Technology Needs and Prioritization Process

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ExoPAG Executive Council Telecon

06/07/16

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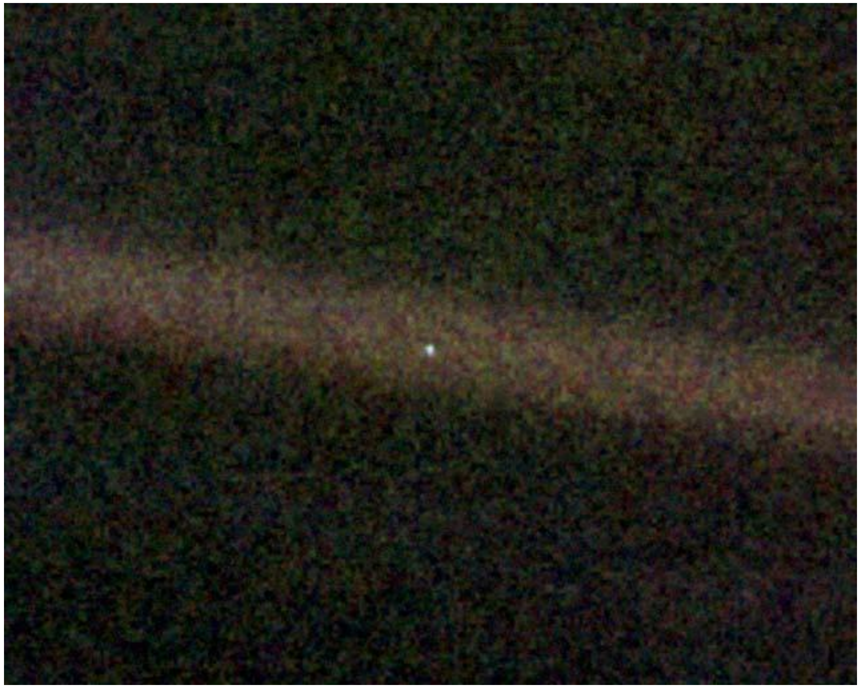
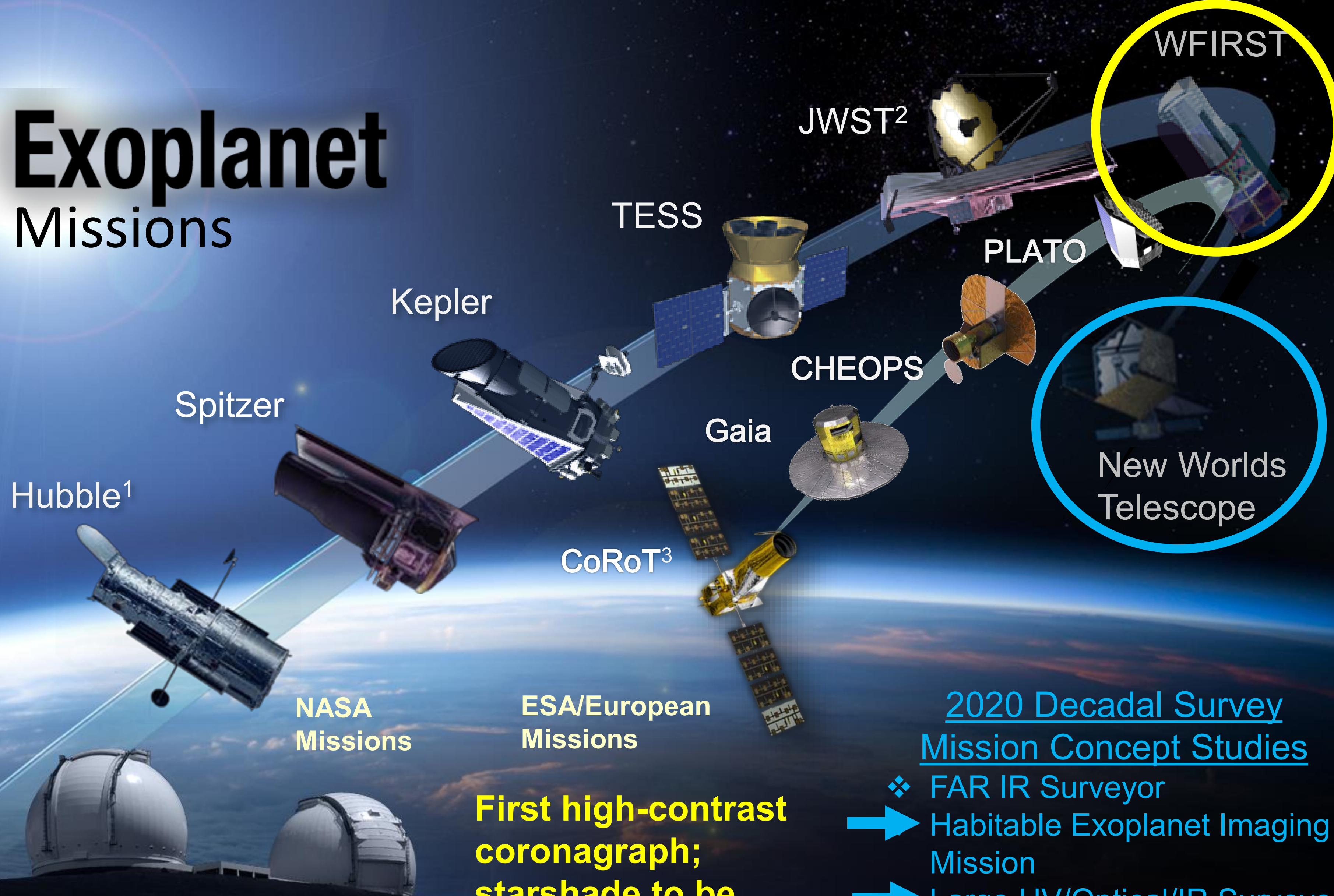
The ExEP Technology Focus

The ExEP technology goals are driven by and focused on enabling the science capability to directly image and spectrally characterize exo-earths in the HZ of Sun-like stars and beyond.

– *all other valuable exoplanet science goals, it is assumed, can be achieved along the way (study of larger planets, disk science, planetary orbits, etc)*



Exoplanet Missions



First high-contrast coronagraph; starshade to be studied

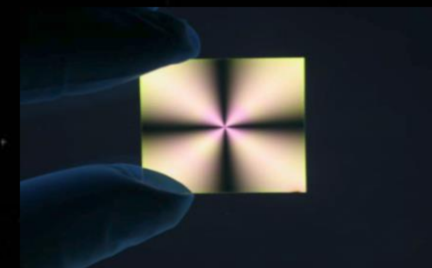
[2020 Decadal Survey Mission Concept Studies]

- FAR IR Surveyor
- ➡ Habitable Exoplanet Imaging Mission
- ➡ Large UV/Optical/IR Surveyor
- X-ray Surveyor

[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA Partnership

ExEP Technology Gap Lists

Enabling Technologies Only



Starshade Technology Gap List

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 material with edge radius ≤ 1 μm 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 validate models of starlight suppression to ≤ 3×10^{-11} at Fresnel numbers ≤ 50 over 510-825 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 at scaled flight separations and estimated centroid positions ≤ 0.3% of optical resolution. Control algorithms demonstrated with lateral control errors ≤ 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, including blankets, edges, and deployment control interfaces. Demonstrate a 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 deployment tolerances with flight-like, minimum half-scale inner disk, with simulated petals, blankets, and interfaces to launch restraint.

Coronagraph Technology Gap List

Table A.3 Coronagraph Technology Gap List.

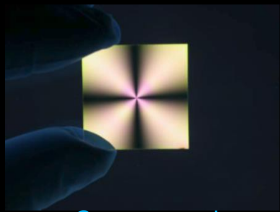
ID	Title	Description	Current	Required
C-1	Specialized Coronagraph Optics	Masks, apodizers, or beam-shaping optics to provide starlight suppression and planet detection capability.	A linear mask design has yielded 3.2×10^{-10} mean raw contrast from 3–16 λ/D with 10% bandwidth using an unobscured pupil in a static lab demonstration.	Circularly symmetric masks achieving ≤ 1×10^{-10} contrast with IWA ≤ 3λ/D and ≥ 10% bandwidth on obscured or segmented pupils.
C-2*	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 ≤ 1×10^{-10} in a simulated dynamic testing environment.
C-3*	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.
C-4*	Large-Format Deformable Mirrors	Maturation of deformable mirror technology toward flight readiness.	Electrostrictive 64x64 DMs have been demonstrated to meet ≤ 10^{-9} contrasts in a vacuum environment and 10% bandwidth.	≥ 64x64 DMs with flight-like electronics capable of wavefront correction to ≤ 10^{-10} contrasts. Full environmental testing validation.
C-5	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).
C-6*	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.

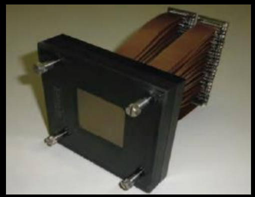
http://exep.jpl.nasa.gov/technology/

Coronagraph Technology Gaps

Starlight Suppression



Coronagraph Architectures (CG-2)



Deformable mirrors (CG-3)

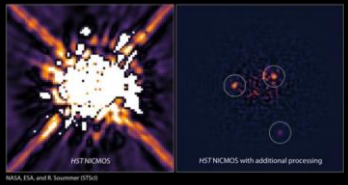
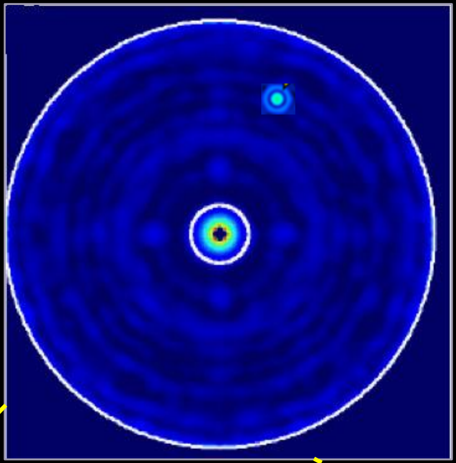
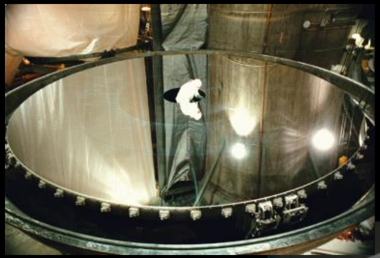


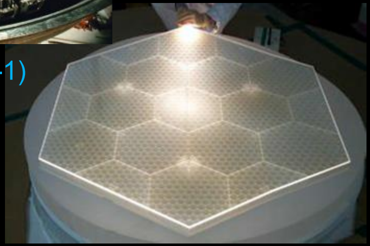
Image post-processing (CG-4)



Mirrors

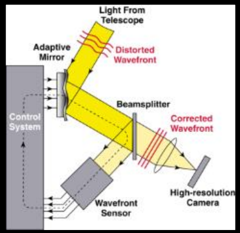


Large monolith (CG-1)



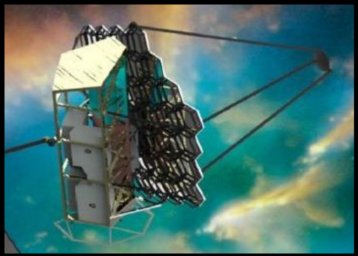
Segmented (CG-1)

WFE Stability



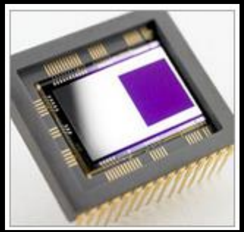
Wavefront sensing and control (CG-5)

Segment phasing and rigid body sensing and control (CG-6)

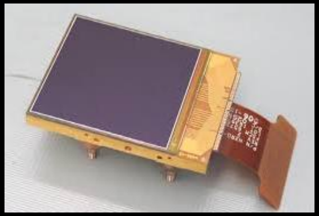


Telescope vibration sensing and control (CG-7)

Detection Sensitivity



Ultra-low noise visible detectors (CG-8)

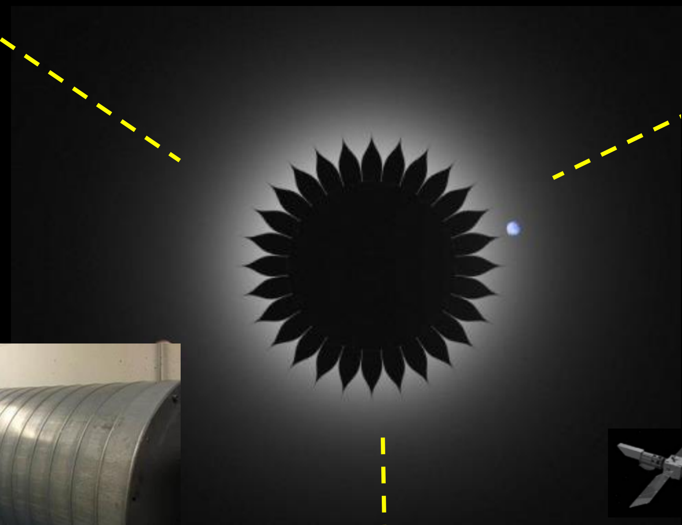


Ultra-low noise infrared detectors (CG-9)

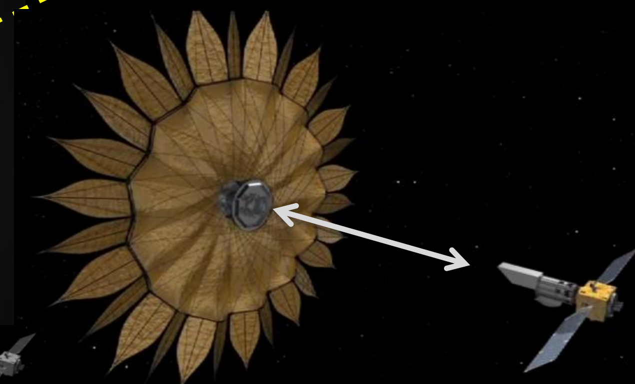
Starshade Technology Gaps

Starlight Suppression

Controlling Sunlight scattering off petal edges (S-2)



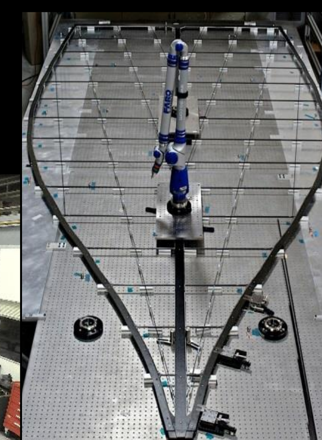
Formation Sensing and Control



Maintaining lateral offset requirement between the spacecrafts (S-3)

Suppressing starlight and validating optical model (S-1)

Deployment Accuracy and Shape Stability



Fabricating the petal to high precision (S-4)

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

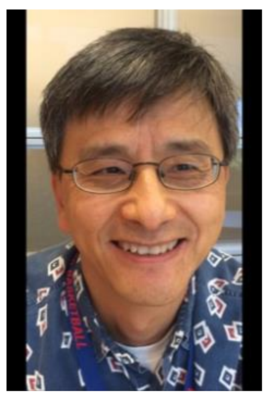
ExEP Technology Development Team

Nick Siegler
Program Chief Technologist

Brendan Crill
Technology Development Manager

David Breda
TDEM Systems Engineer

Stuart Shaklan
SME for coronagraphs and starshades; task lead for the Segmented Coronagraph Design & Analysis



Hong Tang
HCIT Manager

Rhonda Morgan
Senior Optical Engineer

Karl Stapelfeldt
Program Chief Scientist

Technology Needs and Prioritization Process

ID	Activity	Date
1	Technology Needs Input Window Opens	06/08/16
	with email to all three PAGs: Technology Gap Lists, Input Forms, process explanation	
	presentation at June ExoPAG	06/12/16
2	Technology Window Closes	08/26/16
3	Prioritization Criteria Concurred by the ExEP	09/15/16
4	Technology Gaps Prioritized by the ExEP	10/20/16
5	Technology Gap Lists Inform TDEM Amendment	mid-Nov
	Technology Amendment released through NSPIRES	mid-Dec
6	ExEP Technology Plan Appendix Updated and Posted	12/22/16
	Presentation at January ExoPAG	01/02/17
7	TDEM Proposal Deadline	03/17/17
8	TDEM Awards Selected	Aug 2017

– Enabling technologies only - requires ExEP iteration with community members
– PCOS/COR Technology team involved in every step; ExEP involved in their prioritization process

Technology Needs and Prioritization Process Timeline

		TDEM Year												
Activity	**Resp**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**
ExEP Technology Needs and Prioritization Process														
TNPP and TGL Presented to ExoPAG EC	TDM						1st Tue							
TGL Window Opens	TDM						day after							
TGL Presented at Summer ExoPAG	TDM						mid-month							
TGL Window Closes									last Fri					
TGL Prioritization Criteria Concurred	TDM									2nd week				
TGL Prioritization	TDM										mid-month			
Present Final TGL to ExoPAG EC and	TDM											1st Tue		
Provide Input to TDEM Amendment	PCT, PS, TDM											mid-month		
Update Technology Plan Appendix	TDM												mid-month	
TGL Presented at Winter ExoPAG	TDM													1st week

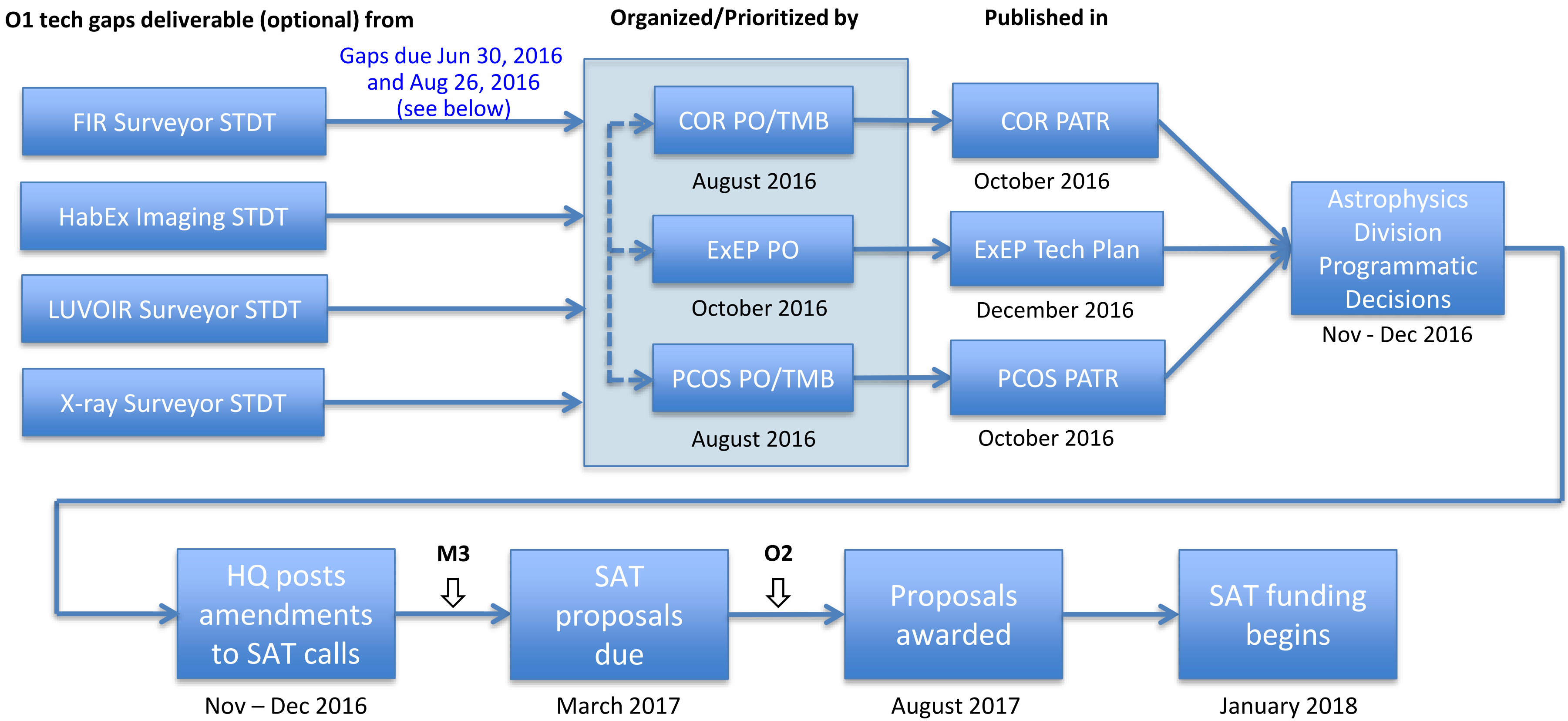
EC	Executive Council
ExEP	Exoplanets Exploration Program
ExoPAG	Exoplanet Program Analysis Group
PCE	Program Chief Engineer
PCS	Program Chief Scientist
PCT	Program Chief Technologist
PM	Program Manager
PS	Program Scientist
TDEM	Technology Demonstrations for Exoplanet Missions
TDM	Technology Development Manager
TGL	Technology Gap List
TNPP	Technology Needs and Prioritization Process

TDEM Timeline

		TDEM Year											TDEM Year plus 1							
Activity	**Resp**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**
TDEM Process																				
Solicitation Released	**PS**	mid-month																		
Amendment Posted	**PS**											mid-month								
Pre-Proposal Briefing Telecon	**PS**												mid-month							
Proposal Due															mid-month					
Proposals Selected	**PS**																			by month end

Astrophysics Technology Gap Process and 2016 SAT Timeline

ExoPlanet Exploration Program



- Non-Exoplanet-related gaps due June 30, 2016; Exoplanet-related gaps due August 26, 2016.
- Community technology gap inputs are also provided to the respective Program Offices (POs) to be prioritized each year by the Programs' Technology Management Boards (TMBs) for COR and PCOS and by the ExEP PO.
- Program Chief Technologists participate in each other's technology prioritization processes.
- Current Program Annual Technology Reports (PATRs) and Technology Plan are available on respective Program websites.
- Gaps identified in M3 (2/2017) and O2 (6/2017) Study Deliverables can also influence the 2016 SAT funding or directed funding decisions.
- SAT funding nominally starts in January but could be ±3 months depending on receiving organization.

Proposed 2017 Coronagraph Technology Gap List (1/2)

	ID	Title	Description	Current Capabilities	Needed Capabilities
Contrast	CG-2	Coronagraph Optics and Architecture	Coronagraph optics and architecture that suppress diffracted starlight by a factor of $\leq 10^{-9}$ at visible and infrared wavelengths.	6×10^{-10} raw contrast at 10% bandwidth across angles of 3-16 λ/D demonstrated with a linear mask and an unobscured pupil in a static vac lab env't (Hybrid Lyot) $< 8.8\times10^{-9}$ raw contrast at 10% bandwidth across angles of 3-9 λ/D demonstrated with a circularly-symmetric mask and obscured pupil in a static vacuum lab	Coronagraph masks and optics capable of creating circularly symmetric dark regions in the focal plane enabling raw contrasts $\leq 10^{-9}$, IWA ≤ 3 λ/D, throughput ≥ 10%, and bandwidth ≥ 10% on obscured/segmented pupils in a simulated dynamic vacuum lab environment.
Angular Resolution (plus sensitivity, integration time, and planet yield)	CG-1	Large Aperture Primary Mirrors	Large monolith and multi-segmented mirrors that meet tight surface figure error and thermal control requirements at visible wavelengths.	Monolith: 3.5m sintered SiC with < 3 um SFE (Herschel) 2.4m ULE with ~ 10 nm SFE (HST) Depth: Waterjet cutting is TRL 9 to 14", but TRL 3 to >18". Fused core is TRL 3; slumped fused core is TRL 1. Segmented: 6.5m 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	Aperture: 4m - 12m; SFE < 10 nm rms (wavelength coverage 400 nm - 2500 nm) Wavefront stability better than 10 pm rms per wavefront control time step. Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control. Environmentally tested.
Detection Sensitivity	CG-8	Ultra-Low Noise, Large Format Visible Detectors	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph	1kx1k silicon EMCCD detectors provide dark current of 8×10^{-4} e-/px/sec; effective read noise < 0.2 e- rms (in EM mode) after irradiation when cooled to 165.15K (WFIRST). 4kx4k EMCCD fabricated but still under development.	Effective read noise < 0.1e- rms; CIC $< 3\times10^{-3}$ e-/px/fram; dark current $< 10^{-4}$ e-/px/sec tolerant to a space radiation environment over mission lifetime. ≥ 2kx2k format
Detection Sensitivity	CG-9	Ultra-Low Noise, Large Format Near Infrared Detectors	Near infrared wavelength (900 nm to 2.5 μm), extremely low noise detectors for exo-earth spectral characterization with Integral Field Spectrographs.	HgCdTe photodiode arrays have read noise <~ 2 e- rms with multiple non-destructive reads; dark current < 0.001 e-/s/pix; very radiation tolerant (JWST). HgCdTe APDs have dark current ~ 10-20 e-/s/pix, RN << 1 e- rms, and < 1kx1k format Cryogenic (superconducting) detectors have essentially no read noise nor dark current; radiation tolerance is unknown.	Read noise << 1 e- rms, dark current < 0.001 e-/pix/s, in a space radiation environment over mission lifetime. ≥ 2kx2k format

Proposed 2017 Coronagraph Technology Gap List (2/2)

	ID	Title	Description	Current Capabilities	Needed Capabilities
Contrast Stability	CG-6	Segment Phasing Sensing and Control	Multi-segment large aperture mirrors require phasing and rigid-body sensing and control of the segments to achieve tight static and dynamic wavefront errors.	6 nm rms rigid body positioning error and 49 nm rms stability (JWST error budget) SIM and non-NASA: nm accuracy and stability using laser metrology	Systems-level considerations to be evaluated but expect will require less than 10 pm rms accuracy and stability.
Contrast Stability	CG-7	Telescope Vibration Control	Isolation and damping of spacecraft and payload vibrational disturbances	80 dB attenuation at frequencies > 40 Hz (JWST passive isolation) Disturbance Free Payload demonstrated at TRL 5 with 70 dB attenuation at "high frequencies" with 6-DOF low-order active pointing.	Monolith: 120 dB end-to-end attenuation at frequencies > 20 Hz. Segmented: 140 dB end-to-end attenuation at frequencies > 40 Hz. End-to-end implies isolation between disturbance source and the telescope.
Contrast	CG-3	Deformable Mirrors	Environment-tested, flight-qualified large format deformable mirrors	Electrostrictive 64x64 DMs have been demonstrated to meet $\leq 10^{-9}$ contrasts and $< 10^{-10}$ stability in a vacuum environment and 10% bandwidth; 48x48 DM passed random vibe testing.	4 m primary: ≥ 96x96 actuators 10 m primary: ≥ 128x128 actuators Enable raw contrasts of $\leq 10^{-9}$ at ~20% bandwidth and IWA $\leq 3\ \lambda/D$ Flight-qualified device and drive electronics (radiation hardened,environmentally tested, life-cycled including connectors and cables) Large segment DM needs possible for segmented telescopes.
Contrast Stability	CG-5	Low-Order Wavefront Sensing and Control	Sensing and control of line of sight jitter and low-order wavefront drift	< 0.5 mas rms per axis LOS residual error demonstrated in lab with a fast-steering mirror attenuating a 14 mas LOS jitter and reaction wheel inputs; ~ 100 pm rms sensitivity of focus (WFIRST). Higher low-order modes sensed to 10-100 nm WFE rms on ground-based telescopes.	Sufficient fast line of sight jitter (< 0.5 mas rms residual) and slow thermally-induced (≤ 10 pm rms sensitivity) WFE sensing and control to maintain closed-loop $< 10^{-9}$ raw contrast with an obscured/segmented pupil and simulated dynamic environment.
Contrast	CG-4	Post-Data Processing	Post-data processing techniques to uncover faint exoplanet signals from residual speckle noise at the focal-plane detector.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10^{-4} to 10^{-5}, dominated by phase errors.	A 10-fold contrast improvement in the visible from 10^{-9} raw contrast where amplitude errors are expected to be important (or a demonstration of the fundamental limits of post-processing)

Proposed 2017 Starshade Technology Gap List

Exoplanet Exploration Program

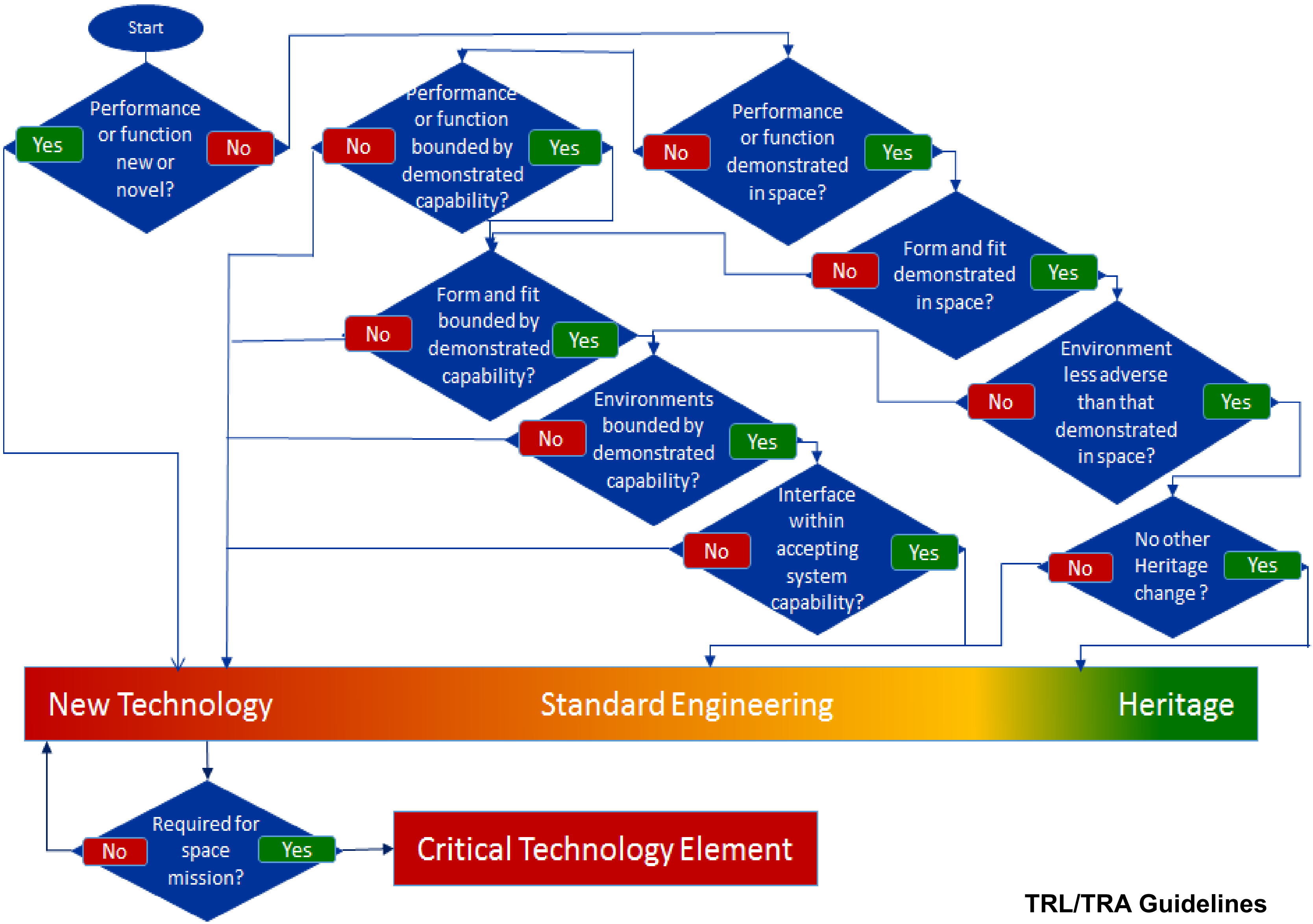
Proposed 2017 Starshade Technology Gap List

	ID	Title	Description	Current Capabilities	Needed Capabilities
Optical Performance and Model Validation	S-2	Optical Performance Demonstration and Validated Optical Model	Experimentally validate the equations that predict the contrasts achievable with a starshade.	3×10^{-10} contrast at 632 nm, 5 cm mask, and ~500 Fresnel #; validated optical model 9×10^{-10} contrast at white light, 58 cm mask, and 210 Fresnel #	Experimentally validate models predicting contrast to $\leq 10^{-10}$ just outside petal edges in scaled flight-like geometry with Fresnel numbers ≤20 across a broadband optical bandpass.
Optical Performance and Model Validation	S-1	Controlling Scattered Sun Light	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 um); 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 limiting contrast contribution of solar glint to $< 10^{-10}$ at petal edges.
Formation Sensing and Control	S-3	Lateral Formation Sensing	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid star positions to ≤ 1/100th pixel with ample flux. 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 ≤ 0.30 m accuracy at scaled flight separations (±1 mas bearing angle). Estimated centroid positions to ≤ 1/40th pixel with limited flux from out of band starlight. Control algorithms demonstrated with scaled lateral control errors corresponding to ≤ 1 m.
Deployment Accuracy and Shape Stability	S-5	Petal Positioning Accuracy and Opaque Structure	Demonstrate that a starshade can be autonomously deployed to within its budgeted tolerances after exposure to relevant environments.	Petal deployment tolerance (≤ 1 mm) verified with low fidelity 12m prototype and no optical shield; no environmental testing (Exo-S design).	Deployment tolerances demonstrated to ≤ 1 mm (in-plane envelope) with flight-like, minimum half-scale structure, simulated petals, opaque structure, and interfaces to launch restraint after exposure to relevant environments.
Deployment Accuracy and Shape Stability	S-4	Petal Shape and Stability	Demonstrate a high-fidelity, flight-like starshade petal meets petal shape tolerances after exposure to relevant environments.	Manufacturing tolerance (≤ 100 μm) verified with low fidelity 6m prototype and no environmental tests. Petal deployment tests conducted but on prototype petals to demonstrate rib actuation; no shape measurements.	Deployment tolerances demonstrated to ≤ 100 μm (in-plane envelope) with flight-like, minimum half-scale petal fabricated and maintains shape after multiple deployments from stowed configuration.

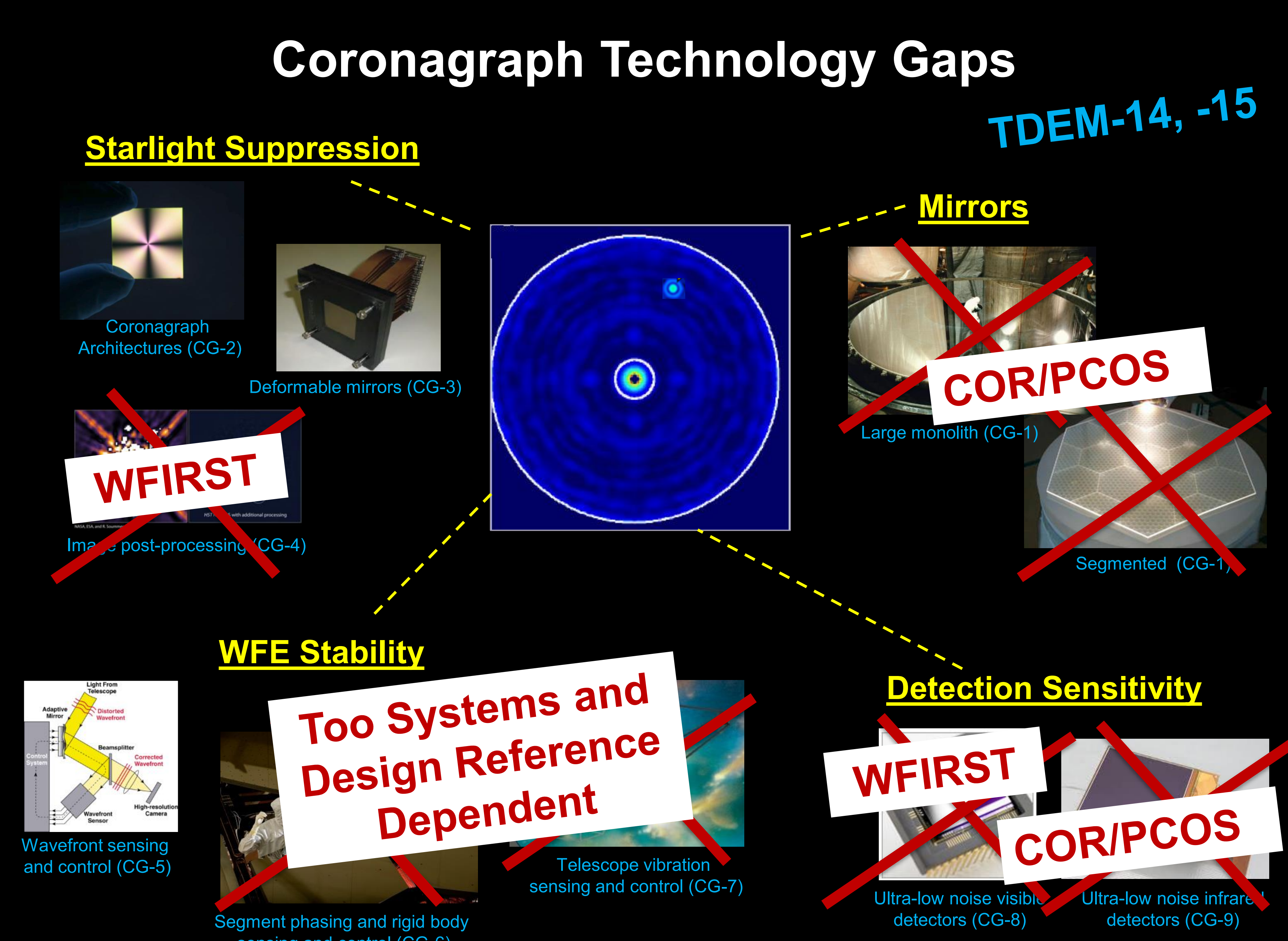
2016 Gap Prioritization Criteria

Legend for Technology Gap Prioritization	
Impact:	4: Critical and key enabling 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:	4: In time for the Decadal Survey (2019); not necessarily at some TRL but reduced risk by 2019
	3: Possible launch date < 10 yr (< 2025)
	2: Possible launch date < 15 yr (< 2030)
	1: Possible launch date > 15 yr (> 2030)
Trend:	4: Very large perceived risk of not being ready in time: (a) no ongoing current efforts (b) little or no funding allocated
	3: Large perceived risk of not being ready in time: (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: Medium perceived risk of not being ready in time: (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: Small perceived risk of not being ready in time: (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

Technology or Engineering?



TRL/TRA Guidelines
Frerking et al (JPL) in review


Coronagraph Technology Gaps
TDEM-14, -15
Starlight Suppression
Coronagraph Architectures (CG-2)
Deformable mirrors (CG-3)
WFIRST
Image post-processing (CG-4)
Mirrors
Large monolith (CG-1)
COR/PCOS
Segmented (CG-1)
WFE Stability
Light From Telescope
Adaptive Mirror
Distorted Wavefront
Beamsplitter
Corrected Wavefront
Control System
Wavefront Sensor
High-resolution Camera
Wavefront sensing and control (CG-5)
Too Systems and Design Reference Dependent
Segment phasing and rigid body sensing and control (CG-6)
Telescope vibration sensing and control (CG-7)
Detection Sensitivity
WFIRST
COR/PCOS
Ultra-low noise visible detectors (CG-8)
Ultra-low noise infrared detectors (CG-9)

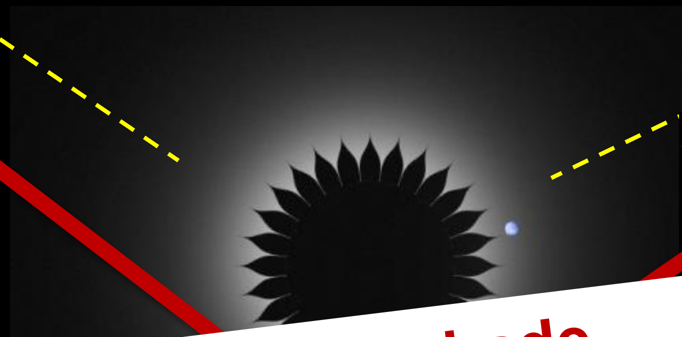
Starshade Technology Gaps

TDEM-16

Starshade Technology Project

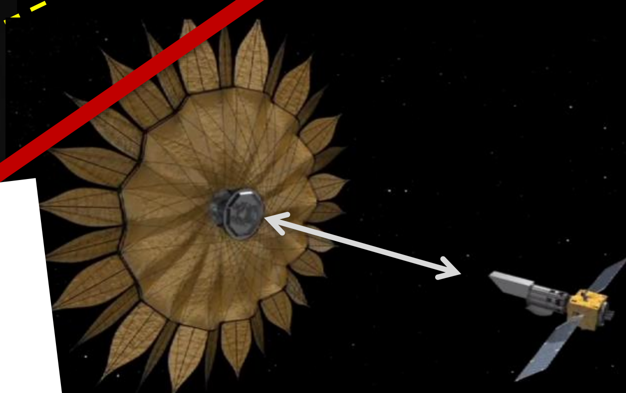
Starlight Suppression

Controlling Sunlight scattering off petal edges (S-2)



Suppressing starlight and validating optical model (S-1)

Formation Sensing and Control



Maintaining lateral offset requirement between the spacecrafts (S-3)

Deployment Accuracy and Shape Stability

Fabricating the petal to high precision (S-4)

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