Coronagraph PSFs from high-contrast NGAO simulations

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1 NGAO coronagraph simulations

The PSFs from the NGAO coronagraph simulations for the high-contrast performance budget (KAON 497) are made available via Keck FTP, and some additional information regarding the simulation parameters are given in this document. Most of the information is available in KAON 497, merely collected and summarized here for convenience.

1.1 PSF image files

The PSFs are saved as image cubes in the FITS format, with the third dimension being wavelength. Three types of files are saved separetely: "cgav.fits" (coronagraph+AO), "imav.fits" (only AO), and "noaoav.fits" (neither AO nor coronagraph – seeing limited image). The coronagraph throughputs, AO Strehl ratios and image plate scales are given in table 1. The PSFs are shifted diagonally by dimension/2 (this is how the FFT in IDL returns the result), so to view them properly they must be shifted back by the same amount (the function rep.pro does this). The three coronagraph sizes 6, 10 and 14 λ/D are in the folders labeled "1x," "2x" and "4x."

occulting	Wavelength Band					
spot size	R	I	J	H	K	L
$6\lambda/D$	0.435	0.267	0.188	0.114	0.068	0.029
$10\lambda/D$	0.365	0.218	0.151	0.092	0.054	0.023
$14\lambda/D$	0.306	0.178	0.121	0.074	0.043	0.018
Strehl Ratio	0.13	0.34	0.49	0.66	0.79	0.91
Plate scale (mas)	3.61	5.16	6.45	8.51	11.34	18.01

Table 1: Coronagraph on-axis throughput and Strehl ratio for the base line 170 nm RMS wavefront error NGAO system configuration (see table 3).

1.2 Coronagraph

A generic apodized Lyot type coronagraph (ApLC) was used in the numerical AO simulations that employed a coronagraph, somewhat adapted for the hexagonal pupil shape of the Keck primary mirror. A sketch of its function and the corresponding diffraction-limited images and pupils are shown in Fig. 1. The occulting spot in the first focal plane was varied from $6\lambda/D$ to $14\lambda/D$, where D is the telescope diameter and the imaging wavelength λ ranged between 0.7μm to 3.5μm. The on-axis throughput of the coronagraph was measured on the primary star (i.e. the guide star) during the simulations in order to normalize the PSFs to the proper photometry for the simulated observing scenarios, see table 1.

1.3 YAO simulation tool

The numerical AO simulation tool used for the current simulation results was the freely available Yorick Adaptive Optics (YAO) package (with some in-house Keck-specific additions and a new coronagraph module). Some residual waffle patterns may be observed at a low level, but they are not a significant source of wavefront error. Configured

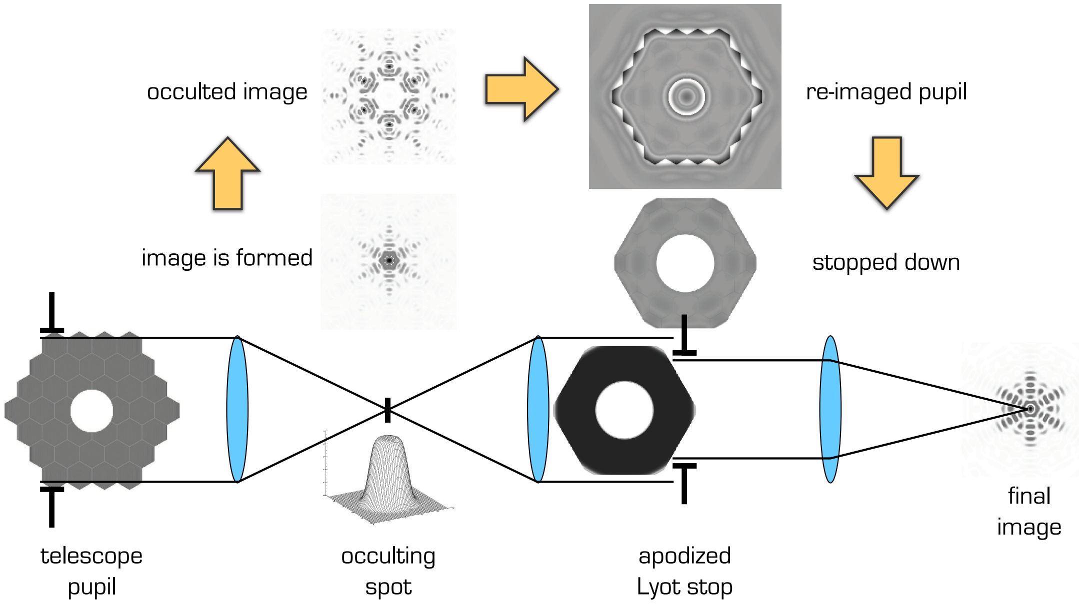

Figure 1: Schematic of a simple apodized Lyot coronagraph used for the numerical Monte Carlo type simulations of the NGAO configuration. The occulting spot size was varied between 6–14 λ/D for wavelengths between 0.7–3.5 μm.

as a 5-LGS narrow-field quincunx AO system of order 36×36 (sub-apertures across the base of the Shack-Hartmann sensor), the NGAO setup was able to deliver down to 160 nm RMS residual wavefront error under typical conditions. The simulation models the following effects with high fidelity (+) and some others not at all (—):

+ Fitting error
+ Spatial aliasing
+ Servo-lag
+ Noise
+ Tip/tilt errors
+ Segment gaps (grey pixel approximation)
+ Segment static aberrations
+ Segment vibrations
+ Telescope wind-shake (common-path)
+ Tomography and LGS
+ Coronagraph effects
— No instrument aberration calibration errors
— No optical quality residual aberrations

1.4 AO system and atmosphere assumptions

The starting point for the NGAO configuration simulated was the 155 nm "Exo Jup LGS" (at zenith) wavefront error budget presented in Appendix 2 of KAON 461, adjusted here to $N = 36$ sub-apertures across the pupil to produce a total wavefront error of 170 nm RMS. The simulation used the 7-layer CN-M3 turbulence model from KAON 303, with $r_0 = 0.18$ m, $\theta_0 = 2.5''$, $\tau_0 = 3.4$ ms and $d_0 = 4.4$ m.

Wavelength Band	central λ (μm)	FWHM (μm)	color correction	zero point flux (10^{10} photons/s)	sky brightness (mag/arcs^2)
U	0.366	0.052	-0.2	19.6	20.90
B	0.438	0.100	-0.6	68.4	22.13
V	0.545	0.083	0.0	40.6	21.99
R	0.641	0.157	0.6	54.1	20.81
I	0.798	0.154	1.3	34.2	20.25
J	1.22	0.260	2.7	26.3	19.60
H	1.63	0.290	3.8	14.2	17.09
K′	2.12	0.410	4.9	9.39	16.99
K	2.19	0.320	4.8	8.02	16.78
L	3.45	0.570	6.8	3.67	9.91

Table 2: Photometric system used for simulated observing scenarios. Based on the Johnson-Cousins-Glass system from Bessel et al. (1998), as outlined in the NGAO_Perf_Budget_Template.xls document (available at the NGAO Twiki site). The zero point was computed for a collecting area of 79 m^2, and is the photon flux at the Keck Nasmyth from a $V = 0$ star.

Parameter	YAO numerical simulation
Telescope diameter	Keck segmented pupil (grey pixel approximation)
Turbulence parameters	CN-M3 7-layer turbulence model, $r_0 = 0.18$ m
WFS sub-apertures	36×36 (determines fitting and aliasing in both methods)
WFS measurement error	$m_{589} = 9$, spot elongation, fratricide effect
Servo-lag error	1 kHz frame rate, integrator
Tomography error	5 Na-LGS at 90 km in 11″ quincunx asterism
Tip/Tilt error	3 NGS (J=16) in 30″ triangular asterism
Static instrument errors	—
Static telescope errors	static segment figures: 65 nm residual error
Exposure time	$\tau_e = 30$ sec (lower limit on speckle noise from simulation)

Table 3: Base line NGAO system configuration.

1.5 Numerical AO simulations

By the demanding nature of the computations involved, no exposures longer than 30 seconds have been generated for the study so far (30 seconds of simulated real time took 56 hours to render). Therefore a limited set of representative cases had to be selected for this study, and while PSFs were obtained for the whole wavelength range of interest, when proceeding to construct the simulated observations only the J band case has been examined in detail so far. In addition to static segment figure errors, a low (but realistic) level of wind shake and 30-Hz segment vibrations were also included in the current simulations, and it is including these disturbances that the total wavefront error of the base line NGAO configuration simulated here amounts to 170 NM RMS. An example of the output from a YAO AO simulation with a coronagraph is shown n Fig. 2.

2 Applicable documents

- Photometric system: NGAO_Perf_Budget_Template.xls
  `http://www.oir.caltech.edu/twiki_oir/bin/view.cgi/Keck/NGAO/NGAOTemplates`
- Analytical evaluations of closed-loop adaptive optics spatial power spectral densities
  `http://www.oir.caltech.edu/twiki_oir/pub/Keck/NGAO/HighContrastBudget/aoclpsd.pdf`
- Estimating the spatial power spectrum of residual wavefront errors from adaptive optics simulations
  `http://www.oir.caltech.edu/twiki_oir/pub/Keck/NGAO/HighContrastBudget/tomoPSD.pdf`
- Yorick Adaptive Optics package (open source): `http://www.maumae.net/yao/aosimul.html`

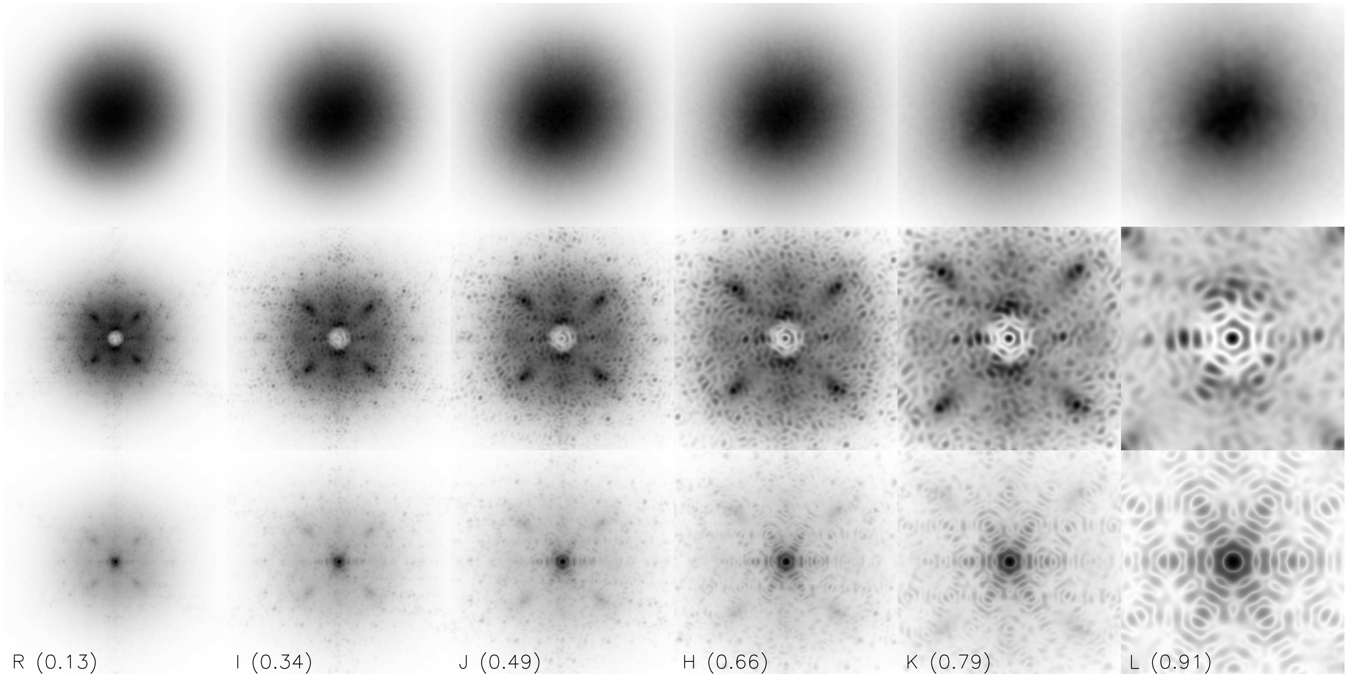

Figure 2: PSFs from 30-second NGAO simulations, ranging from R to L band and showing the AO PSF (bottom row), the on-axis coronagraph image (middle row, $10\lambda/D$ occulting spot, no companion inserted), and the seeing-limited image (top row). The field of view of each image is 1.8 arc seconds. All images are stretched (asinh) and individually byte-scaled.

- KAONs (Keck Adaptive Optics Notes):
  `http://www.oir.caltech.edu/twiki_oir/bin/view.cgi/Keck/NGAO/NewKAONs`
  - KAON 303 : Mauna Kea Atmospheric Parameters (CN-M1,M2,M3 models)
  - KAON 497 : NGAO High-Contrast & Companion Sensitivity Performance Budget