Atmospheric Dispersion Correction for the FORS Focal Reducers at the ESO VLT

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ABSTRACT

The need for atmospheric dispersion correction on large telescopes is well known. Therefore it was decided to implement atmospheric dispersion correctors for FORS, the focal reducer/spectrographs of the ESO Very Large Telescope. The boundary conditions at the VLT Cassegrain foci excluded however all previously known ADC concepts and therefore we were forced to design a new one, the Longitudinal Atmospheric Dispersion Corrector (LADC) consisting of two thin prisms with variable distance. This design has several advantages compared to the "classical concepts": among others it avoids tilting the pupil axis and uses only one material (silica) which has a very high transmission over the operating wavelength range of FORS (330 – 1000 nm).

Keywords: atmospheric dispersion correction, telescopes, multi-object spectroscopy

1. WHY ATMOSPHERIC DISPERSION CORRECTION?

It is well known that atmospheric dispersion can have deleterious effects on astronomical observations with large telescopes[1]. In principle, broadband ($\Delta\lambda \approx 100$ nm) imaging and imaging polarimetry especially in the blue/UV suffer from a loss in spatial resolution which depends on the zenith distance of the object at the time of the exposure whereas photometric accuracy can be recovered through subsequent image processing. However, to avoid a loss of photons in spectroscopy or spectropolarimetry it is either necessary to increase the width of the slit with a corresponding loss in spectral resolution, or to align the slit along the direction of the atmospheric dispersion. This works with point sources but will not generally be possible with extended sources which require a certain orientation of the slit. The situation is similar and even worse with multi-object spectrographs where a certain field orientation will usually be mandatory.

In these cases it is also not possible to include atmospheric dispersion correction in the instrument; it has to be done in front of the slit and therefore becomes essentially a part of the telescope.

In the given case the instruments to be provided with an atmospheric dispersion correctors (ADC) are FORS, the focal reducer/low dispersion spectrographs being built in two copies for the Cassegrain foci of two of the unit telescopes of the ESO VLT[2]. The LADC has been optimized to meet the FORS requirements.

2. ATMOSPHERIC DISPERSION AT THE PARANAL VLT OBSERVATORY

Under the average atmospheric conditions at the VLT Observatory on Cerro Paranal (temperature T = 11°C, atmospheric pressure p = 743 mb, altitude h = 2665 m, relative humidity rh = 15%), the atmospheric dispersion in the Bessel U and V filters as well as for the overall operating wavelength range of FORS as a function of the zenith angle is given in Fig. 1.

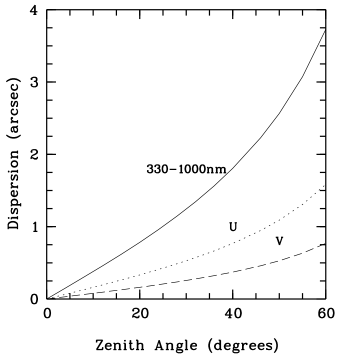

Figure 1: Atmospheric dispersion at the Paranal VLT Observatory as a function of zenith angle, for two broadband filters and white-light imaging

dispersion.ps

Figure 2: Photometric profiles along the dispersion for different star types

The image quality at the FORS detector plane is not only affected by the dispersion and telescope-instrument aberrations. It depends strongly on the spectral characteristics of the stellar object. Fig. 2 shows the photometric normalized profiles of a Gaussian source according to the spectral type. The simulation includes a seeing of $0.45''$, atmospheric extinction (1 airmass), the telescope, the instrument and the CCD quantum efficiency. From the curves, we see that the unbalanced spectral weight of different sources generates differential shifts of their centre of gravity. This effect may, for instance, reduce substantially astrometric measurements. Fig. 3 shows the relative displacement of the center of gravity and the position of the maximum of intensity for different star types and with the full spectral range (330 – 1000 nm).

3. VLT SPECIFIC REQUIREMENTS

The physical and operating conditions of the FORS instrument at the VLT imposed a number of constraints on the practical design of any ADC.

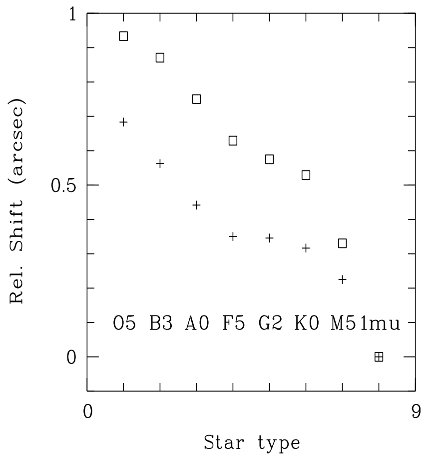

Figure 3: Relative image shift with the star type

3.1. Telescope conditions

The most stringent optical requirement came from the wavefront analyzer for the telescope active optics system. Any ADC located in front of the adapter in which the wavefront analyzer is located should not lead to a tilt between the resulting optical axis and the pupil axis of more than 5 arcsec.

The location inside the M1 mirror cell of the telescope also meant that it would be impossible to remove the ADC from the telescope beam without a major effort. This is however prohibited by the operations policy of the VLT. Therefore the ADC design had to be such that it would neither introduce untolerable aberrations nor significant absorption also in the zenith position (when in principle no ADC is needed).

3.2. FORS instrument conditions

The maximum zenith distance at which full atmospheric dispersion is to be compensated was chosen as z = 50° which is slightly less than the maximum operating zenith distance for which FORS is designed (60°). At the average atmospheric conditions mentioned above this leads to an atmospheric dispersion of 2.6 arcsec over the full wavelength range of FORS (330 – 1000 nm).

The design goal was to preserve the intrinsic image quality at the centre of the FORS high resolution mode field of view of $d_{80} < 0.1''$ at zenith and to keep it at $d_{80} < 0.2''$ at z = 50°.

4. ALTERNATIVE ADC DESIGNS

Fig. 4 compares the basic principles of two of the common ADC designs with our novel LADC.

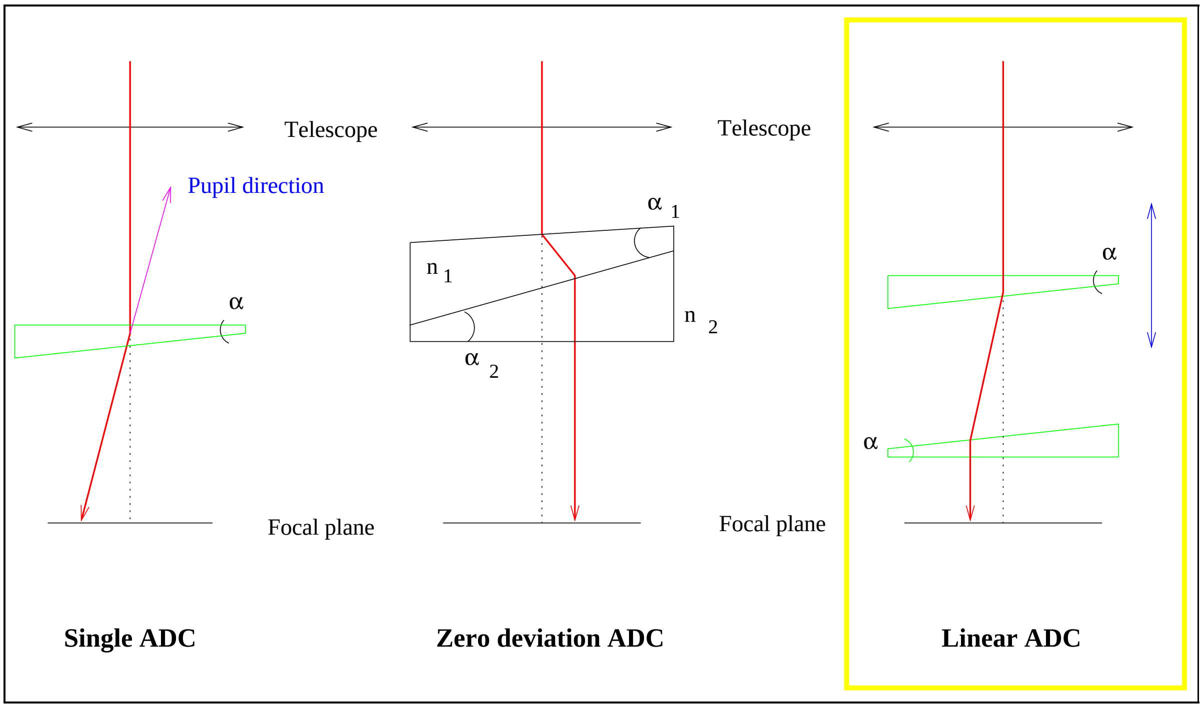

Figure 4: Basic principles of 3 different ADC designs

4.1. Single prism ADC

A single couple of rotating wedges made of suitable material (e.g. silica) appears to be the simplest, compact, cheap and effective design. However, it introduces an image shift and a strong tilt of the pupil at high zenith distances. As mentioned in section 3.1., a pupil displacement on the wavefront sensor detector can not be tolerated.

4.2. Zero deviation ADC

The Zero deviation ADC offers very good image quality, no significant image shift and also no pupil and image tilt. This ADC type is being used in several telescopes worldwide with good results[3]. However, in our case it would have had to be located at a fairly small distance ($\approx$ 150 cm) in front of the telescope focus which would have led to prisms of prohibitive thickness with correspondingly low throughput in the blue region (where the dispersion correction is needed most!) and high cost and weight. Therefore we abandoned also this concept.

4.3. Linear ADC

The design of our choice we named "Linear ADC" because it consists of two prisms of opposite orientation which are moved linearly with respect to each other. The forward prism is in principle the one which does the dispersion correction (as in the case of the "single prism ADC"); the second prism essentially corrects the pupil tilt. What remains is a variable image shift depending on the distance between the two prisms. The LADC is very well suited for alt-az mounted telescopes because of the fixed direction of the atmospheric dispersion with respect to the telescope altitude plane. A single linear motion, excluding any rotation, is therefore sufficient for the dispersion correction. The full optical theory will be described elsewhere[4].

4.4. Comparison of the alternative designs

A relative comparison of the various alternatives described above leads in our case to the following table 1:

ADC type	Single Prism	Zero Deviation	Linear ADC
throughput	+ +	− −	+
image quality	+	+ +	+
image shift	yes (− −)	no (+ +)	yes (−)
image tilt	yes (− −)	no (+ +)	no (+ +)
pupil tilt	yes (− −)	no (+ +)	no (+ +)
weight	+ +	− −	+
volume	+ +	+	− −
cost	+ +	− −	+

Table 1: Relative merits of the various ADC designs considered here

5. THE VLT LADC FOR FORS

5.1. Optical design

The optical design of the LADC is shown in more detail in Fig. 5.

The parameters chosen for the LADC for FORS at the VLT are summarized in table 2.

5.2. Mechanical design

The VLT LADC for FORS is a completely self-contained unit which contains all mechanical, electromechanical and optical components comprising the ADC. It can be removed from the M1 cell of the telescope in one piece, however only after removal of the Cassegrain instrument and the adapter/rotator unit. Since it can be therefore

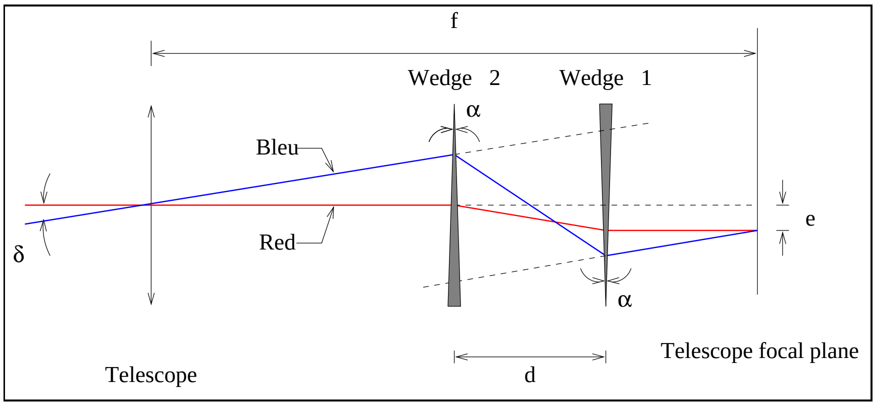

Figure 5: Optical design of the LADC

Material	silica (Herasil)
Diameter	590 mm
Prism angle	2.34°
Prism thickness	22.5 mm (centre)
Anti-reflection coating	MgF_2 @ 420 nm
Prism 2 motion range	20 – 1100 mm = f(z)
Prism 1 (fixed)	600 mm before Cassegrain focus

Table 2: Optical parameters of the VLT LADC

regarded as an integral part of the M1 cell, the LADC was included in the contract for the M1 cell/M3 tower and the conceptual and detailed design of the mechanics was performed by the contractor.

Table 3 gives an overview of the physical properties of the VLT LADC.

overall diameter	900 mm
overall length	1570 mm
prism 2 drive	spindle
positioning accuracy (linear)	± 1 mm
positioning time	$<$ 45 sec

Table 3: Physical properties of the VLT LADC

5.3. Control aspects

Position control of the upper prism is crucial for a proper performance of the LADC. From the control point of view the LADC is considered as a telescope facility; therefore it is controlled by the Telescope Control System (TCS). There will be two basic modes of operation:

1. prism 2 (P2) static during exposure; this means that P2 will be moved to a position corresponding (e.g.) to the middle of the exposure before the opening of the instrument shutter. It will stay there until the shutter is closed again.
2. P2 position is dynamically corrected; this means that P2 will be moved in predefined time intervals to a new position and will stay there until the next correction. Continuous correction is not foreseen.

Several parameters will be taken into account in the calculation of the proper prism position. These are according to their importance the zenith distance, the wavelength range used for the particular exposure (it is defined by the filter band or grism used but can also be set manually), and the prevailing meteorological conditions on Cerro Paranal (air temperature and pressure mainly as measured by the astronomical site monitor).

The telescope guiding system will be also affected by the LADC. The guide probes in the adapter/rotator will detect corrected but shifted images. Contrary to other foci without ADCs, the guide probe does not need to correct for guiding errors due to the differential dispersion between the target and reference star. However, it will correct for residual dispersion (second order effect). In addition, a program inside the TCS will take into account the image displacement to compensate the pointing of the telescope.

5.4. Expected optical performance

5.4.1. Image quality We calculated the expected image quality (d_{80}) of FORS in the most critical case, i.e. in the high spatial resolution imaging mode with an image scale of 0.1″ per 24 μm pixel, comparing the cases with and without the LADC for the field centre and the edge of the field of view (field angle 1.7′) at zenith (z = 0°) and at z = 50°. Table 4 shows the dramatic improvement at z = 50° which is achieved by the use of the LADC in two standard filter passbands and even in the extreme wavelength range 350-850 nm indicative of white light imaging or very low dispersion spectroscopy. It also shows that aberrations introduced by the LADC in the zenith position are negligible.

Field	z	ADC	U-Filter	V-Filter	350-850 nm
center	0°	no	0.04″	0.06″	0.06″
center	0°	yes	0.04″	0.05″	0.06″
center	**50°**	**no**	**0.45″**	**0.38″**	**1.00″**
center	**50°**	**yes**	**0.10″**	**0.10″**	**0.12″**
edge	0°	no	0.08″	0.06″	0.09″
edge	0°	yes	0.06″	0.06″	0.10″
edge	50°	no	0.53″	0.39″	1.14″
edge	50°	yes	0.17″	0.13″	0.18″

Table 4: Calculated image quality of FORS in the high resolution mode with and without LADC

5.4.2. Transmission Since the FORS optics are coated with a single layer of MgF_2 centered at 420 nm it was decided to do the same with the LADC prisms. The following table 5 shows the resulting transmission of the LADC taking into account internal absorption (which is virtually negligible) and surface reflections. It should be noted that this additional absorption is always present, even for observations close to zenith, due to the fact that the LADC cannot be routinely removed from the telescope (see sections 3.1. and 5.2.).

λ/nm	330	400	500	600	800	1000	(1500)
Transmission/%	93	95	94	93	90	89	(87)

Table 5: Calculated transmission (glass plus MgF_2 coating) of the VLT LADC

5.4.3. Ghost images We computed the intensity and position of the primary ghost images created by the internal reflections inside the individual prisms and by the gap between them (case 1: reflection inside P2, case 2: inside P1, case 3: inside the gap). The worst values are given when the two prisms are close together. The results are shown in table 6.

case	ghost offset	ghost blur	ghost relative intensity	
	mm	mm	fraction	Δ mag.
1	2.4 = f(z)	3.0	2.5 $\times 10^{-5}$	11.5
2	76 = const.	1.7	7.8 $\times 10^{-5}$	10
3	72 = f(z)	1.2	16 $\times 10^{-5}$	9.5

Table 6: Calculated ghost images of the VLT LADC

It is obvious that we do not have to worry about ghost images of this relative intensity, spread out over $\approx$ 1 mm $\approx$ 50 pixels.

5.5. Various performance aspects

In the optical error budget used for the design of the VLT-FORS LADC a number of contributions in terms of 80% encircled energy diameter have been taken into account. They are shown together with their relative errors in Tables 7 and 8. All contributions except polishing and dust residuals were considered statistically independent. Therefore they are added quadratically. The reference value is the quality of the Telescope + FORS (ideal design). This error budget just takes the design figure of FORS in the high resolution mode.

Image quality d_{80} = 0.101		
	Optical design 0.076	
	Surface errors 0.0055 + 0.005	Surface flatness 0.0039
		Prism bending 0.0039
		Polishing/dust (systematic) 0.005
	Glass homogeneity 0.021	
	Optical alignment 0.056	P1 tilt 0.012
		P2 tilt 0.025
		P1 rotation 0.033
		P2 rotation 0.033
		P1 - P2 gap 0.012

Table 7: Error budget for the LADC in the FORS High Resolution mode. z = 0°

Image quality d_{80} = 0.25		
	Optical design 0.21	
	Surface errors 0.089 + 0.005	Surface flatness 0.0896
		Prism bending 0.021
		Polishing/dust (systematic) 0.005
	Glass homogeneity 0.013	
	Optical alignment 0.10	P1 tilt 0.055
		P2 tilt 0.055
		P1 rotation 0.041
		P2 rotation 0.041
		P1 - P2 gap 0.029

Table 8: Error budget for the LADC in the FORS High Resolution mode. z = 50°

Since the FORS instruments will be extensively used for multi-object spectroscopy with small ($\approx 0.5''$) slits, it is important to have a precise positioning of the slits which of course would be affected by scale factor variations introduced by the LADC. Again checking the worst case (i.e. going from zenith to z = 50° and looking at an object at the edge of the FORS field of view in the standard resolution mode at a field angle of $3.4'$) we find that the scale factor variation is less than $0.01''$ and therefore not a cause for concern.

6. SUMMARY

We have presented a novel approach to the correction of atmospheric dispersion which can be utilized for telescopes up to very large sizes (according to today's standards) which combines good image quality with relatively simple implementation. We judge that its advantages far outweigh its disadvantages. Two LADCs will be implemented in the ESO Very Large Telescope for the FORS focal reducers.

7. REFERENCES

[1] J. G. Cohen, J. Cromer, "Atmospheric refraction effects on the Norris and Keck multiobject spectrographs", PASP 100,1582(1988)

[2] W. Seifert, W. Mitsch, H. Nicklas, G. Rupprecht, "FORS - a workhorse instrument for the ESO VLT" in: 'Instrumentation in Astronomy VIII', David L. Crawford, Eric R. Crain, Editors, SPIE Proc. 2198,213(1994)

[3] K. Taylor, these proceedings

[4] G. Avila, G. Rupprecht, in preparation