Dimensioning adaptive optics for future VLTI projects

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Dimensioning adaptive optics for future VLTI projects

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ABSTRACT

The European Southern Observatory offers the opportunity to develop a new generation of instruments for the Very Large Telescope Interferometer. Therefore, it is tempting to upgrade the adaptive optics systems for MACAO on the 8-m unit telescope as well as for NAOMI on the 1.8-m auxiliary telescope. It enables to access to new science cases such as active galactic nuclei with the GRAVITY+ project. Moreover, it would allow to perform at short wavelengths with the IVis proposal. We study here the requirements of such AO upgrade by increasing the number of sub-apertures of the wave-front sensor and the number of actuators of the deformable mirror. We evaluate the needs for a high-Strehl mode in the visible and near infrared wavelengths in various conditions of observation. We present numerical simulations to quantify the performance. We show that a moderate upgrade of NAOMI, and a significant upgrade of MACAO can enable both better dynamic range and sensitivity with the VLTI.

Keywords: Adaptive optics, very large telescope interferometer

1. INTRODUCTION

The Very Large Telescope Interferometer (VLTI) is today a leading edge facility for long-baseline astrophysics interferometry. With the end of the first generation instruments (AMBER[1,2] and MIDI[3,4]) and the advent of second generation instruments (GRAVITY[5,6] and MATISSE[7,8]), the facility has reached a level of maturity that allows cutting edge science to be done and images of astrophysical objects to be published as a more common feature.

Yet, the margin for improvements of the VLTI is large. Still just a handful of active galactic nuclei (AGN) can be reached by the VLTI, mainly due today to the limited performances of the adaptive optics (AO). The VLTI is not yet able to make use of its longest baseline (220 m), being limited by its delay lines length. Finally, the VLTI cannot observe in the shortest wavelengths (V, R, I and J) due to a combination of poor performances of AO on both NAOMI[9,10] on the 1.8-m auxiliary telescopes (AT) and MACAO[11,12] on the 8-m unit telescopes (UT), and the decommissioning of the only J band-sensitive instrument: AMBER.

ESO has issued a call for tenders in 2019 to propose new instruments concepts for the future of the VLTI in the 2030s. Several proposals were presented, but it is notable that most – if not all – of them were proposing

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upgrades of the VLTI adaptive optics. GRAVITY+ was selected, which contains itself an upgrade of the MACAO adaptive optics of the UTs to reach new heights in sensitivity for AGN characterization at cosmic scales, and improve contrast of exoplanet detection.

Such AO upgrades would enable for instance: *i.* to improve the sensitivity to reach new and fainter objects like merging AGN (*e.g.* GRAVITY+ project[13]) ; *ii.* to improve the high contrast imaging performance to detect exoplanets (*e.g.* HI-5 proposal[14,15]) ; *iii.* to explore interferometry at visible wavelengths – in R-band or I-band – to spatially resolve fundamental stellar physics (*e.g.* IVis proposal[16,17]).

Therefore, we consider useful to revisit the theoretical study of AO performances on the VLTI, great tools to perform such analysis being available today. We present here the results of numerical simulations obtained with the PAOLA software.[18] We have also compared it with the CAOS software.[19] Both simulation tools yield rather to similar results with discrepancy of the Strehl of only few percents. We study in particular the requirements for a high-Strehl mode, by increasing the sampling of both the wave-front sensor (WFS) and the deformable mirror (DM). We show that a moderate upgrade of NAOMI, and a significant upgrade of MACAO can enable both better dynamic range and sensitivity with the VLTI.

2. MAIN PARAMETERS OF THE NUMERICAL SIMULATION

Telescope optics parameters	
Primary mirror diameter (UT)	8.0 m (MACAO) – 1.8 m (NAOMI)
Central obscuration diameter (UT)f	1.2 m (MACAO) – 0.138 m (NAOMI)
Optical turbulence parameters	
Seeing angle (at 500 nm at zenith)	[0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2] as
Outer scale	25 m
Airmass (or telescope pointing zenith angle)	1.5 (48°)
9 turbulent layers with typical Paranal conditions	Altitude, Cn^2, Wind
Scientific instrument parameters	
Spectral band of the scientific channel	R, J, H, K, L, M bands
Central wavelength of the scientific channel	[0.70, 1.25, 1.65, 2.20, 3.40, 5.00] µm
Spectral bandwidth of the scientific channel	[0.22, 0.30, 0.35, 0.40, 0.55, 0.30] µm
Shack-Hartman wave-front sensor parameters	
Spectral band of the sensing channel	R-band
Central wavelength of the sensing channel	0.7 µm
Spectral bandwidth of the sensing channel	0.22 µm
Bolometric magnitude of the on-axis NGS	[6, 7, 8, ..., 15, 16]
Pixel read noise of the NGS WFS CCD detector	0.5 e-/pixel
Algorithm for SH-WFS spot centroid calculation	Center-of-gravity mode (CG)
Number of pixels across the WFS lenslet width	8 pixels/lenslet
Quantum efficiency of the WFS	0.65
Total transmission of the system up to the WFS	0.23
Integration time of the WFS	*Optimized* (< 10 ms)
Number of lenses across the WFS	[10; 40] (MACAO)
	[4; 5, 6, 7, 8, 9, 12] (NAOMI)
Adaptive optics (AO) & control loop parameters	
Number of actuators across the DM	[11; 41] (MACAO)
	[13; 13] (NAOMI)
Loop gain	*Optimized* (< 0.6)
Servo system time lag (WFS read-out + DM commands)	0.5 ms

Table 1. Main input parameters of the simulations for UT/MACAO and AT/NAOMI.

The main input parameters of the numerical simulations are given in table 1. We study the expected performance (*e.g.* Strehl ratio) while correcting in R-band on the sensing channel and observing in another band (R, J, H, K, L, M bands) on the scientific channel. We mainly evaluate the requested number of subapertures of the WFS and the number of actuators of the DM as a function of the atmospheric conditions (seeing), the wavelength of observation and the natural guide star (NGS) magnitude. The current UT/MACAO system has 10x10 equivalent (curvature) WFS subaperture and about 11x11 DM actuators. The MACAO upgrade foreseen for the GRAVITY+ project will have 40x40 WFS subaperture and 41x41 DM actuators. The current AT/NAOMI system has 4x4 WFS subapertures and 13x13 DM actuators. A NAOMI upgrade would need more WFS subapertures (typically 8x8) while keeping the same number of DM actuators.

We consider a Shack-Hartman WFS having 0.5 e-/pixel read noise, a 6x6 pixel subaperture and a center-of-gravity mode for the spot centroid calculation. The read-out noise and the quantum efficiency of the WFS detector are chosen according to the specifications of the Ocam^2 manufactured by First Light Imaging: read-out noise $<$ 1 electron ; quantum efficiency of 95% pic, and of 65% in the near-infrared at 900 nm. The servo-lag time is set to 0.5 ms, including the WFS integration time, the command computation time and the update of the DM. The WFS integration time and the loop gain are optimized both at a time for each setup so as to minimize the variance of the residual wavefront spectrum. Such optimization is needed especially for faint NGS stars.

The total transmission from the telescope primary mirror up to the WFS is computed as follows:

- Transmission after M8 (i.e. the MACAO DM) = 64%.
- Transmission of M9 dichroic in the optical (450 to 900 nm) = 90%.
- Typical reflectivity of 95% for each optic in the WFS (membrane mirror, SBM1, SBM2, SBM3, SBM4, K-mirror surface 1, 2 and 3).
- Transmission of the lenslet array of the Shack-hartmann. Lenslets are square ones, thus the expected transmission is about 95%.
- Quantum efficiency = 65% at 900nm, assuming the same value at 700nm in R-band.
- Total transmission = $0.64*0.90*0.95^8*0.95*0.65 = 0.236$.
- Total transmission = 23 %.

If the sensor and the detector are both in the same R-band, the transmission is divided by a factor of 2, assuming a dichroic 50/50 for separating the light in between the sensing arm and the scientific arm.

3. RESULTS OF THE NUMERICAL SIMULATION

We show the point spread function obtained with UT/MACAO and with AT/NAOMI in the visible or infrared wavelengths in their current setup and once upgraded (Fig. 1). It appears clearly that such AO upgrade can provide more contrasted images. The dynamic range is strongly improved especially in the visible wavelengths.

Next, for both UT/MACAO and AT/NAOMI, we plot the on-axis Strehl ratio as a function of the guide star magnitude for different numbers of WFS subapertures and DM actuators (4x4 up to 40x40), for various conditions of turbulence (seeing from 0.6 to 1.2) and for different spectral bands of observation (R, J, H, K, L, M bands) while correcting in R-band (Fig. 2, 3, 4, 5). The criteria used here for choosing the optimum setup is to provide a Strehl ratio above 20% while maximizing the NGS magnitude.

3.1 UT/MACAO upgrade

With the current MACAO made of 10x10 WFS sub-apertures, a Strehl ratio of 20% is reached at 0.8 as seeing for a NGS magnitude up to 17 in K-band whereas it remains very low in R-band. With the MACAO upgrade made of 40x40 WFS sub-apertures, a Strehl ratio of 20% is reached at 0.8 as seeing for a NGS magnitude up to 9.5 in R-band and up to 13.5 in K-band. Such upgrade gives access to the visible wavelengths at the cost of a lower magnitude limit in the infrared wavelengths. For bright targets and 0.8 as seeing, the Strehl is improved from 15% to 55% in R-band and from 82% to 95% in K-band (Fig. 2 and 3).

3.2 AT/NAOMI upgrade

With the current NAOMI made of 4x4 WFS sub-apertures, a Strehl ratio of 20% is reached at 0.8 as seeing for a NGS magnitude up to 16 in K-band whereas it remains below 20% in R-band. For upgrading NAOMI, we suggest 8x8 WFS sub-apertures with the current 13x13 DM actuators. Such upgrade enables to reach a Strehl ratio of 20% at 0.8 as seeing with a NGS magnitude up to 10.5 in R-band and up to 14.5 in K-band. It enables also to observe in the visible wavelengths. For bright targets and 0.8 as seeing, the Strehl is improved from 2% to 55% in R-band and from 60% to 95% in K-band (Fig. 4 and 5).

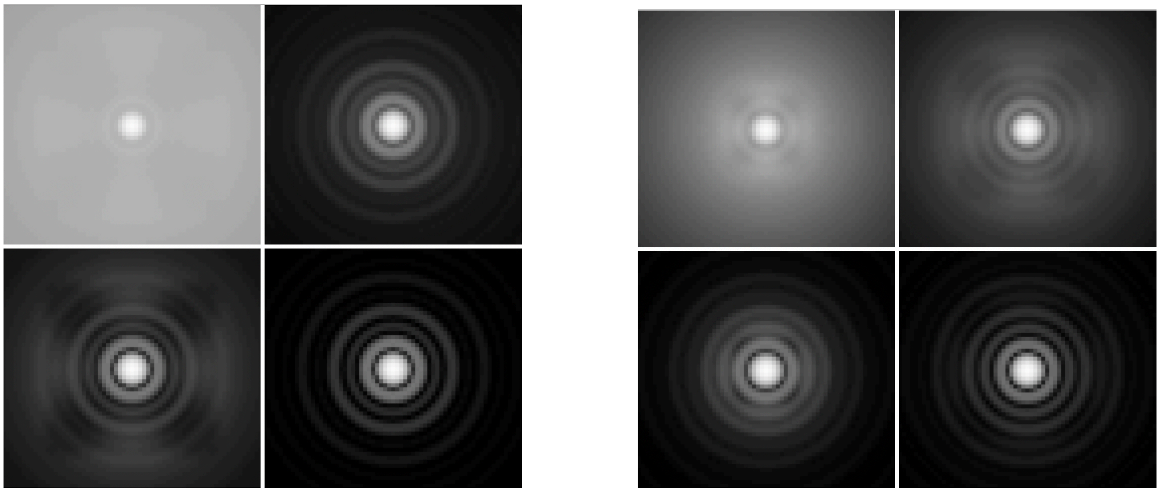

Figure 1. *Figure on the left:* Point spread function obtained with UT/MACAO in its current version with 10x10 WFS subapertures (left) and in its upgraded version with 40x40 WFS subapertures (right). Central wavelength of 0.7 µm (top) and 2.2 µm (bottom). Seeing of 0.8 as. NGS magnitude of 8. *Figure on the right:* Point spread function obtained with AT/NAOMI in its current version with 4x4 WFS subapertures (left) and in an upgraded version with 8x8 WFS subapertures (right). Central wavelength of 0.7 µm (top) and 2.2 µm (bottom). Seeing of 0.8 as. NGS magnitude of 8.

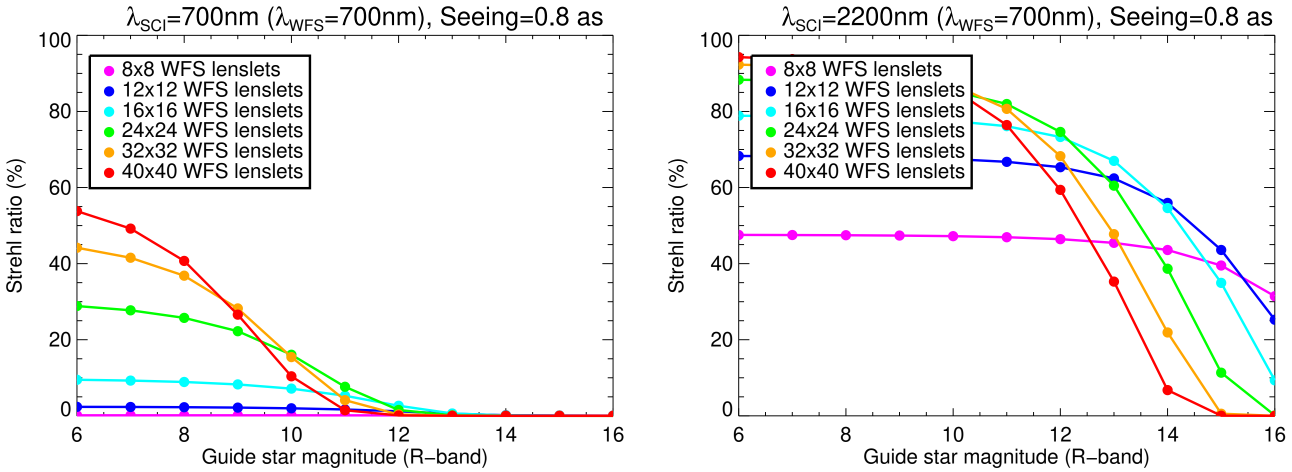

Figure 2. Strehl as a function of the guide star magnitude with UT/MACAO for different numbers of WFS subapertures in R-band (left) and in K-band (right). Strehl of 0.8 as.

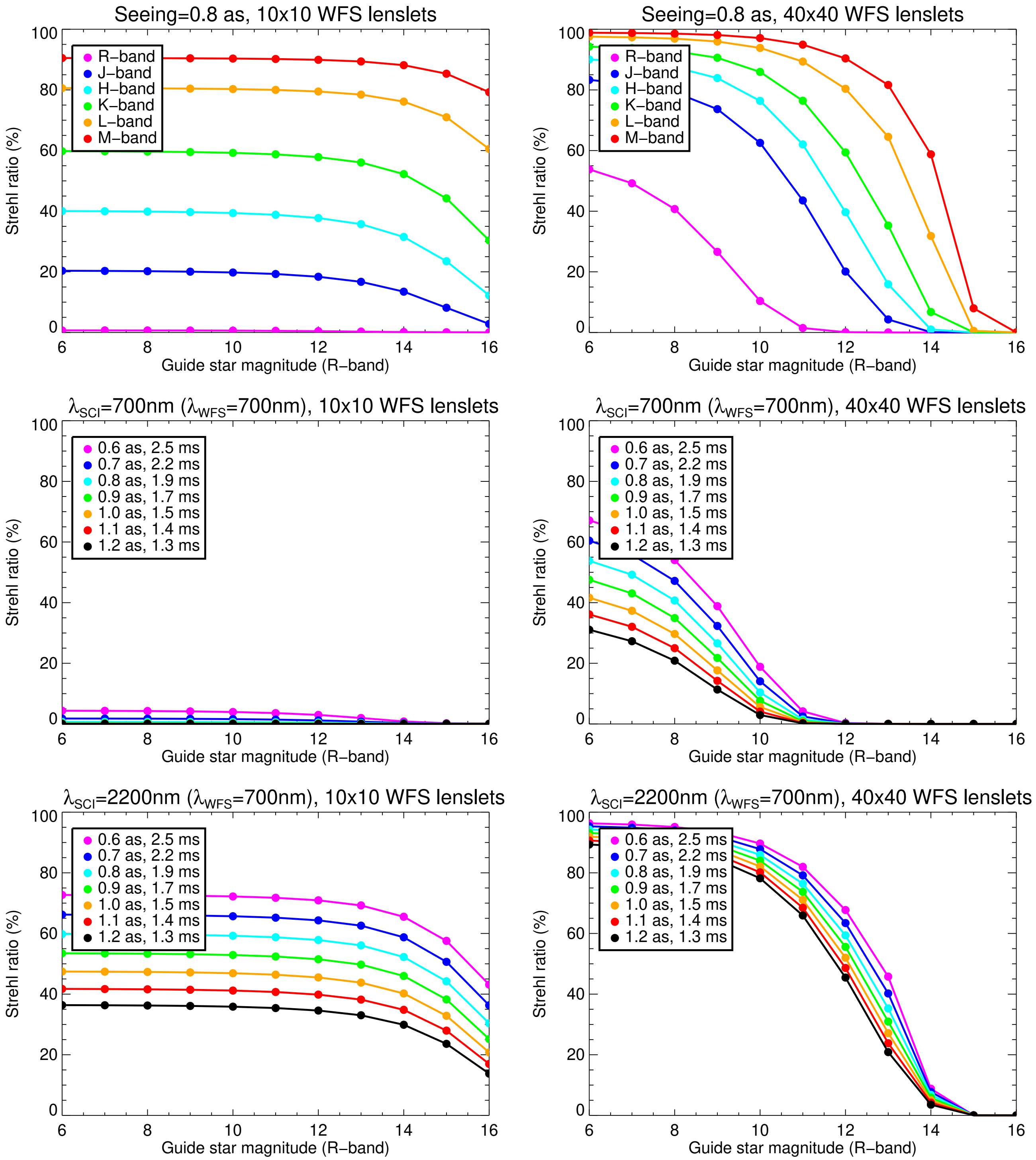

Figure 3. Strehl as a function of the guide star magnitude with UT/MACAO in its current version using 10x10 WFS subapertures (left) and in its upgraded version using 40x40 WFS subapertures (right). Strehl curves for different wavelengths of observation and a Strehl of 0.8 as (top). Strehl curves for different conditions of turbulence in R-band (middle) and in K-band (bottom).

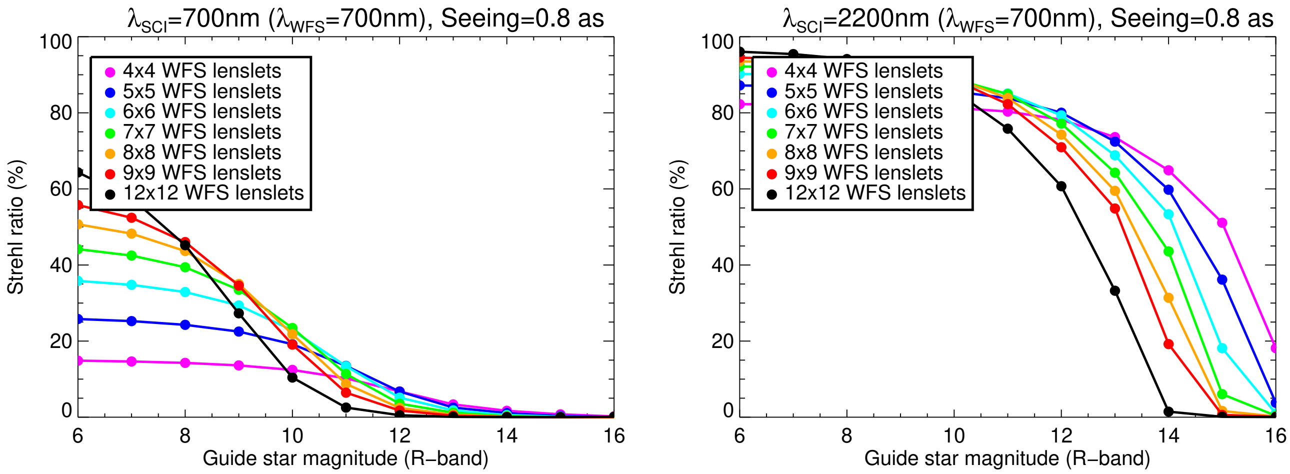

Figure 4. Strehl as a function of the guide star magnitude with AT/NAOMI for different numbers of WFS subapertures in R-band (left) and in K-band (right). Strehl of 0.8 as.

4. CONCLUSION

We have shown by numerical computation that a moderate upgrade of NAOMI, and a significant upgrade of MACAO can enable both better dynamic range and sensitivity with the VLTI. At high flux (if photon noise-limited), fitting error and aliasing error dominate. For compensating that, we can: *i.* increase the number of DM actuators to reduce the fitting error; *ii.* increase the number of WFS subapertures to reduce the aliasing error; *iii.* optimize the WFS integration time and the loop gain. At low flux (if read-out noise-limited), WFS noise error and servo-lag error dominate. For improving that, we can: *i.* increase the subaperture size but decrease the subaperture number, so as to optimize the flux per WFS subaperture; *ii.* decrease the read-out noise with a new detector; *iii.* increase the WFS integration time.

Further, the performance can be improved in the case of faint NGS by increasing the NGS WFS bandwidth. Here the bandwidth is set to 220 nm (R-band only). A bandwidth of 300 nm improves the performance limit by about one magnitude. A good option would be to use a WFS covering not only the R-band but also the V-band.

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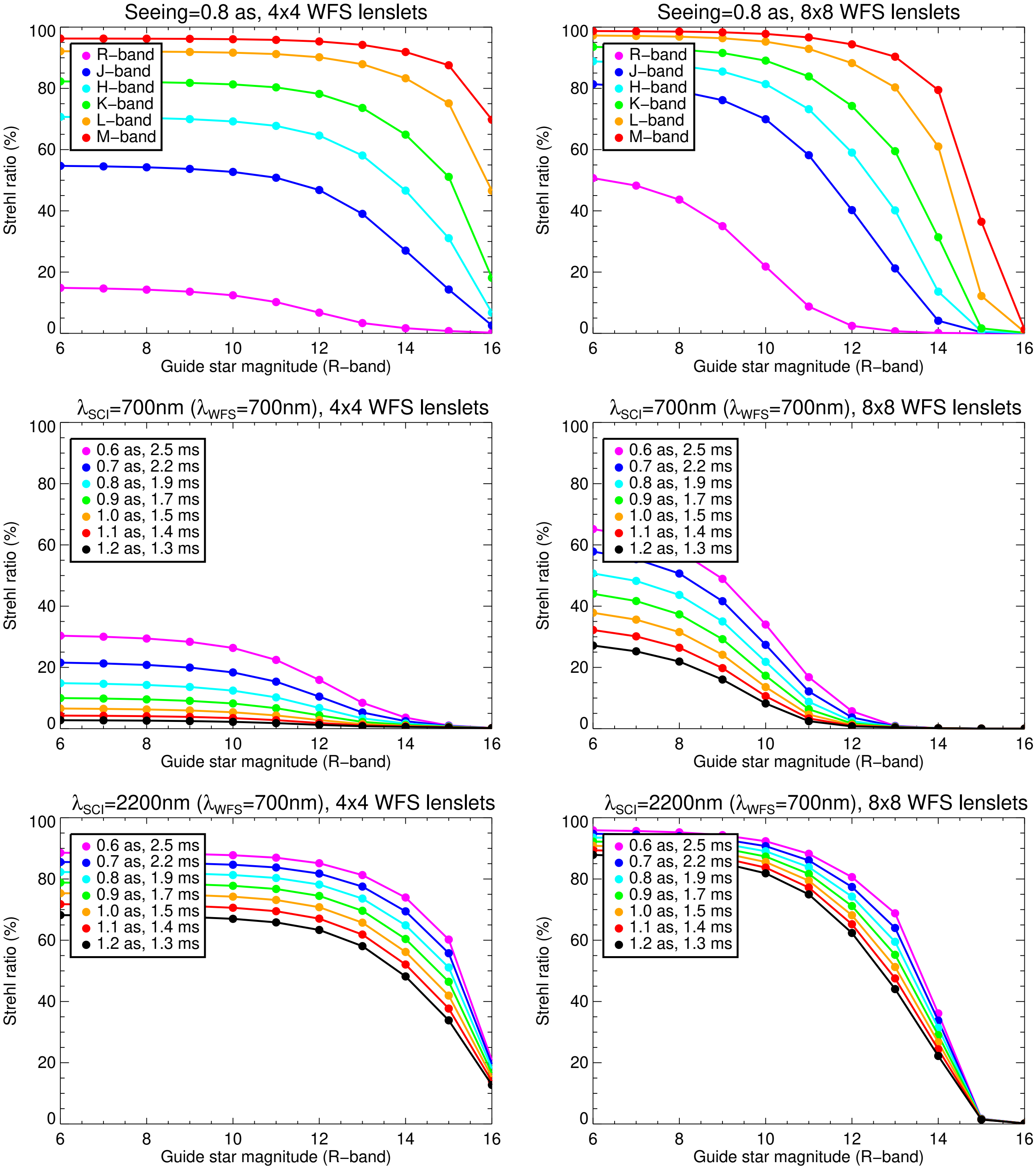

Figure 5. Strehl as a function of the guide star magnitude with AT/NAOMI in its current version using 4x4 WFS subapertures (left) and in an upgraded version using 8x8 WFS subapertures (right). Strehl curves for different wavelengths of observation and a Strehl of 0.8 as (top). Strehl curves for different conditions of turbulence in R-band (middle) and in K-band (bottom).

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