Exoplanet Exploration Program Technology Update

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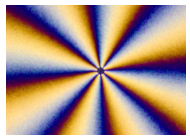
ExoPAG 23
05 Jan 2021

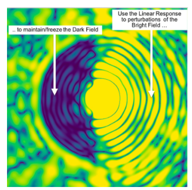
Image Credit:
NASA/Ames/JPL-Caltech/T. Pyle
astropix.ipac.caltech.edu

Technology Activities (in a snapshot)

Technology Gaps

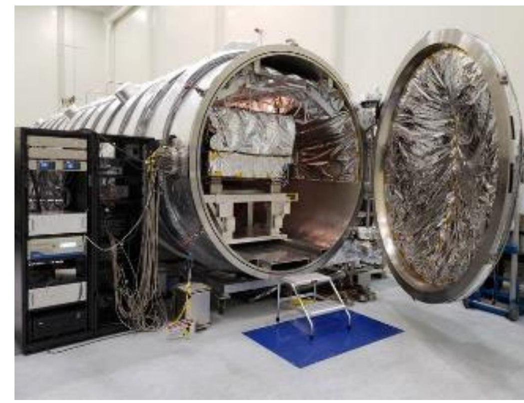
Strategic Astrophysics Technology Grants



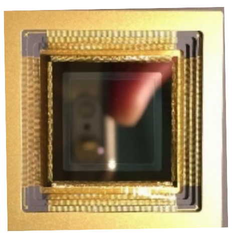


- *Coronagraph architectures: modeling and demonstrations*
- *Wavefront control*
- *Extreme Precision Radial Velocity*
- *Detectors*

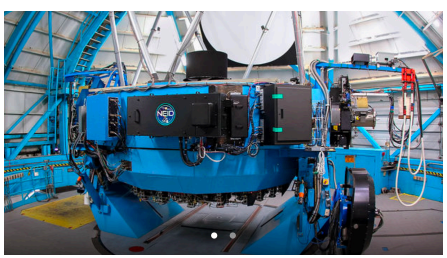
Ultra-Stable Coronagraph Testbeds

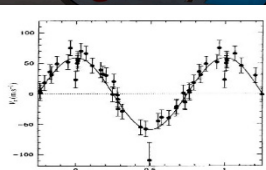


Deformable Mirror Survey

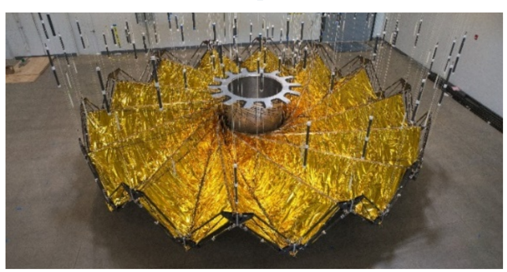


Extreme Precision Radial Velocity

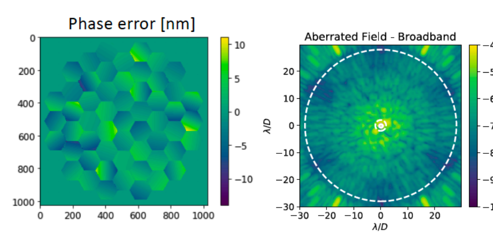


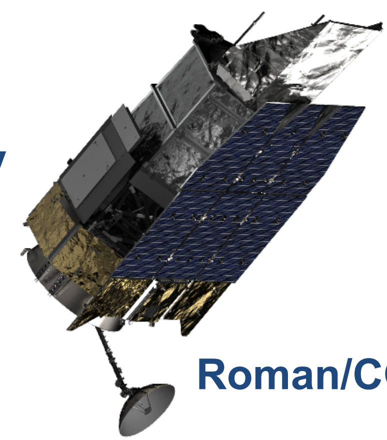


Starshade Technology Development



Segmented Coronagraph Design & Analysis Study





Roman/CGI

Decadal Survey

2010 Decadal Survey

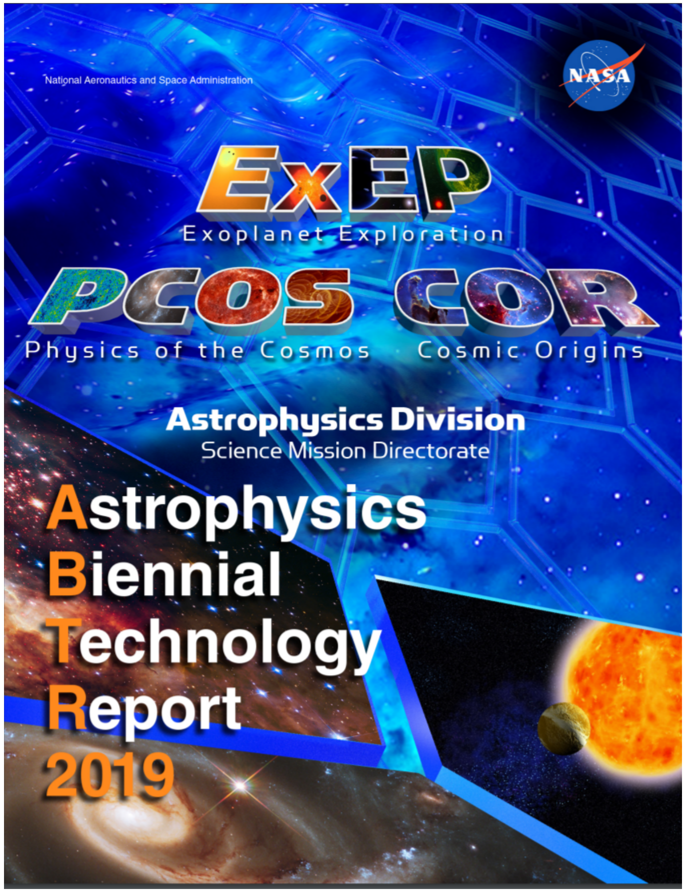
TABLE ES.4 Space: Recommended Activities—Medium-Scale (Priority Order)

Recommendation	Science	Appraisal of Costs[a]
1. New Worlds Technology Development Program	Preparation for a planet-imaging mission beyond 2020, including precursor science activities	$100M to $200M
2. Inflation Probe Technology Development Program	Cosmic microwave background (CMB)/ inflation technology development and preparation for a possible mission beyond 2020	$60M to $200M

2020 Decadal Survey expected in spring 2021

Technology Gaps

NASA EXOPLANET EXPLORATION PROGRAM



www.astrostrategictech.us

Tier 1 Technology Gaps
Angular Resolution (UV/Vis/NIR)
Coronagraph Contrast
Coronagraph Contrast Stability
Cryogenic Readouts for Large-Format Far-IR Detectors
Fast, Low-Noise, Megapixel X-Ray Imaging Arrays with Moderate Spectral Resolution
High-Efficiency X-Ray Grating Arrays for High-Resolution Spectroscopy
High-Resolution, Large-Area, Lightweight X-Ray Optics
Large-Format, High-Resolution, UV/Vis Focal Plane Arrays
Large-Format, High-Spectral-Resolution, Small-Pixel X-Ray Focal-Plane Arrays
Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors
Large-Format, Low-Noise, High-QE Far-UV Detectors
Next-Generation, Large-Format, Object Selection Technology for Multi-Object Spectrometers for LUVOIR
Vis/NIR Detection Sensitivity

Tier 2 Technology Gaps
Advanced Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry
Detection Stability in Mid-IR
Heterodyne FIR Detector Arrays and Related Technologies
High-Efficiency Object Selection Technology for UV Multi-Object Spectrometers
High-Performance Spectral Dispersion Component/Device
High-Reflectivity Broadband FUV-to-NIR Mirror Coatings
High-Throughput Bandpass Selection for UV/Vis
Large-Format Object Selection Technology for Multi-Object Spectrometers for HabEx
Starshade Deployment and Shape Stability
Starshade Starlight Suppression and Model Validation
Stellar Reflex Motion Sensitivity – Astrometry
Stellar Reflex Motion Sensitivity – Extreme Precision Radial Velocity

Tier 3 Technology Gaps
Advanced Cryocoolers
High-Performance, Sub-Kelvin Coolers
Large Cryogenic Optics for the Mid-IR to Far-IR
Long-Wavelength-Blocking Filters for X-Ray Micro-Calorimeters
Low-Noise, High-QE UV Detectors
Low-Stress, Highly Stable X-Ray Reflective Coatings
Photon-Counting, Large-Format UV Detectors
Polarization-Preserving Millimeter-Wave Optical Elements
UV Coatings
UV Detection Sensitivity
UV/Vis/NIR Tunable Narrow-Band Imaging Capability
Warm Readout Electronics for Large-Format Far-IR Detectors

Tier 4 Technology Gaps
Compact, Integrated Spectrometers for 100 to 1000 μm
Optical-Blocking Filters
Rapid Readout Electronics for X-Ray Detectors
Short-Wave UV Coatings

Tier 5 Technology Gaps
Advancement of X-Ray Polarimeter Sensitivity
Far-IR Spatio-Spectral Interferometry
High-Precision Low-Frequency Radio Spectrometers and Interferometers
Mid-IR Coronagraph Contrast
Ultra-High-Resolution Focusing X-Ray Observatory Telescope
Very-Wide-Field Focusing Instrument for Time-Domain X-Ray Astronomy
Wide-Bandwidth, High-Spectral-Dynamic-Range Receiving System for Low-Radio-Frequency Observations on the Lunar Far Side

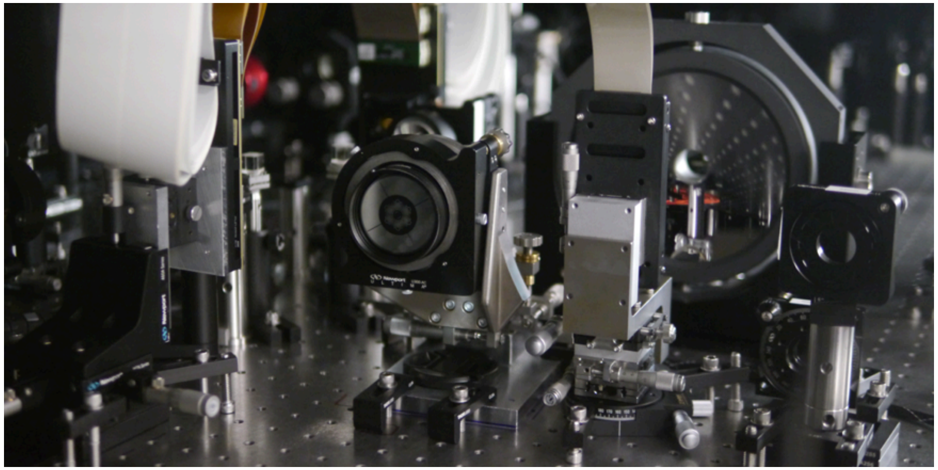
Technology Gap List to be updated by September 2021, responsive to Astro2020 recommendations

-> See Joint PAG talk by Nick Siegler & Thai Pham Friday Jan 8

Strategic Astrophysics Technology

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)



HiCAT testbed at STScI: Soummer SAT-2018

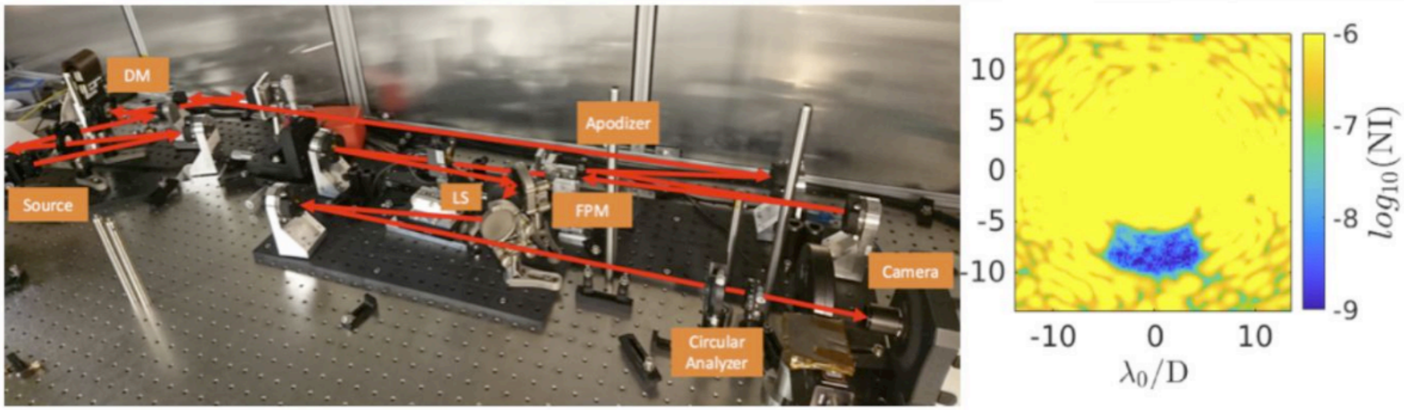
Polarization and coronagraphy (Breckinridge/UA)

- *Final report completed and posted*

Wavefront-control Techniques

Single mode fiber and optimization for spectroscopy (Mawet/Caltech)

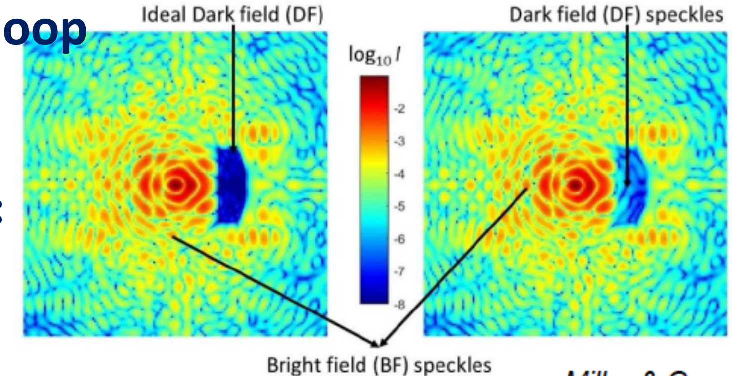
- Enables wide bandwidth at high contrast
- Next Step: demonstrate 20% bandwidth at 10^{-8} contrast in air



Mawet SAT-2018

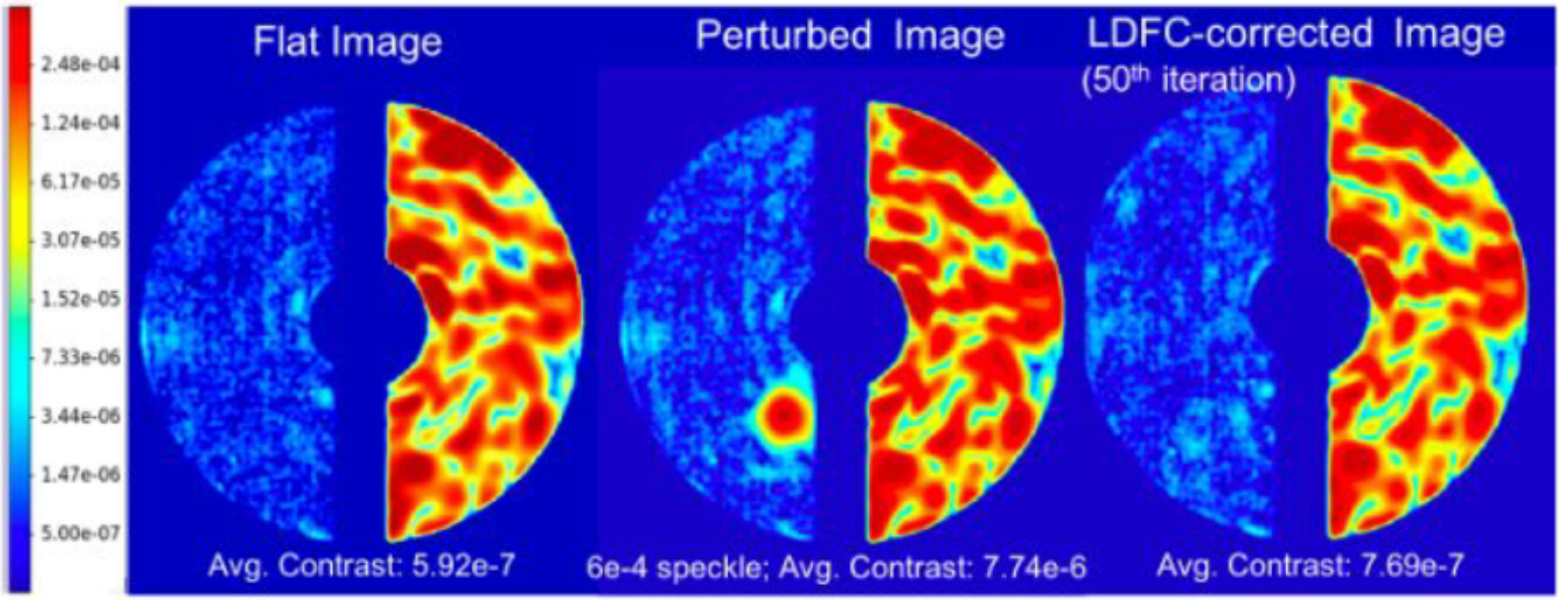
Linear Dark Field Control Milestone

- **Uses signal changes in bright region of coronagraph focal plane in a linear control loop that corrects speckles in the dark hole**



Miller & Guyon 2017

- **Milestone #1 achieved (pending ExoTAC review):**
  - *Demonstration of the technique on an in-air testbed at NASA ARC (Currie et al 2020)*

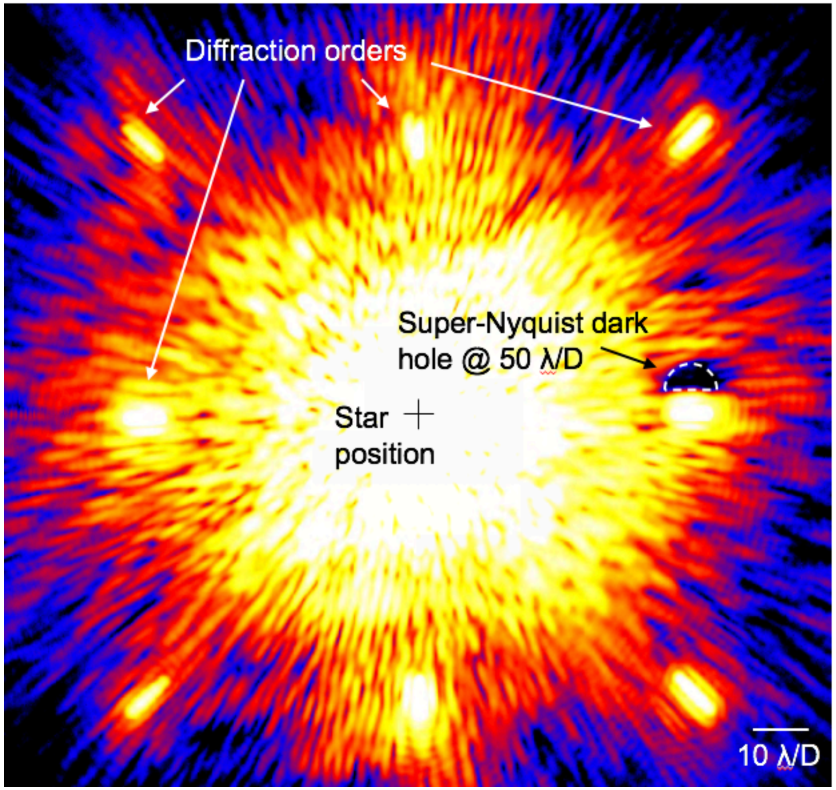


- **Next steps: demos in SCExAO, HCIT**

PI Olivier Guyon (UA)

Multi-Star Wavefront Control in Vacuum

- Demonstrated wavefront control in the vacuum testbed at JPL to create a dark hole at 50 λ/D using diffraction orders of source.



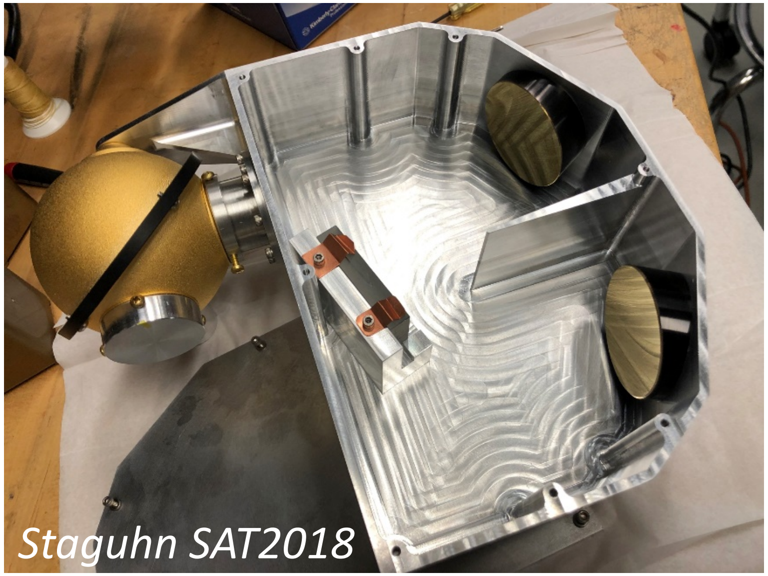
PI Rus Belikov (NASA/ARC)

- Next step: full multi-star (dark hole with two sources) in vacuum.

Detectors and EPRV

Detectors

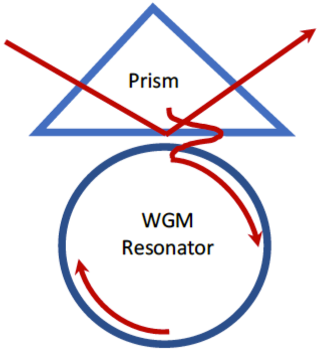
- Vis-band rad-hard photon-counting detectors (Rauscher/NASA-GSFC)
- Ultra-stable mid-IR detector array (Staguhn/JHU)

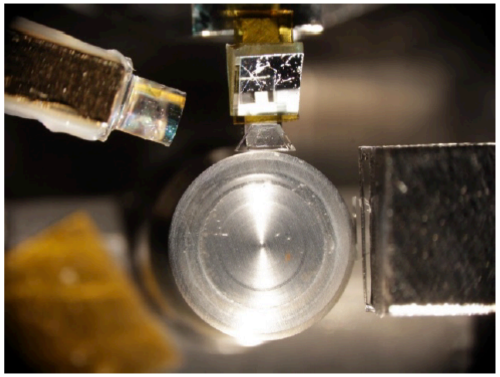


Staguhn SAT2018

Extreme Precision Radial Velocity

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

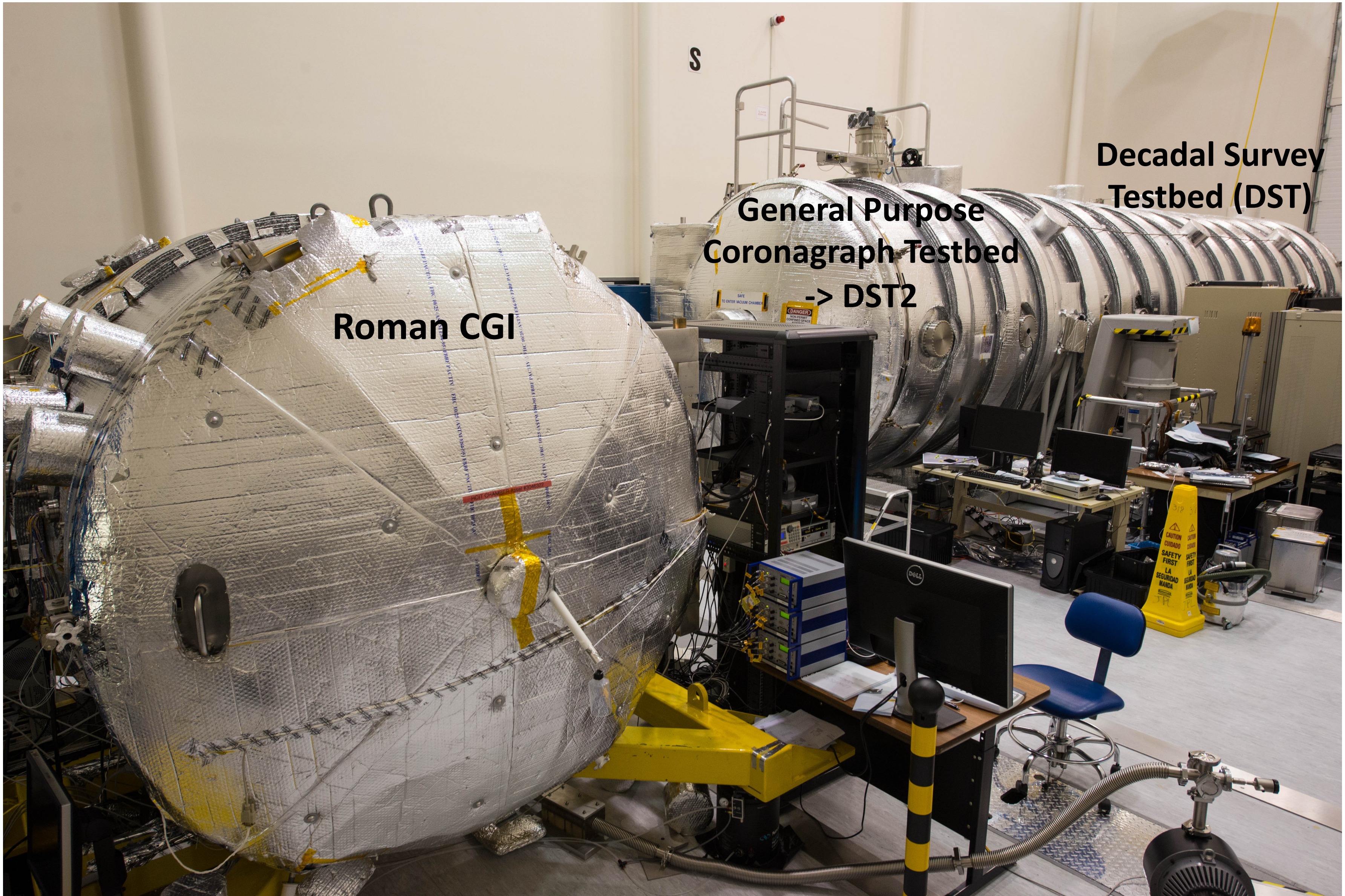




Leifer SAT2018

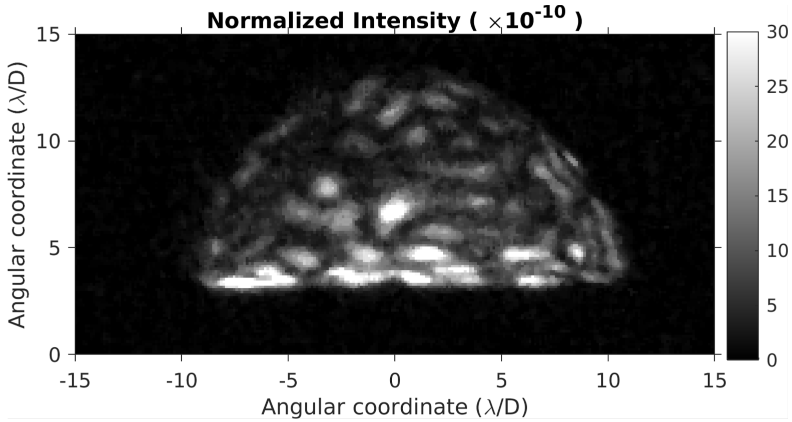
https://exoplanets.nasa.gov/exep/technology/TDEM-awards/

High Contrast Imaging Testbed Facility

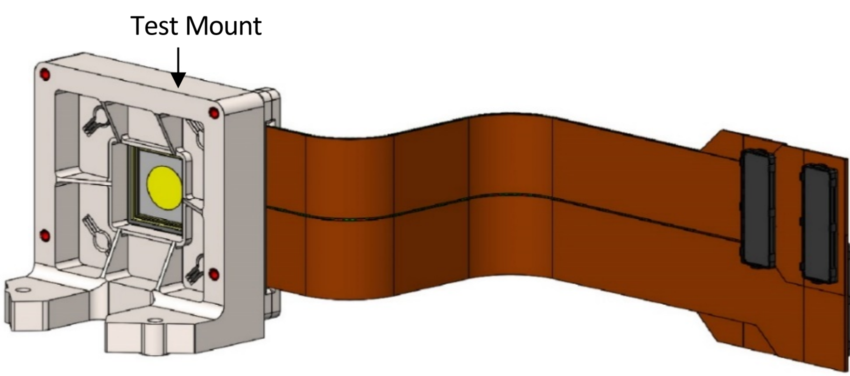


MEMS Deformable Mirrors

- **50x50 Deformable Mirror demonstrations in vacuum**
  - MEMS DM narrowband demo in Decadal Survey Testbed contrast 8×10^{-10} from 3.5 to 13.5 λ/D narrowband at 516 nm; 2×10^{-9} 10% band



- **Two 2000-actuator MEMS DM's to undergo launch-level vibrations**
  - one not coated (to allow IR microscopy)
  - one coated



- **Next step: deliver DM units to JPL for pre-test performance characterization**

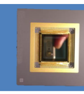
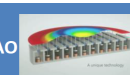
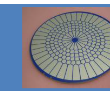
Deformable Mirror Survey

Goals:

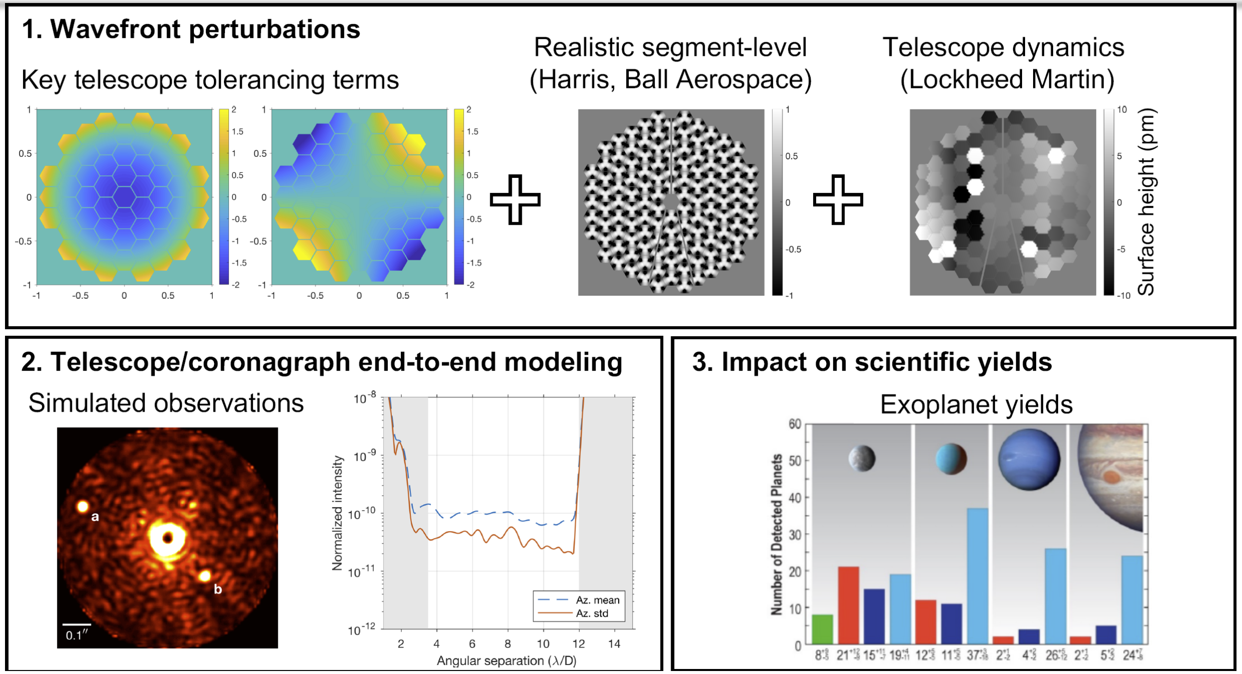
1. Survey and document viable DM technologies across the world to inform future exoplanet space missions
2. Make recommendations for DM technologies
3. Identify new technologies that could be matured rapidly for flight

Status

- **Evaluation criteria determined by a group of DM Subject Matter Experts**
- **Fact finding completed**
  - 13 DM vendors from 6 different countries
- **DM options have been scored relative to each other**
  - Scores to be reviewed and concurred by SMEs
- **Final report expected by 5/2021**

	BMC 	Xinetics 	ALPAO 	Cilas 
Technology	Electro static force between pin and membrane	Electrostrictive (PMN) material	Electromagnetic	Bimorph piezoelectric actuation
Control type	Voltage	Voltage	Current	Voltage
Membrane contact	None	Yes	None	Yes
Actuator pitch	0.3 - 0.45 mm	1.0 - 2.5 mm	0.8 – 20.6 mm	≥ 2 mm
Actuator stroke	1 to 2 μm	0.5 μm	8 – 25 μm	20 μm (OTOS)
Actuator count	4096 (64x64)	4356 (66x66)	3228 (64 across)	188(OTOS has 63)
Capability	Up to 9216 (96x96)	Up to 9216 (96x96)	Up to 12912 (128 across)	Few hundreds
Actuator resolution	15 pm	20 pm measured	120 pm	~300 pm
Capability	15 pm	8 pm	15 pm	50 pm
Key limitations for flagship mission	Surface Quilting, actuator **count**	Actuator **pitch**, stability	Actuator **pitch**	Actuator **count, pitch** and resolution
Company information	U.S. Based DMs are the main business Independent company	U.S. Based DMs are the main business Parent: Northrop Grumman, strategic business unit	France DMs 70% of $4M revenue Parent: Eveon	France DM's 10% of revenue Ariane group and AREVA

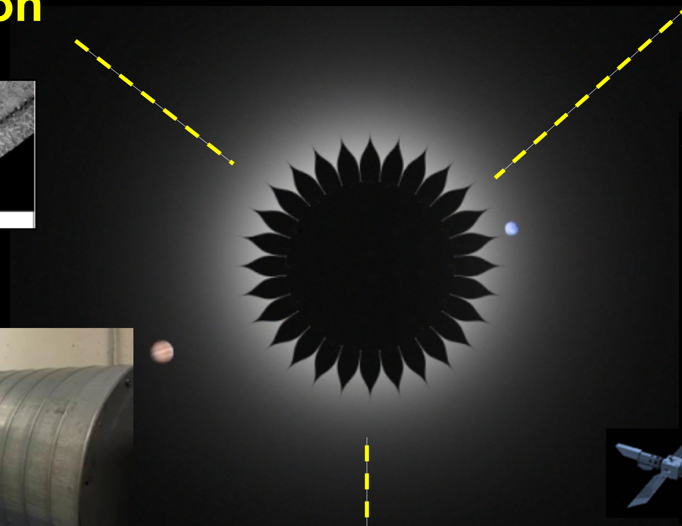
Segmented Coronagraph Design & Analysis



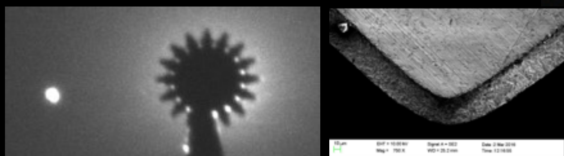
- **Year-to-Date Accomplishments**
  - Incorporated quasi-static and dynamic telescope aberrations (by Ball Aerospace and Lockheed Martin) in simulations of contrast performance
  - Produced coronagraph performance data for exoEarth yield computations
- **Next Steps:**
  - Understanding requirements on telescope dynamics to enable 10^{-10} coronagraph contrast performance
  - Science yield analysis per coronagraph architecture

The Three Starshade Technology Gaps

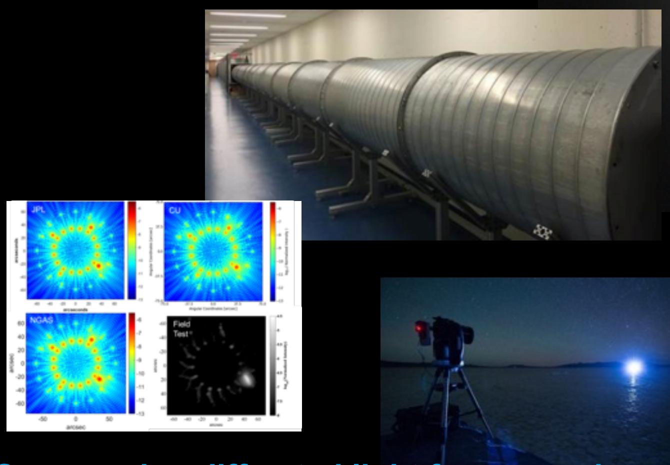
https://exoplanets.nasa.gov/exep/technology/starshade/



(1) Starlight Suppression

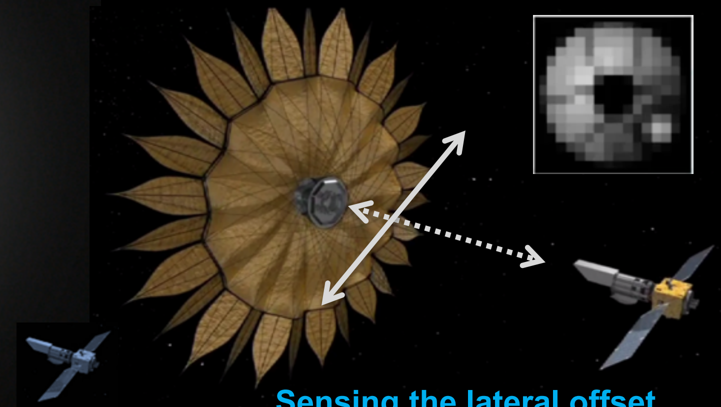


Suppressing scatted light off petal edges from off-axis Sunlight (S-1)



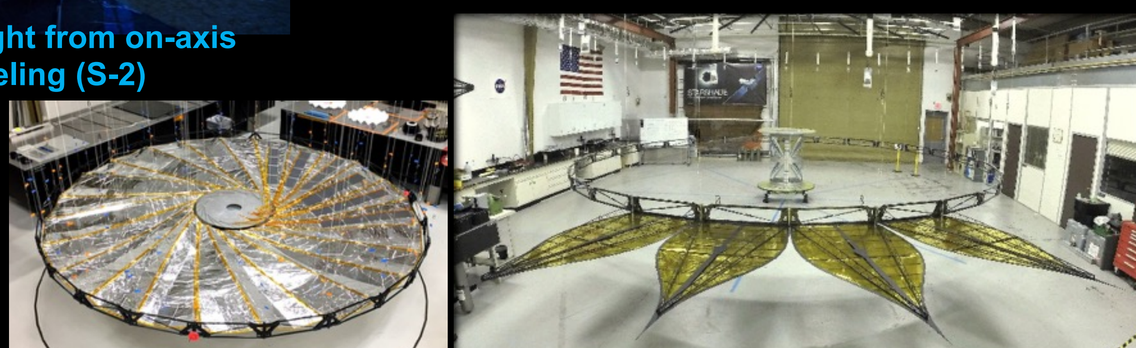
Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

(2) Formation Sensing

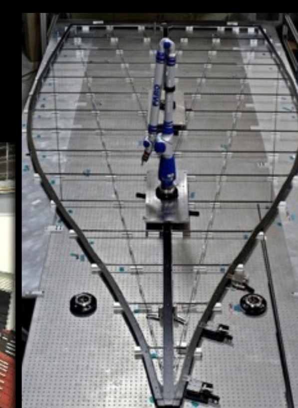


Sensing the lateral offset between the spacecraft (S-3)

(3) Deployment Accuracy and Shape Stability



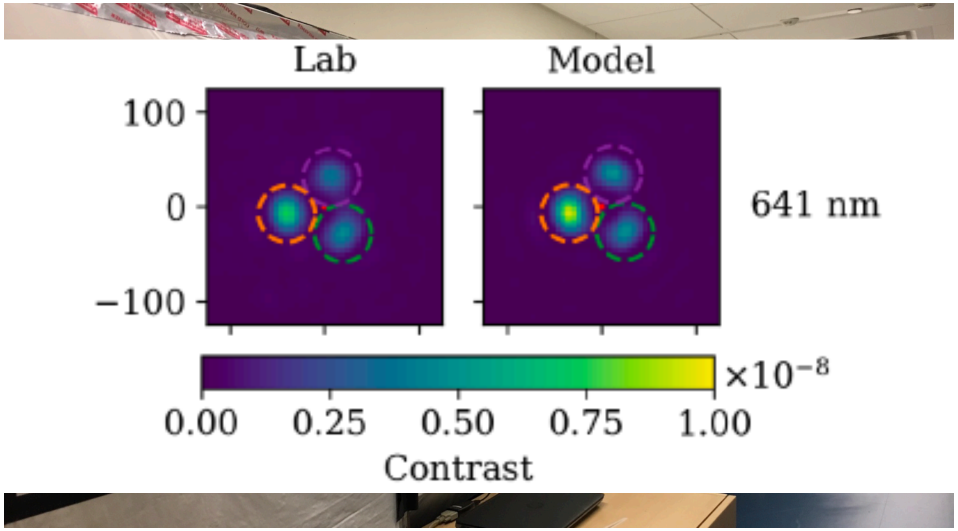
Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)



Fabricating the petals to high accuracy (S-4)

Gap #1: Starlight Suppression and Edge Scatter

- **Subscale Starshade optical tests and model validation continues**
  - Tests of subscale starshades with deliberate shape errors show contrast changes in agreement with model predictions
  - See Harness et al. SPIE 2020 proceedings



- **Edge Scatter:**
  - Antireflection coating on starshade edge provides large margin on solar glint requirement

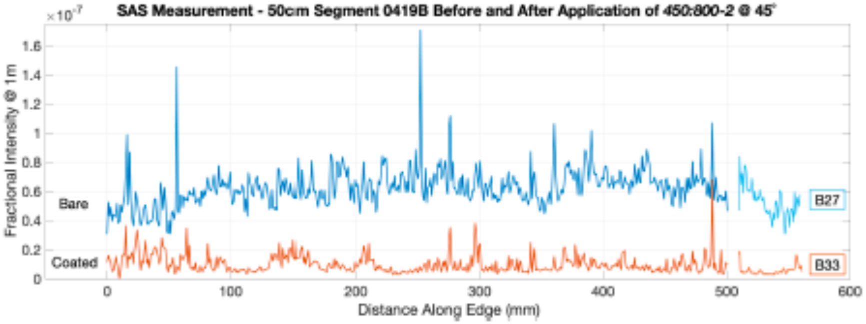
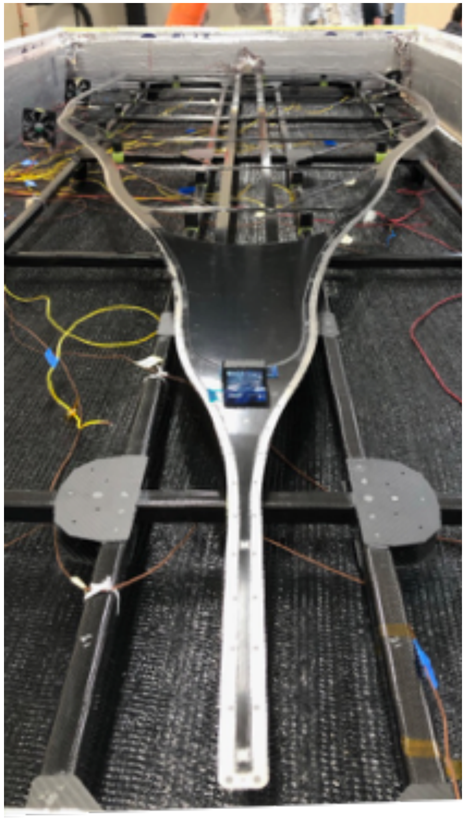


Fig 8: Before and after SAS measurements of a 50 cm AM edge segment which was coated with *450:800-2* at an angle of 45°. Also included in this plot is the representative uncoated coupon B27, as well as the coupon B33 which was coated in the same manner as the segment.

Gap #3: Shape Stability

- **Starshade Petal System successfully demonstrated to maintain prelaunch shape within +/- 70 μm after deploy and thermal cycles**
  - Modeling of results have been upgraded to include epoxy joints to achieve agreement with measurements

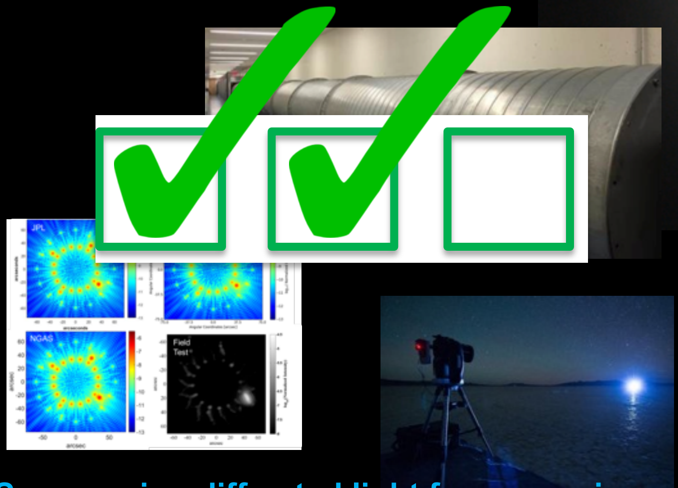


Starshade Technology Gaps Scorecard

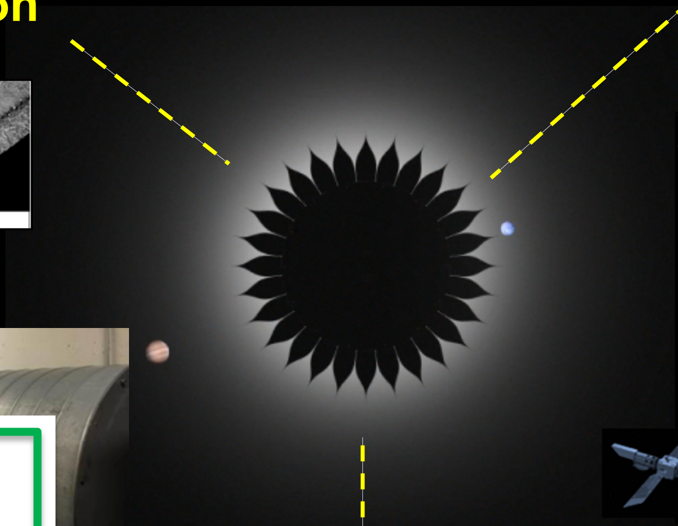
https://exoplanets.nasa.gov/exep/technology/starshade/

(1) Starlight Suppression

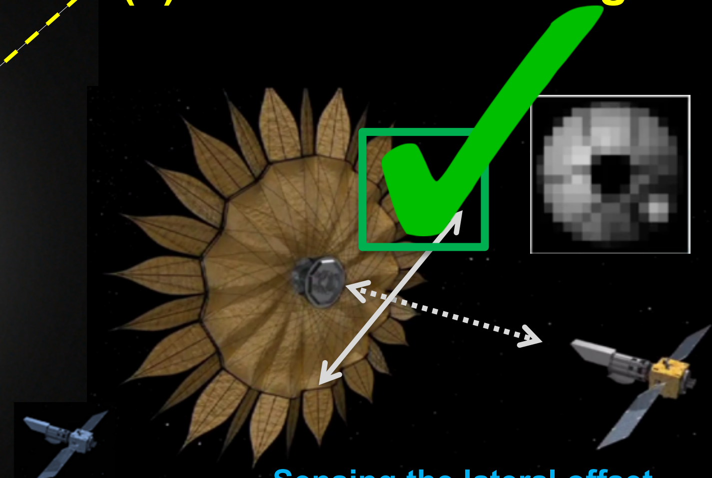
Suppressing scatted light off petal edges from off-axis Sunlight (S-1)



Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

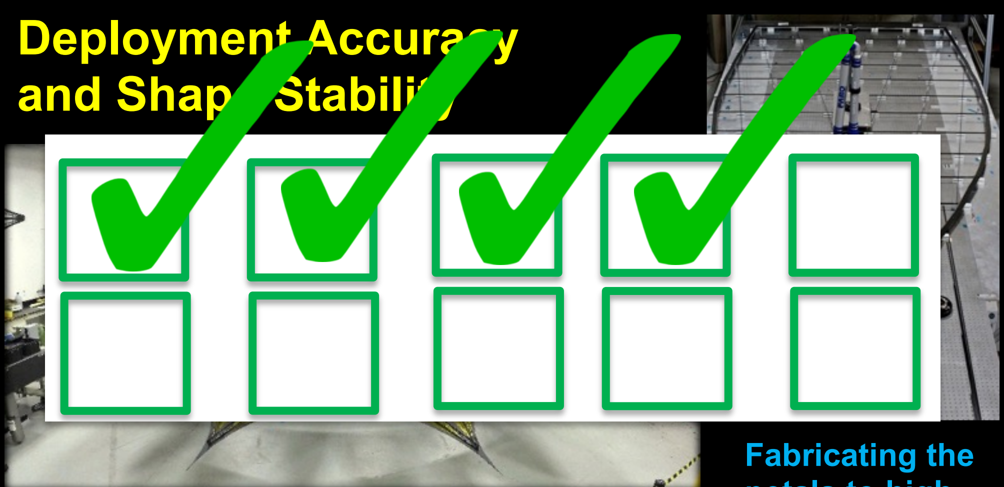


(2) Formation Sensing



Sensing the lateral offset between the spacecraft (S-3)

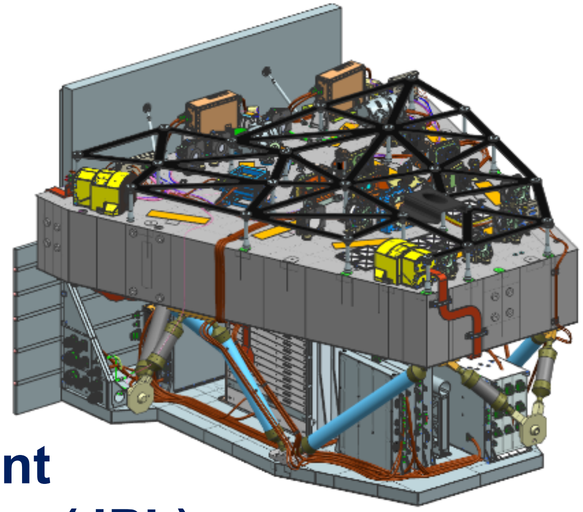
(3) Deployment Accuracy and Shape Stability



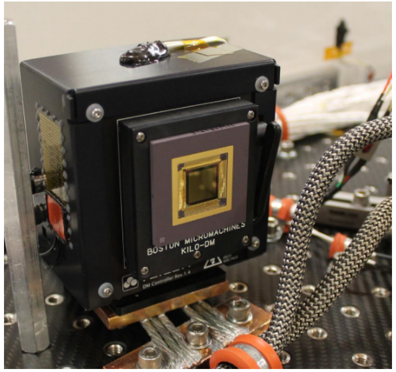
Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)

Fabricating the petals to high accuracy (S-4)

Exoplanet Exploration Technology Colloquium Series



- **Status of the Coronagraph Instrument (CGI) on the Roman Space Telescope, Feng Zhao (JPL)**
- **Status of MEMS Deformable Mirror Development in the HCIT, Eduardo Bendek and Garreth Ruane (JPL)**

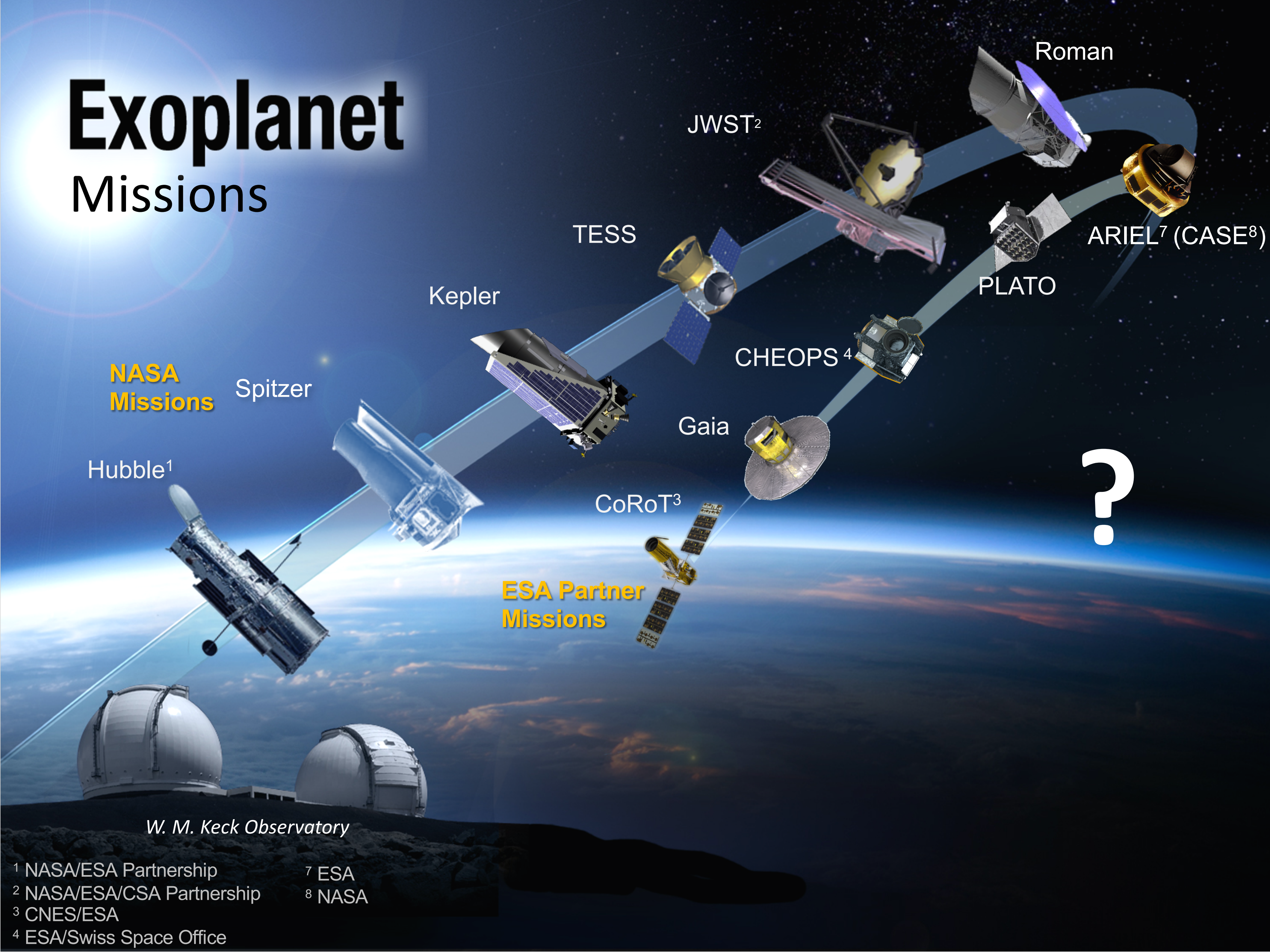


- **Recordings and slides available:**
  - https://exoplanets.nasa.gov/exep/technology/tech_colloquium/

Anticipating the Future…

- **Stellar Astrometry**
  - If Astro2020 recommends a direct imaging mission, will eventually need Earth-mass measurement capability that complements or is an alternative to EPRV
  - Astrometry technology is already on the Technology Gap List but may add new, more focused Technology Gaps: for example, detector calibration, optical field distortion

- **Nulling Interferometry**
  - ExEP kicking off an assessment of technical status and science prospects for mid-IR direct-imaging/spectral characterization of exo-Earths
  - Will include lessons learned since TPF-I from Keck, Palomar, LBT, and the VLT
  - Identification of potential Technology Gaps to add to the gap list
  - Astro2020 recommendations will set prioritization of this approach


Exoplanet
Missions
Roman
JWST2
TESS
ARIEL7 (CASE8)
PLATO
Kepler
CHEOPS 4
NASA
Missions
Spitzer
Gaia
Hubble1
CoRoT3
?
ESA Partner
Missions
W. M. Keck Observatory
1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
4 ESA/Swiss Space Office
7 ESA
8 NASA

BACKUP

Starshade Technology Activity (S5)
Technology Milestones Scorecard

NASA EXOPLANET EXPLORATION PROGRAM

Complete 2020 | Complete 2023

Starlight Suppression

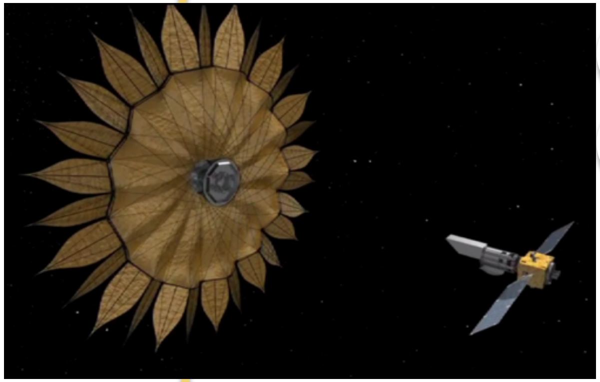
- Contrast NB 1A
- Contrast BB 1B
- Modeling 2

Scattered Sunlight

- Edges 3

Formation Flying

- Sensing 4



Milestone Completed

Report under Review

In Progress

Not Started

Critical Features | All Features

Shape Accuracy

- Petal 5A
- Truss Bay 7A
- Inner Disk 7C
- Petal 5B
- Truss Bay 7B
- Inner Disk 7D

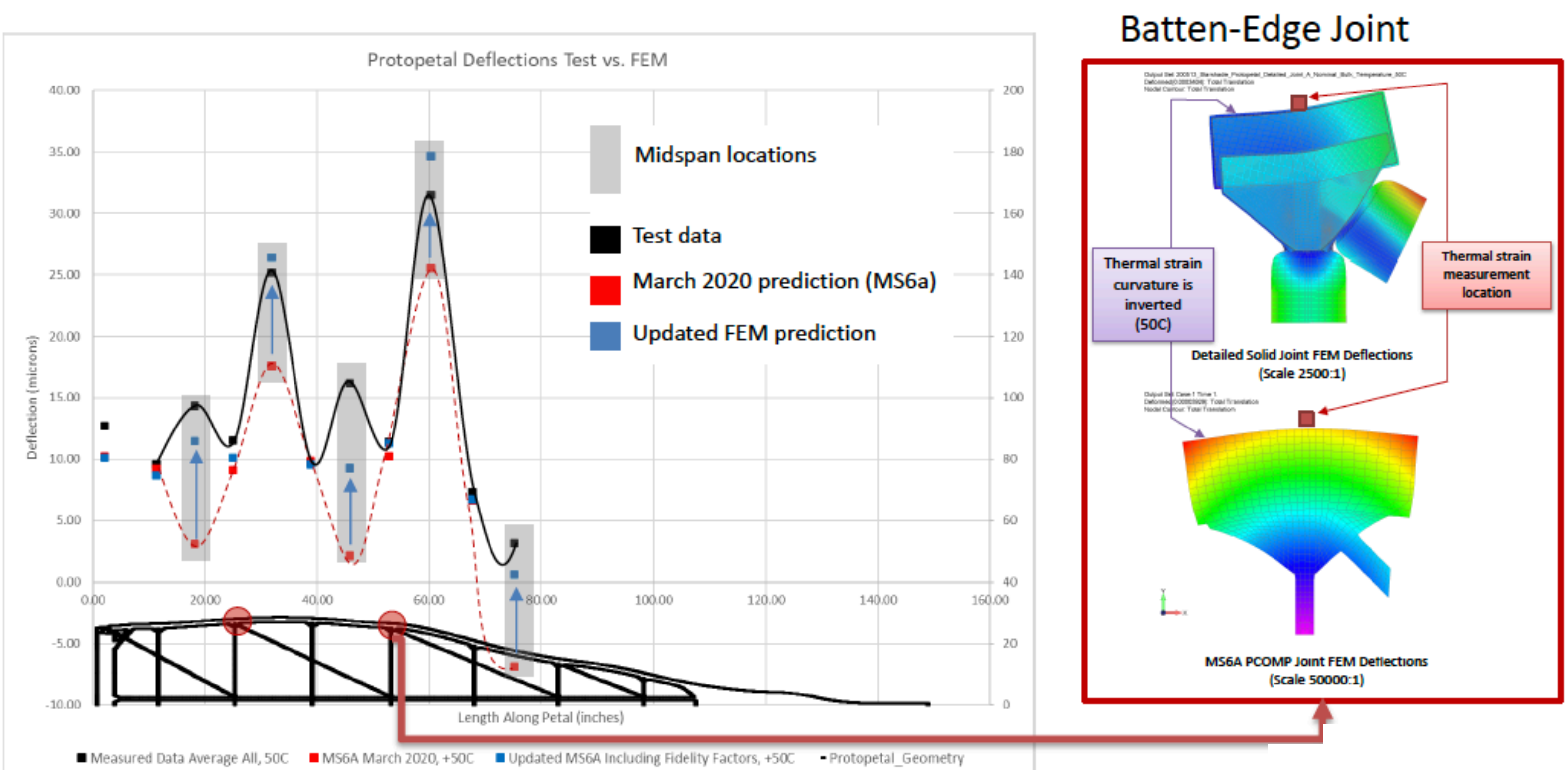
Shape Stability

- Petal 6A
- Inner Disk 8A
- Petal 6B
- Inner Disk 8B

from Phil Willems

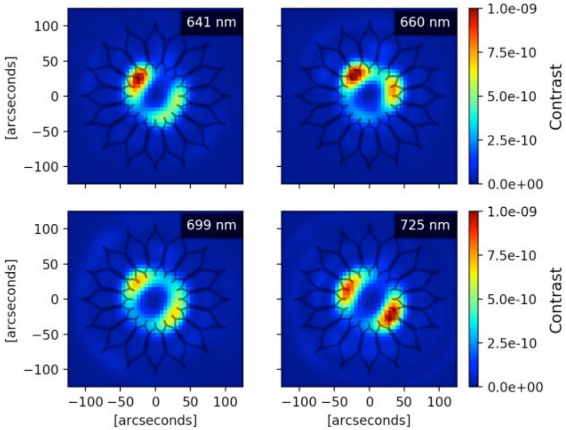
Gap #3: Shape Stability

- **Starshade petal thermal tests meet requirements**
  - Bowing in the petal investigated; traced to thermal expansion of epoxy in the petal joints

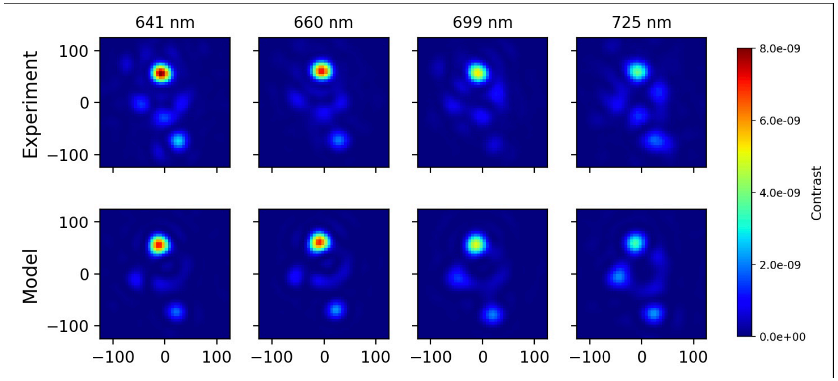


Starlight Suppression and Edge Scatter

- **Validate models of starshade performance**
- **Princeton testbed has been used to demonstrate starlight suppression to $< 10^{-10}$ over a 10% band of sub-scale starshade**

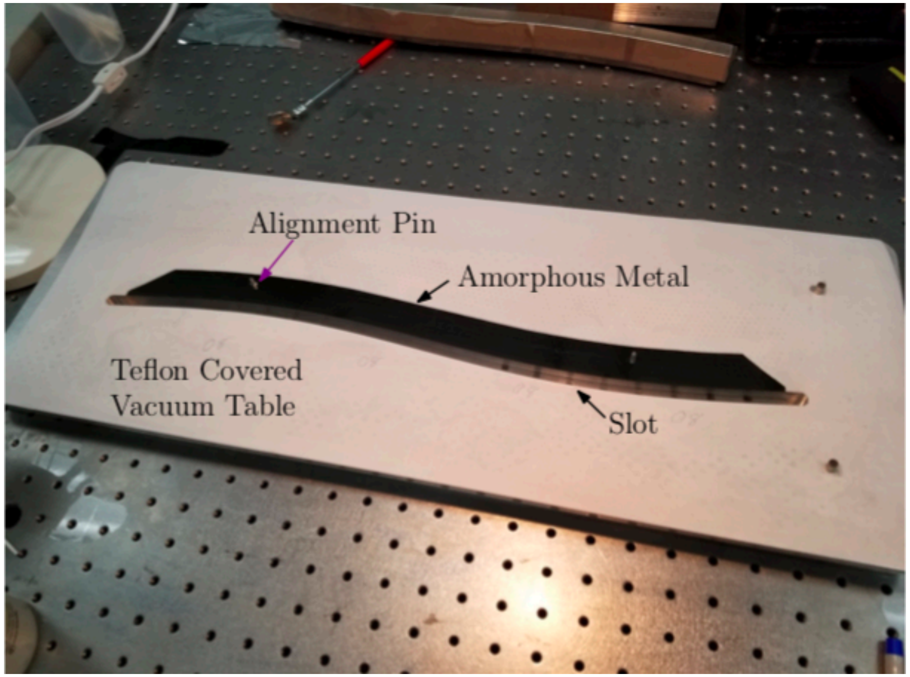


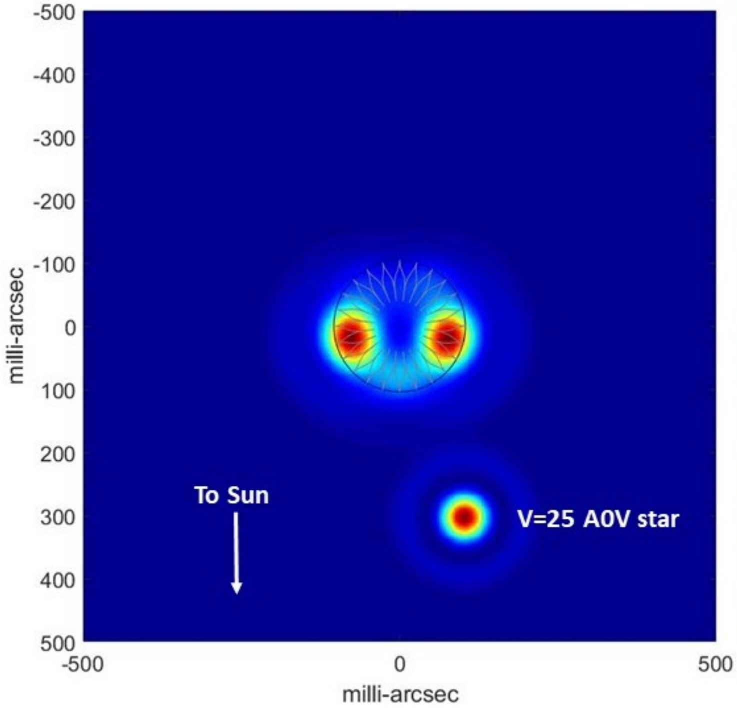
- **Last step: measure deliberately misshapen subscale starshades and compare with model predictions**



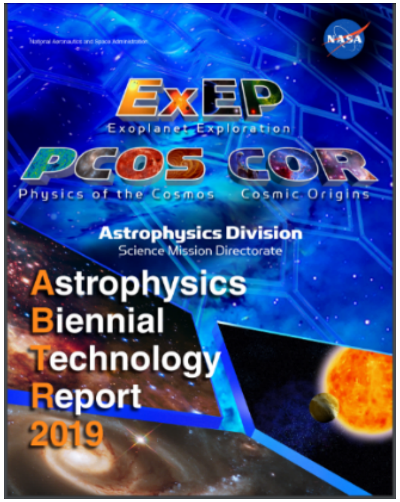
Starlight Suppression and Edge Scatter

- **Demonstrated starshade optical edge limits Solar scatter performance to lobe dimmer than mag 25 and maintains performance after thermal cycling**





Technology Gap List

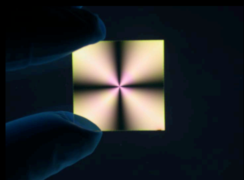


- **Astrophysics Technology Gap List**
  - Technology gaps for all three NASA Astrophysics Division (APD)'s programs
  - Database of technology activities:
    - http://astrostrategictech.us/
  - Update coming in 2021, post-decadal

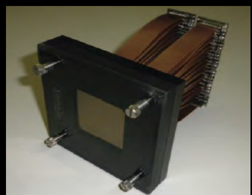
- **Exoplanet Technology Gap List**
  - Subset of APD gap list corresponding to exoplanet science:
    - https://exoplanets.nasa.gov/exep/technology/gap-lists/

V-NIR Coronagraph/Telescope Technology Gaps

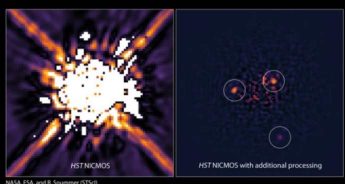
Contrast



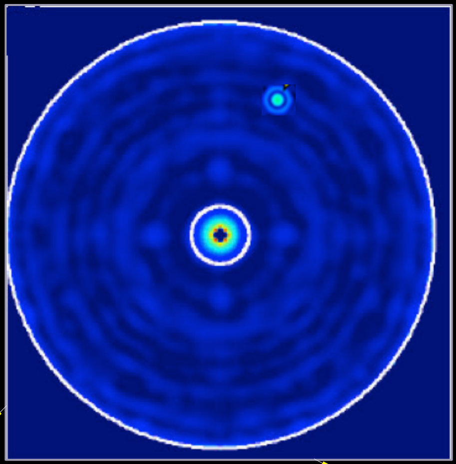
CG-2: Coronagraph Architecture



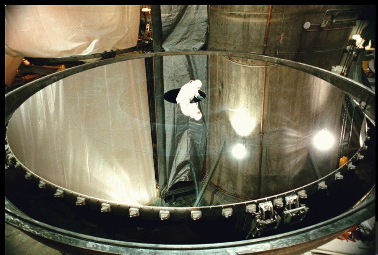
CG-3: Deformable Mirrors



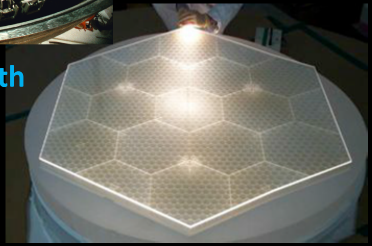
CG-4: Data Post-Processing



Angular Resolution

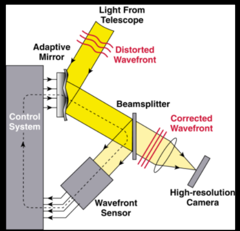


CG-1: Large Monolith Mirrors



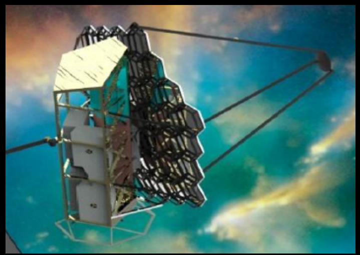
CG-1: Segmented Mirrors

Contrast Stability



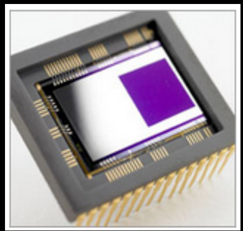
CG-5: Wavefront Sensing and Control

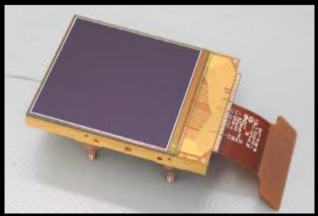
CG-6: Mirror Segment Phasing



CG-7: Telescope Vibration Sensing and Control or Reduction

Detection Sensitivity

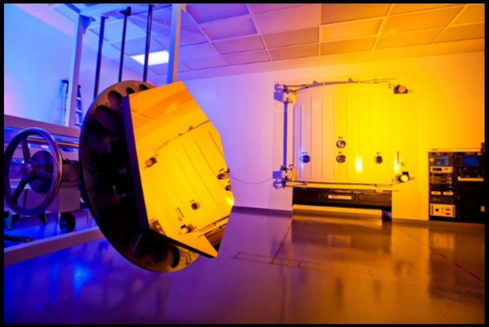




Ultra-low Noise Visible (CG-8) and Infrared (CG-9) Detectors

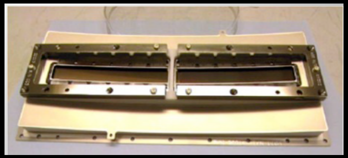
Other Technology Gaps

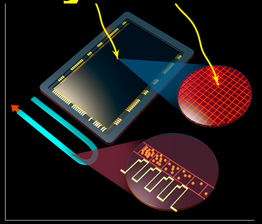
UV Contrast



CG-10 UV/V/NIR Mirror Coatings

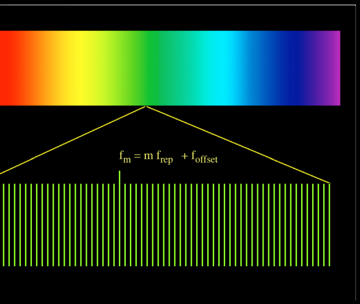
UV Detection Sensitivity



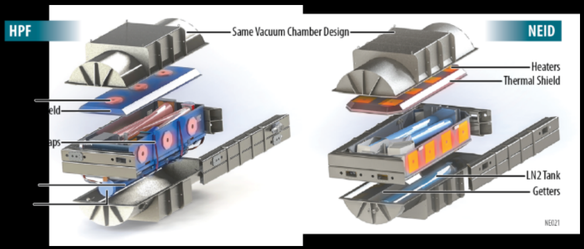


CG-12: Ultra-low Noise UV Detectors

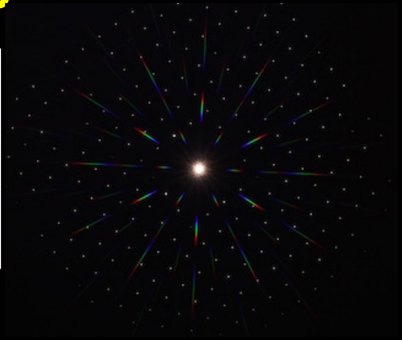
Stellar Reflex Motion Sensitivity



M-2: Laser Frequency Combs for Space-based EPRV

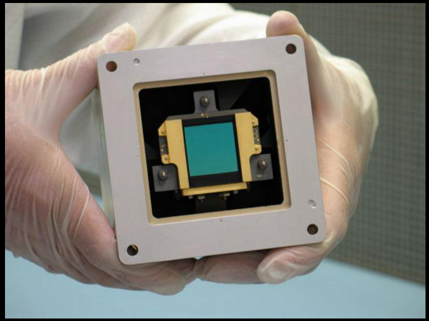


M-1: Ground-based Ultra-high Precision Radial Velocity



M-3: Astrometry

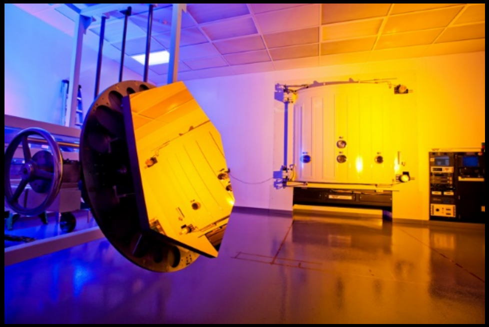
Transit Spectroscopy Sensitivity



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

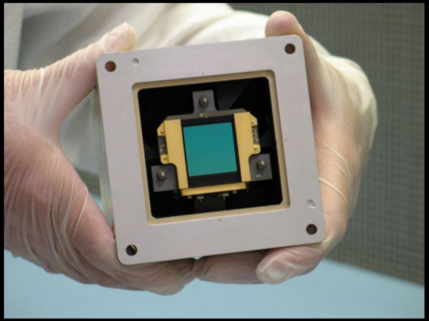
Mid-IR Technology Gaps

Mid-IR Coronagraph Contrast



CG-10 UV/V/NIR Mirror Coatings

Transit Spectroscopy Sensitivity



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