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On-sky performance analysis of the vector Apodizing Phase Plate coronagraph on MagAO/Clio2

Abstract
We report on the performance of a vector Apodizing Phase Plate coronagraph that operates over a wavelength range of $2 - 5 \mu m$, and is installed in MagAO/Clio2 at the 6.5-m Magellan Clay telescope at Las Campanas Observatory, Chile. The coronagraph manipulates the phase in the pupil to produce three beams yielding two coronagraphic PSFs and one faint leakage PSF. The phase pattern is imposed through the inherently achromatic geometric phase, enabled by liquid crystal technology and polarization techniques. The coronagraphic optic is manufactured using a direct-write technique for precise control of the liquid crystal pattern, and multi-twist retarders for achromatization. By integrating a linear phase ramp to the coronagraphic phase pattern, two separated coronagraphic PSFs are created with a single pupil-plane optic, which makes it robust and easy to install in existing telescopes. The two coronagraphic PSFs contain a 180° dark hole on each side of a star, and these complementary copies of the star are used to correct the seeing halo close to the star. To characterize the coronagraph we collected a dataset of a bright ($L = 0 - 1$) nearby star with $\sim 1.5$ hours of observing time. By rotating and optimally scaling one PSF, and subtracting it from the other PSF we see a contrast improvement by 1.46 magnitudes at $3.5 \lambda/D$. With regular Angular Differential Imaging at $3.9 \mu m$, the MagAO vAPP coronagraph delivers a $5\sigma$ $\Delta$mag contrast of $8.3 (\approx 10^{-3.3})$ at $2 \lambda/D$, $10.8 (\approx 10^{-4.3})$ at $2.5 \lambda/D$, $12.2 (\approx 10^{-4.8})$ at $3.5 \lambda/D$, and $12.5 (\approx 10^{-5})$ at $4.5 \lambda/D$.

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6.1 Introduction

In direct imaging, the sensitivity for detecting companions close to the star is primarily limited by residual atmospheric (Racine et al., 1999) and quasi-static wavefront variations (Marois et al., 2005; Hinkley et al., 2007). These time-varying wavefront errors manifest themselves as irregularities in the diffraction halo around the star (speckles). Coronagraphs reduce the diffraction halo of the star at specific angular scales and since errors are modulated by diffraction rings the $S/N$ is thereby increased. This means that a coronagraph can significantly improve the contrast performance by suppressing the diffraction structure around the star. Both pupil and focal plane coronagraphs exist and are used on-sky with success (Guyon et al., 2006; Mawet et al., 2012). Many of the latest generation of instruments optimized for high contrast imaging contain focal-plane coronagraphs, which are typically limited to a raw contrast of $10^{-4}$ at small angular separations from the star (a few $\lambda/D$), mostly because of tip/tilt instabilities of the PSF due to, e.g., telescope vibrations and residual seeing effects (Macintosh et al., 2014; Fusco et al., 2014; Jovanovic et al., 2014). Pupil-plane coronagraphs are inherently impervious to such effects, as their performance is independent of the position of the star on the science detector, and can be amplitude (Carlotti et al., 2011) or phase-based (Codona and Angel, 2004). One type of pupil plane coronagraph, called the Apodizing Phase Plate (APP) coronagraph, sits in the pupil plane and modifies the complex field of the incoming wavefront by adjusting only the phase (Codona et al., 2006; Kenworthy et al., 2007). The flux within the point spread function (PSF) of the telescope is redistributed, resulting in a D-shaped dark region close to the star. Since the apodization is with phase only, the throughput of the APP is higher compared to traditional amplitude apodizers, and the PSF core remains roughly the same angular size. Because the Apodizing Phase Plate is located in the pupil plane it is not only insensitive to residual tip-tilt variations, but also nodding, chopping and dithering motions of the telescope. The PSFs of all stars in the image remain suppressed in the dark hole regardless of the motions of the telescope. In the infrared, the APP can be combined with conventional nodding motions as a background subtraction technique. Early versions of the APP were realized by varying the thickness of a piece of Zinc Selenide substrate (Kenworthy et al., 2007). The phase pattern corresponded to a variation in height of the substrate as a function of position in the telescope pupil. As a result of this, the APP was chromatic, suppressed only one side of the star at a time, and the diamond turning was limited to phase solutions with low spatial frequencies.

The vector Apodizing Phase Plate (vAPP, Snik et al., 2012) is an improved version of the APP coronagraph and is designed to yield high contrast performance across a large wavelength range, typically up to $\frac{\lambda}{\Delta \lambda} = 1$. The phase pattern of the vAPP is encoded in an orientation pattern of the fast axis of a half-wave retarder. Such a device imposes a positive phase pattern upon right-handed circular polarization, and a negative phase pattern upon left-circular polarization, through the geometric (or Pancharatnam-Berry) phase. (Pancharatnam, 1956; Berry, 1984; Mawet et al., 2009). This orientation pattern, as well as any other arbitrary pattern, can be embodied by a liquid crystal layer, that locally aligns its fast axis to a photo-alignment layer. The geometric phase is inherently achromatic, but leakage terms can emerge if the retardance is not exactly half-wave (Mawet et al., 2009; Kim et al., 2015). A typical APP phase design is antisymmetric in the pupil function that results in a D-shaped dark hole next to the star. By splitting circular polarization states with inverse geometric phase signs in the pupil, the vAPP creates two PSFs with dark holes on either side. By combining multiple self-aligning layers of twisting liquid crystals, it is possible
6.2 The vAPP coronagraph for MagAO/Clio2

6.2.1 The grating-vAPP principle

The vAPP coronagraph designed for MagAO/Clio2 has a phase pattern that is composed of two separate patterns - the first is the APP phase pattern, which produces the dark D-shaped hole, and the second is a polarization grating (i.e., a linear phase ramp that is opposite for the two circular polarization states). This polarization grating splits the two PSFs without the need for a quarter-wave plate and Wollaston prism, as introduced in Chapter 4 (Otten et al., 2014b), which greatly improves the ease of installation. As both the modification of the PSF and the splitting direction depends on the handedness of circular polarization cf. the geometric phase, the grating-vAPP produces two separate coronagraphic PSFs with dark holes on opposite sides, providing continuous coverage around the star. The inclusion of the linear phase also means that any leakage term due to the plate not being perfectly half-wave ends up between the two coronagraphic PSFs as a third PSF. The positioning of the leakage term PSF in between the coronagraphic PSFs minimizes the impact of any residual non-half-wave behavior of the retarder to the contrast inside the dark holes (Chapter 3). This PSF can be used as a photometric and astrometric reference, and as an image quality indicator. Both the coronagraphic PSFs and the splitting angle are not dependent on the value of the average retardance of the plate. Only the brightness ratio of the leakage PSF with respect to the coronagraphic PSFs changes with varying retardance. As the splitting between the PSFs is imposed by a diffractive grating pattern, their separation is a linear function of wavelength. Hence, while the vAPP optic offers high-contrast coronagraphic performance over a broad wavelength range, we apply narrowband filters throughout this wavelength range to produce sharp PSFs without radial smearing. By orienting the dark holes left/right with respect to the up/down splitting, this grating effect furnishes low-resolution spectroscopy of point sources inside either of the dark holes.
6.2.2 Phase pattern design

The phase pattern is determined with a simple, iterative algorithm akin to a Gerchberg-Saxton iteration (Gerchberg and Saxton, 1972; Fienup, 1980). We switch between electric fields in the pupil plane and the focal plane with Fourier transformations and enforce constraints in the corresponding planes. In the pupil plane, the amplitude field amplitude is set to unity inside the telescope aperture and zero everywhere else. In the focal plane, we set the electric field amplitude to zero in the dark hole. This process is repeated hundreds of times until we obtain a phase pattern that achieves the desired contrast. This approach does not guarantee the highest Strehl ratio for a desired contrast, but we found it to perform better than any other design approach that we are aware of.

Since this particular APP design only has a dark hole on one side of the focal plane, the phase pattern in the pupil will be antisymmetric. We use this symmetry to improve the performance of the algorithm. Instead of setting the electric field to zero in the dark hole, we add a scaled and mirrored version to the electric field on the other side of the dark hole. This is motivated by the fact that a one-sided dark hole created by an antisymmetric phase pattern is achieved in the focal plane by symmetric and anti-symmetric parts of the electrical field canceling each other in the dark hole and adding to each other on the other side. The scaling enforces energy conservation in the focal plane. A comprehensive description of our design algorithm including applications to symmetric dark holes will be provided in a forthcoming publication by Keller (in prep). For the optimization in this paper we define a dark hole from 2 to 7 \( \lambda / D \) and with a 180° opening angle and a desired normalized intensity of \( 10^{-5} \). The final design has a peak intensity of 40.3% with respect to an unaberrated PSF.

6.2.3 Coronagraph optic specifications

The optic has a diameter of 1 inch and a thickness of approximately 3.3 mm, and is designed to work with the Clio2 camera with a nominal size of 3.32 mm of the MagAO telescope pupil image. The diameter of the vAPP was undersized by 100 microns (from a diameter of 3.32 mm to 3.22 mm) to create a tolerance against pupil misalignments in the instrument. A 1° wedge is added on one side of the coronagraph in order to deflect reflection ghosts. To further suppress ghost reflections, both sides of the optic are broad-band anti-reflection coated with an average transmission between 2 and 5 micron of 98.5%. An aluminum aperture mask, matching the Magellan pupil, with a pixelated edge (with a pixel size of 11.54 microns) is deposited on one of the substrates and is sandwiched directly against the retarder layers, manually aligned using a high power microscope, and fixed in place with an optical adhesive. The phase pattern (the coronagraphic pupil phase pattern plus the grating pattern) is written as an orientation pattern of an alignment layer of “DIC LIA-CO01” by a UV-laser with polarization-angle control (Miskiewicz and Escuti, 2014). The pixel size is 11.54 microns for both the phase and amplitude pattern. During fabrication the writing accuracy of the fast axis is calibrated to approximately 2°, corresponding to a maximum phase error of 4°, i.e. \( \sim \lambda / 100 \). The patterned retarding layer consists of three MTR layers (Merck RMS09-025, see also Table 6.1) and is optimized to produce a retardance \( \delta \) that is half-wave to within 0.38 radians for wavelengths between 2 and 5 microns, corresponding to a maximum flux leakage from the coronagraphic PSFs to the leakage term PSF of 3.5%. The design recipe of the MTR is \([\phi_1 = 78^\circ, d_1 = 3.5 \mu m, \phi_2 = 0^\circ, d_2 = 7.3 \mu m, \phi_3 = -78^\circ, d_3 = 3.5 \mu m]\) where \(d_i\)
stands for layer thickness, $\phi_i$ for the twist of a layer and $i$ for the layer number. This recipe is used to build our coronagraph with our custom fast axis pattern and also a test article with the same parameters but a fixed fast axis. The transmission of this test article is measured between crossed linear polarizers with a VIS-NIR spectrometer up to 2800 nm. A model of the MTR is fitted to the observed transmission between crossed polarizers with 5 free parameters (3 thicknesses and 2 relative twists with respect to the middle layer). The best fit parameters are $[\phi_1 = 81^\circ, d_1 = 3.5 \mu m, \phi_2 = 0^\circ, d_2 = 7.3 \mu m, \phi_3 = -77^\circ, d_3 = 3.9 \mu m]$ and used afterwards to predict the transmission, retardance and leakage at wavelengths out to 5000 nm, which is shown in Fig. 6.1, 6.2 and 6.3.

The leakage PSF intensity is derived by measuring the peak ratio of the coronagraphic to leakage term PSF in a sequence of unsaturated images. The mean and standard deviation of the ratio in this sequence is 31.47 ± 1.07. This ratio is divided by the theoretical strehl ratio 0.403 to yield the ratio as if the coronagraph was not present. This means that the intensity of the leakage term is $1/781 \cdot I_{\text{coron}}$, where $I_{\text{coron}}$ is intensity of the coronagraphic PSF. This value is normalized by the total intensity $(2 + 1/78.1) \cdot I_{\text{coron}}$ to yield the fractional leakage intensity (the amount of light that goes into the leakage term). In the completed coronagraph we measure a leakage term intensity of 0.636% at 3.94 microns, which corresponds to $\delta = 2.98$ rad, using this method which is within the previously defined specifications. While this leakage is larger than the theoretical expectation at that wavelength (0.16%) it is comparable in magnitude to the maximum retardance offset of the curve.

The polarization grating spans 17.5 waves in terms of phase. Corresponding to a displacement of $35 \lambda/D$ between the two coronagraphic PSFs, and so that both of the PSFs fit on the chip at the longest wavelengths ($M'$-band) while minimizing the contribution of the leakage term diffraction pattern into the dark holes. The grating creates a splitting angle that is dependent on the wavelength in terms of pixels of separation, and so the PSFs are laterally smeared. For optimal image quality, where the smearing is at most $1 \lambda/D$, the filter full width half maximum needs to be $\frac{\lambda}{\lambda} \leq 0.06$. Due to the optic's efficiency, narrowband filters can be used anywhere between 2 and 5 microns to produce coronagraphic suppression, leading to a natural use of vAPPs with integral field spectrographic units. Note that even outside the specified wavelength range, the coronagraphic performance is never deteriorated by leakage terms, but the coronagraphic PSFs are less efficient as they lose light to the leakage term PSF.

We collected pupil image measurements with and without the coronagraph at several IR bands during good sky conditions and with AO to obtain accurate on-sky pupil transmission measurements. We determine the transmission of the optic from the ratio of the pupil intensity with and without the coronograph. The theoretical transmission values are detailed in Table 6.1 per layer and compared to the measured transmission. Since the measured retardance is close to half-wave (as expected from the theory), the thickness of the liquid crystal layers must not deviate significantly from the theoretical value. We therefore set the thickness to the fitted value for the MTR recipe which is 14.7 microns. The absorption properties of the retarder layer were measured in a 900 nanometer thick sample at a wavelength of 4 microns and extrapolated to the 14.7 micron thick layer. The absorption coefficient derived from this measurement falls on the high end of the range seen in Fig. 3 of Packham et al. (2010), who used a similar family of liquid crystals. The absorption coefficient of the glue layer is derived from the spectral transmission graph on
Figure 6.1: Transmission of optic between crossed polarizers against wavelength for the theoretical design and a test article with linear fast axis made according to the same recipe. A model of the MTR is fitted to the test article and used for Fig. 6.2 and 6.3.

Figure 6.2: Plot of retardance versus wavelength based on design and best fit of MTR model to the crossed polarizer transmission. The retardation requirement corresponds to a maximum leakage of 3.5% and a retardance offset of 0.38 radians or 21.6 degrees. The on-sky measured datapoint of the leakage is converted into retardance and shown with a blue circle. The measurement error on the datapoint is 0.15 degrees (estimated by propagating the standard deviation of the leakage to retardance) and smaller than the blue circle that was used.

the Norland Products website\(^1\) and the known thickness of their sample. The thickness of the

\(^1\)https://www.norlandprod.com/adhesives/NOA%2061.html
glue layer is the biggest uncertainty as it was not measured during the manufacturing process. Because the other transmission values are well constrained, we let the thickness of the glue layer vary as a free parameter to match the observed transmission. Our derived glue layer thickness of 50 microns is not unexpected for glass-glass interface bonding. The breakdown shows that the throughput is primarily limited by the optical adhesive NOA-61. The absorption features of both the optical adhesive and the retarding layer are related to vibrational modes of chemical bonds with Carbon, such as C-C, C-O, C-N and C-H. The optical adhesive is based on urethane-related compounds.

The coronagraph is located in the pupil stop wheel of Clio2 and orientated with the grating splitting angle perpendicular to the arc traveled by the pupil in the pupil wheel. The wedge splitting angle was orientated parallel to the motion of the pupil. This orientation of the splitting angle corresponds in theory with splitting the PSFs along the short axis of the chip. This leaves a large amount of space along the long axis to nod the PSFs along for background subtraction. From our PSF measurements we see that the orientation of the PSFs on the chip is approximately 26 degrees rotated away from the short axis. This rotation does not interfere with the background subtraction.

\[2\text{https://www.norlandprod.com/msds/noa\%2061\msd.html}\]
Table 6.1: Table describing the thickness and transmission properties of the different layers.

<table>
<thead>
<tr>
<th>layers</th>
<th>material</th>
<th>thickness</th>
<th>3.9 micron</th>
<th>4.7 micron (M')</th>
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</thead>
<tbody>
<tr>
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<td>-</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>substrate with 1° wedge</td>
<td>CaF₂</td>
<td>0.8 mm</td>
<td>0.99</td>
<td>0.99</td>
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<td>evaporated aluminum</td>
<td>250 nm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>bonding glue</td>
<td>NOA-61 epoxy</td>
<td>50 µm</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>substrate</td>
<td>CaF₂</td>
<td>1 mm</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>retarder layers</td>
<td>Merck RMS09-025</td>
<td>14.7 µm</td>
<td>0.85</td>
<td>~ 0.85</td>
</tr>
<tr>
<td>alignment layer</td>
<td>DIC LIA-CO01</td>
<td>50 nm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>bonding glue</td>
<td>NOA-61 epoxy</td>
<td>50 µm</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>substrate</td>
<td>CaF₂</td>
<td>1 mm</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>AR-coating</td>
<td>-</td>
<td>-</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
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</tr>
<tr>
<td>measured throughput</td>
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<td>-</td>
<td>0.51</td>
<td>0.54</td>
</tr>
</tbody>
</table>

6.3 Observations

The observations with the vAPP coronagraph at MagAO/Clio2 were taken during 2015 June 6, 07:38:40 - 10:07:34 UT during excellent conditions (with only high cirrus). The filter used for these observations is the 3.9 micron narrowband filter with a width of 90 nm and a central wavelength of 3.94 microns. The plate scale of the detector is 15.85 arcseconds/pixel. The target discussed in this paper to assess the vAPP’s contrast performance is a single A-type star with an L’-band magnitude between 0 and 1. The star was picked to be bright and without a known companion to reach the limits of the coronagraph’s performance. 287 data-cubes were taken on-sky, each with 20 subframes and an exposure time of 1 second each. The dataset has a total on-target exposure time of 5740 seconds. The derotator was off during the observations and spans a total of 39.45° of field rotation. To perform background subtraction, data-cubes were recorded with the PSF centered approximately 10 arcseconds to the left from the nominal center of the science camera array, so that no sources and ghosts are seen on the same part of the chip. Our target was therefore located off the chip. This background estimation was repeated 4 times during the sequence. No flats have been applied to the data and a sky correction was made using the off-target nods.

Fig. 6.4 shows a comparison between the theoretical and observed PSFs using a median combination of the top 50% best frames in terms of the fitted radius \((1.22 \lambda / D)\) of the leakage term PSF, acting as a proxy for subframe quality as it expands to match increased turbulence. The observed coronagraphic PSFs are saturated in the core and the first diffraction ring but are corrected to the peak flux consistent with the unsaturated calibration images. While the two PSFs have approximately the same brightness, the two PSF halos inside the dark holes have a slight difference. A potential source of the difference is discussed in Section 6.3.2.

https://visao.as.arizona.edu/observers/
Figure 6.4: Comparison of theoretical (left) with observed PSFs (right). Both images are at the same logarithmic scale with a lower threshold of $10^{-3.3}$. The theoretical PSF is calculated for the central monochromatic wavelength of 3.94 microns. The retardance in the simulation was set to $\delta = 2.98$ radians, thereby creating the leakage PSF “0”. The observed image is saturated on the first diffraction ring and the central core but is corrected to the unsaturated flux level. A small asymmetry of the intensities of the wind-driven halos of the star is seen between the two PSFs at the location of the first diffraction ring. Instrumental ghosts are indicated with arrows and not related to coronagraphic optic. Further investigation showed that these ghosts can be removed from the dark hole by setting the rotator to an angle of $30^\circ$. As a reference to the text we indicate the “+”, “0” and “−” PSFs.

6.3.1 Data reduction

To remove hot, dead or flaky pixels in each image, a median filtered image with a $3 \times 5$ pixel box is subtracted from the cleaned and centroided image cube to generate an image where the outliers clearly stand out. The $3 \times 5$ box is chosen because the outlying pixels tend to have structure in the direction of the readout and not perpendicular to it. The data points that deviate more than 1000 counts are replaced by the local value of the $3 \times 5$ median. Four sets of sky reference frames are taken between on-target observations. The sky frames were median combined for every one of the 4 sets. Each of the previously taken frames on target were subtracted by the first consecutive median-combined master sky frame. After the background subtraction, the median of a cosmetically clean part of the chip is subtracted in order to remove any residual background offset. A theoretical diffraction pattern consistent with the geometry of the telescope and wavelength of observation is used as a fiducial. This theoretical PSF is then fit to the central leakage PSF by
minimizing the chi-squared residuals between the theoretical PSF and the leakage PSF, with \( x \), \( y \), radius \( (1.22 \lambda/D) \) and intensity as the free parameters of the fit. All images of the data-cubes are co-registered by shifting the images to the central pixel of the frame with the previously fitted \( x \) and \( y \) values using a bi-linear interpolator. The radius of the leakage PSF fit is used as an sub-frame quality indicator. The few images that have fitted radii significantly smaller (\(< 9 \) pixels) or larger (\(> 12 \) pixels) than the diffraction limit are excluded. The best 91\% (5 200) of images are selected after sorting the frames by radius from smallest to largest. This selection removes the frames where the seeing conditions temporarily worsened or where the AO-system lost its lock. After this selection, the images are reordered to original chronological order and binned by 4 frames, corresponding to 4 seconds integration time per binned frame to reduce memory consumption and computational time. Instrumental ghosts due to internal reflection of the refractive optics are present in the image, see Fig. 6.4. Several of these ghosts are typically \( 10^{-2} \) to \( 10^{-3} \) in intensity, and their position relative to the central PSF changes as a function of position on the chip. To reduce their influence, the regions of identified ghosts are masked off from any subsequent fitting and/or stacking process. These ghosts can be removed from the dark hole by setting the rotator to an angle of 30\°.

6.3.2 Rotation, scaling & subtraction

Each on-target image consists of three PSFs which we label “+” for the upper coronagraphic APP PSF, “-” for the lower coronagraphic PSF with the dark region on the opposite side of the star, and “0”, the leakage PSF which is consistent with the PSF obtained with no coronagraph in the optical path, and with a flux typically \( 10^{-2} \) of the other two PSF cores. To suppress the noise contribution of the seeing-driven halo inside the dark holes, we use one coronagraphic PSF as a reference for the other coronagraphic PSF of the same star, and subtract “-” from “+”. This reduces self-subtraction of the flux of a potential companion as it is very unlikely to have another companion at the same separation and brightness on the opposite side of the star. A similar approach is taken by Marois (2007); Dou et al. (2015) who use the (non-coronagraphic) PSF (itself) under rotation as a reference and measure an order of magnitude improvement compared to normal LOCI (Lafrenière et al., 2007) without rotation. Our approach works by rotating, scaling and subtracting PSF “-” from PSF “+” in a three-step process. First, the image is flipped in both dimensions so that “-” has the same orientation as “+”. We align each “+” and “-” PSF with the median of all “+” PSFs, by performing a cross-correlation on a bright, isolated feature at \( 10 \lambda/D \) on the bright side of the PSF. With the obtained centroids, the “+” and “-” PSFs are sub-pixel shifted to the frame center with the python routine scipy.ndimage.interpolation.shift set to first-order spline interpolation. The “-” cube is then multiplied by a fixed amplitude ratio and subtracted from the “+” cube. An example of the PSFs before and after subtraction can be seen in Fig. 6.5 for three different scaling factors (resp., 0, 1.04 and 0.71). The diffraction structures on the bright side of the PSFs are optimally canceled using an amplitude scaling ratio of 1.04. This is consistent with the ratio of the encircled energies of both PSFs. However, with this ratio the seeing-driven halo in “-” is oversubtracting the halo in “+”, resulting in larger amounts of noise in the final combined image. A likely cause for this is that aberrations create pinned speckles upon the diffraction structure in the dark holes, but the intensities may be different in the left and right dark holes. Although this diffraction structure ideally has an intensity of \(< 10^{-5} \) with respect to the PSF core (and therefore not visible in the left panel of Fig. 6.4), it becomes brighter due to
residual seeing and/or optical aberrations of the telescope and instrument. Because this diffraction structure is fully symmetric between the two PSFs, a rotation-subtraction approach with a variable scaling factor always reduces the intensity in the halo. A simple simulation shows that with the realistic seeing and AO performance the intensity of this halo is practically balanced, even when a AO loop time lag (3 ms) and wind speed (10 m/s) are taken into account. As for (quasi-)static optical aberrations, only odd modes (like trefoil aberration) cause an intensity asymmetry between the holes in the two dark holes. Assuming trefoil is the dominant aberration we simulate how much trefoil is at most allowed to create a PSF that is still consistent with the observed in terms of the asymmetry between the dark holes. Based on this simulation we conclude that the RMS error of the trefoil aberration needs to be at least 0.04 radians (25 nm at 3.94 microns) of trefoil to match the observations.

Another option for scaling the two PSFs is to take the amplitude ratio that minimizes the halo noise in time and applying that to all frames (c.f. Marois et al. (2006)). To determine this ratio we calculate the standard deviation for the temporal intensity variation in many randomly selected \(3 \times 3\) pixel patches across the dark hole. Figure 6.6 shows the standard deviation for various \(3 \times 3\) patches as a function of the amplitude ratio. The vertical lines indicate the ratio at which the noise is minimal on average for a series of radial \(\lambda / D\) bins. As reducing the noise closest to the star is the most important, the value 0.71 that on average minimizes the noise in the bin from \(2 - 3 \lambda / D\) is used to scale the amplitude of the bottom PSF cube before subtracting it from the top PSF. As mentioned before, to minimize the intensity of the brightest parts of the PSF and not the noise an amplitude scaling ratio of 1.04 is required. Fig. 6.7 shows the same optimal scaling factor for each pixel inside the combination of dark holes. It is apparent that rotation-subtracting PSFs is only effective close to the star, at the location of the seeing-driven halo. Further away from the star it is preferred to not perform any subtraction at all, as at the outer parts of the dark holes the noise is uncorrelated (e.g., photon shot noise from the thermal background, and read-noise) and
therefore subtracting the two images will actually inject noise and consequently increase it with a factor $\approx \sqrt{2}$. This effect can be reduced by optimizing the ratio in radial bins as is commonly done with LOCI (Lafrenière et al., 2007) and Principal Component Analysis (Amara and Quanz, 2012; Soummer et al., 2012).

For a scaling ratio of 0.71 we plot in Fig. 6.8 time series and histograms for three $3\times3$ pixel patches at locations inside the dark holes as indicated in Fig. 6.5 before and after the subtraction to see how the rotation-subtraction technique improves the intensity variability. At the location closest to the PSF core ($1.8 \lambda/D$) both the average value and the standard deviation of the intensity is significantly reduced. This effect is seen in both the time series and the histograms. This is particularly evident in cases of worse AO performance (for instance, around the $# = 750$ mark). Moreover, the rotation-subtraction technique produces histograms that are much more Gaussian than before. As discussed already, pixels further away from the central star actually obtain a $\sqrt{2}$ increase in the noise.

### 6.4 Results: contrast curve

The combination of the intrinsic coronagraphic performance of the vAPP coronagraph inside the dark holes, and the optimal rotation-subtraction of its two complementary PSFs to subtract the residual seeing-driven halo delivers essential suppression at very small angular separations from the central star to detect and characterize planetary companions. We apply median-filtering and classical Angular Differential Imaging (Marois et al., 2006) (without excluding frames based on the angular distance) to further suppress static and quasi-static speckles inside the combined dark holes to reach the ultimate contrast. After rotation-subtracting the two PSFs with the optimal ratio, the median value inside a wedge from $5 - 7 \lambda/D$ in the dark hole is subtracted from every pixel in every frame of the data cube. This process is repeated for every frame to remove any residual intensity offsets. The median across the time dimension per pixel is removed from the whole cube to remove any residual static PSF structures. After these steps the frames are derotated and co-added by taking the mean across the time dimension.

Artificial companions are injected in the original datacube at steps of $0.5 \lambda/D$ and with steps in magnitude of 1 with the expected amount of sky rotation. The injected sources are a rescaled and translated version of the unsaturated calibration dataset. Note that a companion in the top (“+”) PSF emerges as a positive signal detection, while a companion on the other side of the star (i.e. in the dark hole of the lower “-” PSF) is seen as a negative signal. The previously described pipeline of optimal rotation-subtraction, median-filtering and ADI is applied to these data-cubes with injected sources of varying contrast ratio. The signal to noise of these planets is calculated by calculating both the sum of the flux in an aperture with a width of $1 \lambda/D$, and the noise in the same aperture without the planet added. The noise in this aperture is multiplied by the square root of the number of pixels in the sub-aperture to obtain the measurement noise on the planet flux, assuming that this noise is Gaussian. The magnitude of the injected point source is rescaled to obtain a $S/N = 5$ and these values are plotted as a contrast curve for $5\sigma$ point source detection sensitivity versus angular separation in Fig. 6.9.

In Fig. 6.9 we note that within $4.5 \lambda/D$ the contrast of a single PSF (ratio = 0) is improved by subtracting the other PSF with a fixed amplitude scaling factor of 0.71. This is most evident at a angular separation of $3.5 \lambda/D$ where the improvement is 1.46 magnitudes (4-fold improvement)
6.4 Results: contrast curve

Figure 6.6: Standard deviation of many randomly selected pixel patches inside the combined dark holes as a function of the scaling factor between the two PSFs. The lines are color-coded according to their distance from the star. For different radial bins the average scaling ratio that creates the minimal noise value is shown with the vertical lines and labeled with the inner and outer angle of that bin.

Figure 6.7: Map showing the optimal scaling factor for every pixel in the data-cube. Far away from the star the optimal ratio is close to zero, as the noise is fully random and uncorrelated between the two PSFs. Close to the star in the seeing halo a ratio of about 0.7 is required for optimal noise reduction. The ghost is seen as a clear outlier at the bottom. While we used a fixed scaling factor in this work, it can also be varied in radial bins to optimally minimize the noise as a function of distance from the star.
Figure 6.8: Time series and histograms before and after PSF subtraction for each of the 4 pixel patches shown in Fig. 6.5. A boxcar-averaged line is overplotted for both cases. The range of the x-axes of the histograms is adjusted to be identical in length before and after PSF subtraction. Within $4.5 \lambda/D$ the histograms after subtraction have an average closer to 0, become more Gaussian, and their width decreases.

To a $\Delta \text{mag}$ of 12.2, which corresponds to a contrast of $10^{-4.8}$. Beyond $4.5 \lambda/D$ the contrast performance for the rotation-subtraction technique is degraded, as here the noise is random and uncorrelated, and therefore aggravated after the combination with the second PSF. As previously commented, we expect to be able to reduce this effect by optimizing the scaling factor in radial bins, although this also increased the degrees of freedom. This turnover point at $4.5 \lambda/D$ is dependent on the brightness of the target and moves inward with fainter targets as the background noise contribution becomes more dominant. For this dataset this turnover point at $4.5 \lambda/D$ has a $\Delta \text{mag}$ of 12.5, corresponding to a contrast of $10^{-5}$. Like many other reduction methods our classical ADI approach also removes part of the planet flux in addition to residual speckles in the stellar PSF. To quantify this effect we retrieve the planet flux after applying the whole data reduction pipeline to the data and compare it to the injected planets. The efficiency of the ADI


### 6.5 Discussion and conclusions

To put this contrast performance of the vAPP coronagraph at MagAO/Clio2 in context, we compare our results to published on-sky contrast curves for different coronagraphic instruments. Such an analysis uses heterogeneous data sets due to variations in the brightness of the star, the wavelength, the size of the telescope and applied data reduction techniques. Nonetheless we attempt to make a comparison to existing coronagraphs. To begin with a related coronagraph; in comparison to the performance of the regular APP at VLT/NACO (Quanz et al., 2010; Kenworthy et al., 2013; Meshkat et al., 2014), the vAPP PSFs do not exhibit any clear diffraction structure close to the star, whereas the VLT APP PSF clearly does. The much-improved manufacturing accuracy of phase patterns now permits the creation of dark holes that are devoid of diffraction structure down

![Figure 6.9](image_url)
to $10^{-5}$. Moreover, the coronagraphic PSFs of the grating-vAPP are not deteriorated by leakage PSFs, as they form a separate PSF, that actually can be used to one’s advantage as a photometric and/or astrometric reference.

The contrast performance is compared in Fig. 6.10 with the following contrast curves: Annular Groove Phase Mask (AGPM) at LBT (Defrère et al., 2014), the Vector-Vortex Coronagraph (VVC) at the 1.5 m well-corrected aperture at Palomar (Serabyn et al., 2010), the GPI first light results (Macintosh et al., 2014), SPHERE with the Apodized Lyot Coronagraph (ALC) (Vigan et al., 2015), and the APP at the VLT (Meshkat et al., 2014). We compare all the contrast curves in terms of $\lambda/D$ to account for differences in telescope diameter and observed wavelength. All the contrast curves are corrected from a $N\sigma$ to $5\sigma$ detection limit. We assume the contrast is limited by speckle noise in all cases and therefore do not correct the curves for differences in exposure time and telescope diameter. The SPHERE P95 User manual comments that while they have several types of coronagraphs to first order they all have the same contrast performance \(^4\). In terms of $\lambda/D$, both the GPI and SPHERE contrast curves tend to reach high contrasts farther away from the star. The inner working angle (IWA) of the SPHERE ALC is restricted by the design of the K-band ALC coronagraph which can be used from 120 mas outwards. The VVC result at Palomar 1.5-m well-corrected aperture is a bit of an outlier because of the significantly different $D/r_0$ ratio compared with the other telescopes, but is included because of its high performance at a $\lambda/D$-sized inner working angle. The assumption of being speckle limited likely does not hold here as the VVC results were within a factor of two from the photon noise on the background. We see that the vAPP outperforms the other coronagraphs within 5 $\lambda/D$ with an improvement up to 2 magnitudes from $2.5 - 3.5 \lambda/D$.

The exceptional contrast performance of the vAPP coronograph is owing to the unique combination of the following properties:

1. Insensitivity to tip-tilt errors that plague focal-plane coronagraphs but not pupil-plane coronagraphs like the vAPP.

2. Deep suppression of the PSF diffraction structure with an accurately manufactured (geometric) phase pattern already at the first diffraction ring down below the seeing-driven halo.

3. Subtraction of the halo in the dark holes by combining both PSFs with a rotation-subtraction technique.

We see that using the second coronographic PSF as a PSF reference gives an improvement of 1 – 1.5 magnitudes (factor 2.5-4 in terms of $S/N$) at $3 - 3.5 \lambda/D$. The PSF subtraction is shown to improve the contrast within 4.5 $\lambda/D$. With a radially optimized subtraction the degradation of the contrast outside of this distance can be reduced. Given a fixed ratio based on optimal contrast close to the star, we obtain a $5\sigma$ $\Delta$mag contrast of 10.8 ($= 10^{-4.3}$) at $2.5 \lambda/D$, 12.2 ($= 10^{-4.8}$) at 3.5 $\lambda/D$, and 12.5 ($= 10^{-5.0}$) at 4.5 $\lambda/D$. With a PCA-based algorithm we expect that our performance will be less impacted by self-subtraction and will improve towards the dashed line of Fig. 6.9. This also makes it possible to make a correction based on the time dependence of the PSF in order to remove the longer scale variations, although it is expected that most of the correction power comes from the same frame. Using a contemporary reference PSF is explored by Dou et al.\(^4\)

\(^4\)SPHERE Period 95, phase 2 User Manual
**6.5 Discussion and conclusions**

Figure 6.10: Comparison of $5\sigma$ contrast as a function of angular separation from the central star from literature. The curves of other studies have been overplotted at the same $\lambda/D$ to correct for different telescope sizes. The vAPP outperforms many other coronagraphs close to bright stars where one expects to be speckle limited.

(2015), who used the roughly symmetric PSF itself under rotation to feed a PCA algorithm. Their approach gave an improvement of an order of magnitude in terms of contrast when compared to LOCI. Rodigas et al. (2015) use a close binary star to build their reference PSF library. By having a simultaneous reference within the isoplanatic patch, and with roughly the same optical path through the telescope, a better sensitivity is expected than using the star as its own reference. In their study a 0.5 magnitude improvement within 1 arcsecond from the star was seen compared to normal ADI. Rodigas et al. (2015) suggests combining their Binary Differential Imaging (BDI) technique with the vAPP coronagraph to reach better contrasts. We can extend this by noting that a double correction can be done by combining BDI and the second vAPP PSF as another reference. In both previous cases the methods are less impacted by self-subtraction because it is unlikely that a companion exists in the reference library with similar brightness, position angle, and radius. Both papers give us confidence that a PCA-based algorithm can be used to generate a better reference PSF and the contrast can be pushed down even more.

One substrate and consequently one adhesive layer can be removed by directly depositing the retarding layer on top of the AR coated substrate and bonding it directly with the substrate with the aluminum mask. This procedure increases the throughput by about 20% but makes manufacturing slightly more difficult and expensive.
6.5.1 Future work

We have shown a manufacturing technique, based on the geometric phase due to patterned liquid crystals, that allows precise control of the phase pattern and a broad-band coronagraphic response that can be optimized anywhere between the visible range and the mid-IR. The optic is relatively straightforward to manufacture and install at existing telescopes as it only uses one pupil plane. Using these capabilities we are looking into new phase patterns with different properties than normally expected from the classical APP theory. For instance, a dark hole spanning $360^\circ$ per PSF, or integrated wavefront sensing solutions (Wilby et al., 2016) has been implemented and tested on-sky. Future work includes improving the $360^\circ$ phase-only solutions to increase the working area of the coronagraph, and the potential development of hybrid coronagraphs as described by Ruane et al. (2015). Furthermore we will study the photometric and astrometric stability of the leakage term to assess how well this reference works. Another option that we intend to explore is using the three PSFs of the vAPP to retrieve the wavefront through phase diversity methods. If they are computationally fast to derive, the wavefront error estimates can be fed back to the telescope to correct quasi-static aberrations.

Following the work of Snik et al. (2014) we also intend to explore the dual-beam polarimetric capabilities of the vector APP in the optical lab and on-sky. For polarized sources an increased sensitivity is expected by simultaneously using the coronagraphic capabilities and polarimetric beam switching.

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