**parTable 11.1-1.** HabEx 4 m Baseline Architecture Technology Gap List.

| Title | Description | Section | State of the Art | Capability Needed | **TRL 2019** | **Expected  2023 TRL** |
| --- | --- | --- | --- | --- | --- | --- |
| Enabling Technologies | | | | | | |
| Starshade Petal Position Accuracy and Stability | Deploy and maintain petal position accuracy in L2 environment | 11.2.1.1 | * + Petal position deployment tolerance (≤150 µm) verified with multiple deployments of 12 m flight-like perimeter truss and no optical shield   + No environmental testing | * + Petal position deployment accuracy on 20 m perimeter truss: ±600 µm (3σ) bias   + Position stability in operational environment: ±400 µm (3σ) random | 4 | 5 |
| Starshade Petal Shape Accuracy and Stability | Starshade petal shape maintained after deployment, thermal at L2 | 11.2.1.2 | * + Manufacturing tolerance (≤100 µm) verified with low fidelity 6 m long by 2.3 m prototype; No environmental tests   + Petal deployment tests conducted on prototype petals to demonstrate rib actuation; No post-deploy cycle and petal shape stability measurements | * + Petal 16 m long by 4 m wide   + Petal shape manufacture: ±140 µm (3σ)   + Post-deploy cycle and petal shape thermal stability ≤ ±160 µm (3σ) | 4 | 5 |
| Starshade Scattered Sunlight for Petal Edges | Limit edge-scattered sunlight and diffracted starlight with petal optical edges | 11.2.2.1 | * + Chemically etched amorphous metal edges limit solar glint flux to 25 visual magnitudes in two main lobes, verified at coupon level * In-plane shape tolerance of ±20 µm met at half meter length after integration onto prototype petal * In plane shape stability demonstrated post-deploy and thermal cycle * Scatter performance on half meter edge verified post environment | * + One meter length edges assembled precisely onto petal   + Petal edge in-plane shape tolerance: ±66 μm (3σ)   + Petal edge in-lane placement tolerance: ±55 μm (3σ)   + Solar glint: 26.25 (TBR) visual magnitudes in two main lobes | 4 | 5 |
| Starshade Contrast Performance Modeling and Validation | Validate at flight-like Fresnel numbers the equations that predict the contrasts | 11.2.2.2 | * + 1.5 × 10-10 contrast demonstrated at Fresnel NumberR=1 ~13 (monochromatic)   + Expect 1 × 10-10 contrast demonstrated at Fresnel NumberR=1 ~13 (10% bandwidth) in March 2019 | * + Experimentally validated models with scaled flight-like geometry and Fresnel NumberR=1 ≥12 across a broadband optical bandpass. Validated models are traceable to 1 × 10-10 contrast system performance in space | 4 | 5 |
| Starshade Lateral Formation Sensing | Lateral formation flying sensing to keep telescope in starshade’s dark shadow | 11.2.3.1 | * + Simulations have shown centroid to ≤1/10th aperture with ample flux to support control loop   + Control algorithms demonstrated control ≤1 m radius within line of sight of the star for durations representative of typical starshade observation times | * + Demonstrate sensing lateral errors ≤0.40 m accuracy (≤1/10th aperture) at scaled flight separations   + Control algorithms demonstrated with scaled lateral control corresponding to ≤1 m of the line of sight | 5 | 5 |
| Large Mirror Fabrication | Large monolith mirror that meets tight surface figure error and thermal control requirements at visible wavelengths | 11.3.1.1 | * + 4.2 m diameter, 420 mm thick blanks standard   + Schott demonstrated computer-controlled-machine lightweighting to pocket depth of 340 mm, 4 mm rib thickness on E-ELT M5 and 240 mm deep/2 mm thick rib on Schott 700 mm diameter test unit   + State-of-the-practice (SOP) lightweighting has yielded large mirrors of aerial density 70 kg/m2   + Zerodur® can achieve 2.83 parts per billion/K CTE homogeneity (DKIST mirror)   + Wavefront stability: 25 nm rms for HST in LEO   + Wavefront Error of WFIRST-like primary mirror (spatial frequency cycles/beam diam. : nm RMS):     - 0-7 cy/D: 6.9 nm RMS     - 7-100 cy/D: 6.0 nm RMS     - >100 cy/D: 0.8 nm RMS | * + 4.04 m diameter substrate   + 3–4 mm ribs, 14 mm facesheet, and pocket depth of 290 mm for 400 mm thick blank   + Aerial density 110 kg.m2   + < 5 ppb/K CTE homogeneity   + First mode ≥60 Hz   + Wavefront stability of 100s to a few picometers rms (depending on spatial frequency) over 100s of seconds   + Wavefront Error (spatial frequency cycles/beam diam. : nm RMS):     - 0-7 cy/D: 6.9 nm RMS     - 7-100 cy/D: 6.0 nm RMS     - >100 cy/D: 0.8 nm RMS | 4 | 4 |
| Large Mirror Coating Uniformity | Mirror coating with high spatial uniformity over the visible spectrum | 11.3.1.2 | * + Reflectance uniformity <0.5% of protected Ag on 2.5 m TPF Technology Demonstration Mirror   + IUE, HST, and GALEX used MgF2 on Al to obtain >70% reflectivity from 0.115 µm to 2.5 µm   + Operational life: >28 years on HST | * + Reflectance uniformity <1% over 0.45–1.0 µm   + Reflectivity comparable to HST:     - 0.115–0.3 µm: ≥70 %     - 0.3 – 0.45 µm: ≥88%     - 0.45 – 1.0 µm: ≥85 %     - 1.0 - 1.8 µm: ≥90 %   + Operational life >10 years | 4 | 4 |
| Laser Metrology | Sensing for control of rigid body alignment of telescope front-end optics | 11.3.2.1 | * + Thermally stabilized Planar Lightwave Circuit fully tested   + Nd:YAG ring laser and modulator flown on LISA-Pathfinder   + Phase meters flown on LISA-Pathfinder and Grace Follow-On   + Sense at 1 kHz bandwidth   + Uncorrelated per gauge error of 0.1 nm   + Laser Met System at JPL expected TRL 6 by 9/19 | * + Sense at 100 Hz bandwidth   + Uncorrelated per gauge error of 0.1 nm | 5 | 5 |
| Coronagraph Architecture | Suppress starlight by a factor of ≤1E-10 at visible and near-IR wavelengths | 11.4.1.1 | * + Hybrid Lyot: 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 vacuum lab environment   + Vector vortex charge 4: 5 × 10-10 raw contrast monochromatic across angles of 2–7 λ/D   + Lyot: 3.6 × 10-10 raw contrast at 10% bandwidth over 3–7 λ/D in a static lab environment (DST)   + Vector vortex charge 6: 8.5 × 10-9 coherent contrast at 10% bandwidth across angles of 3–8 λ/D demonstrated with an unobscured pupil in a static lab environment | * + Vortex Charge 6   + Raw contrast of ≤1 × 10-10   + Raw contrast stability of ≤2 × 10-11   + Inner working angle (IWA) ≤ 2.4 λ/D   + Coronagraph throughput ≥10%   + Bandwidth ≥20% | 4 | 5 |
| Zernike Wavefront Sensing and Control (ZWFS) | Sensing and control of low-order wavefront drift; monitoring of higher order Zernike modes | 11.4.2 | * + <0.36 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 on Mv = 5 equivalent source; ~26 pm rms sensitivity of focus (WFIRST Coronagraph Instrument Testbed)   + WFE stability of 25 nm/orbit in low Earth orbit (HST). Higher low-order modes sensed to 10–100 nm WFE rms on ground-based telescopes | * + LoS error <0.2 mas rms per axis   + Wavefront stability:≤~100 pm rms over 1 second for vortex   + WFE <0.76 nm rms | 4 | 5 |
| Deformable Mirrors | Flight-qualified large-format deformable mirror | 11.4.3 | * Micro-electromechanical DMs available up to 64 × 64 actuators, 400 µm pitch with 6 nm RMS flattened WFE; 3.3 nm RMS demonstrated on 32 × 32 DM   + 8.5 × 10-9 coherent contrast at 10% bandwidth in a static test achieved with smaller 32 x 32 MEMS DMs   + Drive electronics in DST provide 16 bit resolution which contributes ~1 × 10-10 to contrast floor | * + 64 × 64 actuators   + Enable coronagraph raw contrasts of ≤1 × 10-10 at ~20% bandwidth and raw contrast stability ≤2 × 10-11   + <3.3 nm RMS flattened WFE   + Drive electronics of at least 18 bits | 4 | 5 |
| Delta Doped  UV and Visible Electron Multiplying CCDs | Low-noise UV and visible detectors for exoplanet characterization | 11.5.1.1 | * + 1k × 1k EMCCD detectors (WFIRST)     - Dark current of 7 × 10-4 e-/px/s     - CIC of 2.3 × 10-3 e-/px/fram     - Read noise ~0 e- rms (in EM mode)     - Irradiated to equivalent of 6-year flux at L2     - Updated design for cosmic ray tolerance under test   + 4k × 4k EMCCD fabricated (update with test specifics) | * + 0.45–1.0 µm response;   + Dark current <10-4 e-/px/s   + CIC < 3 × 10-3 e-/px/fram   + Effective read noise <0.1e- rms   + Tolerant to a space radiation environment over mission lifetime at L2   + 4k × 4k format for Starshade IFS | 4 | 5 |
| Deep Depletion Visible Electron Multiplying CCDs | Low-noise detectors with improved QE at 940 nm for exoplanet characterization | 11.5.1.1 | * + Under investigation. e2V claims dark current is on boundary surface and not throughout volume   + CCD-201 is not currently made in deep depletion   + CCD-220 (regular CCD) dark current < 0.02 e-/px/s | * QE >80% at 940 nm * thicker silicon (up to 200 µm thick layer), deep depletion devices * 4k × 4k format for Starshade IFS | 4 | 4 |
| Linear Mode Avalanche Photodiode Sensors | Near infrared wavelength (0.9 µm to 2.5 µm), extremely low noise detectors for exo-Earth IFS | 11.5.1.2 | * + 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, read noise <<1 e‑ rms, and < 1k × 1k format   + LMAPD have 0.0015 e-/pix/s dark current, <1 to 0.1 e rms readout noise (SAPHIRA) for 320×256, 24 µm pixels | * + Read noise <<1 e- rms   + Dark current <0.002 e-/pix/s   + In a space radiation environment over mission lifetime   + 320 × 256 pixel array, 24 µm pixels | 5 | 5 |
| * + LMAPD 1k × 1k formats of 15 µm pixels have << 1 e- rms read noise at gain of 25, full testing begins summer 2019 | * + 1k × 1k pixel array, 15 µm pixels | 4 | 5 |
| UV Microchannel Plate (MCP) Detectors | Low-noise detectors for general astrophysics as low as 0.115 µm | 11.4.4 | * + MCPs: QE 44% 0.115–0.18 µm with alkalai photocathode, 20% with GaN; dark current ≤0.1–1 counts/cm2/s with ALD activation and borosilicate plates | * + Dark current <0.001 e-/pix/s (173.6 counts/cm2/s), in a space radiation environment over mission lifetime,   + QE>50% (TBR) for 0.115–0.3 µm wavelengths | 4 | 4 |
| Microthrusters | Jitter is mitigated by using microthrusters instead of reaction wheels during exoplanet observations | 11.6.1.1 | * + Colloidal microthrusters 5–30 µN thrust with a resolution of ≤0.1 µN, 0.05 µN/√Hz, 100 days on‑orbit on LISA-Pathfinder   + Colloidal microthrusters with 100 µN thrust and 10‑year lifetime under development   + Cold-gas micronewton thrusters flown on Gaia (TRL 9), 0.1 µN resolution, 1 mN max thrust, 0.1 µN/sqrt (Hz), 4 years of on-orbit operation | * + Thrust capability: 350 µN with 16 thruster cluster   + Thrust resolution 4.35 µN   + Thrust noise: 0.1 µN/√Hz   + Operating life: 5 years | 5 | 5 |