Closing the technology gap for the Extremely Large Telescope's Planetary Camera and Spectrograph (ELT-PCS): development of the coronagraph and focal plane wavefront control strategies

Sebastiaan Y. Haffert[a,b], Axel Potier[c], Lucie Leboulleux[d], Bachar Wehbe[e], Olivier Absil[f], Pierre Baudoz[g], Carlos M. Correia[h], Louis Desdoigts[a,i], Valentin Fonteneau[j,k], Nicolas Galland[l], Aya Harkat[l], Elsa Huby[g], Jonas Kühn[m], Caroline Kulcsár[l], Rico Landman[a], Maud Langlois[j,k], Matthijs Mars[a], Patrice Martinez[n], Johan Mazoyer[g], Mamadou N'Diaye[n], Gilles Orban de Xivry[f], Dhwanil Patel[a], Raphael Poucelot[m], Henri-François Raynaud[l], Charles Sallard[n], Adam Taras[a], Elena Tonucci[a], and Yinzi Xin[a]

[a]Leiden University, Einsteinweg 55, 2233 CC, Leiden, The Netherlands
[b]Steward Observatory, 933 North Cherry Avenue, Tucson, AZ 85721-0065, USA
[c]LIRA, Université Paris Cité, Observatoire de Paris, Université PSL, Sorbonne Université, CNRS, F-92190 MEUDON, France
[d]Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
[e]Instituto de Astrofísica e Ciências do Espaço, Rua das Estrelas, 4150-762 Porto, Portugal
[f]STAR Institute, Université de Liège, Allée du Six Août 19c, B-4000 Liège, Belgium
[g]Faculty of Engineering, INESC TEC, University of Porto, Porto, Portugal
[h]LIRA, Observatoire de Paris, Université PSL, Sorbonne Université, Université Paris Cité, CY Cergy Paris Université, CNRS, 92195 Meudon, France
[i]Sydney Institute for Astronomy, School of Physics, University of Sydney, Camperdown, NSW 2006, Australia
[j]Centre de Recherche Astrophysique de Lyon, Lyon, France
[k]Université Claude Bernard Lyon 1, CRAL UMR5574, ENS de Lyon, CNRS, Villeurbanne, F-69622, France
[l]Laboratoire Charles Fabry, Institut d'Optique Graduate School, Université de Paris-Saclay, Palaiseau, France
[m]Division of Space and Planetary Sciences, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland
[n]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France
[o]Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

ABSTRACT

The Planetary Camera and Spectrograph (PCS) will be the ELT's dedicated instrument for exoplanet characterization, with a central goal of discovering and studying rocky exoplanets. To prepare for these ambitious objectives, the PCS R&D consortium, launched in January 2025 under ESO's leadership, was established to advance the conceptual design and bridge critical technology gaps. We will report on the progress of the coronagraph and focal-plane wavefront control work package. Our efforts focus on the development of coronagraphs tailored for PCS and on strategies for integrating wavefront control into their operation. A key component of this work is the PCS Coronagraph Evaluation Pipeline (PCS-CEP), designed to provide a uniform framework

Further author information: (Send correspondence to S.Y.H.)
S.Y.H.: E-mail: haffert@strw.leidenuniv.nl

for assessing coronagraph performance and wavefront control, an approach inspired by the Habitable Worlds Observatory coronagraph design survey. PCS-CEP enables a fair comparison of diverse concepts, ensuring a level playing field for innovation.

Keywords: Manuscript format, template, SPIE Proceedings, LaTeX

1. INTRODUCTION

The forthcoming Extremely Large Telescope (ELT) will be the largest optical/infrared telescope ever constructed and is expected to enable transformative advances across many areas of astronomy. Among its most compelling scientific opportunities is the direct detection and characterization of exoplanets. Owing to its unprecedented collecting area and angular resolution, the ELT will make high-contrast direct-imaging observations hundreds of times more efficient than current-generation facilities. To fully exploit this capability, the Planetary Camera and Spectrograph (PCS) was identified as a dedicated ELT instrument for exoplanet science. Following the publication of the initial PCS concept,[1] an international R&D consortium was established in 2025 to mature the technologies and instrument concepts required to achieve the ambitious scientific goals of PCS.

The primary science objective of PCS is the detection and characterization of rocky exoplanets orbiting nearby stars. While this goal represents one of the most exciting frontiers in modern astronomy, it also poses unprecedented technical challenges in high-contrast imaging, wavefront control, and instrument stability. The PCS R&D roadmap was therefore created to assess the feasibility of the instrument concept, identify potential technology gaps, and establish a path toward a future Phase A study. The roadmap encompasses the consolidation of the science case and top-level requirements, the development of enabling technologies for extreme adaptive optics (XAO) and high-contrast imaging on the ELT, the definition of instrument concepts consistent with observatory constraints, the construction of performance and science-yield models, and the evaluation of technical risks.

Within this consortium, a dedicated work package focuses on the development of the coronagraph subsystem and the associated wavefront sensing and control architecture. The objectives of this activity are to identify coronagraph concepts capable of meeting the stringent top-level requirements on inner and outer working angle, field of view, raw contrast, throughput, and spectral bandwidth, while remaining compatible with the planned visible and near-infrared imaging and spectroscopic observing modes. In parallel, the work package investigates advanced wavefront-control strategies, including electric-field conjugation, linear dark-field control, and reinforcement-learning-based approaches, assuming the availability of a dedicated deformable mirror operating independently of the adaptive-optics wavefront sensor. Additional activities include the development of an atmospheric dispersion correction concept capable of achieving sub-milliarcsecond residual errors, potentially through closed-loop operation, and the management of interfaces with the instrument-design work package. The ultimate goal is to raise the technological readiness of these critical subsystems through simulation, laboratory validation, and on-sky demonstrations, thereby providing key inputs to the PCS white paper and future ELT instrumentation decisions.

In this proceeding, we give an overview of the project plan for Work Package 2 - the coronagraph and focal plane wavefront control work package (WP2). We will discuss the individual sub-work packages, WP2.1 - The PCS Coronagraph Evaluation Pipeline, WP2.2 The coronagraph design study, WP2.3 Wavefront sensing and control. Each of the sub-work packages will be discussed in the subsequent Sections 2 - 5.

2. WP2.1 - THE PCS CORONAGRAPH EVALUATION PIPELINE

A key activity within WP2 is the development of the PCS Coronagraph Evaluation Pipeline (CEP). The development of the PCS-CEP was inspired by the coronagraph design survey for NASA's Habitable Worlds Observatory.[2] The objective of this pipeline is to provide a standardized framework for evaluating all coronagraph concepts proposed within the PCS consortium. Rather than relying on independent simulations carried out by the individual design teams, every submitted coronagraph will be assessed using the same simulation framework, assumptions, and analysis procedures. This establishes a common benchmark that enables an objective comparison of the different architectures. A schematic view of the PCS-CEP flow diagram can be seen in Figure 1.

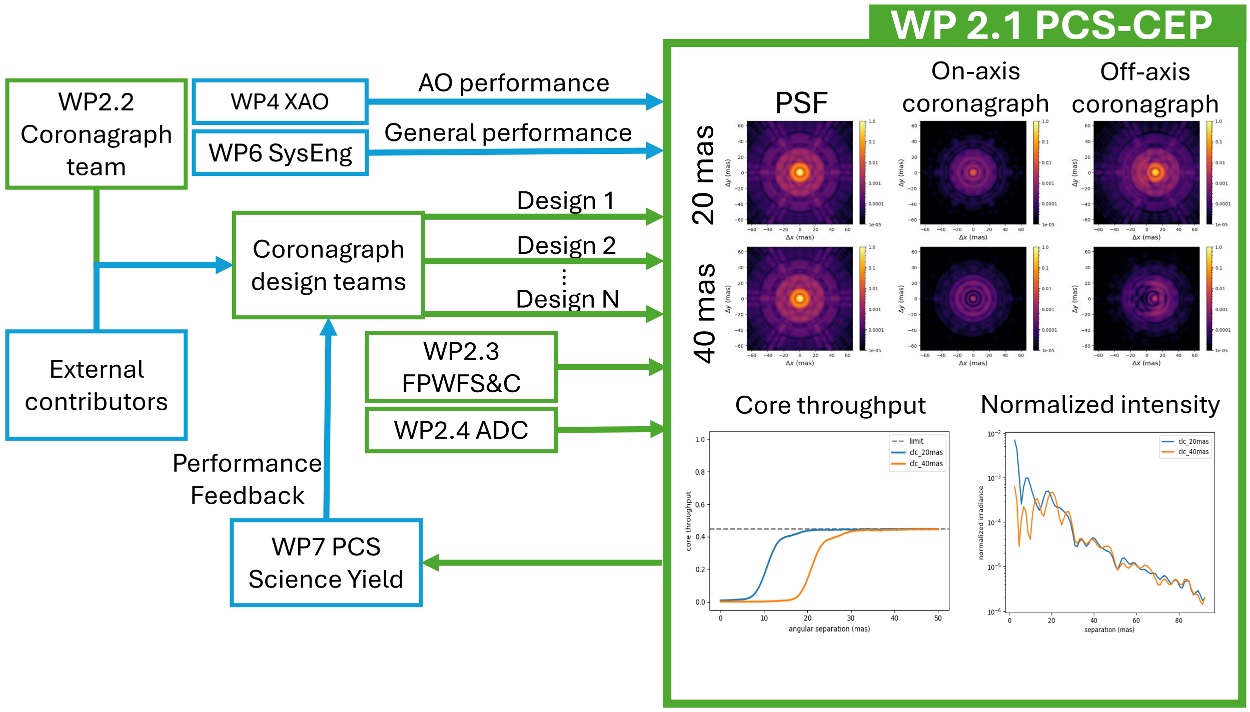

Figure 1. Schematic overview of the PCS-CEP developed in WP2.1. Coronagraph designs submitted by the WP2 coronagraph team and external contributors are evaluated using a common simulation framework that incorporates adaptive optics residuals from WP4, focal-plane wavefront sensing and control concepts from WP2.3, ADC performance from WP2.4, and system-level parameters from WP6. The pipeline produces standardized coronagraph performance metrics and point spread functions that are passed to WP7 for science yield calculations while providing performance feedback to the coronagraph design teams.

The PCS-CEP forms the link between the coronagraph design activities in WP2 and the science yield analysis performed in WP7. Besides providing a fair comparison between coronagraph concepts, the pipeline will generate standardized performance summaries and data products that can be directly used as input for end-to-end science yield calculations. This common evaluation strategy ensures that differences in predicted scientific performance originate from the coronagraph designs themselves rather than from differences in simulation methodology.

The first activity focuses on defining the scope and evaluation goals of the pipeline. This is carried out in close collaboration with the coronagraph design and wavefront sensing and control tasks (Tasks 2 and 3), which provide the scientific and technical requirements that the pipeline should address. Together these activities define the performance metrics that best characterize coronagraph performance for PCS and identify the relevant trade-offs between competing design requirements. A second part of this activity is the definition of the common simulation inputs. This includes selecting a representative telescope pupil, defining the observing scenarios, and compiling a science target list that reflects the primary science cases of PCS. By adopting a common set of input assumptions, all coronagraph concepts are evaluated under identical observing conditions, enabling a direct comparison between designs.

The PCS-CEP also serves as an interface between multiple work packages within the PCS R&D programme. On the input side, the pipeline will receive wavefront residual time series and environmental parameters from the XAO working group and the systems engineering work package, representing the expected performance of the extreme adaptive optics system. These wavefront realizations are propagated through the submitted coronagraph models, allowing each design to be evaluated under realistic operating conditions.

On the output side, the pipeline interfaces with WP7 to ensure that the generated simulation products contain all information required for science yield analyses. This includes defining the required output formats, agreeing on the relevant summary statistics, and identifying the performance metrics that are needed to compare coronagraph concepts from an observational perspective. Close coordination between WP2 and WP7 ensures that the pipeline products can be incorporated directly into the broader PCS performance assessment.

The pipeline itself will be implemented as a modular software package based on the HCIPy framework. Coronagraph developers will provide their designs through a common Python interface, allowing the pipeline to execute identical simulation sequences for every submitted architecture. In addition to evaluating the coronagraph performance, the software will automatically generate standardized summary plots and diagnostic figures that facilitate comparison between concepts and provide feedback to the design teams during the development process.

Ultimately, the PCS-CEP will provide the common evaluation infrastructure for the coronagraph activities within WP2. By combining standardized simulation inputs, common performance metrics, realistic adaptive optics residuals, and reproducible analysis tools, it will enable a transparent comparison of candidate coronagraph architectures throughout the PCS design study. The resulting benchmark will support the down-selection and further optimization of coronagraph concepts and provide the quantitative performance data required for subsequent instrument design and science yield assessments.

3. WP2.2 - CORONAGRAPH DESIGNS

The ELT-PCS science cases are exceptionally broad, spanning rocky planets in the habitable zone of nearby stars, sub-Neptunes and Neptunes in reflected light, temperate and young giant planets, exomoons and exorings, protoplanets, planet-forming disks, and debris disks[3] [**ref to update once we have the full list of authors**]. This diversity translates into a wide and sometimes conflicting set of instrumental requirements: inner working angles ranging from λ/D for nearby rocky planets to several dozens λ/D of field-of-view for wide-separation companions, contrast levels varying by orders of magnitude depending on the target class, and spectral bandwidths spanning from narrow-band accretion line tracers to broad optical and near-infrared windows for atmospheric characterization, in addition with the open question of possible polarimetry capabilities. Rather than prematurely converging on a single architecture that might be optimized for only a subset of these cases, we chose to keep the coronagraph requirements deliberately broad at this stage, to be iteratively refined in collaboration with other work packages (other sub-systems as well as science target work packages). A wide exploration of the coronagraph concepts, from existing to under-development, is therefore needed to identify the most promising designs before entering a down-selection phase.

We began with a state-of-the-art review of existing coronagraph concepts, assessing their performance (contrast, angular separation, working spectral band) and their maturation level. Building on this, we launched an open call for coronagraph concepts to the community, with reminders on the science cases and broad indicative coronagraph requirements: these requirements serve as guidance only and should not constrain nor limit design choices, as the final performance metrics will be assessed through PCS-CEP. Overall, the inner working angle target is approximately 10 mas, with some science cases driving this down to 6 mas. The field of view spans from 100 mas for rocky planet science to 1000–1500 mas for exomoons, rings, and disks. Wavelength coverage extends from the V to the K band, with spectral resolution requirements ranging from $R \sim 10$ for broadband imaging to $R \sim 100,000$ for high-resolution molecular spectroscopy. In terms of contrast, the typical targets are $10^{-9} - 10^{-8}$ at 10 mas and 10^{-9} at 30 mas, understood as post-coronagrpah, post-adaptive optics, post-wavefront control, and post-processing values.

This call resulted in 11 declarations of interest to submit concepts, covering a diverse range of families including scalar vortex coronagraphs,[4–7] apodized pupil Lyot coronagraphs,[8,9] shaped-pupil designs,[10,11] PIAACMC,[12,13] nulling approaches,[14–16] and architectures involving programmable devices.[17–20] Each submitted concept will be evaluated through the PCS-CEP to ensure a fair and uniform comparison across designs, following the same philosophy as the Habitable Worlds Observatory coronagraph design survey. Throughout this process, an ongoing dialogue with WP7 will ensure that throughput, inner working angle, and bandwidth requirements reflect realistic yield expectations, while requirements might be revised, as post-processing capabilities and contributions and limitations from other subsystems are better characterized.

In the coming months, WP2.2 will deliver a catalog of coronagraph concepts with standardized performance metrics produced via PCS-CEP, a down-selected set of baseline and alternative coronagraph designs for PCS

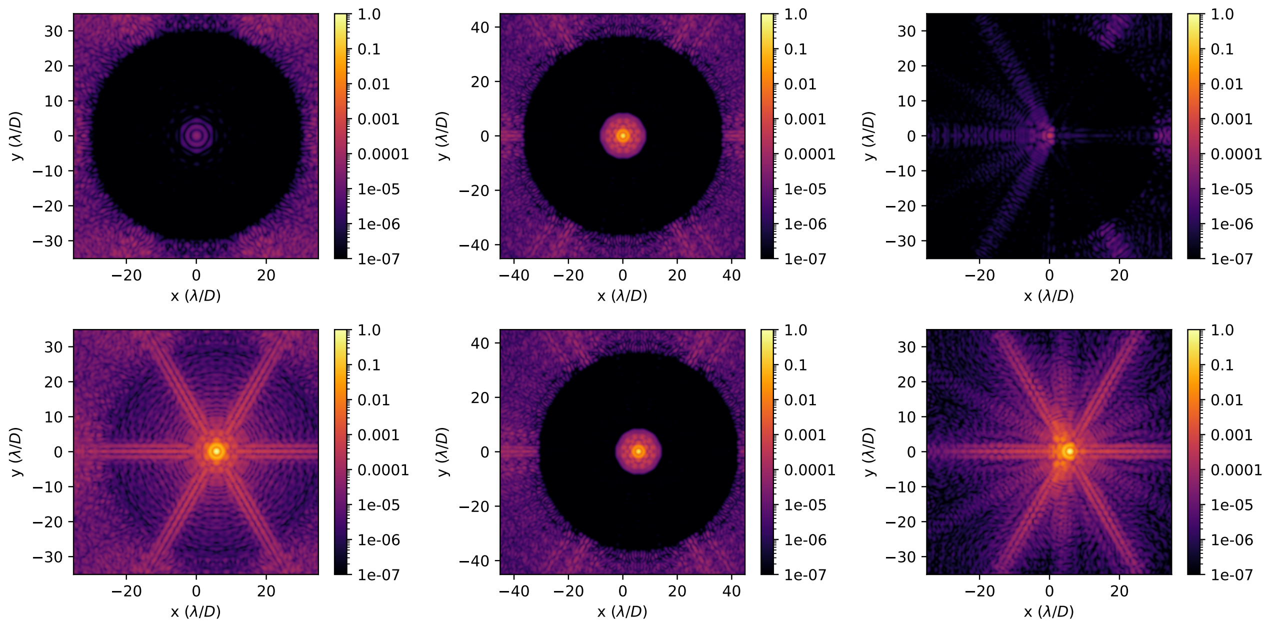

Figure 2. Example submissions for the PCS call of coronagraphs. These three designs are from left to right, an APLC, SPP and PAPLC design. The top row shows the on-axis coronagraphic images while the bottom row shows the off-axis PSF at 30 mas.

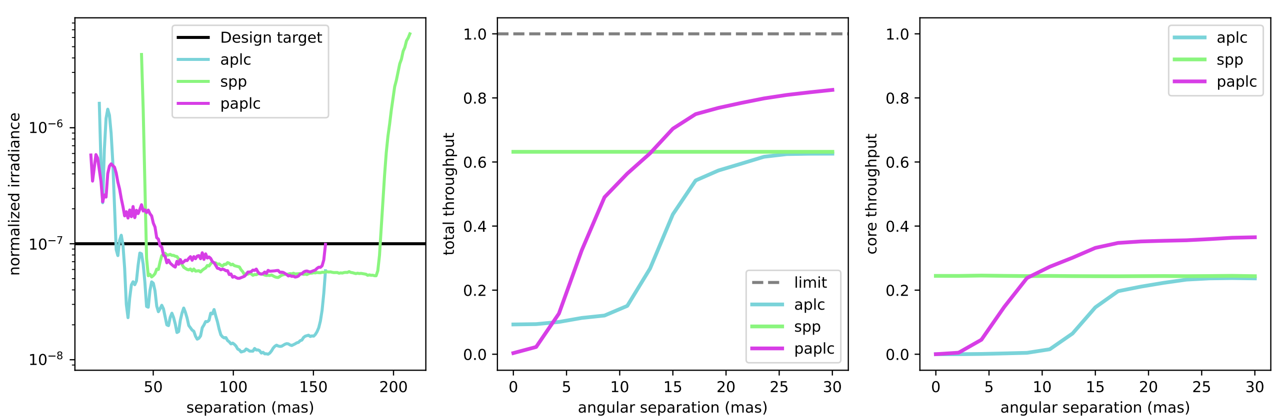

Figure 3. Outputs of the current PCS-CEP for several submitted designs. The left figure shows the normalized intensity, which is the raw contrast divided by the peak intensity of an off-axis PSF. The middle figure shows the integrated throughput of after the coronagraph as a function of angular separation. And finally, the right figure shows the core throughput within $1.4\lambda/D$ as a function of angular separation.

along with their technology readiness levels to flag concepts that require further developments or validation, and an updated requirements document refined through iteration with the science and other subsystems' WPs.

4. WP2.3 - WAVEFRONT SENSING AND CONTROL ARCHITECTURES

4.1 Activities

High-contrast imaging at the contrast levels required for PCS demands not only an optimized coronagraph but also advanced wavefront sensing and control (WFS&C) techniques capable of creating and maintaining deep regions of suppressed starlight. While the extreme adaptive optics (XAO) system corrects atmospheric turbulence, residual quasi-static aberrations ultimately limit the achievable contrast. The objective of WP2.3 is therefore to investigate post-AO wavefront sensing and control architectures (see Figure 4) that are compatible with the proposed coronagraph concepts and capable of delivering the required raw contrast for PCS.

The activities within WP2.3 are closely coupled to the coronagraph development carried out in WP2.2. Different coronagraph architectures place different requirements on wavefront sensing, deformable mirror configurations, and control algorithms. Consequently, the work package aims to develop a consistent set of wavefront control concepts that can be evaluated alongside the proposed coronagraph designs. The resulting requirements and performance estimates will feed back into the overall instrument architecture and support the comparison of candidate coronagraph concepts.

The first activity consists of a literature review of existing wavefront sensing and control approaches. This review summarizes the current state of the art, identify the most promising techniques for PCS, and assess their technology readiness level. Particular attention will be given to methods that have demonstrated high-contrast performance either in laboratory environments or on-sky. Such summary is represented in Table 1

Building on the literature review, the second major activity is the derivation of high-level requirements for wavefront sensing and control. These requirements will be developed in close collaboration with the science requirements defined in WP1 and the coronagraph requirements from WP2.2. Particular attention will be given to defining a suitable pupil stabilization strategy, identifying the required deformable mirror architecture, and evaluating detector technologies and camera requirements for both wavefront sensing and focal-plane control. These studies will provide a consistent set of assumptions for the subsequent development and evaluation of candidate WFS&C concepts.

The primary deliverables of WP2.3 are a comprehensive review of candidate wavefront sensing and control architectures, a set of high-level WFS&C requirements for PCS, and a collection of compatible control concepts for the proposed coronagraph designs. During the first phase of the project the focus will be on the literature review and requirements definition. Subsequently, candidate control strategies will be adapted to the proposed coronagraph architectures and evaluated in collaboration with WP2.2, while maintaining close interfaces with WP3, WP4, and the overall PCS system design activities.

4.2 Litterature review

4.2.1 PSF sharpening

One important topic is point spread function (PSF) sharpening, which aims to maximize the Strehl ratio delivered to the coronagraph by correcting residual non-common path aberrations. Existing approaches based on focal-plane wavefront sensing and calibration will be reviewed together with their demonstrated performance on current high-contrast imaging instruments. Their applicability to the PCS observing regime and expected performance will be assessed.

PSF sharpening will be performed in two different steps. First, a plain PSF sharpening shall be done during instrument integration, using the instrument internal source. It aims to correct for large wavefront errors induced by optics misalignment. Therefore we need for a linear algorithm, although a high sensitivity is not required. We can cite e.g. the Gerberch-Saxton algorithm,[21] a phase diversity algorithm in non-coronagraphic conditions. However, those techniques flatten the wavefront at the science camera plane while coronagraph best performance are obtained when the wavefront is controlled at the focal plane mask plane. Algorithms like COFFEE[26] could therefore be used for such plain correction.

	Numerical simulation	In-lab test	On-sky test
PSF sharpening			
Gerberch-Saxton	Gerchberg (1972)[21]	Kay (2007)[22]	
Phase diversity	Gonsalves (1982)[23]	Fusco (2015)[24]	Kuznetsov (2024)[25]
COFFEE	Paul (2013)[26]	Paul (2014)[27]	
Fast & Furious	Keller (2012)[28]	Bos (2020)[29]	Bos (2020)[29]
APFWS	Martinache (2013)[30]	Martinache (2016)[31]	Martinache (2016)[31]
dOTF	Codona (2013)[32]	Martinez (2023)[33]	
Dr. WHO	Codona (2013b)[34]		Skaf (2022)[35]
ZWFS	N'Diaye (2013)[36]	N'Diaye (2016)[37]	Vigan (2019)[38]
Vortex Phase retrieval	Riaud (2012)[39]		
Photonics lantern WFS	Lin (2022)[40]	Lin (2023)[41]	Lin (2025)[42]
Dark Hole control			
SCC (normal)	Singh (2019)[43]	Singh (2019)[43]	Galicher (2019)[44]
SCC (FAST)	Gerard (2018)[45]	Gerard (2021)[46]	
SCC (spectraly modulated)	Haffert (2022)[47]		
SCC (spatially-clipped)	Liberman (2025)[48]		
SCC (polarization encoded)	Bos (2021)[49]		
PWP	Goulas (2026)[50]	Potier (2019)[51]	Potier (2022)[52]
iEFC	Haffert (2023)[53]	Haffert (2023)[53]	Haffert (2026)[54]
dOTF	Martinez (2025)[55]		
Speckle Nulling		Martinache (2012)[56]	Martinache (2014)[57]
Fiber nulling	Llop-Sayson (2019)[58]	Llop-Sayson (2022)[59]	Xin (2023)[14]
Photonics lantern nulling	Xin (2025)[15]	Xin (2025)[15]	
Wavefront stabilization			
QACITS	Huby (2015)[60]	Huby (2015)[60]	Huby (2017)[61]
FLOWFS	Guyon (2009)[62]	Guyon (2009)[62]	
PAPLC WFS	Por (2023)[63]	Por (2023)[63]	
Encoded ZWFS	Ruane (2023)[64]	Ruane (2023)[64]	
LLOWFS	Singh (2014)[65]	Singh (2015)[66]	Singh (2017)[67]
Spatial LFDC	Miller (2017)[68]	Miller (2019)[69]	Bos (2021b)[70]
Spectral LDFC	Guyon (2017)[71]	Poon (2023)[72]	
DH maintenance	Pogorelyuk (2019)[73]	Redmond (2022)[74]	

Table 1. State of the art of WS&C algorithms with current TRL. Only first author is mentioned. The list is non exhaustive, prioritizing demonstration oriented in ground-based conditions for each technique. The simulation column is mostly non AO conditions, except in some case where simulation of the techniques including AO residuals have been performed. The laboratory demonstration are mostly in non turbulent conditions, include demonstration in non turbulent conditions but at the telescope if they exist or demonstration on testbed with turbulent conditions if they exist.

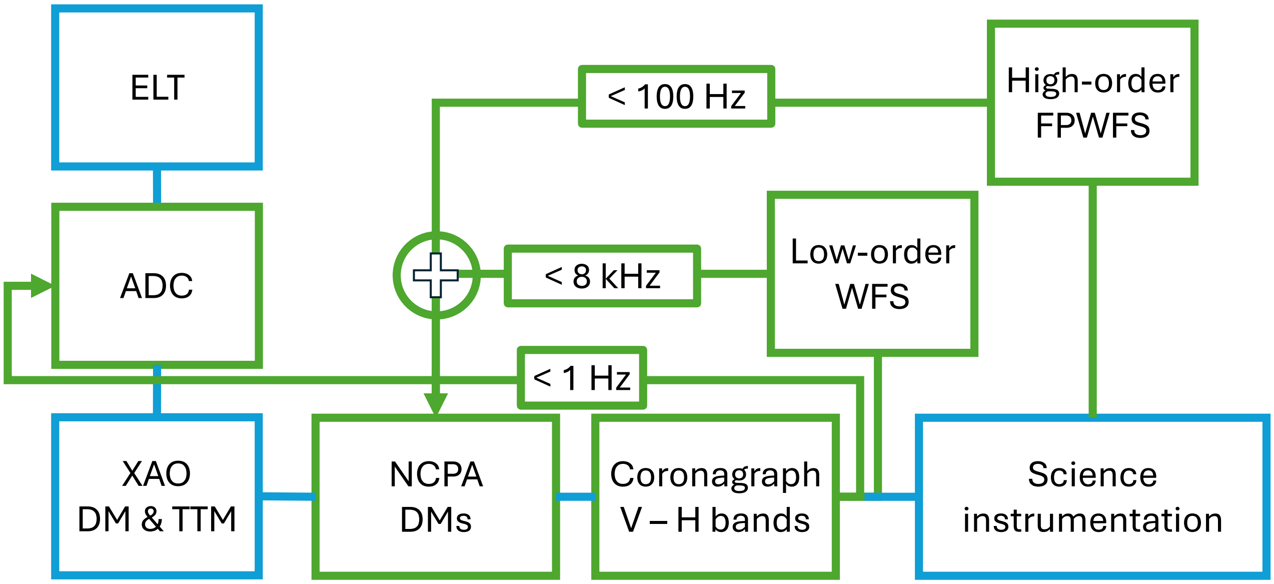

Figure 4. The proposed block scheme of PCS. PCS will consist of an eXtreme AO (XAO) system that provides well corrected wavefronts to the coronagraph sub-system. The coronagraph sub-subsystem will handle non-common path aberrations using dedicated DMs. There will be multiple wavefront control loops for low-order stabilization and high-order dark hole digging. The green boxes are the parts that the coronagraph work package is responsible for. We anticate that we will run the low-order stabilization loops at speeds up to 8 kHz, dark hole digging and maintenance at 100 Hz and control of the ADC at or below 1 Hz.

On a daily basis after commissioning, a fine tuned correction should be perform either with the internal source or on-sky. Indeed we expect thermal instabilities to slowly ruin the initial flattening (by a few nm rms daily). An automatic Zernike Wavefront Sensor[36] (ZWFS, requiring an additional Zernike mask in the FPM filter wheel) or a differential Optical Transfer Function[32] (dOTF) scheme could be employed before operations. On-sky, sensitive and fast algorithms could be employed either without (Fast & Furious,[28] Dr Who[34]) or with (Asymmetric Pupil Fourier Wavefront Sensor or APFWS,[30] Vortex phase retrieval[39]) a coronagraph.

4.2.2 Dark Hole control

A second focus is dark-hole control. Nearly two decades after the first laboratory demonstrations of dark-hole generation using deformable mirrors,[75] these techniques have matured to successful on-sky demonstrations with VLT/SPHERE[52] and, more recently, MagAO-X.[54] Furthermore, the Roman Coronagraph Instrument will provide the first demonstration of active dark-hole digging and maintenance in space.[76] Within WP2.3 we will investigate the applicability of these techniques to PCS, including implementations that operate without a dedicated deformable mirrors,[50,52] and architectures employing dedicated deformable mirrors for focal-plane wavefront control.[54] The advantages and limitations of single- and dual-deformable mirror systems will also be evaluated, particularly with respect to achievable contrast, controllable outer working angle, and algorithmic complexity.[77,78]

Dark Hole wavefront control requires minimizing parameters that are linear with the speckle electric field (E-field). This comes in two main flavors: a temporal or a spatial modulation of such speckles. The former requires the dedicated deformable mirror to inject phase diversities into the system. Those diversities either directly enable the estimation of the speckle E-field by the mean of an instrument model (speckle nulling,[57] pair-wise probing,[79] dOTF[33]) which can be combined with a model-based controller (Electric Field Conjugation[79]),

	FPM	LS	Science camera
Low-order	Encoded ZWFS FLOWFS	LLOWFS	QACITS
High-order in half FoV	PAPLC WFS		Spatial LDFC
High-order in full FoV	Encoded ZWFS		Spectral LDFC DH maintenance

Table 2. Tradeoffs and solutions for wavefront maintenance algorithms. To improve the signal-to-noise ratio and overall correction performance, algorithms utilizing the FPM, the LS, and the science camera should be integrated into a unified sensor fusion architecture to maximize photon efficiency.

or can be completely model-free (iEFC[53]) through the need of an empirical Jacobian to be calibrated on the system itself. The latter needs the introduction of pinholes in the LS, capturing the light rejected by the FPM (Self Coherent Camera or SCC[80]). This light then recombines with the residual speckle intensity, creating fringes through coherence properties. Since those fringes are linear with the speckle E-field, EFC algorithms can be utilized to minimize their intensity in the DH region. The SCC now comes into various flavors to maximize the light going through the pinhole in order to increase the control loop frequency. Either a dedicated coronagraph is used (FAST[45]), or the pinhole is set closer to the LS diaphragm by mean of polarization encoding,[49] spatial clipping[48] or a spectral modulation.[47]

4.2.3 Wavefront maintenance

Beyond establishing the dark hole, maintaining its performance over long science observations will be equally important. Slow instrumental drifts, thermal variations, and changing observing conditions require continuous wavefront monitoring and correction to preserve the required contrast. WP2.3 will therefore investigate wavefront maintenance strategies that can operate alongside the science observations while minimizing interruptions and preserving observing efficiency.

Many wavefront maintenance algorithms use the light rejected either by the coronagraph FPM or LS (see in Table. 2), requiring the introduction of additional optics and camera in the instrument optical layout, that could run faster than the photon-starved science camera. Low-order aberrations can be sensed through in-band and non destructive schemes (FLOWFS[62] and Encoded ZWFS[64] in the FPM, LLOWFS[65] from the LS, QACITS[60] from the science camera), inducing high temporal frequencies and no differential aberrations with the science path. Extending to higher order terms require half dark hole configurations where the degraded side of the field of view is used to correct its counterpart (PAPLC WFS[63] from the FPM, spatial LDFC[68] from the science camera). Finally high-order wavefront maintenance comes at a cost, either requiring an out-of-band scheme (Encoded ZWFS[64] in the FPM, spectral LDFC[72]) or a destructive behavior (DH maintenance[74] in the science camera plane). Their performance are highly coronagraph dependent (e.g. Lyot-type coronagraph are required for FPM rejections) and need to be designed along with the coronagraph in mind.

4.2.4 The case for photonics wavefront sensing solutions

Since PCS aims to perform high-resolution spectroscopy on detected exoplanets, single-mode fibers can replace conventional imaging cameras for light collection. In this architecture, Dark Hole wavefront control remains applicable; however, the objective shifts from creating a null at a specific focal-plane location to minimizing stellar coupling into the fiber, while maintaining high injection efficiency for the off-axis planet.[59]

By utilizing photonics lanterns, either to replace or in combination with a conventional coronagraph, wavefront sensing can be performed directly within the instrument science path, leading the system to measure and correct NCPAs alongside the science capture. Although this technology is currently at a lower TRL, initial demonstrations have successfully utilized lantern outputs to sharpen the PSF[42] and optimize off-axis planet coupling, even while suppressing on-axis stellar light.[15]

4.2.5 Post-AO control enhancement through machine learning and advanced controller

Unlike conventional methods that rely on time-consuming mechanical probes or require specific system knowledge, reinforcement learning (RL) approaches can autonomously learn from sequential focal-plane images to optimize wavefront performance without prior calibration. Although limited by the number of modes that can be corrected, simulations demonstrate that the method achieves near-optimal starlight suppression and Strehl ratios, matching the performance of traditional modal control while offering greater flexibility across diverse coronagraph designs and operating conditions.[81,82] Also, real time utility of such methods extends beyond sensing. By transitioning from static optimization to predictive control, these algorithms can anticipate and counteract aberration evolution rather than merely reacting to past errors. Consequently, by replacing the latency-prone integral controllers typically found in current testbeds with these predictive RL models, instruments can leverage temporal correlations in telemetry data to maintain significantly deeper and more stable starlight suppression. Ultimately, this shift towards data-driven prediction complements and builds upon foundational conventional control techniques, such as the LQG regulator and its Kalman filter, which similarly utilize temporal state prediction to mitigate the deterministic lag inherent in wavefront correction loops.[83,84]

5. WP2 MILESTONES

The development activities within WP2 are organized around a series of milestones that progressively mature the coronagraph, wavefront sensing and control (WFS&C), and atmospheric dispersion corrector (ADC) concepts towards the PCS white paper. These are summarized in Table 3.

Table 3. High-level milestones for the WP2 development programme.

Time	Milestone
Early 2026	• Draft high-level requirements for all WP2 tasks. • Completion of the coronagraph literature review. • Completion of the WFS&C literature review.
Mid 2026	• First draft coronagraph designs. • First draft wavefront sensing and control concepts. • Preliminary optical design of the ADC.
Early 2027	• Completion of the PCS Coronagraph Design Survey (CDS) pipeline.
Mid–Late 2027	• Comparative evaluation of submitted coronagraph concepts using the PCS CDS pipeline. • Science yield assessment in collaboration with WP7. • Proposed WFS&C strategy for the shortlisted coronagraph architectures. • Proposed optical design of the ADC.
Early 2028	• Delivery of the PCS White Paper.

6. CONCLUSION

The PCS R&D consortium was established in 2025 to identify and address the technological challenges that must be overcome before the Planetary Camera and Spectrograph can be realized. Within this effort, WP2 focuses on the development of coronagraph architectures and their associated wavefront sensing and control (WFS&C) strategies. The first phase of the work has concentrated on reviewing the current state of the art in both coronagraphy and WFS&C to determine which concepts have the potential to meet the demanding science requirements of PCS. This survey has identified a diverse range of candidate coronagraph architectures, with inner working angles spanning from approximately λ/D to several λ/D, and covering a broad range of technology readiness levels.

Over the coming two years, these concepts will be further developed and evaluated within the consortium. A central component of this effort is the PCS Coronagraph Evaluation Pipeline (PCS-CEP), which provides a common simulation framework for assessing all submitted coronagraph designs. By evaluating each architecture using identical assumptions, performance metrics, and analysis procedures, the PCS-CEP enables an objective comparison of the proposed concepts. The resulting standardized data products will be passed to the science yield work package (WP7), where they will be used to assess the scientific capabilities of each design and identify potential limitations in field-of-view coverage and overall performance.

Since high-contrast performance ultimately depends on both the coronagraph and the accompanying wavefront control strategy, WP2 also investigates focal-plane wavefront sensing and control techniques that are compatible with the proposed coronagraph architectures. The development of these control strategies proceeds in parallel with the coronagraph studies, ensuring that each candidate concept can be evaluated as part of a complete high-contrast imaging system.

At the time of writing, the consortium has completed the initial literature surveys and established the overall WP2 architecture and interfaces between the different activities. The coming project phases will focus on the development of candidate coronagraphs and wavefront control concepts, their evaluation within the PCS-CEP framework, and the delivery of the resulting performance assessments to support the PCS white paper.

ACKNOWLEDGMENTS

S.Y. Haffert, L. Desdoigts, R. Landman, M. Mars, and Y. Xin are supported by NWO award 184.036.004. A. Taras, D. Patel and S.Y. Haffert are supported by NWO award VI.Vidi.233.144. This work has been supported by PEPR Origins, funded by France 2030 investment plan and operated by the French Research National Agency, grants No. ANR-22-EXOR-0002 and ANR-22-EXOR-0017.

REFERENCES

[1] Kasper, M., Cerpa Urra, N., Pathak, P., Bonse, M., Nousiainen, J., Engler, B., Heritier, C. T., Kammerer, J., Leveratto, S., Rajani, C., Bristow, P., Le Louarn, M., Madec, P.-Y., Ströbele, S., Verinaud, C., Glauser, A., Quanz, S. P., Helin, T., Keller, C., Snik, F., Boccaletti, A., Chauvin, G., Mouillet, D., Kulcsár, C., and Raynaud, H.-F., "PCS — A Roadmap for Exoearth Imaging with the ELT," *The Messenger* **182**, 38–43 (Mar. 2021).

[2] Belikov, R., Stark, C., Siegler, N., Por, E., Mennesson, B., Redmond, S., Chen, P., Fogarty, K., Guyon, O., Juanola-Parramon, R., et al., "Coronagraph design survey for future exoplanet direct imaging space missions," in [*Space Telescopes and Instrumentation 2024: Optical, Infrared, and Millimeter Wave*], **13092**, 2045–2067, SPIE (2024).

[3] Vigan, A., Carrión-González, O., Chauvin, G., Charnay, B., and Desidera, S., "Closing the technology gap for the Extremely Large Telescope's Planetary Camera and Spectrograph (ELT-PCS): definition of science cases and expected science yield," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **13627** (Sept. 2026).

[4] Desai, N., Llop-Sayson, J., Bertrou-Cantou, A., Ruane, G., Eldorado Riggs, A. J., Serabyn, E., and Mawet, D., "Topological designs for scalar vortex coronagraphs," in [*Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave*], Coyle, L. E., Matsuura, S., and Perrin, M. D., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12180**, 121805H (Aug. 2022).

[5] Desai, N., Mawet, D., Serabyn, E., Ruane, G., Bertrou-Cantou, A., Llop-Sayson, J., and Eldorado Riggs, A. J., "Benefits of adding radial phase dimples on scalar coronagraph phase masks," *Journal of Astronomical Telescopes, Instruments, and Systems* **10**, 015001 (Jan. 2024).

[6] König, L., Palatnick, S., Desai, N., Absil, O., Millar-Blanchaer, M., and Mawet, D., "Metasurface-based scalar vortex phase mask in pursuit of 1e-10 contrast," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12680**, 126800Q (Oct. 2023).

[7] König, L., Desai, N., Palatnick, S., Absil, O., Mawet, D., Millar-Blanchaer, M., and Serabyn, E., "Microstructured vortex and azimuthal cosine phase mask design for high-contrast imaging," *Journal of Astronomical Telescopes, Instruments, and Systems* **11**, 025002 (Apr. 2025).

[8] N'Diaye, M., Pueyo, L., and Soummer, R., "Apodized Pupil Lyot Coronagraphs for Arbitrary Apertures. IV. Reduced Inner Working Angle and Increased Robustness to Low-order Aberrations," *The Astrophysical Journal* **799**, 225 (Feb. 2015).

[9] N'Diaye, M., Soummer, R., Pueyo, L., Carlotti, A., Stark, C. C., and Perrin, M. D., "Apodized Pupil Lyot Coronagraphs for Arbitrary Apertures. V. Hybrid Shaped Pupil Designs for Imaging Earth-like planets with Future Space Observatories," *The Astrophysical Journal* **818**, 163 (Feb. 2016).

[10] Carlotti, A., Kasdin, N. J., Vanderbei, R. J., and Delorme, J.-R., "Optimized shaped pupil masks for pupil with obscuration," in [*Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave*], Clampin, M. C., Fazio, G. G., MacEwen, H. A., and Oschmann, Jr., J. M., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8442**, 844254 (Sept. 2012).

[11] Gersh-Range, J., Riggs, A. J. E., and Kasdin, N. J., "Flight designs and pupil error mitigation for the bowtie shaped pupil coronagraph on the Nancy Grace Roman Space Telescope," *Journal of Astronomical Telescopes, Instruments, and Systems* **8**, 025003 (Apr. 2022).

[12] Tonucci, E., Haffert, S. Y., Foster, W. B., Males, J. R., Guyon, O., Close, L. M., Van Gorkom, K., Hedglen, A. D., Johnson, P. T., Kautz, M. Y., Kueny, J. K., Li, J., Liberman, J., Long, J. D., Lumbres, J., Mars, M., McEwen, E. A., McLeod, A., Pearce, L. A., Schatz, L., and Twitchell, K., "Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC) on-sky demonstration with MagAO-X," *Astronomy and Astrophysics* **708**, A144 (Apr. 2026).

[13] Martinez, P., Beaulieu, M., Gouvret, C., Spang, A., Marcotto, A., Guyon, O., Tisserand, S., Sauget, V., Gautier, S., and Le Duigou, J. M., "Design, manufacturing, and testing of phase-induced amplitude apodization and phase-shifting optics for segmented telescopes," *Astronomy and Astrophysics* **680**, A6 (Dec. 2023).

[14] Xin, Y., Xuan, J. W., Mawet, D., Wang, J., Ruane, G., Echeverri, D., Jovanovic, N., Do Ã‘, C., Fitzgerald, M., Horstman, K., Hsu, C.-C., Liberman, J., López, R. A., Phillips, C. L., Ren, B. B., Ruffio, J.-B., and Sappey, B., "On-sky speckle nulling through a single-mode fiber with the Keck Planet Imager and Characterizer," *Journal of Astronomical Telescopes, Instruments, and Systems* **9**, 035001 (July 2023).

[15] Xin, Y., Echeverri, D., Jovanovic, N., Lin, J., Kim, Y. J., Mawet, D., Leon-Saval, S., Amezcua-Correa, R., Yerolatsitis, S., Fitzgerald, M. P., Gatkine, P., Goyal, S., Norris, B., Ruane, G., and Sallum, S., "Implicit electric field conjugation with a photonic lantern nuller," *Journal of Astronomical Telescopes, Instruments, and Systems* **11**, 025004 (Apr. 2025).

[16] Xin, Y., Haffert, S., Kim, Y. J., and Lin, J., "Quantum-optimal coronagraphy with spatial mode sorting for direct exoplanet observations," *arXiv preprint arXiv:2607.02065* (2026).

[17] Leboulleux, L., Carlotti, A., Curaba, S., Delboubé, A., Jocou, L., Moulin, T., Gluck, L., and Sztefek, M.-H., "Coronagraphy for DiRect Imaging of Exoplanets (CIDRE) testbed 1: concept, optical set up, and experimental results of adaptive amplitude apodization," in [*Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12188**, 121884J (Aug. 2022).

[18] Carlotti, A., Baccar, S., Leboulleux, L., Curaba, S., Delboulbé, A., Jocou, L., Moulin, T., Gluck, L., and Sztefek, M.-H., "Amplitude adaptive optics with a digital micro-mirror device for exoplanet high-contrast imaging," in [*Adaptive Optics for Extremely Large Telescopes (AO4ELT7)*], 45 (June 2023).

[19] Kühn, J., Patapis, P., Ruane, G., and Lu, X., "Implementing focal-plane phase masks optimized for real telescope apertures with SLM-based digital adaptive coronagraphy," *Optics Express* **25**, 16686 (July 2017).

[20] Kühn, J. G., Tandon, R., Marquis, L., Lin, L., Ã-ztürk çetni, D., Manurung, I., Potier, A., Jolissaint, L., Baur, A., Piazza, D., Brändli, M., and Rieder, M., "The programmable liquid-crystal active coronagraphic imager for the 4-m DAG telescope (PLACID) instrument: installation and commissioning update," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **13627**, 136270Z (Sept. 2025).

[21] Gerchberg, R. W., "A practical algorithm for the determination of phase from image and diffraction plane pictures," *Optik* **35**, 237–246 (1972).

[22] Kay, J., Kasdin, N. J., and Belikov, R., "Wavefront correction in a shaped-pupil coronagraph using a Gerchberg-Saxton-based estimation scheme," in [*Astronomical Adaptive Optics Systems and Applications III*], Tyson, R. K. and Lloyd-Hart, M., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **6691**, 66910D (Sept. 2007).

[23] Gonsalves, R. A., "Phase Retrieval And Diversity In Adaptive Optics," *Optical Engineering* **21**, 829 (Oct. 1982).

[24] Fusco, T., Sauvage, J.-F., Mouilelt, D., Beuzit, J.-L., Dohlen, K., Petit, C., Beuzit, J.-L., Suarez, M., Soenke, C., Downing, M., Baudoz, P., Sevin, A., Baruffolo, A., Schmid, H.-M., Salasnich, B., Puget, P., Feautrier, F., Rochat, S., Moulin, T., Hugot, E., Vigan, A., Hubin, N., and Puget, P., "SPHERE extreme AO system On-sky operation, final performance and future improvements," in [*Adaptive Optics for Extremely Large Telescopes IV (AO4ELT4)*], E11 (Oct. 2015).

[25] Kuznetsov, A., Oberti, S., Neichel, B., and Fusco, T., "Striving towards robust phase diversity on-sky. Implementing LIFT for VLT/MUSE-NFM," *Astronomy and Astrophysics* **687**, A221 (July 2024).

[26] Paul, B., Mugnier, L. M., Sauvage, J.-F., Ferrari, M., and Dohlen, K., "High-order myopic coronagraphic phase diversity (COFFEE) for wave-front control in high-contrast imaging systems," *Optics Express* **21**, 31751 (Dec. 2013).

[27] Paul, B., Sauvage, J.-F., Mugnier, L. M., Dohlen, K., Petit, C., Fusco, T., Mouillet, D., Beuzit, J.-L., and Ferrari, M., "Compensation of high-order quasi-static aberrations on SPHERE with the coronagraphic phase diversity (COFFEE)," *Astronomy and Astrophysics* **572**, A32 (Dec. 2014).

[28] Keller, C. U., Korkiakoski, V., Doelman, N., Fraanje, R., Andrei, R., and Verhaegen, M., "Extremely fast focal-plane wavefront sensing for extreme adaptive optics," in [*Adaptive Optics Systems III*], Ellerbroek, B. L., Marchetti, E., and Véran, J.-P., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8447**, 844721 (July 2012).

[29] Bos, S. P., Vievard, S., Wilby, M. J., Snik, F., Lozi, J., Guyon, O., Norris, B. R. M., Jovanovic, N., Martinache, F., Sauvage, J.-F., and Keller, C. U., "On-sky verification of Fast and Furious focal-plane wavefront sensing: Moving forward toward controlling the island effect at Subaru/SCExAO," *Astronomy and Astrophysics* **639**, A52 (July 2020).

[30] Martinache, F., "The asymmetric pupil fourier wavefront sensor," *Publications of the Astronomical Society of the Pacific* **125**, 422 (Apr. 2013).

[31] Martinache, F., Jovanovic, N., and Guyon, O., "Closed-loop focal plane wavefront control with the SCExAO instrument," *Astronomy and Astrophysics* **593**, A33 (Sept. 2016).

[32] Codona, J. L., "Differential OTF Wavefront Sensing," *arXiv e-prints* , arXiv:1309.6719 (Sept. 2013).

[33] Martinez, P. and Dharmadhikari, R., "Bisymmetric pupil modification deconvolution strategy for differential optical transfer function (dOTF) wavefront sensing," *Astronomy and Astrophysics* **680**, L12 (Dec. 2023).

[34] Codona, J. L. and Kenworthy, M., "Focal Plane Wavefront Sensing Using Residual Adaptive Optics Speckles," *The Astrophysical Journal* **767**, 100 (Apr. 2013).

[35] Skaf, N., Guyon, O., Gendron, É., Ahn, K., Bertrou-Cantou, A., Boccaletti, A., Cranney, J., Currie, T., Deo, V., Edwards, B., Ferreira, F., Gratadour, D., Lozi, J., Norris, B., Sevin, A., Vidal, F., and Vievard, S., "On-sky validation of image-based adaptive optics wavefront sensor referencing," *Astronomy and Astrophysics* **659**, A170 (Mar. 2022).

[36] N'Diaye, M., Dohlen, K., Fusco, T., and Paul, B., "Calibration of quasi-static aberrations in exoplanet direct-imaging instruments with a Zernike phase-mask sensor," *Astronomy and Astrophysics* **555**, A94 (July 2013).

[37] N'Diaye, M., Vigan, A., Dohlen, K., Sauvage, J.-F., Caillat, A., Costille, A., Girard, J. H. V., Beuzit, J.-L., Fusco, T., Blanchard, P., Le Merrer, J., Le Mignant, D., Madec, F., Moreaux, G., Mouillet, D., Puget, P., and Zins, G., "Calibration of quasi-static aberrations in exoplanet direct-imaging instruments with a Zernike phase-mask sensor. II. Concept validation with ZELDA on VLT/SPHERE," *Astronomy and Astrophysics* **592**, A79 (Aug. 2016).

[38] Vigan, A., N'Diaye, M., Dohlen, K., Sauvage, J.-F., Milli, J., Zins, G., Petit, C., Wahhaj, Z., Cantalloube, F., Caillat, A., Costille, A., Le Merrer, J., Carlotti, A., Beuzit, J.-L., and Mouillet, D., "Calibration of quasi-static aberrations in exoplanet direct-imaging instruments with a Zernike phase-mask sensor. III. On-sky validation in VLT/SPHERE," *Astronomy and Astrophysics* **629**, A11 (Sept. 2019).

[39] Riaud, P., Mawet, D., and Magette, A., "Instantaneous phase retrieval with the vector vortex coronagraph. Theoretical and optical implementation," *Astronomy and Astrophysics* **545**, A151 (Sept. 2012).

[40] Lin, J., Fitzgerald, M. P., Xin, Y., Guyon, O., Leon-Saval, S., Norris, B., and Jovanovic, N., "Focal-plane wavefront sensing with photonic lanterns: theoretical framework," *Journal of the Optical Society of America B Optical Physics* **39**, 2643 (Oct. 2022).

[41] Lin, J. W., Fitzgerald, M. P., Xin, Y., Kim, Y. J., Guyon, O., Norris, B., Betters, C., Leon-Saval, S., Ahn, K., Deo, V., Lozi, J., Vievard, S., Levinstein, D., Sallum, S., and Jovanovic, N., "Real-time Experimental Demonstrations of a Photonic Lantern Wave-front Sensor," *The Astrophysical Journall* **959**, L34 (Dec. 2023).

[42] Lin, J., Fitzgerald, M. P., Xin, Y., Kim, Y. J., Guyon, O., Norris, B., Betters, C., Leon-Saval, S., Ahn, K., Deo, V., Lozi, J., Vievard, S., Levinstein, D., Sallum, S., and Jovanovic, N., "Experimental and on-sky demonstration of spectrally dispersed wavefront sensing using a photonic lantern," *Optics Letters* **50**, 2780 (Apr. 2025).

[43] Singh, G., Galicher, R., Baudoz, P., Dupuis, O., Ortiz, M., Potier, A., Thijs, S., and Huby, E., "Active minimization of non-common path aberrations in long-exposure imaging of exoplanetary systems," *Astronomy and Astrophysics* **631**, A106 (Nov. 2019).

[44] Galicher, R., Baudoz, P., Delorme, J.-R., Mawet, D., Bottom, M., Wallace, J. K., Serabyn, E., and Shelton, C., "Minimization of non-common path aberrations at the Palomar telescope using a self-coherent camera," *Astronomy and Astrophysics* **631**, A143 (Nov. 2019).

[45] Gerard, B. L., Marois, C., and Galicher, R., "Fast Coherent Differential Imaging on Ground-based Telescopes Using the Self-coherent Camera," *The Astrophysical Journal* **156**, 106 (Sept. 2018).

[46] Gerard, B. L., Dillon, D., Cetre, S., Jensen-Clem, R., Yuzvinsky, T. D., and Schmidt, H., "First experimental results of the fast atmospheric self-coherent camera technique on the Santa Cruz extreme adaptive optics laboratory testbed: demonstration of high speed focal plane wavefront control of residual atmospheric speckles," in [*Techniques and Instrumentation for Detection of Exoplanets X*], Shaklan, S. B. and Ruane, G. J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11823**, 118231H (Sept. 2021).

[47] Haffert, S. Y., "The spectrally modulated self-coherent camera (SM-SCC): Increasing throughput for focal-plane wavefront sensing," *Astronomy and Astrophysics* **659**, A51 (Mar. 2022).

[48] Liberman, J., Haffert, S. Y., Males, J. R., Derby, K., and Douglas, E. S., "Single-shot focal plane wavefront sensing with the spatially-clipped self-coherent camera," *arXiv e-prints* , arXiv:2509.03870 (Sept. 2025).

[49] Bos, S. P., "The polarization-encoded self-coherent camera," *Astronomy and Astrophysics* **646**, A177 (Feb. 2021).

[50] Goulas, C., Galicher, R., Vidal, F., Mazoyer, J., Ferreira, F., Sevin, A., Potier, A., Boccaletti, A., Gendron, E., Béchet, C., Tallon, M., Langlois, M., Kulcsár, C., Raynaud, H.-F., Galland, N., Schreiber, L., Dinis, I. B., Wildi, F., and Chauvin, G., "Non-common path aberration compensation and a dark hole loop with a pyramid adaptive optics system: Application to SAXO+," *Astronomy & Astrophysics* **708**, A50 (04 2026).

[51] Potier, A., Baudoz, P., Galicher, R., Huby, E., and Singh, G., "Exoplanet direct imaging in ground-based conditions on THD2 bench," *arXiv e-prints* , arXiv:1910.09064 (Oct. 2019).

[52] Potier, A., Mazoyer, J., Wahhaj, Z., Baudoz, P., Chauvin, G., Galicher, R., and Ruane, G., "Increasing the raw contrast of VLT/SPHERE with the dark hole technique. II. On-sky wavefront correction and coherent differential imaging," *Astronomy and Astrophysics* **665**, A136 (Sept. 2022).

[53] Haffert, S. Y., Males, J. R., Ahn, K., Van Gorkom, K., Guyon, O., Close, L. M., Long, J. D., Hedglen, A. D., Schatz, L., Kautz, M., Lumbres, J., Rodack, A., Knight, J. M., and Miller, K., "Implicit electric field conjugation: Data-driven focal plane control," *Astronomy and Astrophysics* **673**, A28 (May 2023).

[54] Haffert, S. Y., Liberman, J., Males, J. R., Close, L. M., Foster, W. B., Gorkom, K. V., Guyon, O., Hedglen, A. D., Johnson, P. T., Kautz, M. Y., Kueny, J. K., Li, J., Long, J. D., Lumbres, J., Mars, M., McEwen, E. A., McLeod, A., Schatz, L., Tonucci, E., and Twitchell, K., "On-sky dark hole diggin' with implicit electric field conjugation on MagAO-x," (2026). Submitted to A&A.

[55] Martinez, P., Spang, A., Sallard, C., and Beaulieu, M., "Revisiting the differential optical transfer function wavefront sensing technique for high-contrast imaging," *Astronomy and Astrophysics* **700**, A157 (Aug. 2025).

[56] Martinache, F., Guyon, O., Clergeon, C., and Blain, C., "Speckle Control with a Remapped-Pupil PIAA Coronagraph," *Publications of the Astronomical Society of the Pacific* **124**, 1288 (Dec. 2012).

[57] Martinache, F., Guyon, O., Jovanovic, N., Clergeon, C., Singh, G., Kudo, T., Currie, T., Thalmann, C., McElwain, M., and Tamura, M., "On-Sky Speckle Nulling Demonstration at Small Angular Separation with SCExAO," *Publications of the Astronomical Society of the Pacific* **126**, 565 (June 2014).

[58] Llop-Sayson, J., Ruane, G., Mawet, D., Jovanovic, N., Calvin, B., Levraud, N., Roberson, M., Delorme, J.-R., Echeverri, D., Klimovich, N., and Xin, Y., "Demonstration of an electric field conjugation algorithm for improved starlight rejection through a single mode optical fiber," *Journal of Astronomical Telescopes, Instruments, and Systems* **5**, 019004 (Jan. 2019).

[59] Llop-Sayson, J., Coker, C. T., Jovanovic, N., Mawet, D., Ruane, G., Riggs, A. J. E., and Echeverri, D., "Laboratory demonstration of wavefront control through a single-mode fiber over a 20% bandwidth for the characterization of exoplanet atmospheres," *Journal of Astronomical Telescopes, Instruments, and Systems* **8**, 029001 (Apr. 2022).

[60] Huby, E., Baudoz, P., Mawet, D., and Absil, O., "Post-coronagraphic tip-tilt sensing for vortex phase masks: The QACITS technique," *Astronomy and Astrophysics* **584**, A74 (Dec. 2015).

[61] Huby, E., Bottom, M., Femenia, B., Ngo, H., Mawet, D., Serabyn, E., and Absil, O., "On-sky performance of the QACITS pointing control technique with the Keck/NIRC2 vortex coronagraph," *Astronomy and Astrophysics* **600**, A46 (Apr. 2017).

[62] Guyon, O., Matsuo, T., and Angel, R., "Coronagraphic Low-Order Wave-Front Sensor: Principle and Application to a Phase-Induced Amplitude Coronagraph," *The Astrophysical Journal* **693**, 75–84 (Mar. 2009).

[63] Por, E., Pourcelot, R., Klein, A., Soummer, R., Pueyo, L., Sahoo, A., Nguyen, M., and Fox, R., "Simultaneous high-order wavefront sensing and control with the PAPLC coronagraph on HiCAT," in [*American Astronomical Society Meeting Abstracts #241*], *American Astronomical Society Meeting Abstracts* **241**, 461.08 (Jan. 2023).

[64] Ruane, G., Wallace, J. K., Riggs, A. J. E., Wenger, T., Bagheri, M., Jewell, J., Raouf, N., Allan, G., Mejia Prada, C., Noyes, M., and Walter, A. B., "Dual purpose lyot coronagraph masks for simultaneous high-contrast imaging and high-resolution wavefront sensing," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12680**, 1268018 (Oct. 2023).

[65] Singh, G., Martinache, F., Baudoz, P., Guyon, O., Matsuo, T., Jovanovic, N., and Clergeon, C., "Lyot-based Low Order Wavefront Sensor for Phase-mask Coronagraphs: Principle, Simulations and Laboratory Experiments," *Publications of the Astronomical Society of the Pacific* **126**, 586 (June 2014).

[66] Singh, G., Lozi, J., Guyon, O., Baudoz, P., Jovanovic, N., Martinache, F., Kudo, T., Serabyn, E., and Kuhn, J., "On-Sky Demonstration of Low-Order Wavefront Sensing and Control with Focal Plane Phase Mask Coronagraphs," *Publications of the Astronomical Society of the Pacific* **127**, 857 (Sept. 2015).

[67] Singh, G., Lozi, J., Jovanovic, N., Guyon, O., Baudoz, P., Martinache, F., and Kudo, T., "A Demonstration of a Versatile Low-order Wavefront Sensor Tested on Multiple Coronographs," *Publications of the Astronomical Society of the Pacific* **129**, 095002 (Sept. 2017).

[68] Miller, K., Guyon, O., and Males, J., "Spatial linear dark field control: stabilizing deep contrast for exoplanet imaging using bright speckles," *Journal of Astronomical Telescopes, Instruments, and Systems* **3**, 049002 (Oct. 2017).

[69] Miller, K., Males, J. R., Guyon, O., Close, L. M., Doelman, D., Snik, F., Por, E., Wilby, M. J., Keller, C., Bohlman, C., Van Gorkom, K., Rodack, A., Knight, J., Lumbres, J., Bos, S., and Jovanovic, N., "Spatial linear dark field control and holographic modal wavefront sensing with a vAPP coronagraph on MagAO-X," *Journal of Astronomical Telescopes, Instruments, and Systems* **5**, 049004 (Oct. 2019).

[70] Bos, S. P., Miller, K. L., Lozi, J., Guyon, O., Doelman, D. S., Vievard, S., Sahoo, A., Deo, V., Jovanovic, N., Martinache, F., Currie, T., and Snik, F., "First on-sky demonstration of spatial Linear Dark Field Control with the vector-Apodizing Phase Plate at Subaru/SCExAO," *Astronomy and Astrophysics* **653**, A42 (Sept. 2021).

[71] Guyon, O., Miller, K., Males, J., Belikov, R., and Kern, B., "Spectral Linear Dark Field Control: Stabilizing Deep Contrast for Exoplanet Imaging Using out-of-band Speckle Field," *arXiv e-prints* , arXiv:1706.07377 (June 2017).

[72] Poon, P. K., Potier, A., Ruane, G., Walter, A. B., Eldorado Riggs, A. J., Noyes, M., Mejia Prada, C., Ahn, K., and Guyon, O., "Experimental demonstration of spectral linear dark field control at NASA's high contrast imaging testbeds," *arXiv e-prints* , arXiv:2309.17449 (Sept. 2023).

[73] Pogorelyuk, L. and Kasdin, N. J., "Dark Hole Maintenance and A Posteriori Intensity Estimation in the Presence of Speckle Drift in a High-contrast Space Coronagraph," *The Astrophysical Journal* **873**, 95 (Mar. 2019).

[74] Redmond, S. F., Pogorelyuk, L., Pueyo, L., Por, E., Noss, J., Will, S. D., Laginja, I., Brooks, K., Maclay, M., Fowler, J., Jeremy Kasdin, N., Perrin, M. D., and Soummer, R., "Implementation of a dark zone maintenance algorithm for speckle drift correction in a high contrast space coronagraph," *Journal of Astronomical Telescopes, Instruments, and Systems* **8**, 035001 (July 2022).

[75] Bordé, P. J. and Traub, W. A., "High-contrast imaging from space: Speckle nulling in a low-aberration regime," *The Astrophysical Journal* **638**, 488 (02 2006).

[76] Cady, E., Bowman, N., Greenbaum, A. Z., Ingalls, J. G., Kern, B., Krist, J., Marx, D., Poberezhskiy, I., Eldorado Riggs, A. J., Ruane, G., Seo, B.-J., Shi, F., and Zhou, H., "High-order wavefront sensing and control for the roman coronagraph instrument (CGI): architecture and measured performance," *Journal of Astronomical Telescopes, Instruments, and Systems* **11**, 021408 (04 2025). ADS Bibcode: 2025JATIS..11b1408C.

[77] Beaulieu, M., Abe, L., Martinez, P., Baudoz, P., Gouvret, C., and Vakili, F., "High-contrast imaging at small separations: impact of the optical configuration of two deformable mirrors on dark holes," *Monthly Notices of the Royal Astronomical Society* **469**, 218–230 (07 2017).

[78] Mazoyer, J., Pueyo, L., N'Diaye, M., Fogarty, K., Zimmerman, N., Soummer, R., Shaklan, S., and Norman, C., "Active correction of aperture discontinuities-optimized stroke minimization. II. optimization for future missions," *The Astronomical Journal* **155**, 8 (01 2018).

[79] Give'On, A., Kern, B., Shaklan, S., Moody, D. C., and Pueyo, L., "Broadband wavefront correction algorithm for high-contrast imaging systems," *Proc. SPIE* **6691**, 66910A (2007).

[80] Baudoz, P., Boccaletti, A., Baudrand, J., and Rouan, D., "The Self-Coherent Camera: a new tool for planet detection," in [*IAU Colloq. 200: Direct Imaging of Exoplanets: Science & Techniques*], Aime, C. and Vakili, F., eds., 553–558 (2006).

[81] Orban de Xivry, G., Quesnel, M., Vanberg, P.-O., Absil, O., and Louppe, G., "Focal plane wavefront sensing using machine learning: performance of convolutional neural networks compared to fundamental limits," *Monthly Notices of the Royal Astronomical Society* **505**, 5702–5713 (Aug. 2021).

[82] Nousiainen, J., Taskin, I., Kasper, M., Orban de Xivry, G., and Absil, O., "Focal plane wavefront control with model-based reinforcement learning: I. Proof of concept on simulated static and dynamic non-common path aberrations," *Astronomy and Astrophysics* **709**, A267 (May 2026).

[83] Males, J. R. and Guyon, O., "Ground-based adaptive optics coronagraphic performance under closed-loop predictive control," *Journal of Astronomical Telescopes, Instruments, and Systems* **4**, 019001 (Jan. 2018).

[84] Sinquin, B., Prengère, L., Kulcsár, C., Raynaud, H.-F., Gendron, E., Osborn, J., Basden, A., Conan, J.-M., Bharmal, N., Bardou, L., Staykov, L., Morris, T., Buey, T., Chemla, F., and Cohen, M., "On-sky results for adaptive optics control with data-driven models on low-order modes," *Monthly Notices of the Royal Astronomical Society* **498**, 3228–3240 (11 2020).