Handling atmospheric dispersion and differential refraction effects in large-field multi-objects spectroscopic observations[1]

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ABSTRACT

The atmospheric refraction affects the position of objects in the sky in two ways: a chromatic effect and a field differential effect. The former is about the same in the field and can be, in principle, corrected using an Atmospheric Dispersion Compensator (ADC). The latter is dependent of the field size and cannot be corrected. For spectroscopy in wide fields, both effects have to be carefully considered because they affect the spectrophotometry in terms of signal to noise ratio and spectral distortions. The present study aims to evaluate the atmospheric effects in the case of the VIMOS instrument for the ESO VLT. It is shown that provided a carefull operational mode the distortion of spectra can be kept at a level less than 15% with reasonable constraints.

Keywords: atmospheric refraction, wide field, spectroscopy, VLT, operational mode.

1.INTRODUCTION

The effects of atmospheric refraction are well known and several authors (Fillipenko[1], Cohen[2], Donnely[3], Cuby[4]) have extensively discussed some of them.

The effects are two-fold, chromatism induced by the variation of the index of refraction of air with wavelength and field differential refraction due to the variation of airmass across the field which is essentially achromatic even at high airmasses. The wider the field of view, the stronger the effect across the field.

The chromatic effect is about the same in a given field, even at high airmasses and can be compensated with the use of atmospheric dispersion compensator (ADC) even on large fields (as an example see Taylor[5] and Nariai[6]). This is however seldom the case, as ADC over wide fields of view are practically difficult and costly to implement. In any case, the field differential refraction cannot be corrected.

In imaging, these effects lead essentially to a degradation of the PSF - and by the way of the resolution and the signal to noise on the photometry of faint objects - and to a field distortion affecting the astrometry accuracy in the field but which can be corrected by modelling the atmospheric effects corresponding to the conditions of the observations all along the exposure. There is no flux losses as the energy is only spread on the detector.

In spectroscopy, the atmospheric effects may have much more severe consequences as part of the flux can be lost when the light passes through slits or fibers. For single, long slit spectroscopy, a remedy to chromatism is to align the slit with the parallactic direction. Ideally, the slit should be continuously rotated during the exposure to follow the variation of the parallactic angle during the exposure. In practice, the exposure, if long, could be splitted in sub-exposures, and the slit realigned between each of them. However, aligning the slit along the parallactic direction during an exposure induces field rotation which might not be desirable if there are several objects along the slit. In addition, an exact compensation of the atmospheric refraction should require that the field differential refraction was somehow corrected for as if the telescope was guiding at the center of the slit. If guiding is achieved at a large distance from the slit, then field differential effects

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between the slit and the guiding position are added, at the slit level, to the chromatism effects. With such a correction, the flux entering the slit (at all wavelengths) can be kept very close to the optimum and again, the result is some loss in S/N due to the flux spread on more pixels along the slit.

In multi-object spectroscopy over wide fields, the two effects cannot be independently corrected and the only alternative left is to optimize observation conditions so as to minimize the flux losses. With circular apertures like fibers or holes drilled in a mask, a way is to optimize the position of each aperture on the object e.g. compensating the field differential refraction at mid-exposure. With fiber positioning robots, the fibers can even be repositioned from time to time to track the field differential refraction. In any event, this represents some operational constraints which are unavoidable if the best performances are sought for. There is no way to compensate for the chromatic elongation of the images due to the atmospheric dispersion except by using some kind of image slicers with entrance aperture large enough (Baudrand[7]).

With multi-slit spectroscopy, the situation is somehow the opposite as, if the slits can be cut in a mask to be aligned with the direction of the dispersion at e.g. mid-exposure, nothing can be done for compensating for the field differential refraction unless at the expense of a very difficult operational approach. Unlike long slit spectroscopy, it is impossible to align all the slits on the parallactic direction e.g. at mid exposure because of the field rotation which would put most of the objects out of the slits.

This paper investigates the impact of the atmospheric effects for an ESO VLT instrument, VIMOS, to be operated by the year 2000 at Paranal in Chile. This instrument is described in these proceedings (Le Fevre[8]), and consists in a four quadrant spectro imager covering the 370- 1000 nm range. Each quadrant has a field of view of 7'x7', with a central dead cross of 2' x 2' between quadrants. Multi-object spectroscopy is done with masks which are inserted in cabinets manually placed at the instrument focal plane.
We have carried out a detailed analysis of the atmospheric effects, and demonstrate that, provided special care is given in the operational procedures and scheduling of the observations, the flux losses and the spectrophotometric distortions can be kept below a 10 - 20 % level even at moderately high airmasses. To illustrate these results, section 2 presents the field differential effects over the VIMOS field of view (16' x 16' in total) and section 3 deals with the chromatic dispersion. In section 4, we present the computation of the spectrophotometric losses in a variety of cases; conclusions and some recipes are given in section 5.

2.Field differential refraction: monochromatic effects

As already mentioned, field differential refraction occurs irrespective of the wavelength and is a pure geometrical effect across the field. It is interesting to discuss this effect alone as it can be dominant over chromatic effect in the red spectral range at low spectral resolution or at high spectral resolution with a small wavelength intervall.

Because of the operational mode of an instrument like VIMOS, we have to make sure that the object positions derived from a preliminary image of the field (on VIMOS or an other imaging facility) are valid for cutting the masks. Since the imaging and spectroscopic exposures may be taken at totally different hour angles, the positions of slits simply derived from the preliminary image might be slightly off the optimum positions on the objects at the time of the spectroscopic exposures. Also, because during the exposure itself, the objects are distorted and shifted, it is interesting to determine the optimum positionning of objects on the slits at the start of the exposure (for accurate pointing of the telescope).

This section quantifies the amplitude of the field differential refraction with the following parameters:

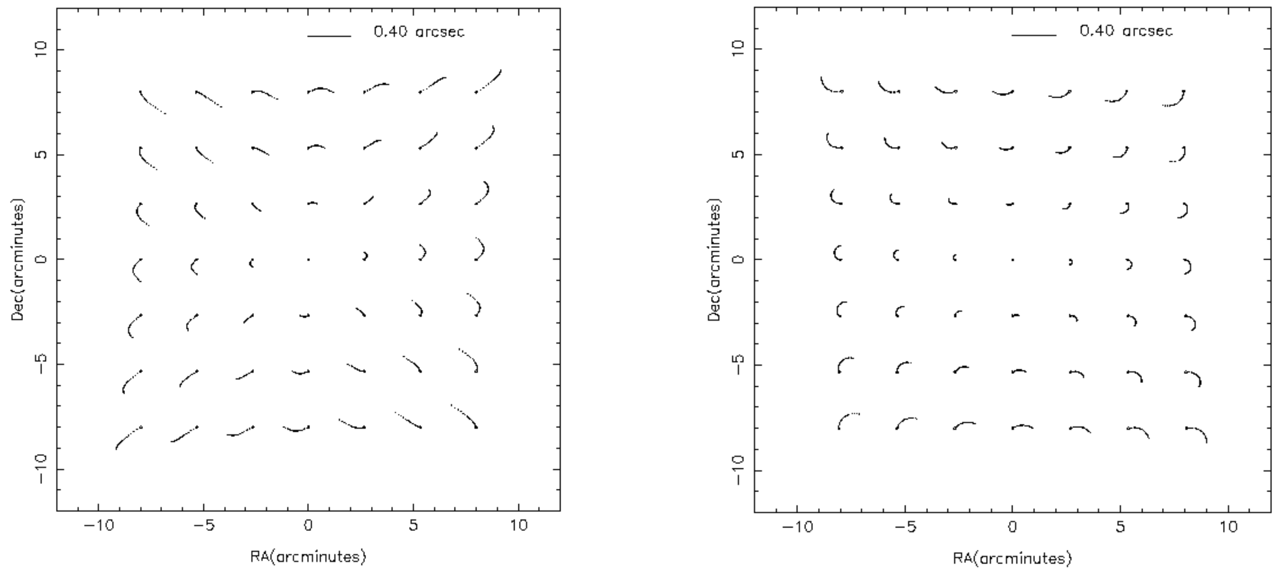
- The site location which in our case is Paranal at a latitude -24.62°
- The atmospheric parameters controlling the index of the air: temperature, pressure, water vapor content etc. We assume for Paranal a 10°C average temperature at an altitude 2665m. Note that if the first order variation of the atmospheric refraction with temperature is relatively important and may affect the absolute astrometry of the objects, the field differential displacements induced by a temperature variation are totally negligible in the field.
- The declination of the field, and the hour angle at the beginning and at the end of the observation. Depending on these two parameters, field differential refraction may induce field rotation superimposed to pure distortion. Field rotation can be compensated for by the Telescope Control System (at least in the case of an Alt-Az mount), and we assume that this is the case in the following. The description of the compensation of field rotation with declination is described by Wallace[9]
- The field of view.

- The guiding wavelength. Usually, the guide probe is sensitive in a given wavelength range, which might not coincide with the wavelength of the observation. It is assumed that the Telescope Control System can compensate for this, and mimic guiding at any wavelength. Cuby[4] has extensively discussed the importance of the guiding wavelength.

- The position of the guide probe outside the field of view of the instrument. To minimize the field differential effect all over the field, the guide probe shall ideally guide at the center of the field. Since this is obviously an unrealistic situation, the TCS has again to compensate for off-center guiding by slight motions of the guide probe, as if guiding was done at the center of the field.

- Misalignments between the polar axis of the telescope and the Earth rotation axis which affect equatorial mounts, are not relevant in case of an Alt-Az mount.

The kind of result that we obtain is summarized on figure 1 which shows the motion of the objects across a field of view of 16' x 16' at two declinations, 25° on fig 1a and -75° on fig 1b, for a 4 hours exposure starting 2 hours before meridian. Note that the traces are very similar, because the field rotation has been corrected and that the figures indicate the very minimum field distortion that can be achieved. The small circles indicate the starting points at 2 hourrs before meridian. The amplitude of the effect is ~ 0.3 arcsec at the edges of the field.



a) b)

Figure 1. Field differential refraction for a 4 hour exposure starting -2 hours from meridian: a) for a northern object at a +25° declination; b) for a southern objetc at a -75° declination

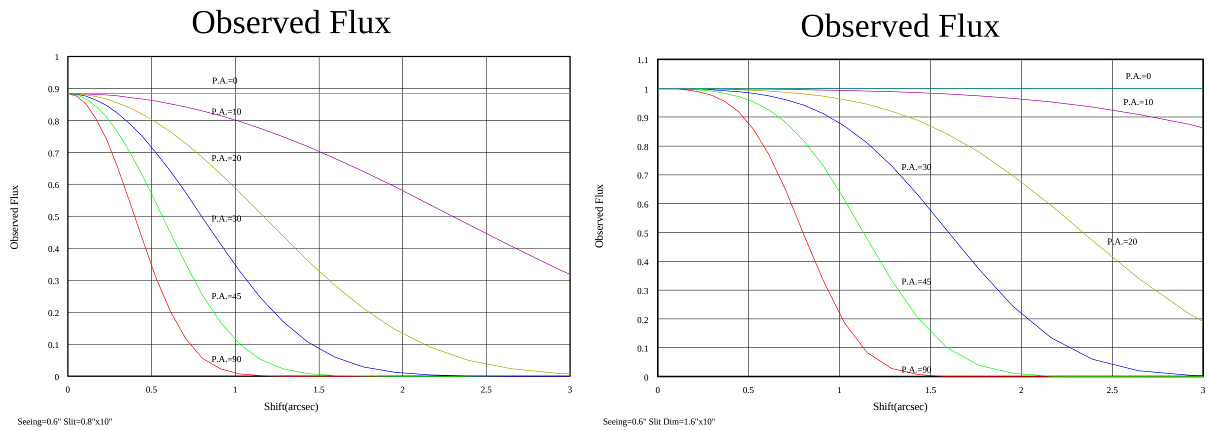
The same kind of results can be obtained for different conditions. Table 1 gives a summary of the kind of expected amplitude of the effect for different declinations and exposure times, all exposures centered across meridian.

These results show that the effects of differential refraction can be neglected for zenith distances smaller than ~ 25 degrees. They are at most at the level of the guiding accuracy for exposure up to 2 hours from the meridian Above this approximate limit, some care has to be taken when deriving slit positions from images taken under different hour angle conditions. The tolerances depend on the type of the objects and the characteristics of the spectroscopic observations, e.g slit widths.

Table 1. Maximum field differential refraction between the center and the edge of a 16' x 16' field of view for different declinations and exposure times.

Declination	± 1H	± 2H	± 3H
-75	0.15	0,35	0.6
-50	<0.1	0,12	0.2
-40	<0.1	0.1	0.13
-10	<0.1	<0.1	0.14
0	<0.1	0.11	0.2
25	0.15	0.35	0.6

The motion of the object during the exposures affects the flux passing through the slit. This is illustrated on figures 2a and 2b for a 0.6" starlike profil respectively in case of slits 0.8 x 10 arsec^2 and 1.6 x 10 arsec^2. Each curve gives the flux variation for different angles PA° (0,10,20,30,45,90) between the image drift direction and the slit. Figure 2a shows that a loss larger than 10% is obtained for drifts of 0.5arsec as soon as this angle is larger than 30°. In case of large slit, Figure 2b shows that the same kind of accuracy is obtained whatever the angle.



a) b)

Figure 2. Flux variation for a stellarlike profil with seeing 0.6", and a slit 0.8 x 10" in case a and 1.6 x 10" in case b, versus the image drift at different orintation from the slit.

As a conclusion we could say that for those fields which may suffer from field differential refraction at the levels indicated above, the procedures to minimize the effects can be to:

- schedule the spectroscopic observations at a time which minimizes the field differential refraction, i.e. centered on meridian and split the total exposure on several nights if necessary.

- carefully correct object coordinates (slit positions) derived from preliminary images from the atmospheric effects, and then apply offsets to the situation corresponding to the spectroscopic observations. Clearly, if the imaging observations are carried out at the same hour angle as the spectroscopic observations, no correction needs to be applied, and this greatly simplifies the problem. Any correction of these effects require a very precise knowledge and modelling of the behaviour of the telescope. These effects are extremely sensitive to the orientation of the polar axis of the telescope in case of an equatorial mount, and to the field rotation compensation in case of an Alt-az mount. In addition, such corrections, whenever necessary, require an a priori knowledge of the scheduling of the spectroscopic observations.

3.Chromatic differential refraction

In addition to the previous achromatic effect, the atmospheric dispersion further introduces image elongation, which rotates with time as the hour angle changes. Slit losses now depend on time and wavelength, and the final spectra of the objects are therefore affected in a relative complex way. This strongly depends on the slit width and orientation and the morphology of the objects (point-like, seeing limited, or extended). We present in this section integrated simulations taking into account both field differential refraction and chromatic dispersion. The corresponding flux losses and spectrophotometric distortions are presented in the next section in the case of starlike profile with 1" seeing.

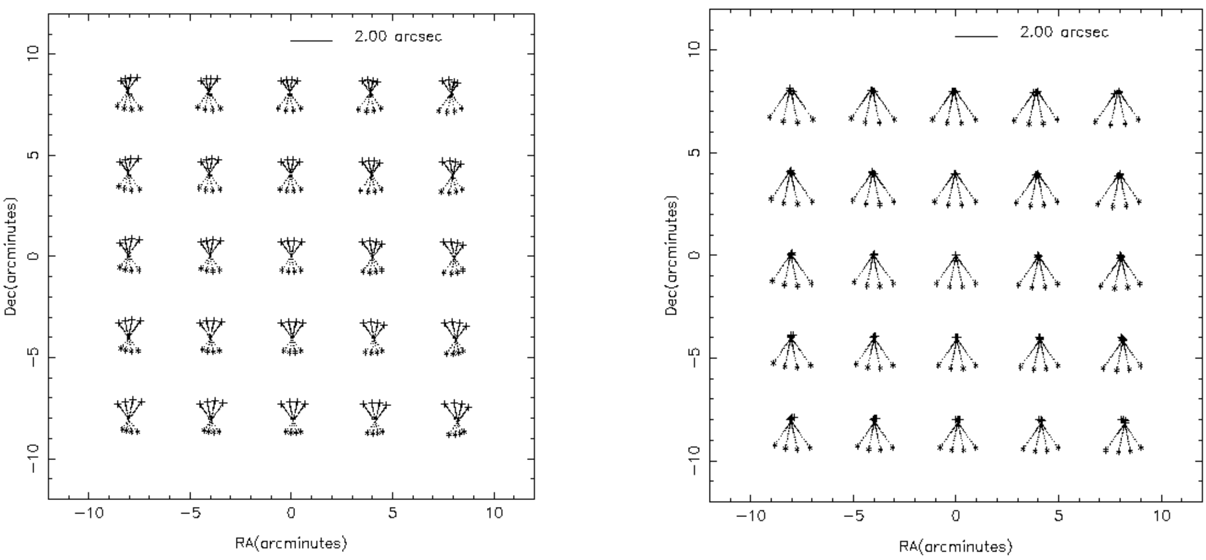
In addition to the parameters controlling the field differential refraction, other are related to the chromatic dispersion:

- The spectral range of the observations. In the following, we will consider three different cases; a blue spectral range (370-650 nm) and a red range (550-1000nm) which correspond to the spectral coverages in the low spectral resolution mode of the instrument and a red spectral range (750-900nm) which corresponds to a higer spectral resolution mode

- The effective guiding wavelength of the telescope which is a key parameter to be controlled. This will become more explicit latter in this section. The actual guiding wavelength (as defined by the guide camera characteristics) does not necessarily coincide with the central wavelength of the observation and it is therefore necessary that the Telescope Control System can simulate guiding at any wavelength. For the aforementioned spectral ranges, the effective guiding wavelengths which balance - and therefore minimize - the effects at the edges of the ranges are:

- 0.45 micron for the [0.37-0.65] micron range
- 0.68 micron for the [0.55-1.00] micron range
- 0.82 micron for the [075-0.9] micron range

These wavelengths will subsequently be referred to as optimum guiding wavelengths.



a)

b)

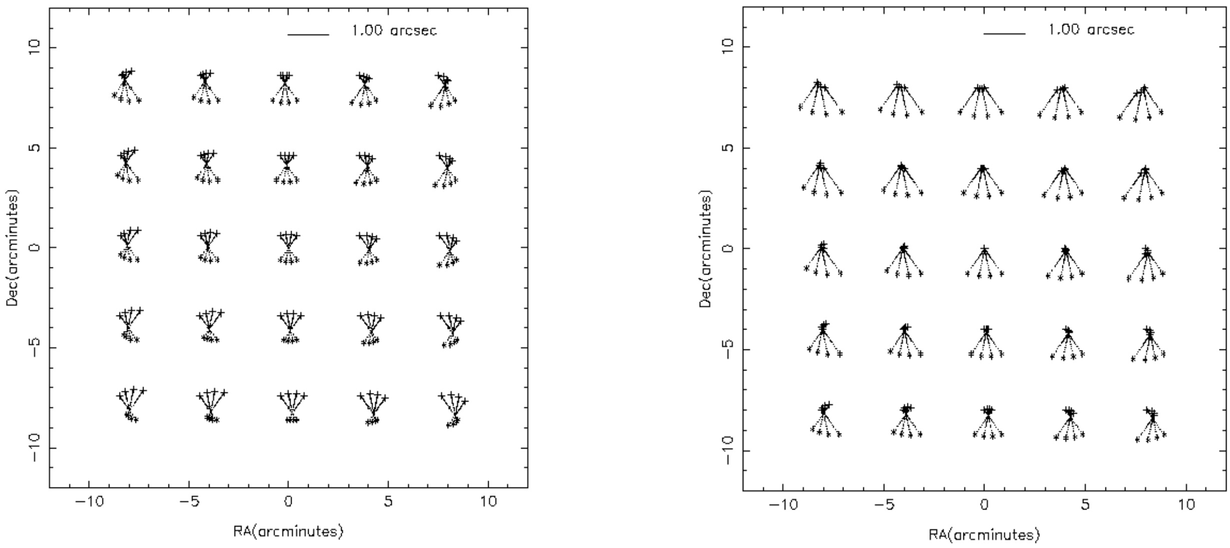
Figure 3. Total atmospheric refraction for two guiding wavelength in the range 380-650n

- The spectral range of the guide probe. The smaller this range, the smaller the dependency of guiding with the spectral type of the guiding star. In the case of the VLT, this spectral range is relatively small and in the red, so that variations of the simulated guiding wavelength with the color of the guiding star are negligible.

The importance of the choice for the guiding wavelength on the resulting effects of the atmospheric dispersion is illustrated on figures 3 and 4 in the case of a large spectral range, either in the blue or in the red. The figure 3a shows the integrated effects of field differential refraction and chromatic dispersion for Paranal, in the blue range, for a declination of

-75 degrees, and a 4 hour integration starting 2 hours before meridian. In this case, the effective guiding wavelength is optimized to balance the shifts in the blue and the red edges of the range. The amplitude of the image degradation is quite important, about 1" and much higher than the sole field differential refraction.
Figure 3b shows the dramatic effect of guiding at a non-optimized wavelength, in this case, a wavelength corresponding to the red edge of the spectral range. The amplitude of the image motions at the blue edge of the spectral range is roughly 2 times that of the previous case.
These figures also illustrate that in the blue range, the global refraction effect is dominated by the chromatic effects over the field differential refraction.

Figure 4a and 4b are similar to figures 3a and 3b, for the red range case. Note the different scale of the motion. As expected, the amplitude of the chromatic effect is clearly much smaller than in the blue range but also, as it can be seen at the edge of the field, the field differential refraction is not negligible.



a) b)

Figure 4. Total atmospheric refraction for two guiding wavelength in the range 550-100nm

Figure 5a and 5b illustrate the case of a smaller spectral range, which correponds to the high spectral resolution mode of the instrument. The chromatic effect is significantly reduced (note the change in scale), but this time, of the same order or less than the field differential effects. Figure 5a corresponds to a declination of 25°, figure 5b to a declination of -75°.

The purpose of all these illustrations was to visualize the complexity of the phenomena and give an idea of their amplitude. A simple conclusion is that when the chromatic effects are dominant, the traces of the image drifts are elongated along the meridian (at least in the cases considered) in all the field, provided the guiding is done at the optimum guiding wavelength. This simple remark suggests to place the slit in the direction of the meridian at mid exposure to minimize the flux losses during the exposure. When the two effects are of the same order, there is no more common orientation of the image drifts in all the field and the minimization is not so obvious. The amplitude of the object motion shown on figure 5 in case of high spectral resolution is small but the slits have also to be smaller (less than 1") and the scientific programs could call for higher accuracy and also benefit from a minimization process. After the phenomenologic approach above, the interesting fact is to investigate quantitatively, the consequences of the global atmospheric effects on the flux losses and the spectrophotometric distortions of the spectra. We adress this point in the next section.

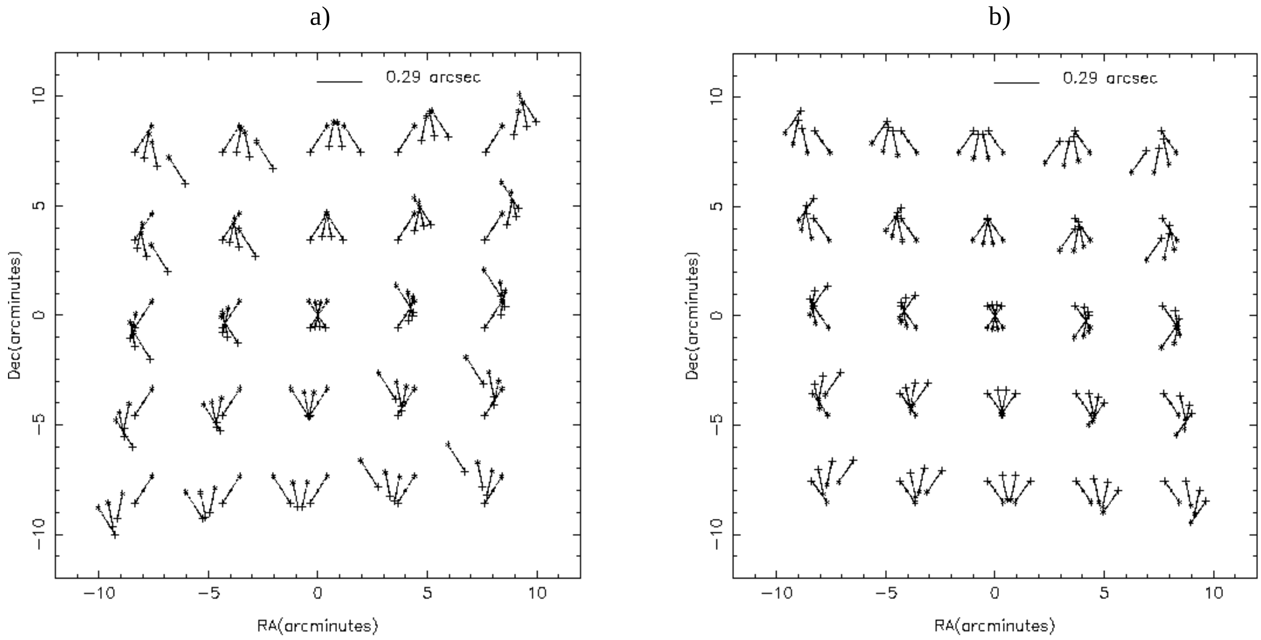


Figure 5. Atmospheric refraction in case of a wavelength range 750-900nm at two different declinations.

4.Flux losses and spectrophotometric distortions

In computing the slit losses with time and wavelength, the parameters to be added to the previous study are:

- The orientation of the slits wrt the dispersion direction at any time during the exposure.

- The positions of the slits wrt the positions of the objects during the exposure due to field differential refraction (see previous section). In the following, it is assumed that the slit center coincide with the objects at mid-exposure at the optimum guiding wavelength (best case) and that the slits are aligned on meridian at mid exposure. From the study above, this is clearly suggested to minimize the flux losses, at least at consequent zenith angles. We will see latter that the situation is different at low zenith angles but in this case, the phenomena have a lower amplitude.

- The seeing, the object morphology and the slit widths. In the following, we will assume 1 x 10" slits, and image sizes of 1" with gaussian distribution.

The slit losses with time are shown on figure 6 on a selection of points across (center, edges and corners) the field of view in the conditions indicated above, in the red range, at a declination of -75 degrees. The dashed line corresponds to 0.55 micron, the solid one to 0.68 micron (guiding wavelength), and the dot-dashed line to 1.0 micron. The slit is aligned with meridian at mid exposure. The flux losses at the edges of the spectral range are at the level of 20% at the beginning or at the end of the exposure.

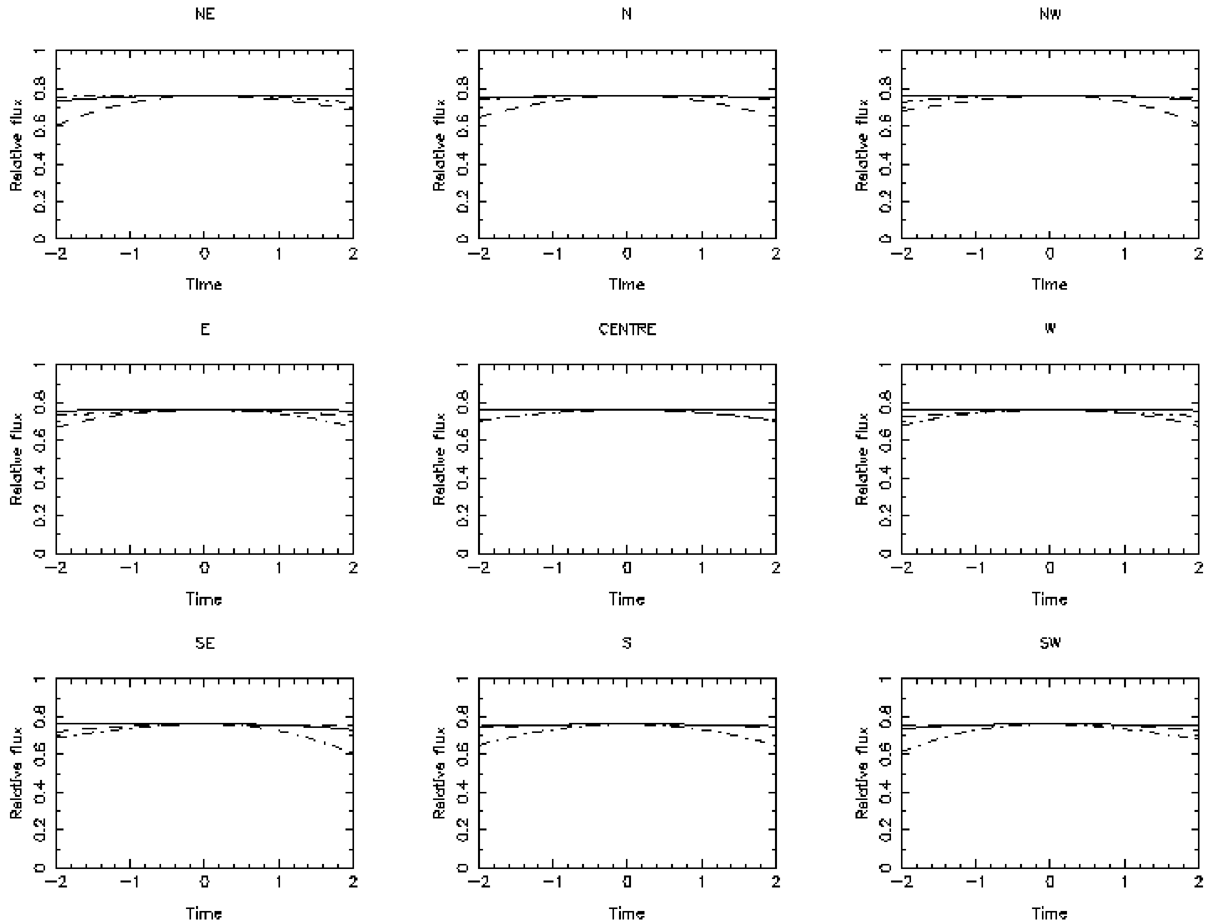


Figure 6. Slit losses versus time at 3 wavelengths (550,680,1000nm) for different positions in the field

The integrated spectra over time, assuming a flat input spectrum is shown in figure 7.

This example shows that for objects at zenith angle less than 50° at meridian, the maximum variations of the spectra are less than 13% in the red spectral range considered, everywhere in the field. Figure 8 is identical to figure 7, but in the blue range. The distortions are obviously more pronounced, but still in the 20% limit.

In the blue, the spectral distortion has about the same shape in all the field, which is consistent with the fact that the chromatic effect is predominant. In the red, the amplitude is smaller but the spectral distortion depends much more on the position of the objects in the field, because the field differential refraction is no more negligible.

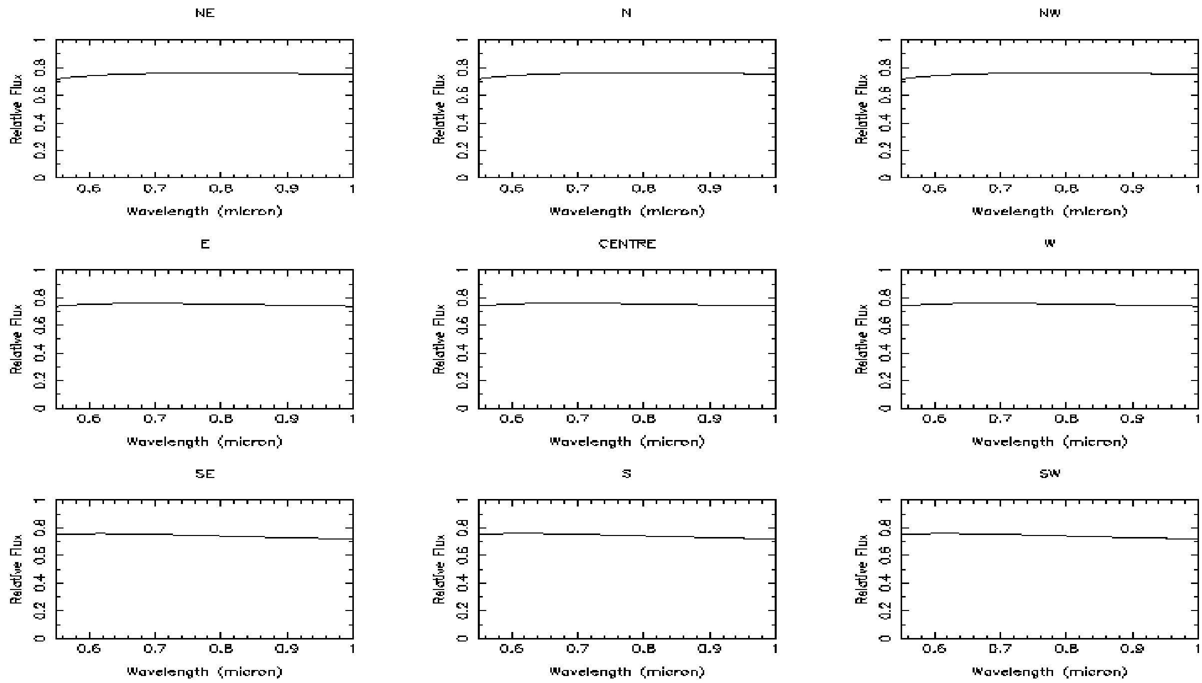


Figure 7. Distorted spectra in the red range on a 4 hours exposure starting 2 hours East at the same positions in the field than on figure 6.

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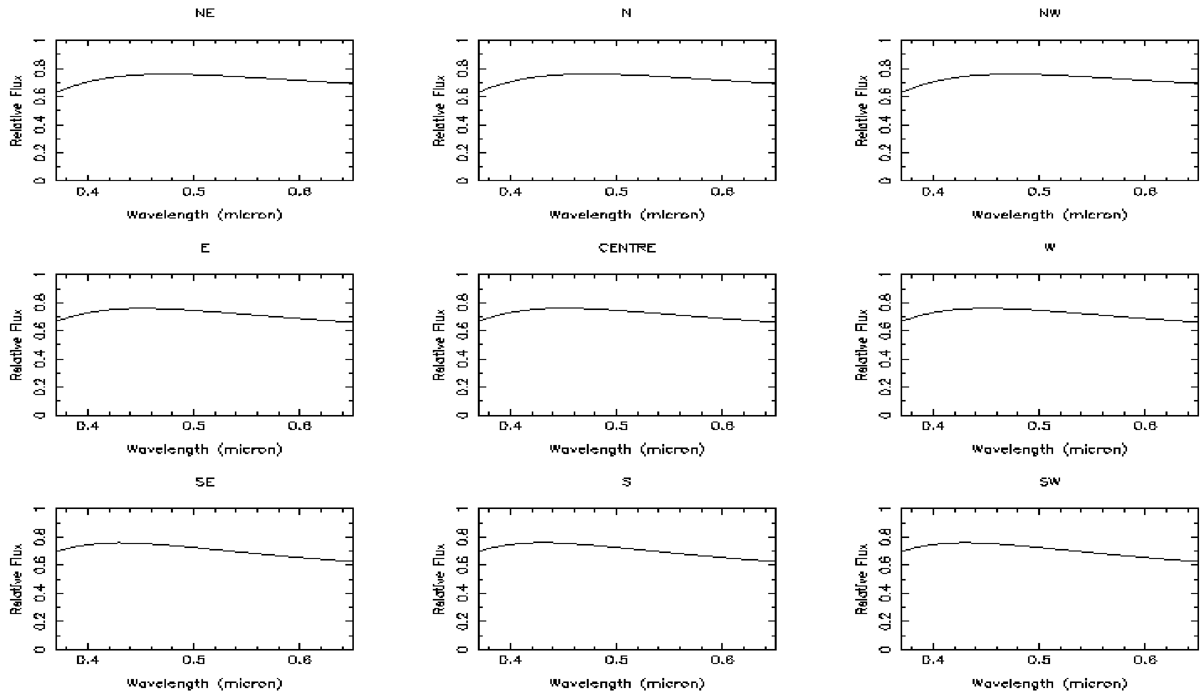

Figure 8. Same as figure 7 but in the blue spectral range.

In the previous study, at large zenith distances, we have been naturally lead to align the slit on the parallactic direction at meridian to minimize the spectral distortion. On figure 9, we give an illustration of how dramatic can be the effect of an uncorrect orientation of the slit. In this case, the slit is aligned in the worse direction, perpendicular to the meridian, i.e. perpendicular to the parallactic dirrection at mid-exposure. The figure shows that, in this improbable case, the amplitude of the spectral distortion can be as large as 60%.

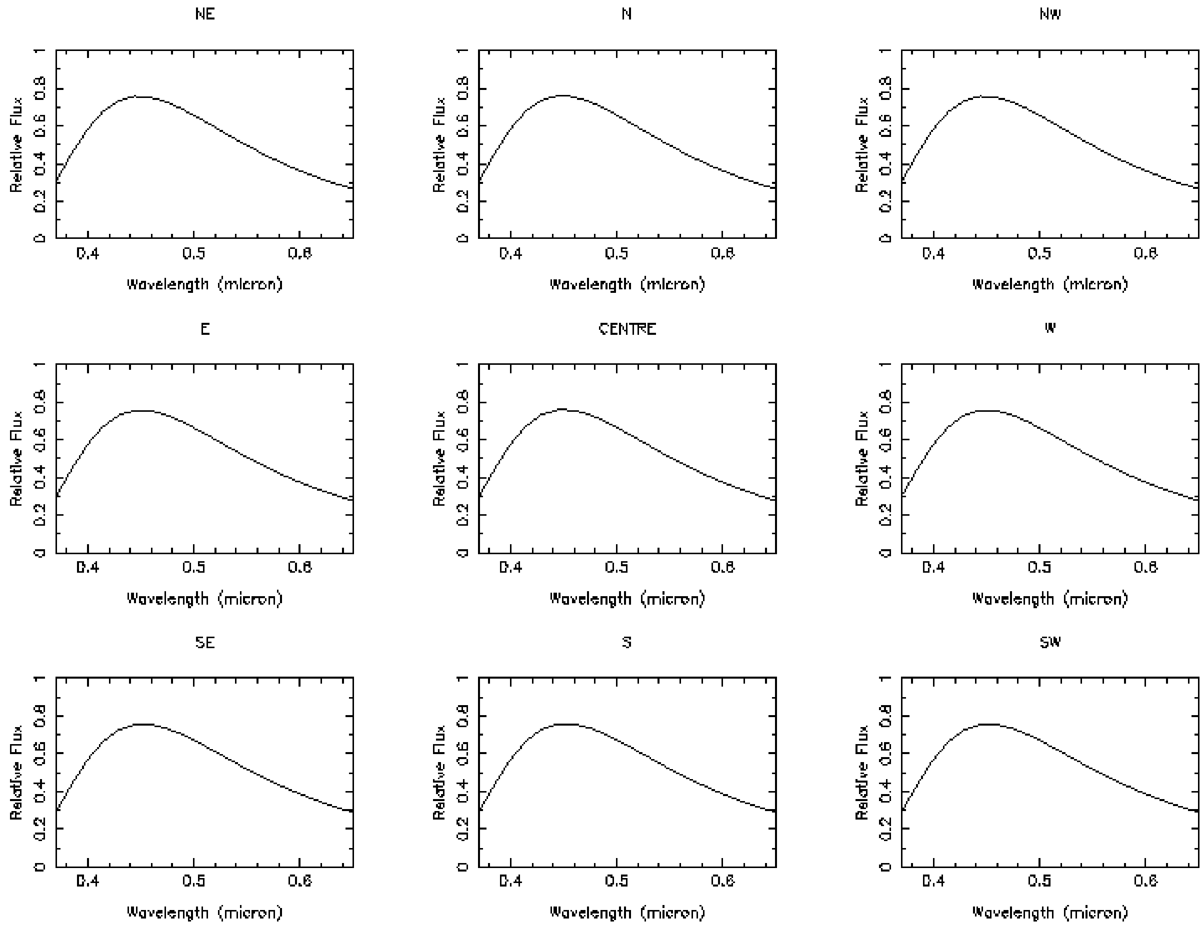

Figure 9. Distorted spectra in the same conditions as figure 8 but with the slit oriented at 90° from the parallactic direction at mid exposure

This example shows that the orientation of the slit has to be carefully optimized for the time of the spectroscopic observation. Obviously, for fields close to zenith at meridian, the dispersion direction evolves essentially along an East-West axis and this is the preferred direction for aligning the slits, which means at right angle from the previous case. If the exposures are centered on the meridian, there are a priori only these two directions to optimize the observations. In case where the exposure would not be centered on the meridian, the situation would be more complex.

The figures 7 to 9 illustrate the fact that at low resolution (ie. large spectral range), the spectrum distortions are dependent of the position of the objects in the field, although they all roughly share an identical distortion shape, at least in the blue. Recovering the true spectrum distributions by applying an "atmospheric response function" seems difficult to achieve in practice, as the distortions further depend on the size of the objects, their exact positions wrt the slits, etc. To say that the results of this section are more aimed at providing an estimate of the amplitude of the effects than to provide recipes for cancelling out the effects.

To quantify a little more the results, we introduce a spectrum distortion parameter defined as the ratio (Flux Max - Flux Min) / Flux Max in the spectral range considered. Table 2 gives some figures for this parameter . The conditions are 4 hours exposures starting 2 hours East of meridain , different declinations, two spectral ranges, one in the blue and the other in the red, and two seeing / slit width cases. The slit is aligned with the parallactic direction at meridian except for the -25 declination where it is perpendicular.

Table 2. Spectrum distortion (in percent) with declination at two spectral ranges for two seeing/slit width cases.

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	Maximum distortion, at the edges of the field			
	Red		Blue	
Declination °	0.5" / 0.5"	1" / 1"	0.5" / 0.5"	1" / 1"
-75	25%	10%	50%	25%
-50	10%	2%	25%	10%
-25	0*	0*	0*	0*
0	10%	2%	25%	10%
25	25%	10%	50%	25%

5.Conclusion

We have quantified the effects of atmospheric dispersion and field differential refraction in case of a 16'x 16' field of view at Paranal, in two spectral ranges. We have shown that the amplitude of the effects can easily be kept below 20% for zenith angle at meridian less than 50° and 4 hours exposures, even in the blue, provided that care is taken in preparing the observations. Much more dramatic effects up to 100 % flux losses can easily arise if the adequate procedures are not taken.

The discussion has shown that the atmospheric effects for spectroscopy over wide fields can be minimized provided that:

- The Telescope Control System is well designed and allows to simulate guiding at any wavelength and at the center of the field of view, irrespective of the actual spectral range and position of the guide probe.

- In addition, the Telescope Control System, for an alt-az mount, shall be able to compensate for field rotation induced by the atmosphere, in addition to the field rotation induced by the Earth rotation.

- The spectroscopic observations are well scheduled in time (e.g. hour angle), so that the slit positions can be safely aligned with the dispersion direction eg. at mid-exposure. In practice, the simplest way should be to schedule all spectroscopic observations at meridian, whenever possible, with exposure time compatible with the maximum zenith angle acceptable. This could lead to a scenario where the observations could be splitted on several nights. Clearly, such a scheme is only possible in a service mode operation of the telescope, provided that the scheduled observations are well distributed in hour angles during a given period of time.

- Ideally, the preliminary observations (when slit positions are derived from a preliminary image of the field with the same instrument, and not from a catalogue of coordinates), should be performed at the same hour angle as the forthcoming spectroscopic observations. This would avoid to compute and remove the effects of the field differential refraction on these images, before retrofitting them for the conditions of the spectroscopic follow-up. If not, the Mask Preparation Software must carefully handle all these conditions.

- The most important constraint is that, because the slits shall have a preferred direction during the spectroscopic observations and the field is a square, the preliminary images shall be taken with a predefined orientation on sky, if the object coordinates are to be defined in pixels relative to the original image, which is generally what is done with spectro imagers. Field orientation is therefore no longer a free observational parameter.

REFERENCES

1. A. Fillipenko, « The importance of atmospheric differential refraction in spectrophotometry », *PASP*, **94**, pp. 715-721, 1982
2. J.G. Cohen and J. Cromer, «Atmospheric Refraction effects on the Norris and Keck Multiobjects Spectrographs», *PASP*, **100**, pp. 1582-1585, 1988
3. R.H. Donnelly, J.P. Brodie, J.V. Bixler, C.J. Hailey, « The implication of atmospheric effects for fiber-fed spectroscopy », *PASP*, **101**, pp. 1046-1054, 1989
4. J.G. Cuby, « Observational aspects in multi-objects fibre spectroscopy », *SPIE*, **2198**, pp. 2-20,1994
5. K.Taylor and P. Gray, « 2dF: The AAT's planned wide-field, multi spectroscopic survey facility. Report on commissioning the 2dF Corrector/ADC », *SPIE*, **2198**, pp. 136-142, 1994
6. K. Nariai and K. Takeshi, « Primary Corrector for SUBARU telescope with a new type of Atmospheric Dispersion Corrector », *SPIE*, **2199**, pp. 532-541, 1994
7. J. Baudrand, M. Casse, L. Jocou, J.P. Lemonnier, « Fibre link for the FUEGOS multi-object spectrograph », *SPIE*, **2198**, pp. 1071-1082, 1994
8. O. Le Fèvre et al, « VIRMOS: Visible and Infrared Multi-Object Spectrographs for the VLT », *SPIE*, this proceeding
9. P.T. Wallace, K.P. Tritton, « Alignement, pointing accuracy and field rotation of the UK 1.2m Schmidt telescvope », *MNRAS*, **189**, pp. 115-122, 1979