

Coronagraph Design Survey for Future Exoplanet Direct Imaging Space Missions

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Starlight Suppression Workshop, Caltech: 8/9/2023





- Motivation (the why?)
- Survey goals and deliverables (the what?)
- Process (the how?)
- Conclusions





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There is a rich trade space of coronagraph designs to explore



Olivier Guyon, 2009

Why do we still need to explore different designs? Didn't LUVOIR / HabEx do this already, and shouldn't we focus on getting to 1e-10?



Reason 1: Designs have improved since LUVOIR / HabEx reports...



Reason 1: ... and still have a lot of room to improve before they hit fundamental physics limits



 Optimal coronagraphs achieve 2-4 greater yield than currently baselined coronagraphs (for a fixed bandwidth and system QE)

 Gap between obstructed and unobstructed apertures can be closed!

- Enabling larger aperture for the same cost, and/or risk reduction / cost savings
- Caveats: optimal coronagraph yields
 - Show where theoretical limits are, but not how to get there practically
 - May or may not require exotic architectures
 - Are partially based on IWA improvements, which may have other limitations
 - Useful as a target, guide, and inspiration for coronagraph design



Reason 2: LMS and Decadal Survey recommend thorough, early, well-funded trades



Classification of Recommendations from the Large Missions Study



- Finding: "During the Pre-Phase-A period, requirements development and architecture trades are often over-constrained, driving the mission unnecessarily toward very expensive solutions[...]"
- Recommendation: "[...]Conduct requirements analyses and architecture trades during pre-phase-A that quantify science vs. cost, thereby preventing unnecessary adoption of very expensive solutions[...]"
 - SMD's large mission study report (<u>https://science.nasa.gov/about-us/large-mission-study</u>)
- "Inadequate funding for concept studies, concept, and technology development"
 - One of several common issues identified by the "Flagship Assessment Team" in 2013: National Aeronautics and Space Administration, "Cost and Schedule Growth in NASA Missions: Findings and Recommendations from the Explanation of Change Study and Flagship Mission Assessment," Office of the Center Director, NASA Goddard Space Flight Center, 2013.
- "annual funding [should be] provided in the early stages of development, to cover feasibility studies, technology developments and prototype development,"
 - Bitten, R.E., Shinn, S. A., Emmons, D. L., "Challenges and Potential Solutions to Develop and Fund NASA Flagship Missions," IEEE (2019).

NASA

Reason 2b: Reducing risk and cost of HWO is an important goal of GOMAP

Two of the top recommendations of Astro2020 decadal survey:

The decadal survey recommends a large (~6m diameter) Infrared/Optical/Ultraviolet space telescope with high-contrast imaging and spectroscopy as the first mission to enter the Great Observatories Mission and Technology Maturation Program. This is an ambitious mission with the goal of searching for biosignatures from habitable zone exoplanets and providing a powerful new facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade with a target launch in the first half of the 2040's.

Given the large costs and development timescales for the next generation of space telescopes, the decadal survey recommends that NASA create the Great Observatories Mission and Technology Maturation Program as a new approach for planning and implementing large missions. The program would provide early investment in technology development for multiple mission concepts to lower the risks and costs of projects before they become too complex, large, and costly. The first entrant for the maturation program should be a large Infrared/Optical/Ultraviolet space telescope. The second entrants should be strategic Far-Infrared and X-ray missions.



https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

Reason 3: More powerful instruments are necessary to guard against "yield erosion"

Mission	Originally expected/desired yield	Actual or currently expected yield
Kepler	~25 Earth analogs (Borucki et al. 2003)	o(1)
Roman CGI	~25 reflected light planets (circa 2013-2015)	o(1)
HWO	~25 characterized potentially habitable planets	?

- There are more ways in which expected science yields can decrease than increase
- So, yield estimates tend to go down as a mission concept matures



Reason 4: On a flagship, improving the instrument is possibly the strongest lever to improve the mission



- Instruments are often performance bottlenecks
 - unless they are physics-limited
 - Instrument technology research and development:
 - Small fraction of mission cost for a flagship
 - large impact on
 - mission performance
 - requirements relaxation
 - risk reduction
 - Iarge, leveraged ROI ("better" is NOT the enemy of "good enough")
 - until physics limits are reached, or investment becomes a significant fraction of mission cost
- On a flagship, should always aim for physics-limited instrument performance
 - at least while development cost of an instrument is a small fraction of mission cost



Reason #5: 1e-10 contrast is important, but is one of many dimensions of trade space



- Coronagraph contrast is of course critical and challenging, but
 - diminishing returns once o(1e-10) contrast is reached (because zodi / exozidi starts to dominate)
 - is NOT fundamentally limited by coronagraph architecture (for point sources): requires primarily time and effort in the lab
- Coronagraph "efficiency" (throughput, IWA, tolerance to stellar size, etc.) is also very critical
 - IS fundamentally coronagraph architecture-limited: decisions made without a thorough trade can be very costly
 - Requires continued innovation (TRL0-4)





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- 1. Survey and document viable coronagraph designs across the world that can inform the Habitable Worlds Observatory about their capabilities and technology readiness.
- 2. Facilitate future evaluation and comparison of the coronagraph designs to advance based on a set of technical and programmatic assessment criteria.
- 3. Identify novel coronagraph technologies that could mature rapidly for which NASA's technology development investments could be efficiently leveraged.

Intended Application

 Provide to GOMAP, START, TAG, and ExEP management an assessment of coronagraph technologies that can be used to evaluate risk and performance for a Habitable Worlds Observatory.



Survey Contents

Background

• Role of coronagraph in the Habitable Worlds Observatory mission and how it affects mission yields and performance

Suggested Wants / Opportunities / Risks / Assumptions

• Establish what are Desirements, Opportunities, Risks, and assumptions the survey will assess for different coronagraph designs.

Survey

- Coronagraph designs and their current TRL
- Quantifying value-added of each technology: potential to increase yield, relax mission/telescope requirements, and reduce cost plus risk.
- Assessing feasibility and schedule of developing each design to TRL 5
- Fact finding, data gathering, analyses when needed, no down-selecting

Results (deliverable Final Report)

- Documented list of coronagraph designs used to compare and inform future down-select options
- List will include the opportunities enabled by promising but less mature options, along with their risks and challenges.
- Survey findings

Fact-finding and organizing using the Kepner-Tregoe matrix



Options, Descriptions, Assessment Criteria, Opportunities,

Survey Matrix

		ily focal-plane coronag		Pi	Primarily pupil-plan	ne coronagraphs		al) plane coronagraphs		onic chip / theoretical limits			nancing technologies		
Science	HLC LCPPC	EvWaCo	MSPM VVC		SPC	PIAA	APLC SPLC	PAPLC PIAA-Vortex	Hybrid photonic ci	hiFull Photonic Chip Optimal Cor limit	DPLC	RAP	ILOWFC f	fiber-nulling	AAFFS
Yield of EECs budgeting for VIS detections only															
Yield of EECs budgeting for VIS detections, orbit determination, and H2O detection Yield of EECs budgeting for VIS detections, orbit, and CO2/CH4 detection at 1.65 microns															
Yield of diverse planet types															
Yield of EECs at glint phase angles			Cai	0 10	0										
Yield of EECs characterizable at near-UV "Number" of detectable molecules			SCI	Pn	4-1	31/1	JIN K	nar	1rc						
			JU		UC			netri	00						
Design performance (contrast and efficiency)															
Median exposure time per target during blind search Exposure time for fiducial star (Earth twin @ quadrature)															A REAL PROPERTY
Exposure time for characterization															
Contrast over xx to yy wavelength range															
Contrast as a function of working angle, stellar size, bandwidth Core throughput as a function of working angle, stellar size, bandwidth															
core throughput @ X I/D															
PSF sharpness															
FOV															
OWA > XX															
Single-coronagraph spectral bandwidth															
Theoretical max performance															A REAL PROPERTY.
Design performance (sensitivities)					C										
Design performance (sensitivities) Sensitivity to LO aberrations Sensitivity to static aberrations Sensitivity to segment misalignments	nnn	Ira	nh	nn	rt,	rm	200	0 00	n rc	101101	nno	20			
Sensitivity to static aberrations				UE						1115		7.7			
Sensitivity to segment misalignments		1. 0				~									
Alignment of instrument to telescope pupil															
Tolerate DM defects (dead actuators)?															
Sensitivity to DM parameters															
Tolerate unknown pupil distortion/magnification errors?															
Tolerate primary and secondary mirror reflectivity variations/errors Tolerate lateral mask alignment errors inside instrument															
Tolerate lateral mask alignment errors inside instrument Tolerate rotational mask alignment errors															
Sensitivity to amplitude aberrations															
Compatibility with telescope and other components															
Compatibility with segmented apertures															
Compatibility with on-axis apertures															
Is the design not easily compatible with critical instrument capabilities Ability to integrate LOWFS?															
Compatibility with WFS&C															
Compatibility with spectrograph															
Requires polarization splitting/filtering?															
Requires specialized optical train (e.g., pupil remapping)															
Potential for hybridizing and/or complementing with another technology			*1+1 /	+-		000	200		20til	oility,					
companie with polarimenty						SIM									
Lab demonstration / model validation	IVICI	LUI	ILY,	LU.	IU		NU L		JULIK	JIILY,					
Demonstrated raw contrast in testbed			,							J ,					
Model accuracy demonstrated on testbed															
Fidelity of model used to predict performance, including error budget and post-processing		20	N 18 -	2010					10 L! -						
Development and programmatic service anti-			Iral	nn	12		NUU	SIND		VIC					
Development and programmatic considerations Path to TRL 5			yiai					side	auc	110					
Development cost															
Development time Manufacturability															
Manufacturability flight instrument much larger or much smaller than average?															
Number of components and/or mechanisms in optical train much different from average?															
Supply-chain robustness															
Single-source fabrication? Does it fill a critical gap?															
Architecture applicable to other missions? (E.g. after HWO)															

Survey Matrix

	Primaril	ly focal-plane coronagraphs		Primarily pupil-plane coronagraphs	Hv	brid (pupil+focal) plane coronag	raphs	photonic chip / theoretical limits		Enhancing technol	ogies
	HLC LCPPC	EvWaCo MSPM	VVC	SPC PIAA	APLC	SPLC PAPLC	PIAA-Vortex	Hybrid photonic chiFull Photonic Chip Optimal Cor	imit D	DPLC RAP ILOWFC	fiber-nulling AAFFS
Yield of EECs budgeting for VIS detections only											
Yield of EECs budgeting for VIS detections, orbit determination, and H2O detection Yield of EECs budgeting for VIS detections, orbit, and CO2/CH4 detection at 1.65 microns											
Yield of diverse planet types											
Vield of EECs at glint phase angles VielScience yield metrics											
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Median exposure time per target during blind search Exposure time for fiducial star (Earth twin @ quadrature)											
Exposure time for characterization Contrast over xx to vy wavelength range											
Contrast as a function of working angle, stellar size, bandwidth											
Core throughput as a function of working angle, stellar size, bandwidth core throughput @ X I/D											
PSF sharpness WA											
FOV											
OWA > XX Single-coronagraph spectral bandwidth											
Theoretical max per Coronagraph											
Sensitivity to dynamic aberrations								Dhatania			
Sensitivity to segment misalignments Alignment of instrument of the second seco				Dupil				Photonic			
Tolerance to instrument component errors (including alignment) Tolerate DM defects (dead actuators)?		ot typo		Pupil		Hybrid		coronagrap	hc	Enhand	oina
Sensitivity to DM parameters Tolerate unknown pupil distortion/magnification errors?		ot-type		apodizatior	<u>ר</u>						
Tolerate primary and secondary mirror reflectivity variations/errors	corol	nagraphs				oronagra	nhe	(and theoret	ical	technolo	naipe
Tolerate lateral mask alignment errors inside instrument Tolerate rotational mask alignment errors	00101	lagraphs		coronagraph		oronagra	ipns			lecimol	Jyles
Sensitivity to amplitude aberrations				coronagrapi	13			limit)			
Compatibility with telescope and other components								initiation (
Compatibility with segmented apertures Compatibility with on-axis apertures											
Is the design not easily compatible with critical instrument capabilities Ability to integrate LOWES2											
Compatibility with WFS&C											
compatibility with spectrograph Compatibility with post-processing											
Requires polarization splitting/filtering? Requires specialized optical train (e.g., pupil remapping)											
Requires coepialized policial train (e.g., pupil remapping) Potential (March 1997) (March 1997) Compatible (March 1997)											
Lab demonstration Compatibility,											
Televance to instabilities domonstrated on testhed											
Adel accuracy deprogrammatic consumption of the solution of th											
Development cost Development time											
Manufacturability flight instrument much larger or much smaller than average?											
Number of components and/or mechanisms in optical train much different from average?											
Supply-chain robustness Single-source fabrication?											
Does it fill a critical gap?											
rchitecture applicable to other missions? (E.g. after HWO)											



Baseline Pupils







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Workflow



Coronagraph technologies / designs submitted to **Coronagraph Design Survey**

asic description

echnologies

SPLCs are a mature coronagraph type after years of

pectra on HWO with currently tested manufacturing

SPLC masks can all be made accurately today. JPL's MDL

tured black silicon apodizer fabrication as part of the

Roman CGI project. Occulters and Lyot stops are easy for

nce-they are most likely to provide exo-Earth

evelopment as part of Roman CGI.

SPLCs are robust, low risk, and moderate



magraph types could be used).

cal layout diagram or technical description

TRL 3: experimental implementation for high-order

Stability depends on DM technology drift speed fo

Effect of ghosts from internal reflections inside the

prism/phase-only apodizer is unknown at high

ont sensing (Por 2020, thesis)

TRI 2 mentode

Risks and next step

large strokes

Needs tests in vacuu

or in-band high-order wavefront sensing.

al layout diagram or technical description

masks. It's appdizer

and two DMs already part of the control system.

Its focal-plane mask and Lyot stop are simple binary

maists of a lun

where only modiling (for 2020) or 2044

· 2.0Ms (Por et al. in prep) NGA: 200 apodiar with

rayscale apodized demo: 4e-8 (Llop-Sayson et al. 2020)	vendors to make via e-beam lithography.	higher-throughput and higher contrast
As and next step: Next-Intel phase mark manufacturing is challenging and long last time. From the step of the step of the step of the step of phase step of the step of the step of the step of the phase step of the step of the step of the step of the phase step of the step of the step of the step of the phase step of the step of the step of the step of the phase step of the step of the step of the step of the phase step of the step of the step of the step of the phase step of the step of the step of the step of the phase step of the step of the step of the step of the phase step of the step of the step of the phase step of the step of the step of the phase step of the step of the step of the step of the phase step of the step of	Optical layout diagram on technical description Core press: colorem mask, facil shap. A field shap to field of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the offset a light with the FIFA and is, making them sense sensitive. Optical 1 (advatchered) results and shap of the shap of the same of a pre-shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the shap of the for semand and distribution.	model polarization induced by small No SPLC-related major risks or long Plan in awarded SAT is to reach TRL years with \$1.5M.
Iller coronagraph	Metasurface-based	d scalar phase mask
Neversh leques introdytation per en makerly and TS. The second se	Raise description 5 solar versions consequents are publications investible (compared to vertex vertex consequently) lost solar time consentible) Microarcian calues planar main directions (Microarcian ta for Microarcian calues planar main directions) (NC) plane main solar ban consensation solar consequences) (NC) plane main solar solar ban constraints in exemandum, and are in plan bandwaldth (Neuril 4), 2023) 2023	Control of mathematical and TRL Control of mathematical and the Calcols A UCS and and Calcols A UCS and and Calcols A UCS and and Control Torus Despring activity and Despring activity and Despring activity and the anti- section of th
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g wavefront sensing, spectroscopy, and polarimetry	Optimal n-th order corona	graphs (theoretical
net maturity and TBL under particle and TRL to Desting VVC concepts introduced of validated (TRL 4) in Destinant at L2020 conceptual behavior to moperasion in 15° over 450-800 nm. narrent monochromatic contrast of trgVVCB prototype in "5=-8 StoOM/vicina and UK/IPL. spail of crystal technology already widely applied for south beside (TCL - 30 <u>Destinant at al</u> 2020) Destinant at all concepts of the technology and the technology approx/phys/Meta P detection.	Easis: description Submaning the an endowed additional and the second second back submaning the page and and the second spream setting as a second sec	Current maturity and TRL • TRL is not applicable because this is ar concept • Certain coronagraph designs aim tor e- including high-throughput bild-optic chip based designs. Please refer to qui designs for TRL
is and next steps Most likely (SA tech development and space qualification program (65064) Sep 2023- Sep 2025. Optimizing liquid-crystal recipes, improvement of writing quality, fully controlling optic integration. High-contrast imaging tests at THO2 in Paris.		Risks and next steps There are two ways of achieving the continued development of high-perf coronagraphs, and photonic chips. Bulk optic coronagraphs have high or mature in time for HWO, but high high

Shaped Pupil Lyot Coronagraphs (SPLCs)

Current maturity and TRL of black silicon apodizers TRL 5 at 4e-9 contrast in 10% BW in a stational station in the station of the stati ent (Cady et al. 2017 SPIE 104000E, Marx et al. 2018 SPIE 106981E) TRL 6 at 9e-9 contrast in 10% BW in a dynamic flight-like nt (Cady et al. 2017 SPIE 104000E TRL 3 (possibly 4) at 1e-10 contrast The best to-date lab results of SPLCs were mainly limited by the Roman Space Telescope's large pup obscurations; less-obscured apertures will enable higher-throughout and higher contrast designs. al 22-SAT22-0010 t

e context of HWO. rate < 4e-10 contrast t error budget each component, and all mask features. 5 for HWO in 3

Contraction of

an abstract theoretic

reach theoretical lim

designs and photor

uad charts for those

oretical limit

ents) needed ring tests, design acturing constraint h 1e-10, e.g. two

l limit)

Dotical

rformance bulk-opti ence of being mature in time for HWO, but high risk of not reaching

Integrated Dynamic Low-Order Wavefront Control

ument maturity and TR

A single integrated element located at an instrument pupil Estimated TRL of components: 3 Development based on a selected 2022 SAT: "A low-order hardware implementation for sensing oftee parallel deformable mirror for correction of low order Terrolas terms 24-211 Bocus, antigmatism, coma, ...) and control is excelanet imaging" Has not been demonstrated in the laboratory inticipates closing the sensing and control loop with abilians the dynamic elements of the wavefront with



provide dynamic low-order wavefront stabiliz

nounting for jitter cantrol (22, 23)

ninimal disturbance to high-order wavefront stability

uidance from a familie acadhort senare

cal layout diagram or technical des

is described as

Rasic description

asic description

Characterize known plane

creating a small dark hole

amplitude or phase apodi

igh throughput (>80%)

Higher tolerance to WFE ti

al. 2017). Molecular maps

phase with piston actuato

0.1 lambda/D accuracy

arlotti et al. 2022)

relies on MEMS (an

node fiber fee

ptical layout diagram or technical description

mall strokes are enough (0.5-1micron)

One phase or amplitude MEMS in a pupil plane

is description

roviding comple

umail localized dark sone).

onagraphs (to see with CDS)

inited by the segment diffraction

pment density mirrors (3 to 5 across pupil diameter

be used for detection (large OWA) or characterization

Ud. d being the segment diameter) -> sptimal for low

cal learned diagram or technical description

spodicer set up in the entrance pupil plane, can b

combined with an APLC or other focal plane mask

Risks and next steps Fabrication of surface parallel deformable min-

part of a 2022 SAT (Pt. J. Trauger). propping through the applicable to all coronagraph type For simplicity and model fidelity, the element will be coronagraph

Hybrid Lyot Coronagraph

Current maturity and TRL

yot coronagraph with a hybrid focal plane mask (FPM) FPMs have been manufa FPM comprises metal and dielectric thin film patterns on a a variety of specialized and commercial techniques glass substrate, to provide leverage over both amplitude HLC designs have been demonstrated extensively d phase in the transmitted optical wavefrom the vacuum coronagraph testbeds at JPL (HCIT, DST) HLC elements are inherently rad-hard. ernike phase dimple can be incorporated into the design for sensing of low order wavefront errors (LOWFS) HLC is one of two coronagraph types built into the nagraph Instrument (CGI) on the Nancy Grace one or more deformable mirrors are used shape the high ontrast dark field over an extended spectral bandwid oman Space Observatory. Relative simplicity enables accurate performance modeling. Estimated TRL of components: 6

Risks and next step

tical layout diagram or technical description Design and manufacturing refinements and laborato tions are ongoing in the context of select NASA/SAT proposals. For simplicity and model fidelity, the HLC layout provides a relatively uncomplicated venue for laboratory performance validations of new wave control technologies.

Adaptive apodization for fiber-fed spectroscopy

ts at R°1E3-1E5 by injecting them	Current maturity and TBL
ing a compact spectrograph after	TBL 3 (maybe 47): Annylinde control demonstra
at the planet location w/ pure	in the lab (off-the-shelf MEMS from TI).
zation (no focal plane mask)	Monochromatic because of old design choices
t 1-2 lambda/D	(Carlott et al. 2018, Leboulieux et al. 2022):
hanks to modal filtering (Wang et	New broadband devices: TT and picton arrays for
ing can further improve that,	Fraunholer institute (Gehner et al., 2020), Piston
plitude with TT actuators, or	array from TI (Berritet et al., 2021).
n; 200x000 acc), J or many masks	Numerical optimization processes are well-know.

Risks and next steps

MEMS are long-lead (2yr), risky, expensive (\$100K for baseline, \$1M for new design). Fraunhofer Institute is High-density piston array can be used as regular DM if open to collaborations. Milestones to TRLS: Validation of new generation MEMS in the lab er injection unit in focal plane a-la KPIC, incl. fiber (2025-2026) + demonstration as adaptive undle, tracking camera, fine guidance TT mirror (require apodizers (w/ fiber injection) r-fed spectrograph (such as PARVI, AWG, VIPA; SNR estimates w/ FastCurves analytical model of molecular mapping post-processing efficiency

Photonic chip with 20 seguential MZIs at TRL2 (~1e-3 matic: Taballione et al. 2022 onagraph can achiev Integration of PIAACMC + PIC at TRL1 (Por et al. in egrated photonic chips (Por et al. in prep.).

lisks and next steps Initial production and testing of a sub-scale version of the photonic coronagraph (funded, to be performed early Il realistic design (funded, to be completed late 2023) This is largely unexplored design space, so many unknow

The nulling performance characteristics of PICs, including spectral bandwidth remain to be modelled and may not each required performance with expected manufacturing

urrent maturity and TRI

Risks and next steps

Shaped Pupil Coronagraph (SPC) asic description

We to have a single non-structure (process a structure) must no support per to the single non-structure (process and process and process per per per per per per per per per per	the critical component, the shaped pupil mask itself.
Inyout diagram	Risks and next steps
Pupit Field Stop	• Work is planned to further mature SPLCs for HWO
Pupit Field Stop	SPLC quad chart)
Provid Example for Open	• Ideally, shaped pupils without a Lyot stop could be
Convert America with	tested in users officer.

top cal Example for Open Circular Aperture with 10 ¹⁰ contrast and 22% Ary throughput.	Biaks and next steps • Work is planned to further mature SPLCs for HWO (s SPLC quad chard) • Ideals, shaped pupils without a Lyot stop could be tested in asme effort. • There are no major rinks for SPCs. • Main disadvantages are challenge of aligning with an obscured or segmented pupil and typically low throughput and large lines.
	 Main disadvantages are challenge of aligning with a obscured or segmented pupil and typically low

Current maturity and TRL

· Maturity is the same as that for SPLCs as they share

Redundant Apodized Pupil L. Laboulleux, A. Carlotti, M. N'Diage - Jucie leboulleus@univ.gov **Current maturity and TRL** entary appollution for other 196, 3 (4-5 in September 2023): Design process of apodication patterns well understoo coronagraphs (ex: APLC, apodized vortex) to mitigate trigant of coghasing errors (Leboudieus et al. 2022). Design 10s more robust to segment level errors (static or dynamic) than classical designs. buil somes solution w/ robustness guaranteed down to a

Concept validated through numerical simulations with obustness up to 1 radian rms (Laboulleux et al. 2022). Experimental validation on the CIDRE testbed (no AD loop) for amplitude errors in January 2023 Journeyt C*52 6 at 6 lambda/01 Validation on Subanu/SCEwAD: use below

Kisks and next steps

other 2023 Validation on Scheru-SCEak (internal source and on sky with observations) for petalwel phasing errors flow-wind effect). By 2025: Getting a design as a first step to an APLC or





Workflow



Performance / robustness pipeline products

(Working group lead: Emiel Por)



APLC



Workflow





Science Yield working group (led by Chris Stark)

Draft evaluation criteria

Science
Yield of EECs budgeting for VIS detections only
Yield of EECs budgeting for VIS detections, orbit determination, and H2O detection
Yield of EECs budgeting for VIS detections, orbit, H2O, and CO2/CH4 detection at 1.65 microns
Yield of diverse planet types
Design performance (contrast and efficiency)
Median exposure time per target during blind search
Exposure time for fiducial star (Earth twin @ quadrature)
Exposure time for characterization

Examples of products





Howe et al. (submitted)

Draft fiducial mission parameters

	Table 2. Co	ronagraph-based Mission Parameters				
Parameter	Value	Description				
		General Parameters				
Σau	2 yrs	Total exoplanet science time of the mission				
$ au_{ m slew}$	1 hr	Static overhead for slew and settling time				
$ au_{ m WFC}$	$2.7 \ \mathrm{hrs^a}$	Static overhead to dig dark hole				
$ au_{ m WFC}^{\prime}$	1.1	Multiplicative overhead to touch up dark hole				
X	0.7	Photometric aperture radius in $\lambda/D_{\rm LS}^{\rm b}$				
Ω	$\pi (X\lambda/D_{ m LS})^2$ radians	Solid angle subtended by photometric aperture ^b				
ζ_{floor}	10-10	Raw contrast floor				
$\Delta mag_{\rm floor}$	26.5	Noise floor (faintest detectable point source at S/N _d)				
$T_{ m contam}$	0.95	Effective throughput due to contamination				
		Detection Parameters				
$\lambda_{ m d,1}$	$0.45~\mu\mathrm{m^c}$	Central wavelength for detection in SW coronagraph				
$\lambda_{ m d,2}$	$0.55 \ \mu \mathrm{m^c}$	Central wavelength for detection in LW coronagraph				
S/N_d	7	S/N required for detection (summed over both coronagraphs)				
$T_{\rm optical,1}$	0.16°	End-to-end reflectivity/transmissivity at $\lambda_{d,1}$				
$T_{\rm optical,2}$	0.33°	End-to-end reflectivity/transmissivity at $\lambda_{d,2}$				
$ au_{ m d,limit}$	2 mos	Detection time limit including overheads				
	Characterization Parameters					
$\lambda_{ m c}$	$1.0~\mu\mathrm{m^c}$	Wavelength for characterization in LW coronagraph IFS				
S/N _c	5^{c}	Signal to noise per spectral bin evaluated in continuum				
R	140	Spectral resolving power				
$T_{ m optical, IFS}$	0.23°	End-to-end reflectivity/transmissivity at $\lambda_{ m c}$				
$ au_{ m c,limit}$	2 mos	Characterization time limit including overheads				
		Detector Parameters				
$n_{ m pix,d}$	$4^{\rm c}$	# of pixels in photometric aperture of each imager at $\lambda_{ m d,\#}$				
$n_{ m pix,c}$	96°	# of pixels per spectral bin in LW coronagraph IFS at $\lambda_{\rm c}$				
ξ	$3 \times 10^{-5} e^{-} \operatorname{pix}^{-1} \mathrm{s}^{-1}$					
RN	$0 e^{-} \operatorname{pix}^{-1} \operatorname{read}^{-1}$	Read noise				
$ au_{\mathrm{read}}$	N/A	Time between reads				
CIC	$1.3 \times 10^{-3} e^{-} \text{pix}^{-1}$ frame					
$T_{ m QE}$	0.9	Raw QE of the detector at all wavelengths				
$T_{\rm read}$	0.75	Effective throughput due to bad pixel/cosmic ray mitigation				

^aSee Eq. 17 from Ref. ?

 $^{\rm b}D_{\rm LS}$ is the diameter of Lyot stop projected onto the primary mirror

^cExample provided at most likely bandpass; AYO optimizes bandpass and adjusts values accordingly.



Workflow





Maturity / Compatibility / Programmatic

(led by Bertrand Mennesson)

Compatibility with telescope and other components	
Compatibility with segmented apertures	
Compatibility with on-axis apertures	Contrast over 10% Bandwidth in Vacuum
Is the design not easily compatible with critical instrument capabilities	$10^{-7} = 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1$
Ability to integrate LOWFS?	
Compatibility with WFS&C	PIAACMC on-axis segmented
Compatibility with spectrograph	- PIAA monolith
Compatibility with post-processing	
Requires polarization splitting/filtering?	$> 10^{-8}$
Requires specialized optical train (e.g., pupil remapping)	$[] 10^{-8} = VVC4 \text{ off-axis}$
Potential for hybridizing and/or complementing with another technology	E monolith 1DM
Compatible with polarimetry	10 ⁻⁸ VVC4 off-axis monolith 1DM VVC4 off-axis
	E VVC4 off-axis
Lab demonstration / model validation	
Demonstrated raw contrast in testbed	
Tolerance to instabilities demonstrated on testbed	
Model accuracy demonstrated on testbed	
Fidelity of model used to predict performance, including error budget and post-processing	10^{-9} $CLC \text{ off-axis monolith 2DMs}$
Development and programmatic considerations	
Path to TRL 5	E 3
Development cost	
Development time	
Manufacturability	
flight instrument much larger or much smaller than average?	10^{-11}
Number of components and/or mechanisms in optical train much different from average?	0 2 4 6 8 10 12
Supply-chain robustness	Angular Separation $[\lambda/D]$
Single-source fabrication?	
Does it fill a critical gap?	
Architecture applicable to other missions? (E.g. after HWO)	



Conclusions / Preliminary Findings

- CDS is surveying viable coronagraph designs to facilitate future trade studies for HWO
 - Results will be summarized by a KT-like matrix, and detailed in a written report
 - Automated pipeline will also be made available
 - CDS is NOT doing any down-selects
- Coronagraph designs have improved since LUVOIR/HabEx reports, and can provide a strong lever to improve HWO performance, reduce risk and cost:
 - Improve yield by 2-4x
 - Relax telescope requirements, such as stability
 - Enable a potentially lower-cost on-axis aperture without sacrificing performance
 - Can leverage future advances in technology driven by large industrial markets (such as photonic chips)
- There is a rich trade space of coronagraphs to explore
 - Demonstrating 1e-10 is important, but other metrics (such as robustness, bandwidth, IWA, throughput) are better levers for improving yield, once we are below ~5e-10.
 - This trade space is coupled with telescope and DMs



