Laser Tomographic AO system for an Integral Field Spectrograph on the E-ELT : ATLAS project

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Abstract. ATLAS is a generic Laser Tomographic AO (LTAO) system for the E-ELT. Based on modular, relatively simple, and yet innovative concepts, it aims at providing diffraction-limited images in the near infra-red for a close to 100 percent sky coverage.

1. Introduction

The future European Extremely Large Telescope (E-ELT) will provide scientific instruments with high flux and high angular resolution [1]. It will be equipped with adaptive optics systems for real time compensation of turbulence and windshake effects. Various adaptive optics (AO) systems are currently under consideration. In order of increasing performance and complexity these are:

a. Ground Layer AO (GLAO), providing a small but uniform correction in a wide field (typically 5 to 10 arcmin diameter) with a close to 100 % sky coverage;
b. Single Conjugate AO (SCAO) providing a good correction in a small field (typically a few tens of arcseconds) but with an extremely poor sky coverage (smaller than1%);
c. Laser Tomographic AO (LTAO), with performance close to that of SCAO over a slightly larger filed of view (FoV) and with a much higher sky coverage (close to 100 %), due to the availability of E-ELT Laser Guide Stars (LGS);
d. Multi-mirror adaptive optics system such as MultiConjugate AO (MCAO) [2] and Multi-Object AO (MOAO) [3], which will allow the full field of view of the E-ELT to corrected from atmospheric turbulence.

As an intermediate range solution, the LTAO topology used in ATLAS (Advanced Tomography with Laser for AO System) has showed a significant gain in performance compared to SCAO in terms of sky coverage, while keeping the complexity of the overall design relatively low compared to that of MCAO/MOAO.

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2. LTAO principle

Classical AO, namely Single Conjugate AO (SCAO), is limited by the anisoplanatism which is a consequence of the turbulence volume distribution above the telescope (first 20 kilometers). It has a significant impact on SCAO systems: it restricts the correction to a small FoV (and thus limits the observation of very extended objects) and it reduces the sky coverage (available bright guide star for the wavefront sensing) to a very limited fraction of the sky (less than 1% typically). In order to get rid of the SCAO sky coverage limitation, the idea was to create artifical laser guide stars (LGS) and thus, in theory, to give much better sky coverage (≈ 100%). But since LGS are focused at a finite altitude (90 km in the case of a Sodium Laser Guide Star), laser assisted AO systems suffer from the so-called "cone effects" which is nothing but a difference of geometry between the beam coming from LGS and from that of the scientific targets (cone vs cylinder). Laser Tomographic AO aims at overcoming this limitation. The idea is to create multiple LGS in order to synthetise the plane wave front geometry. This calls for a tomographic reconstruction of the turbulent volume from the LGS wavefront sensing signal and then a projection of this volume onto a single pupil-conjugated DM. LGS can not be used to measure tip-tilt, and potentially have difficulties in providing an absolute defocus correction due to the Sodium profile fluctuations. This results in the need to make use of limited number of natural guide stars (NGS) to estimate the low order tip-tilt and focus errors. These errors can be measured by making use of low order wavefront sensors (LO WFSs_. Due to the need to use LGS and NGS it is important to define the various Field-of-Views (FoV) used in this paper:

- Science FoV, field on which performance is specified for downstream science instruments. In ATLAS, this science FoV is 60" diameter (with a particular 30" FoV diameter free-from-optics).
- NGS search field of view, in which NGS will be selected for LO-WFS.
- The guide star FoV, location of the LGS for the tomographic reconstruction.

3. Science and technical drivers

3.1. Science drivers

ATLAS (being defined as a generic LTAO module) has no science drivers *per se,* nevertheless several key science drivers have been flown down from the ATLAS client instrument requirements. The wavefront corrected focal plane delivered by ATLAS and the telescope can be utilized by the following Nasmyth mounted instruments:

a. A Single Field Near-Infrared (NIR) Spectrograph (HARMONI [4]).
b. Mid Infra-Red Camera-Spectrograph (METIS [6]).
c. A High Spectral Resolution NIR Spectrograph (SIMPLE [7])

The wavefront corrected focal plane delivered by ATLAS combined with the instrument capabilities should allow to completely deliver four out of the nine E-ELT prominent science cases [8] (circumstellar disks, black hole/AGN, Dynamical measurement of universal expansion and Metallicity of the low-density IGM). It partially addresses an additional four cases (Extrasolar planets, Stellar cluster including Galactic Centre, Resolved stellar populations and Physics of high-z galaxies). Only one (First light – the highest redshift galaxies) of the science cases will not be covered. Where ATLAS is only partially compliant it is nominally due to the size of the required field of view.

3.2. Top Level Requirements

The ATLAS specifications are a mix of generic considerations defined by ESO (especially in terms of mass and dimension) and the more specific requirements were derived from the instrument requirements by working directly with the instrument teams. The specifications are summarized in Table 1

Table 1 ATLAS Derived Top Level Requirements

Performance parameters	**Requirements**
Performance on axis: 50% in K under nominal seeing conditions	LTAO concept (LGS and NGS number and location, RTC requirements)
Performance @ 15” off-axis: 35% (goal 45 %) in K under seeing conditions	AO system design (RTC)
ATLAS waveband : from 0.5 to 13.5 microns	Opto-mechanical Design
Sky coverage: 60% @ 60° galactic latitude	NGS WFS concept, opto-mechanical design
On-axis K-band 100% sky coverage PSF FWHM: 26 mas	AO design, interface with telescope (for windshake correction)
ATLAS clear FoV (with partial obscuration): 60” diameter	LTAO concept and opto-mechanical design
ATLAS free FoV (free from optics): 30” diameter	LTAO concept and trade-offs / opto-mechanical design
ATLAS instantaneous residual jitter: 2 mas	NGS WFS concept
ATLAS tip-tilt long term stability: 1 mas (during 15 min) => Differential tracking to correct for differential atmospheric dispersion	Internal ATLAS metrology. Opto-mechanical design (ATLAS stability)
ATLAS spectral range: 0.5 to 13.5µm with 90 % (goal 95 %) of transmission	Opto-mechanical design
ATLAS additional thermal background: < 30 % (of the telescope including M1 to M5) in K	Opto-mechanical design
ATLAS has to provide a de-rotation of the 60” scientific FoV	Opto-mechanical design
Jitter capability up to 15”	Opto-mechanical design, NGS extraction concepts (POM)
Guiding on a moving source capability with non sidereal speed of 100"/h	Opto-mechanical design, NGS extraction concepts (POM)
ATLAS mass	< 2 tons
Atlas size	< 4m diameter and 1m width

By considering all the requirements and constraints, the team succeeded in designing a ***baseline concept which is modular, relatively simple, and innovative, while relying on existing mature technologies.***

4. ATLAS Overview

ATLAS will make use of the telescope adaptive mirrors (M4 and M5) to implement the AO corrections. It is an opto-mechanical system providing the pick-off mechanisms and the wavefront sensors (LGS and NGS) combined with a dedicated hard real-time computer sub-system (RTCS) to implement a laser tomographic topology. The RTCS uses the laser guide star information and combines that with the extremely good field stabilization (less than 2

mas) to calculate the AO corrections. The field de-rotation is obtained by interfacing ATLAS directly with the Nasmyth station de-rotator, without additional optics or mechanisms. The pupil de-rotation (essential for the AO operation) will be implemented in software.
High order correction through tomographic process: Tomographic reconstruction is essential to correct for the cone effects associated with the particular geometry of the LGS wavefronts. Six LGS are required to synthesize the cylindrical turbulent volume correctly. The wavefront from a typical scientific object of interest has to pass through this turbulent volume of air above the earth's atmosphere. The laser guide stars are used to obtain the High Order correction accurately. To comply with the free from optics scientific 30" field of view requirement, while avoiding implementing large dichroics, the LGS asterism is placed at a 4'20" diameter circular pattern. The LGS beam footprints do not overlap at the ATLAS entrance. This allowed the team to design a pick-off system consisting of small and affordable mirrors and lenses. The six LGS sensors will be Shack-Hartmann sensors, using correlation based methods for centroiding. This appears to be the most ***efficient*** and is more ***robust*** with respect to the spot shape variability (due to the sodium layer structure fluctuations).
Instantaneous Jitter correction: LGS measurements suffer from tip-tilt indetermination problems as well as focus errors due to spatial fluctuation of the sodium (Na) density. It is therefore essential to measure the low order modes using Natural Guide Stars (NGS) close to the clear science field. As such a technical patrol field has been defined with an inner diameter of 30 arcsec and an outer diameter of 2 arcmin (the science field shall be kept clear). The ATLAS design implements two NGS pick-off channels. An original WFS concept has been developed, called the Low Order Focal Plane Sensor (LOFPS). The LOFPS takes advantage of the full aperture gain. Each NGS channel is equipped with a dedicated mini-DM to concentrate the flux. A low noise detector, with a limited number of pixels (typically 8 x 8) is considered. This together with a cold pupil stop (≤ 170° K) allows collection of photons from natural stars over a wide band (H + K short). Lastly, the LO control performance will be improved by implementing an optimal tuned Kalman Filter. This results in predicted ***sky coverage close to 100%.***
Truth sensor capabilities: Errors due to the sodium layer structure fluctuations, telescope field aberrations and LGS arms aberrations, shall be measured by using a so-called "truth sensor" using the light from the natural stars. Once these errors have been measured these measurements shall be used to calibrate the system to reduce the residual error terms. The team also has investigated the possibility to use the NGS sensor as a truth sensor. It is shown that the NGS sensor can provide high order measurements at approximately a rate of 1Hz rate without introducing a loss in the performance of the low order fast rate measurements. This allows us to use an existing sensor to perform an additional function without the introduction of more hardware.
Real Time Control Sub-System (RTCS): A Pseudo Open Loop Control, associated with a temporal controller in DM subspace, has been chosen over the optimal, but much more complex, LQG solutions. In addition, Low Order (LO) measurements with the NGS sensors and High Order (HO) with the LGS sensors are processed separately (split tomography). In addition to the real time tasks, the ATLAS RTCS will have to perform identification procedures using the WFS data in order to estimate exogenous parameters required to apply optimal telescope windshake correction (windshake PSD estimation). In addition to the real time tasks, the ATLAS RTCS shall also perform on-line identification of exogenous parameters required for optimizing the various AO wavefront sensor and control loop features:

a. The LGS WFS reference for the correlation measurements (Na profile estimation).
b. Telescope windshake correction (windshake PSD estimation).
c. The tomographic reconstruction process (Cn^2 profile estimation).

Pointing control and long term PSF stability: The instantaneous jitter stability of the high quality PSF delivered by ATLAS shall be better than 2 mas. However, in the telescope, AO System (ATLAS) and instrument chain, the overall quality of the scientific channel is determined by the weakest link. To preserve the extremely high quality PSF, it is important to ensure the long term stability of the PSF position along the complete chain, down to the instrument camera.

The consequences of this for ATLAS can be summarised as follows:

a. ATLAS has to provide a ***mechanical reference*** that can be used by the instrument.
b. ATLAS has to ensure the long term stability of the NGS channel with respect to the ATLAS mechanical reference. The instability of the NGS channel is due to the mechanical flexures as a result of the rotation of ATLAS around the horizontal axis (de-rotation) and thermal fluctuations (changes in operating temperature). These effects have to be minimised and controlled to a precision of a few microns. To achieve this, an ***internal metrology module has been designed***
c. The long term stability of the ATLAS mechanical reference (instrument link) has to be provided. Although it is the responsibility of the instrument to ensure that it is kept stable during an observation, ATLAS shall make provision to house an instrument sensor. Instruments making use of the ATLAS focal plane shall interface directly with the host sensor. Provision for the host sensor shall be made at the edge of the instrument field of view.

The ATLAS Rotating Platform baseline design is illustrated in Figure 4-1. It is a steel honeycomb structure of 3 m diameter by 450 mm height cylinder for the direct throughput Nasmyth port. An extension ring (3 metres in diameter and 750mm height) is needed for the lateral ports to deal with the difference in distance between the flange and the focal plane (750mm for the straight through ports and 1500mm for the lateral ones). The total mass of the ATLAS Rotating Platform Sub-System (ARPS) is less than 2000 kg.

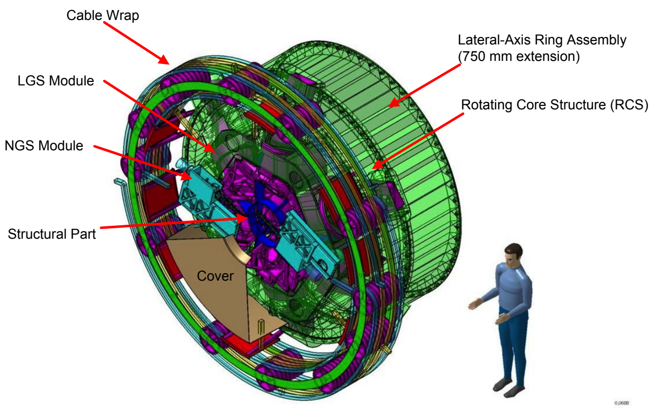

Figure 4-1 ATLAS Concept Design

4.1. ATLAS performance

By design, the ATLAS system has no optics in the 30 arcsec central FoV and only the two small NGS Pick-off arms in the 2 arcmin full scientific FoV. Hence, ***the 30 arcsec beam is fully transmitted to the ATLAS focal plane.*** The thermal background added by the ATLAS hardware is minimal. From a pure AO performance point of view, ATLAS will have a ***Strehl Ratio larger than 50 % in K band with a sky coverage close to 100 %.*** This leads to a very high SR for the L and M bands and a reasonable performance (PSF FWHM smaller than 10 mas) in J, R and even V.

The ATLAS performance predictions are based on the simulation of the PSF using a Fourier based model. The initial PSF only contains the "turbulence related" HO-LGS error terms (namely chromatic, fitting, aliasing, temporal, tomographic + noise and Cn^2 model errors). HO modes induced by the telescope are included in the fitting term. NGS errors are added by the convolution of the PSF with a Gaussian function (representing the PSF long exposure spreading due to tip-tilt residuals).
Finally, calibration errors, LGS NCPA and contingencies are added using the same procedure as that used for the NGS errors. In other words it is assumed that these are mainly affecting the core of the PSF (i.e. low spatial frequencies). This assumption is rather pessimistic from a performance point of view since it will affect ALL the performance criteria (SR, FWHM and EE for all spatial resolutions) whereas in real life, some of the calibration errors will be high frequency modes and will only affect SR. In addition both EE (for various spatial resolutions (box sizes)) and FWHM have been computed for the various ATLAS spectral bandwidths. For FWHM, the performance of ATLAS has been compared for the seeing-limited case.

Table 2 LTAO performance for median atmospheric conditions

NOMINAL CONDITIONS	seeing = 0.8	Zenith = 0°		θ0 = 2.08"									
LTAO Performance													
lambda (nm)	**356**	**440**	**550**	**640**	**700**	**750**	**900**	**1250**	**1650**	**2200**	**3500**	**4800**	**1050**
Ensquared Energy (%)													
Width (in mas) 10	0,4	0,1	7	2,1	3,7	5,2	10,3	21,1	26,1	26,4	17,8	13,7	3,9
20	0,1	0,3	1,2	3,2	5,3	7,4	15,1	32,1	42,5	48,5	45,6	37	14,3
40	0,6	0,8	2,2	4,7	7,2	9,6	18,2	37,8	53,6	63,8	62,8	61	35,1
60	1,2	1,7	3,6	6,6	9,3	11,9	22,4	40,5	56,3	67,8	75,9	69,1	54,2
80	2,1	2,9	5,2	8,5	11,5	14,2	23,2	42,4	58,2	70,2	79,8	80,1	63,8
100	3,3	4,3	7,1	10,7	13,7	16,4	25,6	44,8	59,5	71,7	81,3	84,6	67,5
SR (%)	**0**	**0**	**0,1**	**0,6**	**1,2**	**1,9**	**5,5**	**18,8**	**35,3**	**52,7**	**75,6**	**90,5**	**96,9**
FWHM (Gaussian fit) [mas]	373	211	8,9	8,1	8	8	8,2	9	10,1	12,1	17,6	23,7	49,1
Diffraction													
FWHM (Gaussian fit) [mas]	1,8	2,2	2,7	3,14	3,4	3,7	4,4	6,1	8,1	10,8	17,2	23,6	49,6

Table 2 LTAO performance for median atmospheric conditions

Seeing limited													
FWHM (Gaussian fit) [mas]	778	743	705	685	674	666	646	609	586	546	483	442	357
GLAO (6 LGS – 4'20'')													
SR (%)	0	0	0	0	0	0	0	0,1	0,4	2,8	21,6	42,5	83,8
FWHM (Gaussian fit) [mas]	447	524	408	367	340	318	261	200	146	96,2	20,5	22,5	49,1
HARMONI				SIMPLE									
METIS													

To summarize the ATLAS system fulfils the ESO specifications and reach a SR of ***52.7 % for median seeing conditions (0.8 arcsec)*** in K-band and goes up to 56.8 % in good seeing conditions (0.6 arcsec). In case of bad seeing conditions (1.1 arcsec) the performance remains very decent with a SR around 35 %. It is important to highlight the huge gain brought by the LTAO w.r.t. GLAO both in terms of EE and FWHM. Even though LTAO system will not reach the ultimate performance of a SCAO system (50 % instead of 70 %) on bright stars (typically magnitude lower than 13) it will ensure this performance and thus a diffraction-limited PSF for NIR bands over more than 98 % (see next section) of the whole sky. It will also provide a very sharp PSF (smaller than 10 mas) for J down to V bands.
Such kind of results is achievable thanks to a good LGS-tomographic topology combined with a very accurate correction of the Tip-tilt / defocus on axis using off-axis natural guide star(s). We take benefit from

- the very favourable L0/D ratio which significantly reduces the turbulent jitter;
- a dedicated low order focal plane sensor optimized for very high magnitude guide stars (up to 19 typically);
- an optimized Kalman filter control law which allows us to make temporal predication in order to well correct for telescope windshake;
- a dedicated correction in the NGS direction (using a 30x30 μ-DMs located in the WFS arms and the LGS tomographic data) in order to obtain diffraction limited PSF on the WFS arms in H-Ks bands (and thus an improved SNR on NGS WFS);
- the use of 2 NGS, combined with optimized spatial reconstruction process in order to interpolate the on-axis tip-tilt / defocus data from NGS off-axis (up to 60 arcseconds) measurements.

4.2. Associated Sky coverage

The full sky coverage estimation scheme is based on a random generation of a stellar fields following the Besançon model. A selection of star-star couples is made following a general strategy based on a balance between residual anisoplanatic, temporal and noise errors (see RD12 for a complete description). Sky coverage is extremely dependant on the outer-scale (L0) as well as on the IR detector Read-Out-Noise (RON). For the nominal values of the study (i.e. a 25 m outer-scale and a $6e^-$ RON), a sky coverage of ***98 % of the whole sky*** (larger than 97 % for lat < 60° and larger than 92 for lat ≥ 60°) has been computed.

Assuming a L0 = 50 m (and a 6e$^-$ IR detector RON for), ***this ATLAS performance is applicable to 92 % of the whole sky*** (larger than 88 % for lat < 60° and larger than 73% for lat ≥ 60°)
It is difficult to give one single number for the ATLAS limit magnitude, since it implies the use of 2 NGS for which limit magnitude may evolves depending on they relative positions from the scientific target, a ***The NGS limit magnitude could be roughly estimated to 18.5 / 19*** for a single NGS at 30" from the target. We consider that this value holds in the rest of the NGS patrol Field of View because for stars farer from the target, we can use two NGSs to mitigate the anisoplanatism effects.
For a sky coverage of 100 % we have to assume that the telescope will take care of its windshake and that no NGS are available for ATLAS (we still have a very slow sensor for LGS NCPA). The performance obtained in terms of SR, FWHM and EE in 10, 20, 40, 60, 80 and 100 mas for a 25 m outer scale are summarised in Table 3

Table 3 : Performance for 100 % sky coverage (Lo = 25m)

lambda (nm)		356	440	550	640	700	750	900	1250	1650	2200	3500	4800	1050
Ensquared Energy (%)														
Width (in mas)	10	0	0	0.2	0.6	1.1	1.4	2.7	5.8	7.8	9.1	8.4	7.8	3,1
	20	0,1	0.2	1.0	1.9	3.0	4.2	8.3	17.6	24.1	27.6	26.7	22.7	12.0
	40	0,6	0.8	2.1	4.5	6.7	8.9	16.7	34.8	48.3	56.4	57.4	52.5	29.8
	60	1.2	1.7	3.5	6.5	9.1	11.7	20.4	40.0	55.8	66.9	72.6	68.2	49.2
	80	2.2	2.9	5.2	8.5	11.4	14.1	23.0	42.6	58.1	70.4	78.6	77.6	60.1
	100	3.4	4.2	7.0	10.7	13.7	16.4	25.4	44.8	59.7	71.8	81.5	83.0	65.6
SR %)		**0**	**0**	**0,1**	**0,1**	**0.2**	**0.3**	**0.8**	**3.0**	**7.0**	**13,8**	**31.3**	**46.7**	**77.1**
FWHM (Gaussian fit) mas]		496	336	198	43.0	31.4	28.5	24.9	24.9	25.4	26.8	30.2	33.5	54.4

In conclusion, for a 100 % Sky Coverage, a non-negligible SR in K of 13 % (for L0 = 25).is still obtainable. The PSF FWHM is approximately 25 mas from L to R band.

5. References

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