# ATLAS: An Advanced Tomographic Laser-assisted Adaptive Optics System

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**ATLAS is a generic laser tomographic adaptive optics system for the E-ELT. Based on modular, relatively simple, and yet innovative concepts, it aims at providing diffraction-limited images in the near-infrared for close to 100 percent sky coverage.**

The E-ELT will provide scientific instruments with high light-gathering power and high angular resolution. It will be equipped with adaptive optics systems for real-time compensation of turbulence and windshake effects. Various adaptive optics systems are currently under consideration. In order of increasing performance and complexity these are:
- Ground layer AO (GLAO) providing a small but uniform correction in a wide field (typically 5 to 10 arcminute diameter) with close to 100 % sky coverage;
- Single conjugated AO (SCAO) providing a good correction over a small field (typically a few tens of arcseconds), but with an extremely poor sky coverage (less than 1 %);
- Laser tomography AO (LTAO), with performance close to that of SCAO over a slightly larger field of view (FoV) and with a much higher sky coverage (close to 100 %), due to the availability of E-ELT laser guide stars;
- Multi-mirror adaptive optics systems such as multi-conjugate AO (MCAO) and multi-object AO (MOAO), which will allow the E-ELT to be corrected for atmospheric turbulence.

As an intermediate solution, the planned LTAO topology to be used in ATLAS has shown 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. An added advantage of ATLAS is its potential "wide bandpass" in the third dimension, namely the spectral range. ATLAS provides a science field free from optical elements and obscuration, while transmitting a large range of wavelengths. This feature will enable instruments to analyse astronomical objects over a wide wavelength range.

ATLAS has been designed to be compatible with several potential scientific instruments (HARMONI, METIS and SIMPLE). The requirements for an additional instrument, which can be attached directly to the ATLAS rotating part (instrument mass to be less than 3 tonnes) were also considered. The ATLAS specifications are therefore a mix of generic considerations defined by ESO (at the start of the Phase A study) and more specific requirements derived by working directly with the instrument teams (Fusco et al., 2010). By considering all the requirements and constraints, the team succeeded in designing a baseline concept that is modular, relatively simple, and innovative, while relying on existing mature technologies.

## Science drivers

ATLAS (being defined as a generic LTAO module) has no science drivers *per se*; nevertheless several key science drivers have been identified after interaction with the ATLAS client instrument teams. Hence, the wavefront-corrected focal plane delivered by ATLAS and the E-ELT can be utilised by the following Nasmyth-mounted instruments: a single field near-infrared (NIR) spectrograph (HARMONI); a mid-infrared camera-spectrograph (METIS); a high spectral resolution NIR Spectrograph (SIMPLE); and potentially a large FoV NIR camera (MICADO). In addition, it has been shown that the ATLAS final design (see below), will be able to deliver four out of the nine prominent E-ELT science cases (circumstellar discs, black holes and active galactic nuclei, dynamical measurement of Universe's expansion and metallicity of the low density intergalactic medium) and complies partially with the requirements of four others (Kissler-Patig 2010).

## Instrument design concept

ATLAS can be mounted at any of the Nasmyth focal stations (straight through and lateral ports). It implements an advanced laser tomography topology to calculate the corrections that will be applied by the E-ELT Telescope Control System (TCS) to the M4 adaptive mirror and the M5 field stabilisation mirror. ATLAS uses the six laser guide stars (LGS) provided by the E-ELT laser launch telescope and two natural guide stars (NGS) to sense the wavefront error of the incoming beam by implementing six identical LGS wavefront sensor (WFS) channels and two identical NGS WFS channels. The LGS WFS channels are used to sense the high-order wavefront errors while the NGS WFS channels are used to measure the low order modes. ATLAS can deliver a clear central 30-arcsecond FoV free from optics to the Nasmyth focal stations. An extended FoV of 60 arcseconds, which may be partially vignetted (by the two NGS pick-off arms) is available. In its present layout (see Figure 1), ATLAS

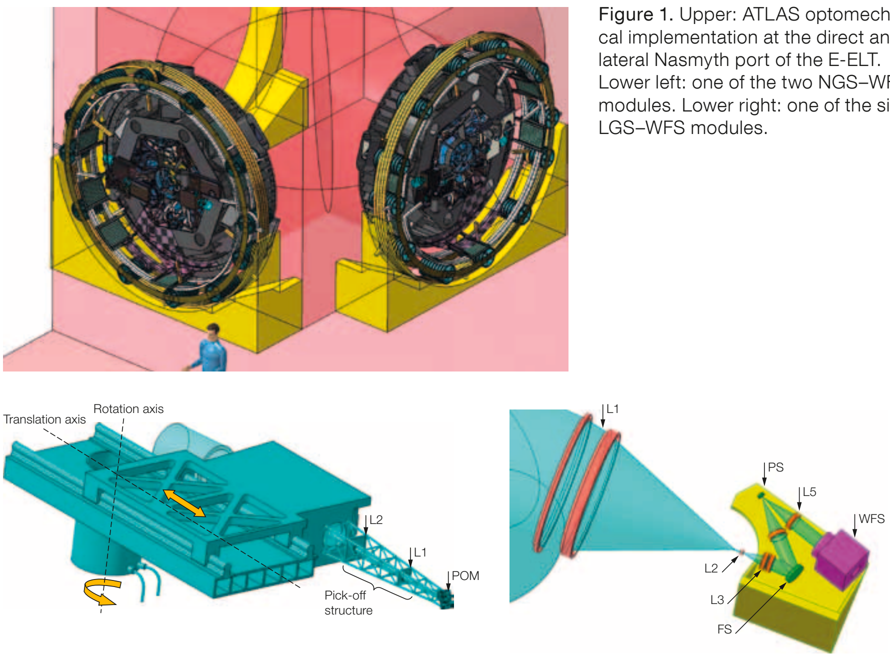


Figure 1. Upper: ATLAS optomechanical implementation at the direct and lateral Nasmyth port of the E-ELT. Lower left: one of the two NGS–WFS modules. Lower right: one of the six LGS–WFS modules.

Table 1. Performance of ATLAS for median atmospheric conditions (0.8-arcsecond seeing, isoplanatic angle of 2.08 arcsecond). The relevant performance data for HARMONI, SIMPLE and METIS have been highlighted.

| Lambda (nm) | | 440 | 550 | 640 | 750 | 900 | 1250 | 1650 | 2200 | 3500 | 4800 | 10500 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ensquared Energy (%) | | | | | | | | | | | | |
| Width (in mas) | 10 | 0.1 | 0.7 | 2.1 | 5.2 | 10.3 | 21.1 | 26.1 | 26.4 | 17.8 | 13.7 | 3.9 |
| | 20 | 0.3 | 1.2 | 3.2 | 7.4 | 15.1 | 32.1 | 42.5 | 48.5 | 45.6 | 37 | 14.3 |
| | 40 | 0.8 | 2.2 | 4.7 | 9.6 | 18.2 | 37.8 | 53.6 | 63.8 | 62.8 | 61 | 35.1 |
| | 60 | 1.7 | 3.6 | 6.6 | 11.9 | 22.4 | 40.5 | 56.3 | 67.8 | 75.9 | 69.1 | 54.2 |
| | 100 | 4.3 | 7.1 | 10.7 | 16.4 | 25.6 | 44.8 | 59.5 | 71.7 | 81.3 | 84.6 | 67.5 |
| SR (%) | | 0 | 0.1 | 0.6 | 1.9 | 5.5 | 18.8 | 35.3 | 52.7 | 75.6 | 90.5 | 96.9 |
| FWHM (mas) | | 211 | 8.9 | 8.1 | 8 | 8.2 | 9 | 10.1 | 12.1 | 17.6 | 23.7 | 49.1 |

does not introduce any additional optics along the line of sight to the instrument. Thus, there are no additional losses due to restrictions coming from the coatings or glass absorption, nor additional thermal background.

In particular, the following critical points have been very carefully addressed:
- Tomographic reconstruction process. This is the key element of the system (true for any laser-assisted wide-field AO system on the E-ELT). Complex trade-offs have been made to find the best solution and balance between the complexity of the control algorithm, its robustness and the cost of computation. The whole process will be based on a regularised pseudo-open loop control (Gilles, 2005) and a clever separation between NGS and LGS control loops. The LGS measurement will rely on Shack–Hartmann WFS with centroiding measurements using a correlation scheme.
- Improvement of the sky coverage. This has been achieved by the design of a new NGS WFS concept, fully optimised for maximising the sky coverage in the context of a laser-assisted AO system (Meimon et al., 2010a). The performance has been fully simulated and the predicted sky coverage is close to 100 %. This is an exceptional sky coverage performance achieved by using existing components and a straightforward optomechanical design. The ATLAS sky coverage is one of its most attractive selling points (Meimon et al., 2010b).
- Simplification of the optomechanical design. As stated before, the pursuit of a simple system has led the team to make radical choices in terms of the design allowing us to minimise:
  - the number of large optical elements (the largest optical element is 400 mm);
  - the number of moving mechanisms; and
  - space and weight.

## Performance

The ATLAS system fulfils the ESO specifications and reaches a Strehl ratio (SR) of 52.7 % for median seeing conditions (0.8 arcsecond) in *K*-band, up to 56.8 % in good seeing conditions (0.6 arcsecond). In case of bad seeing conditions (1.1 arcsecond) the performance remains very decent with an SR around 35 %. A summary of ATLAS performance in terms of ensquared energy and SR is given in Table 1. It is important to highlight the huge gain brought by ATLAS with respect to GLAO both in terms of ensquared energy and full width at half maximum (FWHM), as shown in Figure 2.

Even though ATLAS will not reach the ultimate performance of an SCAO system (50 % instead of 70 %) on bright stars (typically magnitude < 13), it will ensure this performance and thus a diffraction-limited point spread function (PSF) for NIR bands over more than 98 % of the whole sky. It will also provide a very sharp PSF (< 10 milliarcseconds (mas) from *J*-band down to *V*-band. Such results are 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 benefit from:
- the very favourable ratio of the outer scale of turbulence to telescope diameter (most of the time < 1), which significantly reduces the turbulent jitter;
- a dedicated low-order focal plane sensor optimised for very faint guide stars (up to magnitude 19 typically);
- an optimised Kalman filter control law which allows temporal prediction to be made in order to correct telescope windshake well;
- a dedicated correction in the NGS direction (using a 30 × 30 array of micro-deformable mirrors located in the WFS arms and the LGS tomographic data) in order to obtain a diffraction-limited PSF on the WFS arms in *H*- to *Ks*-bands (and thus an improved signal-to-noise ratio on NGS WFS); and
- the use of two NGS channels, combined with an optimised spatial reconstruction process in order to interpolate the on-axis tip-tilt / defocus measurements from the NGS off-axis (up to 60 arcseconds).

The full sky coverage estimation scheme is based on a random generation of 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. Sky coverage is extremely dependent on the outer scale of turbulence ($L_0$) as well as on the readout noise (RON) of the IR detector. For the nominal values of the study (i.e. a 25-metre $L_0$ and 6e⁻ RON), a sky coverage of 98 % for the whole sky (larger than 97 % for Galactic latitude < 60° and larger than 92 % for Galactic latitude ≥ 60°) has been computed.

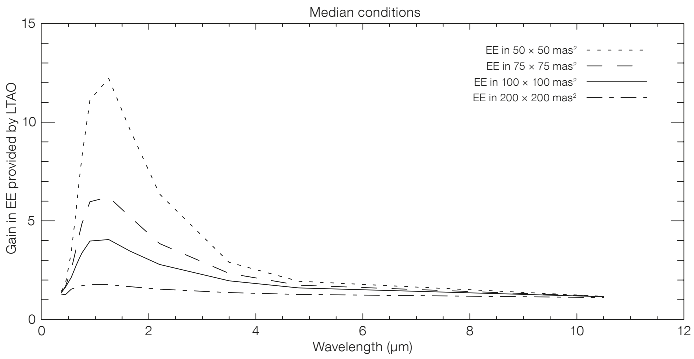


Figure 2. Gain brought by ATLAS with respect to a GLAO system for various imaging wavelengths and various box sizes (for the ensquared energy computation). Median atmospheric conditions (0.8-arcsecond seeing, isoplanatic angle of 2.08 arcsecond) have been considered.

## References


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