The 2019 Exoplanet Exploration Program Technology List

Compiled by: Dr. Brendan Crill, Deputy Program Chief Technologist, NASA Exoplanet Exploration Program, Jet Propulsion Laboratory, California Institute of Technology

No major updates or reprioritization occurred in 2018; Minor updates relative to the 2018 ExEP Technology List indicated in blue font.

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
CG-2	**Coronagraph Demo's and Modeling**	Coronagraph Contrast	Coronagraph optics and architecture that suppress diffracted starlight by a factor of < 10^{-10} at visible and infrared wavelengths	Lab: 6×10^{-10} raw contrast at 10% bandwidth across angles of 3-15 λ/D demonstrated with a linear mask and an unobscured pupil in a static vacuum lab environment (Hybrid Lyot) < 1.6×10^{-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 environment (WFIRST) Flight: 10^{-4} raw contrast 540 nm at 10 λ/D (HST)	Coronagraph masks and optics capable of creating circularly symmetric dark regions in the focal plane enabling raw contrasts ≤ 10^{-10}, with minimal contribution from polarization aberration, IWA ≤ 3 λ/D, throughput ≥ 10%, and bandwidth ≥ 10% on obscured and segmented pupils in a simulated dynamic vacuum environment.

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
S-1	**Controlling Scattered Sunlight**	Starlight Suppression	Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle stowed bending strain.	Edges manufactured with machining and electrical discharge machining do not meet scatter requirements; etched amorphous metal edges meet scatter specs integrated in-plane shape tolerance is to be demonstrated.	Integrated petal optical edges maintaining precision in-plane shape requirements after deployment trials and limit solar glint contributing < 10^{-10} contrast at petal edges.
S-2	**Starlight Suppression and Model Validation**	Starlight Suppression	Experimentally validate at flight-like Fresnel numbers the equations that predict the contrasts achievable with a starshade.	Validated optical model with demonstrated 10^{-6} suppression at white light, 58 cm mask, and Fresnel number F (at the starshade tips) = 210; 6×10^{-6} suppression demonstrated at F = 15; 4.6×10^{-8} suppression demonstrated at F~27	Experimentally validated models with total starlight suppression ≤ 10^{-8} in scaled flight-like geometry, with F between 5 and 40 across a broadband optical bandpass. Validated models are traceable to 10^{-10} contrast system performance in space.
S-3	**Lateral Formation Sensing**	Starshade Contrast Stability	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Sub-scale lab demonstration showing ability to center telescope within ± 1 m of the center of the starshade shadow. The Starshade Contrast Stability Technology Gap is now closed.	Demonstrate sensing lateral errors ≤ 0.24 m 3σ accuracy at the flight signal-to-noise ratio at scaled flight separations. Demonstrate control algorithms with scaled lateral control error ≤ 1m radius.

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
S-5	**Petal Positioning Accuracy and Opaque Structure**	Deployment Accuracy and Shape Stability	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 12 m 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, with petal optical edge interfaces, that is optically opaque when deployed, and includes interfaces to launch restraint. Verify the structure will meet shape stability (petal edge position) after exposure to relevant environments throughout mission lifetime.
S-4	**Petal Shape and Stability**	Deployment Accuracy and Shape 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, no long-duration stowage tests.	Deployment tolerances demonstrated to ≤ 100 µm (in-plane tolerance profile for a 7 m petal on the 34m-diameter Exo-S design; tolerances scale roughly linearly with starshade diameter) with flight-like, minimum half-scale petal fabricated and maintains shape throughout mission lifetime with exposure to relevant environments and is optically opaque.

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
CG-3	**Deformable Mirrors**	Coronagraph Contrast	Flight-qualified large-format deformable mirrors and their electronics	Lab: Electrostrictive 64×64 actuator DMs have been demonstrated to meet ≤ 10^{-9} contrasts and < 10^{-10} stability in a vacuum environment and 10% bandwidth; 48×48 actuator DM passed random vibe testing Flight: No SOA	4 m primary mirror: ≥ 96×96 actuators 10 m primary mirror: ≥ 128×128 actuators Enable raw contrasts of ≤ 10^{-9} at ~20% bandwidth and IWA ≤ 3 λ/D Flight-qualified device and drive electronics (radiation hardened, environmentally tested, life-cycled including connectors and cables) Mirror stability maintains 10^{-10} contrast for observation time scales

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
CG-1	**Large Aperture Primary Mirrors**	UVOIR Angular Resolution	Large monolith and multi-segmented mirrors that meet tight surface figure error, coating uniformity, and thermal control requirements at visible wavelengths	Flight Monolith: 3.5-m sintered SiC with < 3 µm SFE (Herschel) 2.4 m 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 is TRL 3 (AMTD). Segmented (no flight SOA): 6.5 m Be with 25 nm SFE (JWST) Non-NASA: 6 DOF, 1-m class SiC and ULE, < 20 nm SFE, and < 5 nm wavefront stability over 4 hr with thermal control	Aperture: 4–15 m; SFE < 10 nm rms (wavelength coverage 400–2500 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

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
CG-6	**Mirror Segment Phasing Sensing & Control**	Coronagraph Contrast Stability	Segmented or monolith large aperture mirrors require segment phasing and rigid-body sensing and control of the segments or the surface figure 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 Capacitive gap sensors demonstrated at 10 pm. No flight SOA; ground-based (Keck) achieved 6 nm positioning error in operations	Systems-level considerations to be evaluated but expect will require WFE stability less than 10 pm rms sensitivity and control over periods of tens of minutes
CG-7	**Telescope Vibration Sense/Control or Reduction**	Coronagraph Contrast Stability	Isolation, reduction, and/or damping of spacecraft and payload vibrational disturbances	80 dB attenuation at frequencies > 40 Hz (JWST passive isolation) Disturbance-Free Payload demonstrated at TRL 5 for JWST with 70 dB attenuation at "high frequencies" with 6-DOF low-order active pointing. GAIA cold gas microthrusters or LISA pathfinder colloidal microthrusters for fine pointing can reduce disturbance environment.	Vibration isolation or reduction of vibration disturbance sources to a level that enables < 1 nm wavefront error stability.

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
CG-9	**Ultra-Low Noise Near-Infrared Detectors**	NIR Detection Sensitivity	Near-infrared wavelength (900 nm to 2.5 μm), extremely low noise detectors for exo-Earth spectral characterization with Integral Field Spectrographs	Lab: HgCdTe photodiode arrays have read noise ≲ 2 e- rms with multiple nondestructive reads; 2k×2k format; 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 < 1k×1k format Sub-Kelvin photon-counting detectors (KID,TES): 0 read noise/dark current; radiation tolerance is unknown; <1k×1k format Flight: HST WFC3/IR HgCdTe dark current 0.05 e-/px/s, 12 e- read noise, 1k×1k format	Read noise << 1 e- rms, dark current noise < 0.001 e-/pix/s, in a space radiation environment over mission lifetime ≥ 2k×2k format
CG-5	**Wavefront Sensing and Control**	Coronagraph Contrast Stability	Sensing and control of line-of-sight jitter and low-order wavefront drift	Lab: < 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; ~12 pm rms sensitivity of focus (WFIRST) Higher low-order modes sensed to 10–100 nm WFE rms on ground-based telescopes Flight: No SOA	Sufficient fast line-of-sight jitter (< 0.5 mas rms residual) and slow thermally-induced WFE sensing and control (≤ 10 pm rms sensitivity) to maintain closed-loop < 10^{-10} raw contrast with an obscured/segmented pupil and simulated dynamic environment

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
CG-8	**Ultra-Low Noise Visible Detectors**	Vis Detection Sensitivity	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph	Lab: 1k×1k silicon EMCCD detectors provide dark current of 7×10^{-4} e^-/px/sec; CIC of 0.01 e^-/px/frame; zero effective read noise (in photon counting mode) after irradiation when cooled to 165.15K (WFIRST); 4k×4k EMCCD fabricated but still under development Flight: HST WFC3/UVIS CCD 3.1 e^- read noise, dark current 2×10^{-3}, format 2k×2k	Effective read noise < 0.1 e- rms; CIC < 3×10^{-3} e-/px/fram; dark current < 10^{-4} e-/px/sec tolerant to a space radiation environment over mission lifetime ≥ 2k×2k format
M-4	**Ultra-Stable Mid-IR Detectors**	Transit Spectroscopy of Exo-Earths	Ultrastable detectors for the mid-infrared band (7 - 20 microns) enabling transit spectroscopy of rocky exoplanets in the Habitable Zone of M-dwarfs.	Lab: JWST/MIRI is expected to achieve 10-100 ppm transit stability Flight: Spitzer IRAC Si:As detector data have demonstrated about 60 ppm precision in transit observations of several hours	< 5 ppm stability for 5 hours
M-3	**Astrometry**	Tangential Stellar Motion	Measure the mass and orbital parameters of Earth-like planets by performing astrometry of FGK stars to the sub-micro-arcsecond level.	Flight: GAIA typical uncertainty in astrometry for DR1 catalog is 300 microarcseconds; goal for V band magnitude 7-12 stars is 10 microarcseconds.	< 0.1 microarcsecond uncertainty enables survey of nearby FGK stars. Astrophysical limits (such as variable stellar surface structure) need to be well-understood. Telescope wavefront error stability and detector thermal and mechanical stability must enable sub-microarcsecond astrometry measurements.

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
CG-4	**Data Post-Processing Algorithms and Techniques**	Coronagraph Contrast	Data post-processing techniques to uncover faint exoplanet signals from residual speckle noise at the focal-plane detector	Few 100 × 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)
CG-10	**Mirror Coatings for UV/NIR/Vis**	Coronagraph Contrast	Mirror coatings that enable high reflectivity to wavelengths as short as 90 nm; coating uniformity enables 10^{-10} coronagraph performance	Al coating with combination of MgF_2, LiF, and/or AlF_3 overcoat: 90-120 nm: < 50% reflectivity 120-300 nm: 85% reflectivity 300 nm-2 µm: > 90% reflectivity Polarization differences between orthogonal polarization states, uniformity, and durability of coatings on large optics is unknown. Flight: HST uses MgF_2; 85% reflectivity λ > 120 nm; 20% reflectivity λ < 120 nm	A mirror coating that that achieves 90-120 nm: > 70% reflectivity 120-300 nm: > 90% reflectivity 300 nm-2 µm: > 90% reflectivity Polarization phase and amplitude difference < 1% between orthogonal polarization states. Uniformity enables 10^{-10} coronagraph contrast performance

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
M-2	**Laser Frequency Combs**	Radial Stellar Motion	Laser Frequency Combs (LFCs) are precise calibration sources for extreme-precision radial velocity measurement.	Lab: Electro-optic-modulation frequency combs demonstrated on ground-based observatories with needed mode spacing, need miniaturization and power reduction. Non-NASA work is advancing miniaturization. Flight: Fiber laser-based optical frequency combs demonstrated on sounding rocket (TEXUS 51 4/15 and TEXUS 53 1/16) w/ ~ few hundred MHz mode spacing. System mass is > 10 kg.	Space-based Laser Frequency Combs to calibrate high resolution, fiber-fed spectrographs for radial velocity precision better than 10 cm/s. Desired parameters are: • mode spacing of 5-10 GHz • bandwidth span 380 nm to 2400 nm • Allen deviation < 10^{-10} • Low SWaP
CG-13	**Ultra Low Noise Mid-IR detectors**	Mid-IR detection sensitivity	Low noise and detectors for the mid-infrared band (7 - 20 microns) enabling exoplanet direct imaging.	Flight: JWST/MIRI	< 5 ppm stability for 5 hr; noise requirements TBD, likely to be 10 x better than JWST/MIRI
M-1	**Extreme Precision Ground-based Radial Velocity**	Radial Stellar Motion	Ground-based radial velocity instrumentation capable of measuring the mass of candidate exo-Earths in the habitable zone and to maximize efficiency of space telescope surveys.	Single measurement precision: 80 cm/s HARPS instrument; NN-EXPLORE's NEID (WYNN observatory) in development: goal 27 cm/s	Signal from exo-Earths is 10 cm/s; Need to reduce systematic errors to 1 cm/s on multi-year timescales; statistical uncertainties of 1 cm/s on monthly timescales for late F, G, and early K stars

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
CG-14	**Mid-IR Large Aperture Telescopes**	Mid-IR Angular Resolution	Cryogenic (4K), large-aperture (> 6m) telescopes to achieve high angular resolution needed to direct-image cool exoplanets in wide orbits (> 5 AU)	JWST Be mirror segments may meet requirements now, so TRL 5 with an extremely expensive technology; TRL 3 exists for other materials like SiC. Cryogenic low-dissipation actuators exist at TRL 3-5.	Develop a feasible and affordable approach to producing a 6-m-class telescope with sufficiently high specific stiffness, strength, and low areal density to be launched; while maintaining compatibility with cryogenic cooling and FIR surface quality/figure of ~1µm rms. Material property measurements at cryogenic temperatures for structures and optics such as damping, emissivity, thermal conductivity, etc.
CG-15	**Mid-IR Coronagraph Optics and Architecture**	Mid-IR Coronagraph Contrast	Coronagraph optics and architecture that suppress diffracted starlight by a factor of < 10^{-6} over a broad mid-IR band (7-30 microns)	The current state of the art for mid-infrared coronagraphs are the three four-quadrant phase masks of JWST-MIRI. These provide narrow-band imaging with contrasts up to 10^{-4} in three narrow bands from 10.65-15.5 micron with inner working angles of 0.33-0.49”. The MIRI coronagraphs do not offer spectral dispersion.	Contrast should be 10^{-6} at IWA 3 λ/D at 10 µm.
CG-16	**Cryogenic Deformable Mirrors**	Mid-IR Coronagraph Contrast	Flight-qualified deformable mirrors operable at cryogenic temperatures, and their drive electronics.	Lab: MEMS DM with 32x32 actuator count operated at 5k demonstrating 2.6 nm rms repeatability	Requirements on actuator stroke, stroke resolution, heat dissipation, and actuator count are TBD but must be operable at cryogenic temperatures.

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
CG-12	**Ultra-Low Noise UV Detectors**	UV Detection Sensitivity	Low-noise ultraviolet (200-400 nm) detectors to characterize exoplanets.	Lab: Micro-channel Plates (MCP): 0 read noise, $\lambda \sim 90$ – 300 nm, spurious count rate 0.05 - 0.5 counts/cm^2/s; QE 20-45%; resolution element size 20 mm. EMCCD: 0 read noise, dark current > 0.005 e-/res/hr; QE 30-50%; resol. el. size 20 μm Flight: HST HRC: In relevant UV band (250 nm): QE 33%, read noise 4.7 e-, dark current 5.8×10^{-3}, 1024x1024	Read Noise: 0 e- Dark Current: 0 e-/resolution/s Spurious Count Rate: < 0.05 counts/cm^2/s QE: 75% Resolution size ≤ 10 μm Tolerant to space radiation environment over mission lifetime.