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Bringing the New Adaptive Optics Module for Interferometry (NAOMI) into Operation

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NAOMI was developed by a consortium composed of IPAG and ESO. Its Provisional Acceptance Chile review was held in April 2019. The NAOMI systems that have been installed on the Auxiliary Telescopes make the Very Large Telescope Interferometer (VLTI) and its instruments much less dependent on the atmospheric and dome seeing conditions. NAOMI increases the interferometer's operability and improves the performance of its instruments and, very early on, was identified as being critical to the VLTI. In this article, we review the project, describe its principles and architecture, and offer a preview of the improvements it brings to VLTI instruments.

Context

Adaptive optics were considered for interferometric instruments even before non-interferometric instruments, as the measurement of high-quality interferometric observables depends strongly on the wavefront quality. Therefore, the implementation of the adaptive optics (AO) systems on the Auxiliary and Unit Telescopes (ATs and UTs) of the VLTI has been recommended ever since the launch of the VLTI project (Beckers, 1990). Consequently, between 2003 and 2005 the UTs were equipped with the visible Multi-Application Curvature Adaptive Optics systems (MACAO; Arsenault, 2003); later, in 2016, the UT AO coverage was extended into the infrared with the Coudé Infrared Adaptive Optics system (CIAO; Scheithauer, 2016).

The Auxiliary Telescopes

Although the design concept for the ATs developed by the Institut de Radioastronomie Millimétrique (IRAM; Von Der Lühe, 1997) included an AO system, this was omitted when construction started owing to a lack of resources, both in terms of personnel and funds. Instead, a tip/tilt corrector based on the System for Tip-tilt Removal with Avalanche Photodiodes (STRAP; Bonaccini, 1997) and a fast steering mirror was studied and implemented (Koehler, 2002, 2004). The ATs, depicted in Figure 1, each have a primary mirror of 1.8-metre diameter. They are

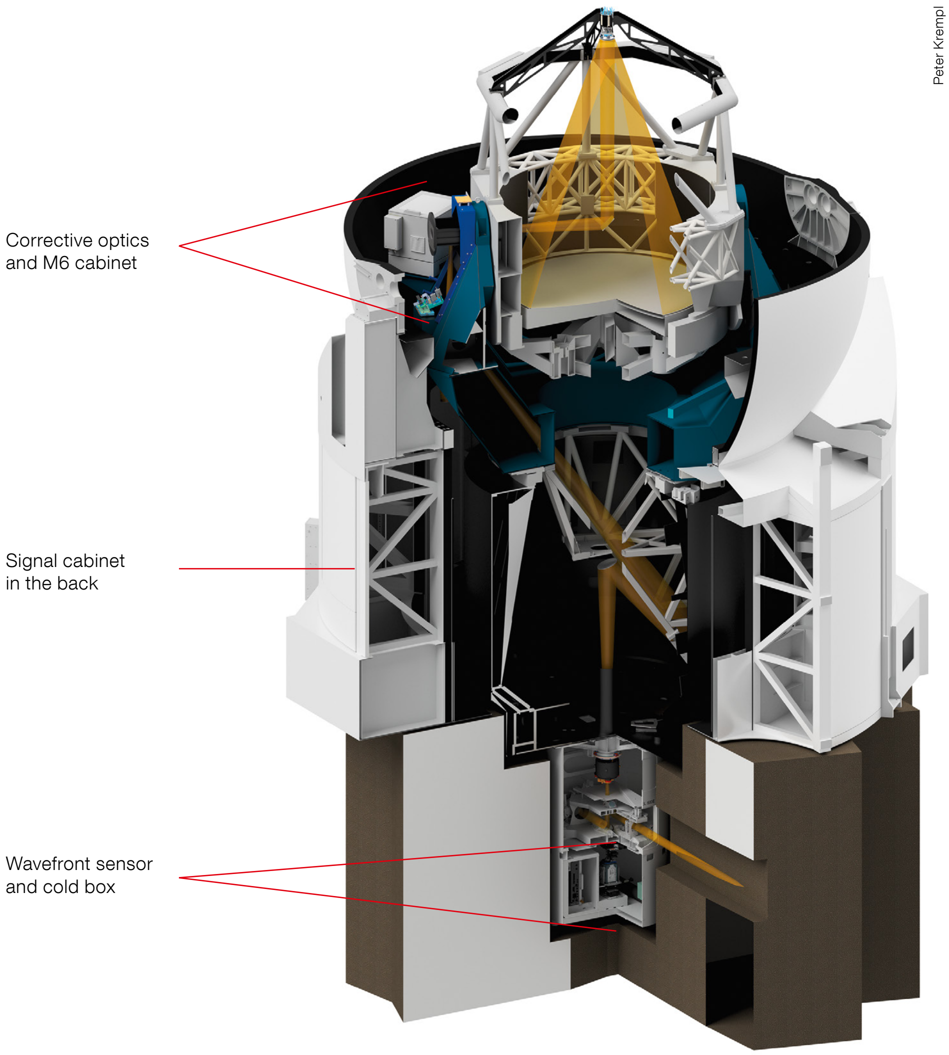


Figure 1. 3D cross-sectional view of an AT showing the locations of the NAOMI components. The corrective optics and its electronics are implemented at the level of the azimuth; the wavefront sensor and its electronics are implemented in the lower part of the Relay Optics Structure. The real-time computer and the remaining control electronics are implemented in the signal cabinet.

used by the VLTI for around 75% of the available nights.

NAOMI

NAOMI has completely replaced STRAP and is now the only wavefront correction system available on the ATs. It has three main components that are fully embedded in the telescopes: a wavefront sensor; a deformable mirror; and a real-time computer. The wavefront sensor was developed at ESO headquarters; it is a Shack–Hartmann Sensor sensitive to visible wavelengths with a 4 × 4 lenslet array, of which 12 sub-apertures are used. The low number of sub-pupils was driven by the requirement to maintain a high sensitivity for the VLTI-AT array. The detector is an off the shelf EM-CCD camera iXon ultra 897 developed by ANDOR (UK). The wavefront sensor is also integrated on a field-tracking stage to pick up the correct field. A neutral density filter wheel has been integrated just above the wavefront sensor to adjust the illumination in case of high flux, and a notch filter has been integrated into the wavefront sensor optics to reject any contamination from the lasers of the Adaptive Optics Facility (AOF; Arsenault, 2017) implemented on UT4. The full wavefront sensor and its filter wheel are installed in the lower part of the Relay Optics Structure. It receives the visible part of the light after the M9 dichroic mirror which redirects the infrared component to the VLTI instruments.

The corrective optics (Le Bouquin, 2018), developed by IPAG, consist of a deformable mirror (DM241), which has 17 actuators across its clear aperture, produced by ALPAO France, and which is integrated in a motorised gimbal mount. It is installed at the M6 pupil location in the coudé train. In addition to compensating for atmospheric turbulence, it provides the chopping capability required by MATISSE. The DM241 has a clear aperture of 37.5 mm, but NAOMI uses only the central part over a 28-mm (11-actuator) diameter pupil as seen in Figure 2 (right).

The deformable mirrors were characterised at room temperature at IPAG and then in a thermal chamber between 5 and 20 degrees C at ESO headquarters. The outcome convinced the project team that a temperature-controlled calibration bench was necessary at Paranal. IPAG finalised this bench, which is now used as a maintenance tool on Paranal. We discovered on Paranal that the deformable mirror had a more complex thermal dependence than previously understood and that the mirror displayed unpredictable behaviour. It is therefore necessary to calibrate the deformable mirror on sky at each target acquisition. The result of the characterisation of the mirrors was presented at the Adaptive Optics for Extremely Large Telescopes (AO4ELT) conference in June 2019[1] (see Haguenauer, 2019).

The real-time computing unit is based on the ESO-standard SPARTA Light platform (Suárez Valles, 2012) and has been customised by PACTUM Ltd for the NAOMI project. It uses the same platform as for the CIAO of the UTs, which facilitated its development in Garching and simplifies the operation on Paranal. The hardware is implemented in the electronics rack of the signal cabinet (see Figure 1). This unit makes the acquisition on the Shack–Hartmann Sensor, analyses the wavefront aberration and the pupil derotation to be corrected, calculates the correction to be applied to the deformable mirror and then sends the command to the mirror. Since the deformable mirror and the

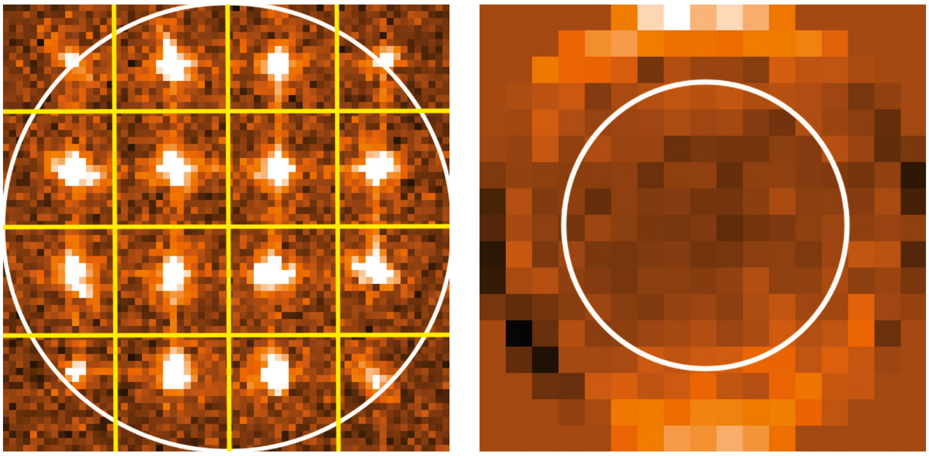


Figure 2. Real-time displays from the real-time computer. The left picture shows the Shack–Hartmann image. The four unused spots at the corners are vignetted at more than 50% by the pupil (represented by a white circle). The sub-apertures are represented in yellow. The picture on the right shows the voltage applied to the actuators of the deformable mirror, the white circle indicating the pupil footprint.

ANDOR camera are commercial products, interfaces between SPARTA light and these components had to be developed. The real-time computer measures 24 gradients on the wavefront sensor at a frequency up to 500 Hz and corrects up to 14 modes on the deformable mirror depending of the brightness of the star.

Manufacturing, Assembly, Integration and Testing (MAIT)

The MAIT phase began in January 2017 with several activities in parallel. IPAG worked on the deformable mirror characterisation, the corrective optics integration and its dedicated electronics while ESO worked on the wavefront sensor, the electronics, the real-time computer, the software and the test bench. The integration and alignment of the NAOMI test bench were carried out by members of the ESO Mechanical Engineering and Optical Engineering Departments. The goal was to replicate as accurately as possible the behaviour of an on-sky target in the laboratory as it would be observed by an AT at Paranal.

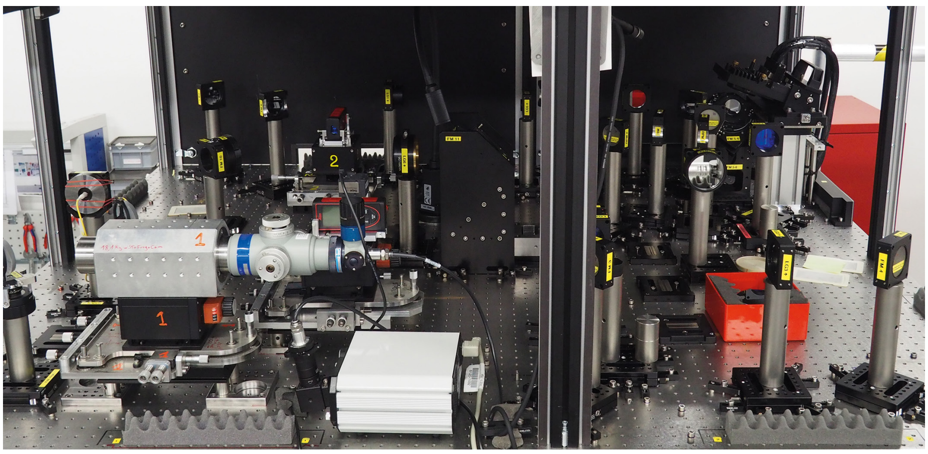
The bench consisted of an optical table and a replica of the Relay Optics Structure used by the AT. The optical table facilitated simulation of sky and AT behaviour. An artificial on-sky target was created via a monomode fibre connected to a halogen lamp. A pupil mask was used to define the spider of the AT (the spider is the strut that supports the mirror) while the deformable mirror itself simulated the atmospheric turbulence thanks to its high density of actuators. IPAG provided phase maps for different levels of turbulence which were run in parallel to the applied correction by the AO loop. This approach was much more flexible and more useful than using a turbulence generator with phase plates. Finally, a derotator integrated into the Relay Optics Structure was used to create the pupil rotation on the wavefront sensor to be fully representative of the Paranal conditions. An infrared camera was integrated into the bench to record the resulting star-like image. This same camera was later re-used during the Assembly, Integration and Verification (AIV) phase for the stand-alone characterisation of NAOMI on sky.

The NAOMI software is fully embedded in the AT software. It was developed in the control model implemented at ESO headquarters before being tested on the NAOMI test bench. The ESO software department obtained two years of external support from CNRS in order to ensure the project team had the required skills. The real-time computer software followed the same approach with model-based testing before its integration onto the test bench and was delivered by PACTUM Ltd.

A prototype of the wavefront sensor was first developed to validate the optomechanical concept as well as the integration and alignment procedure. The required mechanical improvement to the design was then made by KRP Mechatec GmbH who also provided the tooling required for the MAIT and the AIV. The electronics development and integration were supported by the electronics groups at ESO in order to account for the evolution of the ATs and to conduct a thorough analysis of the cabling and interface.

The system test began in November 2017, led by the system engineer and the AO engineer while other team members produced and tested the final versions of the electronics, wavefront sensors and corrective optics. In addition to the NAOMI test bench, the project team developed dedicated test benches for the electronics, the wavefront sensor and the corrective optics. This allowed the

Figure 3. NAOMI test bench in integration. The corrective optics are seen at the top right.



Emmanuel Aller Carpentier

Thibaut Moulin

Figure 4. Some of the members of the NAOMI project team during AIV; first row, from left to right: Thibaut Guerlet, Christian Soenke, Sylvain Rochat, Luis Caniguante; second row, left to right: Pascaline Darré, Pabio Gutierrez, Emmanuel Aller Carpentier, Frederic Gonté, Roderick Dembet, Stefan Huber, Alain Delboulbé, Peter Kreml, Laurent Jocou, Pierre Bourget, Sylvain Guieu, Thibaut Moulin.

verification of all of the components to be delivered to Paranal independently of the main NAOMI test bench, which was fully dedicated to the NAOMI functional and system test.

In parallel with the systems test, the AIV team and several engineers from Paranal were trained on the test bench every time a corrective optics or a wavefront sensor needed to be exchanged to ensure a high level of confidence in the procedures. Provisional Acceptance Europe, held in July 2018, concluded these system tests.

Assembly, Integration and Verification

AIV was prepared well before the arrival of the NAOMI equipment on Paranal. Several missions to Chile were necessary to verify the ATs, check the interfaces, and ensure the feasibility of the AIV plan via discussions with Paranal staff. The plan accounted for various factors, including the availability of tools such as the crane, the staff, the locations where various activities had to be performed, and the logistics of accommodating the 14-member project team at the Residencia.

It became apparent that science operations of the VLTI with ATs would have to be suspended during AIV of NAOMI; which necessitated minimising the time required for AIV. The NAOMI AIV was the first time that a system was implemented simultaneously on four telescopes at Paranal. To mitigate the risks, the main procedures were fully rehearsed before the start of AIV. The plan also included adequate contingency in the schedule, and redundancies in the staff competences.

AIV began on 6 September 2018, following a few days of preparation during which the four Relay Optics Structures were removed and transported to the New Integration Hall and the first AT was moved to the service station to allow the removal of the fast steering mirror and the implementation of the corrective optics.

Many activities were then carried out in parallel, with three teams focusing on different aspects of the implementation. The first team took care of the cooling and cabling upgrade of the Relay Optics Structure and the implementation of the NAOMI components. The second worked on the replacement and upgrade of the electronics cabinets while the third focussed on the internal re-alignment of the ATs with the corrective optics (Figure 5). With so many activities in parallel, regular reorganisation and reassignment of tasks was necessary, requiring the staff to be flexible.

The assembly and integration part of the AIV proceeded faster than planned, and on 18 September the first AT was ready for the first stand-alone verification on sky, during which the functionalities and AO performance could be evaluated (see Figure 6). Soon after, two telescopes were available for verification working together with the VLTI. It was impressive to see the NAOMI team simultaneously in the New Integration Hall, in the AT Service station, in the VLTI building, and in the Control Room working hard toward getting the first closed-loop with NAOMI. The AIV included 32 missions from Europe, with an average of nine project members working at Paranal over a two-month period.

Julien Woillez

Figure 5. Intervention at the beginning of the night on the corrective optics of AT4 conducted by Pascaline Darré and Sylvain Guieu.

Pierre Haguenauer

Figure 6. Acquisition of a star with the infrared Strehl camera (*H*-band) in open loop (left) and in closed loop (right) for quasi-instantaneous Strehl measurement (50 ms integration time) during the stand-alone verification of AT1.

Commissioning

The NAOMI project had two commissioning periods led by IPAG and supported by ESO; these involved 14 missions. During this time NAOMI was also commissioned on the current instrument suite at VLTI: GRAVITY (GRAVITY Collaboration et al., 2017), the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE; Lopez, 2014) and the Precision Integrated Optics Near Infrared ExpeRiment (PIONIER; Zins, 2011). Commissioning began with the first light of NAOMI using the four ATs and GRAVITY on 20 October. It was dedicated to verifying functionality with the VLTI and ensuring stable operation. In order to measure how NAOMI improved the performance of the PIONIER and GRAVITY instruments, several indicators were monitored, including throughput, flux drop-out estimators and fringe tracking residuals. All measurements were compared against tip/tilt-only correction. The chopping capability was functionally tested with MATISSE. The reliability of the NAOMI system was analysed and found slightly non-compliant owing to a few issues that had a minor impact on operation. At the end of the first commissioning on 17 November the ATs were transferred back into science operation.

The ESO team with the support of IPAG continued to follow the performance of NAOMI closely during these operations. The team made extensive use of the Garching Remote Access Facility before the second commissioning, in order to solve issues discovered by the Paranal operation team.

The second commissioning period, which began on 25 February 2019, focused on the VLTI instrument performance gains resulting from NAOMI, in particular the improvement for faint stars, with lower than average seeing and the AT dome seeing effect. NAOMI greatly improves the injection flux in the spatial filters and/or the fibres of the interferometric instruments. It improves the signal to noise of each instrument and significantly reduces the loss of fringes on the Gravity Fringe Tracker. NAOMI is much more robust to atmospheric conditions than STRAP. It corrects the dome seeing observed with low wind conditions and corrects the atmospheric seeing well above 1.4 arcseconds. The performances of VLTI instruments with NAOMI are detailed in Woillez et al. (2019).

Operations

NAOMI is now fully integrated in the operation of the VLTI. A typical observing night always follows the same procedure: two hours before sunset, the VLTI start-up procedure is launched, the functionalities of each subsystem are automatically verified, and the optical path is validated up to the InfraRed Imaging Sensor (IRIS; Gitton, 2004) in the VLTI Laboratory — allowing the verification of the alignment of the pupil and of the field. After twilight, the first preset on the selected target can be launched by the instrument. The sky coordinates are sent to the VLTI which propagates them to each AT.

NAOMI has a specific acquisition procedure called discoball to detect any object within 22.4 arcseconds. This permits precise centring of the AT in the 6-arcsecond acquisition field of view of NAOMI and subsequent closing of the loop. The field of view in the closed loop is 2.25 arcseconds. The full process between the launch of the preset and the closed loop is automatic, requiring approximately 140 seconds. A manual procedure can be used for very specific targets, such as a close binary. At the end of the night, the NAOMI system is automatically re-checked while the ATs are being closed and set in standby mode for the day. The day team then checks the calibration data and applies any corrections that may be needed before the next VLTI start up.

All the telescopes used by the VLTI are now in operation with adaptive optics systems as recommended by Pierre Léna (Léna, 1987) and Jacques Maurice Beckers (Beckers, 1990); we remain indebted to them for their vision.

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Links

[1] Adaptive Optics for Extremely Large Telescopes Conference (A04ELT) held in Québec City, Canada in June 2019: http://ao4elt6.copl.ulaval.ca/