latter allows the telescope to be offset to map a field. There is also a pure imaging acquisition template (XSHOOTER_img_acq) that does not perform any flexure correction or setups of the spectrographs. In most cases we recommend the use of the generic offset template instead of the stare template to achieve better image quality. X-shooter, however, remains foremost a set of spectrographs and imaging-mode-only observation blocks (OBs) are not offered in service mode (SM) except for standard OBs of zeropoints/astrometric references, which will be charged to the users. Visitor mode (VM) users are not affected by this restriction.

In the imaging user manual[1], the allowed combinations of templates in SM and VM and other technical details such as the distortion maps, filters curves, etc., are reported. In addition, because there is no exposure time calculator support, the manual provides some clues about the expected signal-to-noise ratio (SNR) and exposure times. The health of the AGCDD is monitored every day and some plots are publicly available[2].

Science examples and basic data reduction

In Figure 3, two examples of science observations with the X-shooter imaging mode are shown. The planetary nebula, Shapley 1 (PN G329.0 +01.9) was also observed in *BVI*-bands in generic offsets mode and a three-colour image (created with stiff [Bertin, 2011]) is shown in Figure 3 (left). The structures of the nebula are clearly visible. Observations of the galaxy NGC 7259 with the supernova SN2009ip were performed in stare mode and are shown in Figure 3 (right). This object was a luminous blue variable (LBV) star which underwent two strong LBV outbursts in 2009 and 2010, before finally exploding as a SN IIn in 2012 (Mauerhan et al., 2013).

The binary star AA Dor was monitored during several nights (mostly in twilight) using the stare mode and the resulting light curve is shown in Figure 4a. Only the primary transit was observed, but the resulting lightcurve already gives a good indication of what can be done concerning binary objects. A colour–magnitude diagram of the globular cluster 47 Tucanae obtained from multi-band observations is shown in Figure 4b. With 2 s exposure time in *V*-band and 40 s in the *B* and *U* filters, we are able to sample the cluster stars from the tip of the red giant branch (RGB) down to ~ 1.5 mag below the main sequence turn-off (MS–TO).

No pipeline support will be provided. The standard data-reduction tools already available can be used to efficiently pre-reduce and calibrate the data. As an example, to perform the tests shown in this article, we used the *IRAF* tasks imcombine, imarith, ccdproc (for the masterbias, masterdark, mastertwilight flat-fields, and to correct the science frames of the latter). To stack the calibrated science images using the world coordinate system, we suggest using the swarp software (Bertin, 2010). The ESO detmon recipes[3] can be used to analyse the linearity of the images.

To conclude, the X-shooter imaging mode is a tool that complements its spectroscopy. It helps to improve the flux calibration of the spectra and provides photometry for the study of transient objects like gamma-ray bursts, exoplanets or variable stars. In addition, its stability allows time monitoring of these objects to be carried out.

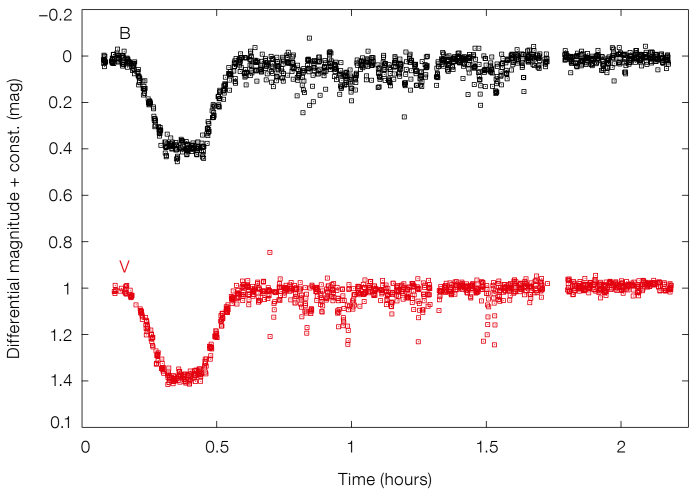


Figure 4a. Photometry of AA Dor: *B* and *V* lightcurves displaying the primary eclipse are plotted. The secondary eclipse has not been observed. The dispersion of some points is possibly related to the sky background variability in twilight. Observations were made in stare mode and the photometry is relative.

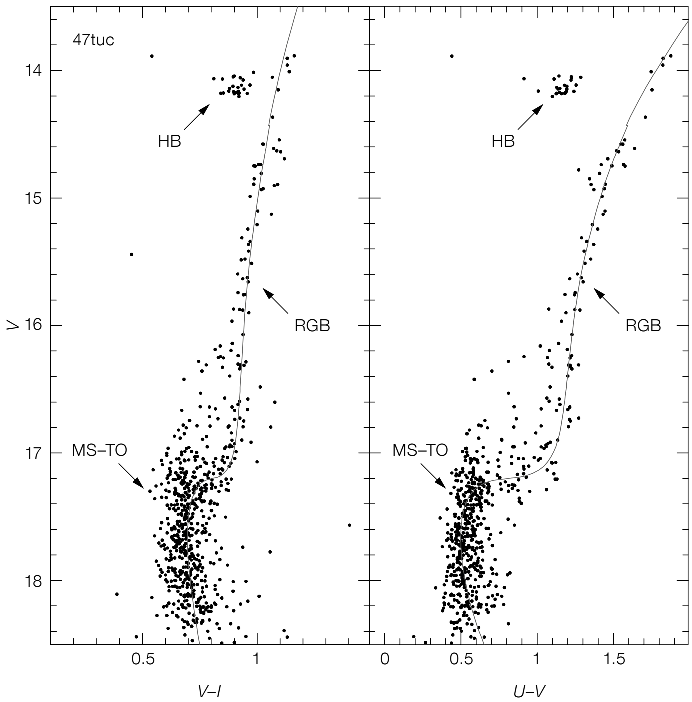


Figure 4b. Colour–magnitude diagrams of the globular cluster 47Tuc: *V* v. *V-I* is shown left and *V* v. *U-V* at right. The positions of the main-sequence turn-off (MS-TO), the red giant branch (RGB) and the horizontal branch (HB) are indicated. The isochrone is taken from Dotter et al. (2008) for a metallicity [Fe/H] = −0.7 and age 12 Gyr for the distance of 47Tuc. Observations were performed in stare mode under photometric transparency.

References

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Acknowledgements

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Links

[1] X-shooter imaging mode manual: http://www.eso.org/sci/facilities/paranal/instruments/xshooter/doc.html
[2] AGCCD health monitoring plots: http://www.eso.org/observing/dfo/quality/XSHOOTER/reports/HEALTH/trend_report_BIAS_AGC_HC.html
[3] Analysis of the CCD linearity with detmon: http://www.eso.org/sci/software/pipelines/detmon/detmon-pipe-recipes.html