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TROIA Adaptive Optics System for DAG Telescope

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ABSTRACT

This paper presents the specifications of TROIA - TuRkish adaptive Optics system for Infrared Astronomy system, the science rationale for these specifications, and description of the site technical and environmental conditions to be taken into account in the adaptive optics (AO) system design for the Eastern Anatolia Observatory - DAG telescope. With it's 468 actuators, EMCCD camera, and the pyramid wavefront sensor configuration; TROIA is able to adapt the degree of correction to a given guide star (GS) brightness during observations. The high actuator density of TROIA AO system will allow DAG to perform astronomical observations at ExAO performances.

Keywords: Adaptive Optics, TROIA, DAG Telescope, Pyramid WFS, ExAO

1. INTRODUCTION

TROIA, already built and delivered to Ataturk University Astrophysics research and Application Center (ATASAM), is the first Turkish AO system. The objective is double and ambitious:

Allowing high resolution astronomy: seeing limited angular resolution is about 1", but 20 times better with a 4 m telescope with adaptive optics correction. The potential science gain is enormous.

Adaptive optics development: developing AO knowledge in universities in Turkey in order to offer this capabilities to the national astronomical community. At first light, DAG will be equipped with an AO system using natural guide stars (NGS). While laser guide stars (LGS) are highly desirable to maximize the sky coverage, AO laser technology is at a level of complexity that would be too difficult to handle on a first AO project. This shall be kept for a future upgrade of the system. TROIA is based on a flexible concept, where the number of corrected modes (aberrations) is systematically adapted to the atmospheric conditions and NGS brightness. This is possible thanks to the use of a 468 actuators deformable mirror (DM) and a pyramid based wavefront sensor (PWFS). In good conditions, Strehl ratio (image contrast) in the range 80 % to 90 % in the near infrared (NIR) will be achievable, while a decent Strehl ratio, allowing science data acquisition, will be accessible in moderate to bad seeing conditions. In this report, the specifications of TROIA system, the science rationale for these specifications, and description of the site technical and environmental conditions to be taken into account in the AO system design are presented.

Science Rationale

DAG first generation instruments

DAG first generation instruments will consist in a 30" FoV near-infrared (NIR) diffraction limited camera and a stellar coronagraph.

An AO infrared imager on a 4 m telescope can support a broad range of scientific interests needing high-definition NIR imaging: from low-mass star and exoplanet search and characterization to studies of star-formation in the Milky Way and nearby galaxies, as well as analyses of intermediate and high redshift galaxies, including imaging of electromagnetic counterparts to gravitational wave detections.

An AO based stellar coronagraph is the most suitable instrument to study nearby stars circum-stellar environment (proto-planetary discs, hot Jupiters etc.) DAG coronagraph will use a novel concept of star light suppression, using a

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programmable spatial light modulator (SLM) which can adapt to the structure of the star system, i.e it can suppress light from a multiple star system in one run, opening a completely new way of exploring stars' immediate environment.

The need for a flexible AO system

The AO coronagraph requires a high quality optical beam, i.e a Strehl ratio higher or equal to 80 % in the K-band (2.16 µm) and a beam tip-tilt of less than 20% of the diffraction limited point spread function (PSF) full-width at half-maximum (FWHM). An AO system tailored for coronagraph science therefore requires a high order wavefront sensor (WFS) and deformable mirror (DM) to get an excellent correction level. This is turns requires bright natural guide stars (NGS), of visual magnitude 10 or lower.

A system tailored for coronagraph science will not be suitable for the more general NIR camera science cases introduced above, which require observations over a FoV quite larger (30") that the maximum 7" coronagraph FoV. Indeed, in order to run an AO observation (other than coronagraph) with the NIR camera, a NGS must be found inside the camera FoV. Now the probability to find a star of a given magnitude in a given FoV goes approximately as $10^{mV/2}$. AO correction is still significant with NGS magnitudes up to 14-15, if the seeing is not too bad. Therefore, the probability to run an AO observation is at least 100 times higher with a 15^{th} magnitude star than with a 10^{th} magnitude star.

Optimal observation with a 15^{th} magnitude star requires a decrease of the number of corrected modes, because the lower the NGS photo flux, the higher the photon noise, therefore the lower the correction quality. This performance drop can be compensated by lower the number of corrected modes, i.e lower the degree of freedom of the system. Therefore, for a given NGS magnitude, there is always an optimum in the number of modes that must be corrected.

In order to allow both coronagraph and classical NIR imaging, DAG AO system must be able to adapt the number of measured and corrected modes to the NGS visual magnitude.

This is impossible if we use a WFS where the spatial sampling is fixed, as with a ShackHartmann system. A SH-WFS has a fixed number of optical lenslets, sampling the beam at a fixed spatial frequency. Changing the sampling period requires a change of lenslet array. This is very cumbersome, as this would require a realignment of the WFS. Besides, it is out of the question to have specific lenslet arrays for each desired sampling period, this would be very expensive.

The solution is to use a Pyramid type WFS[1]. Such system allows an adjustment of the spatial sampling in the pupil plane, because the sampling is done on a pixelized detector array (CCD), and pixels can be binned numerically at will. Moreover, a P-WFS is more light sensitive, and a gain of at least 1 visual magnitude can be expected wrt a SH-WFS system. It is also less sensitive to spatial aliasing than a SH-WFS.

Now, binning has its limitations, as the sampling period is necessarily limited to a few values: it is not possible to generate an arbitrary period by binning a fixed number of pixels across a fixed pupil diameter. Only if the sampling can be done numerically, using a resampling of the signal, can the sampling period be chosen at will. This require a very low noise detector, but today such devices are available, thanks to the electron-multiplied CCD technology (EM-CCD). Such systems have an electron multiplication stage before the reading amplifier, allowing to strongly increase the signal level with respect to the amplifier noise, leading to almost no (relative) noise.

The other strong advantage of a noiseless detector is that it allows an oversampling of the pupil without added noise, allowing a very significant relaxing of the required machining accuracy of the pyramid prism of the P-WFS[2], as the position of the 4 pupil images can be realigned numerically without loss of information.

To conclude, DAG AO system shall integrate the following elements:

- a high order deformable mirror to allow coronagraphic observations
- a pyramid wavefront sensor to allow a adjustment of the pupil plane sampling
- a noise-less detector to allow an arbitrary sampling period and a relaxation of the pyramid prism manufacturing specifications.

2. SELECTED DEFORMABLE MIRROR

The contractual requirements at the beginning of the project were: single DM system, conjugated to the telescope entrance pupil (M1); natural guide star (NGS) based system; single pyramid wavefront sensor; classical AO control, with update towards a flexible control; and all components are based on proven and available technology.

In terms of applied methodology; the main parameter of a classical AO system is the DM inter-actuator distance (pitch). The selection method is the following :

- explore the Strehl performance of the AO system as a function of the DM pitch for a range of NGS magnitudes up to 18;
- for each magnitude, optimize the wavefront sensor integration time (i.e the loop frequency) to get the best possible Strehl;
- we then have a set of cases between two extremes : small pitch, excellent Strehl for bright NGS but low limiting magnitude, and large pitch, low Strehl but high limiting magnitude;
- we select the DM that allows the best Strehl, and a pyramid wavefront sensor to allow for an adjustment of the spatial sampling as a function of the guide star and seeing conditions; then using the flexible concept, we can adapt the number of corrected modes to the PWFS measurements (only the modes with a high enough signal/noise ratio are corrected).

Once the DM pitch is selected, the next steps are:

- compute the required DM stroke and the required tip-tilt mirror stroke in case tip-tilt is corrected using a dedicated mirror,
- design the PWFS (tip-tilt modulation mirror, pyramid prism, relay lens, detector),
- define the AO computer requirements,
- define the wavefront error (WFE) budget for each element of the system (hardware and algorithm),
- finalize the optical design.

The central parameter of an AO system is the DM actuator pitch[3], but there is no absolute optimal choice for this parameter: it depends on the light flux available for wavefront sensing. If a bright NGS is available near the science object (which might be used as the NGS) it becomes possible to finely sample the wavefront with a large number of lenslets, as there are enough photons to get a wavefront measurement with a good SNR. Therefore we could use an equivalently large number of actuators.

On the contrary, if the NGS is faint, we need to increase the light flux by selecting a larger lenslet, and we end up with a coarser sampling. The optimum pitch value is therefore the one that offers a decent correction while allowing the use of relatively faint NGS, to get a good enough sky coverage.

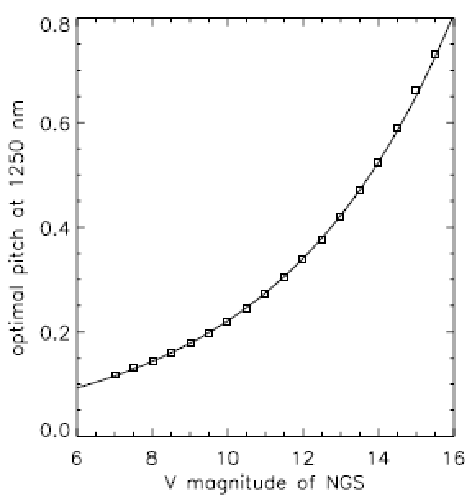

Figure 1: Optimal DM pitch in meters, as projected in the entrance pupil plane (M1) and NGS V magnitude.

To evaluate the effect of the NGS magnitude and DM pitch, we computed with PAOLA the Strehl for these parameters in the ranges indicated in section 5. The WFS integration time was optimized to maximize the Strehl at each magnitude. A SH WFS was considered for simplicity, but the limiting magnitude for a P-WFS would only be better. The results are shown in Figs. 2 and 3.

We can seen that for a given pitch, the Strehl decreases with the magnitude, as expected. If we plot the Strehl as a function of the pitch, for a given NGS magnitude (Fig. 3) we see that there is an optimal pitch, for which the Strehl is maximal. Indeed, the smaller the pitch, the lower the residual wavefront error (what we call the DM fitting error in the AO jargon), but on the other hand, the smaller the pitch, the smaller the amount of light per actuator (or WFS lenslet) then the larger the measurement noise. So, for a given guide star magnitude, there is an optimum pitch size, balancing the WFS noise and the fitting error, as illustrated in Fig. 1.

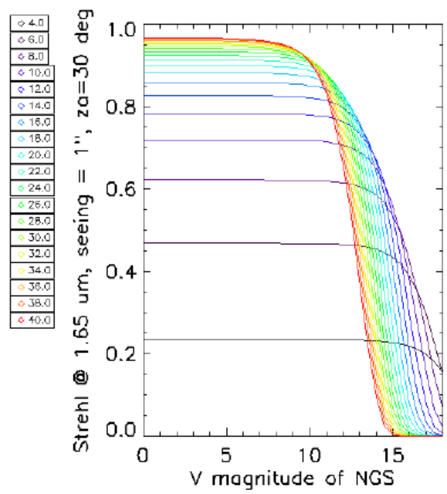

Figure 2: Strehl ratio as a function of the NGS V band magnitude for an increased number of lenslet across the pupil diameter (indicated). Wavelength is 1650 nm.

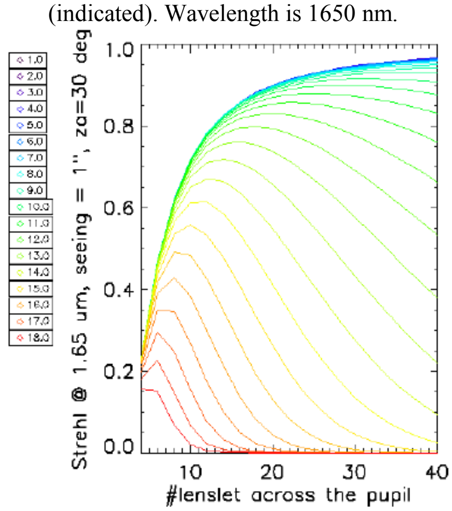

Figure 3: Strehl ratio as a function of the number of lenslet across the pupil diameter for increased NGS magnitudes (indicated).

Starting with 78 modes, we have 10 actuators across the pupil diameter. If we double this to 20 actuators, then we get 312 modes, which is essentially an Extreme AO regime (H-band Strehl of 0.9 according to Fig. 2), allowing excellent angular resolution and contrast. ALPAO (France) are selling DM with many actuators, up to 820. We show have computed the Strehl ratio in the R-I-J-H-K-L bands for a seeing angle of 1" (median) and 0.5" (best), for all the actuators options shown in the table above (from 88 to 820 actuators), considering a bright star, allowing to neglect the effect of the photon noise (which is acceptable in this first order model). The results are shown in Fig. 4.

We can see that there is basically very little difference of performance and cost between the two cases 88 & 97, and the same is true for the two cases 241 & 277. If we were selecting ALPAO as the DM provider, then the basic (low order) system would require the DM-97, and the high order choice would have to be done between the DM-277 and the DM-468. With the former, it is not possible to do ExAO below K-band in median seeing conditions. With the later, it is possible in H-band. In the best seeing case, the DM-468 allows ExAO at 1 μ.

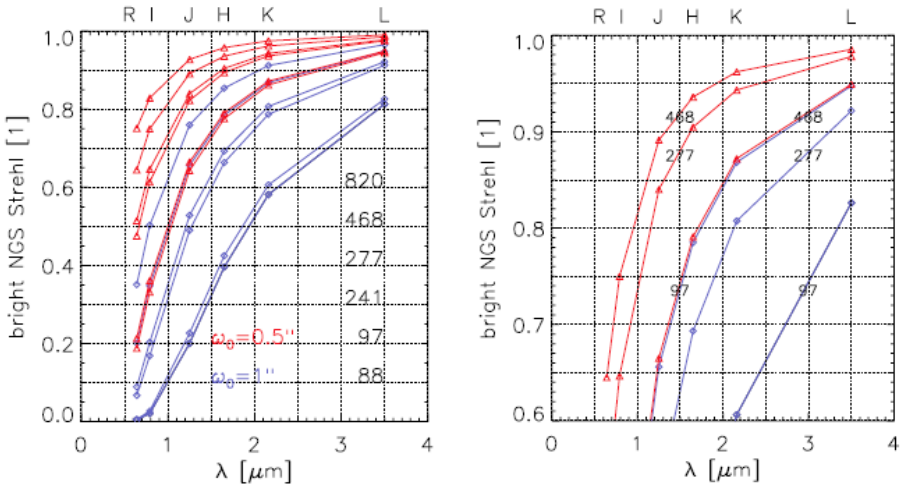

Figure 4: Left : Strehl versus wavelength and number of actuators, for a bright NGS (V=0) for the median and best seeing. Right : zoom on the Strehl above 60%, and for the three selected DM 97-277-468. Note that L-band is beyond the current scientific bands selected for DAG.

Therefore, we have selected ALPAO 468 actuators deformable mirror for DAG AO system. The number of modes that will be corrected will be defined by the AO control computer, on the basis of the NGS magnitude and seeing conditions. This DM, with its high density of actuators, will allow both coronagraphic and NIR imaging science. The DM compliance matrix (Table1) and array of actuators is shown in Figure5.

Table 1: Standard specifications

Property	Specification*	Result	Unit	Pass/Fail
Mirror best flat, residual error	<7	2.10	nm RMS	Pass
Linearity	<3	0.18	%	Pass
Hysteresis	<2	0.87	%	Pass
Peak frequency	>2000	2783	Hz	Pass
Frequency at -45° phase	>1500	2632	Hz	Pass
Settling time	<0.5	0.29	ms	Pass

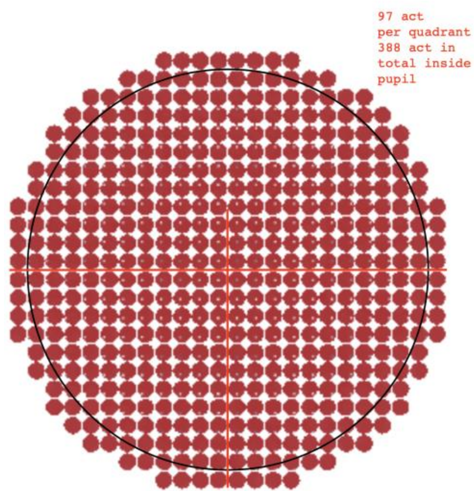

Figure 5: Left : Strehl versus wavelength and number of actuators, for a bright NGS (V=0) for the median and best seeing. Right : zoom on the Strehl above 60%, and for the three selected DM 97-277-468. Note that L-band is beyond the current scientific bands selected for DAG

3. SELECTED WAVEFRONT SENSOR SUB-SYSTEM

The P-WFS detector

Number of pixels The DM has 22 actuators intervals (pitch) across the pupil. Therefore 22 pixels per pupil image would be needed on the detector. Now because the pyramid prism manufacturing tolerance is relaxed, to oversample by a factor 1.5^2. Therefore, 33 pixels/diameter are required, which becomes 66 and 73 as the pupil images needs to be separated on the detector. The most affordable EM-CCD in the market with at least this number of pixels is the camera from the company NUVU, Québec, Canada. This camera has been selected as the P-WFS detector. The camera(s) characteristics are the following :

- frame size 128-by-128 (suits our needs).
- full 128 frame read at 1 kHz.
- read-out-noise (RON) RMS < 0.1 e/px.
- technology based on EM-CCD (electron multiplied CCD); the EM gain is a random variable with known mean and RMS, and this is equivalent to multiply the photon noise variance by a factor 2 (approximately), which is not an issue because with other cameras RON is the main issue, not photon noise, so be removing RON we gain a lot in sensitivity.
- binning to improve RON is useless, because RON is essentially zero.
- air or liquid cooling available.
- camera for AO : detector cooled to -60° .
- GUI is delivered with camera.
- there is a SDK library in C++ language to implement our own codes. • works on Linux and Windows platform.
- size 150-by-150-150 mm.

The P-WFS tip-tilt modulation mirror

Circular modulation of the NGS image around the apex of the pyramid prism is done with a tip-tilt mirror (TTM) positioned in the pupil plane. The specifications of the TTM are given below

Dimensions and incoming beam angle

pupil diameter on the TTM	9.987 mm
NGS beam incidence angle wrt the normal of the TTM	20º
size (diameters) of the elliptical footprint of the NGS beam on the TTM	10.549 mm & 9.987 mm
mechanical size after adding 10% to avoid edge defects	11.721 mm & 11.097 mm

Oscillation maximum angle

According to the analysis done with YAO (see SPIE 2018 AO paper), the maximum modulation off-axis angle we need is 0.25" on sky. This is the optimal value for a seeing of 1.5". The TTM has to be located in an image of the pupil (the AO design provides this). Because this is an angle in the pupil, the TTM modulation angle has to be adjusted for the TTM diameter (Lagrange law). The entrance pupil diameter is 3940 mm, so we get

$$\theta_{tt,opt} = 3940/9.987\ (0.25'') = 98.628'' = 478.163\ \mu\text{rad}$$

now taking into account the fact that the mirror doubles the incidence angle of any ray, we need to divide this by 2, so the required off-axis mechanical modulation angle has to be equal to

$$\theta_{tt,mec} = 49.314'' = 239.082\ \mu\text{rad}$$

TTM manufacturers prefers to specify the mirror angles in µrad therefore we may as well round this specification to 250 µrad.

Oscillation angle accuracy

The TTM shall generate a sin/cos oscillation in both x/y axis. Any error in the position of the beam generates an excess or a lack of time spent on each quadrant, with an immediate proportional impact on the estimation of the signal amplitude, then on the aberrations amplitude measurements.

If we set that the 3-σ error on the angle shall be no more than 1%, which induces a 3-σ error of the wavefront amplitude (for instance 10 nm for an input wavefront of 1000 nm), then,

$$3\ \sigma\theta/\theta_{tt,mec} \leq 0.01 \qquad \text{i.e} \qquad \sigma\theta \leq 0.833\ \mu\text{rad}$$

i.e we want that 99.73 % of the time the angle stays within ± 2.5 µrad of the required angle, assuming that the angle error has a centered Gaussian statistics.

Center of rotation

Ideally, the center of rotation must be located on the vertex (center) of the mirror. But this is not possible because the tip-tilt stage actuators attachment points are not co-located with the mirror surface, but a few mm below.

If the mirror has a thickness of e and if the distance between the pivot point and the platform is h, then, for a tilt angle θ, the displacement of the mirror vertex along and perpendicularly to the optical axis (Δz, Δx) is given by

$$\Delta z = (e + h)\ (1 - \cos\theta)\ \Delta x = (e + h) \sin\theta$$

Typical mirror thickness is 5 mm, and according to preliminary discussions with TT PI stages providers, the pivot point is 4 mm below the platform. For an angle of 250 µrad, we find

$$\Delta z = 0.28\ \text{nm}\ \Delta x = 2.25\ \mu\text{m}$$

in other words the effect is completely negligible.

Oscillation trajectory

The command in θ_x shall follow a sinusoidal function at the specified frequency (max 1.5 kHz) and amplitude (max 250 µrad). The command for the other angle θ_y shall have a phase of π/2 with respect to the other axis, in any direction (leading or trailing) as the direction of rotation has no influence on the wavefront sensor data acquisition.

Oscillation frequency

The beam has to make an integer number of turns during one exposure. The specification is 1 kHz, and the goal is to make it possible to run at 1.5 kHz. The error on the driving frequency must be less than 1 Hz.

Transient response time

The mirror will work in a stationary regime, in a sense that wavefront sensor data acquisition will start only after the specified oscillation frequency and amplitude is reached. The transient time, defined here as the time for the mirror angle to be within ±10% of the specified value, an be up to 10ms, as this is not a critical parameter. After a time not much longer than 10 ms, the mirror angle error shall be no more that the value specified in oscillation angle accuracy.

Mirror mechanical diameter

According to the table at page 10, the mechanical diameter must be larger than 11.7 mm, say 12 mm, or 1/2-inches.

Mirror surface quality

A wavefront RMS value of $\lambda/20$ is enough, corresponding to 30 nm RMS at 600 nm, which is the central wavelength for WF sensing. This WFE applies to a diameter of 10.549 mm centered on the mirror. The rest of the mirror, on the edges, can have a larger WFE. The mechanical, surface error RMS must be therefore 15 nm.

Mirror scratches and digs

Specification 40-20 scratch-dig or better.

Mirror coating specifications

The coating shall allow a transmission above 90 % in the range 500 to 900 nm, for a normal incidence. Besides, the coating shall be able to keep its reflectivity for more than 5 years, ideally 10 years, and it shall be easy to clean its surface.

Specifications summary

maximum mirror mechanical angle	250 µrad
mechanical angle accuracy	≤ 0.8” µrad (3-σ)
trajectory	Circle
center of rotation	can be below the mirror vertex
rotation frequency (1 turn)	1 kHz and 1.5 kHz as a goal
transient response	max 10 ms
mechanical diameter	app. 12 mm (more than 11.7 mm)
surface error RMS	15nm
mirror scratch digs	40-20
mirror coating	≥ 90% refl. 500-900 nm, 10 years.

Selected tip-tilt mirror and gimbal mount

After a market study, it has been decided to buy the TTM model S-331K025 from Physik Instrumente (PI) GmbH (Karlsruhe, Germany). This TTM is itself mounted on a gimbal system allowing a selection of the NGS in the AO system 1’ FoV to align it on the prism apex, before modulation. The gimbal mount that is selected is the model 8816-RC from Newport, Inc.

4. OPTICAL TURBULENCE CONDITIONS AT THE SITE

Seeing angle

A seeing monitor is installed at the site (MASS/DIMM system) and produce data with more and more regularity. Beside, James Osborn (University of Durham, UK) has kindly offered to run his seeing prediction model, using satellite weather data acquired during 1 year. Fig. 6 shows local seeing measurements and Osborn’s model seeing prediction for a full year. The predicted and measured seeing distribution are in close agreement, even if the local measurement data set is limited.

From Osborn prediction, it is possible to estimate that the median seeing at the site is 0.9". The best ever seeing is 0.3", and the worse can be higher than 3". AO design shall be done using the median value.

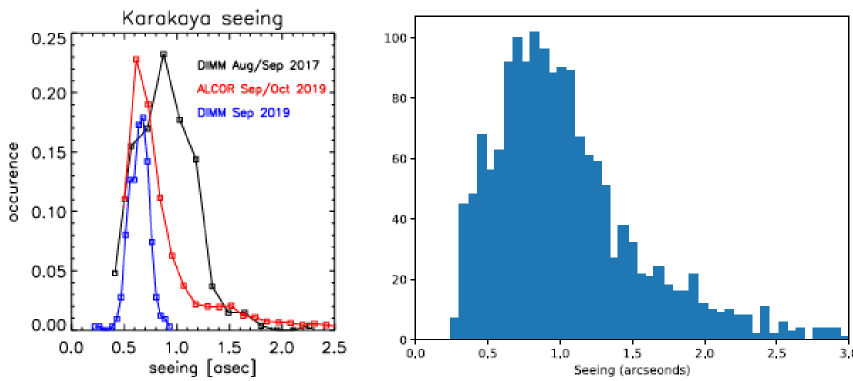

Figure 6: Left : local seeing data distribution for several nights in Autumn. Right : Osborn model seeing prediction for the site.

Coherence time, isoplanatic angle

The coherence time of optical turbulence is defined as the average time after which the turbulent phase RMS as changed by more than 1 rad. It is an indication of the typical period with which the AO loop must be refreshed. Osborn data shows that the loop period shall be between 1 and 10ms, i.e the loop control frequency shall be in the range 100 Hz to 1’000 Hz. This is in line with classical AO loop frequency values.

The isoplanatic angle is the angular field dimension across which the phase difference is 1 rad maximum. It is an indication of the size of the FoV over which the AO correction will remain relatively similar. On average, it is 2.3" for the site, which is typical for good sites.

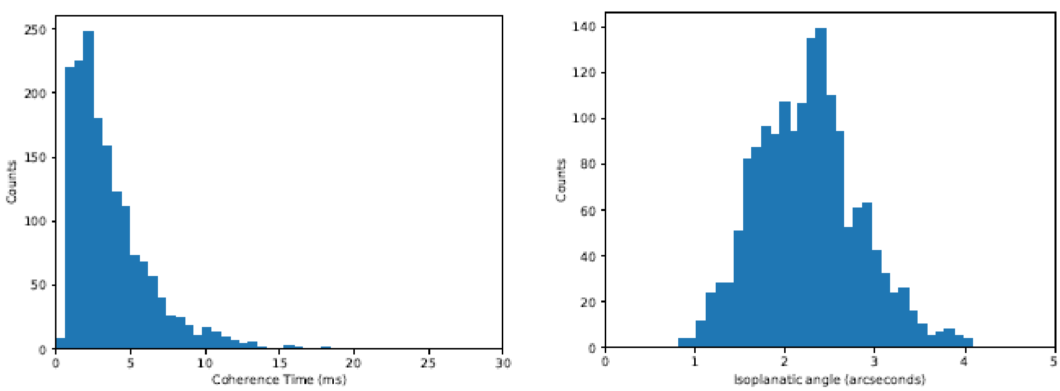

Figure 7: Left : coherence time distribution over 1 year; Right : isoplanatic angle distribution over 1 year.

5. ADAPTIVE OPTICS SYSTEM SPECIFICATIONS

Opto-mechanical design specifications

- The optical design of the system shall limit its size on an area of approximately 1 square meter. The optical fiducial are indicated in Table 1. The AO system shall be installed on an optical table with at least passive damping legs, attached to the Nasmyth platform. The attachment threads on the table will be on a 25 mm square grid.
- The total static WFE RMS without considering the corrective effect of the AO loop must be lower than 200 nm.

- In the domain 600 nm to 900 nm, and up to the WFS detector, the system shall be achromatic, and compensate atmospheric dispersion down to a zenith distance of 70°.
- The pyramid prism shall be a double prism, achromatic in the WFS range 600-900 nm.
- The beam splitter (BS) shall separate the WFS light and the science light at 900 nm. Astigmatism generated by the BS shall be compensated by design (wedge).
- It must be possible to insert, after the BS and in the science beam, a pick-up mirror to send the light to a phase diversity camera, this in order to track non-common path aberrations, and correct them with a DM offset. The phase diversity camera is NOT part of the delivery.
- The science beam shall transmit light up to the end of the K-band.
- Alignment of the system shall be facilitated by using x-y-z-θx-θy adjustment supports as much as possible for all components of the loop.
- Off-the-shelf commercial components shall be selected as much as possible. Optical performance shall be met within a temperature range of 10◦C to 20◦C.
- Exit relay optics shall be selected such that it allows the installation of a set of two pick-up mirrors to send the beam to the coronagraph, and get back the filtered beam to the AO exit optical axis, then send the beam to the NIR camera input.
- Total throughput of the system shall be ≥ 50% in the science arm, and ≥ 30% in the WFS arm.

Control system functionalities

- The loop shall be able to run at a maximum frequency of 1500 Hz.
- Total technical time lag shall be ≤ 0.2 ms.
- The command law shall be an integrator.
- The loop gain and the loop frequency shall be adjustable from a MATLAB, IDL or Python graphical user interface.
- Static calibration of the WFS using a known defocus of the camera shall be possible: the WFS shall be able to reconstruct the wavefront in true optical units (nm).
- Measurement of the interaction matrix shall be possible, and the control software shall compute the command matrix automatically.
- The number of Eigen modes to correct shall be selectable by the user.
- A graphical user interface shall allow an intuitive control of the DM and the AO parameters, and the performance of the AO system shall be displayed in real time.

The details of how the pyramid signal must be read and what are the computer specifications for the wavefront reconstruction are described in the next sections.

Control computer and WFS signal reconstruction from detector pixel data

From the point of view of control, DAG AO is a digital closed loop system (Fig. 8) running at 1.5 kHz (maximum). The error sensor is an optical device (wavefront sensor - WFS) whose output is a vector of real numbers, and the device that is driven is a deformable mirror (DM). The control law is in general a pure integrator, but more sophisticated control scheme can be implemented (Kalman control etc.)

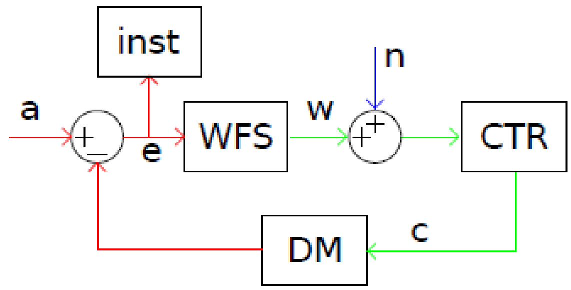

Figure 8: AO loop components. "a" is the atmospheric optical turbulence modes vector, "c" the commands to the DM to compensate "a", and "e" the error vector. Red lines indicates optical quantities, green is for electrical signals, and photon and read noise "n" are blue. "inst" is the science instrument receiving a corrected optical beam. CTR is the control algorithm box, where the raw WFS measurement vector "w" is transformed into a DM command via a control matrix and a control law.

The P-WFS is a slope sensor

The response of the sensor at low spatial frequency is proportional to the wavefront slope, while it is proportional to the wavefront at high spatial frequencies. The limit between the low and high spatial frequencies is typically given by

$$fc = 5/D \ m{-1}$$

where D is the telescope diameter[4]

The raw signal

the raw signal is made of 4 circular illuminated discs, images of the pupil, named A, B, C, D (1st, 2nd, 3rd and 4th quadrant). The local wavefront slope on a pixel of coordinate i, j is given by

$$s^x_{i,j} = a\frac{A_{i,j} + D_{i,j} - B_{i,j} - C_{i,j}}{A_{i,j} + D_{i,j} + B_{i,j} + C_{i,j}} \qquad s^y_{i,j} = a\frac{A_{i,j} + B_{i,j} - C_{i,j} - D_{i,j}}{A_{i,j} + D_{i,j} + B_{i,j} + C_{i,j}}$$

where a is a calibration constant which depends on the modulation angle.

In principle there must be 1 pixel / actuator pitch but in the case of DAG AO we need an oversampling of a factor 1.5, so with 468 actuators, with 22 pitch across the pupil, we get 33 pixels. Because we want to separate the 4 pupil images, 20% of the pupil images diameter is enough, so we end up using a square of 66+7=73 pixels on the camera.

AO computer main sequence of operations, from WFS read to DM update

By main sequence we mean the data flow that shall not be interrupted by any other processes. It starts with the reading of the WFS detector pixels, and ends when sending the commands to the DM. An interruption (data flow or time) in the line would most probably make the AO stop working. We give below the sequence of operations (this might evolve somewhat during the next steps of the loop design but not much).

1. reading the wavefront sensor CCD 128-by-128 pixels detector, or most probably reading the 73-by-73 pixels area is enough;
2. once the WFS detector is read, start a new WFS exposure;
3. selecting the four circular regions-of-interest (ROI) of diameter 33 pixels on the CCD image;
4. arranging the pixels in the four A to D images in a set of four vectors (~a to ~d) of about 855 values each (number of pixels in each pupil);
5. computing the following signals (vectors of 855 values) where the division is component wise (component per component)
6. concatenate the two vectors into a single vector of 1710 values (floating double precision)

7. store the new value of S~ in memory; this can be a parallel process, done while the other operations are executed; this telemetry storage shall not interrupt the main data flow;
8. apply a matrix of 468-by-1710 (lines/columns), where 468 is the actuators count, to the S vector and get the error vector, with 468 DM residual commands; in reality the DM commands will not be actuators commands at this stage but modal commands;
9. apply a filter vector of dimension 468 to the modes coefficients; this filter will be precomputed from an off-line optimization algorithm that makes use of the saved telemetry to get the best modal gains as a function of the turbulent and natural guide star conditions;
10. store the residual commands vector; this can be a parallel process, done while the others operations are executed; this telemetry storage shall not interrupt the main data flow;
11. compute the deformable mirror command by applying the following integrator control law to each of the 468 components of the residual error

    $$c_i = c_{i-1} + g_m r_i$$

    with gm the gain that depends on the component; possibly, a more sophisticated algorithm could be applied at this stage, but this one is a good start;
12. transform the modal command vector into the actuators commands vector by applying a square matrix 468-by-468 components;
13. apply the command vector to the DM actuators;
14. it is clear that the time lag between the end of the WFS reading and the application of the new commands should be smaller or at most equal to the loop period, otherwise the command will not be able to keep its pace with the incoming WFS data; so the total computation loop lag must be lower than 1/1500 s i.e 666 µs;
15. wait for the WFS exposure to complete;
16. start again at point 1.

AO computer secondary sequence of operations

In parallel to the uninterrupted data flow above, some data processing and display are required about every 10 seconds - to serve system diagnostic.

1. apply a FFT algorithm and an abs()2 to each component of the error vector to get their temporal power spectrum; the signal is in principle made of 15’000 new samples every 10 seconds;
2. adjust a 3 parameters power spectrum model to the data; adjusting the 3 parameters of the model shall take less than 1 second;
3. compute the optimal loop gain and frequency from these 3 parameters; there is a model for this and shall take less than 1 second to process;
4. apply the new loop gain and frequency as soon as possible, but without interrupting the main data flow (maybe these variables can be updated while waiting for the WFS exposure to complete);
5. compute the optical system’s response (PSF) using the value of the adjusted model (the response model exist and takes less than 1 second to process); the optical response is by definition the image of a point and shall be displayed on a 256-by-256 matrix on a screen.

Construction of the command matrix

As with a SH-WFS, everything starts with the measurement of the interaction matrix (or poke matrix or influence matrix). Once the system is well aligned, we push the DM actuators the one after the other and measure the response of the sensor. At this point, there are many options. The simplest is the build a command matrix using a pseudo inverse procedure (for instance using a SVD and ignoring the lowest eigen values) or using a more sophisticated algorithm that considers a priori knowledge of the signal and the noise amplitude.

The reconstruction method we will use for DAG AO has not been decided yet. For now, a procedure identical to a SH-WFS slope sensor procedure can be applied. In any case, there will be at the beginning of any procedure a measurement of the interaction matrix.

Memory storage needs

Based on the requirement to keep all the raw WFS data, we need to be able to store, for a period of 6 hours, the S vector made of 1710 lines and as may columns as they are 1.5 kHz measurements for each AO run, i.e., if the AO loop is closed for 6 hours, about 33.5 million of such vectors. At the end of each night, the data are processed for diagnostic purposes and the memory shall be cleared and made ready for the next set of data.

Optical performance specification

In K-band (2.16 µm), using a 10-th visual magnitude NGS, in median seeing conditions, and with a coherence time of 3 ms, the delivered Strehl ratio shall be 80 % or higher. The tip-tilt shall be lower than 0.1".

ADAPTIVE OPTICS OPTICAL DESIGN

In the optical design of TROIA, several constraints are adapted:

- the exit pupil has to be imaged on the DM (Deformable Mirror);
- the DM diameter is fixed to the DM-468 clear aperture from ALPAO; that means Ø33 mm;
- the exit pupil of the telescope has to be imaged on the TT (Tip-Tilt) mirror for the P-WFS modulation;
- the beam has to converge on the pyramid apex;
- the angle of the beam that arrives onto the pyramid apex is calculated in order to get a diffraction limited PSF size of 2 times the pyramid roof;
- the exit pupil has to be imaged onto the Nuvu EMCCD detector;
- the beam footprint diameter onto the detector has to be defined accordingly to the oversampling criterion

We use off axis parabolas (OAPs) for all our design to reduce the aberrations (compared to lenses). We have added one more constraint on the design which is to have parallel beam arriving or leaving each off axis parabola in order to limit the spherical aberrations.

The fixed parameters are resumed here :

- exit pupil diameter : Φ_{ExtP} = 727.4046 mm;
- distance from the exit pupil to the focal plane : ExP-FP = 10338.74 mm;
- DM diameter : Φ_{DM} = 33.0 mm;
- pixel size of the Nuvuu EMCCD AO : PxSize = 24 µm

In order to design the AO bench we started with the telescope model. Indeed, we would try to compensate for the field of curvature introduced by the mirrors of the telescope with the off-axis parabolas (OAP) of the AO. The Zemax model of the telescope shows a curvature radius of about 1255 mm.

We needed to image the pupil on the TT modulation mirror. Moreover, we know that to compensate for the aberration introduced by OAP0 we can use an OAP1 with the same focal length. The F/D ratio would stay the same as the telescope one which is favorable for the science path.

In order to avoid to send back the beam on the focal plane and because we would like to place the dichroic nearby the intermediate focal plane, we fold the beam after the DM with a flat mirror.

We wanted to introduce a dichroic membrane nearby the intermediate focal plane to reduce its diameter. Then a folding mirror is added to send the light to the instruments. This allows avoiding a large incidence angle on the dichroic which would generate a large reflection loss due to polarization. The dichroic tilt angle is set to 20°and in order to send the beam collinear to the output of the telescope, the folding mirror is put at 7°of tilt.

In order to correct for the atmospheric chromatic dispersion we needed to introduce an ADC (Atmospheric Dispersion Compensator) in our system. This one has to be as close as possible to a pupil plane so to avoid to reimage the pupil and add optical surfaces we choose to insert it arount the TT modulation mirror.

The detector is the Nuvu EMCCD with 1282 pixels and a pixel size of 24 μm. We have to sample the beam with at least 1 pixel per actuator. In order to relax the alignment specifications we can oversample the beam (oversampling of 1.5 should be enough).

The pupil had to be imaged on the camera through a relay lens. The pyramid does not act for the ray tracing and so the optical design, it separates the beam in four images only. We can look for the on-axis rays to dimension the relay lens and its position. In order to play with the variables and have a direct result of what could be done or not, we used a sketch on the drawing software SolidWorks. Then, when we find something roughly fine we introduce the values in Zemax and optimize the distances in order to find the proper pupil plane and diameter.

The natural guide star selection in the FoV is made using a XYZ stage where the WFS path is mounted. The TT modulation mirror is on a pupil plane so it can modulate the beam around the apex of the pyramid irrespectively of the star position. However, the pyramid has to be placed at the star focus in the FoV. The XY stage allows the NGS selection while the Z axis allows realigning the pupil when needed.

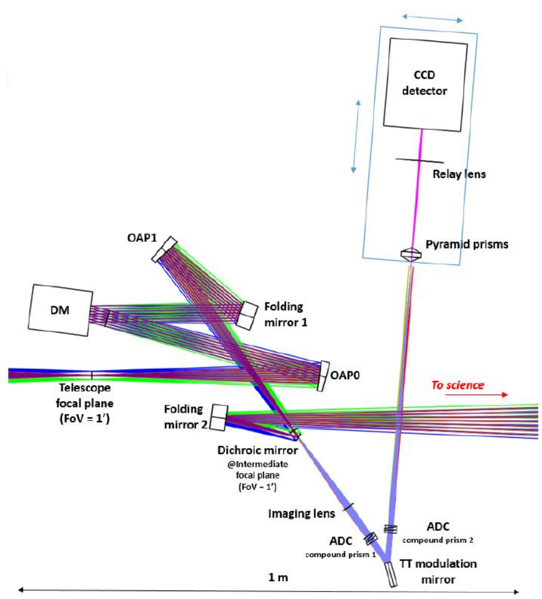

Figure 9: Zemax model of the entire optical train

SUMMARY

This paper mainly focused on the design roadmap of TROIA that has been built for the 4m class VIS/IR Eastern Anatolia Observatory's DAG Telescope. Although this roadmap is given for DAG, it can also be applied by the other AO system designers in the future.

While the technical details of TROIA, i.e. the flexible AO system approach, optical design details, and ADC design are presented by "Towards a flexible adaptive optics concept for the new 4m Turkish observatory", "Optical design of the adaptive optics system for DAG, the new 4 m Turkish telescope", and "Optical design of an atmospheric dispersion compensator for the DAG-AO system", the authors would like to mainly focus and define the overall requirements to be considered for any future AO system.

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