NAOMI: a New Adaptive Optics Module for Interferometry

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ABSTRACT

The New Adaptive Optics Module for Interferometry (NAOMI)[1] is the future low order adaptive optics system to be developed for and installed at the ESO 1.8 m Auxiliary Telescopes (ATs). The four ATs[2] are designed for interferometry which they are essentially dedicated for. Currently the AT's are equipped with a fast, visible tip-tilt sensor called STRAP[3] (System for Tip/tilt Removal with Avalanche Photodiodes), and the corrections are applied through a tip-tilt mirror.

The goal is to equip all four ATs with a low-order Shack-Hartmann system operating in the visible for the VLTI dual feed light beams in place of the current tip-tilt correction. Because of the limited size of the ATs (1.8m diameter), a low-order system will be sufficient. The goal is to concentrate the energy into a coherent core and to make the encircled energy (into the single mode fibers) stable and less dependent on the atmospheric conditions in order to increase the sensitivity of the interferometric instruments. The system will use the ESO real time computer platform Sparta-light as the baseline. This paper presents the preliminary design concept and outlines the benefits to current and future VLTI instruments.

Keywords: Interferometry, adaptive optics, VLTI, ESO

1. 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. The present system provides a good correction in the K and N bands under good seeing conditions. but as soon as the seeing degrades below 1, the instantaneous Strehl delivered by the telescopes degrades significantly and the energy injected into the single mode fibers of the interferometric instruments decreases and becomes very unstable, making the observations difficult or impossible (e.g.: the quality of the PIONIER data degrades, the PRIMA fringe sensors stop providing reliable fringe locks for astrometric observations or in support to MIDI. The new generation of VLTI instruments, GRAVITY and MATISSE through its fringe tracker, would be equally impacted).

Three main factors delimit the wavefront quality and are an impediment to the successful execution of demanding scientific observations:

- The internal stability of the telescope which implies an important variability in the quasi-static wavefront error, mainly focus.
- Nights with poor seeing for which the seeing can not be enhanced by tip/tilt correction.

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- Nights with good seeing and low winds but with an important contribution of the ground layer which produces a slow evolving speckle pattern due to thermal effects ("boiling effect").

Sensitivity is generally associated to the notion of limiting magnitude; this is not what NAOMI is going to improve, at least directly. NAOMI will improve the coherent flux delivered by the AT when observing bright and intermediate magnitude objects (R <13-14, see the intersection between STRAP and NAOMI 4x4 subapertures in figure 2). For these brighter objects, the consequence of this will be twofold:

- First, it will improve the precision of the interferometric measurements, by increasing the number of coherent photons at each telescope. The performance increase will be directly proportional to the mean Strehl increase. Alternatively, one could also reduce the duration of an observation by that same factor, if working in a photon limited regime.
- Second, it will enable robust fringe tracking by forcing the coherent flux to stay at any time above a minimum threshold. Robust fringe tracking, in turn, could mean: either an improve sensitivity for mid-IR instruments (MATISSE), or the possibility to increase the spectral resolution while increasing the exposure time. Indirectly, fringe tracking could also open the door to direct sensitivity improvements, if implemented with dual-field operation.

The global improvement brought by NAOMI are necessary to reach the full performance of the second generation instruments GRAVITY[4] and MATISSE.[5]

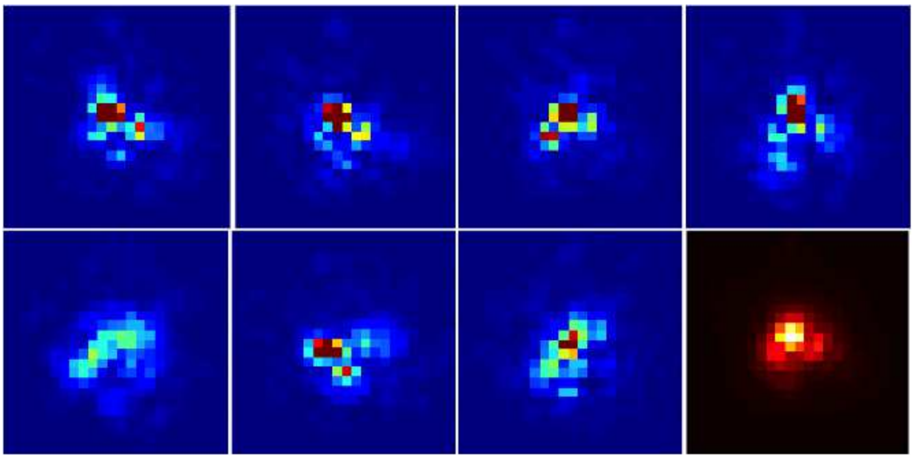

Figure 1. Sequence of images for an AT seen on IRIS[6] (IR tip-tilt sensor placed in the VLTI laboratory) during boiling conditions (seeing between 0.6 and 0.8 arcsec, wind speed between 0.4 and 2 m/s). The image exposure time is 0.015 s and the time between successive images is approximately 1.5 s. Lower right, different color map, image is a long exposure image (10 s integration time), displayed with a different color scale. A strong speckle pattern is present, evolving slowly in time, meaning that either large quasi-static aberrations are caused by the optics or that a turbulence is locally developing.

2. SYSTEM REQUIREMENTS

NAOMI is required to deliver to the VLTI a corrected wavefront after the dichroic M9 of the AT at wavelengths between 1 and 20 μm. Therefore it will operate a visible wavefront sensor working in any natural guide stars (NGS) located in within 2 arcmin diameter FOV of the Coude.

NAOMI will provide a compensated wavefront (at AT coude level) with an average Strehl ratio larger than 30% in the H-band at 1.65 μm under median Paranal seeing conditions along the line-of-sight on an NGS m_R = 10 during an exposure of 10 minutes (excluding the contribution from anisoplanatic effects).

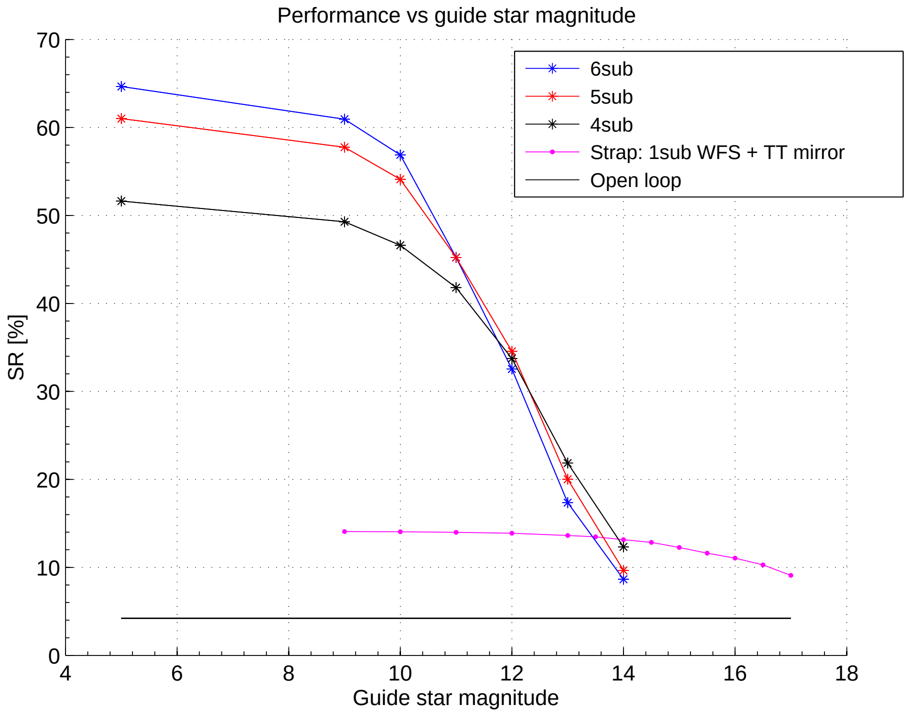

Figure 2. NAOMI performance simulation results showing the Strehl ratio as a function of guide star magnitude for three simulated sub-aperture configurations, 4x4, 5x5 and 6x6. The Strehl ratio was obtained on-axis in the H-band with a 6x6 pixel subaperture, 1 arcsecond seeing, overall delay of the wavefront 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.

A good tip-tilt correction is required when observing low flux targets. Thus, for a NGS of $m_R = 15.5$ a residual jitter no larger than 0.14 arcsec (rms) on the sky over a period of typically 1 min is necessary.

The previous requirements have to be obtained keeping the actual chopping capability as required by the MATISSE science goals (± 6 arcsec, 1-5 Hz).

Due to the size of the ATs (1.8-metre diameter primary mirror), a low-order SCAO system is sufficient to meet the required performance. A trade-off analysis help selecting a 4x4 subaperture system operating at up to 500 Hz frame rate as baseline concept.

Figure 2 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 are within the specifications for high flux and about half of the performance is reached for guide stars of magnitude ≈13.

3. AUXILIARY TELESCOPES AND INTERFACE

Part of the VLTI interferometer consists of 4 UTs telescopes (8 m) and 4 ATs (1.8 m). The Auxiliary Telescopes can be placed at several locations in the platforms (the so-called stations). Depending on the type of observation requested, the ATs will be placed in different configurations and change of station moving through a rail system which connects the stations.

The ATs send the light collected to the coude focus through the optical path shown in figure 3. The dichroic sends the IR light to the VLTI tunnel to feed the interferometric instruments while the visible light is used for the wavefront sensing directly at the coude.

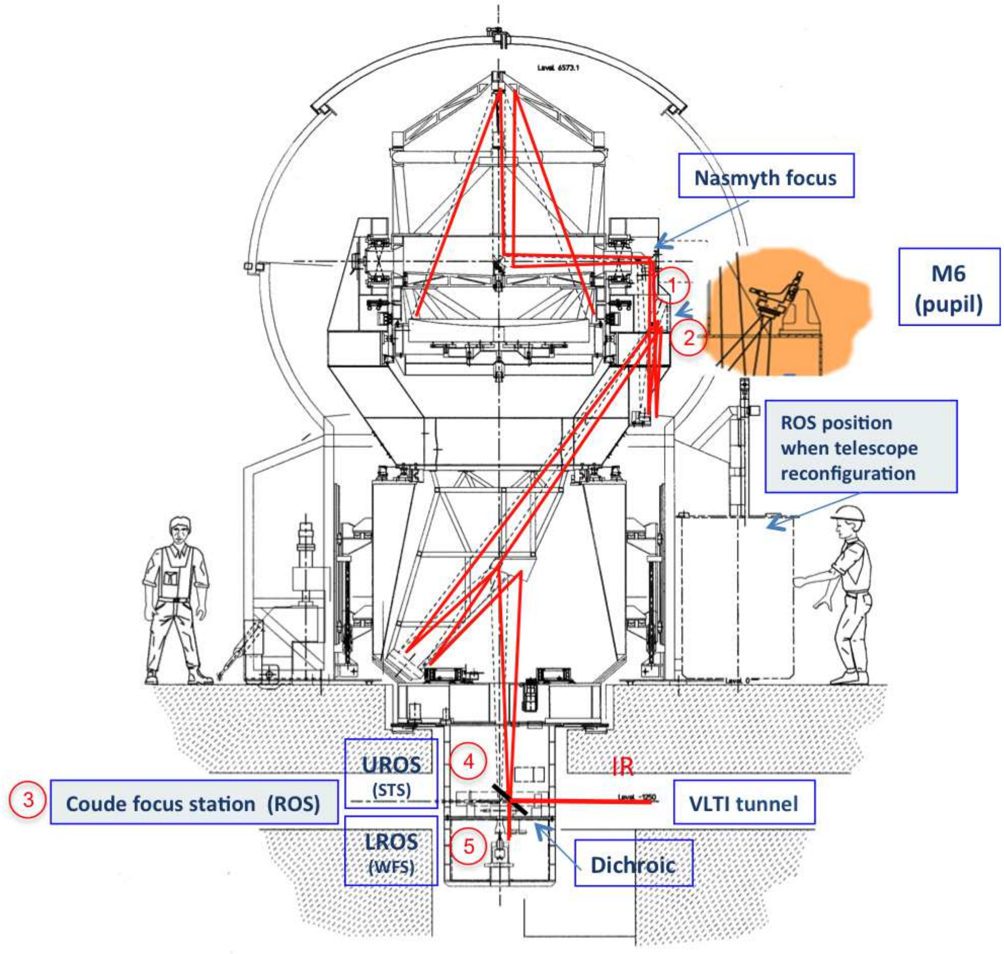

Figure 3. Auxiliary telescope layout. The optical path is shown as well as the main interface components.

An intermediate pupil in the coude optical train located after the Nasmyth focus (1) is used to place the actual steering mirror M6 (2). This mirror is driven by STRAP signals in order to provide the tip-tilt correction (and chopping). NAOMI will reuse this intermediate pupil to replace the steering mirror by a corrective optics device with full AO capabilities and chopping.

The corrective optics will be operated facing down tilted by 15^o from incidence and 20^o from vertical. The pupil is located in a diverging beam with an average diameter of 28 mm. The corrective optics will rotate with the telescope azimuth. A rack close to the corrective optics is foreseen to allocate the corrective optics electronics.

The coude focus is located (as well as in the UTs) under the floor level. For each station there is an allocated volume under the floor for the coude focus. The optomechanical components of the coude focus are allocated in an independent mechanical box, the so-called, ROS (*Relay Optics Structure*) (3). When the ATs need to travel, the ROS is recovered by the AT from the current station and moves together up to the new station. On this point, the ROS is placed in the station and the AT position is readjusted to match the ROS axe.

NAOMI will be designed for the new dual feed ROSs[7] (which offer two interferometrical channels). The ROS is split in two volumes:

- *The Upper-ROS* (4): Volume allocated by the relay optics that send the beam to the VLTI tunnel. The upper ROS of the DF-ROS allocates the derotator, the dichroic and the star separator.

- *The lower-ROS* (5): This volume is fed with the visible light and is foreseen to allocate the AO WFS. Currently, the volume is used by the STRAP sensor which is placed in a X-Y stage table used as field selector (guide star tracking).

A dedicated control cabinet is placed in the side of the telescope for the telescope LCU units and where the *Real-time control unit* will be placed. This cabinet is connected to the ROS and to the M6 cabinet via cables and fiber connections.

Figure 4. An auxiliary Telescope with the lifted ROS module ready to be moved to a different baseline position.

4. NAOMI PRELIMINARY DESIGN

4.1 Operational modes

NAOMI will serve several VLTI 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 include after the guide star acquisition an additional step, the so-called "active telescope compensation". In this step the wavefront sensor will be operated in open loop mode at low frequency. The low-order aberrations of the telescope (tip-tilt, focus and coma) will be measured and averaged out during several seconds in order to partially average the effects of the atmosphere. The corresponding offsets will then be sent to the telescope control system to be corrected by the XY-table and by the M2 mirror. This step can be applied between observational preset in order to compensate for the pointing errors and to avoid the corrective optics working far from the middle range.

NAOMI will provide two guiding modes for the telescope:

- *Full Adaptive optics mode.* This is the "normal" mode of NAOMI foreseen to compensate the full atmospheric turbulence, wind shake and quasi-static telescope errors. The wavefront sensor and corrective optics are working in closed loop on the guide star. The real-time computer is controlling the whole system. If the tip-tilt is drifting, NAOMI shall off-load slow tip-tilt corrections to the axes of the telescope to keep the corrective optics in the middle of its range. Chopping capability is provide in this mode.

- *Tip-tilt mode.* This mode is intended for operation in N-band with MIDI and MATISSE. At this wavelength, the 1.8m telescopes are diffraction limited and adaptive optics is not fully needed. Therefore in close loop the atmospheric tip-tilt turbulence and the telescope wind shake are corrected. Chopping capability is provide in this mode.

4.2 Corrective optics concept

NAOMI will replace the current tip/tilt mirror in the intermediate pupil plane with a corrective optics unit. 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. For this purpose the corrective optics should offer a mechanical stroke (PtV) of 14 μm (not including the chopping). In case the corrective optics consists of a single deformable mirror, then the stroke required is 37 μm in order to achieve the chopping capability (chopping requirement of $\pm$ 6 arcsec in sky).

ESO has launched 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, preproduction unit, manufacturing, assembly, integration and testing of the five to six corrective optics units according to the technical specification.

4.3 Wavefront sensor module

The NAOMI Shack-Hartmann wavefront sensor will sense the visible light transmitted by the dichroic using an array of 4x4 subapertures (12 valid subapertures within the pupil). The wavefront sensor will use 16x16 pixels per sub-aperture, providing a large field of view to be used for star acquisition and open loop operations (active telescope compensation). On the guiding modes (closed loop operations), a window of 6x6 pixels will be sufficient to sense the wavefront distortions. The optimal pixelscale was defined at 0.5 arcsec/pixel. 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. As an example, Andor provides a detector with 128x128 pixels and 24 μm pixel size. This camera has already been used for some prototyping work. Andors iXon3 860 (figure 5) 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^o 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[8] developed by the ESO Detector Department. This card picks up the data via a low voltage differential signalling interface and sends it out as a serial front panel data port pixel stream compatible with SPARTA-Light.

4.4 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[9] will be used. It is the standard platform for building small/medium AO-RTC and is used also for GRAVITYs infrared wavefront sensors. SPARTA-Light is well suited for a loop rate of $>$ 500 frames/s and an RTC latency of $<$1 ms, as required for NAOMI. Furthermore SPARTA will include the possibility to implement the software derotation concept and can host a piston removal algorithm and chopping control.

Figure 5. The package view of Andor IXon3 860: a possible wavefront sensor camera for NAOMI.

4.5 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

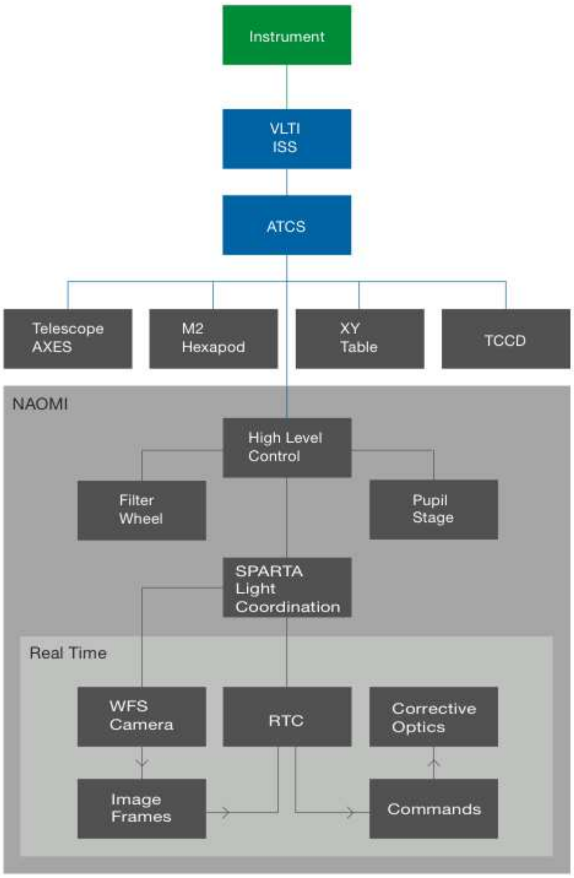

Figure 6. Flowchart of the NAOMI software design within the VLTI software architecture.

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 derotate the commands applied 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 simulations showing no significant loss of performance over a full rotation. More details can be found in this same conference (9148-159, *"A software based de-rotation algorithm concept for the new adaptive optics module (NAOMI) for the auxiliary telescopes of the VLTI."*).

4.6 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. The NAOMI software is a subsystem of the auxiliary telescope control software 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.

5. 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 instruments. The current timeline foresees 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.

REFERENCES

1. R. Dorn and . Aller, E. et Al, “NAOMI: a New Adaptive Optics Module for Interferometry,” *ESO, The Messenger* **156**, 2014.
2. B. Koehler and C. Flebus, “VLTI auxiliary telescopes,” in *Interferometry in Optical Astronomy*, P. Léna and A. Quirrenbach, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **4006**, pp. 13–24, July 2000.
3. D. Bonaccini, D. Gallieni, R. Biasi, F. Gori, M. Ghioni, C. Trottier, and N. N. Hubin, “STRAP for the VLT instruments [3126-77],” in *Adaptive Optics and Applications*, R. K. Tyson and R. Q. Fugate, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **3126**, p. 580, Oct. 1997.
4. F. Eisenhauer, G. Perrin, W. Brandner, C. Straubmeier, K. Perraut, A. Amorim, M. Schöller, S. Gillessen, P. Kervella, M. Benisty, C. Araujo-Hauck, L. Jocou, J. Lima, G. Jakob, M. Haug, Y. Clénet, T. Henning, A. Eckart, J.-P. Berger, P. Garcia, R. Abuter, S. Kellner, T. Paumard, S. Hippler, S. Fischer, T. Moulin, J. Villate, G. Avila, A. Gräter, S. Lacour, A. Huber, M. Wiest, A. Nolot, P. Carvas, R. Dorn, O. Pfuhl, E. Gendron, S. Kendrew, S. Yazici, S. Anton, Y. Jung, M. Thiel, É. Choquet, R. Klein, P. Teixeira, P. Gitton, D. Moch, F. Vincent, N. Kudryavtseva, S. Ströbele, S. Sturm, P. Fédou, R. Lenzen, P. Jolley, C. Kister, V. Lapeyrère, V. Naranjo, C. Lucuix, R. Hofmann, F. Chapron, U. Neumann, L. Mehrgan, O. Hans, G. Rousset, J. Ramos,

M. Suarez, R. Lederer, J.-M. Reess, R.-R. Rohloff, P. Haguenauer, H. Bartko, A. Sevin, K. Wagner, J.-L. Lizon, S. Rabien, C. Collin, G. Finger, R. Davies, D. Rouan, M. Wittkowski, K. Dodds-Eden, D. Ziegler, F. Cassaing, H. Bonnet, M. Casali, R. Genzel, and P. Lena, "GRAVITY: Observing the Universe in Motion," *The Messenger* **143**, pp. 16–24, Mar. 2011.

5. S. Lagarde, S. Robbe-Dubois, R. G. Petrov, B. Lopez, W. J. Jaffe, L. Venema, P. Berio, P. Antonelli, U. Beckmann, F. C. Bettonvil, U. Graser, R. Navarro, and A. Matter, "MATISSE: concept, specifications, and performances," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8445**, July 2012.
6. P. B. Gitton, S. A. Leveque, G. Avila, and T. Phan Duc, "IRIS: an infrared tilt sensor for the VLTI," in *New Frontiers in Stellar Interferometry*, W. A. Traub, ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5491**, p. 944, Oct. 2004.
7. F. Delplancke, J. Nijenhuis, H. de Man, L. Andolfato, R. Treichel, J. Hopman, and F. Derie, "Star separator system for the dual-field capability (PRIMA) of the VLTI," in *New Frontiers in Stellar Interferometry*, W. A. Traub, ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5491**, p. 1528, Oct. 2004.
8. J. Reyes, M. Downing, R. Conzelmann, L. Mehrgan, J. Stegmeier, M. Todorovic, and I. Molina-Conde, "An overview of AONGC and the ESO adaptive optics wave front sensing camera," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8447**, July 2012.
9. M. Suárez Valles, E. Fedrigo, R. H. Donaldson, C. Soenke, S. Zampieri, R. Bourtembourg, and H. Tischer, "SPARTA for the VLT: status and plans," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8447**, July 2012.