The 2017 ExEP Technology Gap List

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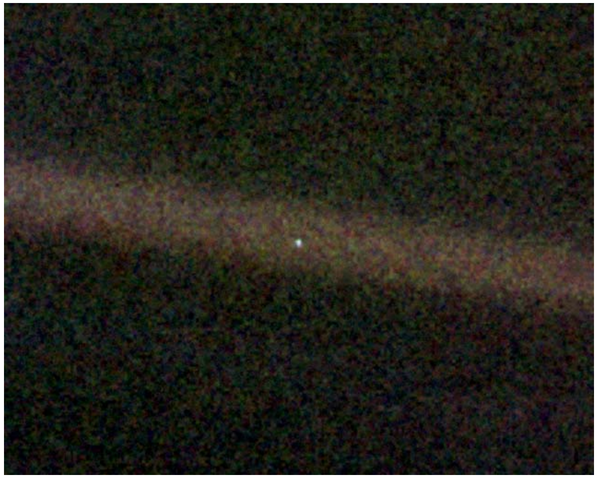
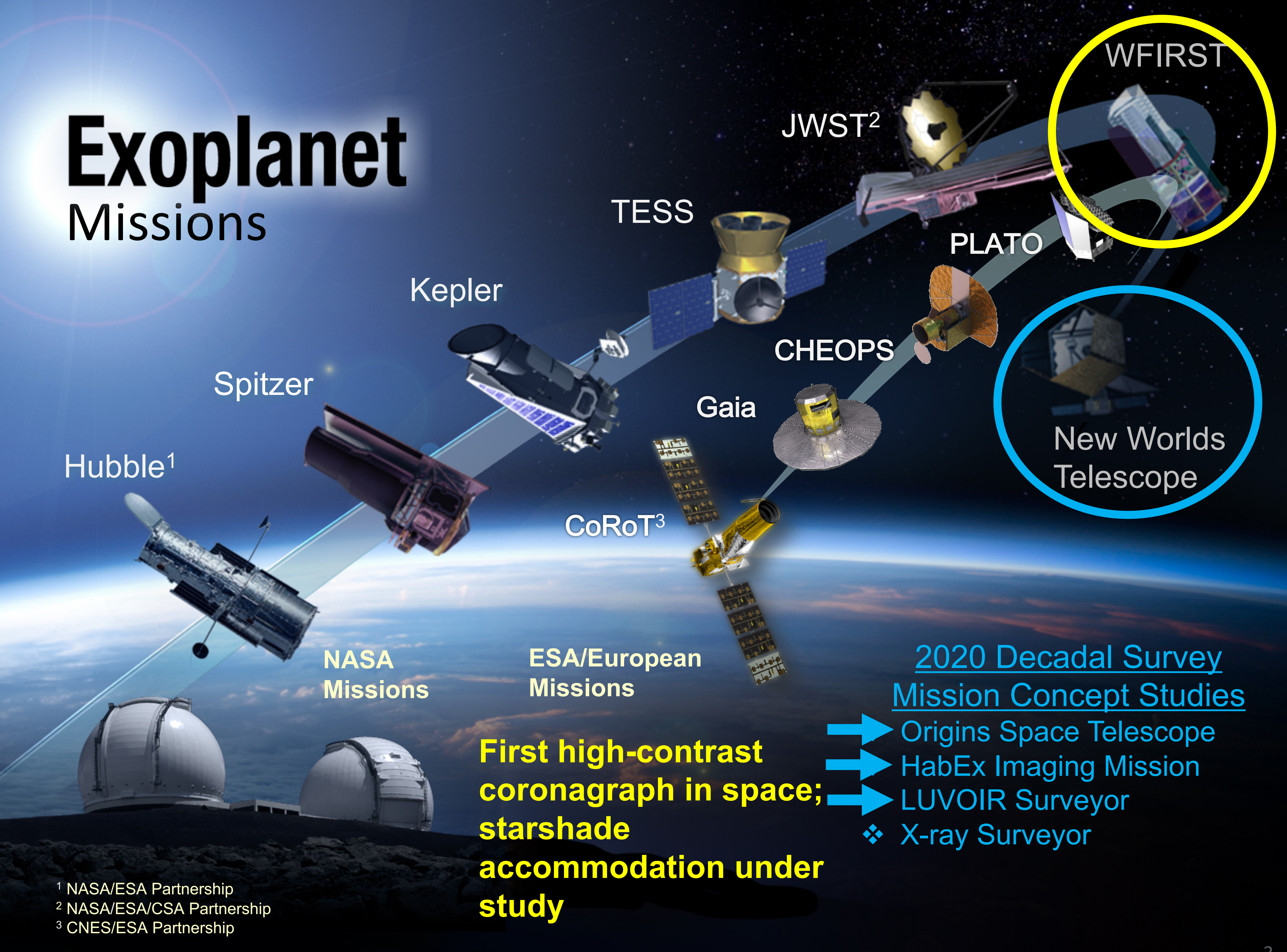
ExEP's Technology Focus

- The ExEP's Technology Gap List (TGL) responds to the missions and technologies cited in the Astrophysics Implementation Plan (AIP), which in turn responds to the 2010 Decadal Survey and mid-decadal assessment.
- The AIP calls for studies of large- and probe-class missions for the direct imaging and characterization of exoplanets.
- The TGL (and the annual Technology Plan Appendix) responds to the enabling and enhancing technology needs of these missions.
- The TGL and the Appendix are used to guide investments, including the SAT/TDEM and directed development or IR&D development.




Exoplanet
Missions
WFIRST
JWST[2]
TESS
PLATO
Kepler
CHEOPS
Spitzer
Gaia
New Worlds
Telescope
Hubble[1]
CoRoT[3]
NASA
Missions
ESA/European
Missions
2020 Decadal Survey
Mission Concept Studies
Origins Space Telescope
HabEx Imaging Mission
LUVOIR Surveyor
X-ray Surveyor
First high-contrast coronagraph in space; starshade accommodation under study
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA Partnership

Technology Gaps Selection Criteria

1. **Technology gaps considered for tracking and development by the ExEP must support APD exoplanet science missions as:**
   - described in the Astrophysics Implementation Plan;
   - directed through the Science Mission Directorate;
   - selected through open competition;
   - described in the APD 30-year roadmap; or,
   - defined by the needs of the 2020 Decadal Survey large mission concepts.

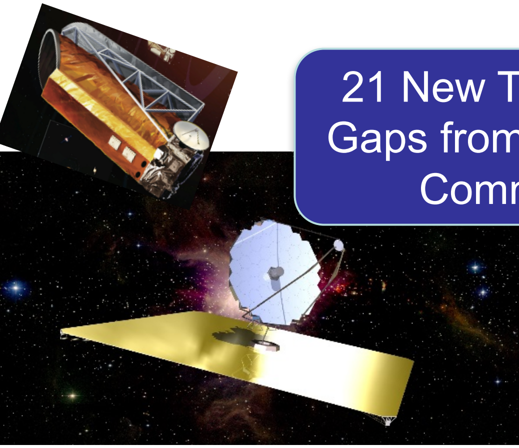
2. **The subset of these gaps that either enables or enhances the direct detection and characterization of exoplanets are selected and prioritized onto the ExEP Technology Gap List (TGL).**
   - Technologies that address these gaps are the ones prioritized for development and considered for resource allocation
   - The list is published in the annual Technology Plan Appendix
   - Some of these technologies may be funded outside of the ExEP and will require collaboration amongst programs.

3. **The remaining technology gaps are considered to benefit exoplanet science and will be captured onto a second "Watch List" in the annual Technology Plan Appendix**
   - These gaps will be tracked and re-evaluated annually for potential TGL inclusion

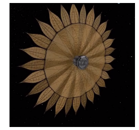
Input from the community

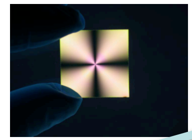
- **Received 21 Technology Gaps**
  - 7 from LUVOIR STDT
  - 2 from HabEx STDT (on top of current ExEP gap list)
  - 8 from Far-IR Surveyor STDT
  - 4 from community at large
- **Most were consolidated within existing gaps or merged with each other**

Technology Selection and Prioritization Process

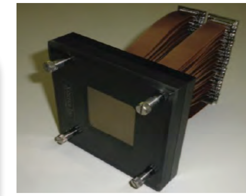


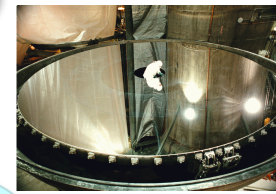
21 New Technology Gaps from Exoplanet Community





14 Technology gaps carried over from 2016





Selection: enables or enhances direct detection and characterization of exoplanets?

Neither enhancing nor enabling → not accepted

No, but could benefit exoplanet science → **Watch List**

Selection and Prioritization Criteria:
- Peer reviewed
- Exo-TAC reviewed

Yes → Prioritize technologies according to criteria (Impact, Urgency, and Trend)

ExEP Technology Gap List

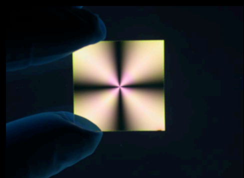
Reviewed by Exo-TAC

Output from the Selection Process

- **Zero new enabling technologies**
  - Polarization, for the first time, added to Coronagraph Architecture gap
- **Four new enhancing technology gaps added to the gap list**
  - UV Ultra-low Noise Detector (LUVOIR)
  - UV/Vis/NIR Mirror Coatings (LUVOIR/HabEx)
  - Extreme Precision Ground-based Radial Velocity (HabEx)
  - Mid-IR Spectral Coronagraph (OST)
- **Four gaps for the Watch List (not currently recommended for funding from ExEP)**
  - Sub-Kelvin Coolers (OST)
  - Advanced Cryocooler (OST)
  - mid-IR Ultra-low Noise Detectors (LUVOIR)
  - Astrometry
- **2017 version of Technology Gap List posted here: https://exoplanets.nasa.gov/exep/technology/gap-lists/**

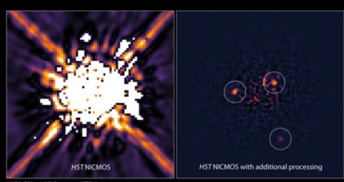
The Enabling Coronagraph/Telescope Technology Gaps

Contrast

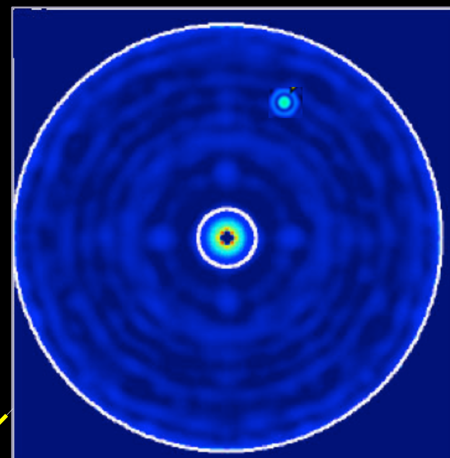


CG-2: Coronagraph Demonstrations and Modeling

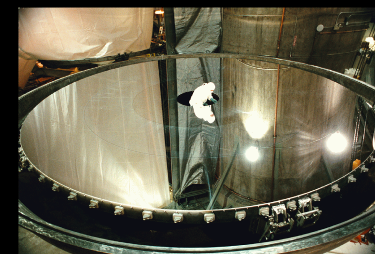
CG-3: Deformable mirrors



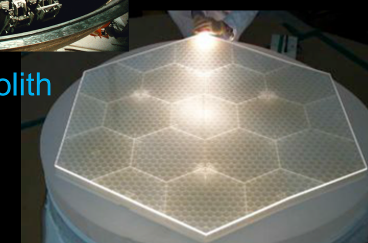
CG-4: Image post-processing



Angular Resolution

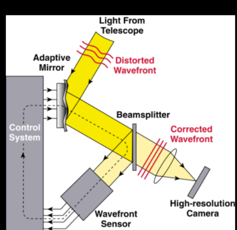


CG-1: Large monolith mirrors



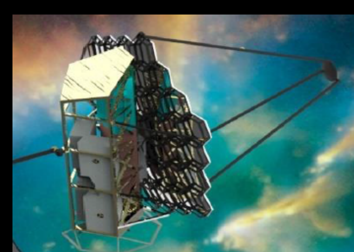
CG-1: Segmented mirrors

Contrast Stability



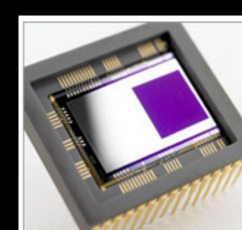
CG-5: Wavefront sensing and control

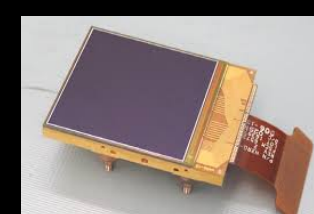
CG-6: Segment phasing and rigid body sensing and control



CG-7: Telescope vibration sensing and control

Detection Sensitivity



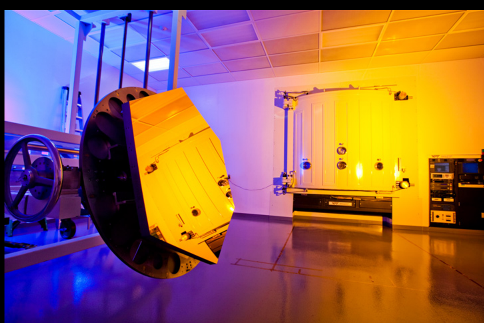


Ultra-low noise visible (CG-8) and infrared (CG-9) detectors

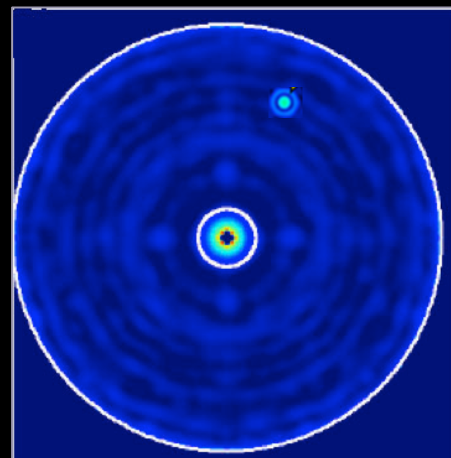
The Enhancing Coronagraph/Telescope Technology Gaps

Contrast

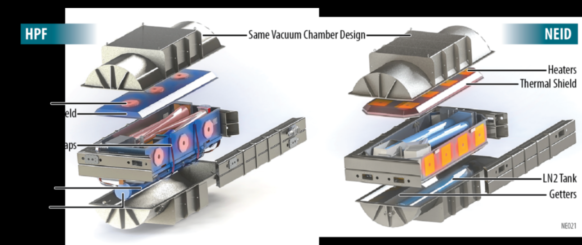
CG-11 Mid Infrared Spectral Coronagraph



CG-10 UV/Vis/NIR mirror coatings

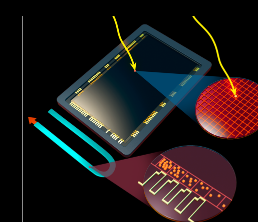


Mission Efficiency



M-1: Ultra-high precision Radial Velociity

Detection Sensitivity

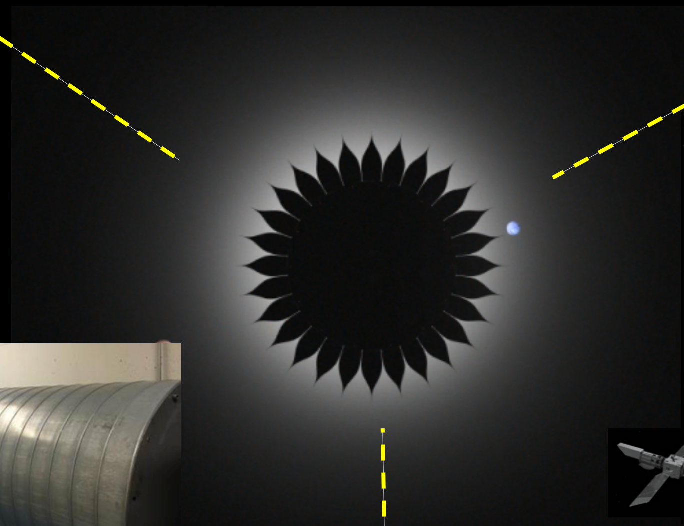


Ultra-low noise UV detectors (CG-12)

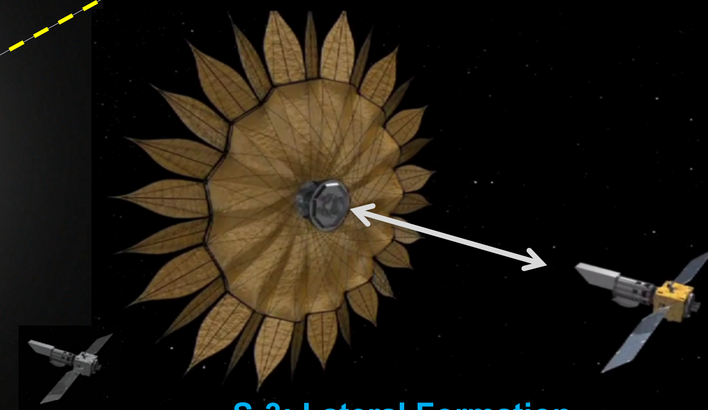
Starshade Technology Needs

Starlight Suppression

S-1: Controlling Scattered Sunlight



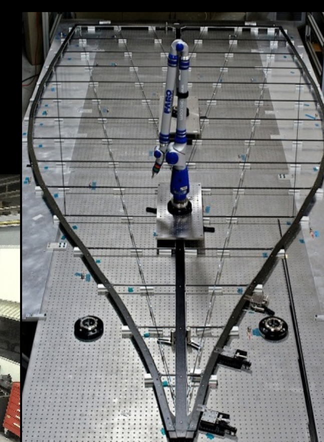
Formation Sensing and Control



S-3: Lateral Formation Sensing

S-2: Starlight Suppression and Model Validation

Deployment Accuracy and Shape Stability

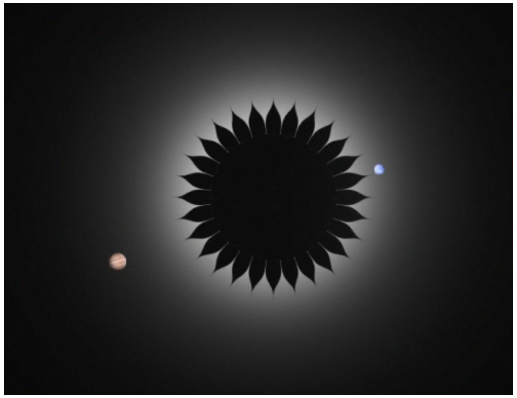


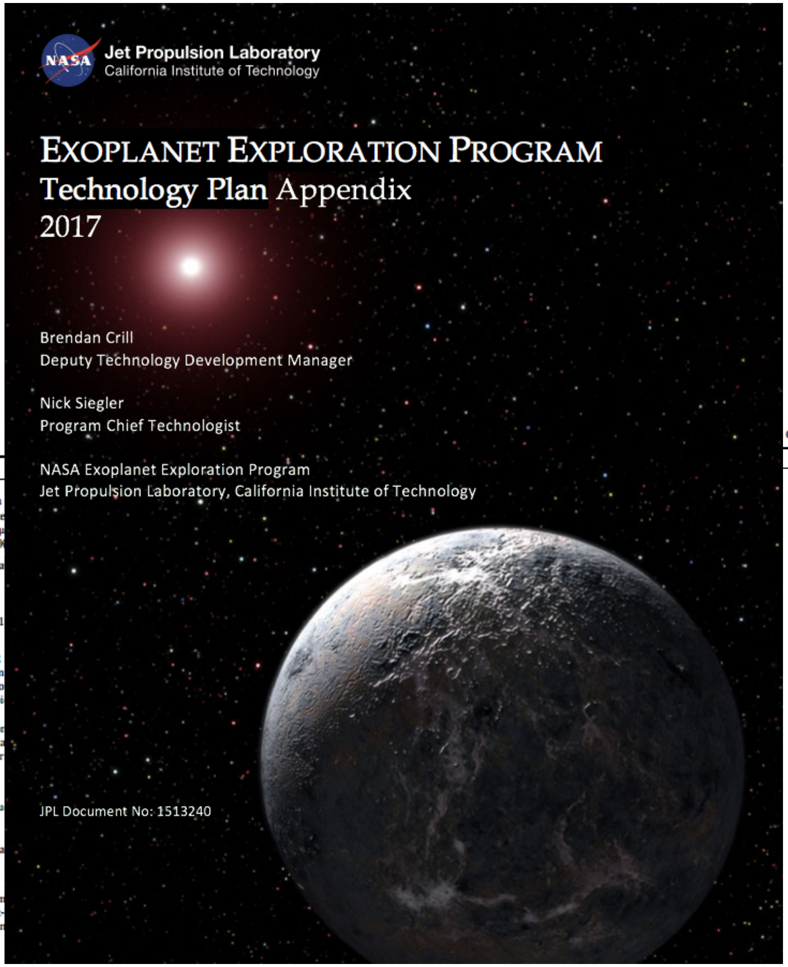
S-4: Petal Shape And Stability

S-5: Petal Positioning Accuracy and Opaque Structure

ExEP Technology Plan Appendix

Starshade Gaps





Coronagraph Gaps

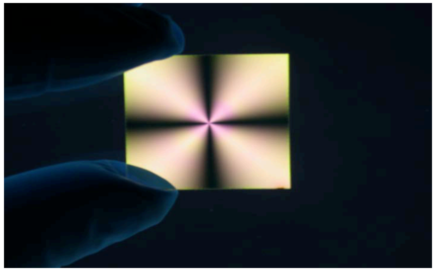


Table A.4 Starshade Technology Gap List

ID	Title	Description	Current	Required
S-1	Control Edge-Scattered Sunlight	Limit edge-scattered sunlight with optical petal edges that also handle stowed bending strain.	Graphite edges meet all specs except sharpness, with edge radius ≥10 μm.	Optical petal edges manufactured of high flexural strength mate with edge radius ≤ 1 μ and reflectivity ≲ 10%
S-2	Contrast Performance Demonstration ar Optical Model Validation	Experimentally validate the equations that predict the contrasts achievable with a starshade.	Experiments have validated optical diffraction models at Fresnel number of ~500 to contrasts of 3×10^{-10} at 632 nm.	Experimentally valida models of starlight suppression to $\leq 3\times10^{-11}$ at Fresnel numbers ≤ 50 over 51 825 nm bandpass.
S-3	Lateral Formation Flying Sensing Accuracy	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid accuracy ≥ 1% is common. Simulations have shown that sensing and GN&C is tractable, though sensing demonstration of lateral control has not yet been performed.	Demonstrate sensing lateral errors ≤ 0.20m scaled flight separatio and estimated centroi positions ≤ 0.3% of optical resolution. Co algorithms demonstra with lateral control er ≤ 1m.
S-4	Flight-Like Petal Fabrication and Deployment	Demonstrate a high-fidelity, flight-like starshade petal and its unfurling mechanism.	Prototype petal that meets optical edge position tolerances has been demonstrated.	Demonstrate a fully integrated petal, inclu blankets, edges, and deployment control interfaces. Demonstra flight-like unfurling mechanism.
S-5	Inner Disk Deployment	Demonstrate that a starshade can be autonomously deployed to within the budgeted tolerances.	Demonstrated deployment tolerances with 12m heritage Astromesh antenna with four petals, no blankets, no outrigger struts, and no launch restraint.	Demonstrate deploym tolerances with flight- minimum half-scale in disk, with simulated petals, blankets, and interfaces to launch restraint.

Coronagraph Technology Gap List.

Title	Description	Current	Required
Specialized Coronagraph Optics	Masks, apodizers, or beam-shaping optics to provide starlight suppression and planet detection capability.	A linear mask design has yielded 3.2×10^{-10} mean raw contrast from 3–16 λ/D with 10% bandwidth using an unobscured pupil in a static lab demonstration.	Circularly symmetric masks achieving $\leq 1\times10^{-10}$ contrast with IWA ≤ 3λ/D and ≥ 10% bandwidth on obscured or segmented pupils.
Low-Order Wavefront Sensing & Control	Beam jitter and slowly varying large-scale (low-order) optical aberrations may obscure the detection of an exoplanet.	Tip/tilt errors have been sensed and corrected in a stable vacuum environment with a stability of 10^{-3} λ rms at sub-Hz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to 10^{-4} λ (~10's of pm) rms to maintain raw contrasts of $\leq 1\times10^{-10}$ in a simulated dynamic testing environment.
Large-Format Ultra-Low Noise Visible Detectors	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph.	Read noise of < 1 e^-/pixel has been demonstrated with EMCCDs in a 1k × 1k format with standard read-out electronics	Read noise < 0.1e^-/pixel in a ≥ 4k × 4k format validated for a space radiation environment and flight-accepted electronics.
Large-Format Deformable Mirrors	Maturation of deformable mirror technology toward flight readiness.	Electrostrictive 64x64 DMs have been demonstrated to meet $\leq 10^{-9}$ contrasts in a vacuum environment and 10% bandwidth.	≥ 64x64 DMs with flight-like electronics capable of wavefront correction to $\leq 10^{-10}$ contrasts. Full environmental testing validation.
Efficient Contrast Convergence	Rate at which wavefront control methods achieve 10^{-10} contrast.	Model and measurement uncertainties limit wavefront control convergence and require many tens to hundreds of iterations to get to 10^{-10} contrast from an arbitrary initial wavefront.	Wavefront control methods that enable convergence to 10^{-10} contrast ratios in fewer iterations (10-20).
Post-Data Processing	Techniques are needed to characterize exoplanet spectra from residual speckle noise for typical targets.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10^{-5} to 10^{-6}, dominated by phase errors.	A 10-fold improvement over the raw contrast of ~10^{-9} in the visible where amplitude errors are expected to no longer be negligible with respect to phase errors.

*Topic being addressed by directed-technology development for the WFIRST/AFTA coronagraph. Consequently, coronagraph technologies that will be substantially advanced under the WFIRST/AFTA technology development are not eligible for TDEMs.

2017 update coming mid-January

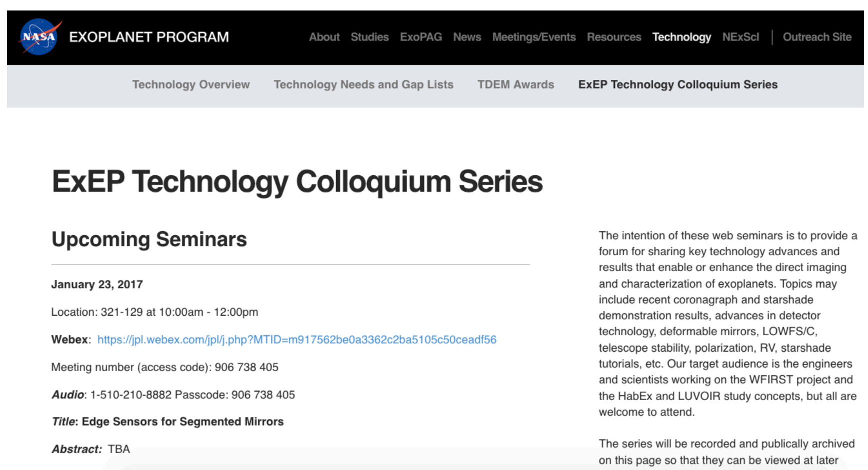
https://exoplanets.nasa.gov/exep/technology

ExEP Technology Web Colloquium Series

- Brings together exoplanet scientists and technologists from WFIRST, LUVOIR, HABEX, and general community to discuss recent technology results

- First installment was on November 29, 2016:
    - Title: ***The ExEP Segmented Coronagraph Design Analysis Study***
    - Speakers: *S. Shaklan (JPL), G. Ruane (Caltech), N. Zimmerman (STScI), R, Belikov (NASA-Ames), O. Guyon (UA)*
    - If you missed it, see the archived audio/video

- Second telecon scheduled for January 23, 2017 (10 am PST)
    - *Title:* ***Edge Sensors for Segmented Telescopes***
    - Speakers: S. Knight (Ball), C. Shelton (JPL)



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

2017 Prioritization Criteria

Impact (weight: 10)	4: Critical technology - required to meet mission concept objectives; without this technology, applicable missions would not launch
	3: Highly desirable - not mission-critical, but provides major benefits in enhanced science capability, reduced critical resources need, and/or reduced mission risks; without it, missions may launch, but science or implementation would be compromised
	2: Desirable - not required for mission success, but offers significant science or implementation benefits; if technology is available, would almost certainly be implemented in missions
	1: Minor science impact or implementation improvements; if technology is available would be considered for implementation in missions

Urgency (weight: 10)	4: reduced risk needed for missions currently in pre-formulation or formulation.
	3: In time for the Decadal Survey (2019); not necessarily at some TRL but reduced risk by 2019.
	2: Earliest projected launch date < 15 yr (< 2030)
	1: Earliest projected launch date > 15 yr (> 2030)

Trend (weight: 5)	4: (a) no ongoing current efforts, or (b) little or no funding allocated
	3: (a) others are working towards it but little results or their performance goals are very far from the need, (b) funding unclear, or (c) time frame not clear
	2: (a) others are working towards it with encouraging results or their performance goals will fall short from the need, (b) funding may be unclear, or (c) time frame not clear
	1: (a) others are actively working towards it with encouraging results or their performance goals are close to need, (b) it's sufficiently funded, and (c) time frame clear and on time

Footnote: to be deemed “ready,” the technology is available to NASA at TRL 6 by the earliest possible Preliminary Design Review (PDR) of a mission; or at TRL 5 by the start of Phase A

2017 ExEP Technology Gap List

Exoplanet Exploration Program

Prioritized List

Gap ID	Gap Title	Impact	Urgency	Trend	Total
	Weight:	10	10	5	
S-2	Starlight Suppression and Model Validation	4	4	2	90
S-1	Control Edge-Scattered Sunlight	4	4	2	90
S-3	Lateral Formation Flying Sensing	4	4	2	90
S-4	Petal Shape	4	4	2	90
S-5	SS Deployment and Shape Stability	4	4	2	90
CG-1	Large Aperture Mirrors	4	3	3	85
CG-2	Coronagraph Architecture	4	3	3	85
CG-6	Mirror Figure / Segment Phasing, Sensing & Control	4	3	3	85
CG-7	Telescope Vibration Control	4	3	3	85
CG-9	NIR Ultra-Low Noise Detector	4	3	3	85
CG-3	Wavefront Sensing and Control	4	3	2	80
CG-5	Deformable Mirrors	4	3	2	80
CG-8	Visible Ultra-Low Noise Detector	4	3	2	80
M-1	Extreme Precision Radial Velocity	3	3	3	75
CG-4	Post-Data Processing	4	2	2	70
CG-10	UV/NIR/Vis mirror coatings	3	3	2	70
CG-11	Mid-IR Spectral Coronagraph	2	3	3	65
CG-12	UV Ultra-low noise detector	2	3	2	60

Enabling Gap
Enhancing Gap
Watch List

Watch List

Sub-Kelvin Coolers
Advanced Cryocooler
Mid-IR Ultra-low Noise Detector
Astrometry

Conclusions

- **2017 Technology Gap List reflects a more formalized and inclusive selection and prioritization process**
  - included inputs from the community, in particular STDTs
  - Included participation from other program offices
  - reviewed by ExoTAC
  - We'll repeat this process starting in June

- **Received 21 new Gaps from the community**
  - Five were either redundant with each other or already captured on the existing gap list
  - Four were folded into the existing gap list (all polarization-related)
  - Four enhancing gaps added to the prioritized list
  - Three gaps added to Watch List
  - Five not selected

- **Results from this process provided to SAT/TDEM Program Officer at NASA HQ**

Recommendation for ExEP Investments

Exoplanet Exploration Program

S-2	Starlight Suppression and Model Validation	Starshade technology development activity
S-1	Control Edge-Scattered Sunlight	Starshade technology development activity
S-3	Lateral Formation Flying Sensing	Starshade technology development activity
S-4	Petal Shape	Starshade technology development activity
S-5	SS Deployment and Shape Stability	Starshade technology development activity
CG-1	Large Aperture Mirrors	Solicited in SAT/TCOR-16; and in SAT/TDEM-16 only as part of a systems-level study
CG-2	Coronagraph Architecture	Solicited in SAT/TDEM-16
CG-6	Mirror Figure / Segment Phasing, Sensing & Control	Solicited in SAT/TDEM-16 only as part of a systems-level study
CG-7	Telescope Vibration Control	Solicited in SAT/TCOR-16; and in SAT/TDEM-16 only as part of a systems-level study
CG-9	NIR Ultra-Low Noise Detector	Solicited in SAT/TCOR-16
CG-3	Wavefront Sensing and Control	Solicited in SAT/TCOR;-16 and in SAT/TDEM-16 only as part of a systems-level study; currently being advanced by WFIRST project
CG-5	Deformable Mirrors	Solicited in SAT/TDEM-16 only as part of a systems-level study
CG-8	Visible Ultra-Low Noise Detector	Solicited in SAT/TCOR-16
M-1	Extreme Precision Radial Velocity	NN-EXPLORE; ADAP, ATP possibly provide opportunities for data analysis / stellar jitter theory
CG-4	Post-Data Processing	Currently being advanced by WFIRST project
CG-10	UV/NIR/Vis mirror coatings	Solicited in SAT/TCOR-16; and SAT/TDEM-16 only as part of a systems-level study
CG-11	Mid-IR Spectral Coronagraph	Solicited in SAT/TCOR-16
CG-12	UV Ultra-low noise detector	Solicited in SAT/TCOR-16