The VLT-VIMOS Mask Preparation Software

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Abstract. VIMOS (VIisible Multi-Object Spectrograph) is a multi-object imaging spectrograph installed at the VLT (Very large Telescope) at the ESO (European Southern Observatory) Paranal Observatory, especially suited for survey work. VIMOS is characterized by its very high multiplexing factor: it is possible to take up to 800 spectra with 10 arcsec long slits in a single exposure. To fully exploit its multiplexing potential, we designed and implemented a dedicated software tool: the VIMOS Mask Preparation Software (VMMPS), which allows the astronomer to select the objects to be spectroscopically observed, and provides for automatic slit positioning and slit number maximization within the instrumental constraints. The output of VMMPS is used to manufacture the slit masks to be mounted in the instrument for spectroscopic observations.

Key words. Instrumentation: spectrographs – Methods: numerical – Techniques: spectroscopic

1. Introduction

VIMOS (VIisible Multi-Object Spectrograph) is a survey multi-object spectrograph operational at one of the Nasmyth foci of the Melipal telescope of the ESO (European Southern Observatory) VLT (Very large Telescope) since April 2003. VIMOS was designed and built by the French-Italian VIRMOS Consortium (Le Fèvre et al. 2000). VIMOS is based on a classical focal reducer design replicated in 4 separate channels operating simultaneously (see Fig. 1). It has 3 operational modes: imaging, with broad band UBVRIz filters; MOS (Multi-Object Spectroscopy), with a choice of 5 grisms giving spectral resolutions from 200 to 2500 in the wavelength range 0.37-1\textmu m; and IFS (Integral Field Spectroscopy), whereby 6400 fibers coupled with micro-lenses produce spectra of a contiguous area of 54 × 54 square arcsec.

In MOS mode, observers design four slit masks (one for each quadrant) from images taken prior to the spectroscopy observing run, hereafter called ”pre-images”, and a user-supplied source catalogue. Then the masks are manufactured by the MMU (Mask Manufacturing Unit) which is a dedicated laser cutting machine (Conti et al. 2001). Once inserted in the focal plane, masks are aligned on the sky before the exposure.

One of the main drivers in the design of VIMOS was the multiplexing factor, i.e. the possibility of packing as many spectra as possible on the detectors. For example, at the limiting magnitude I < 24, with a low-resolution grism, we have been able to obtain up to 1000 spectra.

The number of spectra that can be packed on a detector depends on the detector size, the length of the spectra, the length of the slits, the possibility of placing slits over the whole field of view without losing wavelength coverage, and, last but not least, the spatial distribution of the targets. To maximize the number of slits, we have adopted a similar approach to that successfully used by the Canada-France Redshift Survey (CFRS) on the MOS-SIS spectrograph at CFHT (Le Fèvre et al. 1994), allowing zero order and second order spectra to overlap with
the first order spectra from other slits. This makes for an efficient packing of spectra on the detectors, with several superimposed banks of spectra, and with strict constraints on slit mask design and data processing (Le Févre et al. 1995).

To improve on this concept, the VIMOS optical design is such that slits can be placed anywhere in the field of view, and the optical cameras image the spectra on 2048 × 4096 pixels, the 4096 pixels being placed along the dispersion direction, while the field of view on the sky is imaged only on 2048 × 2340 pixels. This means that for any slit placed in the field of view, the full wavelength range of a low resolution spectrum is recorded on the detector. This property also applies to higher resolution $R \sim 2500$ spectra, which are fully recorded on the detector for most slit positions in the field of view.

The large number of slits (up to ∼200 per quadrant) involved in the VIMOS spectroscopic observations together with slit positioning constraints makes it practically impossible for the astronomer to manually choose and place all the slits, in particular if one wants to maximize the number of slits. The software tool we are describing in this paper, called VMMPS, allows to design the slit masks taking into account all the instrument constraints and solves the problem of maximizing the multiplexing factor given a certain target field (Garilli et al. 1999). This tool has been delivered by our Consortium to ESO, and is now distributed by ESO to all successful proposers.

VMMPS provides the astronomer with tools for the selection of the objects to be spectroscopically observed. It includes interactive object selection, it handles curved slits, and an algorithm for automatic slit positioning which derives the most effective solution in terms of number of objects selected per field. The slit positioning algorithm takes into account both the initial list of user’s targets, and the constraints imposed either by the instrument characteristics and/or by the requirement of easier reduceable data. The number of possible slit combinations in a field is in any case very high, and the task of slit maximization cannot be solved through a purely combinatorial approach. We have introduced an innovative approach, based on the analysis of the function $N_{\text{slit}}/W_{\text{col}}$, where $N_{\text{slit}}$ is the number of slits within a column and $W_{\text{col}}$ the width of the column. The algorithm has been fully tested and validated.

In this paper we describe the MOS observation preparation flow (Section 2), the imaging and catalogue handling (Section 3), the instrumental and data reduction requirements (Section 4) and the slit positioning optimization code (Section 5). We conclude in Section 6.

2. The MOS observations preparation flow

Pre-imaging with VIMOS is required for subsequent spectroscopic follow-up, even when targets come from a pre-defined catalog. Pre-imaging is necessary to set the proper coordinate transformation between an existing catalog with reference astrometry, and the VIMOS coordinate system. Since mask preparation can be done using pre-established astrometric catalogs, pre-imaging is not required to be as deep as to detect all the spectroscopic targets. It should however be deep enough to provide enough targets for a cross-correlation between the catalog extracted from the image itself and the pre-defined astrometric catalog. In the case of a pre-established astrometric catalog, the first step to be performed by VMMPS is the cross-correlation and the subsequent re-coordination to the coordinate grid defined by the VIMOS image. If the catalogue to be used has been obtained directly from a VIMOS image this first operation is not needed. The following step is to define the catalogue "special" objects. These are the objects to be used for mask alignment (reference), the objects which must be observed in any case (compulsory), and the objects you do not want to observe (forbidden). Eventually "special" slits, tilted or curved, can be defined interactively. The last step is to define the set of objects to be observed. This step is performed by SPOC (Slit Positioning Optimization Code), that is the core of VMMPS. SPOC places slits maximizing their number in a VIMOS quadrant, taking into account special objects, special slits and slit positioning constraints.

3. Imaging and catalogue handling

We need tools which allow us either to select objects from an image obtained with VIMOS (or from a catalogue derived from this image) or from our own catalogue. In principle, telescope (VLT) and site (Paranal) characteristics make it conceivable to use slits as narrow as 0.5 arcsec, a possibility which, in turn, requires an excellent mapping of the projection of the sky onto the focal plane. The mapping of the focal plane onto the CCD is part of the calibration procedure of the instrument, and it has been tested that the accuracy of this calibration is better than one pixel (0.2 arcsec) at any point in the field of view. The mapping of the sky onto the CCD, or the astrometric calibration of the images, is a more difficult task, where an accuracy of 0.3 arcsec (absolute astrometry) is commonly considered as an excellent result. Relative astrometry (i.e. the relative position of objects within the field of view) is usually much more accurate (0.1 arcsec or less).

To avoid any problem with the astrometry, it has been decided to place slits only starting from a "preparatory image" acquired with VIMOS. Thus object coordinates are already in VIMOS pixels and the computation of slit coordinates requires only the well known CCD to focal plane calibration. Users having other information derived from observations with other instruments must have the possibility to use their catalogues to select spectroscopic targets. Due to the intrinsic difficulties in absolute astrometric calibrations, the most reliable solution is to follow a two steps approach. First, acquire a preliminary image with a moderately accurate astrometric solution. From this image, a catalogue of objects with X and Y coordinates in VIMOS pixels and approximated sky coordinates can be obtained with any detection algorithm. The approximated coordinates are then matched against the user’s own catalogue. The detection algorithm finds common objects within a given tolerance between the user’s catalogue and the VIMOS pre-image catalogue.
4. Instrumental and Data Reduction Requirements

4.1. Masks

The VIMOS focal plane is divided into 4 quadrants, thus 4 masks (1 mask set) are needed for each MOS observation. The scale at the focal plane where masks must be inserted is 0.578 mm arcsec\(^{-1}\) and each quadrant has a field of view of about 7' × 8'. This defines the gross dimensions of the masks and, together with the expected best seeing at the VLT (∼ 0.3"), the minimum slit width.

Fig. 1 shows an outline of the VIMOS focal plane with its reference system. The size of the masks is 305 × 305 mm, and the contour geometry is determined by the mechanical interface with the focal plane and with the automatic mask insertion mechanism (Conti et al. 2001).

It is important to note that the positioning of masks one relative to each other cannot be changed, therefore when preparing masks relative positions of objects must be consistent over the whole field of view, and not only over a single quadrant.

4.2. Slit Positioning Constraints

Within a limiting magnitude of \( I = 24 \), more than 1000 objects are visible in a VIMOS quadrant. Not all these objects can be spectroscopically observed in a single exposure because the overlap of spectra, both in the spatial and in the dispersion direction, must be avoided. When low dispersion grisms are used, there can be several spectra along the dispersion for the same position on the CCD X coordinate (multiplexing). In this case objects must have a separation greater than their first order spectrum length (see Fig. 2 case a), and the spectra resulting from slits placed on objects at different spatial coordinates must not overlap (see Fig. 2 case b). Furthermore, low resolution grisms produce second order spectra which, although of very low intensity (∼ 3% of the intensity of the first order), can be extremely annoying for the sky subtraction of the weakest objects. For a better estimate of the spectral background, it is preferable to have second order spectra overlapping any eventual first order spectrum in an exact way, i.e. the two slits placed “one above the other” should be of the same length and aligned (see Fig. case 2 c).

This requirement ensures that the second order sky contamination of the slit below and the zero order of the slit above (in the dispersion direction) can be removed together with the first order sky when the spectral background of a slit is processed. This process does not remove the second and zero orders of the objects in the slits below/above, but it completely eliminates the inconvenience of having a step function contamination to remove along the spatial direction of slits when correcting for the sky background.

On the contrary, VIMOS high dispersion grisms produce first order spectra approximately as long as the dispersion direction of a VIMOS quadrant, i.e. only a single column of slits can be placed along the dispersion direction.

The slit length is set by the object size plus a minimum area of sky on both side of the object, required for a stable fitting of the sky signal to be removed during data processing. The size of this area is suggested to be of the order of 2 arcsec per side (i.e. about 10 pixels) to ensure a good sky level fitting.

Slits as narrow as 0.5 arcsec are a real possibility for VIMOS, and it implies an extremely precise pointing and centering of objects in slits. The best and safest way to obtain such accuracy is to have reference objects in the field, to be used

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**Fig. 1.** The figure shows (on scale) the location in the 4 VIMOS quadrants of the 4 masks with contour and orientation. The dispersion direction of the spectra is along the Y axis. The four crosses mark the position of the optical axis of each quadrant, while the dashed line indicates the 244 × 279 mm “useful area” of the detector field of view.
to refine the pointing on the sky. Once the telescope is on the field, an exposure with the mask inserted is taken, and pointing is refined so that reference objects fall exactly at the center of the reference “holes”. Reference objects must be bright and point-like, and they must be part of the same user input catalogue. Reference objects have to be manually chosen. The slit positioning algorithm has to handle them in a special way, as they have square holes with a fixed size instead of rectangular slits. Although in principle only one reference object per quadrant would be required for pointing refining, a minimum of 2 reference objects per quadrant is recommended.

As reference objects are bright, their second order spectrum contamination is strong. For this reason, no slit is allowed in the same spatial coordinate range of reference object holes. The same requirement is applied to curved or tilted slits, for particularly extended and interesting objects, and no spectrum overlapping is thus allowed.

These constraints must be fully taken into account by any slit positioning code.

4.3. Manual selection of objects

VMMPS is based on the astronomical package SKYCAT distributed by ESO. SKYCAT has enhanced real time display capabilities and provides basic functions for catalogue handling. Display and catalogue functions are coupled by good overlay capabilities and WCS is well supported. The VMMPS graphical user’s interface is a SKYCAT plugin developed in TCL/TK. Allowed formats are FITS for images and ASCII for catalogues.

As slits are positioned with an automated procedure which maximizes the number of placed slits, there is no way to choose objects “a priori”. For all scientific purposes which do not rely on systematic surveys, it can be a disadvantage. Compulsory objects are the answer to such needs: the automatic procedure place slits on them (after having checked that they do not violate the constraints described above) before anything else, then it tries to place additional slits on objects randomly chosen from the catalogue.

Forbidden objects are the opposite of compulsory objects: they are flagged by the user so that no slit is placed on them.

Last, but not least, a number of scientific programs would greatly benefit from having curved or tilted slits which better follow the object profile (gravitational arcs are just the most obvious example). The laser cutting machine (Conti et al. 2001) is capable of cutting arbitrary shapes. Therefore, VMMPS allows the user to interactively design curved or tilted slits. Curved slits are defined by fitting a Bezier curve to a set of points chosen interactively by the user.

5. Slit Positioning Optimization Code (SPOC)

The large number of objects and slits involved in the VIMOS spectroscopic observations together with the positioning constraints and the particular objects described above, make it practically impossible for the astronomer to manually choose and place the slits. For this reason a tool for the automatic positioning of slits and the maximization of their number has been implemented: SPOC (Slit Positioning Optimization Code). SPOC is the core of VMMPS. Given a catalogue of objects, it maximizes the number of observable objects in a single exposure and computes the corresponding slit positions. SPOC places slits on the field of view taking into account special objects (reference, compulsory, forbidden), special slits (curved, tilted or user’s dimension defined slits) and slit positioning constraints. An example of SPOC slit positioning for a VIMOS quadrant is shown in figure 3.

The issue to be solved is a combinatory computational problem. Due to the constraint of slits aligned along the dispersion direction, the problem can be slightly simplified: the quadrant area is considered as a sum of columns which are not necessarily of the same width in the spatial direction. Slits within the same column have the same length so that the alignment of orders is fully ensured. The problem is thus reduced to be mono-dimensional. It is easy to show that the number of combinations is roughly given by: \( N_c = N_w^{8/4}, \) where \( N_c \) is the number of combinations, \( N_w \) the number of possible column widths, and \( N_{col} \) the average number of columns.

The slit length (or column width) can vary from a minimum of 4 arcsec (20 pixels, i.e. twice the minimum sky region required for the sky subtraction) to a maximum of 30 arcsec (150 pixels, limit imposed by the slit laser cutting machine) in 1 pixel steps. The average number of columns is estimated as the spatial direction size of the FOV divided by the most probable slit length, typically 50 pixels (10 arcsec), i.e. 2048/50 = 41. The number of combinations is then: \( N_c = (130)^{41} \sim 4.7 \times 10^{86}, \) corresponding to about 10^60 years of CPU work!

The problem is similar to the well-known traveling salesman problem. In the standard approach, it is solved by randomly extracting a “reasonable” number of combinations and maximizing over this subsample. In our case, due to computational time, the “reasonable” number of combinations cannot be higher than 10^8-10^9. So small with respect to the total num-
Fig. 3. Output of the VMMPS/SPOC algorithm run on a single quadrant of a VIMOS image and using an external user catalog: the number of slits positioned is maximized by VMMPS using all the user and instrument constraints.

Fig. 4. Function No.Slits/Column width: increasing the column width this function decreases but a maximum is reached every time a new slit is placed in the column itself.

For each spatial coordinate we have \( K \) (where \( K \) is the number of peaks, in our example \( K = 4 \)) possible columns with their own length and number of slits. Although the number of combinations to be tested is decreased (in our example, about \( 4^4 = 4.8 \times 10^3 \)), it is still too large in terms of computational time.

A further reduction can be obtained if, instead of simultaneously considering all the columns, we consider sequentially \( M \) subsets of \( N \) consecutive columns, which cover the whole quadrant. At this point, we should vary \( N \) (and consequently \( M \)) to find the best solution. In practice, when \( N \) is higher than 8-10, nothing changes in terms of number of observable objects. For \( N = 10 \), thus \( M = 4 \) (i.e. \( 2048/(4 \times 50) \)), the number of combinations is reduced to only \( 4 \times 4^{10} = 4 \times 10^6 \), that means a few seconds of CPU work.

As a consequence of the optimization process, small size objects are favoured against the large size ones. Small objects are statistically fainter than big ones, so weak objects are slightly favoured against the bright ones and this can be a drawback for some observational projects.

To overcome this drawback, a less optimized algorithm has also been implemented in SPOC. This alternative algorithm does not optimize all columns simultaneously, but it builds the \( \frac{N_{\text{Slit}}}{\text{Column width}} \) function (Fig. 4) column by column without considering object sizes, and it takes only the maximum. Then it increases each column width to account for object sizes.

We tested these two different SPOC maximization modalities on a sub-sample of about 90000 objects extracted from the VIMOS-VLT Deep Survey database (Le Fèvre et al. 2004a). The magnitude and the radius distributions of this sub-sample and of the SPOC output (about 7000 objects) are shown in figure 5. The excess of small (Fig. 5 case a) and faint (Fig. 5 case c) objects produced by SPOC with the best optimization modality disappears when the less optimized modality is used (Fig. 5 case b and d) while the number of placed slits decreases by a few percent.
6. Conclusions

1. VMMPS provides the VIMOS observer with user-friendly software tools to select the spectroscopic targets in the instrument field of view, including interactive object selection, handling of curved slits and maximization of the number of targets once the input catalogue is defined. The VMMPS output is a set of files that are passed to the VIRMOS MMU to cut the slits in the masks and included in the file header of the spectroscopic images for the subsequent data reduction.

2. VMMPS has been successfully used by the VIMOS team for the preparation of the VIMOS-VLT Deep Survey (Le Fèvre et al. 2004b), and by the European astronomical community for the preparation of their specific observation programs.

3. VMMPS is a general purpose tool for multi-object spectroscopy, rather than being instrument specific, and its code has been distributed to GMOS (Gemini) and OSIRIS (Gran Telescopio Canarias).

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Fig. 5. Magnitude and radius distribution: the shaded histograms correspond to the input sample, the empty histograms correspond to the SPOC output.