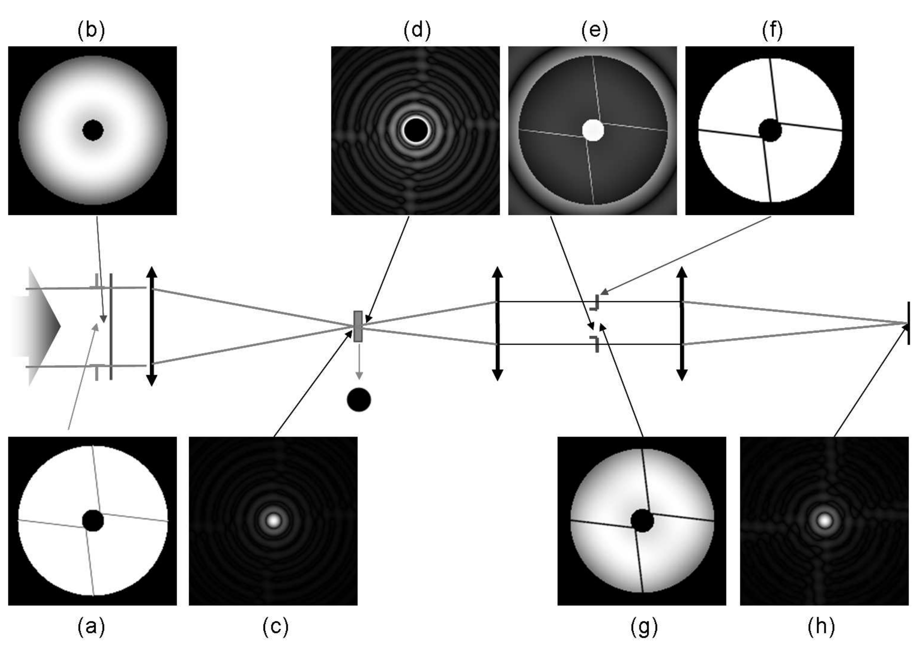
Apodized Lyot coronagraph for SPHERE: numerical study & laboratory performance

M. Carbillet[1], S. Robbe-Dubois[1], G. Guerri[1,2], Ph. Bendjoya[1], R. Douet[1], J.-B. Daban[1], L. Abe[1], C. Gouvret[1], A. Boccaletti[3], K. Dohlen[4], J. Baudrand[3], A. Ferrari[1], F. Vakili[1]

[1] UMR 6525 Hippolyte Fizeau, Université de Nice Sophia Antipolis/CNRS/Observatoire de la Côte d'Azur, Parc Valrose, 06108 Nice Cedex 2, France
[2] Now at: Département d'Astrophysique, Géophysique et Océanographie, Centre Spatial de Liège, Avenue Pré-Aily, 4031 Angleur, Belgium
[3] UMR 8109 LESIA, Observatoire de Meudon/CNRS, 5 Place Jules Jansen, 92195 Meudon, France
[4] UMR 6110 LAM, OAMP, Université de Provence/CNRS, 13388 Marseille cedex 13, France

Abstract: SPHERE (which stands for Spectro-Polarimetric High-contrast Exoplanet REsearch) is a second-generation Very Large Telescope (VLT) instrument dedicated to high-contrast direct imaging of exoplanets which first-light is scheduled for 2011. Within this complex instrument one of the central components is the apodized Lyot coronagraph (ALC). The design study of the ALC for SPHERE/VLT consisted of two phases reported in this paper. The first phase concerned a complete numerical study of the instrument, whose most interesting results are given. The followed method is purely numerical, but with an end-to-end approach largely fed by a number of instrumental feedbacks. The obtained results permitted to finalize the optical design before laboratory performance testing of the ALC, second phase of this design study. During this first laboratory experiment, we measured the transmission profiles of an apodizer prototype on a coronagraphic bench, and the coronagraphic performance of the ALC in Y, J, and H bands, sensitivity included. We concluded that the prototype meets the SPHERE technical requirements for coronagraphy. More generally, the numerical study presented in this paper could hopefully help conceiving future other instruments alike, for example within the very promising extremely large telescope perspective. Also, the procedure for the performance study can be applicable to any type of apodizer.

Introduction

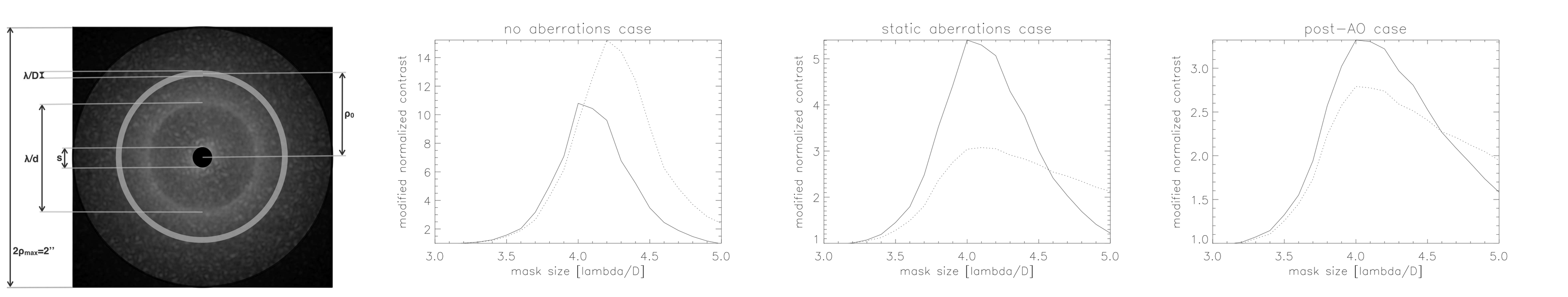


Principle of SPHERE Apodized Lyot Coronagraph: (a) entrance pupil, (b) apodizer, (c) point spread function (PSF) at the focus of the telescope, (d) PSF when the Lyot occulting coronagraphic mask is settled, (e) pupil image before the Lyot stop introduction, (f) Lyot stop, (g) Pupil image with the Lyot stop, (h) final coronagraphic PSF (the contrast scale has been enhanced for better visibility).

1 Detailed numerical study

We report here on the most interesting results of the whole end-to-end numerical study achieved during the design of the ALC for SPHERE/VLT, using a dedicated numerical tool (the `Software Package SPHERE` [Carbillet et al. 2008, SPIE Proc. 7015, 70156Z]), and considering wavefront errors coming from a detailed optical aberrations analysis (see [Boccaletti et al. 2008, SPIE Proc. 7015, 70156E]).

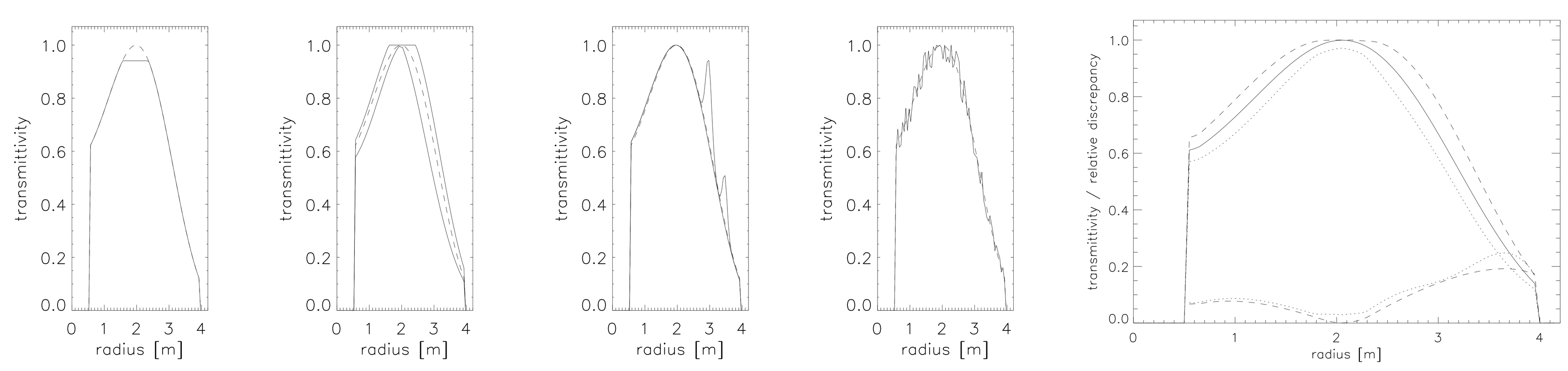
1.1 Apodizer optimization for SPHERE/VLT



From left to right: areas considered for the contrast calculation ; contrast $K'_{\rho_0}(s) = \frac{\langle I_s^{\rho_0}(\rho,\theta)\times \mathrm{disk}^{\rho_0}_{\lambda/D}(\rho,\theta)\rangle_{\rho,\theta}}{\langle I_s(\rho,\theta)\times \mathrm{ring}^{\rho_0}_{\lambda/D}(\rho,\theta)\rangle_{\rho,\theta}} \times \max\left(I_s^{\rho_0}(\rho,\theta)\right)$, for both $\rho \leq \frac{1}{2}\lambda/d$ (solid line) and $\rho \geq \frac{1}{2}\lambda/d$ (dotted line), and for the three cases of aberration. Optimal contrast is obtained for $s \simeq 4\lambda/D \Rightarrow$ optimization for the larger wavelength of the priority-goal band H ($\lambda_{\max}$=1.78 μm), following [Soummer 2005, ApJ 618, L161] $\Rightarrow$ apodizer manufactured for $4\,\lambda_{\max}/D \simeq 4.3\,\lambda_0/D$, whith λ_0 the central wavelength of band H.

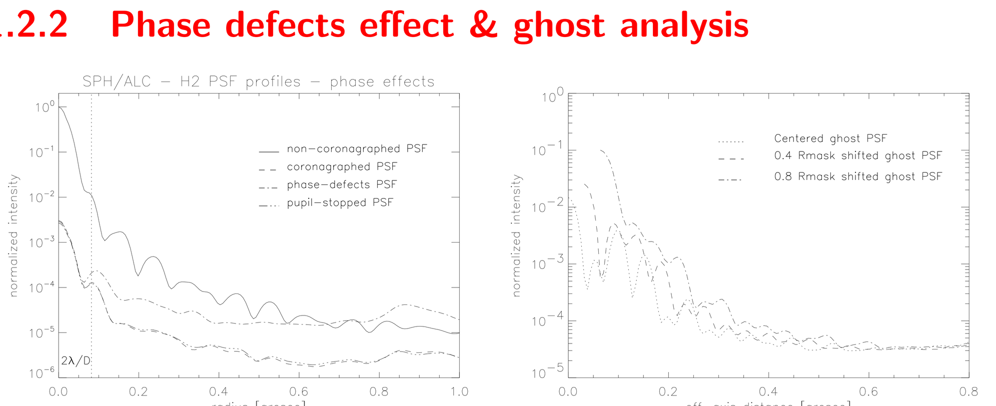
1.2 Critical points studies

1.2.1 Defects of the apodizer profile



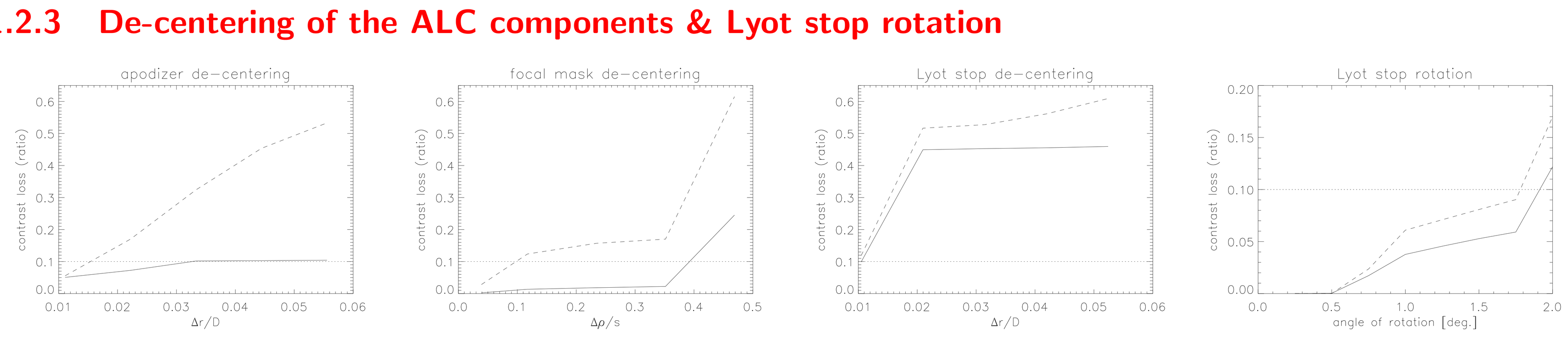
Left: simulated generic defects (plateau, excess and lack of material deposition, bumps, roughness). Right: Specification on the upper and lower limits (and relative discrepancies), when considering a defect acceptable if the contrast loss is less than 10%. Additional specification deduced: bumps such as $\left|1 - \frac{\text{ideal apodizer (r)}}{\text{anomalous apodizer (r)}}\right| \lesssim 2\%$.

1.2.2 Phase defects effect & ghost analysis



Left: profile of the post-coronagraph PSF with phase defects and pupil stop (contrast loss cancelled out when reducing the Lyot stop diameter to $0.98\,D \Rightarrow$ 0.96 D has been chosen in order to take into account a possible additional stop-centering inaccuracy). Right: ghost PSF for an anti-reflection coating of 1% (ghost misalignment $< 0.4\,R_{\mathrm{mask}} \Rightarrow$ ghost intensity attenuated enough so that it does not reduce the contrast).

1.2.3 De-centering of the ALC components & Lyot stop rotation



Contrast losses for both $\rho \leq \frac{1}{2}\lambda/d$ (dashed line) and $\rho \geq \frac{1}{2}\lambda/d$ (solid line). From left to right: contrast loss due to apodizer de-centering (from Δr=0 to Δr=1 mm, with respect to an actual apodizer diameter D=18 mm) ; contrast loss due to focal mask de-centering (from $\Delta\rho$=0 to $\Delta\rho$=120 μm, with respect to an actual focal mask diameter s=264 μm) ; contrast loss due to Lyot stop de-centering (from Δr=0 to Δr=0.5 mm, with respect to an actual Lyot stop diameter D=9.54 mm) ; contrast loss due to Lyot stop rotation (from 0 to 2°). The 10% level contrast loss is given by the straight dotted line.

2 Laboratory tests and performance

2.1 Experimental characteristics of the IR bench

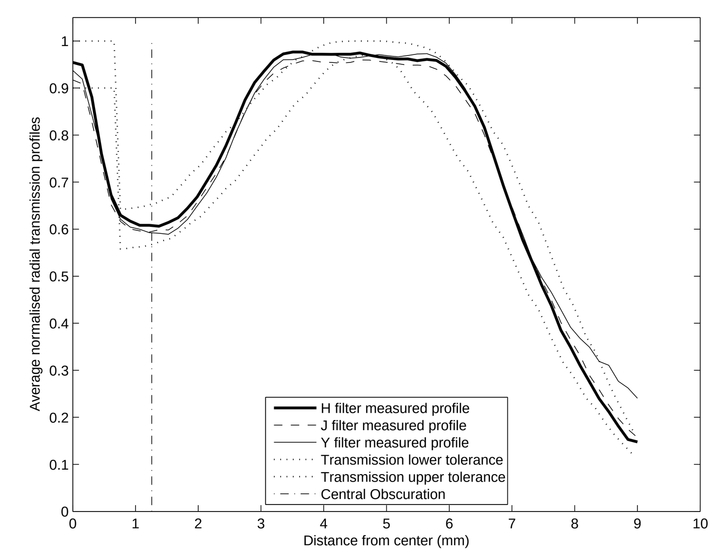
A specific infrared optical bench has been designed at LESIA to test the coronagraph prototypes which will be mounted on the SPHERE instrument. This bench mimics the optical conditions of SPHERE: aperture ratio of F/40 leading to an entrance pupil diameter of 18 mm, achromatic and astigmatic optical set up. The available artificial light source is a polychromatic pigtailed source delivering a large flat spectrum from visible to near-IR. A photonic crystal fiber is coupled to a super-continuum laser source. The output radiation is monomode from 0.45 μm to 2.5 μm with a mean optical power of 1 mW/nm. Several spectral filters are available on the bench, with the following central wavelength and resolution: λ_0 = 1.063 μm and R = 20 in Y band, λ_0 = 1.191 μm and R = 30 in J band, and λ_0 = 1.68 μm and R = 7 in H band.

2.2 Apodizer transmission measurement

The simulations presented in Sect. 1 allowed to define most of the dimensioning and tolerancing on the optical elements. The first measurement performed with the optical bench was the transmission profile of the apodizer, critical element. Then, this profile was used to compare the apodizer coronagraphic performance with respect to the performance of the theoretical ideal apodizer (Sect. 2.3 and 2.4).

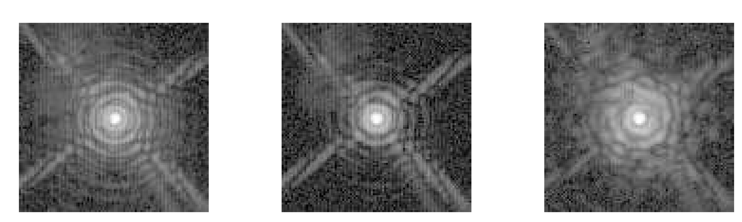
Manufacturing process (Reynard Corp. in California) of the apodizer: a thin layer evaporation of Inconel 600 (low reflectivity coefficient and flat spectral transmission) on a CaF_2 glass substrate.

- The profile is quite constant from Y to H band, assessing so the achromatism of the coating.
- The global transmission coefficient value of the apodizer is 65% ± 3% in J and H bands, and 68% ± 3% in Y band.
- The three profiles are out of the tolerance limits between radius 2.5 mm and radius 4 mm.
- The transmission in the Y band exceeds the upper limit close to the pupil edge.

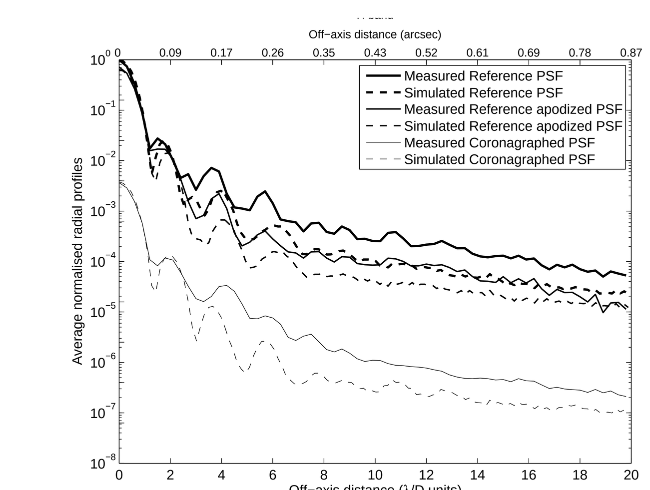


2.3 Coronagraphic performance in Y, J, and H bands of the ALC

From left to right: reference non apodized PSF (T_i = 1 ms), reference apodized PSF (T_i = 1.5 ms, dynamics x2), coronagraphed image (T_i = 300 ms, dynamics x300) in H band.



Criterion	Experimental value	Theoretical value
H Peak attenuation from the ref. PSF	270 ± 10	250 ± 30
H Peak att. from the apodized ref. PSF	190 ± 10	150 ± 20
H Rejection ratio from the ref. PSF	200 ± 40	205 ± 25
H Rej. ratio from the apodized ref. PSF	140 ± 30	135 ± 20
J Rej. ratio from ref. PSF	190 ± 40	150 ± 5
J Rej. ratio from apodized ref. PSF	120 ± 25	100 ± 5
Y Rej. ratio from ref. PSF	180 ± 35	160 ± 5
Y Rej. ratio from apodized ref. PSF	110 ± 25	110 ± 5



Average radial profiles compared with simulations in H band.

2.4 Determination of the Inner Working angle (IWA) value

IWA = 2.29λ/D @ 1.67μm consistent with [Guyon et al. 2006, ApJS, 167, 81]. Value obtained by decentering the coronagraphic mask to simulate an off-axis star, and defined when the star off-axis transmission is greater than 50%.

2.5 Lateral misalignment sensitivity

Tolerance values on the positioning of the ALC components obtained by measurements and compared with our simulations. X-Y: lateral position. Z: longitudinal position.

	Measurements		Simulations
	X-Y	Z	X-Y
Apodizer	±500 μm	±2.5 mm	±270 μm
Lyot mask	±5-10 μm	±1 mm	±25 μm
Lyot stop	±40 μm	±4 mm	±95 μm

- Critical elements: coronagraphic Lyot mask in X-Y-Z, and Lyot stop in X-Y. Same tendencies with the ALC prototype in the visible [Guerri et al. 2008, SPIE, 70143].
- Experiment versus simulation: a larger H band for the measurements making the sensitivity more severe for the Lyot mask and stop; edges of the manufactured apodizer less sharp than the simulated profile making the lateral positioning more tolerant.

Conclusions

In the first part of the poster, we have reported on the most interesting results of the whole end-to-end numerical study achieved during the design of the ALC for SPHERE/VLT: the apodizer is optimal for a mask size of $\sim 4\,\lambda/D$; a tolerance profile, together with specifications on possible bumps, was deduced ; the effects of the expected phase defects lead to a dramatic reduction of the coronagraphic performances, but a slight reduction of the Lyot stop cancels out this effect ; the ghost analysis leads to a very reasonable specification on the ghost misalignment, as well as de-centering of the apodizer, de-centering of the focal mask, de-centering of the Lyot stop, and Lyot stop rotation.
From the set of results presented in the second part, we can assess the ALC instrument complies the final SPHERE instrument specifications. The result is that the coronagraphic setup is particularly sensitive to the lateral and longitudinal positions of the coronagraphic mask, and to the Lyot stop lateral position. The sensitivity study is applicable to any type of apodizer, including microdots.

• **Further informations:** `marcel.carbillet@unice.fr`, `sylvie.robbe-dubois@unice.fr`