Apodized Lyot coronagraph for SPHERE: numerical study & laboratory performance

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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 coronograph (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.

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 (SPHIRE) [Carbillet et al. 2008, SPIE Proc. 7015, 70156Z]), and considering wavefront errors coming from a detailed optical aberrations analysis [Boccacetti 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 $\Delta I_{\text{ap}}(\rho, \theta) = \frac{I_{\text{ap}}(\rho, \theta) - I_{\text{ref}}(\rho, \theta)}{I_{\text{ref}}(\rho, \theta)}$, for both $\rho \leq \lambda/d$ (solid line) and $\rho \geq \lambda/d$ (dotted line), and for the three cases of aberration. Optimal contrast is obtained for $\rho \leq \lambda D / 4\Delta$ at the focus of the telescope, (g) PSF when the Lyot stop is removed, (h) pupil image before the Lyot stop introduction, (f) Lyot stop, (e) pupil image with the Lyot stop, (d) PSF with the Lyot stop, (c) pupil image including microdots.

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%.

1.2.2 Phase defects effect & ghost analysis

Left: profile of the pre-coronagraph PSF with phase defects and pupil stop (contrast loss cancelled out when reducing the Lyot stop diameter to 0.98 $\Delta$) 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 $\leq 0.4$ $\mu$rad => 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 $\rho \leq \lambda/d$ (dashed line) and $\rho \geq \lambda/d$ (solid line). From left to right: contrast loss due to apodizer de-centering (from $\Delta r=0$ to $\Delta r=1\mu m$, with respect to an actual apodizer diameter $D=18\mu m$), contrast loss due to focal mask de-centering (from $\Delta r=0$ to $\Delta r=120\mu m$, with respect to an actual focal mask diameter $\approx 254\mu m$), contrast loss due to Lyot stop de-centering (from $\Delta r=0$ to $\Delta r=0.5\mu m$, with respect to an actual Lyot stop diameter $D=9.54\mu m$), 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 LIESIA 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 monochromatic from 0.45/µm to 2.5/µm with a mean optical power of 1/µW/µm. Several spectral filters are available on the bench, with the following central wavelength and resolution: $\lambda_{\text{J}} = 1.083/µm$ and R = 30 in J band, $\lambda_{\text{H}} = 1.191/µm$ and R = 30 in H band, and $\lambda_{\text{K}} = 1.688/µm$ 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).

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

From left to right: reference non apodized PSF ($T_{\text{PSF}} = 1$ ms), reference apodized PSF ($T_{\text{PSF}} = 1.5$ ms), coronographed image ($T_{\text{PSF}} = 300$ ms, dynamics x100) in H band.

2.4 Determination of the Inner Working angle (IWA) value

IWA = 2.90/µm x 0.67/µm consistent with [Gouret 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 X Y

- Apodizer $\pm 0.10\mu m \pm 0.25\mu m \pm 0.25\mu m$
- Lyot mask $\pm 0.10\mu m \pm 0.25\mu m \pm 0.25\mu m$
- Lyot stop $\pm 0.10\mu m \pm 0.25\mu m \pm 0.25\mu m$
- Lyot stop $\pm 0.10\mu m \pm 0.25\mu m \pm 0.25\mu m$

- Experiment versus simulation: a larger H band for the measurements making the sensitivity more severe for the Lyot stop and mask; edges of the manufactured apodizer less sharp than the simulated profile making the lateral positioning more tolerant.

Conclusions

In the first part of the paper, 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 $\lambda/D$ = 4. Also, the procedure for the performance study can be applicable to any type of apodizer, including microdots.

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