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Change Record from previous Version

Affected Section(s)	Changes / Reason / Remarks
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1. Main takeaways – Executive summary.....	6
2. Introduction	8
2.1 Scope.....	8
2.2 Definitions and Conventions	8
2.2.1 Abbreviations and Acronyms.....	8
3. Conceptual design of the coronagraph sub-system.....	10
3.1 Introduction	10
3.2 Multiple deformable mirrors for one-sided or two-sided control.....	11
3.3 One or multiple coronagraph arms for VIS/NIR split	11
3.4 First optical design of the coronagraph arm.....	12
4. The PCS Coronagraph Evaluation Pipeline	14
4.1 Goal of the PCS-CEP and deliverables	14
4.2 Current state of the module	15
4.3 Schedule for the next term.....	17
5. Coronagraph architectures	18
5.1 Goal and deliverables.....	18
5.2 Current state.....	19
5.3 Schedule for the next term.....	21
6. Focal plane wavefront sensing	21
6.1 Goal and deliverables.....	21
6.2 Current state.....	22
6.2.1 PSF sharpening.....	22
6.2.2 Dark Hole control.....	23
6.2.3 Wavefront maintenance.....	23
6.2.4 The case for photonics wavefront sensing solutions	24
6.2.5 Post-AO control enhancement through machine learning and advanced controller	24
6.2.6 TRL levels for different wavefront sensing schemes	25
6.3 Schedule for the next term.....	26
7. Active atmospheric dispersion compensation	27
7.1 Goal and deliverables.....	27
7.1.1 Imaging and wavefront sensing	27
7.1.2 Coronagraphic suppression.....	28
7.1.3 Chromatic pupil registration.....	29
7.1.4 Design interfaces and verification	29
7.2 Schedule for the next term.....	30
8. Summary.....	30



8.1 The upcoming milestones.....	31
9. References.....	31



1. Main takeaways – Executive summary

- WP1:

- 10mas IWA coronagraphs will be difficult to obtain, especially in the NIR (Sec.5.1).
- Fractional bandwidths that exceed 20% are particularly challenging. Higher simultaneous spectral coverage may require multiple coronagraph arms (Sec.3.3).

- WP3:

- An interface between backend instrument and coronagraph is required for focal plane WS&C (Sec.6).
- Science cameras should be sampled with 4-5 pixels / (λ/D) for SCC-like WS&C schemes (Sec.6.2.2).

- WP4:

- Based on a 128-act XAO DM, ADC requirements establish a strict fractional pupil displacement limit of 0.08% (Sec.7.1.3).

- WP6:

- The final mechanical envelope and space allocation remain closely coupled to decisions regarding DM placement, relay configurations, and whether a dual-channel VIS/IR split is adopted (Sec.3).
- F-number should be >50 at the FPM (Sec.3).
- Out-of-pupil NCPA DMs may be used for compactness (Sec.3.2).
- Dedicated space for photon collection at 1) entrance pupil, 2) focal and 3) Lyot stop planes is required for WS&C. This requirement could drive the hot/cold LS design interrogation. (Sec.6.2.3).
- Optics should be doubled in size after FPM for SCC-like WS&C scheme (Sec.6.2.2).
- ADC designs must account for residual chromatic errors that can restrict the usable spectral bandwidth, even when employing advanced WS&C (Sec.7).
- ADC dispersion should be $<0.05 \lambda/D$ (Sec.7.1.2).

- WP7:

- Inputs for yield calculation will be generated through the PCS-CEP (see Sec.4).
- 2 NCPA-DM solutions is a trade-off between FoV, achievable contrast, throughput and spectral bandwidth that need to be investigated (Sec.3.2).



PCS R&D roadmap plan

Doc. Number: ESO-652253

Doc. Version: 1.0

Released on: 21/10/2026

Page: 7 of 37



2. Introduction

2.1 Scope

This document is made for the midterm review of the PCS R&D roadmap plan. It describes the current state of work package 2 that covers the coronagraph and focal plane wavefront sensing and control.

2.2 Definitions and Conventions

2.2.1 Abbreviations and Acronyms

The following abbreviations and acronyms are used in this document:

ADC	Atmospheric dispersion corrector
ADI	Angular Differential Imaging
AO	Adaptive Optics
APFWS	Asymmetric pupil Fourier wavefront sensor
APLC	Apodized Lyot Coronagraph
AVC	Apodized Vortex Coronagraph
CDI	Coherence Differential Imaging
CDS	Coronagraph Design Survey
CEP	Coronagraph Evaluation Pipeline
CMC	Complex Mask Coronagraph
COFFEE	Coronagraphic focal-plane wave-front estimation for exoplanet detection
DH	Dark hole
DM	Deformable Mirror
dOTF	Differential optical transfer function
EFC	Electric Field Conjugation
ELT	Extremely Large Telescope
ESO	European Southern Observatory
FAST	Fast Atmospheric SCC Technique
FoV	Field of view
FPM	Focal-plane mask
FPWFC	Focal Plane Wavefront Control
FPWFS	Focal Plane Wavefront sensing
iEFC	Implicit electric field conjugation



PCS R&D roadmap plan

Doc. Number: ESO-652253

Doc. Version: 1.0

Released on: 21/10/2026

Page: 9 of 37

IWA	Inner working angle
LC	Lyot Coronagraph
LDFC	Linear dark-field control
LLOWFS	Lyot-based low-order wavefront sensor
LQG	Linear quadratic Gaussian
LS	Lyot stop
NCPA	Non-common path aberrations
NIR	Near-infrared
OWA	Outer working angle
PAPLC	Phase Apodized Lyot Coronagraph
PCS	Planetary Camera and Spectrograph
PCS-CEP	Planetary Camera and Spectrograph Coronagraph Evaluation Pipeline
PIAA	Phase Induced Amplitude Apodization
PIAACMC	Phase-induced amplitude apodization complex mask coronagraph
PSF	Point spread function
PWP	Pair-wise probing
QACITS	Quadrant analysis of coronagraphic images for tip-tilt sensing
QSS	Quasi-static speckles
R&D	Research and development
RL	Reinforcement learning
SCC	Self-Coherent Camera
SLM	Spatial-light modulator
TBC	To Be Confirmed
TBD	To Be Defined
TRL	Technology readiness level
VC	Vortex Coronagraph
VIS	Visible
VVC	Vector Vortex Coronagraph
WFC	Wavefront control
WFS	Wavefront sensing
WFS&C	Wavefront sensing and control
WP	Work package
XAO	Extreme Adaptive Optics
ZWFS	Zernike wavefront sensor



3. Conceptual design of the coronagraph subsystem

3.1 Introduction

The 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 (Kasper et al., 2021), 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.



3.2 Multiple deformable mirrors for one-sided or two-sided control

Using multiple deformable mirrors (DMs) in a coronagraph system enables simultaneous control of phase and amplitude aberrations, providing greater flexibility in suppressing residual starlight. In a typical two-DM configuration, one mirror is located in a pupil plane and the second outside it. Fresnel propagation between the mirrors converts part of the imposed phase modulation into amplitude modulation, allowing their combined response to control the complex electric field. This enables correction of amplitude errors that a single pupil-plane DM cannot independently compensate across the full image, and supports the formation of a dark hole on both sides of the star. For PCS, this capability offers a route to deeper stellar suppression and more complete angular coverage around the target, motivating its consideration within the WP2 coronagraph and wavefront-control studies. ([Pueyo et al., 2009](#))

A key disadvantage is the restriction on the usable field of view introduced by the finite size of the out-of-pupil DM. Beams from off-axis sources are displaced relative to the on-axis stellar beam at this mirror, causing increasing vignetting and reduced planet throughput at larger angular separations. ([Mazoyer & Pueyo, 2017](#)) A potential mitigation is to introduce an additional pupil relay with an appropriate magnification or demagnification, adjusting the beam size to provide sufficient aperture margin and preserve the required field of view even when using two similarly sized DMs. However, this introduces a strong trade-off with the correction radius of the dark hole: reducing the beam diameter on a DM illuminates fewer actuators across the pupil, lowering the maximum controllable spatial frequency and hence the achievable outer working angle. The relay configuration also changes the propagation conditions governing amplitude correction and adds optical complexity. Over the next six months, **the PCS trade study will evaluate these competing effects to identify configurations that balance the required field of view, dark-hole correction radius, achievable contrast and planet throughput.**

3.3 One or multiple coronagraph arms for VIS/NIR split

A single coronagraphic subsystem covering the full PCS spectral range would minimise duplication of optics, deformable mirrors and control hardware, simplifying integration and providing a common optical path for visible and infrared observations. However, achieving simultaneous stellar suppression across this range requires both a sufficiently achromatic coronagraph and a wavefront-control solution that remains effective over a very broad bandwidth. The wavelength dependence of aberrations, Fresnel propagation and the DM response makes it increasingly difficult to maintain a deep dark hole across the entire band. Our experience with current systems indicates that fractional bandwidths exceeding approximately 20–30% are particularly challenging, although this is a practical limitation that depends on the architecture and target contrast rather than a universal cutoff. A shared subsystem may therefore require compromises in contrast, dark-hole extent or instantaneous spectral coverage, even if its optics transmit the full wavelength range. ([Groff et al., 2012](#))

Splitting the beam into separate visible and infrared channels upstream of their respective coronagraphs would allow simultaneous, independent optimisation of stellar suppression in



each band. Dedicated coronagraphs and wavefront-control DMs could address the chromatic behavior and aberrations of each channel, reducing the bandwidth that each control solution must accommodate and allowing different dark-hole geometries to match the science requirements. These benefits come at the cost of additional optics, DMs, calibration effort, instrument volume and alignment requirements, together with dichroic losses and differential aberrations between the channels. Furthermore, a VIS/IR split alone may not sufficiently narrow the bandwidth within either channel, so operation in selectable spectral sub-bands may still be necessary. Over the next six months, **the PCS trade study will compare the shared and split architectures in terms of achievable contrast, simultaneous spectral coverage, dark-hole extent, throughput and implementation complexity**, in coordination with the science-instrument requirements.

3.4 First optical design of the coronagraph arm

WP2 has developed a preliminary optical layout for the coronagraphic subsystem to establish its spatial requirements and interfaces with the PCS common path and science instruments. The initial concept uses four off-axis parabolic mirrors to provide the pupil and focal planes required for wavefront control and coronagraphy, with provision for two deformable mirrors and pupil apodisation. This layout has F/100 input and output beams and an optical footprint of approximately 5.25×1.85 m. Further development with WP6 is exploring alternative relay configurations compatible with the common-path optics. The concept presented in the October update uses an F/17.7 input focus and an 18.6 mm pupil, with dedicated planes for the apodiser, focal-plane mask and Lyot stop. The DM positions remain provisional and will be refined alongside the phase and amplitude control studies.

The volume allocation therefore remains coupled to the choice of coronagraph and wavefront-control architecture. The required pupil sizes, propagation distances between DMs and number of relay stages determine the optical footprint, while a potential VIS/IR split would require accommodation of two coronagraphic channels. The mechanical envelope must additionally provide space for optical mounts, mask mechanisms, wavefront-sensing paths and alignment access. Over the next six months, **the optical-design work will assess these requirements together with the trade-offs in field of view, dark-hole extent and spectral coverage, and consolidate the subsystem layout with WP6**. This will establish a space envelope and optical interfaces that support the candidate architectures and their integration with the downstream science instruments.

The optical layout and performance can be seen in Figures 3.1 and 3.2.

PCS coronagraph optical design

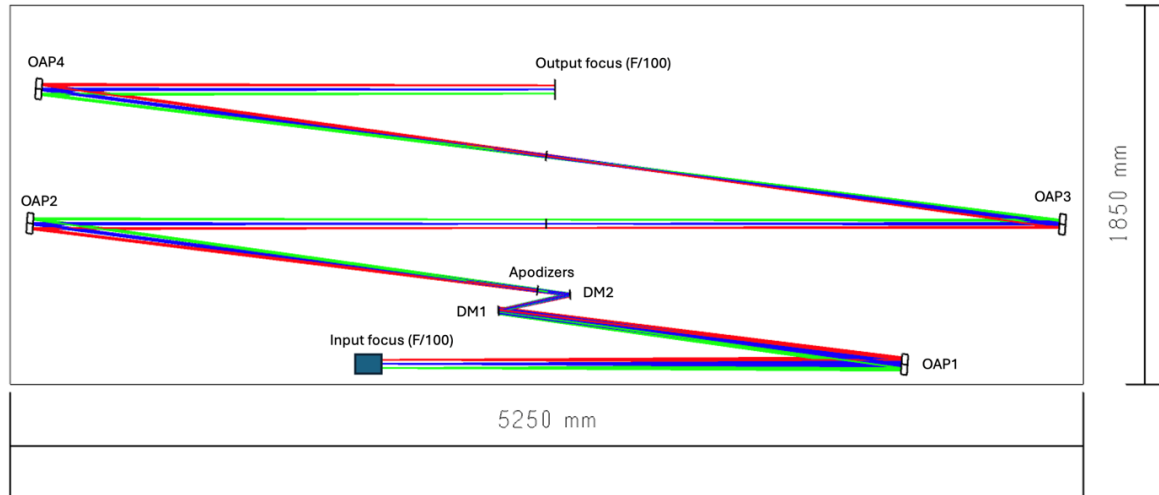


Figure 3.1 The Zemax design using two OAP relays at F/100. There is space for 2 DMs and all the apodizer wheels.

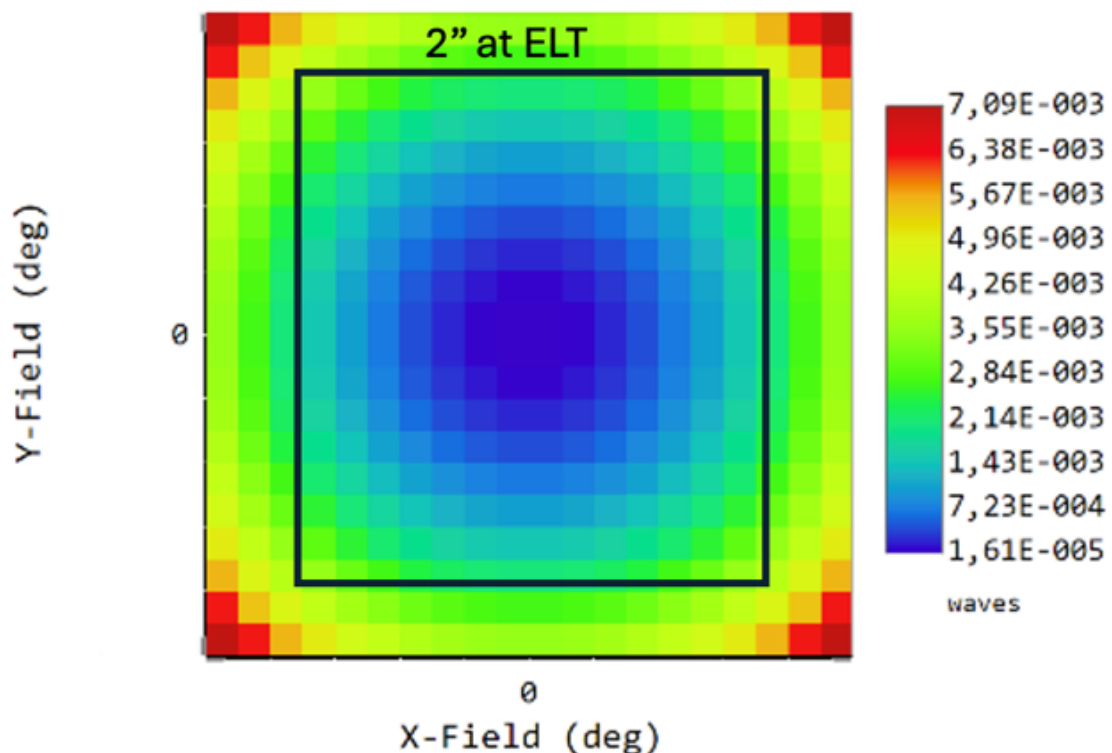


Figure 3.2 The wavefront error as a function of field angle. The full field of PCS is diffraction-limited using the OAP relay demonstrating that this design will not add strong field dependent aberrations. It is also symmetric and does not create asymmetric aberrations.

4. The PCS Coronagraph Evaluation Pipeline

4.1 Goal of the PCS-CEP and deliverables

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 (Belikov et al., 2024). 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 4.1.

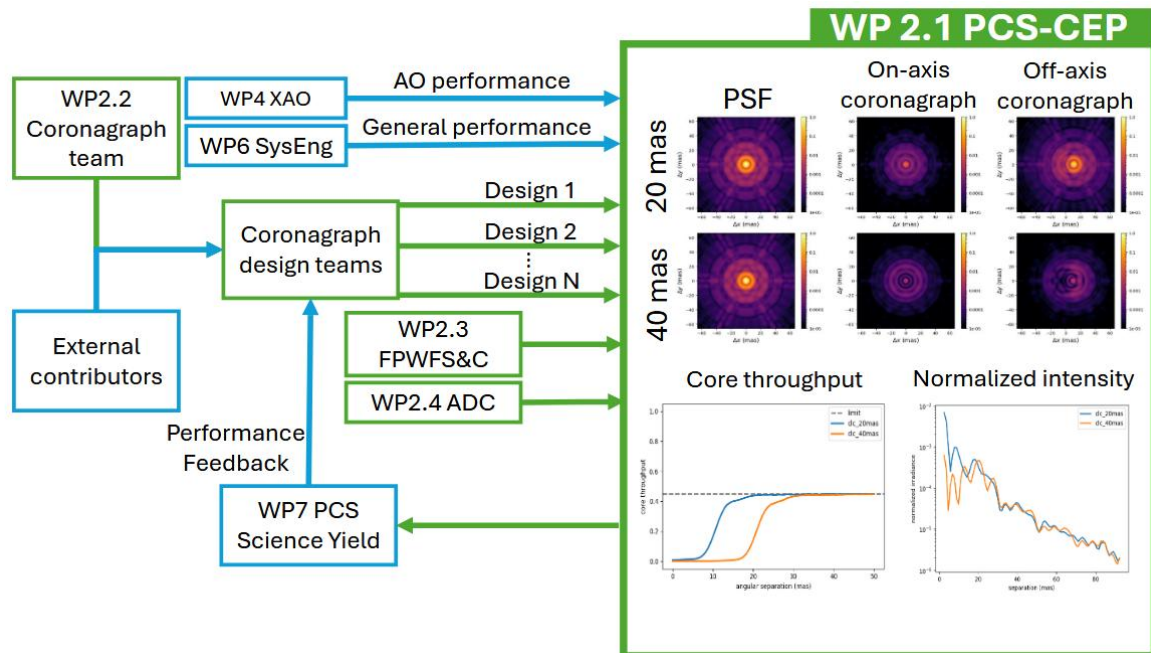


Figure 4.1 Schematic overview of the PCS-CEP developed in WP2.1. Coronagraph designs submitted by the WP2 coronagraph team and external contributors are evaluated using a common simulation framework that incorporates adaptive optics residuals from WP4, focal-plane wavefront sensing and control concepts 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 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.

4.2 Current state of the module

The PCS-CEP currently provides the core functionality needed to simulate and compare most of the coronagraph architectures of interest to the community. The PIAACMC architecture remains to be implemented. The analysis framework supports four performance metrics:

- **Total throughput:** the fraction of incident light transmitted through the coronagraph.



- **Core throughput:** the fraction of incident light contained within the core (e.g. $1.4 \lambda/D$) of the coronagraphic point spread function.
- **Normalized irradiance:** the image-plane irradiance relative to a defined reference.
- **Raw contrast:** a measure of residual stellar light relative to the response to an off-axis source.

Additional metrics, including robustness to optical misalignments and wavefront aberrations, will be introduced at a later stage. The existing capabilities nevertheless provide a basis for initial comparisons between coronagraph designs. Figures 5.2 and 5.3 present a first indication of their performance.

The pipeline also includes the software interfaces needed to integrate wavefront sensing and control algorithms. The first coronagraphic low-order wavefront sensor (LOWFS) implemented is a focal-plane LOWFS, which uses the starlight rejected by the focal-plane mask of a Lyot coronagraph. This rejected light is deliberately defocused so that low-order wavefront aberrations produce measurable changes in the recorded intensity distribution. These intensity measurements can then be used to estimate the aberrations through an approach similar to phase retrieval.

A linear reconstructor is currently available to estimate the low-order aberration coefficients from the sensor measurements. Combined with an integral controller, it enables closed-loop simulations to assess convergence and sensitivity to low-order aberrations.

The PCS-CEP can also seamlessly interface with the PSFSIM module, which is a semi-analytical adaptive optics simulator. PSFSIM is being developed under WP4. The simulated AO outputs are used to create radial profiles for WP7.

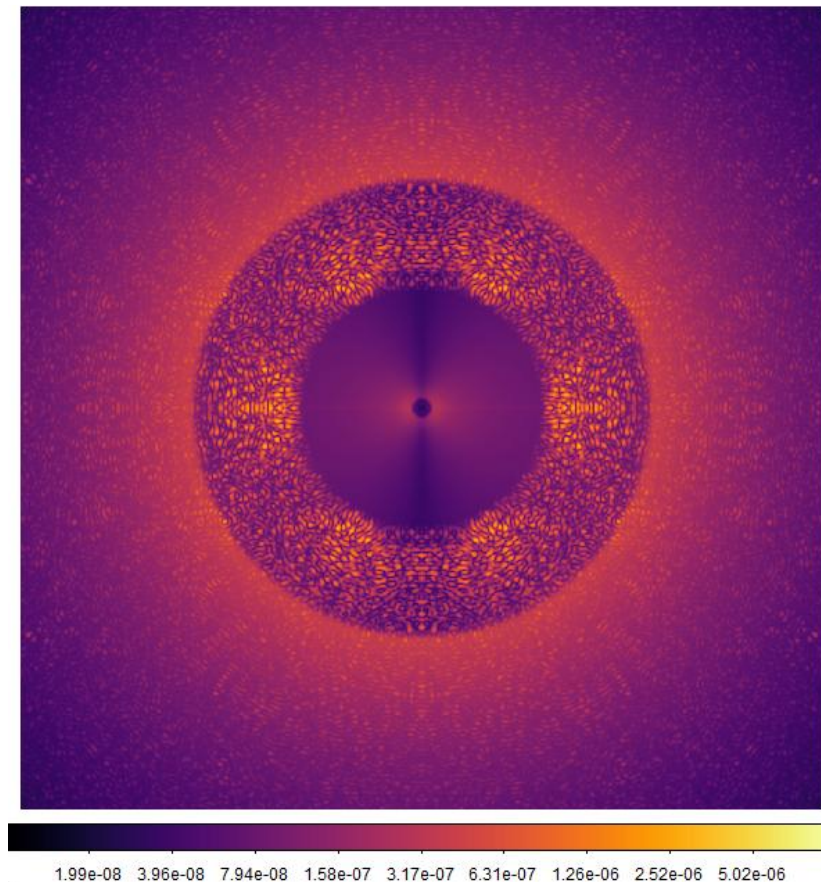


Figure 4.2 An example output of the semi-analytical simulation framework together with PCS-CEP. The coronagraph simulated is an APLC with a 30 λ/D outer-working angle. The guide star is a 5th magnitude star.

4.3 Schedule for the next term

The next stage of development will extend the coronagraph simulator to assess its sensitivity to optical misalignments and low-order wavefront aberrations. This will include modelling the effects of misaligned optical elements, such as lateral shifts and rotations of the Lyot stop, and quantifying the resulting changes in coronagraphic performance. We will also evaluate robustness against aberrations such as tip, tilt, defocus, and astigmatism. Together, these simulations will help establish alignment tolerances and wavefront stability requirements.

In parallel, we will expand the wavefront sensing and control capabilities of the simulator by implementing selected coronagraphic wavefront control algorithms identified in the literature review. Comparing these algorithms under consistent simulation conditions will allow us to assess their ability to estimate and correct residual wavefront errors, their convergence behaviour, and the contrast they can achieve in the presence of optical imperfections.



5. Coronagraph architectures

5.1 Goal and deliverables

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 (Vigan et al., 2026). This diversity translates into a wide and sometimes conflicting set of instrumental requirements: inner working angles ranging from $1 \lambda/D$ 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 λ/D at 10 mas and λ/D at 30 mas, understood as post-coronagraph, post-adaptive optics, post-wavefront control, and post-processing values.

A very quick trade-off of inner-working angle and spectral bandwidth is shown in Figure 4.1. For some science cases, an inner-working angle of 6 mas in K-band is required. This is well within $1 \lambda/D$ and not achievable. For now, the blue line representing $1 \lambda/D$ is the smallest inner-working angle that we can design for.

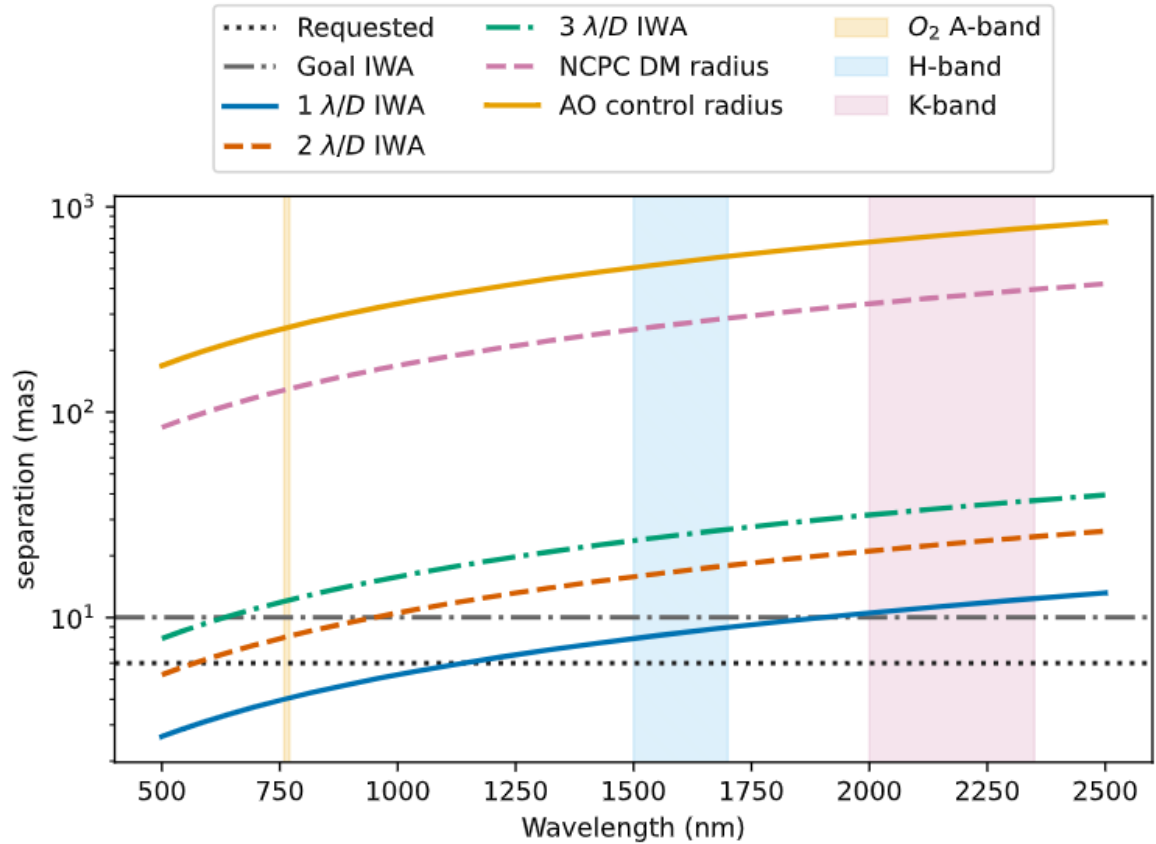


Figure 5.1 The angular separation of various limits as a function of wavelength. Three reference bands are shown by vertical transparent bands. The angular separation of $1, 2$ and $3 \lambda/D$ are shown and the outer-working angles defined by the NCPC DM control radius and the AO control radius.

5.2 Current state

This call resulted in **11** declarations of interest to submit concepts, covering a diverse range of families including scalar vortex coronagraphs (Desai et al., 2022; Desai et al., 2024; König et al., 2023; König et al., 2025), apodized pupil Lyot coronagraphs (N'Diaye et al., 2015; N'Diaye et al., 2016b), shaped-pupil designs (Carlotti et al., 2012; Gersh-Range et al., 2022), PIAACMC (Tonucci et al., 2026; Martinez et al., 2023a), nulling approaches (Xin et al., 2023; Xin et al., 2025; Xin et al., 2026), and architectures involving programmable devices (Lebouilleux et al., 2022; Carlotti et al., 2023; Kühn et al., 2017; Kühn et al., 2025). 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.

Table 5.1 A summary of the properties of the submitted coronagraphs up to now.

Coronagraph	IWA (λ/D)	OWA (λ/D)	Bandwidth	Max core throughput
Binary APLC	2.7	30	20%	0.23
Binary SPP	8.0	40	20%	0.23
PAPLC	1.4	30	20%	0.38

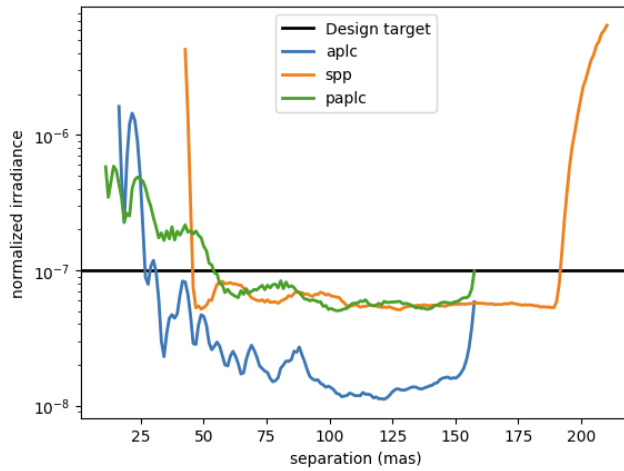


Figure 5.2 Outputs of the current PCS-CEP for several submitted designs. The figure shows the normalized intensity, which is the raw contrast divided by the peak intensity of an off-axis PSF.

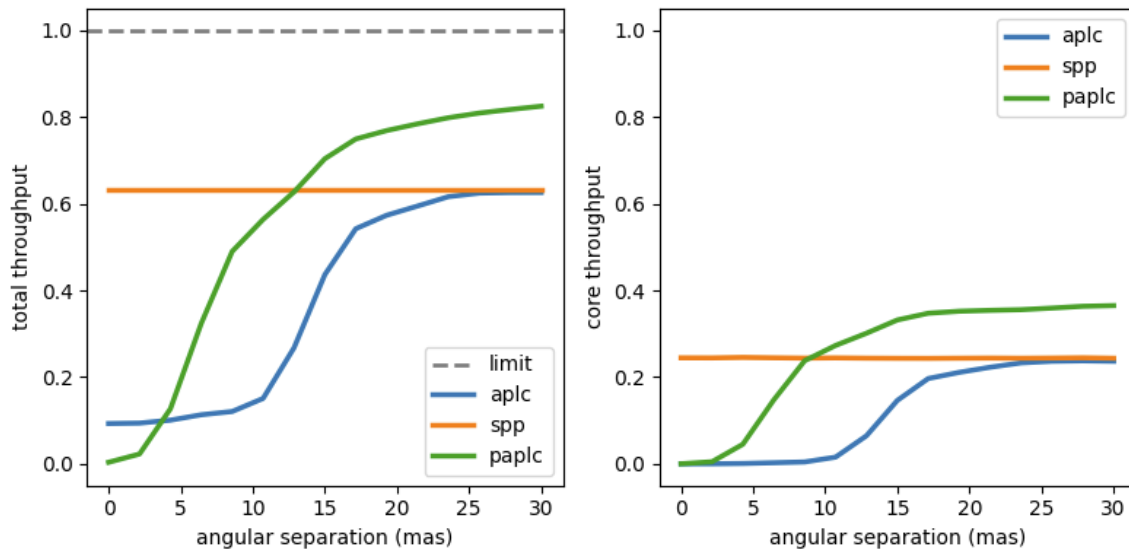


Figure 5.3 Outputs of the current PCS-CEP for several submitted designs. The left figure shows the integrated throughput of after the coronagraph as a function of angular separation. And the right figure shows the core throughput within $1.4\lambda/D$ as a function of angular separation.



5.3 Schedule for the next term

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

6. Focal plane wavefront sensing

6.1 Goal and deliverables

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 5.1) 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 5.1.

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.

6.2 Current state

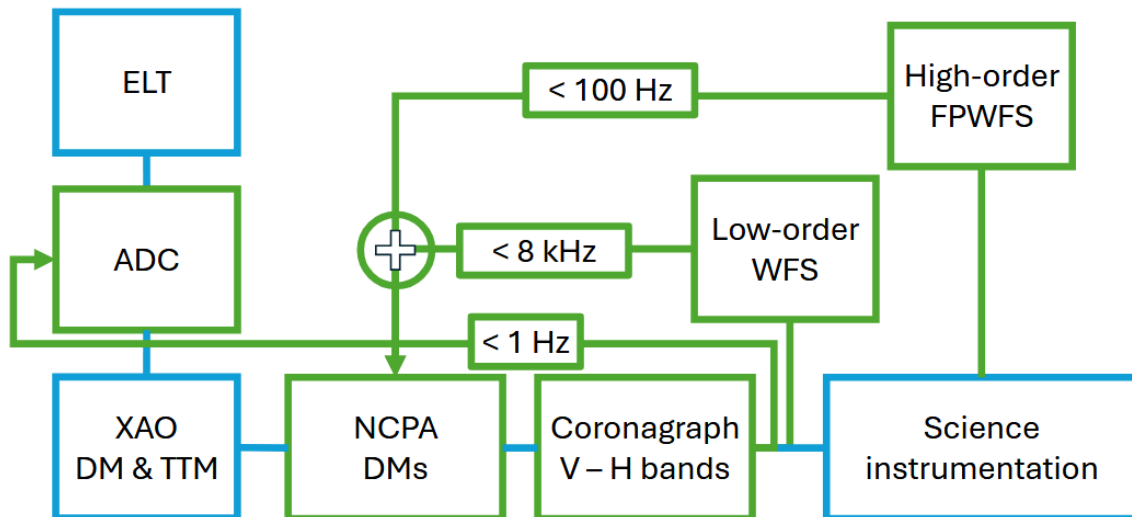


Figure 5.1 The proposed block scheme of PCS. PCS will consist of an eXtreme AO (XAO) system that provides well corrected wavefronts to the coronagraph sub-system. The coronagraph sub-subsystem will handle non-common path aberrations using dedicated DMs. There will be multiple wavefront control loops 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 anticipate 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.

6.2.1 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 (Gerchberg, 1972), 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 (Paul et al., 2013) could therefore be used for such plain correction.

On a daily basis after commissioning, a fine tuned correction should be performed 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 (N'Diaye et al., 2013) (ZWFS, requiring an additional Zernike mask in the FPM filter wheel) or a differential



Optical Transfer Function (Codona, 2013a) (dOTF) scheme could be employed before operations. On-sky, sensitive and fast algorithms could be employed either without (Fast & Furious (Keller et al., 2012), Dr Who (Codona & Kenworthy, 2013b)) or with (Asymmetric Pupil Fourier Wavefront Sensor or APFWS (Martinache, 2013), Vortex phase retrieval (Riaud et al., 2012)) a coronagraph.

6.2.2 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 (Bordé & Traub, 2006), these techniques have matured to successful on-sky demonstrations with VLT/SPHERE (Potier et al., 2022) and, more recently, MagAO-X (Haffert et al., 2026). Furthermore, the Roman Coronagraph Instrument will provide the first demonstration of active dark-hole digging and maintenance in space (Cady et al., 2025). Within WP2.3 we will investigate the applicability of these techniques to PCS, including implementations that operate without a dedicated deformable mirrors (Potier et al., 2022; Goulas et al., 2026), and architectures employing dedicated deformable mirrors for focal-plane wavefront control (Haffert et al., 2026). 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 (Beaulieu et al., 2017; Mazoyer et al., 2018).

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 (Martinache et al., 2014), pair-wise probing (Give'On et al., 2007), dOTF (Martinez & Dharmadhikari, 2023b)) which can be combined with a model-based controller (Electric Field Conjugation (Give'On et al., 2007)), or can be completely model-free (iEFC (Haffert et al., 2023)) 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 (Baudoz et al., 2006)). 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 (Gerard et al., 2018)), or the pinhole is set closer to the LS diaphragm by mean of polarization encoding (Bos, 2021a), spatial clipping (Lieberman et al., 2025) or a spectral modulation (Haffert, 2022). In any case, the SCC requires enlarging the optics after the FPM to collect the photons outside the Lyot stop and demands a higher resolution for the science camera (4–5 pixels per λ/D).

6.2.3 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, 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 (Guyon et al., 2009) and Encoded ZWFS (Ruane et al., 2023) in the FPM, LLOWFS (Singh et al., 2014) from the LS, QACITS (Huby et al., 2015) 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 (Por et al., 2023) from the FPM, spatial LDFC (Miller et al., 2017) from the science camera). Finally high-order wavefront maintenance comes at a cost, either requiring an out-of-band scheme (Encoded ZWFS (Ruane et al., 2023) in the FPM, spectral LDFC (Poon et al., 2023)) or a destructive behavior (DH maintenance (Redmond et al., 2022) 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.

6.2.4 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 (Llop-Sayson et al., 2022).

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 (Lin et al., 2025) and optimize off-axis planet coupling, even while suppressing on-axis stellar light (Xin et al., 2025).

6.2.5 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 (Orban de Xivry et al., 2021; Nousiainen et al., 2026). 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 (Males & Guyon, 2018; Sinquin et al., 2020).

6.2.6 TRL levels for different wavefront sensing schemes.

Table 5.1 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 demonstrations 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.

	Numerical simulation	In-lab test	On-sky test
PSF sharpening			
Gerberch-Saxton	Gerchberg (1972)	Kay (2007)	
Phase diversity	Gonsalves (1982)	Fusco (2015)	Kuznetsov (2024), Kueny (2024)
COFFEE	Paul (2013)	Paul (2014)	
Fast & Furious	Keller (2012)	Bos (2020)	Bos (2020)
APFWS	Martinache (2013)	Martinache (2016)	Martinache (2016)
dOTF	Codona (2013a)	Martinez (2023b)	
Dr. WHO	Codona (2013b)		Skaf (2022)
ZWFS	N'Diaye (2013)	N'Diaye (2016a)	Vigan (2019)
Vortex Phase retrieval	Riaud (2012)		
Photonics lantern WFS	Lin (2022)	Lin (2023)	Lin (2025)
Dark Hole control			
SCC (normal)	Singh (2019)	Singh (2019)	Galicher (2019)
SCC (FAST)	Gerard (2018)	Gerard (2021)	
SCC (spectraly modulated)	Haffert (2022)		
SCC (spatially-clipped)	Liberman (2025)		
SCC (polarization encoded)	Bos (2021a)		



	Numerical simulation	In-lab test	On-sky test
PWP	Goulas (2026)	Potier (2019)	Potier (2022)
iEFC	Haffert (2023)	Haffert (2023)	Haffert (2026)
dOTF	Martinez (2025)		
Speckle Nulling		Martinache (2012)	Martinache (2014)
Fiber nulling	Llop-Sayson (2019)	Llop-Sayson (2022)	Xin (2023)
Photonics lantern nulling	Xin (2025)	Xin (2025)	
Wavefront stabilization			
QACITS	Huby (2015)	Huby (2015)	Huby (2017)
FLOWFS	Guyon (2009)	Guyon (2009)	Mars (2026)
PAPLC WFS	Por (2023)	Por (2023)	
Encoded ZWFS	Ruane (2023)	Ruane (2023)	
LLOWFS	Singh (2014)	Singh (2015)	Singh (2017)
Spatial LFDC	Miller (2017)	Miller (2019)	Bos (2021b)
Spectral LDFC	Guyon (2017)	Poon (2023)	
DH maintenance	Pogorelyuk (2019)	Redmond (2022)	

6.3 Schedule for the next term

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.



7. Active atmospheric dispersion compensation

7.1 Goal and deliverables

The atmospheric dispersion corrector (ADC) must preserve image quality, coronagraphic suppression and registration between the wavefront-sensing and science pupils. WP2 has translated these needs into separate limits on residual focal-plane dispersion and chromatic pupil shear. The requirements study establishes a 500–2400 nm operating range and zenith angles from 0° to 60° from the top-level science requirements, then derives subsystem limits using numerical simulations and a spatial-frequency analysis [1].

Table 7.1 Requirement baseline

Parameter	Requirement or design criterion	Origin
Spectral coverage	500–2400 nm	Science requirements
Zenith angle	$0^\circ \leq \theta_z \leq 60^\circ$	Science requirements
Imaging and wavefront sensing	Residual dispersion $<0.2 \lambda/D$; dispersion-only Strehl $\geq 99\%$	20% bandwidth simulation
Coronagraphy	Residual dispersion $<0.05 \lambda/D$; leakage $\leq 10^{-7}$ at $1 \lambda/D$	Fourth-order coronagraph; 20% bandwidth
Chromatic pupil shear	<0.1 actuator pitch, approximately $<0.08\%$ of pupil diameter	$\geq 90\%$ modal power correction at 64 cycles/pupil

Here λ/D is the angular diffraction scale at wavelength λ for telescope aperture diameter D . The full operating range and the instantaneous bandwidth of an individual observation are distinct.

7.1.1 Imaging and wavefront sensing

The study injects residual dispersion into an image formed over a 20% fractional bandwidth and measures the reduction in peak intensity. Requiring at least 99% Strehl from this effect limits chromatic image elongation and preserves the image quality available to imaging and wavefront sensing. The numerical results are described by $S \approx \exp[-(0.462 \Delta\sigma)^2]$, with $\Delta\sigma$ expressed in units of λ/D . At $\Delta\sigma = 0.2$, this gives $S \approx 0.9915$, supporting the adopted limit of one fifth of a diffraction element [1, slides 5–6]. This is an allowance for dispersion alone, rather than a requirement for 99% total on-sky Strehl.

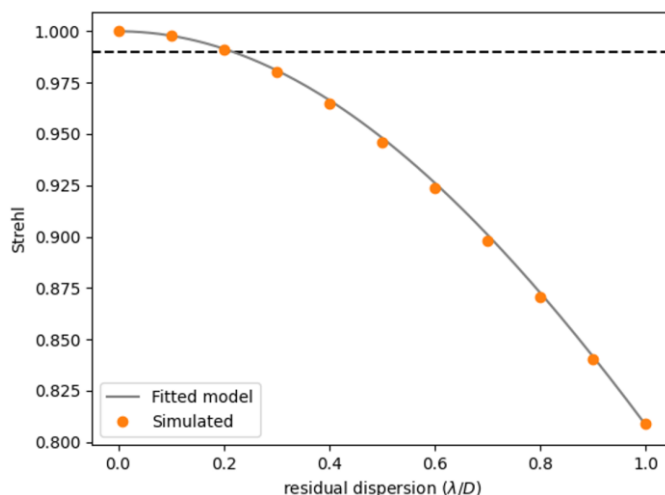


Figure 7.1 The impact on Strehl as a function of residual dispersion over a spectral bandwidth of 20% which roughly corresponds to a single photometric band. The measurements are well fitted by a single exponential function.

7.1.2 Coronagraphic suppression

The coronagraph analysis evaluates radial profiles of normalised residual intensity over a 20% bandwidth. A fourth-order coronagraph is used because a second-order design is considered insufficiently robust to pointing errors and finite stellar angular diameter for PCS. The adopted criterion is leakage no greater than 10^{-7} at $1 \lambda/D$, motivated by the intended laboratory dark-hole depth and its maintenance on sky. A residual of $0.1 \lambda/D$ fails this test, whereas $0.05 \lambda/D$ meets it, giving a dispersion limit four times tighter than the imaging allowance [1, slides 8–10]. These are simulated requirements, not a demonstration of delivered ADC performance.

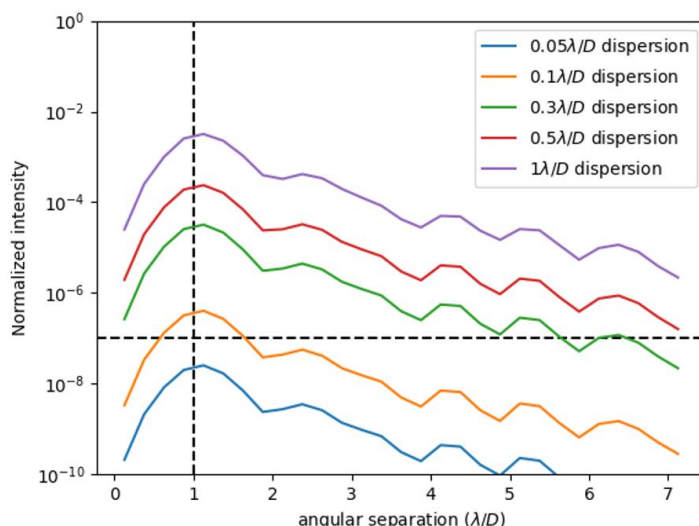


Figure 7.2 The radial contrast profile as a function of angular separation for different amounts of dispersion across a single photometric band (20% spectral bandwidth). The coronagraph is a fourth-order coronagraph. The requirement is a contrast of $1e-7$ at $1\lambda/D$.

7.1.3 Chromatic pupil registration

Chromatic pupil shear produces a mismatch between the atmospheric phase sensed at one wavelength and the correction applied at another. The study represents the residual as the difference between an atmospheric spatial mode and a laterally displaced DM mode. For a sinusoid of spatial frequency f , a displacement δ produces a phase mismatch of $2\pi f\delta$. Averaging over a modal period gives the relative residual power $P_{res} = 4 \sin^2(\pi f\delta)$, where f is in cycles per pupil and δ is a fraction of the pupil diameter. The error therefore grows towards the highest corrected spatial frequencies [1, slides 12–15].

The assumed ALPAO tweeter has 128 actuators across the pupil, giving a Nyquist limit of 64 cycles per pupil. Requiring at least 90% of the power in this highest-frequency mode to be corrected means $P_{res} \leq 0.1$. A shear of 0.1 actuator pitch corresponds to $\delta = 0.1/128$ and gives $P_{res} \approx 0.098$, consistent with that criterion. The resulting fractional displacement is 0.078125%, rounded to 0.08% in the requirements summary. This limit depends on the assumed actuator sampling and must be revisited if the illuminated actuator count changes. It concerns differential pupil registration across wavelengths, including contributions from the optical train and atmospheric propagation.

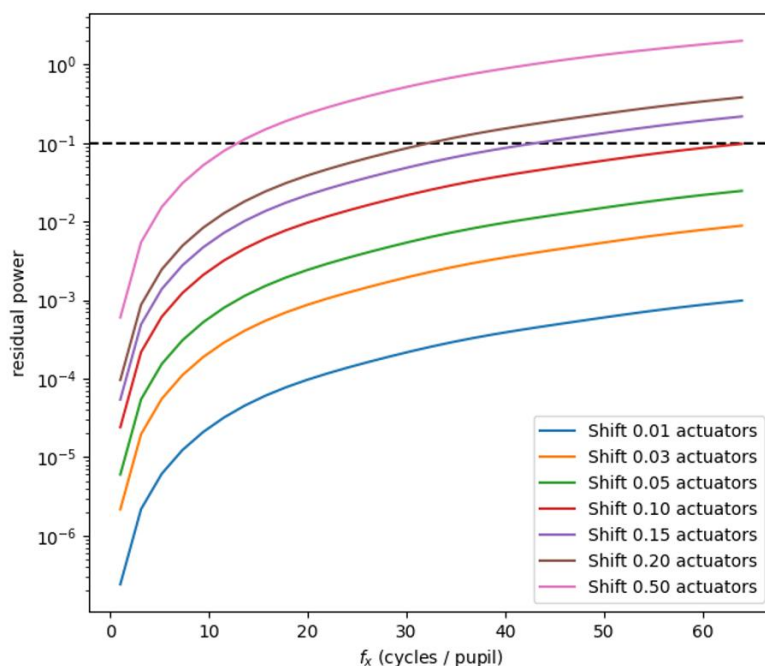


Figure 7.3 The residual wavefront error as a function of spatial frequency after compensating a shifted mode. The amount that a particular mode is shifted is varied between 0.01 times the actuator pitch to 0.5 times the actuator pitch. A requirement of 90% compensation is set, which is a 10% residual power after wavefront compensation.

7.1.4 Design interfaces and verification

The consortium plan assigns this work to WP2.4, with inputs from WP1 science requirements, WP2.2 coronagraph requirements and WP4 wavefront sensing and control. WP6 provides the system context for the ADC beam size and location. The planned sequence is to establish atmospheric-dispersion boundary conditions, assess the adequacy of the refraction model, develop an optical ADC design and adapt its control to the selected



coronagraph [2]. The derived limits provide quantitative targets for this process; they do not yet prescribe a prism configuration, mechanical tolerance budget or control-loop rate.

Verification should test the residual image displacement and pupil shear over the required zenith-angle range, using the actual observing bands and wavefront-sensor wavelengths. The 20% simulations establish the present performance basis; they do not demonstrate simultaneous correction across the entire 500–2400 nm range. The imaging summary applies its limit over the working wavelength range, but its numerical derivation uses a single photometric band. The band definitions, reference wavelength and residual-dispersion convention therefore need to be fixed when these limits are flowed into an optical acceptance specification. Coronagraph-specific checks should repeat the contrast calculation for the selected design and its operating bandwidth.

7.2 Schedule for the next term

Single-mode fibre injection remains an explicit open item in the ADC note. A requirement comparable to the imaging limit is anticipated from the relationship between coupling efficiency and Strehl, but it has not yet been derived. The next design stage should quantify that sensitivity and allocate the residual budget between optical correction, atmospheric-model errors and control residuals. Closed-loop ADC control is a stated project objective [1, slide 17; 2].

WP2 is also collaborating with WP6 on the optical design of the ADC itself. See WP6 documentation for more details on the ADC design.

8. Summary

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 $1 \lambda/D$ 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.

8.1 The upcoming milestones

Time	Milestone
Early 2026	• Draft high-level requirements for all WP2 tasks (done). • Completion of the coronagraph literature review (done). • Completion of the WFS&C literature review (done).
Mid 2026	• First draft coronagraph designs (done). • First draft wavefront sensing and control concepts (in progress). • Preliminary optical design of the ADC (done together with WP6).
Early 2027	• Completion of the PCS Coronagraph Evaluation Pipeline (PCS-CEP).
Mid–Late 2027	• Comparative evaluation of submitted coronagraph concepts using the PCS-CEP. • 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.

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