The achromatic design of an atmospheric dispersion corrector for extremely large telescopes

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Abstract: For off-zenith observations with ground-based astronomical telescopes, the effect of atmospheric dispersion relative to diffraction on image size increases with telescope diameter. Correction of atmospheric dispersion in extremely large telescopes (ELTs) might become critical. A common solution for ELTs is to use linear atmospheric dispersion correctors (ADCs). In spite of their simplicity, the intrinsic chromatic aberrations of linear ADCs could render diffraction-limited imaging impossible when used in a fast focus. The chromatic problems of the linear ADC in ELTs can be resolved by replacing the linear ADC by the achromatic ADC designs presented here, which provide diffraction-limited image quality and offer several opto-mechanical advantages over linear ADCs.

OCIS codes: (110.6770) Telescopes; (220.1000) Aberration compensation; (010.1300) Atmospheric propagation; (010.1080) Adaptive optics.

References and links

1. A. V. Goncharov, N. Devaney, and C. Dainty, "Atmospheric dispersion compensation for extremely large telescopes," Opt. Express **15,** 1534–1542 (2007).
2. N. Devaney, "Review of astronomical adaptive optics systems and plans," Proc. SPIE **6584,** 658407 (2007).
3. M. Hart, "Recent advances in astronomical adaptive optics," Appl. Opt. **49,** D17–D29 (2010).
4. J. Nelson and G. H. Sanders, "The status of the Thirty Meter Telescope project," Proc. SPIE **7012,** 70121A (2008).
5. S. Shectman and M. Johns, "GMT overview," Proc. SPIE **7733,** 77331Y (2010).
6. R. Gilmozzi and J. Spyromilio, "The 42 m European ELT: status," Proc. SPIE **7012,** 701219 (2008).
7. B. Delabre, "Optical design for an adaptive anastigmatic five-mirror extremely large telescope," Astron. Astrophys. **487,** 389–397 (2008).
8. E. Diolaiti, J. Conan, I. Foppiani, E. Marchetti, A. Baruffolo, M. Bellazzini, G. Bregoli, C. R. Butler, P. Ciliegi, G. Cosentino, B. Delabre, M. Lombini, C. Petit, C. Robert, P. Rossettini, L. Schreiber, R. Tomelleri, V. Biliotti, S. D'Odorico, T. Fusco, N. Hubin, and S. Meimon, "Conceptual design and performance of the multiconjugate adaptive optics module for the European Extremely Large Telescope," Proc. SPIE **7036,** 77360R (2010).
9. B. Ellerbroek, S. Adkins, D. Andersen, J. Atwood, S. Browne, C. Boyer, P. Byrnes, K. Caputa, R. Conan, R. Cousty, D. Erikson, J. Fitzsimmons, F. Gamache, L. Gilles, G. Herriot, P. Hickson, O. Lardier, P. Morin, J. Pazder, T. Pfrommer, D. Quinn, V. Reshetov, S. Roberts, J. Sinquin, M. Schoeck, M. Smith, G. Tyler, J. Vaughn, J. Veran, C. Vogel, L. Wang, and I. Wevers, "First light adaptive optics systems and components for the Thirty Meter Telescope," Proc. SPIE **7036,** 773604 (2010).
10. P. M. Hinz, A. Bouchez, M. Johns, S. Shectman, M. Hart, B. McLeod, and P. McGregor, "The GMT adaptive optics system," Proc. SPIE **7036,** 77360C (2010).
11. J. Atwood, P. Byrnes, and G. Herriot, "NFIRAOS: the optical design of an adaptive optics system for the Thirty Meter Telescope," Proc. SPIE **7439,** 74390G (2009).
12. N. Devaney, A. V. Goncharov, and C. Dainty, "Chromatic effects of the atmosphere on astronomical adaptive optics," Appl. Opt. **47,** 1072–1081 (2008).

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13. G. Avila, G. Rupprecht, and J. M. Beckers, "Atmospheric dispersion correction for the FORS Focal Reducers at the ESO VLT," Proc. SPIE **2871,** 1135–1143 (1997).
14. A C. Phillips, J. Miller, D. Cowley, and V. Wallace, "The Keck-I Cassegrain atmospheric dispersion corrector," Proc. SPIE **6269,** 62691O (2006).
15. W. J. Smith, *Modern Optical Engineering* (McGraw-Hill, 2000).
16. C. G. Wynne and S. P. Worswick, "Atmospheric dispersion correctors at the Cassegrain focus," Mon. Not. R. Astron. Soc. **220,** 657–670 (1986).
17. E. Atad-Ettedgui, M. Owner-Petersen, and A. V. Goncharov, "Atmospheric dispersion effects in ELTs and their compensation," Proc. SPIE **7018,** 70181D (2008).
18. C. G. Wynne, "Atmospheric dispersion in very large telescopes with adaptive optics," Mon. Not. R. Astron. Soc. **285,** 130–134 (1999).
19. C. G. Wynne, "Correction of atmospheric dispersion in the infrared," Mon. Not. R. Astron. Soc. **282,** 863–867 (1996).
20. R. N. Wilson, *Reflecting Telescope Optics I* (Springer, 2007).
21. C. G. Wynne, "A new form of atmospheric dispersion corrector," Mon. Not. R. Astron. Soc. **262,** 741–748 (1993).
22. D. J. Jones, "Wide-field prime focus corrector for the Anglo-Australian telescope," Appl. Opt. **33,** 7362–7366 (1994).
23. L. Gilles, L. Wang, and B. L. Ellerbroek, "Impact of laser launch location on the performance of laser tomography and multiconjugate adaptive optics for extremely large telescopes," Appl. Opt. **49,** G114–G119 (2010).
24. C. Cesarsky, "The birth of the European ELT," ESO Messenger **127,** 2–3 (2007).
25. R. Gilmozzi and J. Spyromilio, "The European Extremely Large Telescope (E-ELT)," ESO Messenger **127,** 11–19 (2007).

1. Introduction

For off-zenith astronomical observations with ground-based optical telescopes, the atmospheric dispersion elongates star images to spectra with the blue end pointed toward the Zenith. This effect of the atmospheric dispersion on image size relative to the diffraction limit (Airy disk) increases with telescope diameter. Finding a suitable atmospheric dispersion corrector (ADC) for extremely large telescopes (ELTs) is a real challenge. One possible solution for atmospheric dispersion correction is to use a linear ADC (LADC) [1]. Despite the simplicity of LADCs, their intrinsic aberrations could make it difficult to achieve diffraction-limited imaging. The monochromatic aberrations are usually compensated by adaptive optics (AO) system [1–3]. In ELTs the intrinsic chromatic aberrations are not significant in slow beams (e.g. f/15), however their correction becomes critical in fast beams (faster than f/5). In ELTs, sometimes there is an intermediate fast focus, which helps to reduce the linear size of an ADC. The drawback of using a fast focus is that the chromatic aberrations of the ADC are magnified at the final slow focus. The chromatic aberrations in the final focus could prevent ELT from achieving its diffraction-limited image quality. We show an example of an ELT with an intermediate fast focus, which presents an opportunity to revisit traditional approach of atmospheric dispersion correction with new achromatic ADC design.

There are currently three ELT projects under development: Thirty Meter Telescope (TMT) [4] , Giant Magellan Telescope (GMT) [5] and the European ELT (E-ELT) [6]. In contrast to the TMT and GMT designs, which are classical aplanatic two-mirror systems, the baseline design of the European Extremely Large Telescope (E-ELT) is a 42-m five-mirror telescope with three powered aspheric mirrors. The ellipsoidal segmented primary mirror (M1) converges light toward the 6-m convex hyperboloidal secondary mirror (M2). These two mirrors make an image at the intermediate focus (F1) located 27 m after M2. The light is focused again by a 4-m concave aspheric tertiary mirror (M3) at the final focus (F2). To bring the final focus to a Nasmyth platform, the beam is folded by two flat mirrors (M4 and M5); the telescope optical layout is shown in Section 4. M4 is a 2.5-m deformable mirror designed to compensate the optical effects of atmospheric turbulence. M5 is intended for image stabilization (compensating for telescope vibrations) [7]. For a more detailed description of AO systems in the current ELT projects see Ref. [8–11].

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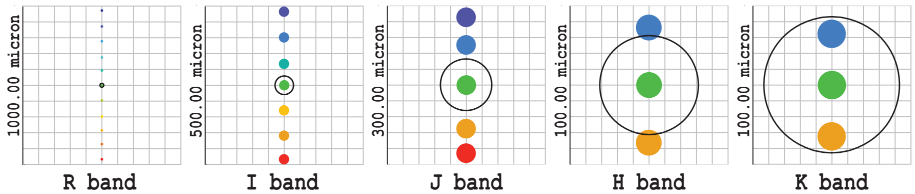

Fig. 1. Spot diagrams for the E-ELT operating at 45 deg off Zenith at different spectral bands. The black circle represents the Airy disk.

Atmospheric turbulence is not the only factor preventing diffraction-limited imaging in ELTs. Atmospheric dispersion in telescopes of such large aperture significantly elongates the image spots vertically. Figure 1 depicts the spot of the central field point of the E-ELT in the R band (0.59-0.81 µm), I band (0.78-1.02 µm), J band (1.06-1.44 µm), H band (1.5-1.7 µm), and K band (1.96-2.44 µm) at 45 degrees off Zenith. Although the spot size produced at each individual wavelength is smaller than the Airy disk (the black circle), the image of a star in the R band would appear elongated vertically by about 70 times of the Airy disk diameter. In this paper, the atmospheric dispersion effects are modeled by using ZEMAX optical design software. Various chromatic effects introduced by the atmosphere are described in more detail in Ref. [12].

To reduce the elongation of polychromatic point sources, it is essential to use an atmospheric dispersion corrector (ADC) in the telescope system. It is more practical to place an ADC at F1 rather than at the final focus F2. The linear size of the full field at F1 is about 0.6 m, whereas in the final focus F2 it is 1.95 m. Manufacturing lenses of this size is not possible and segmented lenses are not desirable in view of segmentation employed already for the primary mirror M1 and deformable mirror M4. In light of this, it has been suggested to use an LADC for the E-ELT close to F1, where the image scale is 3.5 times smaller than at F2 [7]. In spite of apparent simplicity of LADC it has some drawbacks, which are discussed in Section 2.

LADCs are not the only possibility for the E-ELT. In Section 3, we consider other types of ADC and in Section 4 we present our design of a rotating achromatic atmospheric dispersion corrector (RADC) for the intermediate focus (F1) of the E-ELT .

2. Limitations of LADC in fast focus

The linear ADC was originally proposed by Beckers in 1997 [13]. It contains two identical thin prisms (wedges) W1 and W2 with opposite orientation. The amount of longitudinal dispersion produced by the LADC is proportional to their axial separation. One of the wedges can move along the optical axis to adjust the amount of dispersion needed for different Zenith angles (Fig. 2). LADCs are commonly employed in large telescopes for compensating atmospheric dispersion [14]. LADCs work in a converging beam usually near the final focus. Both wedges are made of the same materials (usually silica because of its high optical transmittance).

The glass wedges in a converging polychromatic light produce monochromatic and chromatic aberrations [15, 16]. The amount of aberrations increases in fast foci. Linear ADCs also introduce a noticeable vertical displacement of the exit pupil and the focal surface. This unwanted displacement can be, in principle, compensated by decentering all optical elements that come after the ADC in the telescope system [1]. To reduce the required dynamic range of the deformable mirrors M4, it has been suggested to correct image motion by the tip-tilt movement of M5. A linear ADC introduces field aberrations such as coma and astigmatism, which could be corrected by AO system (using the deformable mirror M4) or by active optics using the secondary mirror M2. In principle correcting the intrinsic monochromatic aberrations of

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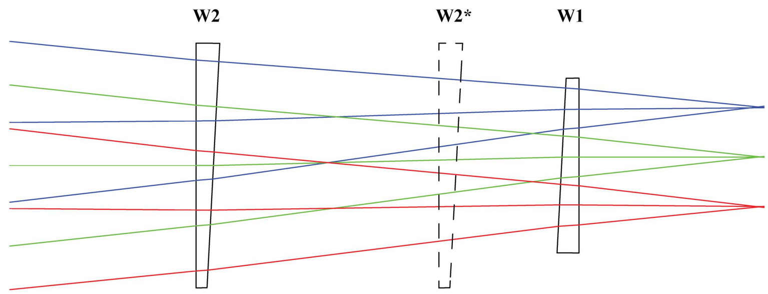

Fig. 2. A typical layout of LADC; W2 can move and tune the intrinsic dispersion of the system for different Zenith angles.

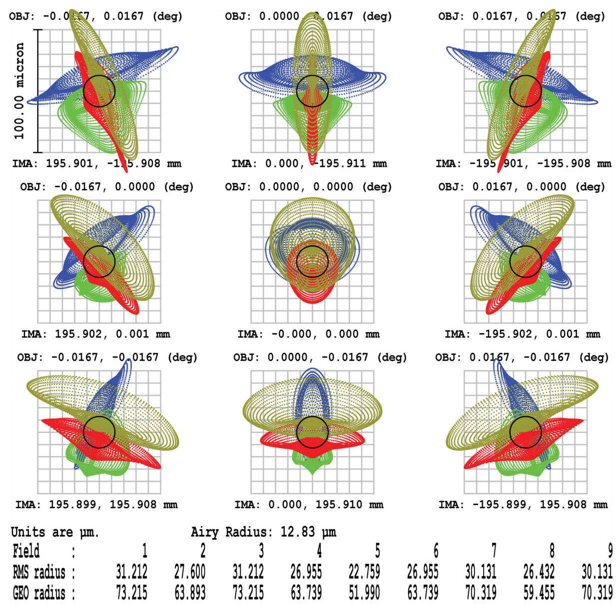

Fig. 3. The spot diagrams of a designed LADC for the E-ELT operating at 45 deg from Zenith over 2-arcmin full field.

LADC may be achieved by the combined deformation of M2 and M4, so that the demands on AO system are reduced. Since the LADCs typically operate in slow foci, chromatic aberrations are relatively small to be of any concern. However, there are two points, which make the chromatic effect of wedges critical for the E-ELT: the intermediate focus F1 is fast (f/4.6), and M3 re-images F1 to the final focus F2 (f/16), which magnifies the chromatic effects [17]. Figure 3 shows the spots of an LADC designed for 45 degrees from Zenith and 2 arcmin full field of view. The wedge angle is 1.5 deg, central thickness 40 mm, and the maximum axial separation 2 m.

The task of correcting these intrinsic chromatic aberrations of the LADC in the E-ELT is very challenging. Two wedges put together in contact form a thick glass plate. In term of chromatic effects, such a glass plate acts like a negative lens and shows positive axial color [15]:

$$\delta_{ax} = \frac{t(n-1)}{n^2 V}, \tag{1}$$

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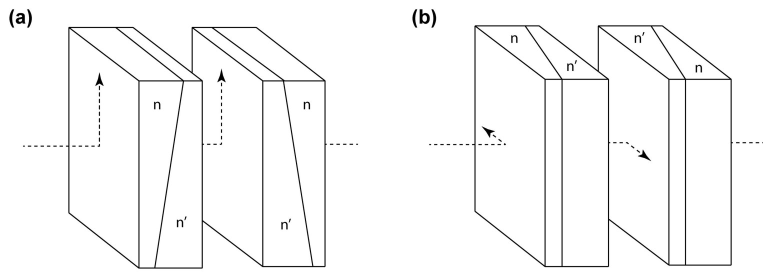

Fig. 4. A simple RADC: (a) maximum dispersion, (b) zero dispersion.

where δ_{ax} is the axial chromatic aberration of the plate, n the refractive index, t the thickness of the plate, and V the Abbe number. Correcting the axial color of such a plate requires a positive compensating lens. Because of the significant thickness of the plate ($t = 80mm$) the needed optical power of a single positive lens would make it the most powerful element in the telescope. This lens will affect the rest of the telescope system after F1 leading to a different geometry of the light path, pupil mis-conjugations in the AO system, and vignetting. One could avoid excessive optical power by using a two-lens corrector instead, however due to high level of aberrations at F1 (see Section 6) the two-lens corrector does not have sufficient number of degrees of freedom to keep the telescope achromatic. In this case only three-lens corrector is able to provide achromatic correction. Instead of using F1, one can think of adding a lens corrector close to the final focus F2, but the size of the usable image is limited by the diameter of the lens (which can be as large as 1 m at most). Alternative ADC designs are discussed in the following section.

3. Other types of ADCs

Before introduction of LADCs, rotating ADCs were the common solution for atmospheric dispersion. The simplest type of RADC contains two identical counter-rotating plates, so called Amici prisms [18]. Each plate is made of two cemented prisms. The ADC will show its maximum (zero) dispersion when the apex angles of the prisms are in the same (opposite) directions, see Fig. 4 and Ref. [19]. This simple RADC is used in collimated light (typically in the pupil plane).

An *ideal* ADC compensates for atmospheric dispersion and also provides zero-deviation for the chief rays at the reference wavelength to preserve the pupil position in the telescope. In LADCs there are two identical prisms and the tilt of the pupil plane introduced by the first prism is corrected by the second one. The rotation of prism pairs in an RADC is the basis for its function, however the angles between the two interfaces in prism pairs depends on the Zenith angle. This means that each plate should fulfill the zero-deviation condition individually. This can be achieved in two ways. The first method is to add appropriate tilts to the outer surfaces of the plates insuring that the outgoing ray will be parallel to the incoming ray. In this case, the vertical displacement like the one found in LADCs is applied to outgoing rays. The second method is to use two different types of glasses for the prisms, which show different dispersions, but the same refraction index at some prime wavelength. Such an ADC does not present any tilt or even vertical displacement in the image at this mean wavelength. Finding these two glasses is the main challenge. In addition to the requirement of having a certain common point in the dispersion curves, their differential dispersion should match the atmospheric dispersion as close as possible. In Section 7, we show that it is possible to find such glass pair.

The exit pupil of the E-ELT is located close to M4, where the diameter of the beam is even

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larger than the field diameter at the final focus F2. Using an RADC in a convergent beam introduces noticeable amount of aberrations. To avoid this problem, optical designers usually introduce some curvature on the surfaces [20]. Although this can in principle improve monochromatic aberrations, chromatic aberrations might get worse. A surface with some optical power introduces more axial and lateral color than a flat surface. Correcting chromatic aberrations is related to the curvature of the surfaces as well as the material of the elements. This makes the design of such an ADC more complicated and the process of finding the suitable glasses difficult.

Historically optical designers have tried different ideas to improve the performance of RADCs in a converging beam. Wynne suggested making the surfaces of the wedges concentric to the focal plane [21]. This eliminates axial color and gives a better aberration correction. Since concentric lenses are powerful elements and they will drastically change the configuration of the telescope, this design is not helpful in the E-ELT. What is needed here is an *ad hoc* design, which solves the atmospheric dispersion problem and, at the same time, does not change anything else in the telescope system.

Apart from concentric ADCs, there have been some work on adding more lenses to RADC operating as a focal corrector [20, 22]. A new kind of an RADC for the E-ELT inspired by this work is presented in Section 4.

4. The achromatic design of ADC for the E-ELT

Figure 5 presents an optical layout of the E-ELT featuring the new achromatic design of the RADC. The ADC consists of three lenses and it is located near the intermediate focus F1. The first two lenses, L1 and L2, are the counter rotating elements, which tune the intrinsic dispersion of the ADC for different Zenith angles. The third lens L3 preserves the geometry of the beam at F1. Therefore, L3 makes the ADC an afocal system and it also corrects for the residual aberrations of L1 and L2. It is worth pointing out that in contrast to linear ADCs, the proposed ADC does not use any tilt or decentering of M3, M4 and M5. The diameter of the largest lens covering the 10-arcmin full technical field is less than 780 mm and the total length of the ADC is less than 850 mm. The range of rotation angles for L1 and L2 (0 deg to 90 deg) provides the atmospheric compensation up to 55 deg from Zenith. The glasses used are S-PHM52 and N-F2 for L1 and L2, and F5 for L3. As can be seen from Table 1, these glasses have high transmittance between 500 nm and 1530 nm. This is the achievable range for the ADC designs presented here.

Table 1. The Transmittance Coefficients for Silica and the Glasses Used in the ADC

λ (nm)	Transmittance for 10 mm thickness			
	Fused Silica	S-PHM52	N-F2	F5
1530	0.999	0.993	0.991	0.995
1060	0.999	0.996	0.998	0.999
700	0.999	0.998	0.997	0.999
660	0.999	0.998	0.996	0.998
620	0.999	0.998	0.996	0.998
580	0.999	0.998	0.997	0.998
546	0.999	0.998	0.997	0.998
500	0.999	0.996	0.994	0.998

To keep the pupil and M4 conjugations unchanged special constraint on the position of the exit pupil in the optimization merit function is used. The exit pupil of the E-ELT is located 590 mm after M4, whereas deformable mirror M4 is conjugated to an atmospheric layer that

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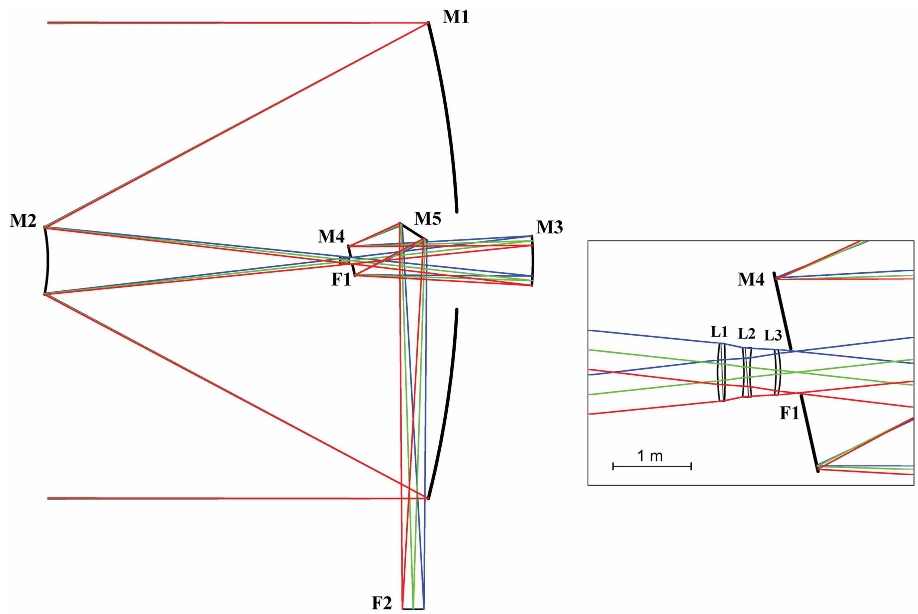

Fig. 5. The optical layout of the E-ELT featuring the new design of the three-lens rotating achromatic ADC.

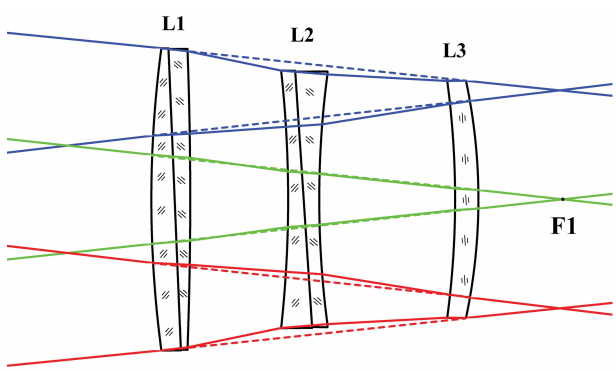

Fig. 6. The three-lens achromatic ADC with the unchanged path of the rays.

is about 200 m above the primary mirror M1. Since the path of the rays is not changed by the ADC (see Fig. 6), the ADC preserves this conjugation in the telescope.

Another constraint in the E-ELT is the image quality of a turbulent layer on M4. This is of high importance for successful operation of the adaptive optics (AO) system. Since the atmospheric correlation length r_0 is smaller in the B (0.391-0.489 μm) and V (0.505-0.595 μm) bands compared to the R band, the performance of the AO system will not be as effective. For this reason, we have designed the ADC for the R, I and J bands. As can be seen in Fig. 1, the atmospheric dispersion correction in the H and K bands is not critical. The main ADC should be removed from the telescope when operating in those bands. For the R band, the E-ELT gives nearly diffraction-limited image of a turbulent layer on M4. Adding the ADC near F1 reduces the quality of the turbulent layer image on M4, but is still acceptable for the AO system. The image size of the atmospheric correlation length $r_0 = 300$ mm on M4 is about 18 mm. The

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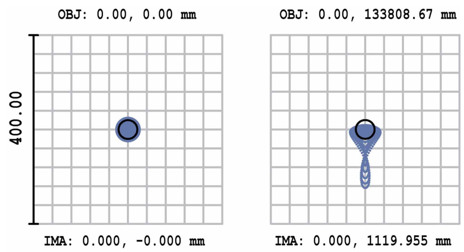

Fig. 7. The image of an LGS situated at 92 km altitude above the E-ELT.

image spot size is smaller than 1.5 mm, which is only 8% of the image size of r_0 on M4. Thus, this gives sufficient resolution for the deformable mirror M4 to correct atmospheric turbulence.

The AO system requires laser guide stars (LGSs) for wavefront sensing at any point in the sky, especially when there is no sufficiently bright natural star available near the science object. LGSs are essential for laser tomography of the atmospheric turbulence [23]. The E-ELT is an LGS-friendly telescope [24, 25], since the LGS spots are comparable to the airy disk (see Fig. 7). Adding the ADC to the telescope affects the image quality of LGSs. To restore the original quality of LGSs, a dedicated monochromatic correctors could be applied in front of the LGS wavefront sensors.

The spot diagrams of the 2-arcmin full field in the R band for three different Zenith angles are presented in Fig. 8, which also shows the corresponding orientations of the counter-rotating lenses L1 and L2.

In the R band, the achromatic ADC does not need any aberration correction by AO system. The RMS of the spots is smaller than the Airy disk at Zenith angles less than 45 deg. Even at 55 degrees from Zenith, the spots are still near diffraction limited over the 2-acrmin full field. As can be seen from the spot positions in Fig. 8, contrarily to the LADC, the proposed ADC design does not introduce any image displacement in the vertical direction. This has been achieved by a proper choice of the glasses for L1 and L2. As discussed in Section 3, the prime wavelength here is the point at which the dispersion curves meet (Fig. 9). As mentioned in Section 3, there are two methods for achieving a zero deviation condition in an ADC. Because of the fast focus and the giant size of the aperture in the E-ELT, it is better to use the second method than introducing a tilt at the external surfaces of the prisms. Tilting powered surfaces to achieve the zero-deviation condition would result in a noticeable amount of residual aberrations in the E-ELT.

The ADC has also a good performance in the I and J bands (Fig. 10).In this case, a small compensation for defocus is needed, which is much less than what is required for an LADC in the original design of the E-ELT.

Figure 11 shows the centroid motion of an NGS (in milli-arcseconds) as a function of wavelength (from 0.6 to 1.6 microns) after correction of atmospheric dispersion with a linear ADC and achromatic ADC operating in the R band. The centroid position is given for an NGS that is located at the edge of the 2 acrmin full field for a representative Zenith angle of 45 deg. It is clear that the residual chromatic effect in the achromatic ADC design is 5 times smaller than that of the linear ADC. To compensate this residual effect one could use a dedicated ADC for the NGS wavefront sensor. This could be achieved with an Amici prism pair placed near the pupil in the NGS wavefront sensor.

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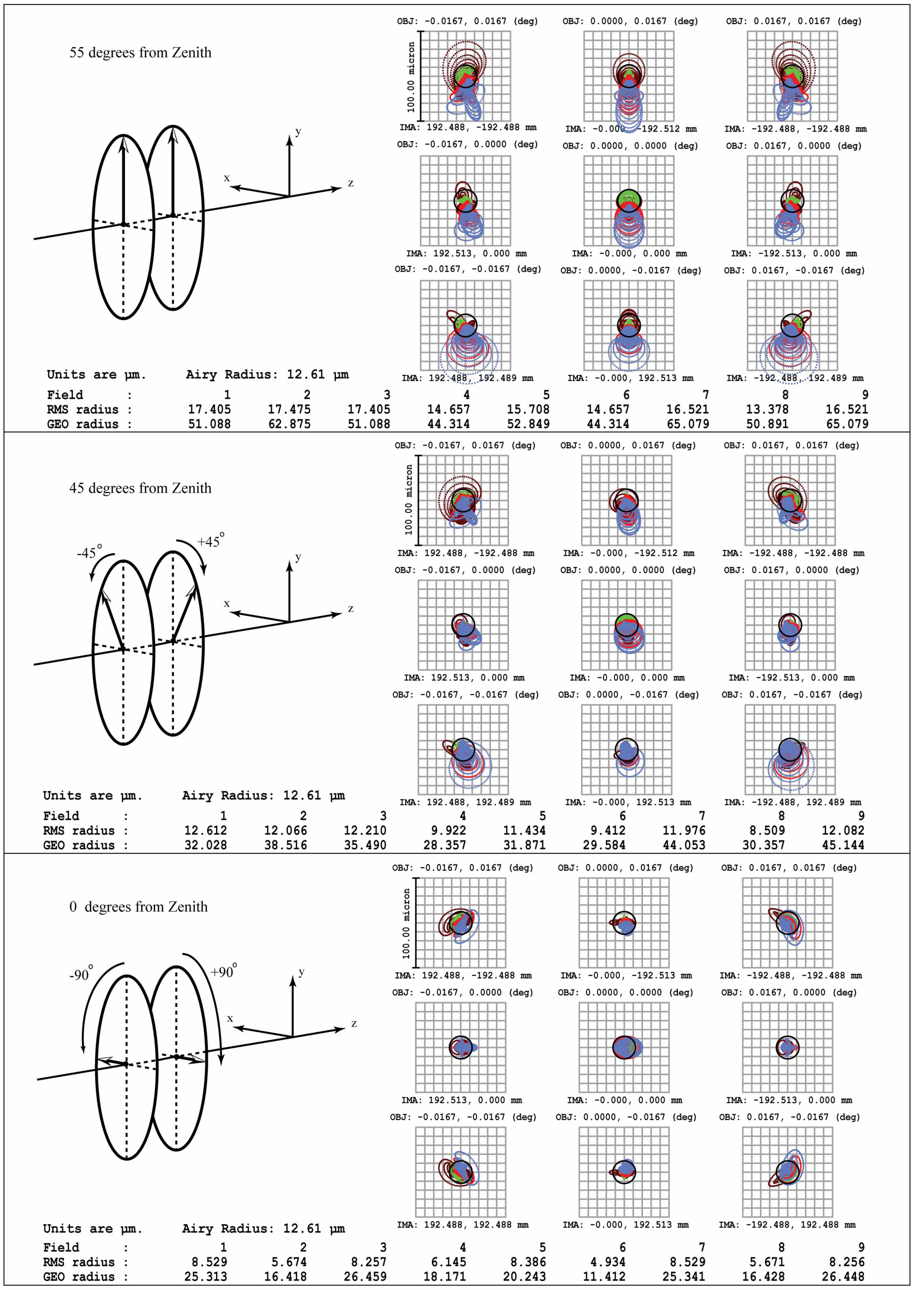

Fig. 8. The orientations of the counter-rotating lenses of the ADC for three different Zenith angles and corresponding spot diagrams over the 2-arcmin full field in the R band.

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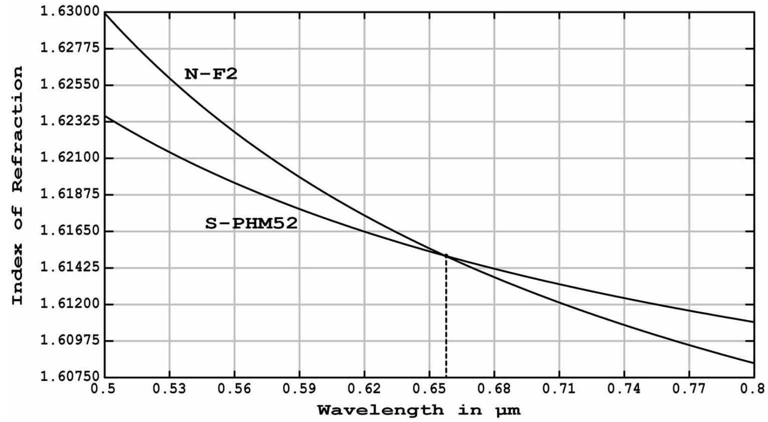

Fig. 9. The dispersion curves of N-F2 and S-PHM52 crossing at the prime wavelength, $\lambda = 0.657\mu m$.

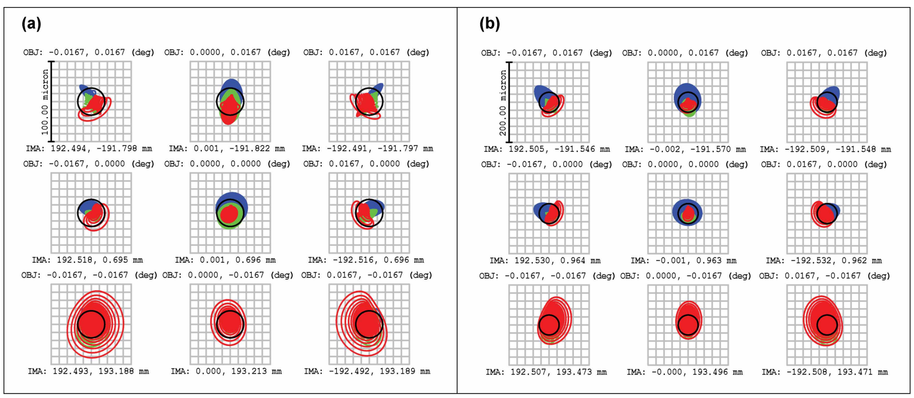

Fig. 10. Spot diagrams for the 2-arcmin full field of view of the E-ELT with the three-lens ADC in the I band (a) and J band (b).

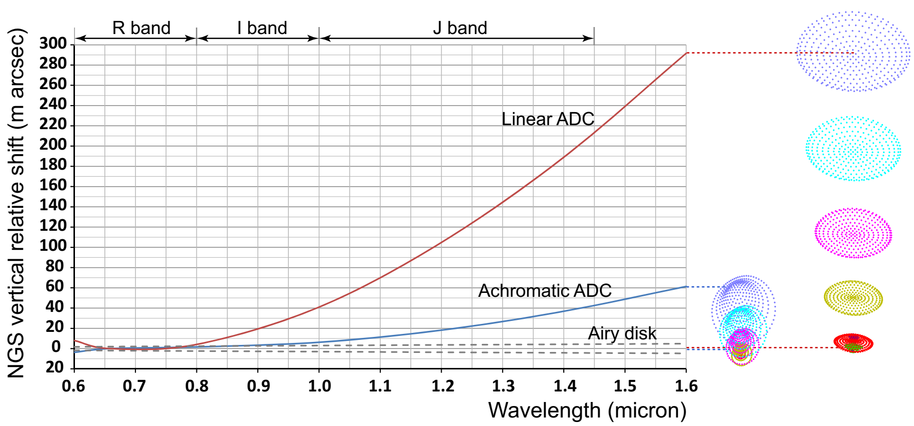

Fig. 11. NGS vertical displacement relative to the primary wavelength (0.657 µm) for the E-ELT operating in the R band at 45 deg off Zenith.

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5. The optical design of the achromatic ADC

Table 2 presents the main optical parameters of the achromatic three-lens ADC. The flat surfaces have different angles of tilt. This ensures that the contribution of L1 and L2 to the atmospheric dispersion compensation is the same. That is why the counter-rotating lenses operate with identical angles of rotation (see Fig. 8).

Table 2. The Optical Prescription of the Achromatic Three-Lens ADC

Lens	Surface	Radius (mm)	Thickness (mm)	Glass	Diameter (mm)	Tilt X (deg)
L1	1	2936.233	6.000	S-PHM52	776.816	0
	2	infinity	40.000	N-F2	771.984	-2.35841
	3	-10563.000	251.760		761.624	0
L2	4	-3050.150	40.000	S-PHM52	662.076	0
	5	infinity	40.000	N-F2	655.660	-3.78378
	6	2455.459	349.361		642.116	0
L3	7	-2301.700	60.000	F5	608.329	0
	8	-1467.920			609.804	0

Now we shall analyze the aberration compensation in the original E-ELT system, the E-ELT with the ADC, and the ADC alone. Figure 12(a) shows that the intermediate focus of the telescope is highly aberrated. This is due to the fact that M1 and M2 only partly compensate spherical aberration and coma at F1. The main task of the telescope is to achieve anastigmatic correction at the final focus F2, which is possible with three powered aspheric mirrors. In a perfect focus, re-optimized L1 and L2 could do the job without using L3. However in the aberrated focus F1, the design of the ADC is more complicated and one needs L3 to achieve diffraction-limited correction.

In Fig. 12(b) the ADC takes part in the aberration balancing of the telescope. The ADC shows some positive spherical aberration and negative coma, which affect the outgoing beam. Due to this, M3 produces more negative spherical aberration and less positive coma in comparison to the original aberration balancing in the telescope. As a result, the overall image quality in the telescope is not degraded in the presence of the ADC.

Figure 12(c) specifies the main differences between the LADC and the three-lens ADC. Axial and lateral color introduced by L1 are corrected by L2, and L3 further removes the residual aberrations. Thus, the three-lens ADC corrects simultaneously atmospheric dispersion and its own chromatic aberrations.

6. Optical performance of an achromatic two-lens ADC

As mentioned in Section 5, in a perfect intermediate focus, the additional correction by L3 is not necessary. Figure 12(c) shows that L3 produces significantly less aberrations than L1 and L2. This motivates us to investigate optical performance of an achromatic two-lens ADC in the E-ELT.

After removing L3 and re-optimizing L1 and L2, there will be some noticeable amount of residual monochromatic aberrations in the final focus F2. To reduce the residual aberrations and achieve the comparable image quality as with the three-lens ADC, one could change the conic constants of M1 and M2: from -0.992726 to -0.988459 for M1 and from -2.307544 to -2.244125 for M2. This corresponds to less than 0.3 mm change in the mirror sag at the edge of the mirrors. In addition, one needs to add a small amount of defocus (less than what is required for the LADC).

Figure 13 shows that the two-lens ADC preserves the original image scale in spite of the modified shape of M1 and M2. The two-lens ADC is showing more intrinsic coma (Fig. 14).

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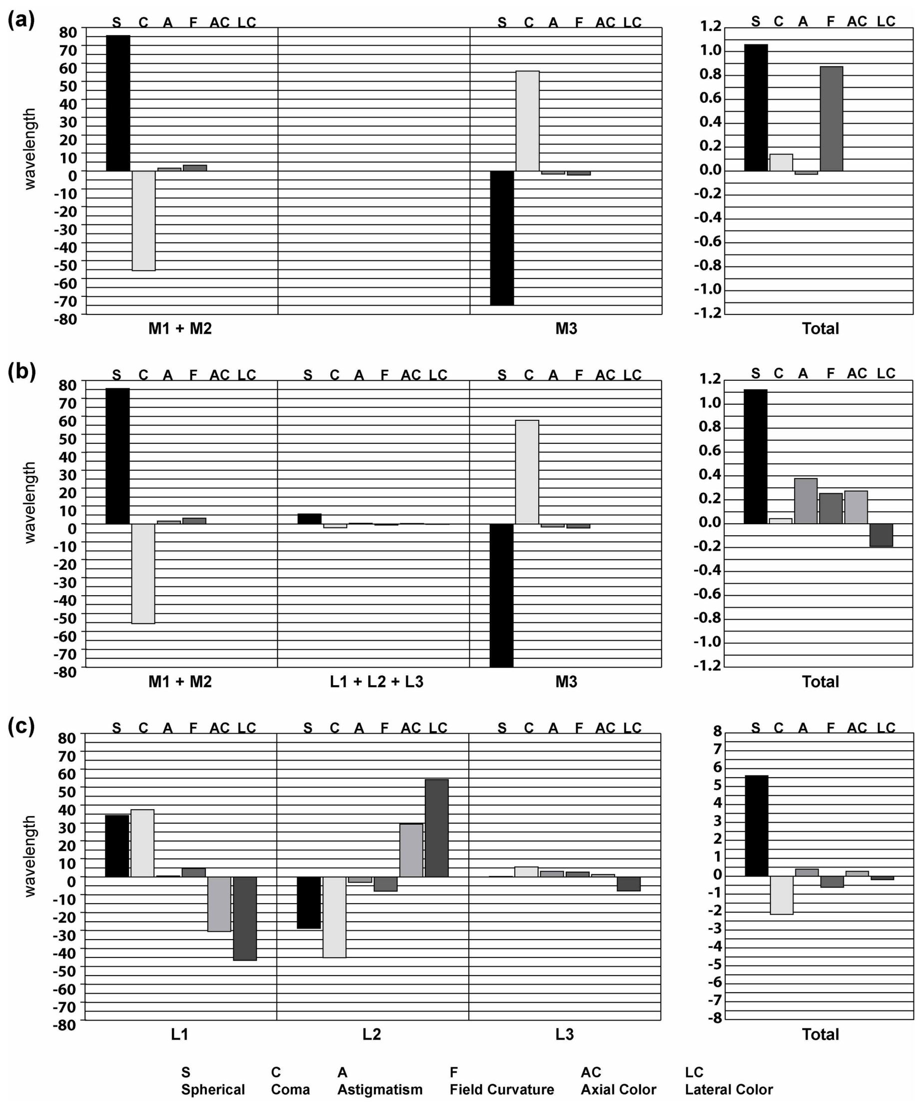

Fig. 12. Aberration diagrams for: (a) the E-ELT without the ADC, (b) E-ELT with the three-lens ADC, and (c) the three-lens ADC alone (The scales in the diagrams describing the total aberrations are different and the tilts of the surfaces are not considered.)

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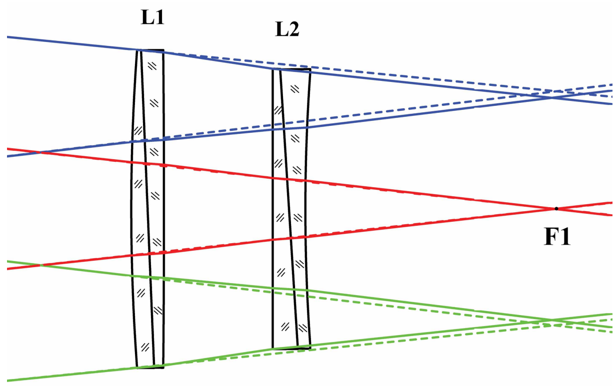

Fig. 13. The two-lens ADC and its effect on the path of the rays at F1. The dashed lines correspond to rays reflected from the modified M1 and M2 without *seeing* the ADC.

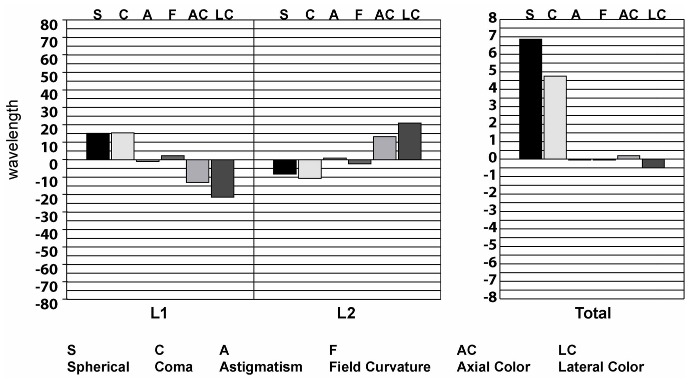

Fig. 14. The aberration diagrams for the two-lens ADC.

However, this coma is compensated by changing the conic constants on M1 and M2. Obviously, removing the ADC from the telescope will require reshaping of M1 and M2 to their original shape using active optics. Table 3 represents the optical prescription of the two-lens ADC; the optical diameters are given for 10-arcmin technical field.

Table 3. The Optical Prescription for the Achromatic Two-Lens ADC

Lens	Surface	Radius (mm)	Thickness (mm)	Glass	Diameter (mm)	Tilt X (deg)
L1	1	5348.556	40.000	S-PHM52	779.950	0
	2	infinity	40.000	N-F2	778.856	-2.35422
	3	-44629.100	266.060		768.432	0
L2	4	infinity	40.000	S-PHM52	687.640	0
	5	infinity	40.000	N-F2	685.574	-3.61044
	6	4665.763			706.472	0

The optical transmittance (OT) of the E-ELT with the achromatic two-lens ADC in the R, I, and J bands is presented in Table 4 for Zenith angle $Z = 0$ deg. For comparison we also give the OT of the E-ELT using a linear ADC in the R band (see Fig. 3). We assumed that each mirror surface has reflectance of 0.946, and we did not consider any special coatings for lens surfaces.

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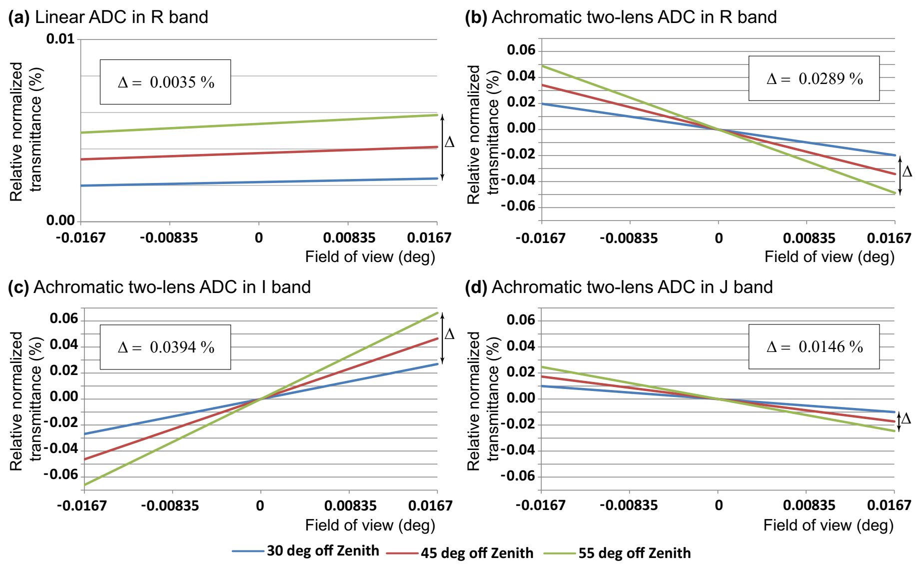

Fig. 15. Optical transmittance of the E-ELT (relative to the telescope transmittance at Zenith) as a function of field angle at different Zenith angles.

Figure 15 shows the relative normalized optical transmittance (OT^*) of the telescope at Zenith angles $Z = 30$, 45 and 55 deg, across the 2 arcmin full field in the vertical meridian. This is considered with respect to the optical transmittance of the telescope at Zenith ($Z = 0$ deg):

$$OT^*(Z) = \frac{OT(Z) - OT(0)}{OT(0)} \times 100\%, \tag{2}$$

As can be seen in Fig. 15, the OT of ADCs varies not only across the field, but also with Zenith

Table 4. Optical Transmittance of the E-ELT with the Linear and Achromatic ADC at Zenith

	-0.0167 (deg)	-0.0083 (deg)	0 (deg)	0.0083 (deg)	0.0167 (deg)
Linear ADC in R band	0.6940	0.6940	0.6940	0.6940	0.6940
Two-lens ADC in R band	0.6101	0.6102	0.6102	0.6102	0.6101
Two-lens ADC in I band	0.6113	0.6113	0.6113	0.6113	0.6113
Two-lens ADC in J band	0.5970	0.5971	0.5971	0.5971	0.5970

angle. For a given zenith angle the variation of the OT across the field can be calibrated during flat fielding. However, the OT variation with Zenith angle will alter the flat field by a small amount in the range of 0.01-0.04 % for a long exposure starting at $Z = 30$ deg and finishing at 55 deg. For shorter exposures this effect should not present any problems.

7. Conclusion

In spite of the simplicity of LADCs, their chromatic performance in fast foci may not be good enough for diffraction-limited imaging. Using other kinds of ADCs in fast foci, for example traditional RADCs, could be difficult. They usually have powered elements with noticeable amount of aberrations. Employing an LADC in the E-ELT shows unacceptable amount of chromatic aberrations, especially axial color, which due to the stringent optical constrains in

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the E-ELT is not easily correctable by additional lens correctors. These constrains include the optical conjugation of M4, fixed beam geometry and minimal vignetting.

To resolve the problem of intrinsic chromatic aberrations we have designed an achromatic three-lens ADC for the E-ELT. The new ADC is intended for operation in the R, I, and J band up to 55 deg off Zenith providing near diffraction-limited image quality over 2 arcmin full filed. In addition to its exceptional optical performance, the ADC preserves the beam geometry, which keeps the optical configuration of the E-ELT unchanged. The proposed three-lens ADC has several advantages over an LADC. The main advantage is that the three-lens ADC gives superior optical performance at the R, I and J bands. The intrinsic aberrations of this ADC are so low that there is no need for any AO correction through the range of Zenith angles. It is two times more compact than a typical LADC. The three-lens ADC does not require any translation along the optical axis and also it does not introduce any vertical displacement of the image.

An LADC exceeds the performance of the three-lens ADC only in terms of the optical throughput and image quality of LGSs. To improve these two characteristics we have designed an achromatic two-lens ADC based on the same principle. The LGS image quality in the E-ELT with a two-lens ADC is comparable to that of an LADC case. The image quality for science objects observed at the R, I and J bands are about three times better in the E-ELT equipped with the two-lens ADC. However, such good optical performance is achievable if the conic constant of the primary and secondary mirror are slightly adjusted by active optics.

In the summary we would like to emphasize that the chromatic problems of using an LADC in the E-ELT is solved by replacing an LADC with one of the two ADC designs presented here. They provide diffraction-limited image quality up to 45 deg off Zenith and have several opto-mechanical advantages over an LADC. The achromatic ADC designs can operate in the final focus, yet their superior optical performance is more evident in fast foci.

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