Turkey's Next Big Science Project: DAG the 4 Meter Telescope

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ABSTRACT

The DAG (Turkish for Eastern Anatolia Observatory) 4-m telescope project has been formally launched in 2012, being fully funded by the Government of Turkey. This new observatory is to be located on a 3170 m altitude ridge near the town of Erzurum in Eastern Anatolia. First light is scheduled for late 2017. The DAG team's baseline design of the telescope consists of a Ritchey-Chretien type with alt-az mount, a focal length of 56 m and a field of view up to 30 arcmin. Multiple instruments will be located at the Nasmyth foci. The optical specifications of the telescope are set by DAG team for diffraction limited performance with active and adaptive optics. Modern mirror control technologies will allow defining in a most cost effective way the figuring requirements of the optical surfaces: the low order figuring errors of the combined optical train constituted of M1-M2-M3 are defined in terms of Zernike coefficients and referred to the M1 surface area. The high order figuring errors are defined using the phase structure functions. Daytime chilling of the closed enclosure volume and natural ventilation through suitable openings during observations will be used to ensure optimal mirror and dome seeing. A design of a ground layer adaptive optics (GLAO) subsystem is developed concurrently with the telescope. In this paper, main design aspects, the optical design and expected performance analysis of the telescope will be presented.

Keywords: Telescope, Turkey, active optics, adaptive optics, GLAO

1. INTRODUCTION

As a ground-based telescope, the capabilities of DAG are necessarily bound by the fact that it must make its observations through the earth's atmosphere, and has to function within the atmospheric environment. Given these constraints, the telescope itself has to have the smallest possible impact on its potential performance. Therefore in the optical design of DAG telescope:

- The largest possible collecting area
- The best possible angular resolution (diffraction limit)
- The smallest background fluxes
- The largest usable field of view
- The widest wavelength coverage
- The greatest observing time
- Beeing cost-effective
- and technically achievable with the highest practical mirror reflectivity for maximum achievable collecting efficiency was required.

This paper presents the optical design for the DAG telescope project in 6 sections; starting assumptions, requirements and design choices and theory are presented in section 2; Telescope optics dimensioning is

Ground-based and Airborne Telescopes V, edited by Larry M. Stepp, Roberto Gilmozzi,
Helen J. Hall, Proc. of SPIE Vol. 9145, 914547 • © 2014 SPIE
CCC code: 0277-786X/14/$18 • doi: 10.1117/12.2067599

given in Section 3; reference conditions for wavefront errors budgeting is given in section 4; error budget metrics is given in section 5; and mirrors manufacturing error budget will be presented in section 6.

2. DESIGN REQUIREMENTS OF DAG

Having the goal to build a 4 meter diameter telescope; the requirements chosen by the telescope committee, assumptions made for the design, and design equations are briefly introduced.

2.1 Telescope Central Obscuration

In DAG, a central obscuration of 20 % would generate a loss of light flux of 4 % or 0.04 magnitudes and a central obscuration of 30 % a flux loss of 10 % or 0.1 magnitudes. Thus, it is decided to make the optical design based on a telescope with a primary mirror 4-m in diameter with a central obscuration range of 20-30 % as our target, and 20% or less as a goal.

2.2 Ritchey-Chrétien Optical Configuration

DAG telescope will be a general purpose telescope, dedicated to both seeing limited and adaptive optics (AO) corrected observations with narrow to moderate FoV. Amongst the different two-mirrors designs Ritchey-Chrétien (RC) design is chosen to cancel the off-axis coma as well as the spherical aberration by its hyperbolic-hyperbolic primary-secondary combination.

2.2.1 Secondary Mirror

Secondary mirror (M2) can be located at two positions along the optical axis: before or after the focal plane of the primary mirror (M1). In the first case, M2 is a divergent mirror; in the second case, M2 is convergent, and the configuration is called a Gregorian. The advantage of the Gregorian configuration is that M1 focal plane is available for an instrument or a calibration source. The disadvantage over the RC configuration is that it makes the telescope tube at least 50 % larger, requiring a larger dome, at extra costs. In our case, there are no specific reasons to get access to M1 focus, so the RC configuration is selected.

2.2.2 Focal Planes Location: Nasmyth Platforms

There are usually three places where the focal plane can be located on a RC: the Cassegrain focus, behind the primary, and the two Nasmyth foci, on both side of the telescope, aligned with the elevation axis. Nasmyth foci have the advantage of providing gravity invariant focus, which is not the case for the Cassegrain focus. Besides, Cassegrain focus access requires the primary to be cut with a central hole. Nasmyth foci on the other hand require a tertiary mirror (M3) located above the primary mirror (M1) at the level of the elevation axis, to send the beam sideway. Gravity vector orientation variation and field derotation at the Cassegrain focus makes it challenging to design instrument supports that are stiff enough to avoid flexures and damps vibrations but not too heavy. Vibrations are therefore a threat for Cassegrain instruments, in particular for high angular resolution (AO corrected) ones. One the other hand, suppressing the Nasmyth platforms allows a much compact dome. Finally, a large number of instruments can benefit from both Nasmyth platforms at the same time, with a selection mirror located at the platform entrance. Thus the design adopted the Nasmyth foci approach.

The distance between the telescope optical axis and the Nasmyth focal plane must be larger than the primary mirror radius, plus an extra space to account for the elevation axis fork and bearings. Because this focal plane must be easily accessible and there must be enough space for diverse equipment before focus (derotator, calibration sources, telescope alignment, etc) it is important for this extra distance to be long enough. Counting M1 radius, the telescope mount and a space of 2.5 m for AO and a post-AO instrument along the optical axis, the design ended up with a required distance $\overline{M3F}$ = 5000 mm.

2.2.3 Tertiary Mirror Location

M3 is an elliptic mirror, located above the primary, inclined at an angle of 45 ^{o} wrt the telescope optical axis. It will be supported by a rotation mechanism to redirect the beam to either of the two Nasmyth platforms. If the distance between M3 and the Nasmyth foci is fixed (5000 mm), simple geometry shows that the diameter of the optical beam at the level of M3 center is given by

$$D_3^{min} = \frac{\overline{M3F}}{f_T} \tag{1}$$

where fT is the telescope overall f-number (FT=D). This diameter represents approximately the minor axis (B3) of the tertiary elliptic mirror. The major axis of M3 ellipse is given by

$$A_3 = \overline{M3F}\ \sin\frac{\gamma}{2}\left(\frac{1}{\sin\alpha_1} + \frac{1}{\sin\alpha_1}\right) \tag{2}$$

with

$$\alpha_1 = \frac{\pi}{4} - \frac{\gamma}{2}, \qquad \alpha_2 = \frac{3\pi}{4} - \frac{\gamma}{2}, \qquad \frac{\gamma}{2} = \tan^{-1}\frac{1}{2f_T} \tag{3}$$

One can see that the size of M3 is only set by the telescope f-number and the distance to the Nasmyth foci.

M3 mirror vertical height (along the optical axis) is given by A3/√2. Thus, M3 center must be at least at half this distance to M1 vertex. M3 support mechanics will require some space, and it seems reasonable to dedicate to this mechanism the same vertical space as what is taken by M3 height. In this case, the distance from M1 to M3 must be at least,

$$|\overline{M1M3}| \geq \frac{3A_3}{2\sqrt{2}} \tag{4}$$

Now initial design of the telescope mount indicates that this distance cannot be smaller than 1000 mm. Therefore, we will consider the longer of these two limit as the design value.

Note that these formulas do not take into account yet the o_-axis beam intersection with M3 plane which requires M3 to be slightly larger than the values computed here. But the difference with the later will be minor (no more or on the order of 10%), so the current values are used as a starting point.

2.3 Telescope Nominal Focal Length

DAG design must be done with the most demanding observation mode as the reference. This mode will be adaptive optics (AO) corrected diffraction limited imaging, in the near infrared (NIR). Current AO systems allow for diffraction limited imaging starting at 0.8 µm, and this is an optimistic value, for bright guide stars and excellent seeing (0.2"-0.3"). In the case of DAG, the median seeing is larger, therefore we can expect the diffraction limit to be reached at 1 µm instead.

With the telescope diameter and the knowledge of the available NIR detectors pixel scales, 27 µm (CONICA/VLT) to 7 µm (NIRC-2/KECK), we can now compute what must be the telescope focal length to make the diffraction limited PSF Nyquist sampled at 1 µm. With D_1 = 4 m, we find a PSF full-width- at-half-maximum (FWHM) of 0.25 µrad, or 51.7 masec, so the pixel size must be half this, i.e. Δx_f= 0.125 µrad or 25.8 masec. With F_T the telescope focal length:

$$F_T\ [m] = \frac{\Delta x_f\ [\mu m] * 206'264.81}{\Delta x_f\ ["] * 10^6} \tag{5}$$

it can be seen that the telescope focal length is proportional to the camera pixel size. There are good reasons to keep the focal length not too long, in particular to keep the back focal length (distance between M2 and the focal plane) at a value compatible with the 4000 mm specified for the Nasmyth plane location.

Therefore, it is reasonable to select for 7 μm the pixel size. With this pixel size, F_T becomes 56 m and the telescope f-number is $F_T/D_T = 14$. This value is typical of 4-m class telescopes.

2.4 Telescope Overall Length

Telescope length, essentially set, for a RC, by the distance between the primary and the secondary mirrors, must be limited to minimize the dome size. For 4-m class telescopes designs, tube lengths are in the range 5 m to 8 m approximately, which is basically proportional to the primary mirror focal length, then the primary mirror f-number. The shorter the telescope (the smaller M1's f-number) the smaller the dome but the more curved the mirrors surfaces therefore the more expensive the mirror machining.

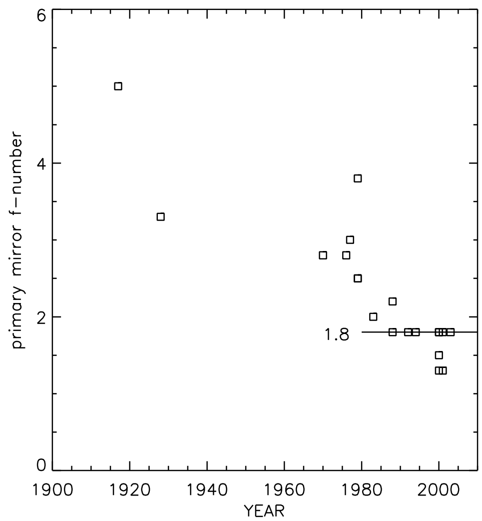

Figure 1. M1 f-number trends since 1900[1] (data taken from Ref. 1)

This being said, since the year 1980 and the venue of modern, actively controlled mirrors shape (active optics - aO), no primary mirror has been build with a f-number larger than 2 (see Figure 1), and 1.8 is clearly the norm[1], even for 4-m class telescopes. It was therefore reasonable to chose a primary f-number of 1.8 as well. Besides, dome cost goes with the cubic power of the primary focal length[1], so going for instance from 2.2 to 1.8 saves almost a factor 2 in the dome cost.

2.5 Normalized Parameters for the two Mirrors Telescope

Two mirror telescopes optical design is made simpler by the use of four so-called normalized parameters[2], defined below,

$$\left(\begin{array}{l|c} k & ratio\ {}^{D_2}/_{D_1}\ when\ the\ telescope\ FoV\ is\ 0^o \\ m_2 & ratio\ {}^{F_T}/_{F_1},\ M2\ lateral\ magnification \\ \rho & ratio\ of\ the\ radius\ of\ curvature\ of\ the\ mirrors\ {}^{R_2}/_{R_1} \\ \beta & back\ focal\ distance\ (M1\ vertex\ to\ focal\ plane)\ in\ units\ of\ F_1 \end{array}\right)$$

can’t you make it a classic table

and we will use for our design the following relations between the normalized parameters and the telescope lengths and diameters,

$$\beta = \frac{1}{F_1}\left(\overline{M3F} + \overline{M1M3}\right), \quad m_2 = \frac{F_T}{F_1}, \quad k = \frac{1+\beta}{1+m_2}, \quad \rho = \frac{m_2 k}{m_2 - 1} \tag{6}$$

2.6 Imaging Modes, Geometric Field of View and Detector Size

The FoV in AO and seeing limited modes are quite different, first the case where there's no off-axis aberrations was considered.

2.6.1 Single guide star diffraction limited AO mode

In single star adaptive optics (SSAO), the isoplanatic patch is tiny and depends on the altitude of the dominant turbulent layers and the seeing angle. Its diameter is given by the relation[3] :

$$FoV_{SSAO}[''] = \frac{6546}{\langle h \rangle\, w_0} \tag{7}$$

where w_0 is the local seeing in asec, and <h> the average altitude of the turbulent layers in m. In most locations except Antarctica, the isoplanatic patch is in the range 1" to 10". This corresponds, for a focal length of 56 m, to a linear size of the FoV of 0.27 to 2.7 mm, or about 40 to 400 pixels (if the pixel size is 7 µm.) This is easily achievable with current NIR detectors.

2.6.2 Improved Seeing Mode – GLAO

The width of the field over which a GLAO correction is efficient is on the order of several arc-minutes to several tens of arc-minutes. In DAG case, the structure of the turbulent profile is not yet known, it was wise to assume a conservative value (that works for most observatories): a corrected field of 5' (10' at most) with a corrected PSF FWHM of about 0.2".

A PSF four times larger than in SSAO means that we can have an angular pixel size Δx_f four times larger, therefore a focal length F_T four times shorter for the same linear pixel size (7 µm), i.e. 14 m. This focal length reduction can be achieved with optics added before the SSAO detector.

An other alternative is to have a GLAO dedicated camera with a larger pixel size, (28 µm) on the same Nasmyth platform, feed by a flip mirror. In the first case a 5' (10') FoV would correspond to a linear width of 21 mm (42 mm), and in the second case to a linear width of 84 mm (168 mm). In both cases the detector would be about 3'000 (6'000) pixels wide. Such detectors are available for a 5' FoV, but for 10' mosaics of detectors would be required.

2.6.3 Seeing Limited Imaging Mode

This was technically the simplest case, with potentially the largest FoV and focal plane extension. Assuming a seeing angle of 0.5" in the visible (500 nm) (because the design has to be defined by the best cases and not the worst), and a Nyquist sampled PSF, a FoV of 20' would require a detector 4800 pixels wide, and 7200 pixels for a 30' FoV. It must be noted that this number is independent of the telescope focal length: a shorter FT would only make the linear extension of the FoV smaller, but the number of pixels would remain the same. Note also that because the seeing angle is a slow function of the wavelength[3] , these values would essentially be identical in the NIR domain.

Panoramic detectors can be designed for 4800 pixels using mosaics of sub-array but 7200 pixels arrays are more challenging. Therefore the geometric (i.e without aberrations) FoV specification is set to 20' un-vignetted and 30' un-vignetted as a goal.

2.7 Off-Axis Aberrations and Practical Field of View

Off-axis aberrations are the reason why the FoV cannot be arbitrarily large, even if large detectors were available. Aplanatic (RC) telescopes have off-axis astigmatism, and focal plane field curvature (which generates defocus).

2.7.1 Astigmatism

For a RC telescope, the angular radius of the geometric astigmatism spot, as projected on the sky, is given by[2] :

$$AAS\ [rad] = \left[\frac{m_2\,(2m_2+1)\beta}{2m_2(1+\beta)}\right]\frac{\theta^2}{2f} \tag{8}$$

where m_2 and β are the normalized parameters, θ the off-axis angle, and *f* the f-number of the telescope. One can see that astigmatism increases with the square of the off-axis angle, so the FoV limitation can be very strong depending on the design and the aberration tolerancing. Astigmatism is the first cause of FoV limitation on an aplanatic telescope.

2.7.2 Focal Plane Curvature

The focal plane of a two mirror telescope cannot be flat[2], and in first approximation the surface is a sphere (of large radius). For an aplanatic configuration, the radius of curvature of the focal plane is given by

$$Rc = \frac{R_1 m_2^2(1+\beta)}{2(m_2+1)\left[m_2^2-\beta(m_2-1)\right]} \tag{9}$$

so the shorter R1, the stronger the field curvature. Today, detectors are flat, and it is not possible to bend them to fit the focal plane surface as it was done with photographic plates. As a consequence the PSF on the field edge is defocused, and objects become blurry. Field curvature is the second case of FoV limitation for a RC telescope.

2.7.3 Computation of the Practical FoV

The PSF with aberrations is computed first with a physical optics model, and the true structure of the PSF is later modeled. In fact because the astigmatism is largely dominated by the defocus we do not include (yet) astigmatism in the diffraction model but only consider astigmatism as a quadratic addition to the defocused PSF FWHM. The practical FoV will be defined as the angle for which the FWHM gets 50% larger wrt the on-axis FWHM. This is already a strong degradation and practically the off-axis Strehl degradation is more severe than the FWHM degradation. For computation, the FWHM metrics are kept.

2.7.4 Secondary mirror optical diameter and practical FoV

Because marginal rays for an off-axis source should be reflected by M2, M2 diameter must be larger than the simple diameter of the M1-reflected beam at the level of M2, and must be equal, for a FoV of angular diameter θ_{FoV}, to

$$D_2 = k\,D_1 + \theta_{FoV}\,F_1\,(1\text{-}k) \tag{10}$$

where D_1 and F_1 are the primary mirror diameter and focal length. And seeing limited FoV is the FoV value that will be used to compute M2 diameter, note that it is larger than the GLAO and SSAO FoV.

2.8 Primary and Secondary Mirrors Conic Constants

In an aplanatic telescope, the conic constants1 of M1 and M2 are chosen in order to cancel both the spherical aberration and the 3rd order off-axis coma. Expressed in terms of the normalized parameters, the aplanatic conic constants are given by

$$K_1 = -\frac{2\,(1+\beta)}{m_2^2-(m_2-\beta)} - 1 \quad (11)$$

and

$$K_2 = -\left(\frac{m_2+1}{m_2-1}\right)^2 - \frac{2m_2(m_2+1)}{(m_2-\beta)(m_2-1)^3} \quad (12)$$

For a RC the conic constants are < -1 therefore both mirrors are hyperbolic.

3. TELESCOPE OPTICS DIMENSIONING

Selection of the mirrors parameters is the result of a compromise between two contradictory requests: (1) making the telescope tube as shorter as possible to minimize the dome size; (2) increasing as much as possible the telescope practical FoV. The main tuning parameter here is the primary mirror focal length. A short F_1 makes a short telescope, but a small FoV and a primary mirror difficult to machine (i.e. more expensive). A long F_1 makes a large FoV, a primary mirror easier to machine, but a large and expensive dome.

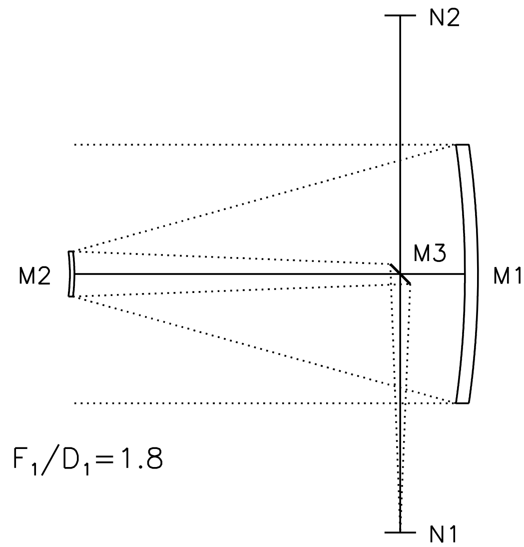

Figure 2. Optical layout for design F_1/D_1=1.8. All dimensions are to scale. N_1/N_2 are the Nasmyth foci.

Five designs in the range F_1/D_1 2 [1.6; 2] offering reasonable and cheap solutions, taking into account all the constraints and specifications discussed in the previous sections are selected. In Figure 2, a drawing to scale of our solution for the case F_1/D_1= 1.8, which we have decided to select as our nominal (goal) design is shown: this central value offers a good compromise between telescope length and dome size.

4. WAVEFRONT ERRORS BUDGETING

There are several key aspects and facts at the root of the mirrors wavefront errors (WFE) budgeting:

- M1 will be a thin mirror actively controlled in shape, in line with what is done on modern, current monolithic (plain mirrors) telescopes;
- M2 will be a mirror controlled in decentering, piston, and tip-tilt; stiffness will be ensured by thickness;
- M3 will be a at, elliptical mirror, inclined at 45_ with respect to the telescope optical axis; stiffness will be ensured by thickness;
- A ground layer adaptive optics system (GLAO) will be installed at one of the Nasmyth platform to feed science instruments with an improved seeing (0.2") over a moderate field of view (4');

- The GLAO system could be turned into a single conjugate natural guide star (SCAO) high angular resolution AO system, using the same deformable mirror and wavefront sensors;
- Seeing limited large FoV instruments (imagers, spectrographs) will be located at the other non-AO Nasmyth focus (port). aO will be active during seeing limited observation as well;
- Optical turbulence (OT) aberrations cannot be compensated by the telescope aO because turbulence time scale - on the order of 1 to 10 ms - is much faster than the aO system loop rate. In other words, OT aberrations will pass through the telescope without being affected at all.

As seen from the instruments focal plane, aberrations will be a combination of (1) optical turbulence aberrations (residual if AO is on), (2) aO-corrected telescope pseudo or slow varying static aberrations and (3) instruments internal optics aberrations.

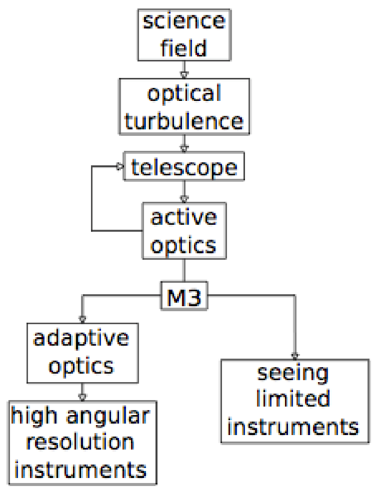

Figure 3. System's components from sky to instruments

The AO system will be dimensioned to compensate for optical turbulence aberrations, but as residual telescope aberrations will be seen by the AO system (Figure 3), these will naturally be compensated, up to the AO system's cut-off frequency (see Section 5). Now, because the AO system deformable mirror stroke is dedicated essentially to correct OT, the telescope static aberration should be kept under a reasonable level, discussed in Section 5.

Besides, telescope high order aberrations (mainly due to polishing residuals) above the AO system's cut-off frequency will not be corrected at all. These high order static aberrations therefore have to be kept under a certain level, discussed below as well.

Finally, SCAO being by far the most demanding mode in term of performance, its turbulent aberrations residual will be our point of comparison for the mirror manufacturing error budget determination.

5. ERROR BUDGET METRICS

The basic characterization metrics for optical systems performance in the context of astronomical instrumentation with AO are the wavefront error (WFE) standard deviation (or root mean square), the Strehl ratio4, the FWHM of the point spread function (PSF) and the energy proportion within a given aperture shape (slit, circle, square).

Integrated energy metrics are well adapted to spectroscopy, but not to mirror error budgeting because their relationship with the WFE is not straightforward. The same is even worse for FWHM. The relationship between the WFE and the Strehl ratio, on the other hand, is simple and direct: it is given by Maréchal's law, an approximation valid for Strehl values above 20%,

$$s \approx \exp\left(-\sigma_\varphi^2\right) \tag{13}$$

where σ_φ^2 is the variance of the phase, in units of rad^2, related to the WFE (unit nm or µm) with

$$\sigma_\varphi^2 = (2\pi WFE/\lambda)^2\ [rad^2] \tag{14}$$

where λ is the observation central wavelength, expressed in the same unit as WFE. Using Maréchal's law, a quadratic sum of WFE is equivalent to a product of Strehl ratios. Note that the relationship between any integrated energy metrics and the Strehl is close to a power law, so the better the Strehl, the better the integrated energy metrics. Therefore, for the purpose of mirror manufacturing, using the WFE and the Strehl metrics for budgeting is sufficient and also very practical because the WFE can be easily measured during manufacturing.

6. MIRROS MANUFACTURING ERROR BUDGET

An AO system is able to correct wavefront aberrations, into the entrance pupil, up to the AO cutoff spatial frequency given by

$$f_{AO} = \frac{1}{2\Lambda_{AO}}\ [m^{-1}] \tag{15}$$

where Λ_{AO} is the average distance between the actuators of the AO system's deformable mirror (DM), as seen from the entrance pupil plane. This spatial cutoff frequency separates the WFE into two components, the low frequency and high frequency ones. A preliminary study of DAG AO modes (single conjugate and ground layer AO) made us conclude that the best DM actuator pitch is, as seen from the entrance pupil plane, equal to 40 cm. Therefore, phase aberrations at scales larger than $2\Lambda_{AO} = 80\ cm$ are (partially) corrected by the AO system, while structures at smaller scales cannot be corrected.

6.1 Low Order Wavefront Error Mirror Specifications

As stated above, telescope residual static error will be seen by the AO system wavefront sensor (WFS), therefore the AO system will automatically try to compensate for these static aberrations by applying an offset to the DM commands. The DM mirror has a limited stroke, though, so an offset is acceptable only if it is significantly smaller than the DM stroke dedicated to the correction of OT.

When dimensioning a DM for OT correction, a stroke equal to five times the standard deviation (RMS) of the turbulent wavefront (which has a Gaussian statistics) is usually chosen, in order to minimize the occurrence of DM saturation. It is therefore generally required for the offset stroke not to be larger than a fraction of the turbulent wavefront RMS.

Table 1: Telescope Zernike modes specification for radial orders 2 to 11

n	J - indexes	$\lvert a_j \rvert$ spec	nm goal
2	5-6	14.6	7.3
3	7-10	7.5	3.8
4	11-15	4.7	2.4
5	16-21	3.3	1.7
6	22-28	2.5	1.2
quadratic sum to a_{29} to a_{78}			
7-11	29-78	9.3	4.7
total error nm		31	15

In the case of DAG's telescope AO system (see Figure 4), a pitch Λ_{AO} of 40 cm allows for about 80 actuators regularly spaced inside the 4-m entrance pupil. Assuming that the DM is flexible enough, it would be possible to compensate for all the Zernike polynomials up to index $j_{max}(80) = 79$ or radial order $n = 11$ (see Eq. below) that we can limit to 78 (last polynomial of the nearest radial order, $n = 11$).

$$j_{max} = 2\frac{N_{act}}{\pi} + 5\sqrt{\frac{N_{act}}{\pi}} + 3 \tag{16}$$

where maximum number of Zernike modes that can be adjusted with Nact actuators over a infinitely exible mirror is presented.

Because the overall RMS of a wavefront error expressed in terms of Zernike coefficients is given by the quadratic sum of the coefficients, we find that the overall low order WFE must be less or equal to 31 nm, and 15 nm goal. Then, Maréchal's law gives an associated Strehl ratio of 86% in the visible (at 500 nm) for the specification, and 96% for the goal. The first value is easily achievable, the second is more challenging.

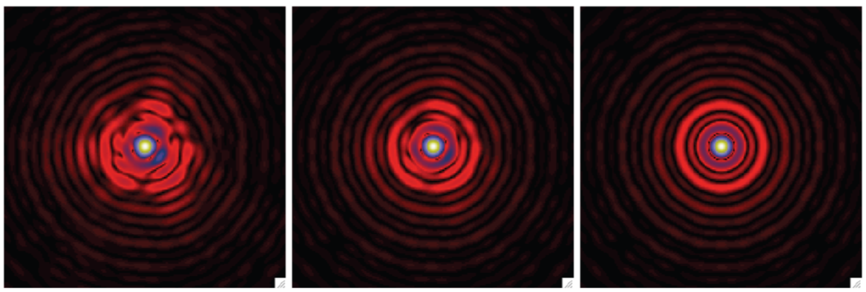

Figure 4: Left: simulated random realization of the telescope PSF at 500 nm in accordance with the WFE specification; Center: same, for the goal; Right: perfect telescope PSF. Central obscuration 0.7/4. The square root of the PSF is shown to increase the wings contrast

Telescope PSF at 500 nm simulated using the wavefront errors given in Table 2 are shown in Figure 4, for illustration. The sign of the Zernike coefficients were chosen randomly. It is important to remember that these aberrations will in principle not affect the performance in AO mode, as these will be compensated by a DM offset. In seeing limited mode, though, these aberrations will not be corrected, but will be largely dominated by the non-corrected OT anyway: to give an order of magnitude, the seeing limited PSF FWHM will be at least 20 times larger than the telescope PSF FWHM.

6.2 High Order Wavefront Error Mirror Specifications

Let us now discuss the high order aberrations, i.e. the ones at spatial scales smaller than $2\Lambda_{AO}$. These aberrations, generated by a residual wrap of the telescope optics and manufacturing residuals (polishing, mirror sup-ports print-through), cannot be corrected at all by the AO system. They are on the same spatial scale domain as what is called fitting error in AO.

Fitting error comes from uncorrected OT aberrations at scales under $2\Lambda_{AO}$. It is well described using the so-called structure function (SF) tool, which is a measure of the mean square difference of the phase between two points in the pupil, separated by a vector Δ_u

$$D_\varphi(\Delta_u) = \langle[\varphi(\Delta_u + r) - \varphi(r)]^2\rangle_r \tag{17}$$

where the average is taken over each point inside the entrance pupil. It is important to note that

$$D_\varphi(0) = 0 \tag{18}$$

and

$$D_\varphi(\infty) = 2\sigma_\varphi^2 \tag{19}$$

Note that Zernike polynomials are not practical to describe the high order aberrations, as an infinite number of coefficients would be required: the SF approach is preferred here.

When the AO system is working in favorable conditions, i.e. when the guide star is bright and the wind is slow, the performance of the system is essentially limited by the fitting error (WFS aliasing is another error but lower than the fitting error, and in this context can be ignored). As a consequence, it is important that the high order mirror error stays at a lower level than the residual uncorrected OT aberrations. If we consider the favorable case of a 0.5" seeing, and a DM pitch of 0.4 m, we get a fitting error of 68 nm (see Section 6.1 for computation). What we require is that the Strehl decrease due to the high order mirror error should not be more than 0.95 (goal 0.98) in J-band (1.25 μm), which is the shortest AO wavelength we are probably going to use at the beginning.

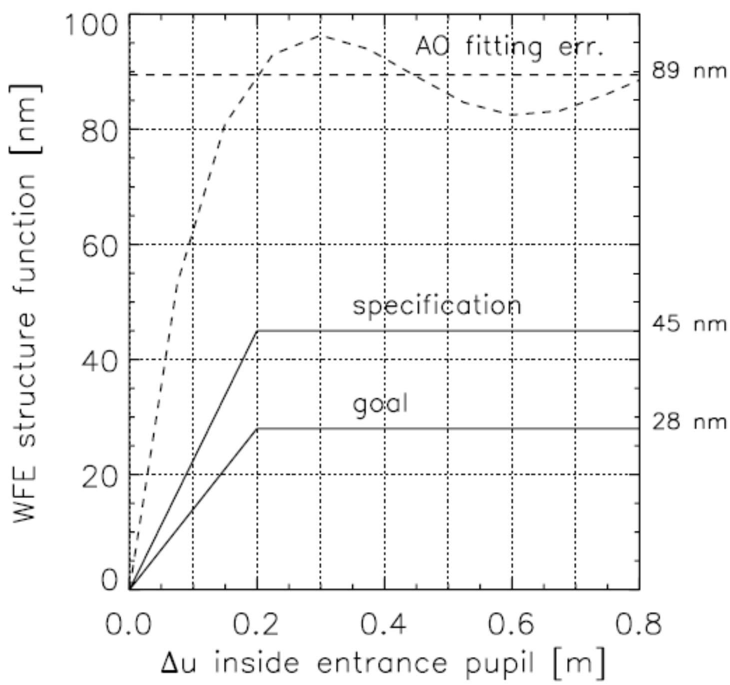

Figure 5: Specification and goal for the structure function wavefront error of the three mirrors combination, at high spatial frequencies, in the range 0 to 0.8 nm. Dashed line shows the AO fitting error SF, for comparison

Because the high order WFE of the mirrors is in principle isotropic and homogeneous over the entrance pupil, the specifications/goal given in Figure 5 have to be understood as independent of the orientation of the separation vector Δ_u.

7. SUMMARY

In the optical design of DAG telescope, the specification not to excess a total length of 10 m for the telescope is easily met. The maximum length ($\overline{M1M2}$) is 6.5 m. The FoV in seeing limited mode is about 10' when considering the PSF FWHM degradation, but is half smaller when considering the Strehl degradation. This is typical for RC designs and cannot be much larger. This FoV already corresponds to a CCD array imager size of about 2400 pixels (or 1200 px for the 5' FoV) if we consider a typical seeing of 0.5". A solution to increase the FoV is to build mosaics of CCD arrays, and these CCD arrays can be adjusted to follow the field curvature surface, so the seeing limited FoV can actually be significantly larger than 5' or 10'. In GLAO mode, the FoV is about 6' and will actually be limited more by the turbulent isoplanatic patch, which is in principle smaller than this, than by off-axis defocus.

8. ACKNOWLEDGMENTS

The authors acknowledge the support of State Planning Organization of Turkey, FMV Işık Universitesi, Atatürk Üniversitesi, Orta Doğu Teknik Üniversitesi, and Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud for their technical and financial support .

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