The 2019 Exoplanet Exploration Program Technology Gap List

Adapted from the 2019 ExEP Technology Plan Appendix

Technology Gap	***Need***	***State-of-the-Art***	***Current Efforts***
Coronagraph Contrast	Maximized science yield for a direct imaging telescope/mission. ≤ 10^{-10} raw contrast, >10% throughput, IWA ≤ 3 λ/D, obscured/segmented pupil	unobscured pupil: 6×10^{-10} raw contrast at 10% bandwidth, angles of 3-15 λ/D (HLC demo in HCIT); obscured pupil: 1.6×10^{-9} raw contrast at 10% bandwidth across angles of 3-9 λ/D (WFIRST)	SCDA in CY 2019 will answer the questions: 1.can a coronagraph provide high science yield on a segmented telescope, while maintaining robustness to wavefront error instabilities, levying unrealistic requirements on a space telescope. 2. can the necessary grayscale apodizer mask be built. Decadal Survey Testbed (DST) in CY 2019, aims to demonstrate 10^{-10} on a clear aperture, enable future static (CY19) and dynamic (CY20) demos for segmented/obscured apertures TDEM funded contrast demos in HCIT: Super Lyot (Trauger), PIAACMC (Belikov) aiming for ~10^{-10} contrast demos in HCIT in CY19 and 20, Vortex (Serabyn) aiming for 10^{-9} in CY19
Coronagraph Contrast Stability	Contrast stability on time scales needed for spectral measurements (possibly as long as days). Achieving this stability requires an integrated approach to the coronagraph and telescope, possibly including wavefront sense/control, metrology and correction of mirror segment phasing, vibration isolation/reduction This stability is likely to require wavefront error stability at the level of 10-100 pm per control step (of order 10 minutes).	WFIRST CGI demonstrated ~10^{-8} contrast in a simulated dynamic environment using LOWFS (which obtained 12 pm focus sensitivity) SIM and non-NASA work has demonstrated nm accuracy and stability with laser metrology Capacitive gap sensors demonstrated at 10 pm 80 dB vibration isolation demonstrated Gaia gold gas microthrusters and LISA pathfinder colloidal microthrusters can reduce vibrations	LUVOIR and HabEx concept studies are developing reference telescope and coronagraph architectures that includes the need for contrast stability as a driving requirement. NASA APD Systems-level Segmented Telescope industry studies will generate system-level error budgets for a coronagraph/ telescope/ spacecraft systems and identify key trades.
Angular Resolution (UV/Vis/NIR)	Large (4–16 m) monolith and multi-segmented mirrors for space that meet SFE < 10 nm rms (wavelength coverage 400–2500 nm); Wavefront stability better than 10 pm rms per wavefront control	<u>Monolith</u>: 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 TRL 3 (AMTD).	HabEx and LUVOIR studies investigating monolith and segmented architectures, including materials (Si carbide, glass) manufacturing, coating, mounting, thermal control, vibration isolation.

	time step; Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control.	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	SLSTC industry study is investigating manufacturability of large segmented mirrors In-space assembly of future large telescopes (>20m) under study
Vis/NIR Detection Sensitivity	Near IR (900 nm to 2.5 µm) and visible-band (400-900nm) extremely low noise detectors for exo-Earth spectral characterization with Integral Field Spectrographs. NIR Read noise << 1 e^- rms, dark current noise < 0.001 e^-/pix/s, Vis band read noise < 0.1 e^- rms; CIC < 3×10^{-3} e^-/px/frame; dark current < 10^{-4} e^-/px/sec , functioning in a space radiation environment over mission lifetime; large ≥ 2k×2k format	Vis: 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 165.15 K (WFIRST); 4k×4k EMCCD fabricated but still under development NIR: 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 Cryogenic superconducting photon-counting detectors (MKID,TES): 0 read noise/dark current; radiation tolerance is unknown; <1k×1k format	HabEx and LUVOIR have baselined existing EMCCD (Vis) and HgCdTe (NIR) detectors while keeping an eye on potential improvements in other areas, particularly in read noise, dark current and radiation hardness WFIRST CGI is advancing the EMCCD technology for the Vis band, in particular aiming to improve radiation hardness Superconducting detectors (MKID, TES, etc.) developing under APRA for sub-orbital and ground-based efforts
Starshade Starlight Suppression and Model Validation	Experimentally validate at flight-like Fresnel numbers (F) the equations that predict starshade starlight suppression: total starlight suppression ≤ 10^{-8} in scaled flight-like geometry, F between 5 and 40 across a broadband optical bandpass. Contrast model accuracy validated to better than 25%. Limit edge-scattered sunlight and diffracted starlight with optical petal edges that also handle any stowed bending strain. Limit solar scatter lobe brightness to better than visual magnitude (V) 25	Validated optical model with demonstrated 10^{-6} suppression at white light, 58 cm mask, and F (at the starshade tips) = 210; 6×10^{-6} suppression demonstrated at F =15; 4.6×10^{-8} suppression demonstrated at F ~ 27 Etched amorphous metal edges meet scatter specs integrated in-plane shape tolerance is to be demonstrated.	S5 is continuing sub-scale tests at Princeton that should achieve flight suppression. Currently limited by manufacture of the subscale starshade. S5 developing amorphous metal edges that demonstrate shape specs. The edge scatter technology scheduled to be at TRL 5 by the S5 project in 1-2 years Suppression demos are high priority for S5 Because of reliance on models, once flight-like suppression is demonstrated, should also validate equations in a slightly wider range of parameters (wavelengths, subscale starshade size, etc.)

Starshade Formation Sensing	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.	Sub-scale lab demonstration showing ability to center telescope within ± 1 m of starshade shadow.	WFIRST starshade accommodation and S5 created a scaled benchtop demonstration of using an out-of-band pupil-plane camera (For WFIRST, the LOWFS camera will suffice) to provide misalignment sensing Control algorithms based on the sensor are also to be demonstrated at subscale. This gap is expected to be closed in CY18 for a potential WFIRST rendezvous The pupil-plane camera approach will be roughly independent of starshade and telescope diameter
Starshade Deployment and Shape Stability	A system that will deploy the petals from a launch-stowed configuration to the needed shape (to better than ≤ 1 mm (in-plane envelope) and maintain petal edges to ≤ 100 μm (in-plane tolerance profile for a 7 m petal on the 34 m-diameter Exo-S design; tolerances scale roughly linearly with starshade diameter), and be optically opaque.	Manufacturing tolerance (≤ 100 μm) verified with low fidelity 6 m 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. Petal deployment tolerance (≤ 1 mm) verified with low fidelity 12 m prototype and no optical shield; no environmental testing (Exo-S design).	S5 is wrapping up a trade study that will select a deployment architecture to use as a baseline towards reaching TRL 5 by the early 2020s. Work on this mechanical deployment will accelerate when the trade study is complete. This technology gap is scheduled to be closed by early 2020s for a WFIRST rendezvous design (30m-diameter class starshade). A larger starshade may require a different autonomous deployment architecture or in-space assembly.
Mid-IR Contrast	Coronagraphy in the mid-IR to detect ~100-300K planets in emission and perform spectroscopy between 10-30 mm wavelength, with 2 λ/D inner working angle and of order 10^{-6} contrast. Maximum spectral dispersion should be sufficient to resolve the 15 micron CO_2 band (R ~ 500).	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.	OST is currently studying the science case for mid-infrared coronagraphy and technology development needed to achieve the science goals. JAXA is studying the mid-IR instrument (MISC) in OST. If OST uses a segmented telescope, this technology benefits from lessons learned in the Vis/NIR SCDA study. The relatively modest contrast may not require small deformable mirrors such as those needed for speckle nulling in the visible band. If this is the case, this coronagraph could be ready on the time scale of a Vis/NIR coronagraph.
Detection Stability in the Mid-IR	Ultrastable detectors (< 10 ppm over 5 hours) for the mid-infrared band (7 - 20 microns) enabling transit spectroscopy of rocky exoplanets in the Habitable Zone of M-dwarfs.	JWST/MIRI is expected to achieve 10-100 nm transit stability.	OST is currently studying the science case for transit spectroscopy and technology development needed to achieve the science goals. OST STDT is developing a detector technology roadmap, including mid-IR detectors with these stability requirements.

		Spitzer IRAC Si:As detector data have demonstrated about 60 ppm precision in transit observations of several hours	Analysis of MIRI transit spectroscopy data when JWST on-orbit performance will provide additional lessons
Mid-IR Angular Resolution	Cryogenic (4K), large-aperture (> 9m) 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, but other materials like SiC or simply aluminum may. Cryogenic low-dissipation actuators may play a role if active surface figuring is deemed necessary	OST studying telescope technologies. SLSTC industry study is investigating manufacturability of large cryogenic segmented mirrors
Mid-IR Detection Sensitivity	Low noise and detectors for the mid-infrared band (7 - 20 microns) enabling exoplanet direct imaging. noise requirements TBD, likely to be 10 x better than JWST/MIRI	JWST/MIRI's band-impurity detectors is the state of the art in this wavelength band.	OST's MISC instrument includes a coronagraph and will study sensitivity needs JWST's performance on orbit will set the state of the art in this band. NeoCAM is developing H2RGs with sensitivity at wavelengths as long as 12 microns. The needs specified in OST's final report will determine the current level readiness. If improvement is needed in band-impurity-type detectors, building up an industrial base may be needed.
UV Contrast	Mirror coatings that enable high reflectivity to wavelengths as short as 90 nm while maintaining good performance in Vis/NIR band. Coating uniformity must be good enough that polarization phase and amplitude difference < 1% between orthogonal polarization states across the whole wavelength band.	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 $\lambda > 120$ nm; 20% reflectivity $\lambda < 120$ nm	HabEx and LUVOIR studies are both looking into trading ability to do coronagraphy across a wide band while maintaining UV sensitivity. TDEM-funded study (PI Breckinridge) looking into sensitivity of polarization aberrations and possibly will set requirements from a coronagraph on coating uniformity.
UV Detection Sensitivity	Low-noise ultraviolet (200-400 nm) detectors to characterize exoplanets with an integral field spectrograph. Read Noise: 0 e-; Dark Current: 0 e-/resolution/s; Spurious Count Rate: < 0.05 counts/cm2/s; QE: 75% ; Resolution size ≤ 10 mm; Tolerant to space radiation environment over mission lifetime.	Lab: Micro-channel Plates (MCP): 0 read noise, 90 – 300 nm, spurious count rate 0.05 - 0.5 counts/cm^2/s; QE 20-45%; resolution element size 20 μm. 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}, 1024×1024 format	LUVOIR and HabEx studies determining whether these detectors are already good enough for their needs. APRA and SAT awards are advancing these detectors. These detectors are likely to be ready within a few years

Stellar Reflex Motion Sensitivity: Radial Velocity	Capability to measure exoplanet masses down to Earth-mass. The radial velocity semi-amplitude of a Solar-mass star due to an orbiting Earth-mass planet at 1 AU is 9 cm/s. Technology to make radial velocity mass measurements may include using a space-based instrument to avoid atmospheric telluric lines and simultaneous measurements of stellar lines across a broad band (both Vis and NIR). Theoretical understanding of astrophysical noise sources (stellar jitter) and how to mitigate them	Ground-based RV: state-of-the-art demonstrated stability is currently 28 cm/s over 7 hours (VLT/ESPRESSO). Laser frequency combs demonstrated on ground-based observatories with correct mode spacing, non-NASA work is advancing miniaturization. Fiber laser-based optical frequency combs demonstrated on sounding rocket though with closer line spacing than useful for RV.	NASA-chartered probe study (EarthFinder) investigating benefits of RV instrument on a space telescope. Ground-based RV instruments expected to achieve 20-30 cm/s single measurement precision by NN-EXPLORE's NEID instrument (WIYN telescope) and the iLocator instrument (LBT) both planned for 2019
Stellar Reflex Motion Sensitivity: Astrometry	Capability to measure exoplanet masses down to Earth-mass. Astrometric detection of an exo-Earth at 10pc requires 0.1 microarcsecond uncertainty. Technology with the stability neeed to make astrometric measurements to this level, possibly requiring detector metrology and/or diffractive pupils Theoretical understanding of astrophysical noise sources (star spots) and how to mitigate them.	GAIA preliminarily achieved 34 micro arcsecond error but ultimately could achieve 10 microacrseconds on bright targets after all systematics are calibrated TDEM-funded demonstration (Bendek) of diffractive pupil showed 5.75×10-5 λ/D or 1.4 microarcsecond on a 4m telescope (limited by detector calibration) Preliminary study of 1-m space telescope and instrument with in-situ detector calibration can achieve 0.8 micro arcsecond in 1 hr	none