# Astro2020 APC Whitepaper

# Status of Space-based Segmented-Aperture Coronagraphs for Characterizing Exo-Earths Around Sun-Like Stars

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# 1. Executive Summary

A decade ago, a space-based coronagraph capable of detecting terrestrial planets in the habitable zone behind a segmented/obscured telescope was not known to be possible. *Thanks to investments in modeling and laboratory demonstrations there are now viable designs, estimates of scientific return, and better understood key challenges that are enabling future exoplanet space observatories to credibly include a baseline science coronagraph instrument capable of characterizing Earth-like planets in the habitable zone around Sun-like stars. This was exactly the intention of the 2010 Astronomy and Astrophysics Decadal Survey when they made exoplanet technology development their highest medium-scale recommendation.* In this whitepaper, we aim to inform Astro2020 of the status of coronagraph technology for use with a space-based segmented and/or partially obscured primary mirror. A NASA/Exoplanet Exploration Program (ExEP)-commissioned study is investigating whether there are coronagraph architectures that can meet the demanding contrast, inner working angle, and throughput goals necessary to directly image these Earth-size planets, and what are the key stability requirements they would place on the observatory. This design and modeling study has determined that multiple coronagraph architectures can indeed achieve the necessary performance and some preliminary observatory requirements appear challenging but achievable. A key fundamental challenge is designing the coronagraphs to minimize starlight leakage in the presence of the unresolved, but finite (e.g., 1 milli-arcsecond diameter), stellar disk. This is a challenge that is exacerbated by the segmentation of the aperture and especially the presence of a central obscuration. Key technical challenges for the observatory flying the coronagraph are the required pointing stability (~ 1 mas) and segment jitter (~10 picometers). While modeling shows that these designs are feasible, laboratory demonstrations have not yet begun to fully realize model predictions thus far for even unobscured apertures. In this whitepaper, we also describe the available software modeling tools and the steps taken towards demonstrating the necessary performance in the lab (see also Mazoyer et al. APC whitepaper). Based on studies of theoretical limits of coronagraphs, continued support of coronagraph design may to lead to even more improvements, potentially increasing science yield or reducing telescope size by a factor of ~2 or more.

# 2. Key Science Goals and Objectives

Achieving the capability to directly image and spectrally characterize terrestrial exoplanets in the habitable zones of Sun-like (type F/G/K) stars is a key step in searching for life in the Universe (Arney et al. 2019), and was the intention of the 2010 Astronomy and Astrophysics Decadal Survey when they made exoplanet technology development their highest medium-scale recommendation. Surveying habitable zones of Sun-like stars in a greater volume of space and detecting planets as dim as magnitude 30 through diffuse exo-zodiacal dust drives one to use telescopes with large (≥ 4-m diameter) primary mirrors (Stark et al. whitepaper) and these are likely to be segmented-mirror apertures due to the limited scalability of monoliths. Larger telescopes also enable measurements at longer wavelengths as $\lambda/D$ increases; many important biosignatures like methane, carbon dioxide, and water can be seen longward of 1 μm.

The brightness ratio of an Earth- like planet to a Sun-like star seen in reflected visible and near-infrared light is of order $10^{-10}$, requiring unprecedented starlight suppression. One path to achieving the necessary starlight suppression is a high-contrast coronagraph instrument with active wavefront control (Pueyo et al whitepaper). The term “contrast” refers to the fraction of starlight that appears in the image plane. Modern high-contrast coronagraphs designed for exoplanet imaging in the presence of a bright star incorporate masks or mirrors in pupil and image planes that block starlight, direct diffracted light to where it can be removed, and reduce residual scattered starlight by adjusting the amplitude and phase of the incoming starlight. Adaptive optics, with feedback to fast steering mirrors and deformable mirrors, improve contrast and contrast stability by correcting static and slowly varying dynamic wavefront errors.

While ground-based coronagraphy is an important technical and scientific proving ground (Currie et al 2019), the contrast achievable from the ground in the visible band is expected to be limited to ~$10^{-8}$, several orders of magnitude away from levels needed to detect exo-Earths around Sun-like stars (Stapelfeldt 2006), requiring the use of a space observatory.

Some future space observatories with segmented primary mirrors may also be configured with a centrally obscured entrance pupil due to an on-axis secondary mirror, like the large mission concepts Large UV/Optical/IR Surveyor (LUVOIR) and Origins. This type of entrance pupil impacts the bandwidth, throughput, contrast, and aberration sensitivity of the coronagraph. The wavefront error from the telescope must be stable to unprecedented levels; the requirements are a function of temporal and spatial frequency, but are typically less than 1 nanometer RMS (see. Shaklan et al, 2005).

Developing a coronagraph and space observatory capable of detecting Earth-like exoplanets requires technology development in many areas, a path that is already well underway. The 2010 Astronomy and Astrophysics Decadal Survey *New Words, New Horizons*, and NASA's response in the series of Astrophysics Implementation Plans, highly prioritized the development of technology for a space mission that achieves this capability, a task managed by NASA's ExEP. The Exoplanet Science Strategy (NAS 2018) reaffirmed the scientific importance of developing coronagraph technology for a future exoplanet direct-imaging mission.

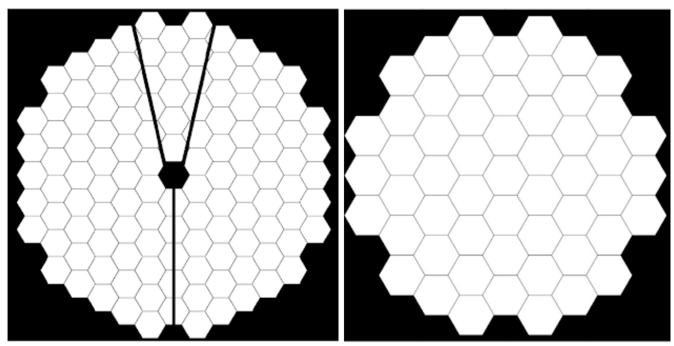

Figure 1. LUVOIR-A 15 m pupil (left) and LUVOIR-B 9 m pupil (right).

To address the challenges specific to a coronagraph with a segmented primary mirror on a space telescope, the ExEP commissioned a Segmented Coronagraph Design and Analysis (SCDA) study in 2016 to answer the question of whether any coronagraph could achieve the necessary performance and robustness given a segmented, partially obscured, feasibly stable pupil. The study investigated multiple types of segmented telescope pupils, with both on- and off-axis secondary mirrors. As a representative pupil for future exoplanet coronagraph missions, the study focused on LUVOIR's A (15m primary mirror with on-axis secondary) and B (8m primary mirror, off-axis secondary) architectures (Fig 1). They represent the currently best-studied coronagraph-compatible space observatory designs that include a segmented primary mirror. Results from the SCDA study can be applied to any type of future segmented space telescope. The Study has also been keenly interested in the requirements the coronagraphs would levy on the observatory in terms of optical alignment, segment phasing, and stability, and to assess their feasibility.

# 3. Technical Overview

## 3.1. Coronagraph Architectures

Coronagraphs use combinations of binary and/or complex amplitude masks in the pupil and image planes to shape and remove starlight. A generic layout is shown in Fig. 2. All designs utilize a pair of deformable mirrors (DMs) to control scattered light and assist with pupil apodization. The use of DMs not only for wavefront compensation but also as an integral part of pupil apodization has played a key role in the success of new designs (Pueyo et al whitepaper). A key result is that *coronagraph designs can tolerate segmentation with gaps up to ~0.1% of the pupil diameter* (Ruane 2018b). However, in an on-axis system, even a relatively small central obscuration and the necessary secondary mirror support struts significantly impact coronagraph performance.

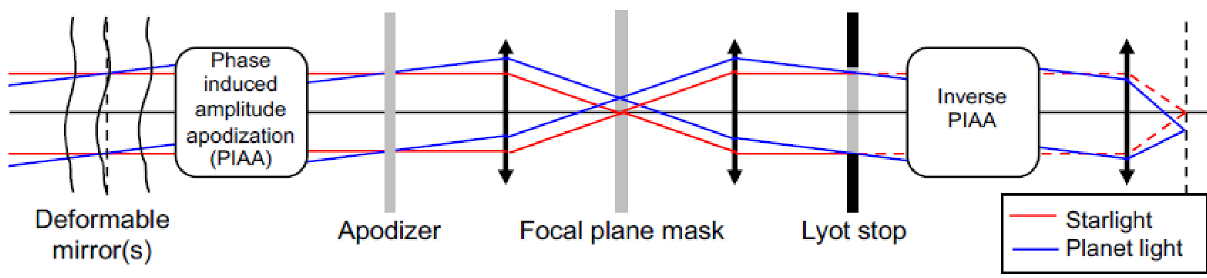


Figure 2. General coronagraph layout (adapted from Ruane et al, 2018). The schematic shows a coronagraph with one or more deformable mirrors, optics for phase induced amplitude apodization (PIAA), a pupil-plane apodizer mask, an image plane mask, a Lyot stop, and inverse PIAA optics. Modern coronagraph designs employ various combinations of these planes.

Below, we briefly describe the main coronagraph architectures under study for segmented apertures. See Ruane et al (2018) for a review of coronagraph architectures, components, and design and analysis software.

### 3.1.1 Apodized Pupil Lyot Coronagraph (APLC)

The APLC is the baseline coronagraph for LUVOIR-A (Dressing whitepaper). It combines binary masks in the pupil plane, focal plane, and Lyot plane to achieve high levels of suppression while remaining relatively insensitive to starlight leakage and pointing errors as will be shown in Section 3.2. A major function of the combination of pupil apodizer and Lyot stop is to reduce sensitivity to the central obscuration. Figure 3 shows an APLC design for the LUVOIR-A aperture.

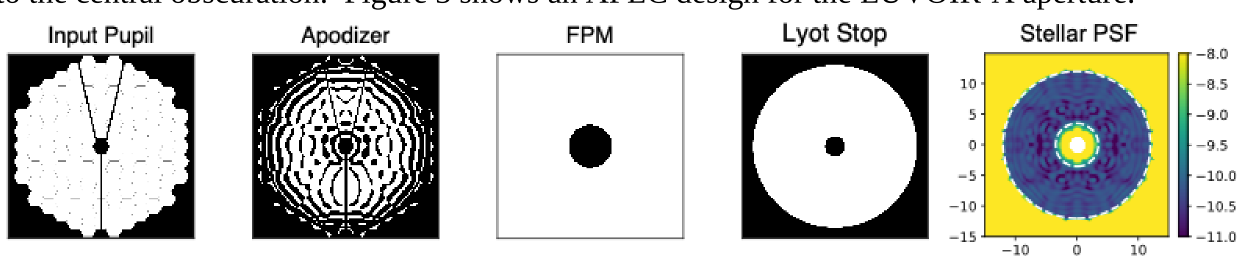


Figure 3. APLC. The combination of apodizer, focal plane mask, and Lyot stop provides a 10% bandpass with better than $10^{-10}$ contrast.

### 3.1.2. Vortex Coronagraph (VC)

The VC is the baseline design for LUVOIR-B and HabEx (Gaudi et al whitepaper). It uses a phase- or polarization-based focal plane mask to imprint a screw dislocation on the incoming PSF, creating an on-axis dark hole that grows to fill the pupil completely so that a simple diaphragm (the Lyot stop) blocks the light rejected outside the geometric pupil area. The VC is in operation at major ground-based facilities (Palomar, VLT, Subaru, LBT, and Keck). The VC has high throughput and is robust to low-order aberrations, but has not been shown to reach the contrast goals of future space telescopes with centrally obscured apertures.

### 3.1.3. Phase-Induced Amplitude-Apodized Coronagraph (PIAA)

The PIAA technique is a full-efficiency alternative to conventional apodization, and relies on beam shaping using aspheric optics (mirrors or lenses) instead of selective absorption/binary masking. The lossless apodization preserves the angular resolution and sensitivity of the full telescope aperture. Recent SCDA evaluation of recent jitter-robust PIAA designs has shown that they are compatible with centrally obscured apertures while maintaining high throughput.

### 3.1.4. Hybrid Lyot Coronagraph (HLC)

The HLC is a modification of the classical Lyot coronagraph that consists of an occulting mask located at an intermediate focal plane followed by a Lyot stop at a subsequent pupil plane. In the HLC the focal plane mask is a combination of a patterned amplitude modulator (usually a metal coating such as nickel) with an overlaid phase modulator (a patterned dielectric coating). While baselined for WFIRST, the HLC designs have not been shown to meet the goals of centrally future space-based centrally obscured apertures.

### 3.1.5. Visible Nuller Coronagraph (VNC)

The visible nulling coronagraph uses shearing interferometry to form an on-axis null while providing off-axis sensitivity. Originally proposed as a two-stage, lateral shearing nuller (Shao et al, 2004), it is well suited for a regularly segmented aperture. A modification to this approach (Lyon 2015), known as the Phase Occulted - Visible Nulling Coronagraph (PO-VNC) in theory allows nulling with only a single interferometer by shaping optics in each arm to provide the desired interference pattern. The VNC has also been coupled to a segmented aperture in the laboratory (Hicks et al, 2018), but it has experienced challenges in recent testbed demonstrations and has been unable to replicate past performance.

## 3.2. Robustness

To assess design feasibility and inform the engineering requirements of a future segmented aperture coronagraph instrument and observatory, we track the robustness of the coronagraph to various sources of performance degradation including wavefront errors (global low-order errors, segment errors, vibrations, and drifts), line-of-sight pointing jitter, and resolved stars. Here we show examples of our evaluations, for an APLC designed for the LUVOIR-A concept, a VC designed for the LUVOIR-B concept, and a PIAA design for LUVOIR-A.

### 3.2.1. Robustness to stellar diameter

Coronagraphs work best with stars that resemble point sources. As telescopes get larger, the stellar disk remains unresolved but nonetheless introduces leakage of starlight around the focal plane mask. This is the most fundamental issue for coronagraphs – stellar diameter is not something we can control! But we have learned how to optimize designs to minimize the stellar leakage. The SCDA study simulated the performance of several mask designs across a range of stellar diameters by incoherently summing up the PSF for a grid of plane waves approximating a resolved stellar disk. In Fig. 4 we plot the resulting radial contrast profiles of three designs: an APLC and PIAA for LUVOIR-A and a VC for LUVOIR-B. Because the LUVOIR-A and LUVOIR-B mission concepts have different primary mirror sizes (15 and 8 m, respectively), the VC model telescope pupil was scaled up to 15 m, so that the performance of the coronagraphs can be meaningfully compared for a given angular star diameter. The degradation in the dark zone caused by the resolved star is generally confined to the inner region of the coronagraph image. The VC is inherently more sensitive than the APLC to this effect due to its higher transmission at small angles interior to the IWA. We continue to make progress in reducing sensitivity to stellar diameter.

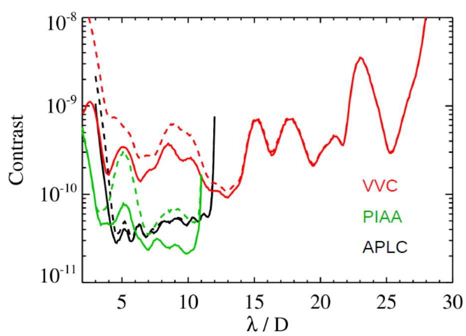


Figure 4. Sensitivity of contrast to stellar diameter (x-axis). Solid curves are for a point source. Dashed curves are for a 1 mas diameter star, typical for a exo-Earth survey.

### 3.2.2. Robustness to low-order wavefront error stability

The low-order wavefront – generally considered to be focus, astigmatism, coma, trefoil, and spherical aberration – arise when thermal gradients move through the optical system. They are expected to be the largest contributors to starlight leakage, and they concentrate their light around the IWA where most exo-Earth observations will be made. Optimization for low-order robustness is one area where both the APLC and VC design families have improved significantly over the course of the SCDA study. For most low-order errors, the degradation for an individual mode injected at 100 pm RMS is below $10^{-10}$ in contrast units. Spherical aberration remains the most sensitive mode for the APLC and PIAA, resulting in ~$10^{-9}$ contrast at 4 $\lambda$/D, while the LUVOIR-B VC design (with a charge-6 mask) is most sensitive to trefoil aberrations ($10^{-8}$ at 4 $\lambda$/D, but < $10^{-10}$ for all other aberrations. The trefoil sensitivity, and indeed sensitivity to other low-order aberrations, can be greatly relaxed at the expense of larger IWA and lower throughput, by moving to an $8^{th}$-order VC. While the designs appear to be adequately robust to aberrations, we continue to make significant progress in reducing aberration sensitivity to further relax telescope requirements.

### 3.2.3. Robustness to segment phasing stability

Primary mirror segment phasing errors are expected to play a critical role in the coronagraph performance. Previous studies (Nemati et al., 2017, Juanola-Parramon et al., 2019) show that segmented telescopes equipped with internal coronagraphs are more sensitive to segment-to-segment piston and tip/tilt errors than to any global Zernike aberrations. For piston errors, in order to remain below the $10^{-10}$ raw contrast target, the wavefront RMS should not exceed ~30 pm and tip/tilt errors should not exceed ~60 pm for the LUVOIR-A APLC design. The combined impact of piston and tip/tilt errors is shown in Figure 5.

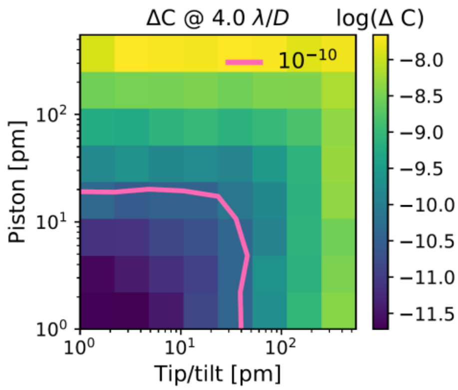


Figure 5. Combination of piston and tip-tilt evaluated for LUVOIR-A APLC in an annulus centered at 4 λ/D from the star. Contrast is better than $10^{-10}$ to the left and below of the curve.

While maintaining segment positions within 10s of picometers is beyond the current state of the art and will be difficult to achieve, preliminary studies show it is feasible. Piezoelectric rigid body actuators with 5 pm resolution are commercially available and have been validated in a laboratory environment (Saif, et al. 2019). Edge sensors and laser metrology systems can be used to measure segment motions with picometer precision, providing a closed loop control system to maintain segment alignment stability. A system level demonstration has not yet been conducted to the required levels of performance. This will be critical

We emphasize that these requirements are applied to the stability, and not the absolute accuracy, of the wavefront. The required accuracy is consistent with diffraction-limited performance, typically requiring tens of nm cophasing and low-order shaping of the wavefront.

Kasdin et al (Kasdin whitepaper) report on a wavefront sensing technique based on DM dithering that may allow a significant relaxation of wavefront drift requirements.

## 3.3. Custom Software Tools for Design and Modeling

The advances in coronagraph design are in large part due to advances in the efficiency and scale of modeling and design software. These advances allow for the rapid study and optimization of designs across multiple key parameters: IWA, bandwidth, throughput, contrast, and jitter and higher-order aberration sensitivity.

### 3.3.1. Coronagraph Modeling Software

The coronagraph community primarily uses two open-source software libraries, PROPER[1] (Krist 2007) and Physical Optics Propagation in Python (POPPY[2]) (Perrin et al. 2012), for Fourier optics modeling at high-contrast. PROPER is available in Python (2 and 3), MATLAB, and IDL; POPPY is written in Python 3. Both PROPER and POPPY provide functions to model Fresnel diffraction, generate apertures, make deformable mirror surfaces, and generate several types of wavefront aberrations.

Neither PROPER nor POPPY implements ray tracing or vector diffraction. However, ray tracing is performed with commercial packages such as Zemax or CODE V. Polarization effects are modeled sufficiently accurately for coronagraphy by using commercial software to compute the polarization states at the entrance to a coronagraph instrument. Each of those states is then Fourier-propagated separately through the coronagraph, and any major change in polarization state (such as from polarizers or liquid-crystal devices) is calculated on a per-optic basis.

[1] https://sourceforge.net/projects/proper-library/
[2] https://poppy-optics.readthedocs.io/en/stable/index.html

In the last two years, two open-source software toolboxes have been released on Github for the end-to-end modeling and design of several common coronagraph types. The Fast Linearized Coronagraph Optimizer (FALCO[3]) (Riggs et al. 2018) is written in MATLAB with a Python 3 version in development, and High Contrast Imaging for Python (HCIPy[4]) (Por et al. 2018) is written in Python. Both FALCO and HCIPy contain their own libraries. FALCO also makes extensive use of the PROPER library and is set up to use end-to-end optical prescriptions written with PROPER in wavefront correction simulations. Distinctive features of HCIPy are the modeling of atmospheric turbulence and wavefront sensing and control (WFSC) for ground-based optical systems. FALCO focuses WFSC for space-based optical systems; it is being used for some of the coronagraph design and modeling work for the WFIRST Coronagraph Instrument and for LUVOIR. Distinctive features of FALCO are its ability to optimize Hybrid Lyot Coronagraphs and its rapid calculation of the linearized response matrix for deformable mirrors, which would otherwise dominate the time needed for any WFSC simulation.

### 3.3.2. Coronagraph Design Software

At the time of the last Decadal Survey, no coronagraph design methods existed to utilize obscured telescope apertures. Since then, several groups have developed methods and software to overcome pupil obscurations. The APLC (N'Diaye et al. 2016) and Shaped Pupil Lyot Coronagraph (SPLC, Zimmerman et al. 2016) teams use commercial software, the AMPL language and Gurobi solver, to optimize pupil apodization masks. Several coronagraph design groups (Trauger et al. 2016, Ruane et al. 2018, Mazoyer et al. 2018) use FALCO or other custom software to optimize deformable mirror shapes that mitigate diffraction from segment gaps or secondary mirror support struts. A general-purpose coronagraph design tool called CSIM[5] is under development at NASA ARC. An early version is available on github and was used to design the PIAACMC coronagraph for LUVOIR-A which will commence HCIT-2 testing this summer.

## 3.4. Connections to Experimental Results

There has been substantial progress validating models with ground-based demonstrations and in manufacturing suitable apodizers.

Early designs of the APLC were adopted on several ground-based facilities (Palomar/P1640, Gemini Planet Imager (GPI), and VLT/SPHERE) and for the future E-ELT (Martinez et al. 2007, Soummer et al. 2009). Similarly, vortex coronagraphs are widely used for infrared high-contrast imaging (wavelengths ranging from 1-12 μm) with ground-based adaptive optics instruments, including Palomar/PHARO/SDC, Subaru/SCExAO, Keck/NIRC2, VLT/NACO, and VLT/VISIR (NEAR experiment). While ground-based telescopes have provided crucial experience in the implementation and operation of coronagraph instruments, space-based telescopes will require similar coronagraph architectures operating at shorter wavelengths, potentially ranging from the UV to near-infrared, as well as several orders of magnitude improvement in the contrast performance.

Several testbeds have been built to enable laboratory demonstrations of SCDA designs (Mazoyer et al APC whitepaper). These testbeds include the High Contrast Spectroscopy Testbed for Segmented Telescopes (HCST) at Caltech, the High-contrast Imager for Complex Aperture

[3] https://github.com/ajeldorado/falco-matlab
[4] https://github.com/ehpor/hcipy
[5] https://github.com/stevepur/csim

Telescopes (HiCAT) experiment at the Space Telescope Science Institute (STScI), The High Contrast Imaging Lab (HCIL) at Princeton, a PIAA testbed for in-air demonstrations at NASA/ARC, and the ExEP Decadal Survey Testbed (DST) at the Jet Propulsion Laboratory. Teams at each institution are working toward laboratory demonstrations of coronagraphs for segmented apertures.

The Caltech HCST is focused on the development of apodized vortex coronagraphs and high-contrast spectroscopy. The HCST has achieved contrasts better than $10^{-7}$ in the visible with 10% bandwidth ($10^{-8}$ monochromatic). Work is underway to reach similar contrast levels including the obscurations from segment gaps.

The HiCAT testbed at STScI is focused on the development of APLCs for on-axis, segmented telescopes. Contrast levels below $10^{-7}$ have been achieved, with $10^{-8}$ as the goal performance (Soummer et al, 2019).

Princeton's HCIL is equipped with a shaped pupil coronagraph for starlight suppression and a pair of continuous surface DMs for wavefront control. It is currently able to reach a mean contrast of around 2 x $10^{-7}$. The specific focus of this testbed is to prototype the space-based wavefront sensing and control (WFSC) software for future space coronagraph missions.

The in-air, thermally stabilized PIAA testbed at NASA Ames Research Center (ARC) has demonstrated deep contrasts of ~$10^{-8}$ at an aggressive IWA of 2 $\lambda$/D. For deeper contrasts approaching ~$10^{-10}$, a companion PIAACMC testbed (Belikov et al., 2018) is being commissioned in collaboration between ARC and JPL for vacuum testing in the HCIT using the LUVOIR-A on-axis, segmented aperture (see rightmost pane of Fig. 6).

While the aforementioned testbeds are approaching $10^{-8}$ contrast levels, each are fundamentally limited by air turbulence and vibrations. The DST at JPL, on the other hand, is situated inside of a vacuum chamber to enable ~$10^{-10}$ contrast performance. It has recently been commissioned, and, using an unobscured aperture, achieved 3.9x$10^{-10}$ contrast in an annular region of angles 3-9 $\lambda$/D, in a 10% bandpass centered at 550nm. The testbed will test segmented apertures and to validate coronagraph models through experimentation. The DST's commissioning plan (Ruane et al., 2019) includes the demonstration of a Lyot coronagraph with a segmented aperture (see leftmost three panes of Fig. 6). Further development will be carried out by principal investigators of NASA/SAT (Strategic Astrophysics Technology) awards.

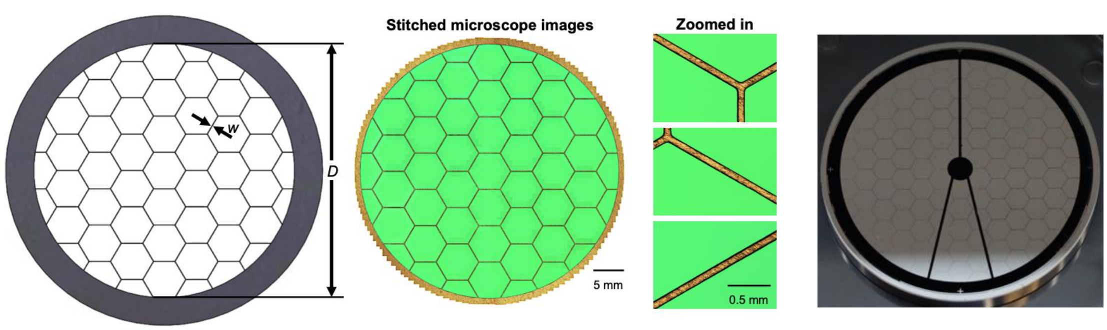


Figure 6. Segmented pupil masks manufactured for *(Left)* the Decadal Survey Testbed using the off-axis LUVOIR-B aperture. The mask diameter is $D$ = 41.75 mm and the gap width, $w$, of 50-100 µm. *(Right)* the PIAACMC testbed using the on-axis LUVOIR-A aperture with D = 43mm and gap width of 20 µm.

# 4. Technology Drivers

NASA's ExEP identifies technology gaps pertaining to possible exoplanet missions and works with the community to identify and track technologies to prioritize for investment, and ultimately to close the gaps. These technologies are summarized in the ExEP's annually-updated Technology List and captured in detail in their Technology Plan Appendix. For coronagraphy, these lists include technology components that are directly associated with the coronagraph optical system such as coronagraph masks and architecture, deformable mirrors, wavefront sensing/control, and detectors, and those technology components that are associated with the space observatory system such as large mirrors, mirror segment metrology/phasing, vibration isolation/reduction, etc. (Crill et al whitepaper)

The large mission concept studies, in particular LUVOIR, and the NASA-funded industry-led System-Level Segmented Telescope Design studies have focused on the ultra-stable observatory system, taking a systems-level look at a coronagraph and telescope working together.

The Coronagraph Instrument (CGI) on WFIRST is the first space coronagraph to include active closed-loop wavefront control and is compatible with a highly obscured pupil. While it will not achieve contrast sensitivity at the level that enables the study of Earth-like exoplanets, the work in systems engineering, coronagraph mask development, and model validation will continue to develop key capabilities relevant to a future exo-Earth characterization mission.

The Small Business Innovative Research (SBIR) program has played a significant role in the development of coronagraph technologies, especially in the area of wavefront control and coronagraph masks. Currently, there are five proposals in Phase II including large format (100x100) DMs, combined segmented and continuous face sheet DMs, integrated ASICs, broadband vortices, and carbon nanotube masks. Additionally there are a number of Phase I proposals. The annual total SBIR investment in these technologies is ~$2-3M.

The Strategic Astrophysics Technology program is an element of NASA's ROSES grant program aimed at maturing technologies to the point where they can be infused with low risk into NASA's strategic astrophysics missions. Since 2010, these competitive awards have enabled the demonstration of multiple coronagraph architectures and the associated techniques for wavefront sensing and control. Four currently active awards will demonstrate basic functionality in the critical environment of PIAA, Hybrid Lyot, Vortex, and Apodized Pupil Lyot Coronagraphy techniques by the end of calendar year 2021. The list of annual awards dating back to 2009 is available at https://exoplanets.nasa.gov/exep/technology/TDEM-awards/.

## 4.1. Theoretical Limits

Coronagraph technology has made great strides over the past few decades and it is worth asking how far current performance remains from fundamental physics limits of coronagraphs.

Our analysis is based on the work of Guyon (2006). A trade between IWA and tolerance to aberrations is shown in Fig. 7, using HabEx's 4-m aperture as an example. The y-axis represents the IWA of a coronagraph, and the x-axis represents the maximum amount of off-axis tip or tilt before a coronagraph leak grows greater than about $\sim 10^{-11}$. The blue balloon represents roughly the performance region currently occupied by state-of-the-art designs showing the room for improving real coronagraphs by future technology development. Thus, an ideal coronagraph could have 2-3 x larger planet yields improvement over current baseline. Alternatively, the size of the telescope can shrink by ~2x and maintain the same science as the current baseline, if the theoretical performance limit of coronagraphs can be reached.

Another important conclusion is that the fundamental limit (black line in Fig. 7) does not have a strong dependence on the obstruction or segmentation of the pupil, and would remain roughly the same for a monolithic aperture. There does appear to be more room for improving coronagraph designs for obstructed apertures than for monolithic apertures, and in general, there is still a lot of room for improvement in both, with further technology development. This would have a significant impact on the expected number of exo-Earth detections.

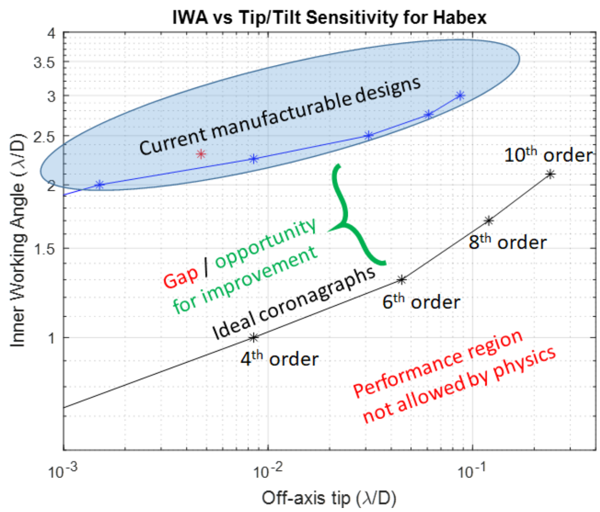


Figure 7. Trade space between tolerance to tip/tilt jitter (x-axis) and IWA HabEx. Every (x,y) point on this plot represents a different coronagraph (in terms of IWA and tip/tilt jitter tolerance). The values shown on the x-axis represent the maximum tip-tilt jitter before coronagraphic leak becomes about $10^{-11}$ contrast. The black line represents allowed physical performance for “ideal n-th order coronagraphs”, which we believe is a fundamental limit. Modern designs typically fall into the blue balloon area, with a large gap that represents the potential possible improvements for coronagraphs with further technology development.

# 5. Summary

Achieving a direct imaging contrast sensitivity of $10^{-10}$ is a significant challenge that is complicated by a centrally obscured, segmented aperture. The ExEP Segmented Coronagraph Design and Analysis study has led to breakthroughs in the design of coronagraphs for segmented apertures. The study has shown that segmentation of the primary mirrors is not a limiting factor; coronagraph designs combined with DM apodization effectively control the segment diffraction even in broadband light. A central obscuration such as a secondary mirror and its thick support struts is more significant, but even so coronagraph designs with ideal (non-aberrated, stable) optics have significant science yield (Stark et al whitepaper). Studies trading ideal performance parameters (contrast, throughput, IWA, bandwidth) with robustness to non-ideal conditions such as pointing jitter, aberration drift, and segment motions have identified no showstoppers, but observatory stability requirements remain a major challenge that we are continuing to study. Cooperation between design teams has been crucial – they have shared optimization codes, approximation techniques, design methodologies, and wavefront control and calibration approaches (Pueyo et al whitepaper, Kasdin et al whitepaper). Existing facilities across the US and the world are available for advancing coronagraph technology with special emphasis on segmented apertures (Mazoyer et al whitepaper). The ExEP continues to support advances in segmented, obscured aperture coronagraph design, analysis and laboratory demonstrations.

# 6. References

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