VIMOS IN OPERATION AT THE VLT

The performance of VIMOS, the powerful large field imager, multiobject spectrograph at the VLT, is critically assessed after the first four months of operation and the current activities for its upgrade are presented.

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VIMOS is the large field (4 times 6′.7 × 7′.7, approximately) imager and multi-object spectrograph built for the Nasmyth focus of the VLT MELIPAL. Its field size (diagonal ~24″) matches the full unvignetted field of a Nasmyth focus of the VLT. The combination of the large field, good image quality, high slit multiplexing (masks with up to 1000 short slits can be inserted in the focal plane for low-resolution spectroscopy) makes the instrument the most powerful MOS spectrograph available at telescopes of the 8-10 m class. A detailed description of the instrument can be found at *http://www.eso.org/instruments/ vimos*.

The instrument (and the associated Mask Manufacturing machine) was built by a Consortium of French and Italian institutes (*http://www.astrsp-mrs/virmos*) with Olivier Le Fèvre of LAM, France and Paolo Vettolani of IRA-CNR, Italy, as P.I. and co-P.I. respectively. ESO provided the detector systems and support in other areas of the project.

VIMOS had its first commissioning on the sky in its full configuration in September 2002, only ~5 years after the signature of the contract between ESO and the Consortium. Results from the commissioning and from a first allocation of guaranteed nights received by the Consortium have been presented by Le Fèvre et al. (2002 and 2003, respectively). The instrument has been offered to the ESO users in service mode as of the start of Period 71, on April 1st 2003.

Instrument Performance and Tips on the Preparation of the OBs

Imaging

VIMOS offers a number of advantages but also draw-backs with respect to the other two optical imagers at the VLT, FORS1 and FORS2. Among the advantages, clearly the wide field (~4 times the FORS field) ranks top and makes it an unique instrument for imaging surveys at any very large telescope. Since the field of view of the instrument takes almost all of the Nasmyth unvignetted field, the arm used to pick up the guide star do mask in most cases a small part of one quadrant. The observers are requested to choose the guide star using a special tool, *GuideCam*, made available by ESO for the preparation of the observations.

Although the VIMOS Nasmyth location implies the additional M3 reflection, the VIMOS efficiency of a single channel is higher than that of the two FORS at UV and blue wavelengths, comparable in *V*, and lower than FORS2 in the Red and *I* band (by factors 1.5 and 1.9 respectively) mainly due to differences in the CCD QE curves. The different efficiencies have been well estimated from the zero points measurements for the three instruments reported in the ESO Quality Control pages*. One has however to keep in mind that VIMOS uses non-standard broad-band filters and the color corrections have not yet been introduced.

The image quality (FWHM of the stellar images) in the VIMOS quadrants reported in the same web pages is fairly good lying in the range 0.5 – 1.0 arcsec FWHM during the first four months of observations (Fig. 1 and 2). The difference between quadrants is below 20%. We estimate that there is still room to improve the quality in some of the quadrants by optical realignement. Clearly VIMOS image quality cannot reach the unique performance of the FORS when used in the high resolution mode in very good seeing condition because of the larger field and coarser sampling but it is on the other hand fully adequate for deep photometry of compact sources much fainter than the sky.

One VIMOS limitation is a significant variation of the Point Spread Function (PSF) across the four quadrants, mainly due to the difficult optimization of the optics over the large field. Furthermore, the field being so large, the telescope guide probe (used for the active optics correction in the telescope optics) is often forced to pick a star in a region where the telescope pupil is slightly vignetted and the resulting active optics correction not

*The ESO Quality Control pages can be found on http://www.eso.org/observing/dfo/quality

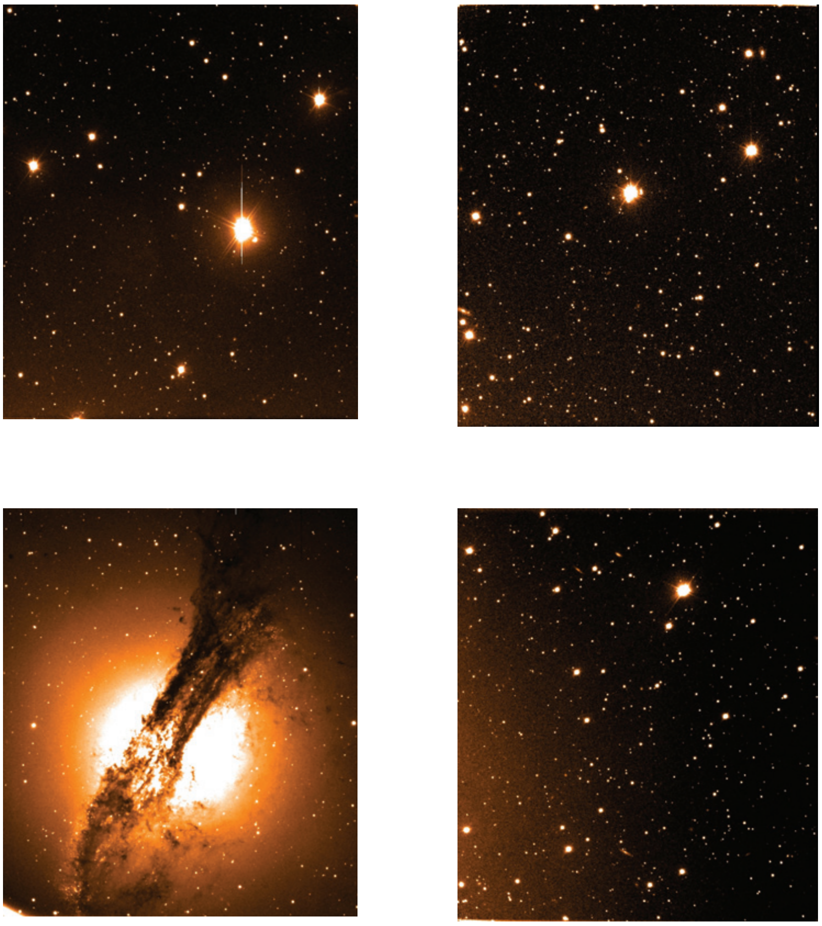


Figure 1: The NGC 5128 (Cen A) field in a V exposure (30s) with the four channel of VIMOS taken in Feb. 2003. North is to the top, East to right. Each of four channels covers $6'.7 \times 7'.7$ approximately, the gaps in the X- and Y-directions ~ $2'$. The average FWHMs of the stellar images in the four quadrants in this exposure vary between 0.69 and 0.77.

optimal. The image deformations highly depend on the location of the guiding star.

Programmes heavily relying on excellent and consistent image quality (e.g. to measure accurate object shapes) are probably best performed with FORS. If the large field is needed and VIMOS is the choice, in the selection of the guide star it is better to accept some obscuration of one quadrant by the guide probe rather than to use a guide star in the vignetted telescope field of view or to have to change the guiding star during the observations because this will modify the PSF.

Two other points must be taken into account in the planning of the observations. Sky emission lines do cause relatively strong fringing (at the 10% background level) in the *I* and *Z* bands, and thus dithered exposures to build a night flat field are strongly recommended when deep photometry is the main scientific goal. Bright stars (< 8^{th} mag) in/around the middle of the field can cause reflections at a few percent of the typical background light at specific orientations of the instrument. We are investigating systematically the effect to identify the best orientation to be used as default for imaging.

Multi-Object Spectroscopy

There are two spectroscopic modes of VIMOS: MOS (Multi-Object Spectroscopy with four field-specific, laser-cut masks remotely inserted in the focal planes) and IFU (area spectroscopy of a field covered by a fibre head). The absolute performance of MOS is consistent with the efficiencies observed in imaging with respect to the two FORS. The two low resolution and the intermediate VIMOS grisms have transmissions which are comparable to the best FORS grisms, while the high resolution grisms have significantly lower efficiencies. Of course, the actual gain in spectroscopic survey depends on the density and overall distribution of the program targets. If the sources are numerous and uniformly distributed in the VIMOS field, the number of targets acquired in one exposure can be between 4 and 10 times larger than with FORS2.

Absolute depth limits in MOS spectroscopy are not easily pinpointed as they depend on many factors: the accuracy in matching the masks to the targets, the strategy of the observations, the flexures of the instrument during exposures and the accuracy with which fringing (more than 30% peak to valley past 850 nm) in the spectra are corrected. The preliminary results from the first GTO allocation (Le Fèvre et al., 2003) suggest that the limiting magnitudes in *V* and *R* are close to the ones with FORS1 or FORS2.

There is an additional effect to be taken into account in MOS observations. When multiple spectra in the dispersion direction are taken (mostly in low-resolution spectroscopy) each 1^{st} order spectra is contaminated at a few percent by the 0^{th}, -1^{st}, or 2^{nd} order spectra of the aligned slitlets (see also Fig. 4).

VIMOS is installed at the Nasmyth focus of UT3 and rotates around a horizontal axis during observations. There are no flexures or thermal effects in the focal plane (in particular due to masks made of Invar). This, together with a good mechanical positioning of the masks, ensures a stable positioning in the focal plane. However, there are significant flexures between the detector plane and the telescope focal plane through rotation of the instrument, smaller than ± 1 pixel (0.2 arcsec) in quadrant 2 (Q2) and less than ± 1.5 pixel in Q1, Q3 and Q4. These motions are reproducible, and low enough that they guarantee an effect below 0.5 pixel at maximum through a typical exposure even at maximum field rotation close to zenith. However, flexures are annoying for mask preparation. The positions of the slits are determined from pre-images and from a mask to CCD transformation matrix. If the matrix and the pre-images are obtained at different rotation angles of the instrument, there will be a systematic error in the derived slit positions. The final differential effect between the flexures of the 4 quadrants will typically amount to ~ 1–2 pixels positioning errors in 1–2 quadrants. The component of relative motion across the slits will imply some light losses: their amplitude depend on slit width and object size, and/ or seeing conditions.

As it is the case for imaging, users are required to use the *GuideCam* tool to

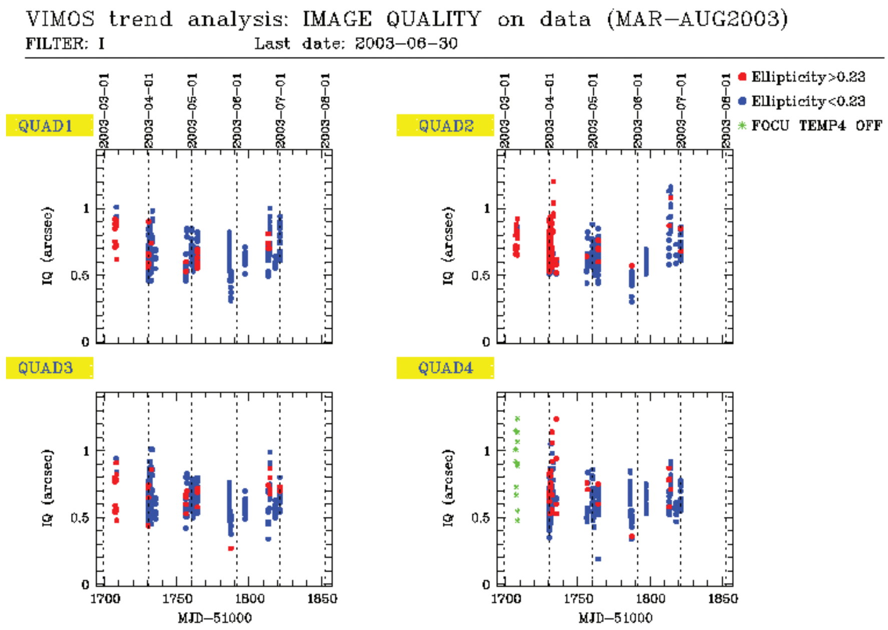


Figure 2: Image quality of the four VIMOS quadrants from I-band observations taken during four months of service operations. Monitoring of these parameters is a task of the DFO group of the Data Management Division.

prepare their pre-imaging observations*. The telescope guide star is carried along in the header and later in the aperture definition file, so that the same guide star is eventually used during the spectroscopic observations. Here also, allowing some vignetting of the field by the Guide Probe might be better than picking a guide star outside the unvignetted telescope field of view.

IFU

IFU is one of the most used mode in VIMOS in the first period. In low resolution it is the largest IFU currently offered at any observatory (54″ × 54″), in medium to high spectral resolution it still offers a fantastic 27″ × 27″ field. Its throughput is below the original expectations and lies on average at 50–60% of the MOS transmission value.

Among the known caveats figures the image quality. The current PSF is elongated and shows chromatic effects. These can be observed when spectra from single spatial resolution elements (along the CCDs Y-direction) are compared: only when all spectra forming a PSF are combined (typically from 3-4 fibres in 0.8″ seeing) the energy distribution is properly reconstructed.

The individual fibres coming from the IFU head are packed at their output such that spectra from contiguous fibres on the detector are spaced by 5 pixels, comparable to their FWHM. A significant overlap/crosstalk is thus present.

Given the tight space between spectra, the instrument flexures of 1–2 pixels (plus an additional, comparable contribution from the IFU slit masks itself) amplify the problem. To be able to cope with these shifts in the data reduction, we are currently adding a night time calibration to each OB taken at the same rotator position of the science exposure, but clearly this reduces the overall time efficiency of the instrument for collecting scientific data.

Finally, we can currently only verify the right pointing after the first exposure (and only when at least two bright objects lie in the field). The astronomers are required to use the *GuideCam* tool in preparing Phase 2 of the observations and to select a guide star taking care to specify accurate pointing coordinates in the coordinate system of that guide star. Following that recipe will typically lead to a 1–2″ pointing accuracy.

The First 4 Months of Operation in Service Mode

The first months of operation have been marred by reliability problems, most of them of mechanical nature. Problems were particularly encountered with the Mask Exchange Units (MEU) and the Grism Exchange Units (GEU). Admittedly, these units are complex: the MEUs select the masks in the 15-slot cabinets, grip, translate and clamp them into the focal plane with high accuracy ; the GEUs select from a 6-position carousel the grisms (up to 15 kg a piece for the high resolution grisms) and insert them in the pupil plane. All these motions are to work under any orientation of the instrument. Because each function exists in the four units, the probability of a failure to happen is multiplied accordingly. In total there are 64 functions in VIMOS, each of them associated with its set of sensors. The overall instrument design appears sound and most of the reliability problems have originated from insufficient workmanship, e.g. inappropriate quality of many components: screws, linear guides, clamps around axes, sensors, etc.

From January to April, the instrumentation group on Paranal had to spend alone 200 hrs of technical work to keep the instrument into operation. The next months were followed by alternate periods of satisfactory reliability followed by intensive periods of troubleshooting, often requiring interventions at night from technical staff and support astronomers. Special operation procedures were implemented to e.g. setup the instrument at particular rotator positions known to generate less problems, change programmes when one mode was not available, etc. In parallel, and as part of the so-called "Paranalisation", extensive efforts were

Table 1: Status of approved programs in Period 71 as of July 28, 2003

Type of observing run	Number of completed runs	Number of ongoing and pending runs (degree of completion, in % of the allocated hours)
Preimaging (for MOS preparation)	7	3 (0%)
Imaging	6	5 (38%)
IFU	15	12 (33%)
MOS	3	7 (10%)

*see the instructions at http://www.eso.org/observing/p2pp/VIMOS/VIMOS-P2PP.html also devoted to improve the software operation of the instrument, in particular for mask operation and configuration control of the instrument calibrations which are operation critical, e.g. the mask to CCD calibrations etc.

In view of the shaky status of the instrument prior to beginning of operations, the decision was made to transfer all P71 runs, and subsequently also those of P72, to service mode, so as to ensure as high a completion rate as possible for the highest ranked programmes.

The technical downtime attributable to VIMOS was limited to approximately 15% during the period April-July 2003. Although already high on its own (Paranal standards for technical downtime are, all included, at the level of 3–4%), this performance could only be achieved due to the hard work by the technicians, engineers and astronomers who concentrated their efforts on this instrument during this period and by the flexibility offered by service observations. Part of the negative impact of the technical downtime on the completion of scientific programmes was absorbed by performing additional VIMOS observations outside the formal time allocation.

Table 1 summarizes the status of advancement. A total of 374 hrs of observations have been successfully completed, 320 remain to be executed.

An unfortunate side effect of these operational difficulties is that the characterization of the instrument, in particular of the IFU mode, could not be carried out as desired because the resources were mainly directed towards maintaining the instrument operational.

Status of Data Reduction Pipelines

The VIMOS Pipeline is operational on Paranal since April 1st 2003 and is used to process VIMOS service mode data. The pipeline recipes are based on the data reduction software ESO obtained from the VIRMOS consortium, which have been upgraded during the commissioning phase to fulfill the requirements set by Paranal Science Operation group and the Data Flow Operation (DFO) in terms of operations and data quality.

The current version of the pipeline supports the imaging and multi-object spectroscopy modes of VIMOS .

Imaging Pipeline

The VIMOS imaging pipeline provides recipes to create a complete set of master calibrations needed for the processing of scientific observations. Scientific observations are bias subtracted, flat field corrected and photometrically calibrated. Optionally the images may be dark subtracted and corrected for bad pixels and cosmic ray hits. In case of a jitter observation the individual observations can also be co-added. With the current algorithm used for the image combination residual offset are sometimes present in the combined image, depending on the step size. An algorithm with improved accuracy will be available in the course of Period 72.

For the photometric calibration standard star fields are regularly observed and processed and serve to monitor the zero point trends of the instrument.

Software routines are used by the Observatory staff to create bad pixel maps and to compute the coordinate transformations from CCD to mask plane and a model of residual geometrical distortions which is used to compute an improved world coordinate system. The CCD to mask transformation is crucial to the preparation of masks used for MOS observations. The RMS of the residuals of this transformation typically is about 5 10^{-3} mm in the focal plane where the masks are inserted, while the RMS of the inverse transformation is about 0.04 pixels at the detector.

MOS Pipeline

The existing MOS pipeline provides recipes to create a normalized flat field from a set of individual flat fields, to compute the inverse dispersion solution and to process scientific observations taken in stare or jitter mode. Science observations are bias and, optionally, dark subtracted and flat field corrected. The spectra are corrected for curvature and optical distortion effects. Residual shifts of the slit positions (due e.g. to instrument flexure between the scientific and the calibration exposures) are corrected using the position of sky lines. The dispersion solution is applied re-sampling the spectra to a constant wavelength step, and the spectra are sky subtracted. If the observation was in jitter mode, the images can be co-added using offsets computed from the positions of the brighter objects detected on the individual images. Objects are detected and extracted using either a simple sum, or a Horne extraction (Horne K., 1986, *PASP* 98, 609).

The MOS pipeline relies on the presence of models in the FITS header describing the spectral curvature, the optical distortions and the inverse dispersion solution. These models are used in two ways. For the pipeline on Paranal, which runs unattended, these models are used to process science data because the full set of required calibrations for the mask used is typically not available when the data is processed. When the scientific data is processed in Garching, DFO uses the calibrations specifically created for the science mask. In this case the model is just used as a "first guess". In particular the inverse dispersion solution is then computed for each individual slit of a mask.

Table 2 shows the RMS of the wavelength calibration for the different grisms averaged over the four quadrants using a global dispersion solution and a solution computed locally on the CCD. The two approaches give very similar results

The large RMS value for the low resolution grisms (especially LR_blue, with RMS values up to 2 pixels in worse cases) is probably due to the –1 and 0 order contamination of neighboring spectra along the same CCD columns, an adverse effect of the multiplexing. This contamination can be removed from the calibration spectra by using the built-in instrument mask shutters, whose implementation in the calibration procedure is expected in the last quarter of 2003.

Table 2: RMS of Inverse Dispersion Solutions (pixels-Å)

GRISM	Model	Single slit procedure
LR blue	1.4 – 7.4	1.4 – 7.4
LR red	0.9 – 6.4	0.8 – 5.7
MR	0.5 – 1.3	0.4 – 1
HR blue	0.6 – 0.36	0.4 – 0.24
HR orange	0.4 – 0.38	0.4 – 0.38
HR red	0.4 – 0.26	0.4 – 0.26

IFU Pipeline

The complete set of software modules needed for the IFU data reduction was received just recently from the VIRMOS Consortium and it has been tested on the low resolution data only. It is currently being checked and validated at ESO and will be available in one of the next pipeline releases (for availability dates please have a look at: *http://www.eso.org/qc/pipeline-status.html*).

At the Paranal Observatory there is so far just a quick-look IFU image reconstruction tool developed by ESO to allow the quick verification of the telescope pointing.

Quality Control, Processing and Delivery of VIMOS data

The VIMOS data will go eventually through a Garching-based full quality control process as it is customary for VLT instruments (Hanuschik & Silva 2002). Given the large number of subsystems of the instrument such a QC process is critical for ensuring that useful data with a consistent quality are being delivered to VIMOS users.

At this time, most QC parameters which are extracted from the observations of the first four months of service observing are related to detector and/or imaging performance. For each detector, fundamental properties such as bias level, read noise, gain, flat-field stability, image quality (Fig. 2) and photometric zero-points are measured and compared to nominal values on a regular basis. In time, parameters related to MOS and IFU observations will also be regularly monitored. Various QC reports and trending diagrams for VIMOS are available from the ESO Data Flow Operations Quality Control Web pages: *http://www.eso.org/qc/*.

As for all other VLT instruments, all VIMOS data obtained for Service Mode programmes are processed and distributed to the appropriate Principal Investigators (PIs). Basic processing consists of organising all incoming raw science data by observing run and associated them with appropriate raw calibration data. All PIs receive these basic data plus a variety of file listings when their observing run is completed.

In addition to these basic data, imaging and MOS mode users receive both calibration and science data products created by the VIMOS pipeline. Detailed information about production and nature of these science and calibration products is provided to the users and is available from the DFO QC Web pages mentioned above.

The data from all four VIMOS quadrants are organized and processed separately. Imaging mode users receive bias-corrected, flat-fielded science frames as well as the master bias and master flat-field frames used to process the science frames. Whenever appropriate, they also receive processed standard star frames and zero-point tables. For normal imaging, the most recent calibration data is used to process the science data. Pre-imaging data, however, are processed using archival calibration data to facilitate rapid delivery.

MOS users receive the following science products: an image containing all the 1D extracted spectra, an image containing the two-dimensional (2D) extracted spectra (Fig. 3), and an image containing the 2D extracted sky spectra (Fig.4). Tables containing identification information for each extracted spectrum as well as their individual dispersion solutions are also provided together with the master calibration frames used to process the science data (e.g. bias, flat-field, and arc-lamps).

These spectra have been corrected to a linear dispersion and aligned in wavelength. They have not been divided by the flat-field. Division by the master FF does not yet provide good results and the procedure is being refined and tested. The use of the uncorrected data has little effect below ~8000 Å because the cosmetics of the CCDs is excellent but it is more serious above that wavelength because of the CCD fringing. The problem is partly resolved by the combination of jittered spectra as discussed in Le Fèvre et al. (2002).

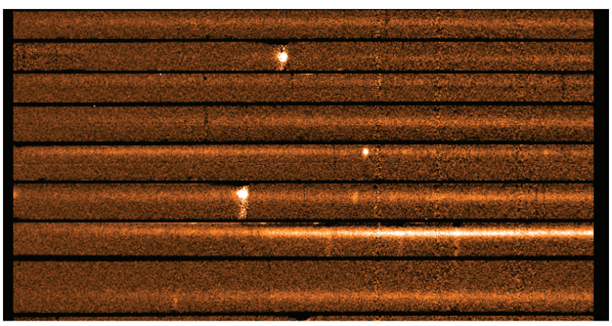
The distributed data do not yet include the spectrophotometric correction.

As mentioned above, the IFU pipeline is still under development. Only a basic re-constructed image of the central 27 × 27 arcsec and a IFU sky-slit comparison table are provided to help the user correlating the fibre spectra with the fibre position in the IFU head.

Per standard ESO procedure, the goal is to deliver VIMOS data packages to the users within one month after the completion of the final OB for an observing run. By the end of Period 72, this goal should be met on a regular basis. In the special case of MOS pre-imaging, processed images are already being made available to users within 2 – 3 working days of pre-image acquisition using an ESO Science Archive based process.

Instrument Repair and Upgrading Plans

As reported above, the operational experience with VIMOS has consistently shown relatively high failure rates for some key functions, during commission-



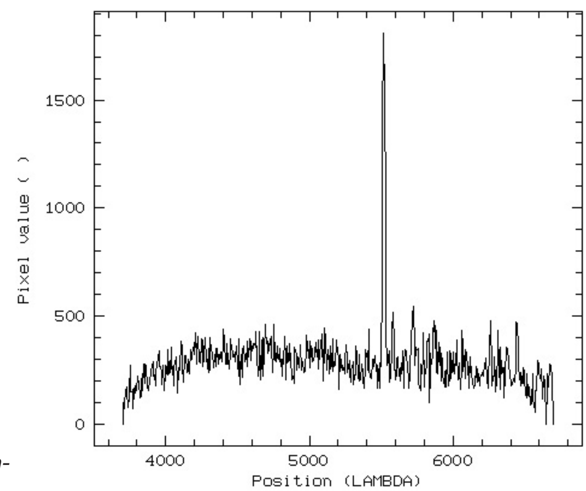


Figure 3: A portion of a 2D pipeline-extracted MOS frame, as presently delivered to the service mode users. It results from the combination of 3 jittered spectra of 840s. They were obtained with the low resolution B grism. Eight wavelength calibrated and aligned spectra slits are shown in the 2D image. Continuum and emission lines of the target objects are visible together with the residual of sky subtraction and ,for slits 2 and 6 from the top, residual contamination from the saturated zero orders from multiplexed slits. The 1D extracted spectrum of the object in slit 5 from the top is shown to the side.

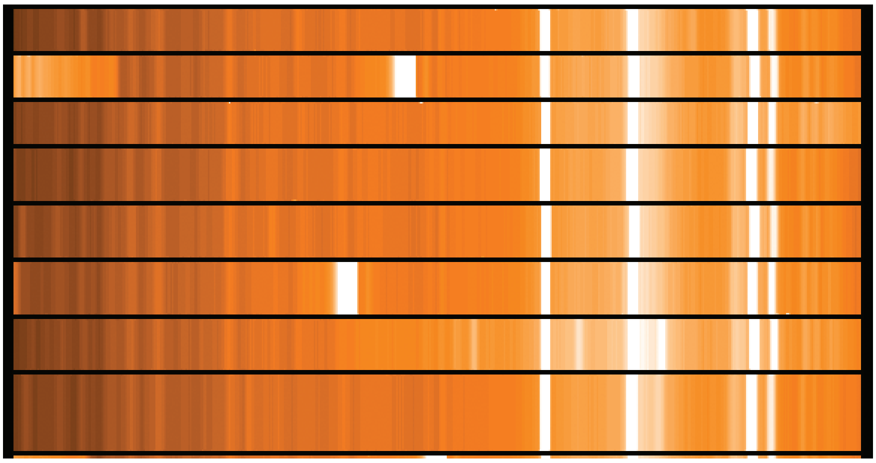


Figure 4: A portion of the sky spectrum for the 8 slits shown in Figure 3. The spectra have been calibrated and aligned in wavelength. The strong sky emission line close to the centre is the 5577.4 Å [O I] line, followed at longer wavelength by the blended doublet of Na I at 5893 Å and the 6300 and 6364 Å lines of [OI]. Some other features of the VIMOS low-resolution spectral data format are also visible. In the slit #2 and #6 from the top the strongest line is the zero order from contiguous multiplexed spectra. In slit #2 from the above, the contamination from the slit in the lower part of the mask is visible on the left. In the slit #7 from above, the –1 order contamination is visible, overlapping the right part of the spectrum.

ing time last year, test runs between November 2002 and March 2003 and the first four months of regular operation in service mode since April 2003. Periods of acceptable reliability following a major tuning of the instrument by the Consortium technical team did not prove to last long. If left unchecked, we fear that the instrument could progressively degrade to a level where its regular operation would become impossible.

With the instrument taken over by ESO from June of this year, we have decided to launch a major repair/upgrade plan, based on two extended interventions by the Instrumentation Division and the Paranal Observatory within the next 12 months.

Although the time when the instrument is off the telescope is concentrated around full moon, the interventions will still result in some loss of useful observing time and they imply some additional cost and manpower to the project. It is however a good investment considering the total value of the project and its scientific capability.

This first, 6 week-long, intervention is taking place in August-September of this year. We are in particular going through extensive verification and refurbishing of the instrument focal plane assembly (including the Mask Exchange Units and the IFU) to improve its reliability and possibly reduce the IFU flexures. The time will also be used to investigate the changes required by the Grism Exchange Units. The instrument is expected to come back into regular operation in the second half of September.

The second intervention is planned for the spring of 2004. The main objective will then be the full refurbishing of the complex GEUs. We now plan also to use this occasion to replace eight high-resolution classical grisms (four blue and four red) with Volume Phase Holographic ones, which are now available in the large size (160 mm) required for VIMOS. The new sets have been just ordered. Besides a substantial reduction in weight, hopefully beneficial to the reliability of the exchange mechanism, they will boost the VIMOS efficiency in these sub-modes by almost a factor 2. The start of P 73, 1st April 2004, should find VIMOS in a much more robust state and able to deliver efficiently the unique science for which this complex machine has been developed.

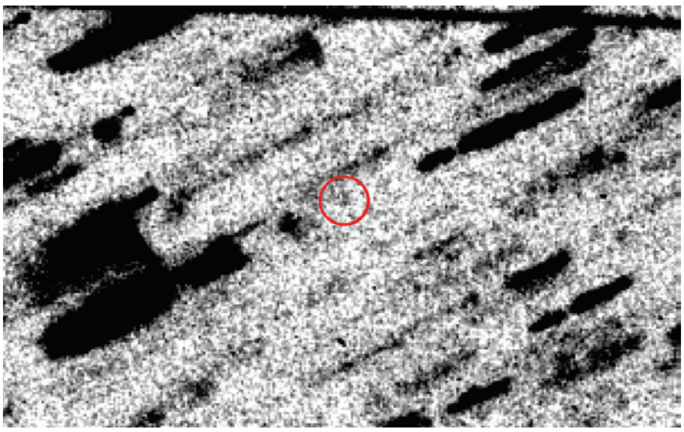
References

Le Fèvre O. et al., 2002, *ESO Messenger*, 109, 21

Le Fèvre O. et al., 2003, *ESO Messenger*, 111, 18

Hanuschik H. & Silva D., 2002, *ESO Messenger*, 108, 4

VLT Observes Comet Halley at Record Distance



Sky field in which Comet Halley was observed with the ESO Very Large Telescope (VLT) at the Paranal Observatory on March 6-8, 2003. 81 individual exposures with a total exposure time of 32284 sec (almost 9 hours) from three of the four 8.2-m telescopes were cleaned and added while shifting their positions according to the motion of the comet. The faint, star-like image of Comet Halley is visible (in circle, at centre); all other objects (stars, galaxies) in the field are "trailed". A satellite trail is visible at the very top. The field measures 60 x 40 arcsec^2; North is up and East is left. ESO Press Photo 27c/03

Seventeen years after the last passage of Comet Halley, the ESO VLT has captured a unique image of this famous object as it cruises through the outer solar system. It is completely inactive in this cold environment. No other comet has ever been observed this far (28.06 AU heliocentric distance) or that faint (V = 28.2). The image of Halley was obtained by combining a series of exposures obtained simultaneously with three of the 8.2-m telescopes during 3 consecutive nights with the main goal to count the number of small icy bodies orbiting the Sun beyond Neptune, known as Transneptunian Objects (TNOs). The combination of the images from three 8.2-m telescopes obtained during three consecutive nights is not straightforward. The individual characteristics of the imaging instruments (FORS1 on ANTU, VIMOS on MELIPAL and FORS2 on YEPUN) must be taken into account and corrected. Moreover, the motion of the very faint moving objects has to be compensated for, even though they are too faint to be seen on individual exposures; they only reveal themselves when many frames are combined during the final steps of the process. It is for this reason that the presence of a known, faint object like Comet Halley in the field-of-view provides a powerful control of the data processing. If Halley is visible at the end, it has been done properly. The extensive data processing is now under way and the intensive search for new Transneptunian objects has started. (*see ESO PR Photo 27/03*)