Exoplanet Exploration Program Technology

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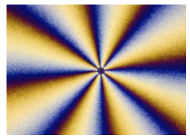
ExoPAG 26
11 June 2022

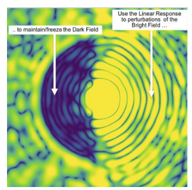
Image Credit:
NASA/JPL-Caltech/T. Pyle
astropix.ipac.caltech.edu

Recent Technology Activities

Technology Gaps

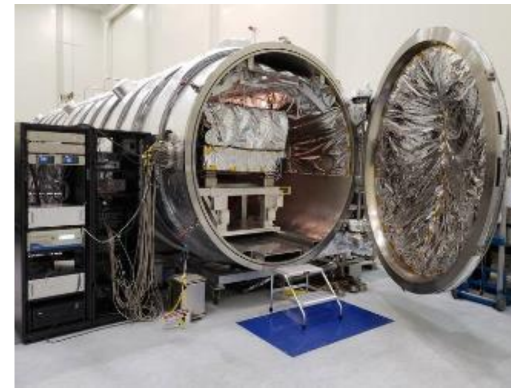
Strategic Astrophysics Technology (SAT) Grants





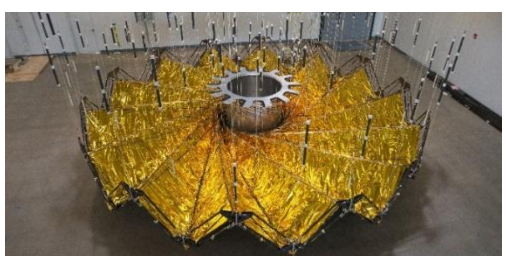
- *Coronagraph architectures: modeling and demonstrations*
- *Wavefront control*
- *Extreme Precision Radial Velocity*
- *Detectors*

Ultra-Stable Coronagraph Testbeds

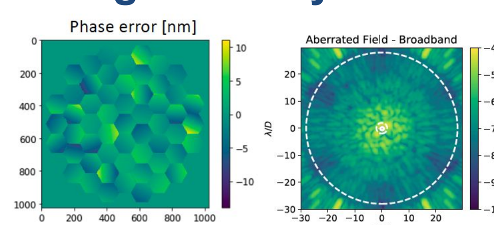


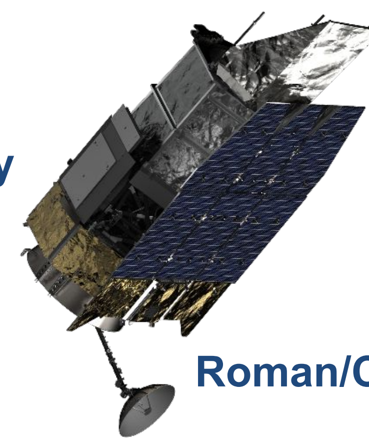
Technosignatures Gap List Study

Starshade Technology Development



Segmented Coronagraph Design & Analysis Study





Roman/CGI

Astrophysics Technology Gaps

https://apd440.gsfc.nasa.gov/tech_gap_priorities.html

- **A technology gap is the difference between a capability needed to enable a future mission and the current state-of-the-art**
- **The Astrophysics Division maintains a prioritized Technology Gap List**
- **Program Office technologists carry out a biennial Technology Gap List Process:**
  - **Identify Technology Gaps** applicable to Astrophysics strategic objectives
  - **Rank Technology Gaps** to prioritize them for investment
  - **Inform the community** of NASA's technology needs
- **Published in the NASA Astrophysics Biennial Technology Report**

2022 Astrophysics Technology Gaps

ExEP NASA EXOPLANET EXPLORATION PROGRAM

Tier 1 Technology Gaps

- Advanced Cryocoolers
- Coronagraph Contrast and Efficiency
- Coronagraph Stability
- Cryogenic Readouts for Large-Format Far-IR Detectors
- Heterodyne Far-IR Detector Systems
- High-Performance, Sub-Kelvin Coolers
- High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings
- High-Resolution, Large-Area, Lightweight X-ray Optics
- High-Throughput Bandpass Selection for UV/VIS
- High-Throughput, Large-Format Object Selection Technologies for Multi-Object and Integral Field Spectroscopy
- Large Cryogenic Optics for the Mid IR to Far IR
- Large-Format, High-Resolution Focal Plane Arrays
- Large-Format, Low-Darkrate, High-Efficiency, Photon-Counting, Solar-blind, Far- and Near-UV Detectors
- Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors
- Long-Wavelength-Blocking Filters for X-ray Micro-Calorimeters
- Low-Stress, High-Stability, X-ray Reflective Coatings
- Mirror Technologies for High Angular Resolution (UV/Vis/Near IR)
- Stellar Reflex Motion Sensitivity – Astrometry
- Stellar Reflex Motion Sensitivity – Extreme Precision Radial Velocity
- Vis/Near-IR Detection Sensitivity

Tier 2 Technology Gaps

- Broadband X-ray Detectors
- Compact, Integrated Spectrometers for 100 to 1000 μm
- Far-IR Imaging Interferometer for High-Resolution Spectroscopy
- Far-IR Spatio-Spectral Interferometry
- Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution
- High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy
- High-Resolution, Direct-Detection Spectrometers for Far-IR Wavelengths
- Improving the Calibration of Far-IR Heterodyne Measurements
- Large-Aperture Deployable Antennas for Far-IR/THz/sub-mm Astronomy for Frequencies over 100 GHz
- Large-Format, High-Spectral-Resolution, Small-Pixel X-ray Focal-Plane Arrays
- Polarization-Preserving Millimeter-Wave Optical Elements
- Precision Timing for Space-Based Astrophysics
- Rapid Readout Electronics for X-ray Detectors
- Starshade Deployment and Shape Stability
- Starshade Starlight Suppression and Model Validation
- UV Detection Sensitivity

Tier 3 Technology Gaps

- Advancement of X-ray Polarimeter Sensitivity
- Detection Stability in Mid-IR
- Far-UV Imaging Bandpass Filters
- High-Efficiency Far-UV Mirror
- High-Efficiency, Low-Scatter, High- and Low-Ruling-Density, High- and Low-Blazed-Angle UV Gratings
- High-Quantum-Efficiency, Solar-Blind, Broadband Near-UV Detector
- Photon-Counting, Large-Format UV Detectors
- Short-Wave UV Coatings
- Warm Readout Electronics for Large-Format Far-IR Detectors

Tier 4 Technology Gaps

- Advanced Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry
- Improving the Photometric and Spectro-Photometric Precision of Time-Domain and Time-Series Measurements
- UV/Opt/Near-IR Tunable Narrow-Band Imaging Capability
- Very-Wide-Field Focusing Instrument for Time-Domain X-ray Astronomy

Tier 5 Technology Gaps

- Complex Ultra-Stable Structures for Future Gravitational-Wave Missions
- Disturbance Reduction for Gravitational-Wave Missions
- Gravitational Reference Sensor
- High-Performance Spectral Dispersion Component/Device
- High-Power, High-Stability Laser for Gravitational-Wave Missions
- Laser Phase Measurement Chain for a Decihertz Gravitational-Wave Mission
- Micro-Newton Thrusters for Gravitational Wave-Missions
- Stable Telescopes for Gravitational Wave-Missions

The 10 ExEP Technology Gaps

Where to find the Gap List

ExEP NASA EXOPLANET EXPLORATION PROGRAM

https://apd440.gsfc.nasa.gov/tech_gap_priorities.html

ASTROPHYSICS TECHNOLOGY DEVELOPMENT

Overview | Technology | Outreach

Astrophysics Program Offices

2022 Astrophysics Strategic Technology Gaps

TECHNOLOGY GAPS: OVERVIEW / TECH GAP PRIORITIES / PRIORITIZATION PROCESS / TECH GAP DESCRIPTIONS

Gap Name	Description	Current SOA	TRL	Performance Goals and Objectives	Scientific, Engineering and/or Programmatic Benefits	Applications and Potential Relevant Missions	Urgency
Coronagraph Stability	The capability to maintain the deep starlight suppression provided by a coronagraph for a time period long enough to detect light from an exo-Earth.	RST CGI demonstrated ~10^{-8} contrast in a simulated dynamic environment using LOWFS (which obtained 12 pm focus sensitivity) SIM and non-NASA work has demonstrated nm accuracy and stability with laser metrology Capacitive gap sensors demonstrated at 10 pm 80 dB vibration isolation demonstrated Gaia cold gas microthrusters and LISA pathfinder colloidal microthrusters can reduce vibrations	3	Contrast stability on time scales needed for spectral measurements (possibly as long as days). Achieving this stability requires an integrated approach to the coronagraph and telescope, possibly including wavefront sense/control, metrology and correction of mirror segment phasing, vibration isolation/reduction This stability is likely to require wavefront error stability at the level of 10-100 pm per control step (of order 10 minutes). Sub-gaps that could partially or fully close this gap: - Ultra-stable Telescope - Integrated Modeling of Telescope/Coronagraph system - Disturbance Reduction and	This gap is likely to be closed by a combination of many factors in a coronagraph/observatory system, including active wavefront control at the coronagraph level, thermal control, active and passive ultra-stable structures, and disturbance isolation/ reduction. Integrated modeling for tracability to flight environments is likely to be a key capability to close this gap.	IR/O/UV Great Observatory; or any other coronagraph-based exoplanet direct-imaging mission.	Demonstration of feability and as much risk reduction as possible prior to mission formulation. TRL 6 in the mid-to-late 2020's.

Click on the tiers for details

Exoplanet Technology Gaps and Subgaps

https://exoplanets.nasa.gov/exep/technology/gap-lists/

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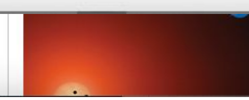
EXOPLANET PROGRAM   About   Studies   News   Meetings/Events   Resources   Technology   NExScI   ExoPAG   For the Public

Technology Gap and Description	*Current State-of-the-Art*	*Performance Goals and Objectives*
Mirror Technologies for High Angular Resolution (UV/Vis/NIR) The capability to resolve the habitable zones of nearby star systems in the UV/Vis/NIR bands with a large space telescope.	Monolith: 3.5-m sintered SiC with < 3 µm SFE (Herschel); 2.4-m ULE with ~10 nm SFE (HST); Waterjet cutting is TRL 9 to 14" depth, but TRL 3 to >18" depth. Fused core is TRL 3; slumped fused core is TRL 3 (AMTD); 4-m class Zerodur mirrors from single boules are TRL 4. Segmented: (no flight SOA): 6.5 m Be with 25 nm SFE (JWST); Non-NASA: 6 DOF, 1-m class SiC and ULE, < 20 nm SFE, and < 5 nm wavefront stability over 4 hr with thermal control	Large (4–16 m) monolith and multi-segmented mirrors for space that meet SFE < 10 nm rms (wavelength coverage 400–2500 nm); Wavefront stability better than 10 pm rms per wavefront control time step; CTE uniformity characterized at the ppb level for a large monolith; Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control. Sub-gaps that could partially or fully close this gap: - Mirror Substrate and Structure - Mirror Positioning Actuators - Gravity Sag Offloader - Coefficient of Thermal Expansion Characterization - Mirror Finishing - UV Coatings: Wavefront Effects
Coronagraph Contrast and Efficiency The capability to suppress starlight and receive planet light with a coronagraph to the level needed to detect and spectrally characterize Earth-like exoplanets in the habitable zones of Sun-like stars.	unobscured pupil: 4×10^{-10} raw contrast at 10% bandwidth, angles of 3-15 λ/D (Lyot coronagraph demo in HCIT); obscured pupil: 1.6×10^{-9} raw contrast at 10% bandwidth across angles of 3-9 λ/D (Roman CGI Lab Demos); segmented/unobscured pupil: 2.5×10^{-8} raw contrast in monochromatic light across 6-10 λ/D (Lyot coronagraph demo in HiCAT)	Maximized science yield in imaging and spectroscopy for a direct imaging telescope/mission. $\leq 10^{-10}$ raw contrast, >10% throughput, inner working angle $\leq$ 3 λ/D, outer working angle >= 45 λ/D [TBD], 20% bandwidth; obscured/segmented pupil For the two distinct cases of monolith and segmented primary mirrors, Sub-gaps that could partially or fully close this gap:

Download the ExEP's latest *Technology Gap and Sub-gap Lists* here

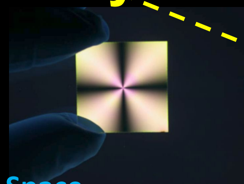
The ExEP works to close Technology Gaps so as to enable or enhance NASA's future strategic exoplanet missions.



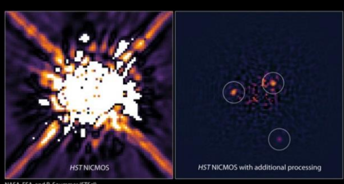
Click here for a PDF with all exoplanet technology gaps and subgaps

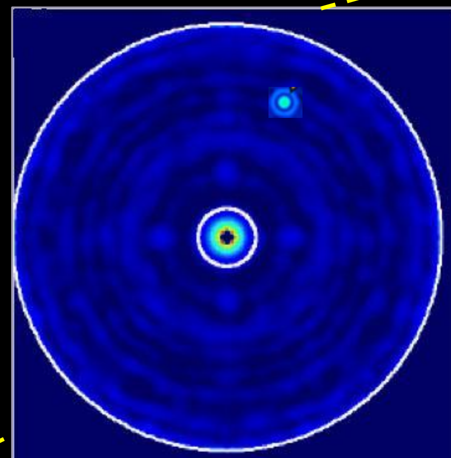
V-NIR Coronagraph/Telescope Technology Gaps

Coronagraph Contrast and Efficiency



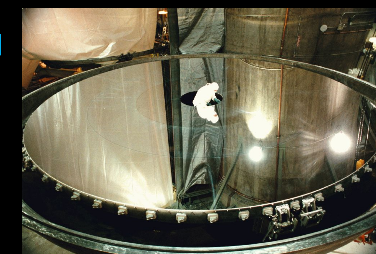
- Coronagraph Architectures
- Deformable Mirrors
- Coronagraph Efficiency
- Computational Throughput in Space
- High Bandwidth Optical Comm
- Autonomous On-board WFSC Architectures





Mirror Technologies for High Angular Resolution

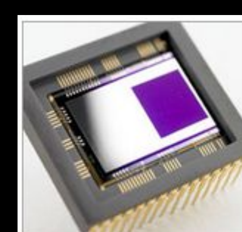
- Mirror Substrate and Structures
- Mirror Finishing
- Mirror Positioning Actuators
- Gravity Sag Offload
- CTE Characterization
- UV Coatings: Wavefront Effects



Coronagraph Stability

- Wavefront Sense/control
- Precision Pointing Stability
- Disturbance Reduction and Observatory Stability
- Segment Relative Pose Sense/Control
- Telescope Thermal Sense/Control
- Vibration Isolation
- Laser Gauges
- Integrated Modeling of Coronagraph/Telescope System

Vis/NIR Detection Sensitivity

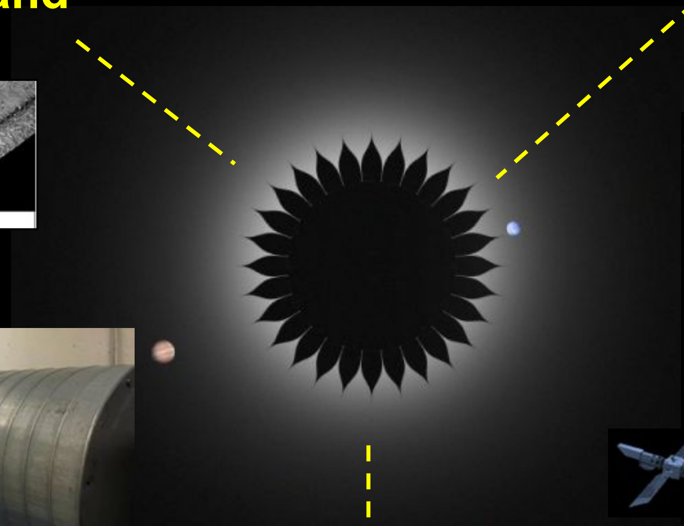


- NIR Detectors
- UV/Vis Detectors
- Photon-counting energy-resolving detectors

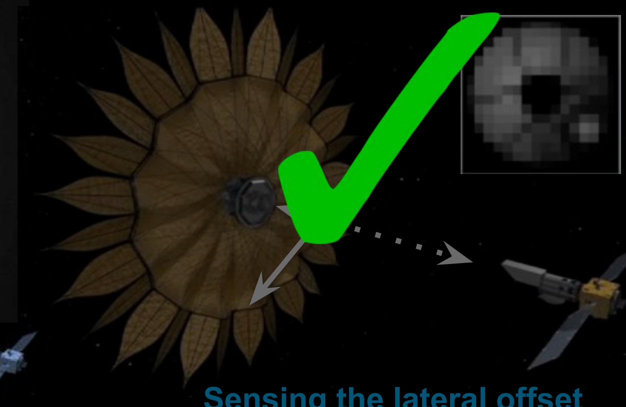
Starshade Technology Gaps

Starlight Suppression and Model Validation

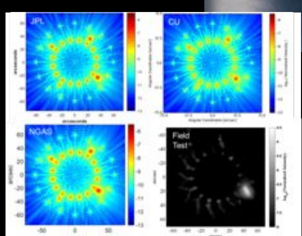
Suppressing scatted light off petal edges from off-axis Sunlight



Formation Sensing

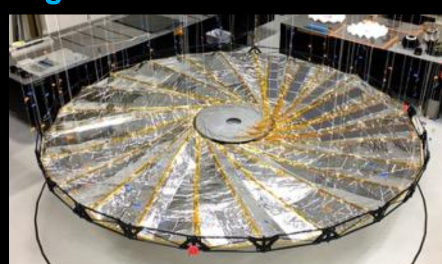


Sensing the lateral offset

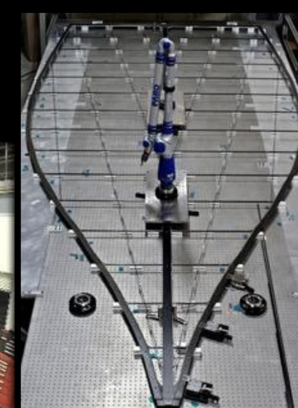


Suppressing diffracted light from on-axis starlight and optical modeling

Deployment Accuracy and Shape Stability



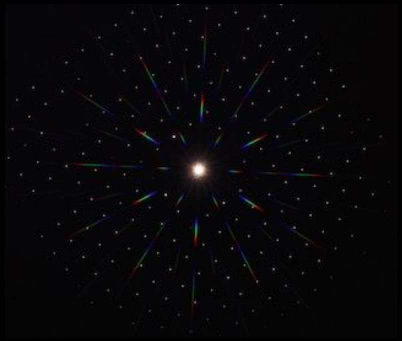
Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure

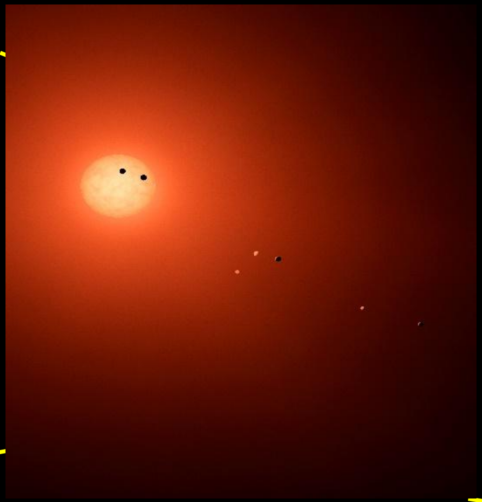


Fabricating the petals to high accuracy

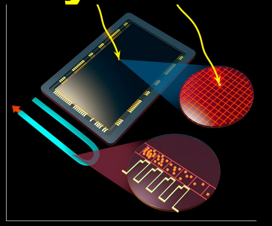
Other Technology Gaps

Stellar Reflex Motion ensitivity: Astrometry



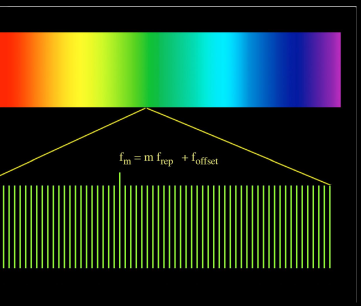


UV Detection Sensitivity



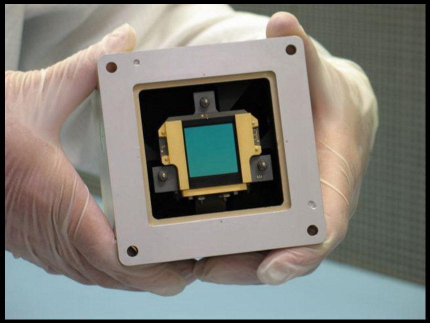
Ultra-low Noise UV Detectors

Stellar Reflex Motion Sensitivity: Extreme Precision Radial Velocity



- Detectors for High-res Spectrographs
- Dispersive Optics
- Advanced Photonics
- Ground-based Visible-light Adaptive Optics
- Precision Calibration

Detection Stability (Mid-IR)



Ultra-stable Mid-IR Detectors for Transit Spectroscopy

10 Currently Active Strategic Astrophysics Technology (SAT) Awards

ExEP NASA EXOPLANET EXPLORATION PROGRAM

Coronagraph masks/architectures

- Vortex Coronagraph (Serabyn/NASA-JPL)
- Phase Induced Amplitude Apodization Complex Mask Coronagraph (Belikov/NASA-ARC)
- Super-Lyot Coronagraph (Trauger/NASA-JPL)
- Apodized Pupil Lyot Coronagraph (Soummer/STScI)

Ultra-low Noise Detectors

- Vis-band rad-hard photon-counting detectors (Rauscher/NASA-GSFC)
- Ultra-stable mid-IR detector array (Staguhn/JHU)

Wavefront-control techniques

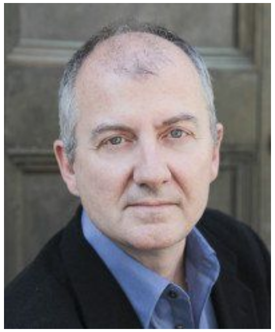
- Single mode fiber and optimization for spectroscopy (Mawet/Caltech)
- Linear Dark Field Control (Guyon/Arizona)
- Multi-star Wavefront Control (Belikov/NASA-ARC)

Extreme Precision Radial Velocity

- Micro-resonator optical etalon for radial velocity measurements (Vasisht/NASA-JPL)

Newly Selected SAT-2021 Awards

- ***Dual-Purpose coronagraph masks for enabling high-contrast imaging with an IR/O/UV flagship mission***
  PI J. Kent Wallace (JPL)
  - Aims to monitor wavefront errors in a coronagraph using a Zernike wavefront sensor and out-of-band light, and to actively correct the errors.



- ***Adaptive High-order Wavefront Control Algorithms for High-contrast Imaging on the Decadal Survey Testbed***
  PI Kerri Cahoy (MIT)
  - Will demonstrate methods to maintain a coronagraph dark hole using focal plane data

- **Next call issued in ROSES-2022 with TBD due dates, likely to be due Dec 2022**

SAT Coronagraph Demonstrations in the High-Contrast Imaging Testbed

- **Vortex coronagraph (PI Serabyn)**
  - Vortex coronagraph was LUVOIR-B and HabEx baseline
  - Achieved a new contrast record for the vector vortex at 10% bandwidth between 3-9 λ/D of 1.5×10^{-9}.
  - See papers at upcoming July SPIE meeting

- **Super Lyot ExoEarth Coronagraph (PI Trauger)**
  - Hybrid Lyot coronagraph has demonstrated the deepest contrast to-date
  - Replicated contrast performance with simple Lyot coronagraph at 3.4×10^{-10} at 10% band 3-9 λ/D 360-degree dark hole
  - Results coming soon with next generation masks

- **Next in testbed:**
  - Multi-star wavefront control demonstrations (PI Belikov)
  - High-bandwidth coronagraph demonstrations (PI Mawet)

Other Recent SAT Highlights

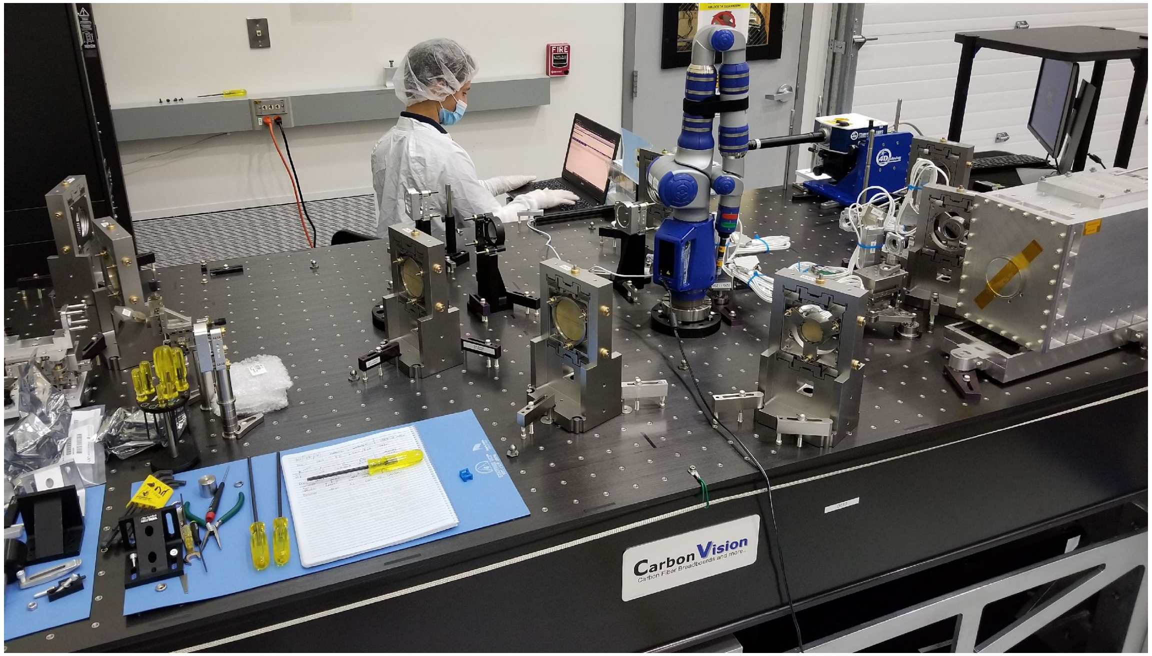
- **Environmental Tests of MEMS Deformable Mirrors (PI Bierden)**
  - Final Report completed and available on ExEP website
  - performed random vibration testing on an earlier generation of MEMS deformable mirrors, showing they survived launch loads.

- **Linear Dark Field Control (PI Guyon)**
  - Uses residual starlight outside coronagraph dark hole to stabilize the dark hole, potentially leading to looser telescope stability requirements
  - Milestone Whitepaper approved for tests in vacuum at higher contrast and using spectral information and posted on ExEP website
  - Technique will be tested at high contrast in HCIT using spectral information in the coming months

- **Astrometry Bench installed in vacuum chamber (PI Bendek)**
  - APRA-funded demonstration of diffractive pupil technology in vacuum

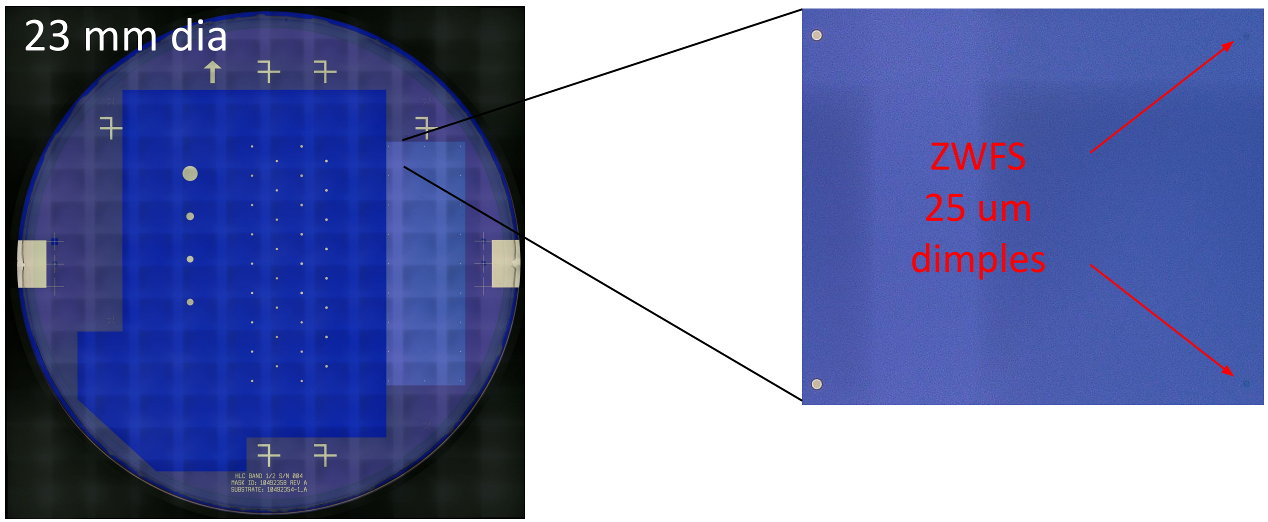
Testbed Infrastructure

- **Decadal Survey Testbed 2**
  - New ultrastable coronagraph testbed bench with additional pupil plane
  - Achieved first light in November 2021
  - Installation planned for mid-July
  - Available to future investigators ~ next FY

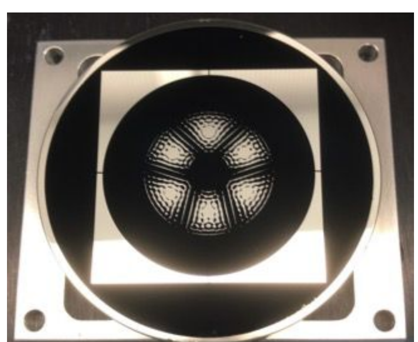


ExEP-Contributed Masks for Roman Space Telescope Coronagraph Instrument (CGI)

- **CGI currently in flight build: all coronagraph masks have been fabricated including ExEP contributions:**
- **Zernike Wavefront Sensor (ZWFS) dimple masks:**

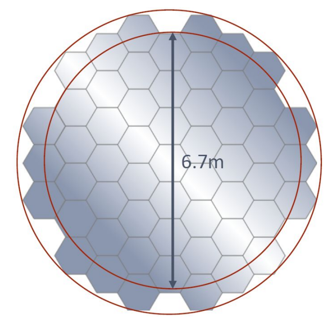


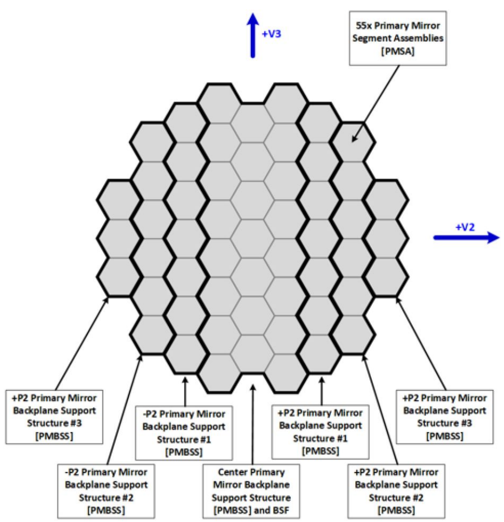
- **Multi-star Wavefront Control mask:**



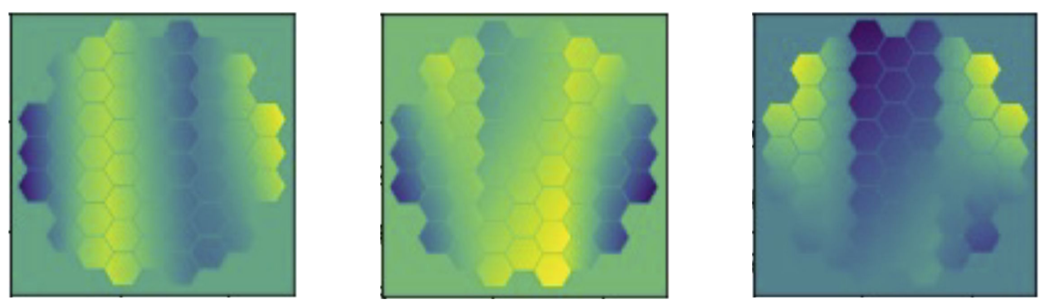
Segmented Coronagraph Design & Analysis Study

- **Multi-institutional study of end-to-end modeling of telescope dynamics, wavefront control, and coronagraph -> science yield**
- **Studies Currently Underway**
  - End-to-end modeling of a LUVOIR-B-like telescope dynamics, wavefront control, and coronagraph exo-Earth yield (in collaboration with Lockheed Martin)
  - Effect of polarization aberration on exo-Earth yield
  - Effect of segment-edge roll-off on exo-Earth yield





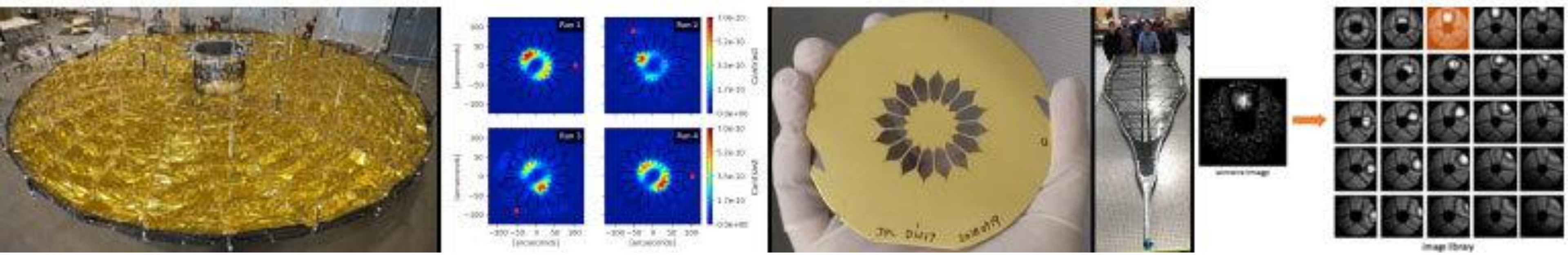
[LUVOIR Final Report]



The 3 most dominant modes in dynamical wavefront variance of the modeled telescope structure. Effects of vertical hinges in the primary mirror's backplane support are evident. [Credits: L. Dewell (Lockheed Martin), R. Juanola-Parramon (NASA GSFC)]

Starshade Technology Development

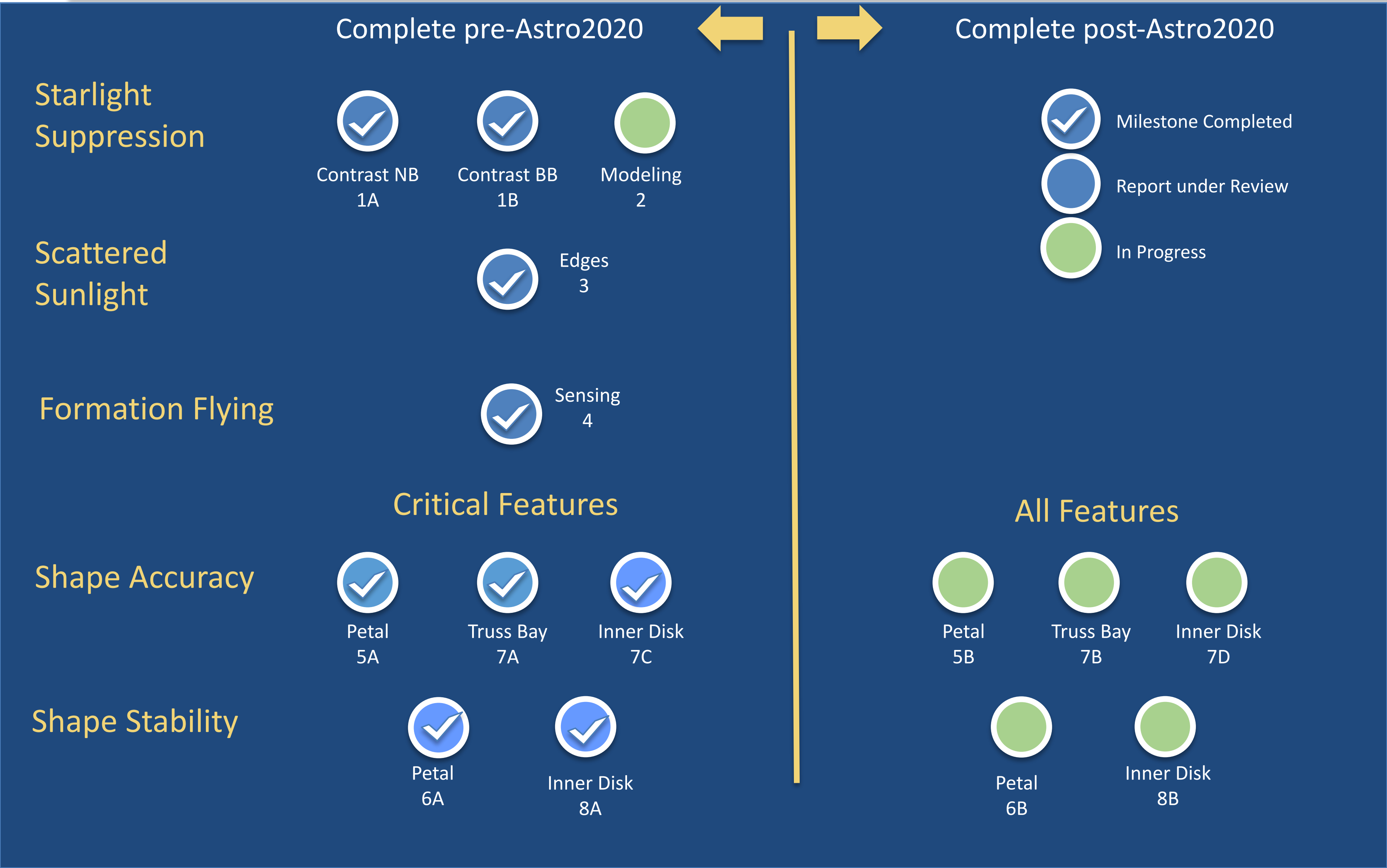
- **Since 2016, Starshade Technology Activity has overseen technology development, achieving a series of milestones that worked towards closing the starshade technology gaps**
  - https://exoplanets.nasa.gov/exep/technology/starshade/



- **Starshade technology development will transition from directed funding to a competed funding model**

- **Remaining work to TRL 5:**
  - Complete analysis of subscale demos and model validation
  - Further demonstrations of deployment and shape stability at higher levels of integration

Starshade Scorecard



Technosignatures Gap List Study

- The ExEP commenced a fact-finding study to understand where it can make a positive impact towards the search for technological life.

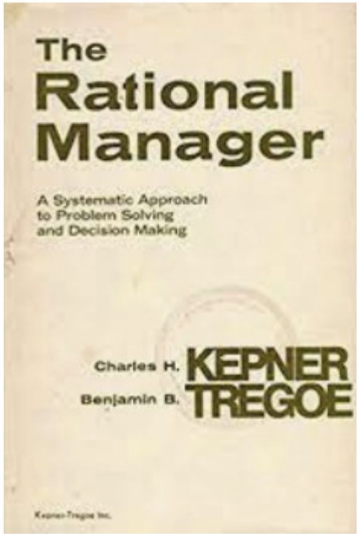
- The Study will help the ExEP better understand the landscape and needs of the field if investments are ever considered again (Congress, donors).

- Key fields within the database will include:
  - ❖ Technosignature search approaches
  - ❖ Technology needs and gaps
  - ❖ Other needs to advance the searches (access to existing facilities, future facilities, AI/ML, $'s, data archiving)

- Study is planned to conclude in CY22
  - ❖ Second milestone completed this month (search approaches)
  - ❖ Reviewed by an external Technosignatures Assessment Committee

Exoplanet Exploration Technology Colloquium Series

- **Choosing the Future: Kepner-Tregoe Matrix for Complex Trades**
  Gary Blackwood (JPL)



Decision Statement									
Description				Option 1		Option 2		Option 3	
	Feature 1								
	Feature 2								
	Feature 3								
Evaluation	**Musts**								
	M1			✔		✔		✔	
	M2			✔		?		?	
	M3			✔		✔		✖	
	Wants	Weights							
	W1	w1%		Rel score		Rel score		Rel score	
	W2	w2%		Rel score		Rel score		Rel score	
	W3	w3%		Rel score		Rel score		Rel score	
		100%	Wt sum =>	Score 1		Score 2		Score 3	
	Risks			C	L	C	L	C	L
	Risk 1			M	L	M	L		
	Risk 2			H	H	M	M		
Final Decision, Accounting for Risks									
C = Consequence, L = Likelihood									

- **Coming soon: TRL assessment, coronagraph stability studies.**
- **Recordings and slides available:**
  - https://exoplanets.nasa.gov/exep/technology/tech_colloquium/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Join our Sunday morning session for more details on
Precursor science, the Science Evaluation Team,
the Technology Strategy Team and how you, the ExoPAG
can be involved.
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