PILMOS: Pre-Image-Less Multi-Object Spectroscopy for VIMOS

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The primary observing mode of the VLT visible imager and multi-object/integral field spectrometer, VIMOS, is multi-object spectroscopy, for which pre-imaging with VIMOS is currently mandatory. We report on the results of a study of the astrometric calibration of the VIMOS imaging mode and the efforts to improve it. Based on this study, we announce the introduction of an option that allows users to omit the VIMOS pre-imaging step and create masks directly from sufficiently accurate astrometric catalogues.

Introduction

The VIMOS upgrade over the last couple of years has covered hardware (including detectors and prisms), software, maintenance and operations (see Hammersley et al., 2010; Hammersley et al. in prep.). Here we concentrate on one operational issue that has now been addressed, namely the option to create multi-object spectroscopy (MOS) masks without the need to obtain pre-image exposures with VIMOS.

The original concept for VIMOS foresaw the possibility of creating MOS masks directly from astrometric catalogues, but the imaging capability was included to provide accurate astrometry in cases where no suitable catalogue was available and to aid users in placing custom slits (tilted or curved) on specific targets. In practice, when VIMOS started to be used in operations, it was decided that pre-imaging should be mandatory to ensure that uncertainties in the mapping of celestial coordinates to detector coordinates did not lead to incorrectly placed slits. This requirement had the effect of increasing the total telescope time required to obtain a typical MOS exposure by up to about 15% (Hammersley et al., 2010). Moreover, pre-images are typically obtained several weeks to a month prior to the MOS observations, but sometimes much older pre-images are used to prepare the MOS masks and the follow-up MOS observation blocks (OBs).

Ironically, the very fact that the pre-imaging procedure adopted for VIMOS worked, and the fact that pre-images as old as one or two years produced reliable MOS masks, was a good indication that the transformation from the sky to the mask plane was stable and could be calibrated in such a way to allow pre-image-less MOS observations (hereafter PILMOS). Therefore a detailed investigation of issues that can affect the reliability of PILMOS masks was undertaken to ensure that the consequent saving in pre-image exposure time would not be accompanied by large slit losses. Following the positive conclusion of this investigation, a procedure that enables users to create PILMOS masks via the use of a simple observation preparation tool was devised. This procedure has recently been tested on realistic MOS observations.

Feasibility of pre-image-less mask creation

In order to create PILMOS masks we need to be able to reliably map celestial coordinates to locations in the VIMOS mask plane. In practice we cannot calibrate this mapping directly since we do not have a detector at the location of the mask plane. However we can calibrate the sky-to-detector transformation (known as Sky2CCD) with exposures of astrometric fields and then map the mask-to-detector transformation (Mask2CCD) via calibration exposures of pinhole masks. The sky-to-mask transformation can then be derived from these two transformations. (Mask2CCD embodies the distortions resulting from the spectrograph optics, so we can effectively subtract this from Sky2CCD leaving just the sky-to-mask transformation.)

Astrometric calibration exposures were part of the original VIMOS calibration plan, but they became essentially redundant when pre-images were made mandatory and were subsequently neglected. Since the start of this project, astrometric calibration has been monitored on a monthly basis.

As part of the PILMOS project, the astrometric catalogues used by VIMOS were refined by filtering out stars with large errors in their positions and correcting for proper motions. The accuracy of the calibration of Sky2CCD is in fact limited by the form of the fit and the sparse sampling of the field of view (FoV), even for relatively dense astrometric fields, rather than by any systematic effects (such as flexure, thermal expansion, atmospheric dispersion, aging, etc; see below). Despite this limitation, the Sky2CCD calibration is still good enough to ensure that targets are not lost from the slits when performed properly.

Figure 1 is a histogram of the residuals between the predicted (using the Sky2CCD solution) and measured astrometric star positions. The measured positions are from several exposures of astrometric fields spread over several months and that differ from those used to obtain the Sky2CCD transformations being tested. It is clear that towards the edges, and especially the corners, of the detectors the fit is less reliable, but even there the vast majority of stars will be found within 2.5 pix (0.5 arcseconds) of where they are expected. Moreover, vignetting by the intregral field units (IFUs) precludes the use of the very top and bottom edges of the detectors (most of the red zone in Figure 1).

Pinhole Mask2CCD calibration exposures are essential for both the conventional pre-imaging strategy and PILMOS. They measure the distortions in the collimator and camera optics. Analysis of several months of pinhole exposures obtained at a fixed orientation (i.e., free of flexure as the field is rotated) revealed the expected thermal effects; once these were removed the Mask2CCD transformation

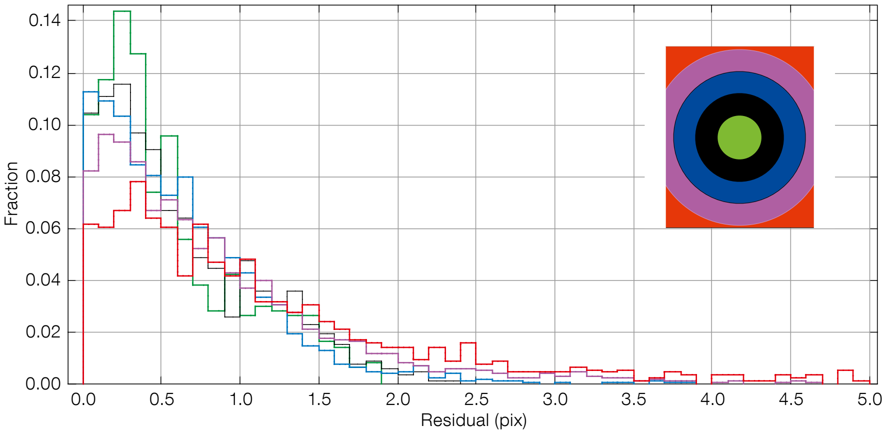

Figure 1. Histogram showing residuals between predicted and measured centroids for stars in astrometric fields. The colours indicate samples of stars at different distances (r, in pixels) from the centre of the detectors as follows: green $r < 300$; black $300 < r < 600$; blue $600 < r < 900$; pink $900 < r < 1200$; red $r > 1200$. The inset indicates how these annuli map onto the imaging FoV of a VIMOS detector. Each histogram is normalised by the sample size.

was constant to < 0.25 pixels across the FoV. In practice some residual flexure (not seen in the pinhole exposures, which were all obtained at a fixed orientation) is to be expected even after the implementation of the automatic flexure compensation system (described in Hammersley et al., 2010). These same effects will be present in the astrometric calibrations as long as the astrometric and pinhole mask calibrations are obtained under similar conditions (epoch, temperature and orientation) and cancel out when the resulting sky-to-mask transformation is derived. The ESO quality control pages[1] provide access to diagnostics from these calibrations during VIMOS operations.

Another effect that may cause some changes in the sky-to-mask transformation for a given observation is the variation of apparent relative positions of sources with air mass and parallactic angle caused by atmospheric dispersion (see Cuby et al., 1998). The constraints applied to VIMOS observations currently in place effectively ensure that the atmospheric dispersion present in pre-images is very similar to that in MOS observations. Hence, the hour-angle constraints for MOS exposures (see below) have been retained, at least for the initial phases of PILMOS.

Several other VIMOS upgrade activities (Hammersley et al., 2010) have helped to improve the positioning of slits. For example:

- Automatic flexure compensation (AFC): Although AFC only improves the stability of VIMOS after the mask plane, it has improved the stability of the Mask-2CCD transformation and thus also the derived sky-to-mask transformation;
- Mask insertion: Procedures for loading masks have been made more robust and pinholes are now added to masks to allow their proper insertion to be automatically verified.

These activities will be described in greater detail in Hammersley et al. in prep.

The PILMOS tool

PILMOS mask preparation is done with a new (extended) version of the Guidecam application, with which VIMOS users are already familiar in selecting their FoV and guide star. The new options in Guidecam are the upload of the user-contributed catalogue and a button that initiates the generation, for all four quadrants, of:

- A simulated pre-image that includes the targets in the catalogue and the area vignetted by the guide probe as well as a header containing all of the keywords and values that would have been in a real pre-image;
- A VIMOS catalogue with detector coordinates matched to celestial coordinates for each target. This intermediate catalogue enables users to prepare masks directly within VIMOS mask preparation software (VMMPS) application, thus skipping the first cross-correlation step that would have required a pre-image. A guide to the use of this tool will be available in the forthcoming release of the VIMOS User Manual (see the VIMOS support pages[2]).

Trial results

While investigating the feasibility of PILMOS, we gathered sufficient evidence to suggest that PILMOS would perform at least as well as pre-imaging in terms of minimising slit losses. Nevertheless, before offering the tool to observers we performed realistic end-to-end on-sky tests in order to rule out any unexpected problems in the PILMOS strategy.

We used the PILMOS tool to prepare masks for three stellar fields at declinations of 0, −25 and −60 degrees. Each target had a 2 arcsecond wide slit so that it was possible to accurately measure the centroids of the targets in the acquisition images. For comparison we obtained pre-images of the same fields and used these to create masks with the conventional procedure. Analysis of the acquisition images obtained with these masks revealed small but systematic differences in the mean residuals (of the order of one pixel, 0.2 arcseconds) for the PILMOS and pre-image cases that varied from quadrant to quadrant and to a lesser extent from field to field. However the scatter in the residuals was very similar and the overall performance in terms of the fraction of targets that were within about one pixel of the slit centres for each field did not differ significantly between the two methods, as summarised in Table 1.

δ (°)	Method	$\lvert\Delta y\rvert > 1.0$ pix.	$\lvert\Delta y\rvert > 1.5$ pix.
0	PILMOS	18(10)/58	6(5)/58
0	Pre-image	4(3)/57	1(1)/57
−25	PILMOS	22(15)/50	9(9)/50
−25	Pre-image	21(16)/50	7(11)/50
−60	PILMOS	16(9)/41	7(4)/41
−60	Pre-image	10(12)/33	10(8)/33

Table 1. Scatter in residuals for pre-image and PILMOS object centroiding. The number of targets having more than 1.0 and 1.5 pixel offsets in the three stellar test fields is listed in columns 3 and 4. The first figure in each column is the number directly measured in the data, the number in brackets is the value that would be measured if the reference stars had been optimally centred and the final number is the sample size.

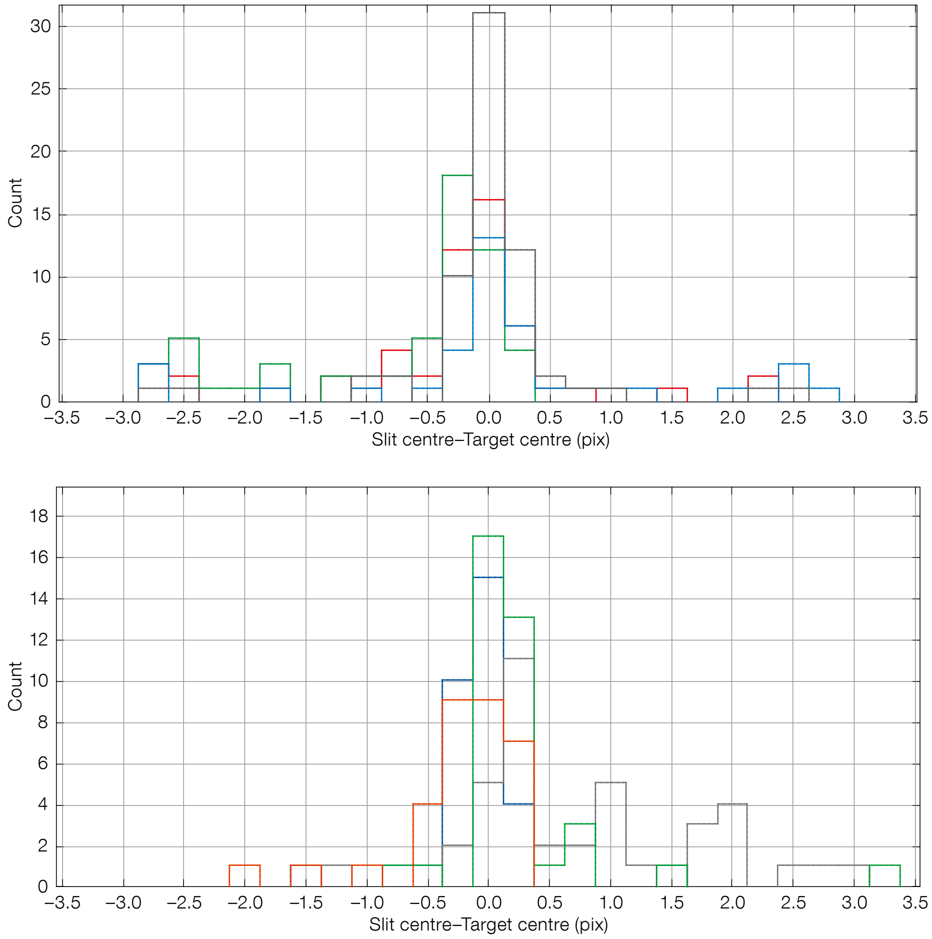

Figure 2. Centring of sources relative to the slits in the PILMOS mask acquisition image (upper) and the pre-image mask acquisition image (lower) is shown. The colours indicate the quadrants as follows: Q1 = red; Q2 = blue; Q3 = green; Q4 = grey.

As a further test, in collaboration with the Cluster Lensing and Supernova Survey with Hubble (CLASH) VIMOS Large Programme (described in Postman et al., 2012), we used the PILMOS tool to create masks based on the same input catalogue used to prepare one of the existing MOS OBs that was part of their regular programme (and thus prepared using pre-imaging). All the other details were identical. Figure 2 shows the centring of targets in all four quadrants as determined from the acquisition images of the conventional pre-image masks and the PILMOS masks. In deriving these results we corrected for slit vignetting. Note that about 40 % of the targets were too faint to be identified in the short, undispersed acquisition images and do not contribute to these statistics.

Figure 2 indicates that, bearing in mind the omission of the faintest targets, whilst within any quadrant the offsets vary by less than half of a 1 arcsecond slit width, not all quadrants are well aligned, both for PILMOS and pre-imaging acquisition images. Hence, in this test, performance was non-optimal in at least one quadrant for both methods, but there is no indication that the use of PILMOS significantly degrades performance relative to pre-imaging (here it is slightly better, but not at a level that is statistically significant). Global offsets are easily corrected when centring the MOS stars in their boxes during the acquisition exposures, although offsets between quadrants cannot be corrected in this way.

Figure 3 shows two typical extracted spectra, each obtained with both the PILMOS and pre-image masks, after processing by the CLASH project team using their standard data reduction. In general they found that the signal-to-noise in the pre-image and PILMOS derived spectra were very similar, confirming that the PILMOS strategy can deliver equally valid results. In this case PILMOS would have saved four minutes of pre-imaging for one hour of MOS follow-up, and once overheads are factored in, the saving is approximately 14 %.

Introduction of PILMOS

From summer 2012 observers will be able to choose to omit pre-imaging and create their MOS masks directly from catalogues with the PILMOS tool. In order to do this they will need to obtain the latest version of the Guidecam tool from the ESO Phase 2 web pages[3]. In addition the following restrictions will apply to PILMOS observations:

- Slits should be at least 1 arcsecond wide (this is currently the most typically used slit width for VIMOS observations);
- Only straight slits aligned north–south are permitted (no waivers for rotator angle different from 90 degrees are allowed for PILMOS);
- Fields should be obtained within two hours of the meridian (as is currently the case for pre-image based MOS exposures);
- The contributed catalogue must have relative astrometry better than 0.2 arcseconds and absolute astrometry must be consistent with the Guide Star Catalogue to within 2 arcseconds;
- The catalogues should contain at least two suitable reference stars per quadrant that are corrected for proper motion and on the same astrometric system as the other targets.

We are continuing to monitor the stability of VIMOS distortions and the impact of issues such as atmospheric dispersion (Sanchez-Janssen et al.,in prep.) with a view to relaxing these restrictions in the future. The conventional pre-imaging strategy is available for observers who cannot meet these requirements. Pre-imaging will continue to be offered as the main option, at least during the first period that this mode is offered, for the reasons given in the introduction.

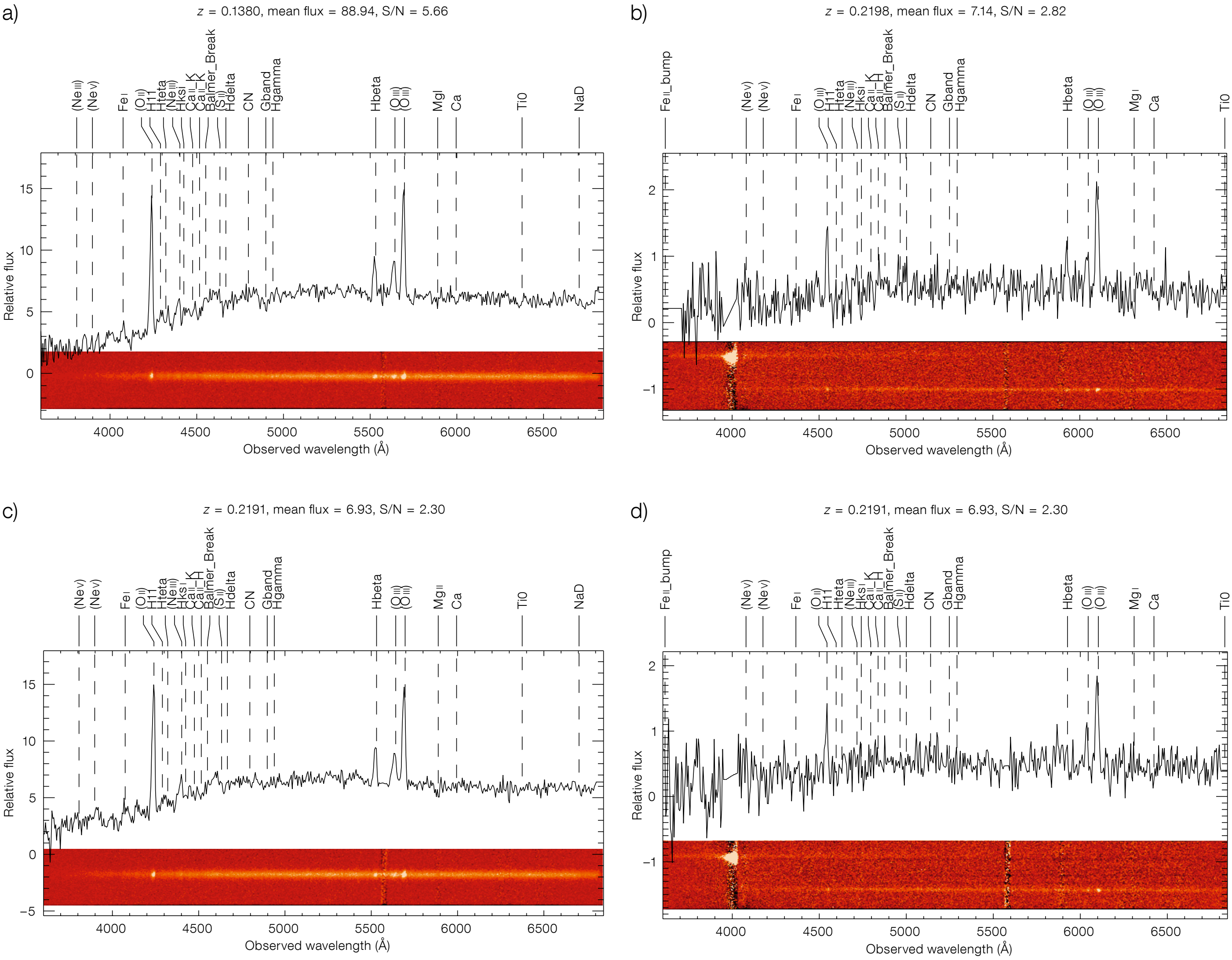

Figure 3. Example VIMOS processed spectra are shown with pre-imaging and with PILMOS: (a) and (b) were obtained with the PILMOS masks; (c) and (d) are the same sources obtained with pre-image masks. Line identifications are also shown. Note that in (b) and (d) it is the lower spectrum that is extracted.

Acknowledgements

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References

Cuby, J. G., Bottini, D. & Picat, J. P. 1998, Proc. SPIE, 3355, 36
Hammersley, P. et al. 2010, The Messenger, 142, 8
Postman, M. et al. 2012, ApJ, 199, 25

Links

[1] ESO quality control pages for VIMOS: http://www.eso.org/observing/dfo/quality/VIMOS/qc/mask2ccd_qc1.html

[2] VIMOS support pages: http://www.eso.org/sci/observing/phase2/SMGuidelines/VMMPS.VIMOS.html

[3] VIMOS Service Mode guidelines: http://www.eso.org/sci/observing/phase2/SMGuidelines/Guide-camVIMOS.html