ExEP Technology Updates Since Last ExoPAG

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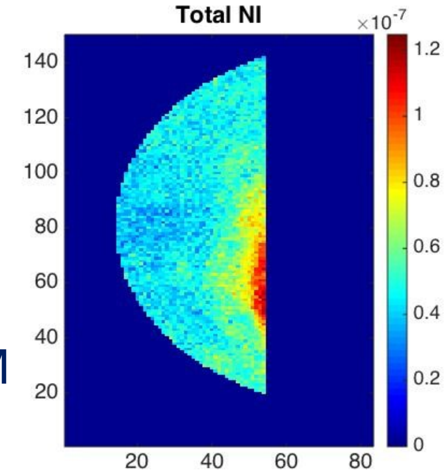
ExoPAG 18
29 July 2018

Exoplanet Exploration Program

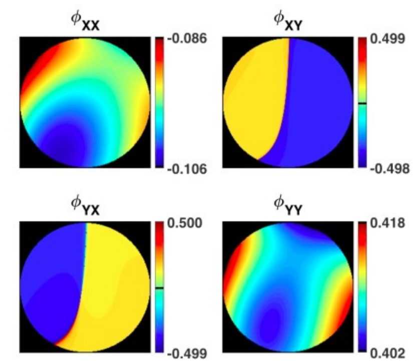
Active TDEMS

- **Vortex Coronagraphy**
  - TDEM-14 PI Gene Serabyn charge-4 vortex tests in HCIT.
  - Achieved 2×10^{-9} contrast in monochromatic light (milestone is to get to 1×10^{-9} contrast at 10% bandwidth)
  - Demonstration used for the first time within the HCIT a MEMS deformable mirror
  - 2×10^{-9} contrast is a world contrast record using a MEMS DM



In-process results from dark hole created by vortex coronagraph (PI Serabyn)

- **Polarization Effects in Coronagraphy**
  - TDEM-15 Jim Breckinridge team performed an independent polarization ray-trace of the HabEx optics (4 m aperture).
  - Showed good agreement with the HabEx team's calculations: no show-stoppers from polarization aberrations from the primary optics
  - The work highlights the importance of setting requirements on the spatial uniformity of the coatings on the large optics (see Breckinridge et al and Davis et al Austin SPIE papers for details).

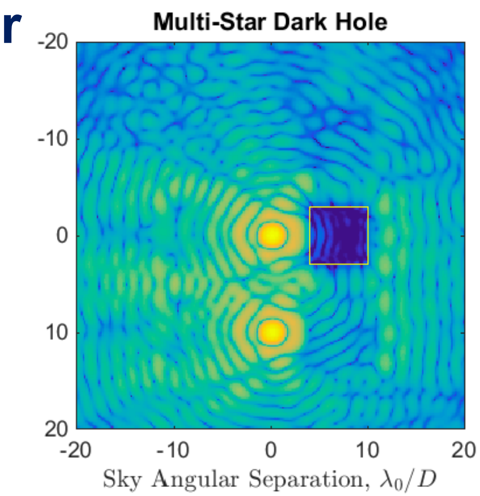


HabEx Jones exit pupil phase (From Breckinridge et al (2018))

Active TDEMS (cont'd)

- **MEMS Deformable Mirrors (DMs)**
  - TDEM-10 PI Paul Bierden (Boston Micromachines) will have ten MEMS deformable mirrors dynamically tested at GSFC in mid-Aug
  - The DMs will return to JPL for post environment testing scheduled in September
  - SBIR is producing a 50x50 DM

- **ExoTAC approved the test plans and milestones for the three TDEM-16 awards:**
  - **PI Rus Belikov: PIAACMC**
  - **PI John Trauger: Super Lyot Coronagraph**
  - **PI Rus Belikov: Multi-star wavefront control**



Segmented Mirror Technology Program

- **Telescope apertures will continue to get larger and structural and wavefront error stability will be challenging when working with coronagraphs.**
- **Industry awards created to address system-level design and modeling challenges for achieving picometer-level wavefront error stability in a segmented UV/V/NIR space telescope.**

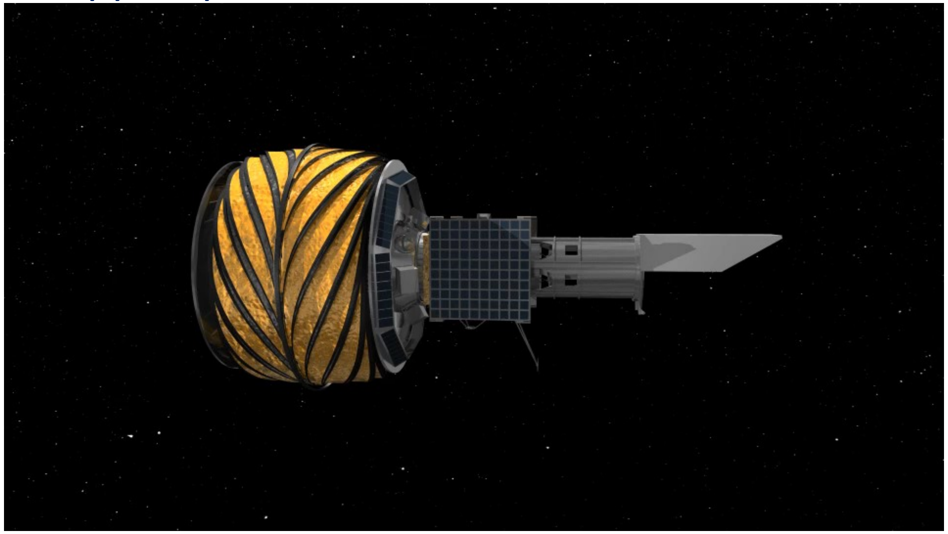
Ultra-Stable Large Telescope Research and Analysis (ULTRA),
PI Scott Knight (Ball Aerospace)

System-Level Segmented Telescope Design
PI Larry Dewell (Lockheed Martin)

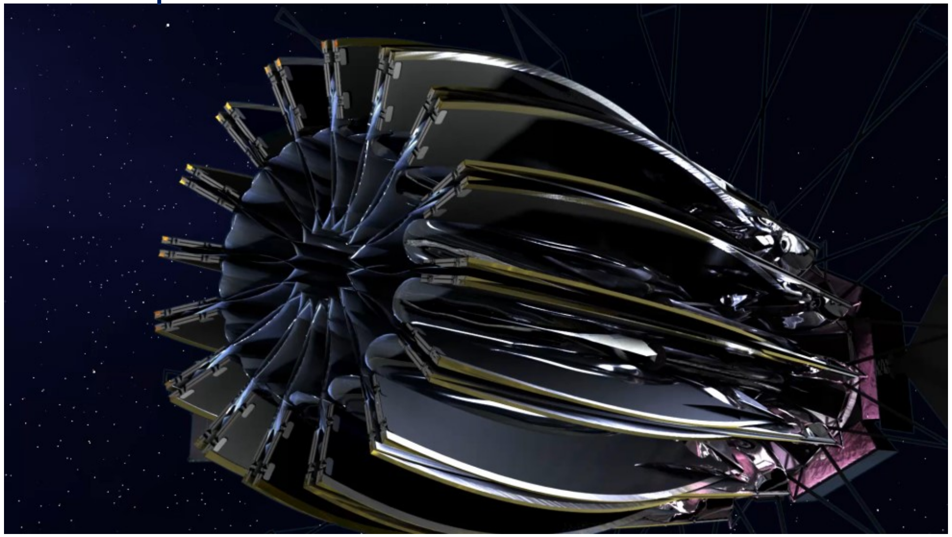
- **Managed by PCOS/COR**

Starshade Technology Development

Wrapped-petal architecture

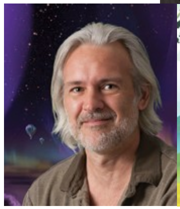


Folded-petal architecture



- **Trade study completed**
  - ***Wrapped-petal architecture selected for further development***
- **Technology Development Plan being advanced to close the three technology gaps.**
  - Review of milestones by ExoTAC in August
  - Delivery of Plan for NASA HQ approval in September
- **Thanks John Ziemer!**

- **Welcome Kendra Short and Phil Willems**



Segmented Coronagraph Design and Analysis

- **Purpose:** Ensure there is at least one coronagraph architecture that can meet the contrast requirements of future large segmented space telescopes to directly image and characterize exo-Earths.

- **Promising designs delivered of the APLC (STScI/GSFC) and Vortex (Caltech/JPL) teams; HLC catching up, PIAACMC and VNC struggling to meet metrics.**

- **Lessons learned (See Austin SPIE papers for details)**
  - Big dropoff in throughput seen when secondary obscuration exceeds 30% of the primary mirror diameter
  - Maximize inscribed diameter of the primary mirror
  - Segmentation gaps are not a major problem (if small)

- **Next steps**
  - Test new apodization masks in testbeds (not yet vacuum)
  - Test the robustness of the designs to wavefront errors and tolerancing: Do these coronagraphs put constraints on the telescopes that are unrealistic?

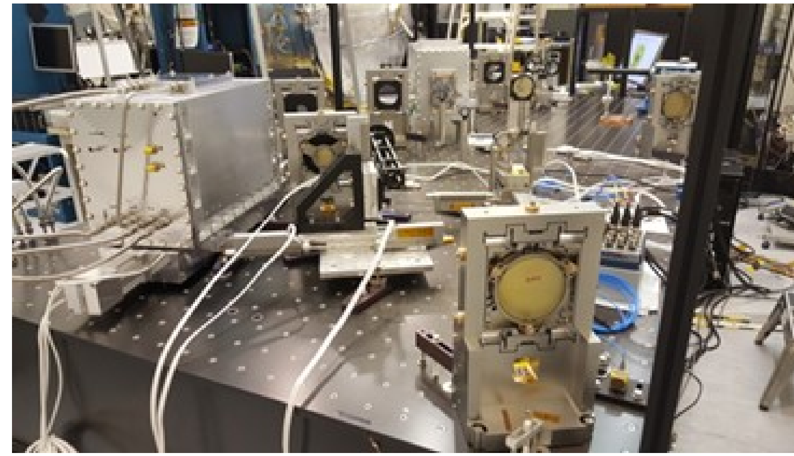
- **Public release of FALCO code (joint deformable mirror / apodizing mask optimizer); A.J. Riggs (JPL) is the lead.**

Decadal Survey Testbed

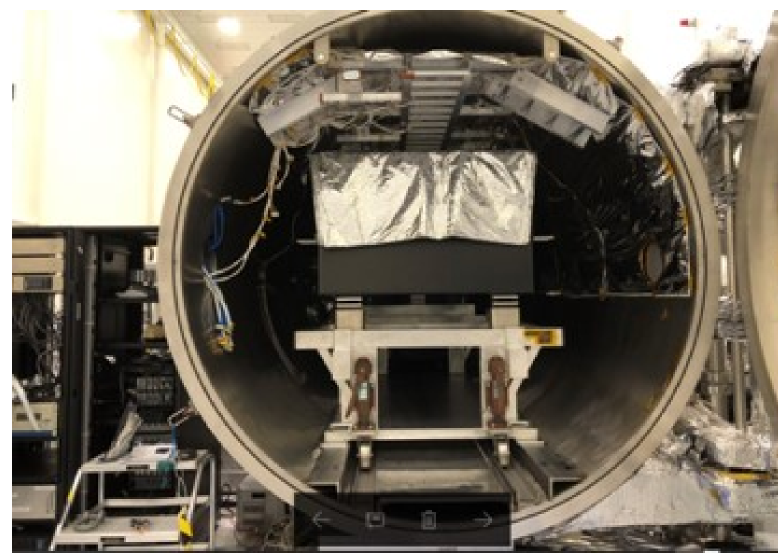
Advancing the next generation of coronagraphs

- **Purpose:**
  - Develop a testbed that is sufficiently low noise to demonstrate next-generation coronagraphs reach 10^{-10} contrast
  - To be made available to community
- **Currently in Phase I:**
  - Commissioning with a clear aperture plus Hybrid Lyot
  - **Plan is to reach a new contrast record by the end of this CY ($\leq 10^{-10}$)**
- **Phase II in CY19:**
  - Add a segmented/obscured mask to simulate (in a static environment) the segmentation pattern of a large space telescope mirror
- **Status Briefing to be scheduled in October with WFIRST, HabEx, and LUVOIR teams**

Assembled optical bench



Installed in the chamber: June 2018



Inputs to National Academies Committees

- **Whitepaper submitted to the Astrobiology Science Strategy: Siegler et al. *Technology Needs for Detecting Life Beyond the Solar System: A White Paper in Support of the Astrobiology Science Strategy* arXiv:1801.07811**

- **Whitepaper submitted to the National Academies Exoplanet Science Strategy: Crill et al. *Key Technology Challenges for the Study of Exoplanets and the Search for Habitable Worlds* arXiv:1803.04457**

- **Briefed the NAS Exoplanet Science Strategy committee at their Irvine meeting on April 20, 2018 on "Exoplanet Technology Gaps" https://exoplanets.nasa.gov/internal_resources/893/**

New Technology Selection and Prioritization Process

- **NASA HQ directed the three APD Program Offices (ExEP, PCOS, COR) to develop a plan for closer coordination of the technology prioritization processes.**

- **Concerns from the community:**
  - Potential stove piping
  - Differences in the way technologies were prioritized
  - Different schedules
  - Duplication of technology gaps

- **Brendan Crill and Nick Siegler worked with Thai Pham and Opher Ganel of PCOS/COR.**

- **The plan was approved by Paul Hertz in June; Program Office technologists are now implementing the plan.**

New Technology Selection and Prioritization Process Highlights

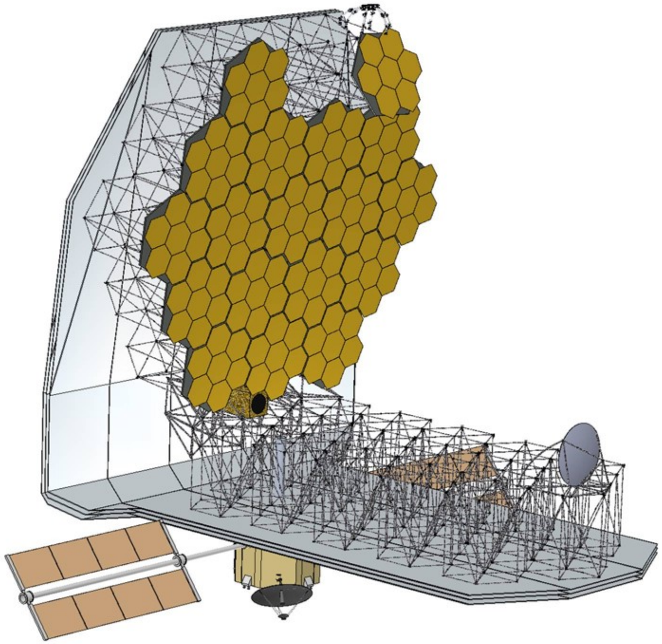
- **The prioritized technology gap lists will be updated every two years instead of annually.**
  - Next update will be in in calendar year 2019.
  - SAT/TDEM proposal cycle is unchanged, pending funding.
  - December amendments to the SAT will continue.
- **Program Offices will share a common schedule and jointly solicit new technology gaps from the community.**
- **There will be no duplication of technology gaps.**
  - Each gap will be evaluated and facilitated by only one Program Office.
  - Any new technology gaps will be evaluated and facilitated by the Program Office with the most suitable expertise.
- **The Program Offices will use same prioritization criteria and scoring.**
- **Resulting lists will be merged into a single prioritized APD technology list.**
- **An executive summary-level document: *Astrophysics Biennial Technology Report* will be released to support the work**
  - *ExEP's Technology Plan Appendix will continue annual publication.*

in-Space Assembled Telescope (iSAT) Study

- Chartered by NASA SMD and APD to answer the question:

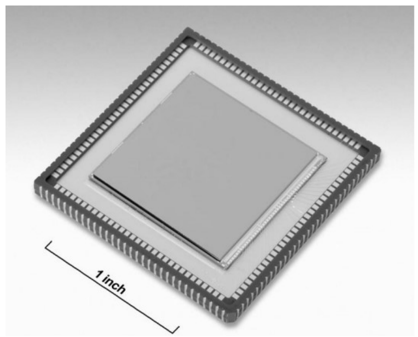
  When is it worth assembling telescopes in space rather than building them on the Earth and deploying them autonomously from individual launch vehicles?"

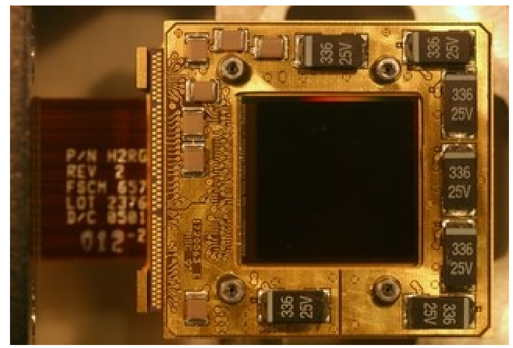
- Study leads Nick Sigler (JPL), Harley Thronson (GSFC), Rudra Mukherjee (JPL)
- Final deliverable is a White Paper to the Decadal Survey Committee in Spring 2019
- Activity 1a: *Modularizing a 20 m space telescope*
  - Workshop held at Caltech June 5-7
- Activity 1b: *Assembling and testing the 20 m modularized telescope in space*
  - Robotics, orbit, launch vehicle, assembly platform
  - Workshop scheduled for October 2-4 at LaRC



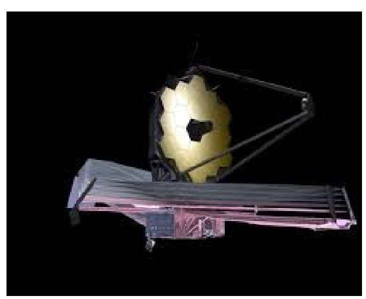
Technology Colloquium Series Continues

- **Stability of Mid-Infrared Detectors for Future Space-based Transit Spectroscopy Measurements (C. McMurtry, Rochester)**





- **Cost Drivers for Traditional Space Telescope Missions (H. Phil Stahl, NASA/MSFC , K. Warfield, NASA/JPL)**



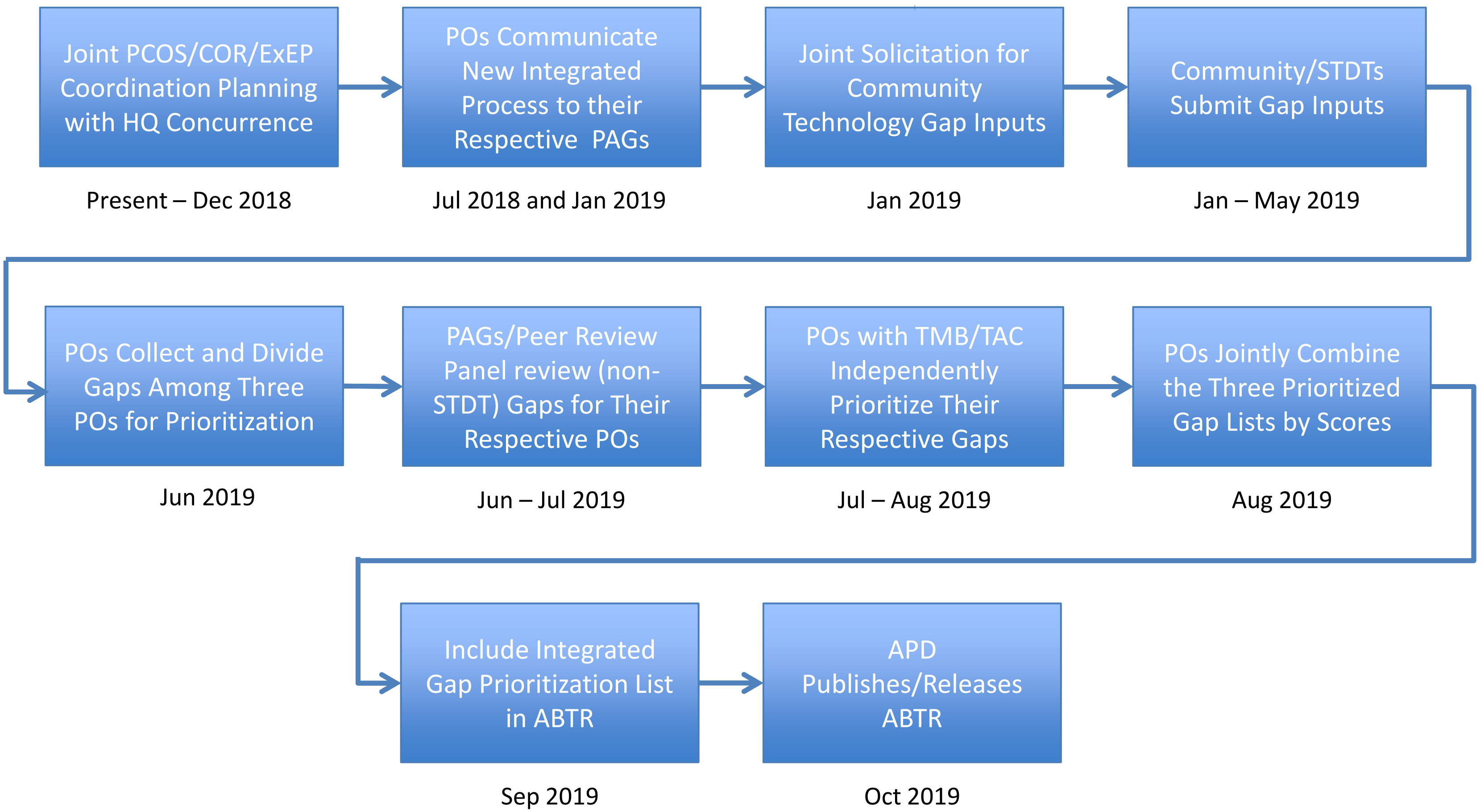
https://exoplanets.nasa.gov/exep/technology/tech_colloquium/

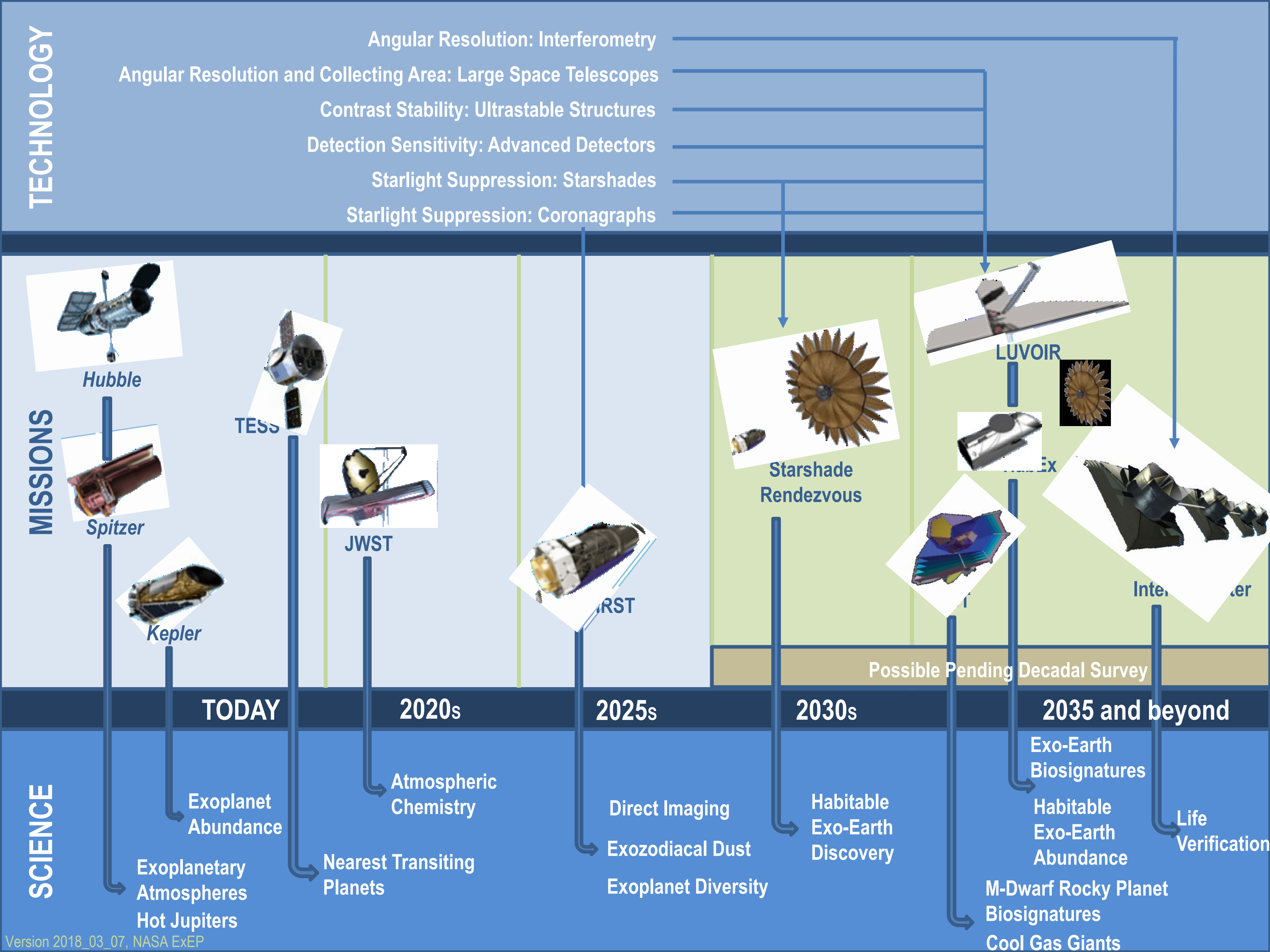
Talk slides and recordings available

ADDITIONAL SLIDES

Flow Diagram of Coordinated Prioritization and Reporting Cycle

Exoplanet Exploration Program



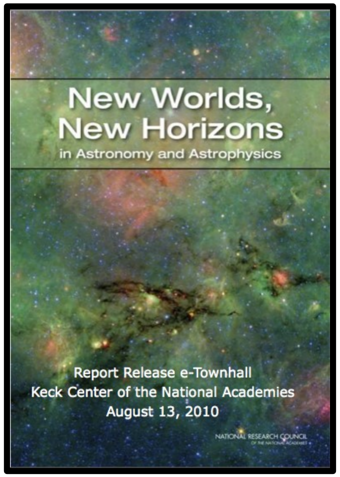


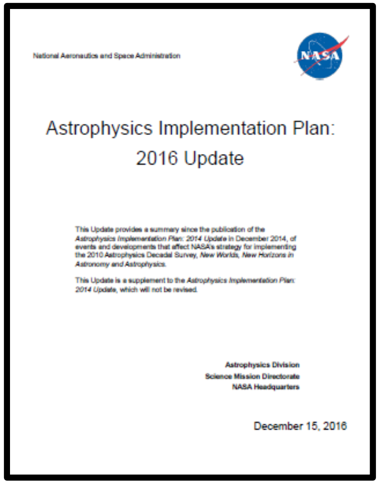
TECHNOLOGY
Angular Resolution: Interferometry
Angular Resolution and Collecting Area: Large Space Telescopes
Contrast Stability: Ultrastable Structures
Detection Sensitivity: Advanced Detectors
Starlight Suppression: Starshades
Starlight Suppression: Coronagraphs
MISSIONS
Hubble
Spitzer
Kepler
TESS
JWST
IRST
Starshade
Rendezvous
LUVOIR
Ex
Inte
er
Possible Pending Decadal Survey
TODAY
2020s
2025s
2030s
2035 and beyond
SCIENCE
Exoplanetary
Atmospheres
Hot Jupiters
Exoplanet
Abundance
Nearest Transiting
Planets
Atmospheric
Chemistry
Direct Imaging
Exozodiacal Dust
Exoplanet Diversity
Habitable
Exo-Earth
Discovery
Exo-Earth
Biosignatures
Habitable
Exo-Earth
Abundance
Life
Verification
M-Dwarf Rocky Planet
Biosignatures
Cool Gas Giants
Version 2018_03_07, NASA ExEP

ExEP's Technology Focus

- **The driving ExEP science goals are to:**
  1. Discover planets around other stars
  2. Characterize their properties
  3. Identify candidates that could harbor life

- **As recommended in the 2010 Astrophysics Decadal Survey and planned in NASA's Astrophysics Implementation Plan, the ExEP develops technologies that will enable the direct imaging and characterization of exoplanets in the habitable zone of Sun-like stars.**




National Aeronautics and Space Administration

Astrophysics Implementation Plan:
2016 Update

This Update provides a summary since the publication of the *Astrophysics Implementation Plan: 2014 Update* in December 2014, of events and developments that affect NASA's strategy for implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*.

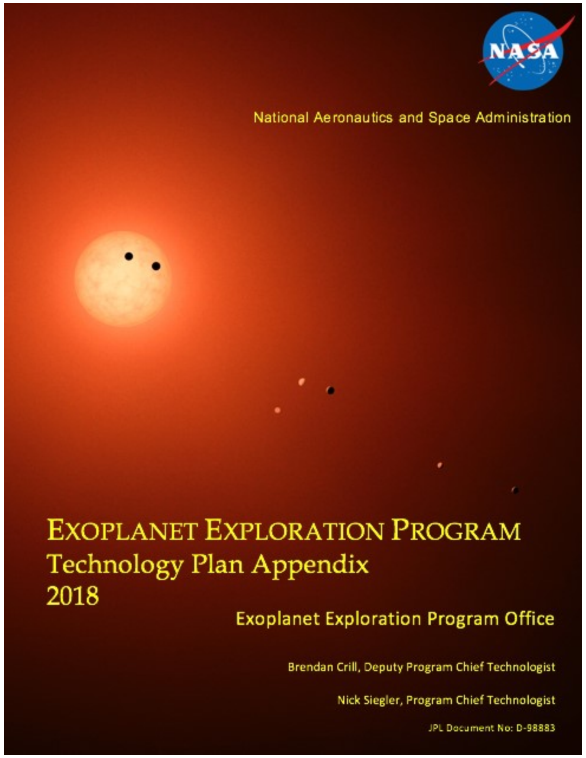
This Update is a supplement to the *Astrophysics Implementation Plan: 2014 Update*, which will not be revised.

Astrophysics Division
Science Mission Directorate
NASA Headquarters

December 15, 2016

ExEP Technology List

ID	Technology	Technology Gap	Technology Description	Current Capabilities	Needed Capabilities
S-1	**Controlling Scattered Sunlight**	Starshade Contrast	Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle stowed bending strain.	Machined graphite edges meet all specs but edge radius (≥ 10 µm); etched metal edges meet all specs but in-plane shape tolerance (Exo-S design).	Integrated petal optical edges maintaining precision in-plane shape requirements after deployment trials and limit solar glint contributing < 10^{-10} contrast at petal edges.



- **24 technologies currently tracked**
- **Technology List posted here:** https://exoplanets.nasa.gov/exep/technology/gap-lists/
- **More detail coming soon in the Technology Plan Appendix**

2018 Technology Selection and Prioritization Process Results

- **In the 2017 Technology Plan Appendix, we had 18 items on the prioritized Technology List and 4 on the Watch List**

- **This summer, we received 37 technology inputs from the community**
  - 14 from LUVOIR STDT
  - 15 from HabEx STDT
  - 4 from OST STDT
  - 2 from community at large
  - 2 redirected from COR

- **Results:**
  - None were rejected
  - 32 were consolidated into existing technologies already on the List
  - 5 new additions to the Technology List
  - 2 from Watch List upgraded to the Technology List
  - 0 additions to the Watch List
  - 1 listed technology was broken down into 3 finer component/subsystem technologies

- **There are now 24 technologies on the 2018 prioritized list and 2 on the Watch List** https://exoplanets.nasa.gov/exep/technology/gap-lists/

2018 ExEP Prioritized Technology List

Exoplanet Exploration Program

Tech. ID	Technology Title	Impact	Urgency	Trend	2018 Score	2017 Score
	weight:	10	10	5		
CG-2	Coronagraph Architecture	4	4	2	**90**	85
S-2	Starlight Suppression and Model Validation	4	4	2	**90**	90
S-1	Controlling Scattered Sunlight	4	4	2	**90**	90
S-3	Lateral Formation Sensing	4	4	2	**90**	90
S-5	Petal Positioning Accuracy and Opaque Structure	4	4	2	**90**	90
S-4	Petal Shape and Stability	4	4	2	**90**	90
CG-3	Deformable Mirrors	4	4	2	**90**	80
CG-1	Large Aperture Primary Mirrors	4	3	3	**85**	85
CG-6	Mirror Segment Phasing	4	3	3	**85**	85
CG-7	Telescope Vibration Sense/Control or Reduction	4	3	3	**85**	85
CG-9	Ultra-Low Noise Near-Infrared Detectors	4	3	3	**85**	85
CG-5	Wavefront Sensing and Control	4	3	2	**80**	80
CG-8	Ultra-Low Noise Visible Detectors	4	3	2	**80**	80
M-4	Ultra-Stable Mid-IR detector	3	3	4	**80**	
M-3	Astrometry	3	3	3	**75**	
CG-4	Data Post-Processing Algorithms and Techniques	4	2	2	**70**	70
CG-10	Mirror Coatings for UV/NIR/Vis	3	3	2	**70**	70
M-2	Space-based Laser Frequency Combs	3	3	2	**70**	
CG-13	Ultra Low-noise Mid-IR detectors	2	3	4	**70**	
M-1	Extreme Precision Ground-based Radial Velocity	2	3	3	**65**	75
CG-14	Mid-IR Large Aperture Telescopes	2	3	3	**65**	
CG-15	Mid-IR Coronagraph Optics and Architecture	2	3	3	**65**	
CG-16	Cryogenic Deformable mirror	2	3	3	**65**	
CG-12	Ultra-Low Noise UV Detectors	2	3	2	**60**	60

Carried over from 2017
New to list in 2018

Investments in ExEP Technologies

Exoplanet Exploration Program

Tech. ID	Technology Title			
CG-2	Coronagraph Architecture	✓	✓	✓
S-2	Starlight Suppression and Model Validation	✓	✓	
S-1	Controlling Scattered Sunlight	✓	✓	
S-3	Lateral Formation Sensing	✓	✓	✓
S-5	Petal Positioning Accuracy and Opaque Structure	✓	✓	
S-4	Petal Shape and Stability	✓	✓	
CG-3	Deformable Mirrors	✓		✓
CG-1	Large Aperture Primary Mirrors	✓	✓	✓
CG-6	Mirror Segment Phasing		✓	✓
CG-7	Telescope Vibration Sense/Control or Reduction		✓	✓
CG-9	Ultra-Low Noise Near-Infrared Detectors	✓		
CG-5	Wavefront Sensing and Control		✓	✓
CG-8	Ultra-Low Noise Visible Detectors	✓		✓
M-4	Ultra-Stable Mid-IR detector			✓
M-3	Astrometry	✓		
CG-4	Data Post-Processing Algorithms and Techniques			✓
CG-10	Mirror Coatings for UV/NIR/Vis	✓	✓	
M-2	Space-based Laser Frequency Combs			✓
CG-13	Ultra Low-noise Mid-IR detectors			✓
M-1	Extreme Precision Ground-based Radial Velocity	✓	✓	
CG-14	Mid-IR Large Aperture Telescopes			✓
CG-15	Mid-IR Coronagraph Optics and Architecture			✓
CG-16	Cryogenic Deformable mirror			✓
CG-12	Ultra-Low Noise UV Detectors	✓		

✓ SAT / APRA

✓ directed

✓ mission or mission concept

funded to TRL 5 *

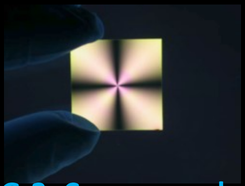
funded to TRL 5 * for some mission architectures

Carried over from 2017
New to list in 2018

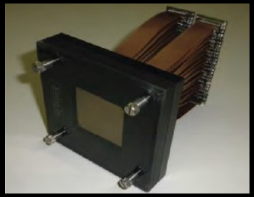
* for an exo-Earth imaging mission

V-NIR Coronagraph/Telescope Technology Gaps

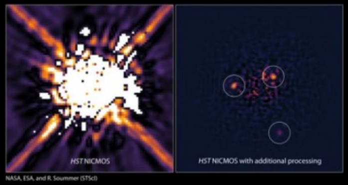
Contrast



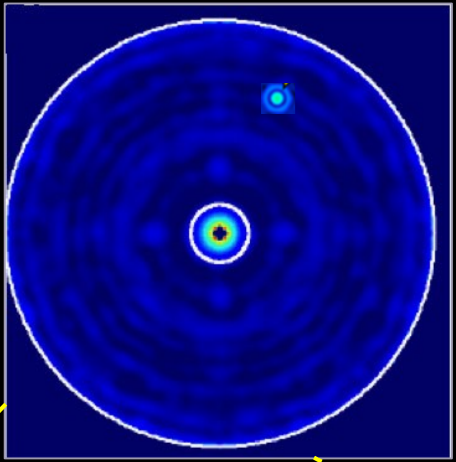
CG-2: Coronagraph Architecture



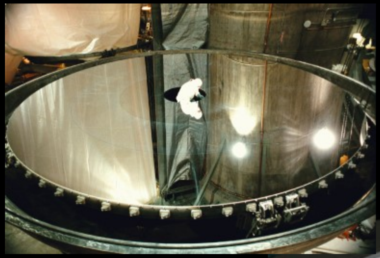
CG-3: Deformable Mirrors



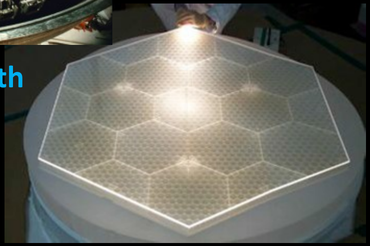
CG-4: Data Post-Processing



Angular Resolution

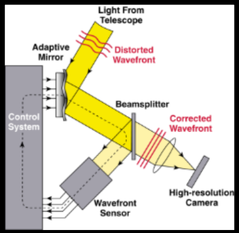


CG-1: Large Monolith Mirrors



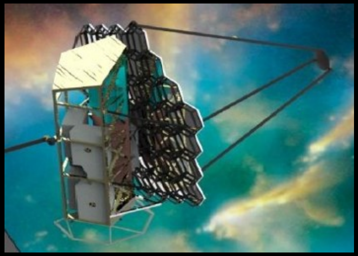
CG-1: Segmented Mirrors

Contrast Stability



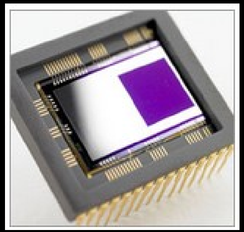
CG-5: Wavefront Sensing and Control

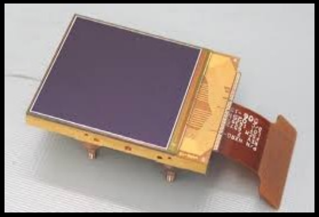
CG-6: Mirror Segment Phasing



CG-7: Telescope Vibration Sensing and Control or Reduction

Detection Sensitivity





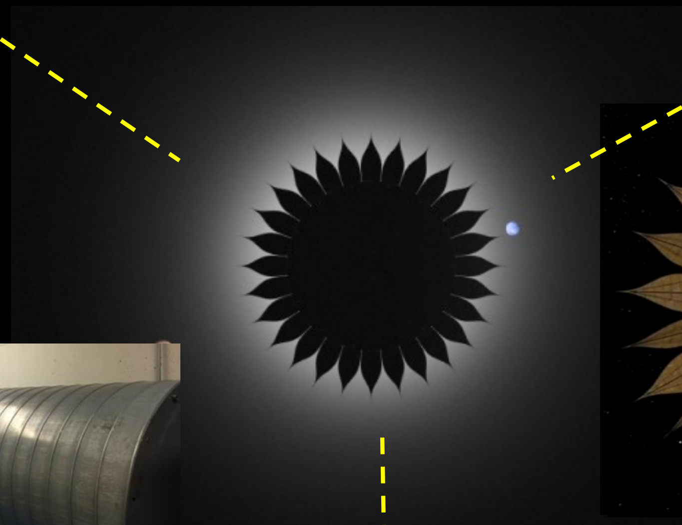
Ultra-low Noise Visible (CG-8) and Infrared (CG-9) Detectors

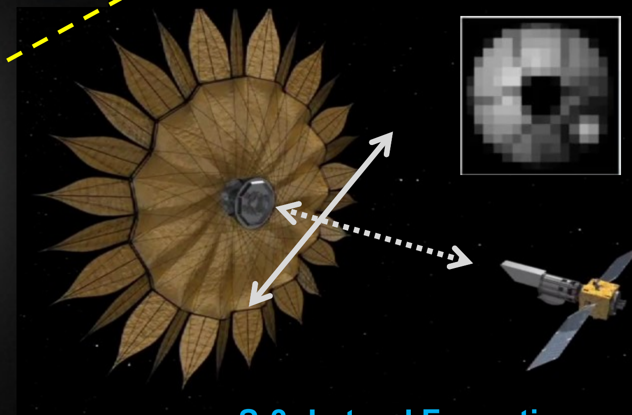
Starshade Technology Gaps

Starlight Suppression

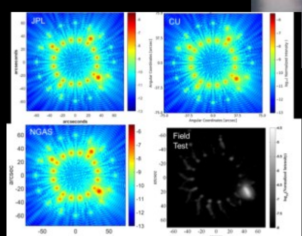
S-1: Controlling Scattered Sunlight

Formation Sensing



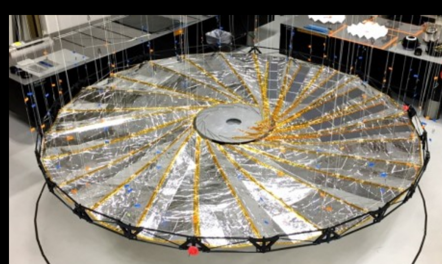


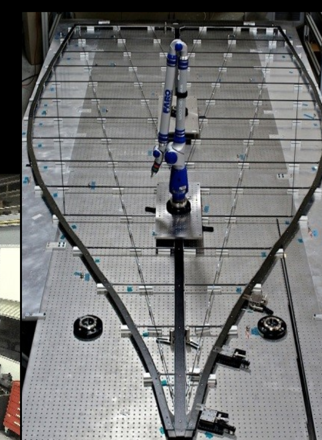
S-3: Lateral Formation Sensing



S-2: Starlight Suppression and Model Validation

Deployment Accuracy and Shape Stability



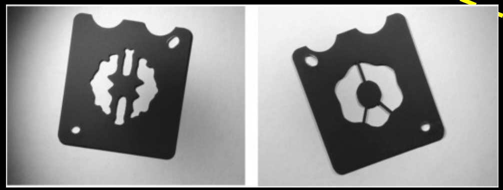


S-4: Petal Shape And Stability

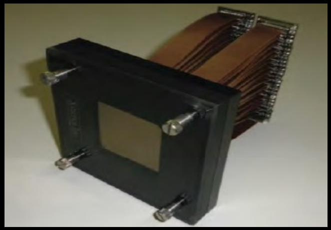
S-5: Petal Positioning Accuracy and Opaque Structure

Mid-IR Coronagraph/Telescope Technology Gaps

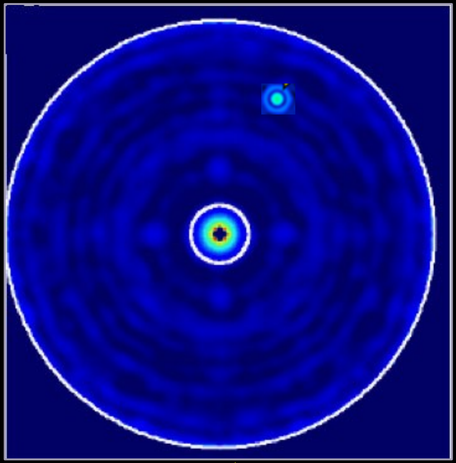
Contrast



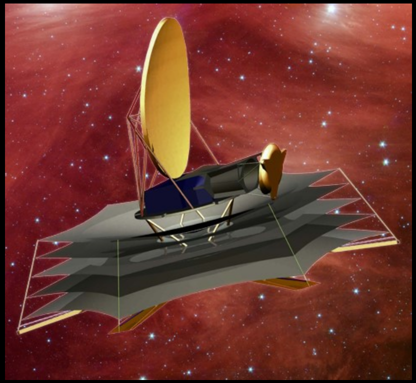
G-15: Mid-IR Coronagraph Optics and Architecture



CG-16: Cryogenic Deformable Mirror

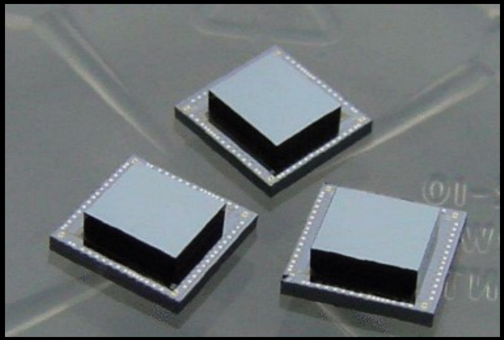


Angular Resolution



CG-14: Mid-IR Large Aperture Telescopes

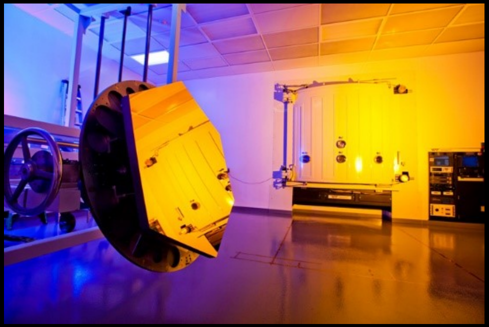
Detection Sensitivity



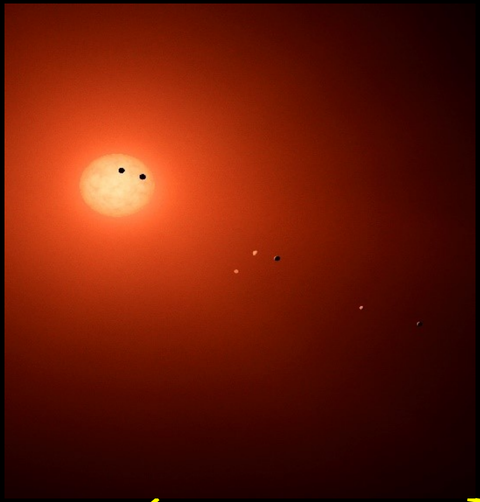
CG-13: Low-Noise Mid-IR Detectors

Other Technology Gaps

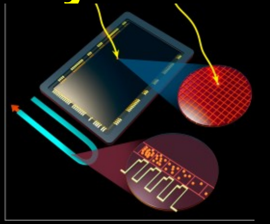
UV Contrast



CG-10 UV/V/NIR Mirror Coatings

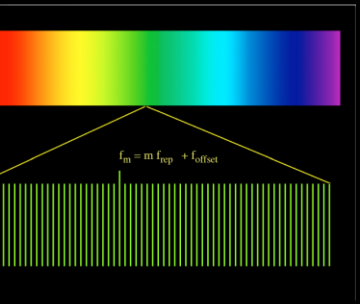


UV Detection Sensitivity

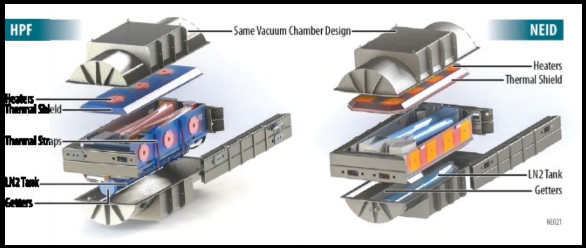


CG-12: Ultra-low Noise UV Detectors

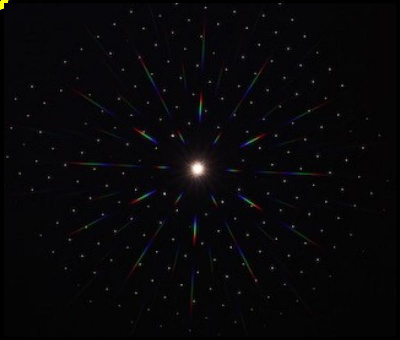
Stellar Reflex Motion Sensitivity



2: Laser Frequency Combs for Space-based EPRV

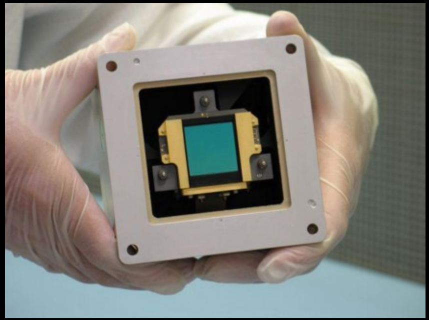


M-1: Ground-based Ultra-high Precision Radial Velocity



M-3: Astrometry

Transit Spectroscopy Sensitivity



M-4: Ultra-stable Mid-IR Detectors for Transit Spectroscopy