Revisiting the Impact of Atmospheric Refraction on VIMOS-MOS Observations: Beyond the Two-hour Angle Rule

Rubén Sánchez-Janssen[1]
Fernando Selman[2]
Steffen Mieske[2]
Paul Bristow[2]
Peter Hammersley[2]
Michael Hilker[2]
Marina Rejkuba[2]
Burkhard Wolff[2]

[1] NRC Herzberg Institute of Astrophysics, Canada
[2] ESO

Multi-object spectroscopic (MOS) observations with VIMOS have traditionally been limited to a narrow two-hour range from the meridian to minimise slit losses caused by atmospheric dispersion and differential refraction. We revisit the impact of these effects on the quality of VIMOS-MOS spectra through extensive simulations of slit losses. We show that MOS observations can be effectively extended to plus/minus three hours from the meridian for fields with zenith angles smaller than 20 degrees at culmination — provided a nonstandard rotator offset angle of 0 degrees is used. The increase in target observability will enhance the efficiency of operations, and hasten the completion of programmes — a particularly relevant aspect for the forthcoming spectroscopic public surveys with VIMOS.

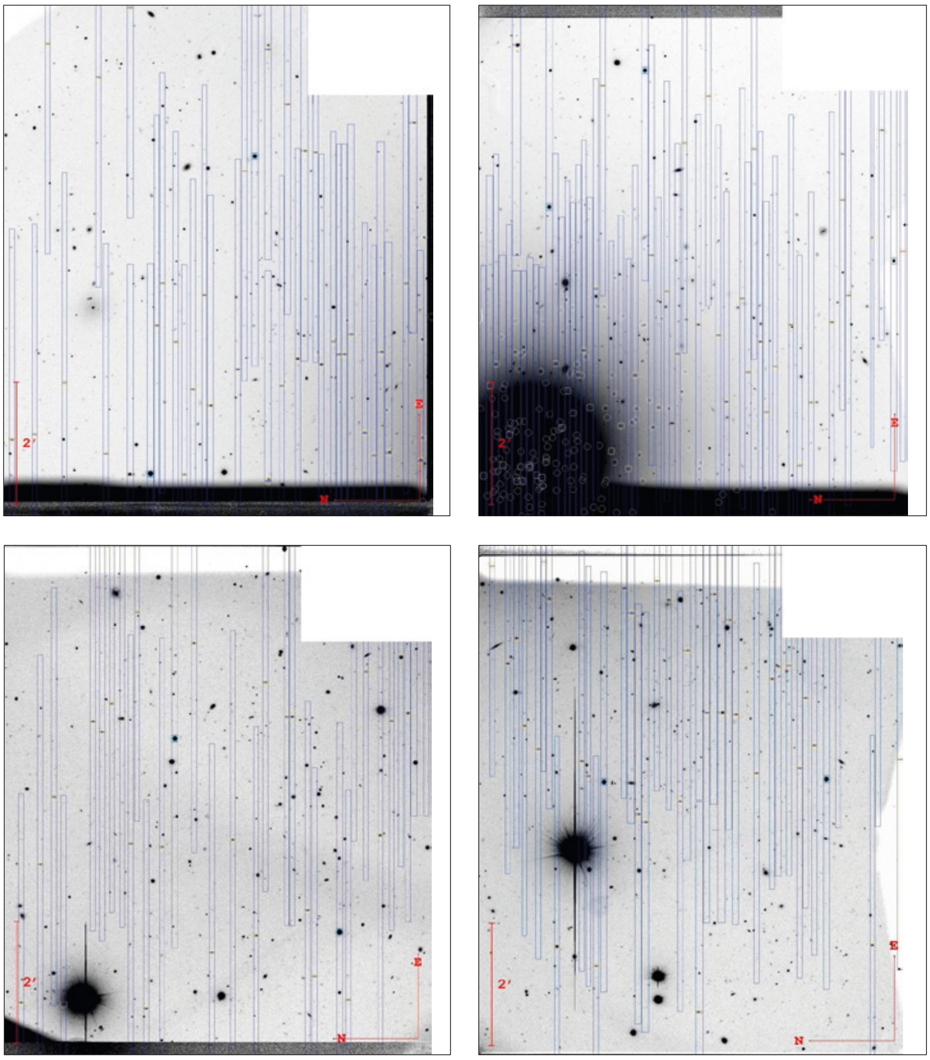

Figure 1. Example of a VIMOS finding chart for MOS observations. Each quadrant is 7 by 8 arcminutes, and they are separated by two arcminute gaps. Allocated slits are overplotted in blue. The blank areas (upper right of each finding chart) are masked out proposal information.

Atmospheric refraction in VIMOS-MOS observations

VIMOS (Le Fevre et al., 1998) is a wide field-of-view (four fields of 7 by 8 arcminutes) instrument with imaging, integral field, and multi-object spectroscopic capabilities mounted at the Nasmyth B focus of the Very Large Telescope (VLT) Unit Telescope 3. The instrument operates in the optical wavelength range (360–1000 nm), and is equipped with six sets of grisms, six sets of broadband filters, plus three additional filter sets specifically designed to be used in combination with the grisms to block the second-order spectra. During the last few years the instrument performance has been significantly enhanced (see Hammersley et al., 2012; 2013): changing the detectors to red-sensitive, low-fringing CCDs; replacing the HR-blue grism set with higher throughput volume phase holographic grisms; introducing an active flexure compensation system; redesigning the focusing mechanism and mask cabinet; and introducing a new pre-image-less MOS mode (Bristow et al., 2013). All these improvements have made VIMOS a much more stable instrument, and have extended its lifetime to prepare it for the start of the spectroscopic public surveys for which ESO has recently issued a call.

Further work to improve the operational efficiency of the instrument includes the present study, which has, as its main goal, to revisit the need for restricted observability of targets only within plus and minus two hours from the meridian in the MOS mode — the two-hour angle rule. VIMOS is not equipped with atmospheric dispersion compensators (ADCs), and MOS observations are carried out using multi-slit masks (see Figure 1). As a result, atmospheric dispersion (caused by the wavelength variation of the index of refraction of air) and field differential refraction (resulting from airmass variations across the field of view [FoV]) introduce a wavelength-dependent flux reduction, due to slit losses, that cannot be corrected. Unfortunately, field rotation further prevents the alignment of all slits along the parallactic angle (PA), so that slit losses can only be minimised by a careful optimisation of the observability windows.

The atmospheric effects in VIMOS-MOS were studied with great detail in Cuby et al. (1998). They show that: i) atmospheric dispersion dominates at shorter wavelengths, while differential refraction is not negligible at the red end of the visible spectrum; ii) in the former case, image drifts occur along the meridian; iii) differential refraction can be almost neglected for zenith distances smaller than 25 degrees for exposure times of duration up to two hours from the meridian. In view of these results they recommended that, in order to minimise flux losses, the slits be positioned along the dispersion direction at mid-exposure (north–south), and observations be limited to a narrow two-hour range from the meridian crossing. This guarantees that losses remain below 20% for zenith angles < 50 degrees at culmination.

These rather limiting guidelines have always been in place for all MOS observations since the start of operations in 2003, and, in practice, translate into mandatory airmass constraint limits for the VIMOS-MOS observing blocks. Increasing the observability of targets in the MOS mode provides more flexibility to operations, because the number of masks that can be loaded into the instrument before the beginning of each night is limited. VIMOS is very often used for deep observations of cosmological fields, where very long integrations are taken for the same field. By increasing the target visibility (relaxing the two-hour angle rule), observing programmes can be completed faster.

In this report we revisit the impact of atmospheric refraction on the quality — in terms of slit losses and spectrophotometric distortions — of VIMOS observations for all the different MOS setups. We note that the parameter space of this problem is huge. Irrespective of image quality and weather conditions, slit losses depend on slit orientation and position within the FoV, observed wavelength range, target declination, total exposure time, and hour angle (HA) of the observations. We have tried to condense all this information to provide VIMOS users with clear, optimal recommendations.

A model to address slit losses

In order to investigate potential operational improvements that could enhance the efficiency of VIMOS, we have simulated the effects of slit losses under different circumstances. Our fiducial model assumes a flat input spectrum and nine slits evenly distributed across the entire VIMOS FoV, from the centre to the corners, and with relative separations of seven arcminutes. All slits have a length of 10 arcseconds and width of 1 arcsecond, which is typical for the majority of VIMOS-MOS observations. We assign two different orientations for the slits at meridian crossing, namely north–south (PA = 0 degrees), and east–west (PA = 90 degrees). Here we follow the usual on-sky convention for orientations, but note that this differs from the rotator offset angle described in the VIMOS manual: the default offset angle of 90 degrees corresponds to a north–south on-sky orientation, while a non-standard rotator offset angle of 0 degrees corresponds to east–west on sky.

Alignment and guiding are assumed to be done at either 450 nm (for the blue grisms only) or 700 nm (for the rest), and the seeing point spread function is considered to be wavelength- and airmass-independent, with a Gaussian full width at half maximum of 1 arcsecond. In reality, of course, the seeing will vary as a function of both parameters, but we note that, during actual service mode operations, seeing constraints have to be satisfied at any given airmass and instrument setup — and therefore our assumption provides the closest match to reality. This setup results in a 24% fiducial flux loss due to finite seeing and slit width, and under the assumption that the objects are perfectly centred within the slits. We adopt the average night-time pressure (743 mbar) and temperature (12 C) at the Paranal Observatory within the last five years (courtesy of J. Navarrete) in our computation of atmospheric refraction. Finally, for each of the six VIMOS grisms (and filter combinations) we assume observations with 3600 s exposure times, within four hours from meridian crossing, and for targets in the $-75 \leq \delta \leq +25$ degree declination range.

Figure 2 shows an example of the output from the simulations. Each panel shows, for the nine different positions across the VIMOS FoV, the output spectra obtained after a one hour long integration ($-3 < \mathrm{HA} < -2$) on a $\delta = 0$ degree field, and using the LR-red grism. Solid (dotted) lines correspond to slits oriented along the north–south (east–west) direction at meridian crossing. The dashed lines indicate the fiducial maximum flux mentioned above. For each slit we also provide the corresponding values for the two figures of merit with which we characterise the results of the simulations: the total relative flux loss (f), and the spectral distortion ($\Delta = 1 - f_{min}/f_{max}$). In this particular case, even though the two slit orientations result in very similar median slit losses ($f = 0.10$ and $f = 0.09$ for the north–south and the east–west orientation, respectively), the east–west alignment provides more stable results across the FoV, and lower median spectral distortions ($\Delta = 0.07$ *vs.* $\Delta = 0.15$). This should therefore be the preferred orientation.

Figures 3 and 4 illustrate the final results for the entire set of simulations in the case of the LR-blue and the LR-red grisms respectively. In all panels the solid curves show the minimum, median and maximum flux losses, and spectral distortions, of the nine simulated slits as a function of target declination, and for the two different slit orientations at meridian crossing. Each column corresponds to a one hour long integration with target hour angle as indicated at the top. We note that the behaviour of the curves is similar for both grisms, but both losses and distortions are significantly smaller at the red end of the visible spectrum.

The general trends for the two slit orientations can be summarised as follows. For the north–south (PA = 0 degree) orientation, we find that at fixed HA there is a very weak dependence on declination (except for |HA| > 2 hr and the bluest wavelengths). The minimum of the loss/distortion distributions increases and moves towards southern declinations at larger HAs. For any given grism, there is a strong dependence with HA, such that

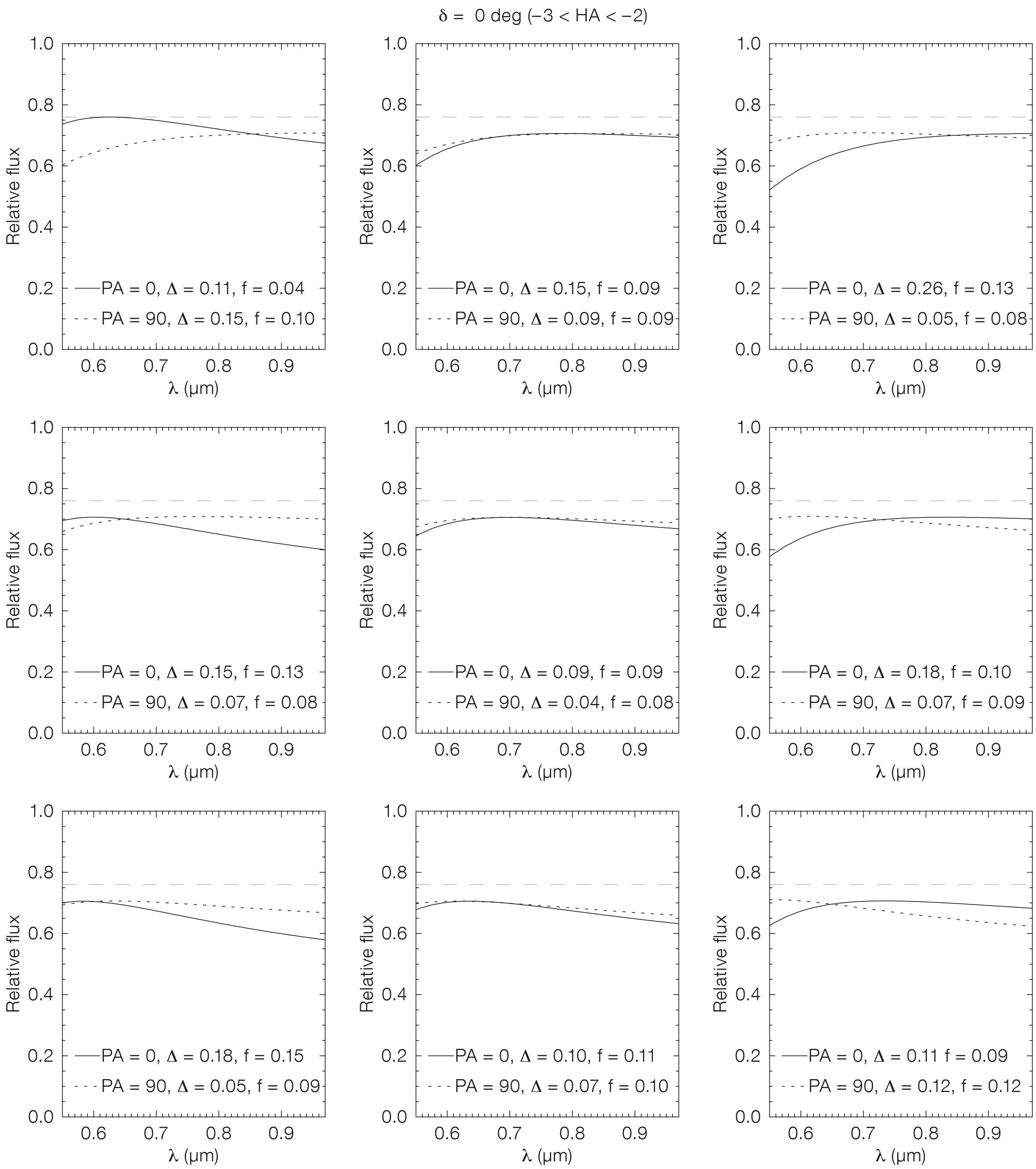

Figure 2. Output simulated spectra for nine different slit positions across the VIMOS FoV. These are the result of a one hour long integration (−3 < HA < −2) on a δ = 0 degree field using the LR-red grism for an input flat spectrum. In each panel we show the spectra for two different slit orientations, as well as the corresponding relative flux loss (*f*) and spectral distortion (Δ).

larger distortions and flux losses occur at larger HAs. Both the amount of losses/distortions, and the dependence on declination, increase for bluer wavelengths.

On the other hand, for the east–west (PA = 90 degree) orientation, we see that at fixed HA there is a very strong dependence on declination, but the behaviour flattens towards redder wavelengths. The minimum of the loss/distortion distributions slightly decreases and moves towards southern declinations at larger HAs. For any given grism, there is very little dependence on HA (except for extreme declinations). Finally, the dependence on declination of losses/distortions increases towards bluer wavelengths.

Beyond the two-hour angle rule

Extracting simple rules from a problem with such a high dimensionality requires a certain level of data compression. Following the previous work by Cuby et al. (1998), we set the tolerance level for losses/distortions at 20%. In Figure 5 we show the declination–hour-angle pairs (colour-coded according to slit orientation) for which the median spectral distortion (top row) or median flux loss (bottom row) across the VIMOS FoV remain below this tolerance value during a one hour long integration. It is evident that for fields culminating at small zenith distances the

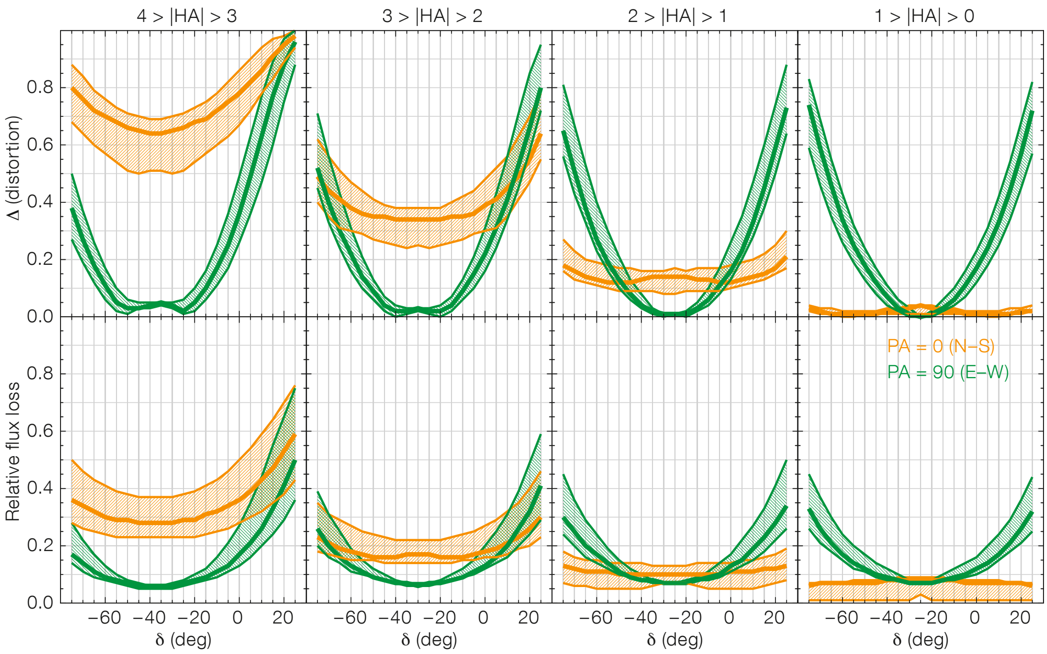

Figure 3. Curves show, for the LR-blue grism, the minimum, median and maximum flux losses (lower row) and spectral distortions (upper row) for the nine simulated slits as a function of target declination. The region between the minimum and maximum, about the median, is shaded. The plots show the effects for two different slit orientations at the meridian (north–south in orange and east–west in green).

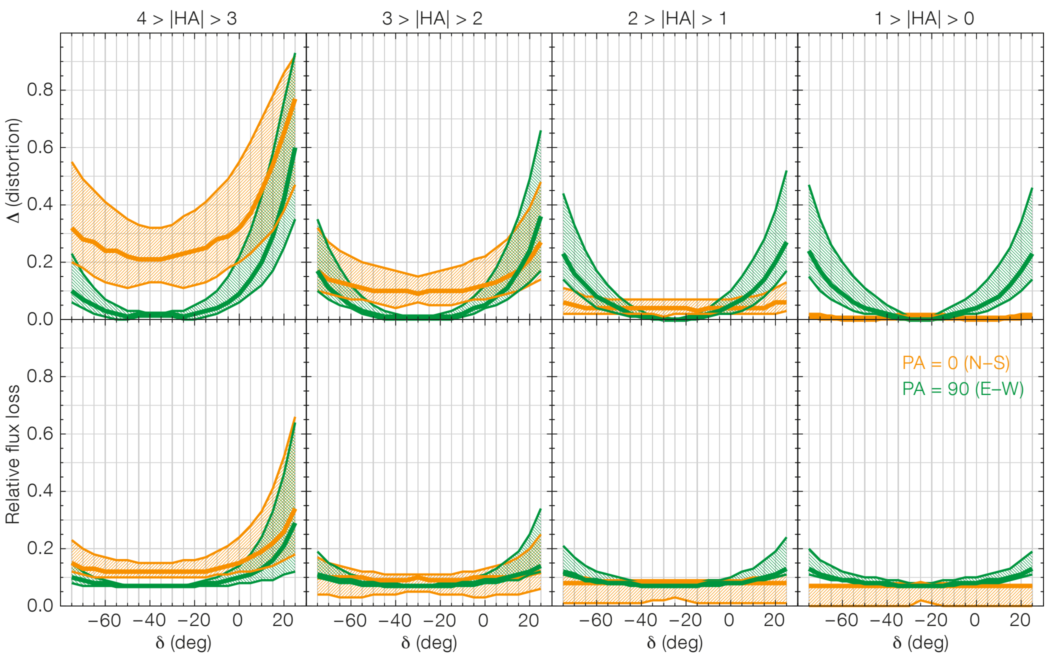

Figure 4. Same as Figure 3, but for the LR-red grism.

optimal slit alignment is the one that follows the east–west direction at meridian crossing. This is expected, as this slit orientation is closer to the parallactic angle at high airmasses, and dispersion is almost negligible close to meridian crossing. We note, however, that the flux loss differences between the north–south and east–west orientations are small for these fields when observed within two hours from the meridian — as was originally pointed out by Cuby et al. (1998). We also note that the most stringent constraints arise from the blue grisms.

In summary, the two-hour angle rule, together with the default north–south slit orientation, provide the most stable results, with slit losses and spectral distortions below 20% and almost independent of target declination. This should always be the preferred option for users with targets at $\delta \gtrsim -5$ or $\delta \lesssim -45$ degrees. However, for targets within the $-45 < \delta < -5$ degree range, the east–west orientation is generally preferred. This slit orientation allows for observations to go past the two-hour angle rule, and be effectively extended up to $|HA| = 3$ hours. This holds for all grisms currently offered in VIMOS, provided the acquisition is done with a filter that closely matches the grism wavelength

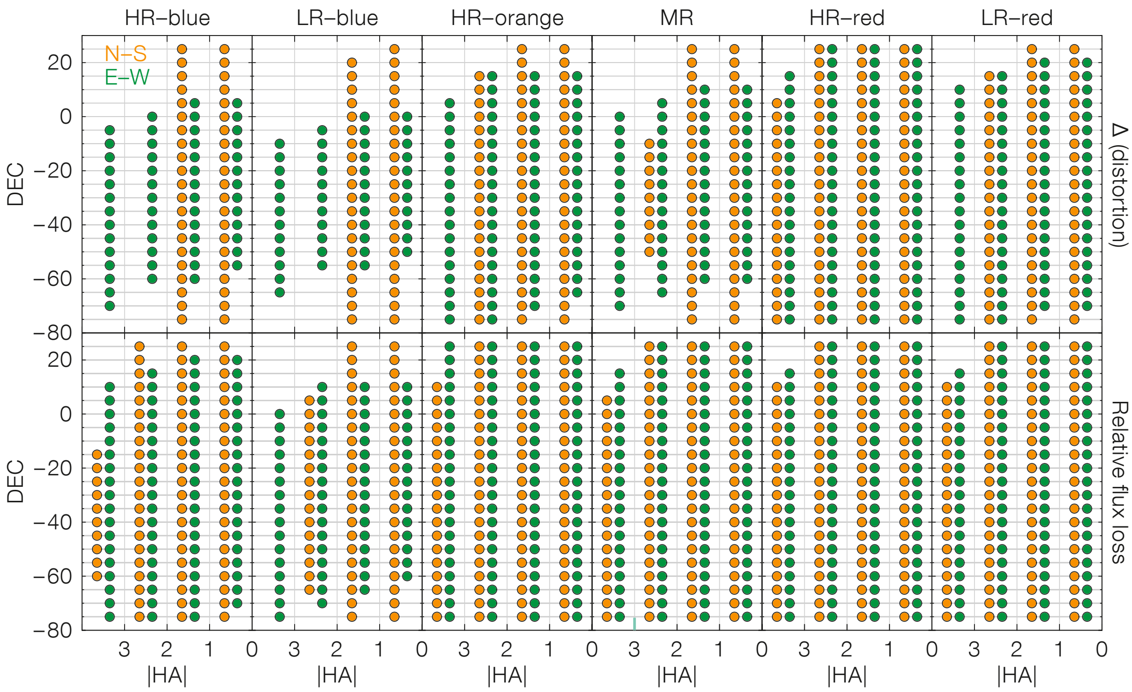

Figure 5. Circles show the declination–hour-angle pairs (colour-coded according to slit orientation — orange for north–south and green for east–west) for which the median spectral distortion (top row) or median flux loss (bottom row) across the VIMOS FoV remain below 20% during a one hour long integration, for all the VIMOS grisms.

range. Figure 6 shows the new airmass constraint limits for MOS observation blocks. They have been significantly relaxed for fields culminating at small zenith distances, thus increasing target observability. This will enhance the efficiency of operations, and speed up the completion of programmes — a particularly relevant aspect for the forthcoming spectroscopic public surveys with VIMOS. These recommendations for MOS observations have already been in place since September 2013. To define the optimal slit position angle for any specific target declination and instrument setup, we refer the users to the summary plots in the slit losses report at the VIMOS news section[1].

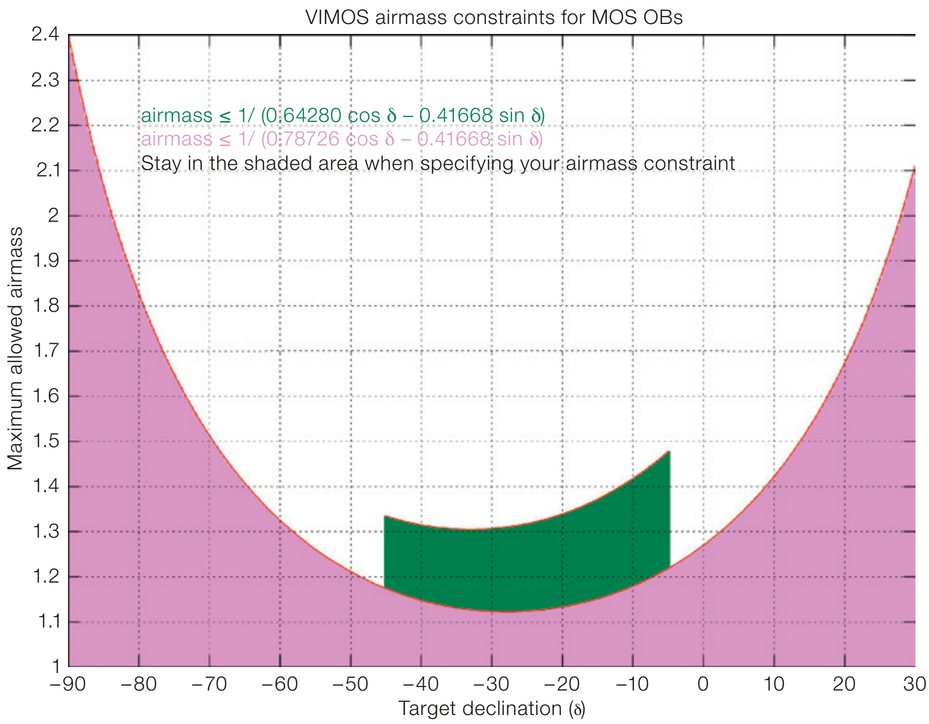

Figure 6. VIMOS airmass constraints for MOS observing blocks. The two different shaded areas correspond to the limits for fields that can be observed with slits having north–south orientations at meridian (purple), or east–west orientations (green). The generating formulae for these curves are shown with the same colour coding.

References

Bristow, P. et al. 2012, The Messenger, 148, 13
Cuby, J.-G. et al. 1998, Proc. SPIE, 3355, 36
Hammersley, P. et al. 2012, The Messenger, 142, 8
Hammersley, P. et al. 2013, The Messenger, 151, 2
Le Fèvre, O. et al. 1998, Proc. SPIE, 3355, 8

Links

[1] Report on VIMOS slit losses: http://www.eso.org/sci/facilities/paranal/instruments/vimos/doc/rsjvimosslitlossessept2013.pdf