

# NAOMI – A New Adaptive Optics Module for Interferometry

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The future adaptive optics system for the Auxiliary Telescopes of the Very Large Telescope Interferometer (VLTI), NAOMI, is presented. The NAOMI project will equip the telescopes with a low-order Shack–Hartmann system for the VLTI dual-feed light beams. The key benefits to current and future VLTI instruments and the preliminary design concept are described.

## Introduction

The New Adaptive Optics Module for Interferometry (NAOMI) will be developed for and installed at the 1.8-metre Auxiliary Telescopes (ATs). The four ATs (Koehler et al., 2000) are designed for interferometry applications. Currently the ATs are equipped with a visible tip/tilt sensor called STRAP (System for Tip/tilt Removal with Avalanche Photodiodes; Bonaccini et al., 1997) and the corrections are applied with a fast steering mirror. Under good seeing conditions this provides a reasonable correction of the atmospheric turbulence in the *K*- and *N*-bands, but as soon as the seeing degrades below 1 arcsecond, the instan-

taneous Strehl ratio delivered by the telescopes degrades significantly.

The goal of the project is to equip all four ATs with a low-order Shack–Hartmann adaptive optics system operating in the visible, in place of the current STRAP, in order to overcome the current limitations.

## Motivation

Similar to high angular resolution instruments on single telescopes, the Very Large Telescope Interferometer is impacted by the residual wavefront errors from each of the telescopes in the array. These errors either degrade the fringe contrast directly or lower the flux coupled into a single mode fibre instrument. Whatever the exact mechanism, the sensitivity of the array is affected. With just the tip/tilt correction provided by STRAP, the quality of the wavefront delivered by the ATs depends heavily on the turbulent conditions. Nights with poor seeing, either in the free atmosphere or in the turbulent ground layer when there is almost no wind, are an impediment to the successful execution of demanding scientific observations.

By improving the wavefront quality delivered by the ATs for guide stars brighter than  $R = 13$  mag, NAOMI will make the existing interferometer performance less dependent on the seeing conditions.

The quality of interferometric data will therefore improve as a result. Fed with better and more stable image quality, the fringe trackers will achieve the fringe stability necessary to reach the full performance of the second generation instruments GRAVITY (Eisenhauer et al., 2011) and MATISSE.

## Expected performance

Simulations based on the top-level requirements have been carried out to predict NAOMI's performance in various configurations and for different concepts. A trade-off analysis selected a  $4 \times 4$  sub-aperture system operating at up to 500 Hz frame rate. On account of the limited size of the ATs (1.8-metre diameter primary mirror), a low-order system is sufficient to meet the required performance. Other drivers for this choice were simplicity and low-flux performance. The most stringent top-level requirement, that for a natural guide star of magnitude  $R = 15.5$ , NAOMI will be able to close the tip/tilt loop with a root mean square (RMS) of 0.14 arcseconds (measured at 500 Hz) on the sky over a period of typically 1 minute, is met with this configuration. Figure 1 shows the expected NAOMI Strehl ratio as a function of guide star magnitude. One can see that more sub-apertures bring a higher on-axis performance, but suffer somewhat at the faint end. All the presented configurations

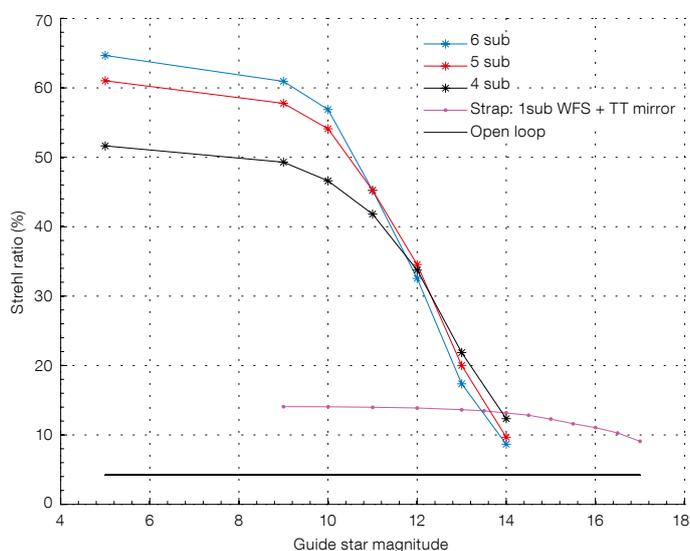


Figure 1. NAOMI performance simulation results showing the Strehl ratio as a function of guide star magnitude for three simulated sub-aperture configurations,  $4 \times 4$ ,  $5 \times 5$  and  $6 \times 6$ . The Strehl ratio was obtained on-axis in the *H*-band with a  $6 \times 6$  pixel sub-aperture, 1-arcsecond seeing, overall delay of the wavefront sensor data by 2 ms and simulated at a frame rate of 500 Hz. Additionally the theoretical Strehl ratio curve for a tip/tilt correction with one sub-aperture (roughly corresponding to the current STRAP system) is shown, as well as the open-loop performance caused by the seeing.

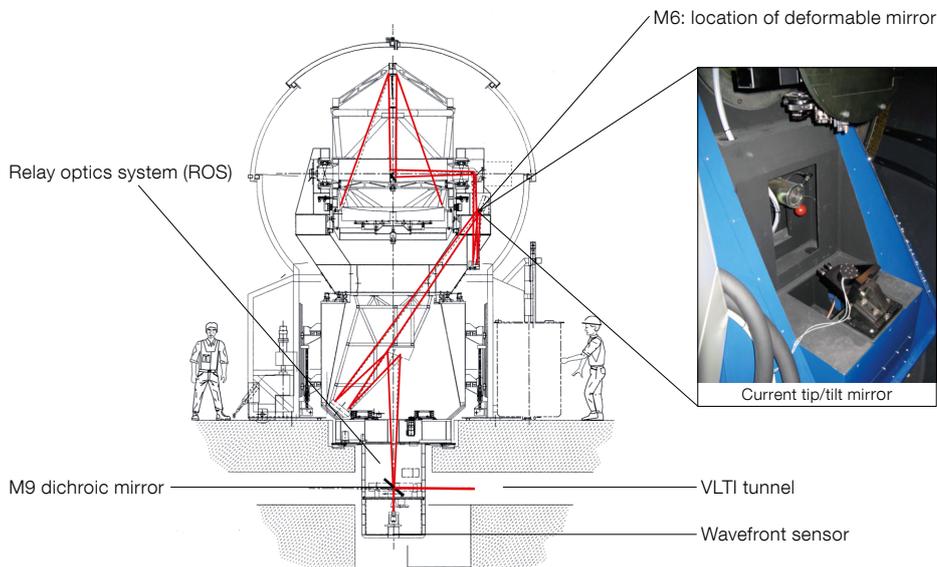


Figure 2. Schematic of an Auxiliary Telescope showing the optical train and the positions of the new modules for NAOMI: corrective optics (upper right) and wavefront sensor (below VLT tunnel).

are within the specifications for high flux and about half of the performance is reached for guide stars of magnitude  $\sim 13$ .

### NAOMI preliminary design

NAOMI will serve several VLT modes and instruments operating from *H*- to *N*-band (i.e., PIONIER, AMBER, MATISSE and GRAVITY). The NAOMI operating mode will depend on the observing wavelength and the magnitude of the guide star and will be optimised accordingly. NAOMI will correct for active turbulence, tip/tilt and focus errors (also introduced by the telescope). In addition a chopping capability up to 5 Hz will be provided to be used for MATISSE to subtract the thermal background and to suppress low frequency detector noise.

Figure 2 shows the opto-mechanical layout of an AT and the lightpath through the telescope to the VLT tunnel. The Coudé train re-images the pupil at an intermediate location (M6) where the actual fast steering tip/tilt mirror is installed. The dichroic (M9) splits the visible and infrared photons between the wavefront sensor in transmission and the interferometer in reflection. The infrared

photons are reflected and sent via a field mirror and collimator to the delay line tunnel. For each telescope there is a dedicated relay optics system (ROS) located under the telescope. This relay optics system contains the Coudé optics, the star separators and the adaptive optics system wavefront sensor. If the telescope needs to be relocated to a different baseline position, the ROS is disconnected, lifted up and moved together with the telescope to the new location. Figure 3 shows an AT with a raised ROS module.

### Corrective optics concept

NAOMI will replace the current tip/tilt mirror in the intermediate pupil plane with a corrective optics unit. M6 is located in the Coudé train facing down 20 degrees from the vertical in a diverging beam. This corrective optics module will be able to correct for the atmospheric turbulence, including tip/tilt, telescope static and dynamic errors, and should provide a chopping capability. ESO has launched a call for proposals for a competitive process to several institutes. The selected institute is expected to work with ESO on the preliminary and final design, prototyping, pre-production unit, manufactur-



Figure 3. An Auxiliary Telescope with lifted ROS module ready to be moved to a different baseline position.

ing, assembly, integration and testing of the five to six corrective optics units according to the technical specification.

In order to reduce the cost and complexity of the corrective optics design we are exploring in parallel the use of other devices in the optical train to meet the chopping needs. One option under investigation is the use of the chopping capabilities of the star separator module. The star separator provides four major functions: pointing, chopping, tip/tilt control and pupil alignment. The mirror used for pointing can also be used for chopping because it coincides with the pupil plane. We are testing this function to compare the performance with the currently used tip/tilt mirror M6.

### Wavefront sensor module

The NAOMI wavefront sensor will sense the visible light transmitted by the dichroic. The wavefront sensor (WFS) will use  $16 \times 16$  pixels per sub-aperture, providing a large field of view to be used for star acquisition and open loop operations. Once the loop is closed, a window of  $6 \times 6$  pixels will be sufficient to sense the wavefront distortions. This robust setup provides relative simplicity and is

compatible with the ESO Standard Platform for Adaptive optics Real Time Applications (SPARTA) baseline.

The main drivers for the choice of wavefront sensor are detector read noise ( $< 1$  electron RMS) and high frame rate capability. The camera selected for NAOMI can be bought as a standard product from various companies and will be placed in the coudé focus fixed to the relay optics system ground plate on a movable  $xy$ -translation stage working as a field selector. As an example, Andor provides a detector with  $128 \times 128$  pixels and  $24 \mu\text{m}$  pixel size. This camera has already been used for some prototyping work. Andor's iXon3 860 (Figure 4) is a back-illuminated EMCCD (E2V CCD-60) and is designed for very rapid imaging of low-light events, combining  $> 500$  frames/s with single photon detection capability and  $> 90\%$  quantum efficiency. Thermoelectric cooling down to  $-100^\circ\text{C}$  minimises electron multiplication amplified dark current.

The raw image data of such cameras can be extracted for adaptive optics purposes by introducing a cable splitter box into the cable link between the camera head and a peripheral component interconnect express card from which the camera is controlled. The pixel stream from the camera is received via an in-house developed field programmable gate array card based on the AO new generation detector controller developed by the ESO Detector Department (Reyes et al., 2012). This card picks up the data via a



Figure 4. View of the package for Andor iXon3 860: a possible wavefront sensor camera for NAOMI.

low voltage differential signalling interface and sends it out as a serial front panel data port pixel stream compatible with SPARTA-Light.

### Software de-rotation

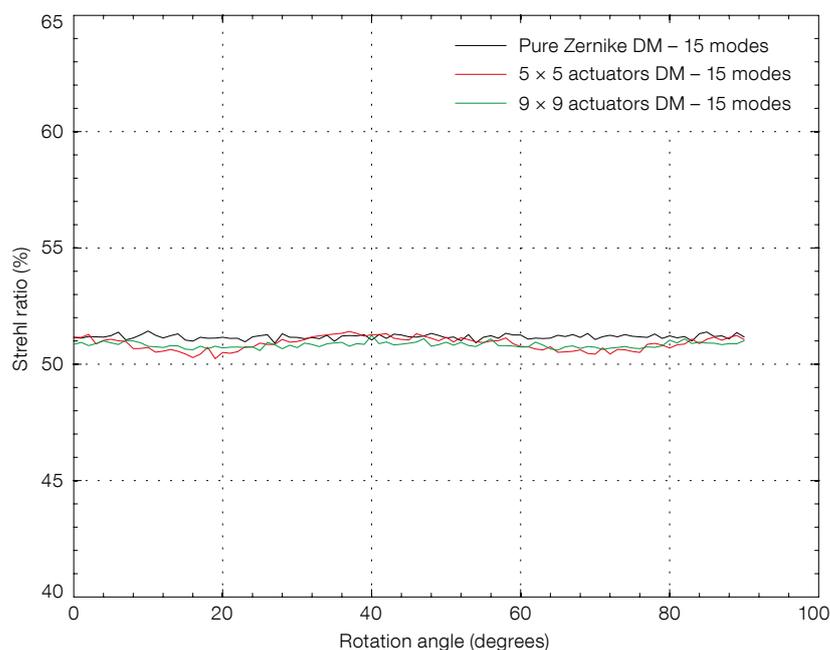
The deformable mirror (DM) for NAOMI rotates with the AT azimuth axis, whereas the wavefront sensor, which provides the control signals for the DM, has a fixed position in the telescope basement and does not co-rotate with the DM. The result is that the projection of the actuator pattern is rotating with respect to the wavefront sensor when the telescope is tracking an object on the sky. In order to avoid the use of an optical de-rotator, we have developed an algorithm to de-rotate the commands to the DM. NAOMI employs an algorithm based on the projection of the slope measurements into a modal base in order to recover the projected coefficients. A rotation matrix is then applied to the coefficients to recover the correct values for the DM orientation. The calculated and de-rotated coefficients are then projected into the DM space to recover the DM commands. The de-rotation matrix can be easily computed using the Zernike modal base due to its symmetric properties over a full rotation. The performance of this concept has been verified with end-to-end simula-

tions. Figure 5 shows the software de-rotation performance expressed as Strehl ratio values as a function of rotation angle for the three DM configurations.

### Real-time computing

For real-time computing, the ESO standard platform for Adaptive Optics Real Time Control (AO-RTC) applications, in its simplified version SPARTA-Light, will be used (Suarez Valles et al., 2012). It is the standard platform for building small/medium AO-RTC and is used also for GRAVITY's infrared wavefront sensors. SPARTA-Light is well suited for a loop rate of  $> 500$  frames/s and an RTC latency of  $\leq 1$  ms, as required for NAOMI. Furthermore SPARTA will include the possibility of implementing the software de-rotation concept and can host a piston removal algorithm and chopping control.

Figure 5. The software de-rotation performance as a function of rotation angle for the three DM configurations controlling 15 Zernike modes (pure Zernike,  $5 \times 5$  and  $9 \times 9$  actuators for the deformable mirror) is plotted. The simulations have been obtained in  $H$ -band with  $6 \times 6$  pixels per sub-aperture at 1 arcsecond seeing conditions with a wavefront sensor data delay of 3 ms. The Strehl ratio varies between 51.4% and 50.2%. This is less than 2% (relative) and hence the result shows no significant loss in performance due to the rotated pupil images.



### Software architecture

The NAOMI-related software architecture can be split into different layers or modules: the RTC software, the NAOMI control software, the telescope control software and the VLTI interferometer supervisor software (ISS). The NAOMI software is a subsystem of the auxiliary telescope control software (ATCS) as depicted in Figure 6. It includes a high-level control component responsible for driving the AO software and all additional hardware devices like the filter wheel and the pupil alignment function. The AO software is based on the SPARTA software, providing the coordination components running on the NAOMI workstation and a real-time part executed by the RTC. The RTC software processes the data coming from the WFS camera and calculates the commands to be applied to the corrective optics. The auxiliary telescope control software will be updated to support the new calibration and alignment procedures required by NAOMI. The selected architecture minimises the changes to the interface between the interferometer supervisor software and the auxiliary telescope control software.

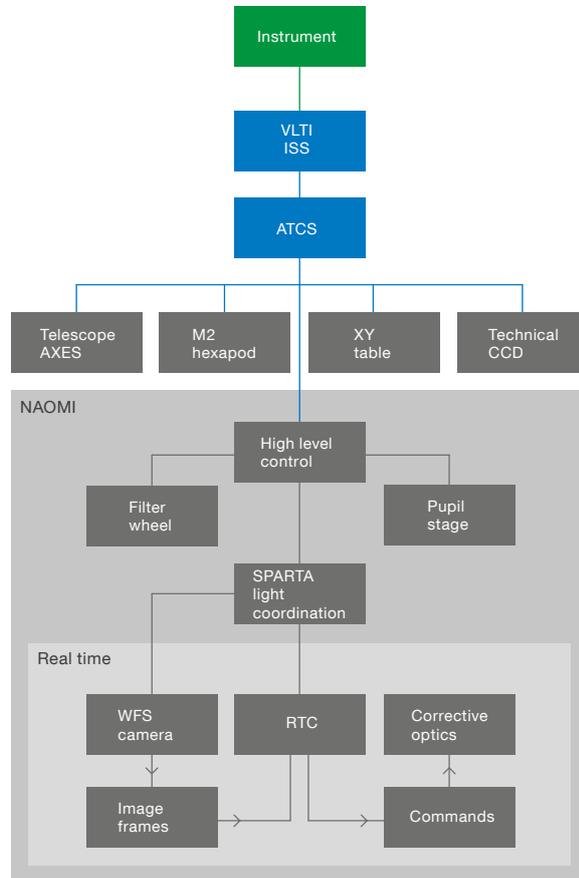


Figure 6. Flowchart of the NAOMI software design within the VLTI software architecture.

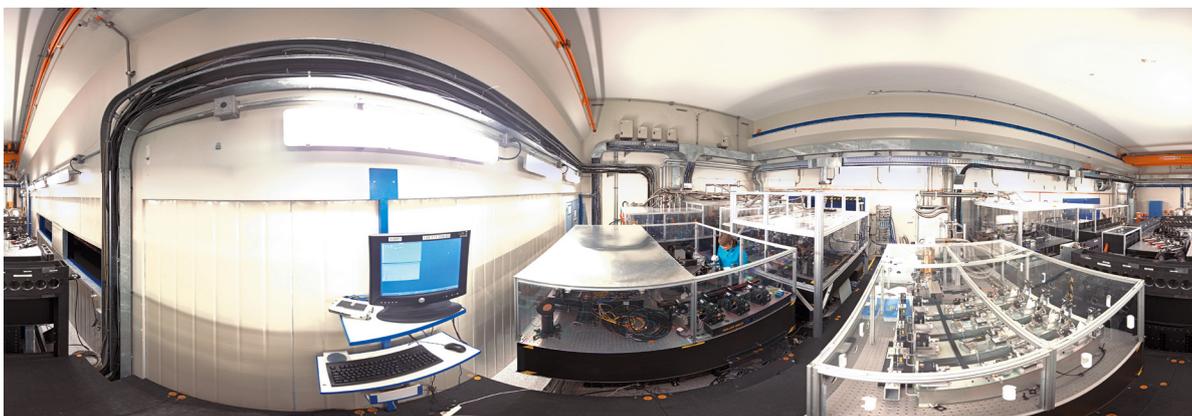
### Project schedule

NAOMI was originally proposed in 2008. The project held a design review in March 2011 presenting a conceptual design and its scientific and technical rationale. NAOMI is now being promoted due to the upcoming second generation VLTI instru-

ments. The current timeline foresees the preliminary design review by the end of this year, the shipment of a first system to Paranal in 2016 with the installation of the remaining three systems by the end of 2017.

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360-degree panorama image of the Very Large Telescope Interferometer (VLTI) underground laboratory.