NACO performance: status after 2 years of operation

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ABSTRACT

NACO is a VLT/Yepun instrument which provides adaptive optics corrected images in the near and thermal infrared. It is composed of the NAOS adaptive optics system and of an infrared imager CONICA. NACO has been operating since October 2001 and has already delivered a large amount of scientific results in various fields, eg the Solar System (Titan), the Interstellar Medium (outflows in Orion-OMC1), the Galactic Center, the central regions of AGN and ULIRG, ... We present the instrument performance in terms of image quality after two years of operation at Paranal. We first remind the system performance obtained from simulations, design, tests and compare them to the original specifications. We point out the telescope vibrations as a source of performance degradation. We then evaluate the impact of these vibrations on the Strehl ratio. We eventually analyze studies of the telescope vibrations to identify the systems that could excite the telescope vibration modes.

Keywords: adaptive optics, performance, image quality, vibrations

1. INTRODUCTION

NAOS/CONICA (hereafter NACO) is a VLT instrument installed at UT4/Yepun, Paranal Observatory. It is made of an adaptive optics (AO) system, NAOS, and an infrared (IR) camera, CONICA. NAOS has been built by a consortium of French institutes: Observatoire de Paris (LESIA, formerly DESPA), Observatoire de Grenoble and ONERA. CONICA has been made by German Max Planck institutes: Max-Planck-Institut für Astronomie in Heidelberg and Max-Planck-Institut für Extraterrestrische Physik in Garching.

NACO has been installed in November 2001. Commissioning runs have followed in 2002 and the instrument has been opened to the astronomical community in Period 70 (October 2002 - March 2003).

2. NACO PERFORMANCE: FROM THE SPECIFICATIONS TO THE FIRST RESULTS ON THE SKY

This section is a reminder of NAOS performance in terms of image quality as they were specified at the beginning of the project, modelled from simulations, expected from the design of the instrument and eventually obtained during laboratory tests and commissioning runs in 2001/2002. These results are extracted from ESO documents and part of them have already been published (Rousset et al., 2000, 2003).

2.1. NAOS specified performance

The reference conditions are given in Table 1. In these conditions, the NAOS specifications, in terms of image quality, are given in Fig. 1. For the visible wavefront sensor (WFS), an on-axis Strehl ratio at 2.2 μm of 70% for a star with m_V=10 is specified and for the infrared (IR) WFS, an on-axis Strehl ratio at 2.2 μm of 70% for a star with m_K=6.

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Table 1. Reference conditions for the visible and IR WFS specifications

	Visible WFS	IR WFS
FWHM seeing at 0.5μm	between 0.25” and 0.85”	
AO correlation time at 0.5μm	>3 ms	
Performance stability over	>20 min	
Large outer scale of the turbulence	infinite	
Telescope altitude angle	<30 deg (0 deg zenith)	
Reference source apparent diameter	from point like up to 2”	
Reference source spectrum	G0	
Reference source position	on axis	
WFS bandpass	450-900 nm	1-2.5 μm
Ground wind speed	<10 m/s	
Assumed readout noise	2 e^- at 150 Hz frame rate 3 e^- at 700 Hz 4 e^- at 1250 Hz	10 e^- at 100 Hz

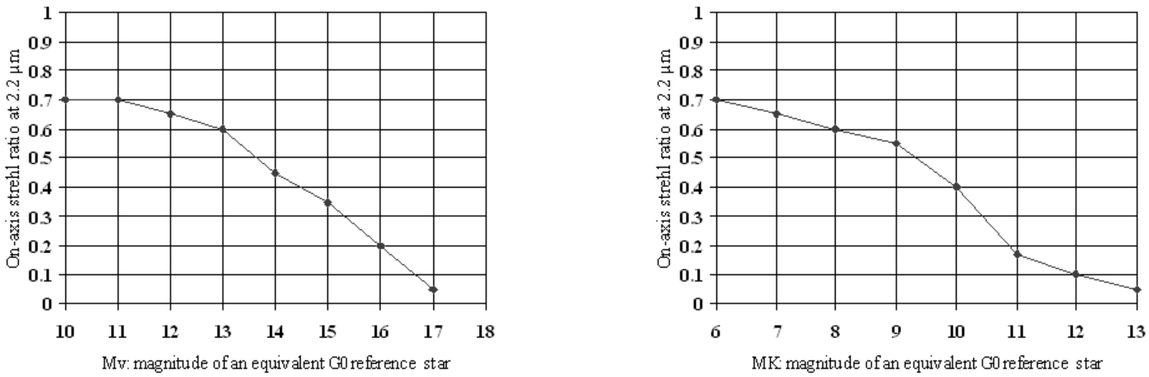

Figure 1. Strehl ratio requirements at 2.2 μm for the visible (left) and IR (right) WFS.

2.2. NAOS simulated performance

2.2.1. The visible WFS

The atmospherical conditions had been chosen after discussions between the NAOS consortium and M. Sarazin and were assumed to be representative of Paranal conditions. The seeing requirements mentioned in Sect. 2.1 had also been included. An infinite outer scale of turbulence with Kolmogorov statistics had been used. Simulations had been computed for an 8m telescope and a 1.126m central occulation.

Note that the conjugation of a seeing angle of 0.85” at a telescope altitude of 30 deg (as specified in Sect. 2.1) is equivalent to a seeing angle of 0.93” with the telescope at zenith: the Fried parameter r_0 evolves as $\cos^{3/5}(\alpha)$, where α is the zenith angle. Then a seeing angle of 0.93” and a telescope at zenith had been adopted in the simulations.

Fig. 2 summarizes NAOS performance, as predicted from simulations for a seeing angle of 0.93” (telescope at zenith) and after optimization of different parameters: Shack-Hartmann configuration (14×14 for the bright reference source case, 7×7 for the low flux case), number of pixels per subaperture, FOV per pixel, sampling frequency, threshold, loop gain. In the 14×14 configuration, there were 8 pixels per subaperture with 0.29”/pixel, the sampling frequency was ranging from 500 to 100 Hz, the threshold was equal to 6 (except for m_V=15.5 where t=2) and the loop gain was ranging from 0.5 to 0.3. In the 7×7 configuration, there were 4 pixels per subaperture with 0.55”/pixel, the sampling frequency was ranging from 350 to 75, the threshold was equal to 4 (except for m_V=17 where t=2) and the loop gain was 0.4.

As a conclusion, the simulated NAOS performance was matching the specifications at high flux. For an intermediate range of flux, $13<m_V<16$, the performances were below the specifications, as well as for lower flux. These simulations had not taken into account different error sources (such as optical surface quality, scintillation, reference and calibration quality, telescope jitter, ...) and were therefore supposed to overestimate the expected performance.

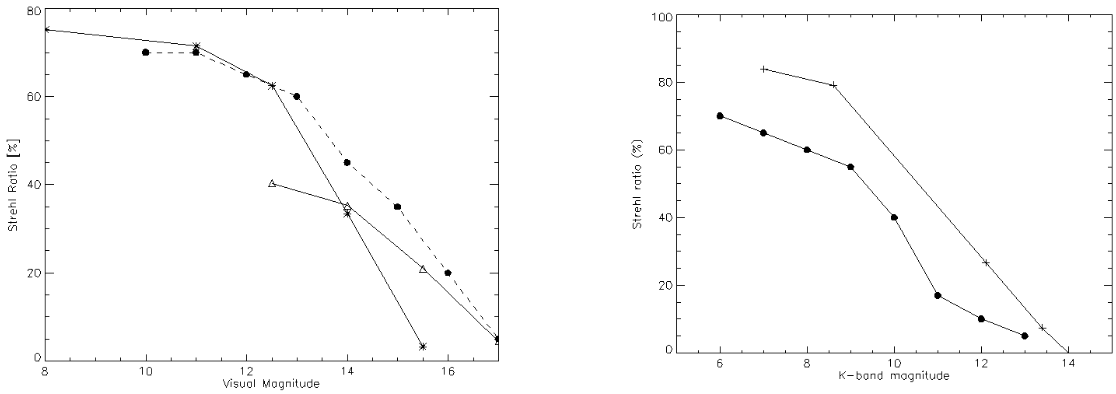

Figure 2. Left: theoretical NAOS performance for the visible WFS. Stars are for the 14×14 Shack-Hartmann configuration, triangles for the 7×7 Shack-Hartmann configuration and filled circles are the specifications given in Fig. 1. Right: theoretical NAOS performance for the IR WFS (crosses). Filled circles are the specifications given in Fig. 1.

2.2.2. The IR WFS

The performances were scaled from the simulations made for the visible WFS, taking into account the fact the performance of a WFS, whatever the bandpass it operates, is determined by the number of subapertures, the noise in the phase determination and the temporal correction bandwidth. By computing the noise in the phase determination for a given performance of the visible WFS, one can then calculate the corresponding flux level and thus the magnitudes for which the IRWFS reaches the performance formerly computed for the visible WFS. The translation of the noise into flux level into magnitudes had been made after taking into account the detector readout noise and the background emission. As a result, the theoretical performance (Fig. 2) was well above the specifications whatever the reference flux was.

2.3. NAOS performance, expected from design

This is the expected performance from the design of NAOS. The original ESO requirement was to achieve a Strehl ratio of 70% in the reference conditions (see Sect. 2.1). This specification had been divided into two contributions:

– the AO residuals, corresponding to a Strehl ration of 77.8%,

– all other contributors, corresponding to a Strehl ration of 90%.

After the design of NAOS, the expected AO residuals had lead to a Strehl ratio of 75.2%. This value, not compliant with the specification, was a direct consequence of the selection of a 14×14 lenslet configuration. This choice was a trade-off between high Strehl ratio values and a better mechanical performance: keeping the 77.8% Strehl ratio requirement would have lead to beam instabilities, which were already the major contributor to the wavefront error budget.

The expected other contributors value was 94.1% and was mainly corresponding to wavefront sensor calibration errors. Together with the AO residuals, it was giving a total Strehl ratio of 70.8%. This value was then compliant with the ESO specifications for NAOS.

2.4. NAOS performance during laboratory tests

The first estimated performance was done in closed loop without turbulence using on-line measurements of the RTC (Fusco et al., 2004). On a resolved source, the measured performance was SR=99.4% at 2.2 μm in the high flux configuration. The 0.6% loss was due to system vibrations at frequencies larger than the system bandwidth. On an unresolved source, the measured performance was 96% at 2.2 μm. The 4% loss was due to the uncentering of the spots at the cross of four pixels. NAOS ans CONICA static aberrations had been then evaluated by a phase diversity algorithm (Blanc et al., 2003; Hartung et al., 2003) and a focusing optimization. The compensation of these aberrations was not possible during the laboratory tests and the Strehl ratio without turbulence $\mathrm{SR_{noturb}}$, measured on the NAOS+CONICA PSF, was 86% with the Brackett γ filter.

Performance estimations, with a simulated turbulence, had been performed with a 0.93" seeing phase screen during the laboratory tests in Bellevue (France). For the visible WFS, the performance (Brackett γ) was $\mathrm{SR_{NAOS}}$=65% for $\mathrm{m_V}\approx$8.7, including the static aberrations (Fig. 3).

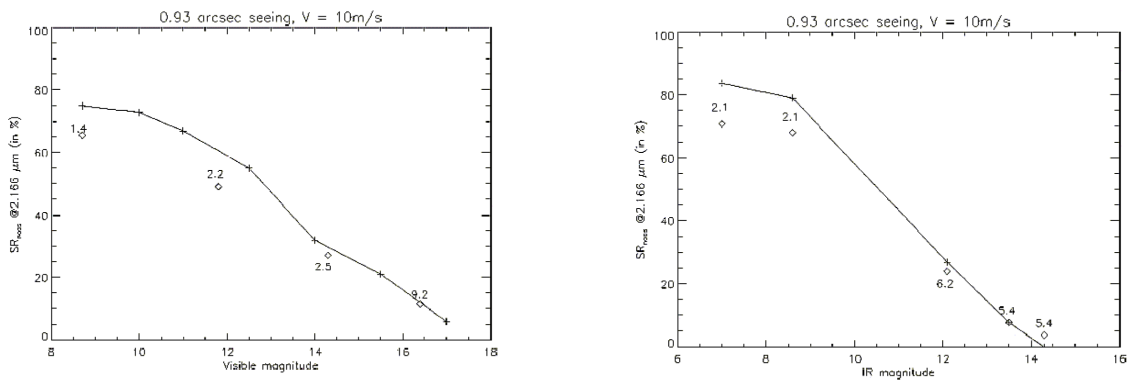

Figure 3. Left: measured visible WFS performance during the laboratory tests. Diamonds are the measurements (with the chosen VIS WFS mode). The line is the theoretical performance given in Fig. 2. Right: measured IR WFS performance during the laboratory tests. Diamonds are the measurements (with the chosen IR WFS mode), after correction for the badly optimized focus of the N20C80 dichroic. The line is the theoretical performance given in Fig. 2.

The IR WFS performance had been estimated during the Preliminary Acceptance tests (20-23 jul. 2002) using the 0.93" seeing phase screen and the N20C80 beam splitter, the defocus being not optimized for this dichroic during the tests. After estimating the effect defocus of this beam splitter (SR=79% at 2.166 μm), the performance of the IR WFS (Brackett γ filter) was found to be $\mathrm{SR_{NAOS}}$=70% for an IR magnitude of 7 (Fig. 3).

In conclusion, the compensation of the dichroic aberrations was not available in Bellevue and on-sky performance was expected to be very close to the specifications after the correction for these aberrations.

2.5. On-sky NAOS performance

2.5.1. Introduction

The compensation for static aberrations had been implemented during the commissioning runs. It resulted in an improved image quality of the internal fiber without turbulence, from a Strehl ratio of 86% (cf. Sect. 2.4) to 91%.

The full calibration of NAOS and CONICA focus and high order aberrations were only available during Commissioning 4. The performance was measured by raw CONICA Strehl ratio without any correction of possible error sources. In addition during commissioning runs 2 and 3, the poor quality of the CONICA collimator lens had reduced the performance to more than 10%. It had been replaced afterwards.

2.5.2. NAOS performance during the commissioning runs 1 to 4

Strehl ratios measured with the visible WFS are given in Fig 4. The dispersed results were mainly originating from the various seeing conditions (up to 2"), not always optimized calibrations of NAOS and the variable vibrations. The same remarks/conclusions applied to the IR WFS performance, but less measurements had been performed.

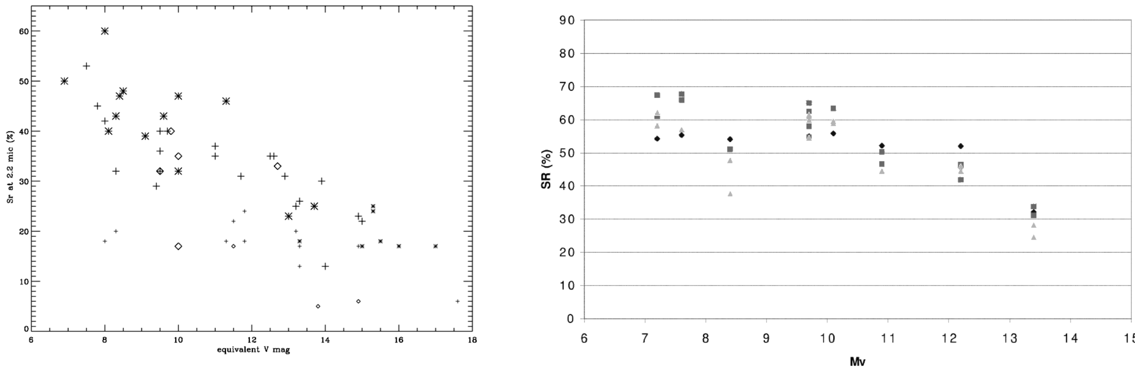

Figure 4. Left: visible WFS performance during the commissioning runs 1 to 4. Stars are for good seeing (≤0.7"), crosses for moderate seeing (≤1.1") and diamonds for poor seeing (>1.1"). Small symbols are for the 7×7 lenslet array. Right: performance during the September 2002 commissioning run 5. Diamonds are for Preparation Software measurements, squares for RTC×0.9 and triangles for CONICA images

2.6. NAOS performance during the Sept. 2002 commissioning run 5

The last Commissioning period took place in 2002 from September 17^{th} to September 29^{th}. Various interventions had been done (counter-chopping implementation, validation of the pointing model, dichroic calibration, ...) in addition to performance measurements.

Strehl ratios had been measured on both counter-chopped images and steady images for comparison. No Strehl ratio loss had been observed on the former ones. The relative NAOS/CONICA defocus has been checked. The measured Strehl ratio without turbulence was 94% (visible dichroic and WFS, Brackett γ filter), slightly better than what was obtained during the previous commissioning runs.

The performance measurements had been obtained in the following conditions: a seeing between 0.6" and 0.8", the Brackett γ filter, the S13 camera, an on axis guide star close to zenith, the visible WFS.

The performance had been evaluated though three different measurements:

– RTC measurement, always multiplied by 0.9 to take into account the almost 10% Strehl ratio loss in static aberration compensation

– computation from CONICA images (ONERA algorithm)

– Preparation Software (PS) estimation

Results are given in Fig. 4. At high flux, RTC×0.9 measurements were near the 70% ESO specifications (except for the m_V=8.4 point for which the correlation time was 2 ms in the visible).

RTC×0.9 and PS measurements were in good agreement except for high Strehl ratios, because PS had been previously adjusted to account for the vibrations observed during the commissioning runs 1 to 4. RTC×0.9 and CONICA measurements exhibited a systematic 7% error which could not originate from calibration effect since the static Strehl ratio has reached 94%.

Since the IR WFS was suffering from noise effects, only one performance measurement had been done in the same conditions (filter, camera, high flux) in the 14×14 configuration, leading to the following Strehl ratios: PS=55%, RTC×0.9=66% and CONICA=72%.

3. THE VIBRATION ISSUE

3.1. Impact on the performance

3.1.1. Measurements during laboratory tests

During the laboratory tests performed after the integration of the system, an overexcitation of the tip-tilt X axis had been observed around 80 Hz, well after the system bandwidth. This vibration was attributed to the CONICA Close Cycle Cooler (CCC) and was found to represent only a 0.5% Strehl ratio loss in case of optimal CONICA CCC functioning. When not optimal, the Strehl ratio loss had increased up to 7%.

3.1.2. Measurements during the commissioning runs

During the first four commissionning runs, several excitated frequencies had been observed, with a much greater impact than during the laboratory tests. They appeared in both open and closed loop data, were not present on the NAOS internal fiber and tests were supporting the CONICA CCC as the main exciting source of the telescope vibrations. It resulted in the reduction of the gain of the excited modes chosen by the modal optimization and then in a Strehl ratio loss. On a particular example, by comparing the residual variance found during laboratory tests and during commissioning runs, one could estimate a Strehl ratio loss of 15%. But depending on many parameters such as turbulence strength, system frequency, etc, the loss had increased up to 25%.

The frequencies with the greatest impact on performance had been observed on Tip and Tilt Zernikes . For these modes, the excited range of excited frequencies were the following (in the case of a 0.65" seeing):

– 16-18 Hz, with an estimated Strehl ratio loss between 2.5 and 8%

– 48-55 Hz, with an estimated Strehl ratio loss between 2 and 4%

– 68-70 Hz, with an estimated Strehl ratio loss between 0 and 1%

Much less vibrations had been measured during the last commissioning run in September 2002: the Strehl ratio loss decreased to 2.5/4% (Fig. 5). The reason for this improvement was not really understood and a temporary effect not excluded.

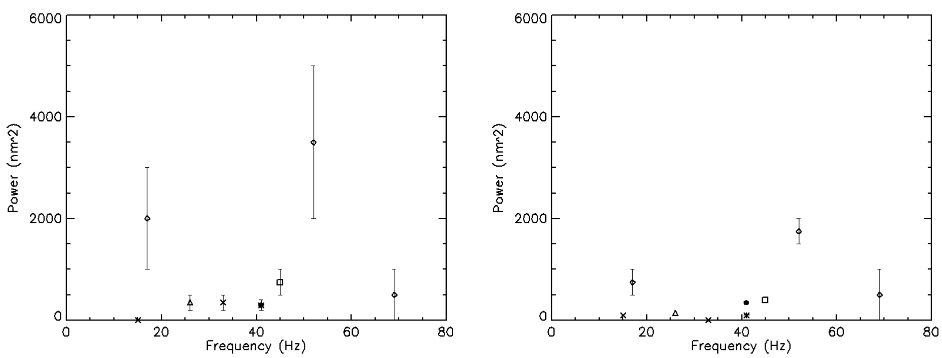

Figure 5. Left: vibration spectrum as obtained before September 2002. Right: vibration spectrum as obtained during the September 2002 commissioning run. Diamonds are for Zernike 2 and 3 (Z2/Z3), squares for Z4, triangles for Z5, crosses for Z6, stars for Z9 and filled circles for Z10. Bars represent the range of the measured values.

3.1.3. Results from dedicated tests

Since mid 2003 a number of slopes measurements in close loop have been acquired to evaluate the level of the vibrations and their effect on NAOS performance:

– on a regular basis since December 2003 (25 sets of data)

– during a NACO Laser Guide Star technical run in November 2003 (20 sets of data)

– 5 sets of data during summer 2003

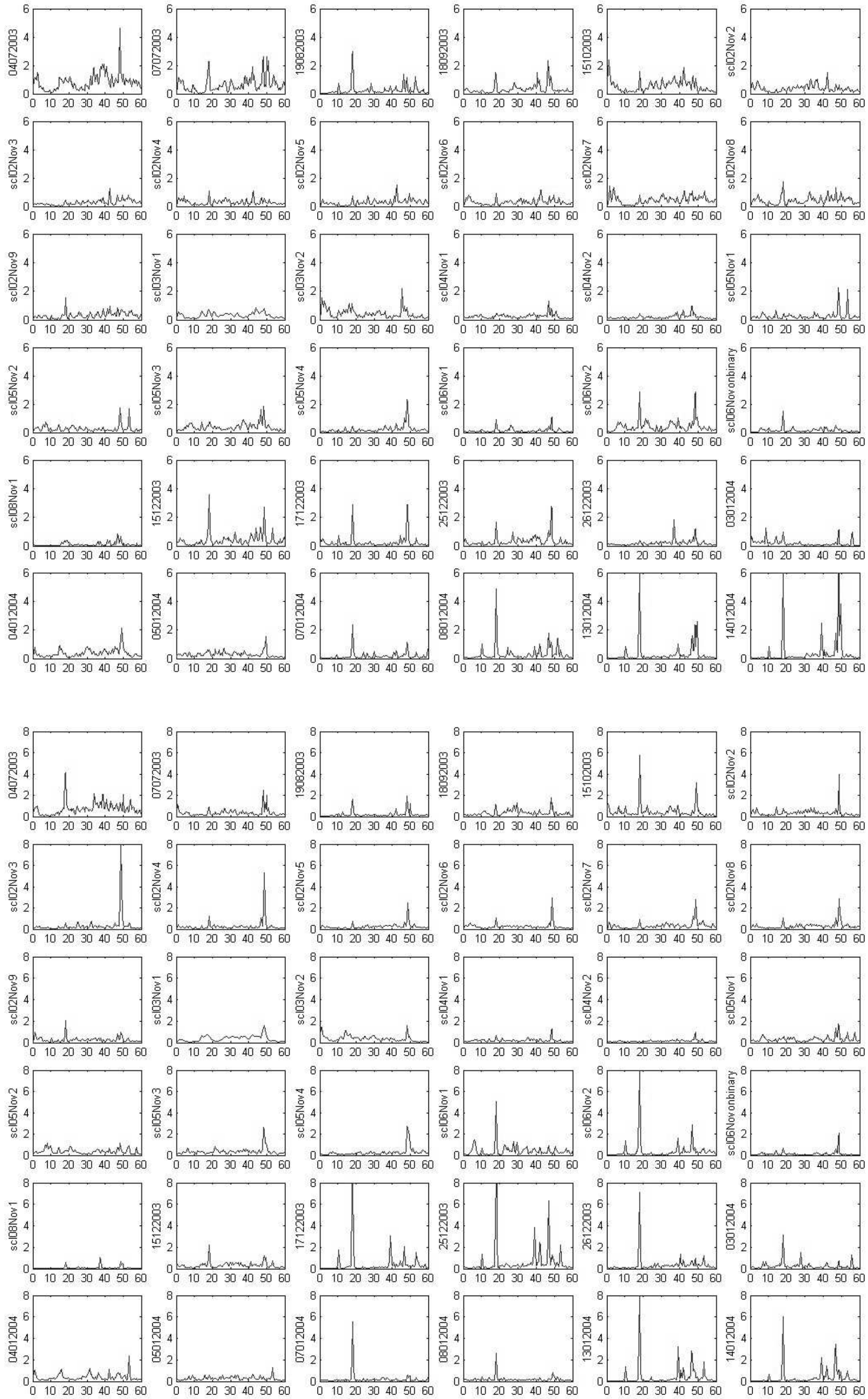

Figure 6. Up: power spectral density of Zernike #2 for 36 data sets. Down: same as left for Zernike #3. The X-axis represents frequencies in Hz, the Y-axis the power spectral density in 10^3 nm^2/Hz.

These data have been obtained with a bright ($m_V \approx 10$) on axis guide star close to zenith. Fig. 6 shows, for 36 data sets, the power spectral density (PSD) of the tip and tilt zernikes. A number of frequencies are excited (14, 18, 24, 38, 42, 48, 52, 72 Hz, ...). Their strength is highly variable.

For each data set, the effects of all excited frequencies have been added and an histogram of the total Strehl ratio loss has been computed (Fig 7). Vibrations are thus responsible for a total Strehl ratio loss between 2.5 and 25%. Though, no correlation appears between the total Strehl ratio loss and the seeing or the observation date (Fig 7).

As already noticed during the commissioning runs, the vibrations at 18 and 48 Hz are the major contributors to the total Strehl ratio loss. Histograms showing the Strehl ratio loss due to these vibrations with respect to the total Strehl ratio loss are given in Fig. 8. They demonstrate that the impact of the 48 Hz vibration is slightly higher than the 18 Hz one: the mean value of the ratio between the Strehl ratio loss due to the 18 Hz and the total Strehl ratio loss is 21%, its median value 19%. For the 48 Hz vibration, these values are 29% and 24% respectively. The fact that the former is out of the system bandwidth and not the latter could partly explained this different impact between the two vibrations.

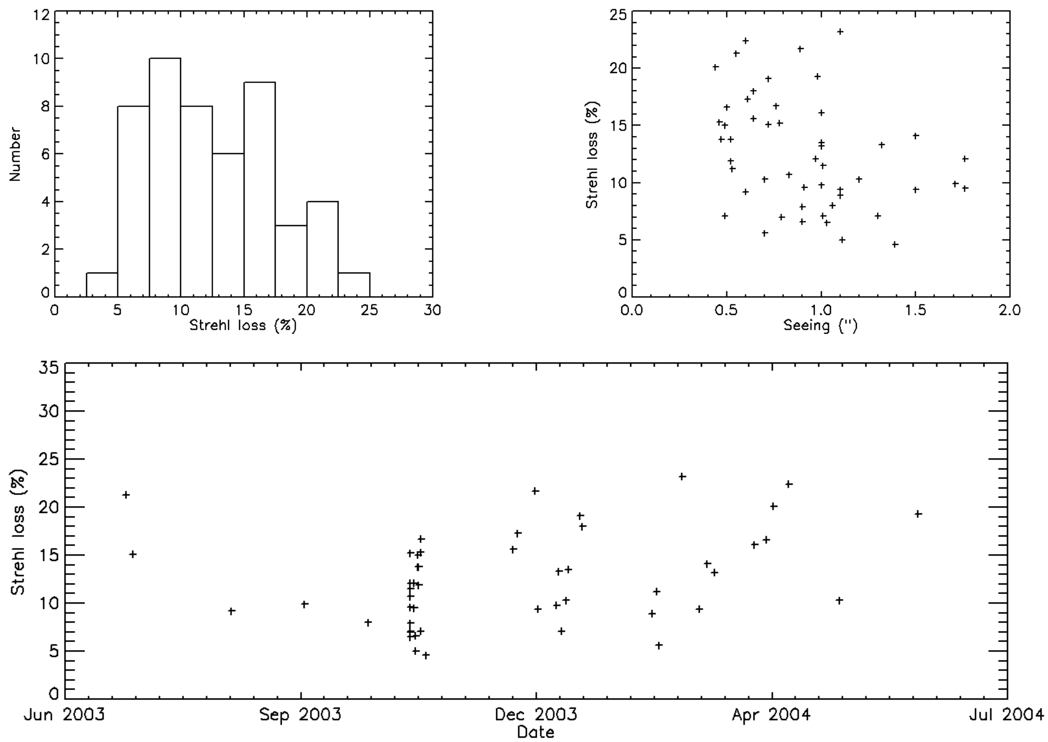

Figure 7. Top left: histogram of the total Strehl ratio loss computed for all the data sets. Top right: the total Strehl ratio loss plotted with respect to the seeing during the observation. Down: the total Strehl ratio loss plotted with respect to the observation date.

3.2. Possible origins of the excited frequencies

3.2.1. Optical difference path studies of the VLT telescopes

Bertrand Koehler (ESO) has performed Optical path difference (OPD) tests on the different VLT teslescopes to check for their compliance with the OPD stability criteria imposed by interferometric observations. For this purpose, he has placed an accelerometer on each of the different UT4 mirrors (2 on M1). Having first all the UT subsystems switched off, he has then computed the PSD of the accelerometers measurements after switching on each subsystem one by one: telescope cooling pumps, CONICA CCC, NAOS cooling system, CONICA

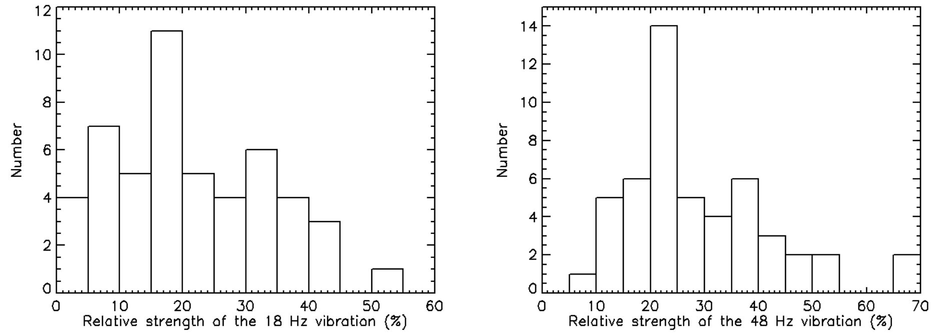

Figure 8. Left: histogram of relative strength of the 18 Hz vibration with respect to the total Strehl ratio loss. Right: same as left for the 48 Hz vibration. The x-axis represents the ratio between the Strehl loss due to the corresponding vibration and the total Strehl ratio loss.

electronics, NAOS electronics, telescope fans and enclosure equipments, hydrolic bearing system (HBS), ... Fig. 9 shows two of these PSD.

When switching on some of these subsystems, one can observe the appearance or the increase of modes observed in the PSD of the slopes measurements reported in Sect. 3.1.3: 14 HZ, 18 Hz, 24 Hz, 40 Hz. From his study, B. Koehler's conclusions were the following:

– the main disturbances are the CONICA CCC (+136 nm in the infrared OPD) and the NAOS electronics (+40 nm in the infrared OPD)

– the CONICA CCC excites several telescope modes at even eigenfrequency, more particulary in the 10-20 Hz range; hence the intensity of the 18 Hz mode is multiplied by a factor 1.5 to 2

– the origin of the 18 Hz mode might be a tilt mode of the M1 cell (this was still to be investigated) and the 48 Hz mode was also observed on UT1 and UT3.

By comparing all the PSD measurements, additional conclusions can be made:

– the HBS seems to be responsible for an increase of the 18 Hz mode intensity

– the NAOS electronics appears to increase the intensity of the 40 Hz mode

– the telescope cooling pumps excites a telescope mode at 24 Hz

3.2.2. Study of the telescope vibrations

Pedro Saavedra from the Laboratorio de Vibraciones Mecanicas of the Conception University (Chile) has performed an analysis of the VLT telescopes vibrations in order to determine their origins. In this purpose, he has placed an acceleromter on the M1 mirror and switched on/off different telescope subsystems: HBS, fans, ATUS. Fig 10 shows the measurements made on UT4.

As for the previous study, the excited modes (Fig. 10 and 11) are also found in the NAOS slopes measurements (Sect. 3.1.3): 14 Hz, 18 Hz, 44 Hz.

From his study, P. Saavedra's conclusions were the following:

– the HBS is responsible for a global increase of the telescope vibrations

– the telescope fans excite a telescope mode at 44 Hz

– the major excited frequencies are at 14 and 18 Hz, in the resonance domain of the M1 cell (from 12 to 19 Hz)

– the CONICA CCC generates vibrations at the frequencies found on M1: 14 and 18 Hz (Fig 11)

– the same conclusions have be made for the UT3 and ISAAC, which is equipped with the same kind of close cycle cooler

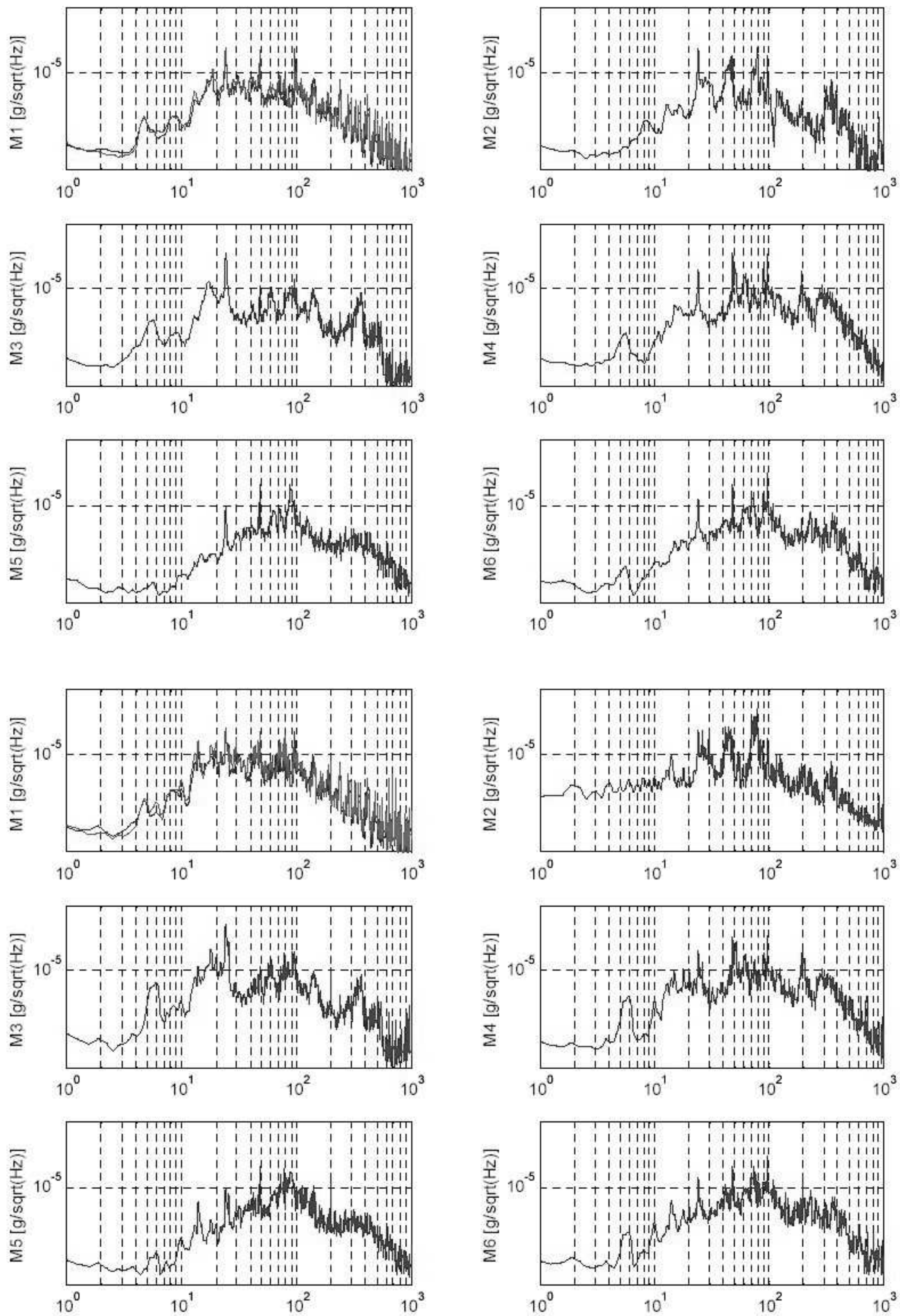

Figure 9. PSD of the accelerometers measurements. Up: only the telescope cooling pumps are switched on. Down: the telescope cooling pumps and the CONICA CCC are on.

In addition to these first conclusions, this study shows also that the HBS is responsible for an increase of the 18 Hz mode.

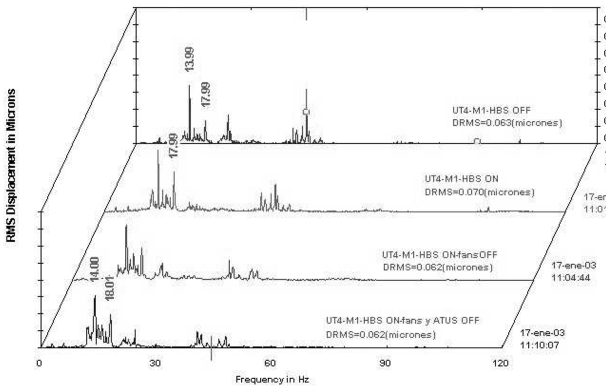

Figure 10. Spectrum of the vibrations on UT4-M1 from the accelerometer measurements.

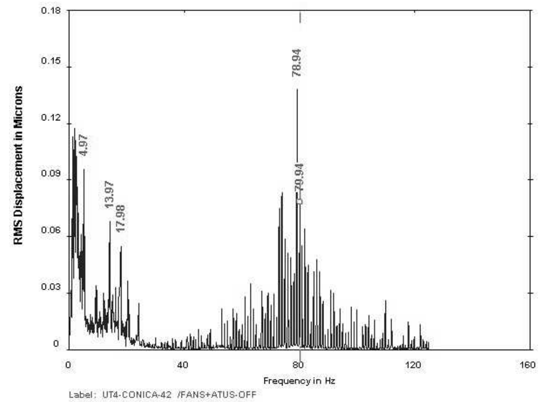

Figure 11. Spectrum of vibrations directly measured on the CONICA CCC.

4. CONCLUSIONS

Since its installation at Paranal in November 2001, NACO has suffered from a degradation of its image quality performance. This deterioration is highly variable and does not show any correlation with the seeing condition nor with the observation time. The total (multiplicative) Strehl ratio loss ranges from 2.5 to 25%.

The main excited frequencies are at 18 Hz and 48 Hz and mainly affect the tip and tilt zernikes. Two studies of the telescope vibrations show that the Hydrolic Bearing System of the telescope is responsible for an increase of the 18 Hz vibration intensity while the CONICA Close Cycle Cooler excites several frequencies in the 10-20 Hz domain (hence also the 18 Hz mode). Additionally, the telescope fans could be at the origin of vibrations around 44 Hz, the telescope cooling pumps of vibrations around 24 Hz and the NAOS electronics of vibrations around 40 Hz.

Some actions are currently being planned to reduce the effect of the CONICA Close Cycle Cooler on NACO performance.

ACKNOWLEDGMENTS

The authors would like to thank the NAOS team for their ESO NAOS documents, which have been extensively used in this article, and more particularly Thierry Fusco (ONERA), Jean-Marc Conan (ONERA), François Lacombe (Observatoire de Paris) and Eric Gendron (Observatoire de Paris). We are also grateful to Pedro Saavedra (Universidad de Conception, Laboratorio de vibraciones mecanicas) for his studies of the telescope vibrations.

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