The 2022 Exoplanet Exploration Program Technology Gap List

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Technology Gap and Description	***Current State-of-the-Art***	***Performance Goals and Objectives***
Mirror Technologies for High Angular Resolution (UV/Vis/NIR) The capability to resolve the habitable zones of nearby star systems in the UV/Vis/NIR bands with a large space telescope.	Monolith: 3.5-m sintered SiC with < 3 µm SFE (Herschel); 2.4-m ULE with ~10 nm SFE (HST); Waterjet cutting is TRL 9 to 14" depth, but TRL 3 to >18" depth. Fused core is TRL 3; slumped fused core is TRL 3 (AMTD); 4-m class Zerodur mirrors from single boules are TRL 4. 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	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 time step; CTE uniformity characterized at the ppb level for a large monolith; Segmented apertures leverage 6 DOF or higher control authority meter-class segments for wavefront control. Sub-gaps that could partially or fully close this gap: - Mirror Substrate and Structure - Mirror Positioning Actuators - Gravity Sag Offloader - Coefficient of Thermal Expansion Characterization - Mirror Finishing - UV Coatings: Wavefront Effects
Coronagraph Contrast and Efficiency The capability to suppress starlight and receive planet light with a coronagraph to the level needed to detect and spectrally characterize Earth-like exoplanets in the habitable zones of Sun-like stars.	unobscured pupil: 4×10^{-10} raw contrast at 10% bandwidth, angles of 3-15 λ/D (Lyot coronagraph demo in HCIT); obscured pupil: 1.6×10^{-9} raw contrast at 10% bandwidth across angles of 3-9 λ/D (Roman CGI Lab Demos); segmented/unobscured pupil:2.5×10^{-8} raw contrast in monochromatic light across 6-10 λ/D (Lyot coronagraph demo in HiCAT)	Maximized science yield in imaging and spectroscopy for a direct imaging telescope/mission. ≤ 10^{-10} raw contrast, >10% throughput, inner working angle ≤ 3 λ/D, outer working angle >= 45 λ/D [TBD], 20% bandwidth; obscured/segmented pupil For the two distinct cases of monolith and segmented primary mirrors, Sub-gaps that could partially or fully close this gap: - Coronagraph Architecture - Deformable Mirrors

		- Computational Throughput on Space-rated processors - High bandwidth optical communication between space and ground - Coronagraph Efficiency - Autonomous on board WFSC architectures
Coronagraph Stability The capability to maintain the deep starlight suppression provided by a coronagraph for a time period long enough to detect light from an exo-Earth.	RST 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 cold gas microthrusters and LISA pathfinder colloidal microthrusters can reduce vibrations	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). Sub-gaps that could partially or fully close this gap: - Ultra-stable Telescope - Integrated Modeling of Telescope/Coronagraph system - Disturbance Reduction and Observatory Stability - Wavefront Sensing (low-order and out-of band) - Laser Gauges for Metrology - Segment Relative Pose Sensing and Control - Thermal Sensing and Control - Wavefront Sensing and Control Algorithms - Observatory Pointing Control
Vis/NIR Detection Sensitivity The capability to detect single photons in the Vis and NIR to enable imaging and spectroscopy of Earth-like exoplanets.	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 (Roman); 4k×4k EMCCD fabricated but still under development	Near IR (900 nm to 2.5 μm) and visible-band (400-900nm) extremely low noise detectors for exo-Earth spectral characterization with spectrographs or intrinsic energy resolution. 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/s, functioning in a space radiation environment over mission lifetime (5-10 years); may need large ≥ 2k×2k format Sub-gaps that could partially or fully close this gap:

	NIR: HgCdTe photodiode arrays have read noise $\lesssim$ 2 e-rms with multiple nondestructive reads; 2k×2k format; dark current < 0.001 e-/s/pix; very radiation tolerant (JWST), high QE down to 750nm;HgCdTe APDs demonstrated dark current ~10–20 e-/s/pix, RN << 1 e-rms and 1k×1k format Cryogenic superconducting photon-counting, energy-resolving detectors (MKID,TES): 0 read noise/dark current; space radiation tolerance not systematically studied; <1k×1k format	- NIR Low-noise Detector - UV/VIS Low-noise Detector - Rad-Hard, High-QE, Energy Resolving, Noiseless Single Photon Detector Arrays for the NIR, VIS, and UV
Stellar Reflex Motion Sensitivity: Extreme Precision Radial Velocity Capability to measure exoplanet masses down to Earth-mass.	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.	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). Stability of the instrument and its absolute calibration must be maintained on long time scales in order to enable the measurement. Theoretical understanding of astrophysical noise sources (stellar jitter) and how to mitigate them. Sub-gaps that could partially or fully close this gap: - Detectors for high-resolution, cross-dispersed spectrographs - High-Precision, High-Throughput, High-Spectral Resolution Dispersive Optics - Advanced Photonics for extreme-precision radial velocity spectroscopy - Ground-based Visible-light Adaptive Optics - Precision calibration for extreme-precision radial velocity spectroscopy
Stellar Reflex Motion Sensitivity: Astrometry Capability to measure exoplanet masses down to Earth-mass.	GAIA preliminarily achieved 34 micro arcsecond error but ultimately could achieve 10 microarcseconds on bright targets after all systematics are calibrated	Astrometric detection of an exo-Earth at 10pc requires 0.1 microarcsecond uncertainty. Technology with the stability need to make astrometric measurements to this level, possibly requiring detector metrology and/or diffractive pupils

	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	Theoretical understanding of astrophysical noise sources (star spots) and prospects for mitigating them.
Starshade Deployment and Shape Stability The capability to deploy on-orbit a starshade that is stowed in a launch vehicle fairing to a precise shape, and to maintain that shape precision during all operational environments.	Manufacturing tolerance (≤ 100 μm) verified with low fidelity 6 m prototype. Petal deployment tests conducted to demonstrate rib actuation. Petal deployment tolerance (≤ 1 mm) verified with low fidelity 12 m prototype; limited environmental testing.	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 micron (in-plane tolerance profile for a 7 m petal on a 34 m-diameter starshade; tolerances scale roughly linearly with starshade diameter), and be optically opaque. Performance goals are under re-evaluation for the IROUV Great Observatory. Overall starshade diameter likely to be > 50m.
Starshade Starlight Suppression and Model Validation The capability of a starshade to suppress diffracted on-axis starlight and scattered off-axis Sunlight to levels needed to characterize Earth-like exoplanets. The capability to experimentally validate model of the starshade's optical performance at subscale.	10^{-10} contrast at inner working angle demonstrated over 10% bandpass using 24 mm starshade in Princeton testbed with F = 13. Validated optical model with demonstrated 10^{-6} suppression at white light, 58 cm mask, and F = 210. Optical model validated to within a factor 2 at 10^{-8} contrast at F=13. Etched amorphous metal edges with anti-reflection coating meet scatter specs with margin; integrated in-plane shape tolerance is to be demonstrated.	Experimentally validate at flight-like Fresnel numbers (F) the equations that predict starshade starlight contrast: total starlight contrast $<=10^{-10}$ in a scaled flight-like geometry, F between 5 and 40, across a broad UV/optical/IR bandpass. Contrast model accuracy validated to better than 25%. Limit edge-scattered sunlight and diffracted starlight with optical petal edges that simultaneously meet scatter requirements and in-plane shape tolerances. Limit solar scatter lobe brightness to better than visual magnitude (V) ~26. Performance goals are under re-evaluation for the IROUV Great Observatory.
UV Detection Sensitivity The sensitivity to perform imaging spectroscopy of exoplanets in the ultraviolet.	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	Low-noise ultraviolet (200-400 nm) detectors to characterize exoplanets with an imaging spectrograph. 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.
Detection Stability in the Mid-IR The capability to detect mid-infrared light with ultrastable detectors to carry out transit spectroscopy of	JWST/MIRI is expected to achieve 10-100 ppm transit stability.	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.

terrestrial exoplanets in the Habitable Zone of M-dwarf stars.	Spitzer IRAC Si:As detector data have demonstrated about 60 ppm precision in transit observations of several hours	

ExEP SubGaps

Subgap Name	Description	Current State-of-the-Art	Performance Goals and Objectives
Mirror Substrate and Structures	Mirror substrate material advancements will likely be required to meet 10 pm/10 minute WFE stability requirements, with particular emphasis in homogeneity and isotropy. Additional characterization, material processing understanding, and potential advancements in structural composite materials may be required to ascertain long term dimensional changes which may drive critical actuator stroke range and capabilities. Advances in latch mechanisms will be necessary to reach precision, stability, and hysteresis levels likely required.	JWST: Beryllium mirror segments, 1.32-m flat-to-flat with 25 nm surface figure error (TRL 6). Multiple Mirror System Demonstrator (MMSD) demonstrated fabrication or partial fabrication of five, 1.4-meter point-to-point ULE mirror segment substrates, achieving 10 kg/m^2 areal density and a production schedule of 3 mirrors on three-week centers. One of the five mirror segment substrates was flight qualified. Thermal modeling performed with as-measured CTE distributions indicate that these fabricated mirrors can achieve the necessary thermal stability when properly controlled. ULE segment substrate is TRL 5; fully integrated ULE segments are TRL 4. Materials with near-zero coefficient of thermal expansion (CTE) are desired for optimal thermal stability. Thus, candidate mirror segments using closed-back ULE (TRL 5) or open-back Zerodur (TRL 4) are under consideration. (a) Study indicates <10mK temperature stability in ULE mirror required to bound uncorrected wavefront errors due to higher spatial frequency mirror surface figure errors to <6 pm rms (Stahl, 2020), which may be achievable (Dewell, Section7, 2019). Less thermally stable segmented PM designs may be susceptible to launch acoustics. JWST beryllium PM segments are SOTA metallic mirror substrates. Need: – Additional characterization/process advancements for thermal stability/homogeneity – Characterization of consistent long-term crack growth parameters to demonstrate safe life. (b) JWST OTIS structures made from various graphites with 954-6 cyanate ester thermoset resin are SOTA precision composite structures. Other resins exist with low outgassing, moisture uptake, high fiber compatibility. Observation efficiency, dimensional stability, & micro dynamics will be impacted by thermal microcracking & moisture desorption. Need SOTA characterization of these properties. (c) Mechanism deployment repeatability and stability are critical for WFE stability. Latches with <1nm/N hysteresis have been demonstrated (Carrier, 2003).	Surface Figure Error: ~5 nm RMS First Free Mode: > 400 Hz Areal Density: <19 kg/m^2 • Perform system performance studies to determine detailed homogeneity requirements for critical mirror substrates • Demonstrate ability to characterize material inhomogeneity to required resolutions • Characterize long-term crack growth behavior of mirror substrates within required precision to assure mission safe life • Characterize microcracking & moisture absorption/desorption of critical telescope composite structures • Demonstrate through similitude to potential flight structures low/no microcracking & moisture absorption/desorption meeting mission requirements • Determine detailed requirements for latched mechanisms with emphasis on repeatability, hysteresis, and stability • Build and demonstrate latches suitable for incorporation into a UVOIR mission based on segmented architecture • Demonstrate mitigation of support print-through.

Mirror Positioning Actuators	Rigid-body positioning of the primary mirror segments will require actuators that simultaneously have high dynamic range (millimeters of travel) and ultra-fine resolution (picometer step sizes). For the ultra-fine actuation, piezo-electric (PZT) actuators are the primary candidate.	The JWST mechanical bipod actuators currently achieve the necessary level of coarse and fine stage actuation (TRL 6). Commercial off-the-shelf PZT actuators with 5 picometer resolution are available and have been demonstrated in controlled laboratory environments (Saif et al. 2019). However, development is needed to incorporate PZT actuators with the coarse and fine stage mechanical bipod actuators. PZT launch survivability and reliability must also be studied and developed (TRL 3). The ULTRA-TM program recently demonstrated closed loop gap stability of a capacitive sensor and 3 ultra-fine actuators to <2.5 pm RMS in gap (0.01-10 Hz)	Stroke: 10 mm Resolution: < 10 pm Creep: < 1 pm / 10 min. Design an initial test article actuator that incorporates mechanical coarse stage motion and PZT ultra-fine stage motion. Co-develop the necessary drive electronics to manage the actuator motion. Fabricate a test article actuator and verify its performance in a laboratory setting to achieve TRL 4. Following the TRL 4 demonstration, design and fabricate a complete, flight-like bipod actuator, and electronics. Complete functional and performance testing of the actuator with a mirror segment mass simulator (TRL 5) and complete environmental qualification testing to bring the actuator technology component to TRL 6. Incorporate actuators into full-scale mirror segment assembly to raise system-level TRL to 6. (see LUVOIR final report for more detailed plan, schedule, and cost)
Gravity Sag Offload	Capability to trace surface figure error measurements in 1-g to the 0-g environment.	Ability to characterize gravity sag and compensate for it is TRL-9 for space telescopes such as Hubble, Kepler, and Webb. But, it is TRL-4 for a potential 4 to 6m monolithic IROUV exoplanet mirror. The reason is amplitude. For a potential 4 to 6m mirror, it is necessary to characterize and compensate for several millimeters of gravity sag with an uncertainty of <4 nm rms. The Hubble, Kepler and Webb mirrors had gravity sags of a few 10s to 100s micrometer.	To meet the Decadal 2020 identified gap, technology is needed to characterize and compensate primary mirror gravity sags on the order of several millimeters with an uncertainty of <4 nm rms.
Coefficient of Thermal Expansion Characterization	Capability to characterize the homogeneity of the coefficient of thermal expansion (CTE) in mirror substrates to the parts-per-billion (ppb) level.	‘Zero’ CTE materials such as ZERODUR® made by SCHOTT and ULE® made by Corning have flown in space and thus are TRL-9 in sizes from 1-m to 2.4-m. And both Corning and SCHOTT have standard processes for characterizing CTE. However, the CTE maps produced by these standard processes do not have sufficient spatial resolution to predict the mirror’s thermal performance at the fidelity needed for coronagraphy with a large IROUV telescope. Furthermore, STOP (Structural Thermal Optical Performance) models created with state of art CTE maps have not correlated well with measured mirror cryo-deformation.	To meet the Decadal 2020 identified gap, technology is needed to characterize the primary mirror’s CTE homogeneity < +/- 5-ppb/K at spatial frequencies up to 100 cycles/diameter. And ideally, this technology needs to be able to assess if a mirror blank compliance with this specification before it is made into a mirror.

Mirror Finishing	IR/O/UV Flagship mirror requirements allow only nanometers of deviation from a perfect optical performance. This is approximately 5 – 10x better than JWST. Areas in need of development include: polishing techniques to control surface figure errors (SFE) to achieve a high-quality optical surface out to the edge of the part, radius matching of mirror segments to meet UV-quality phasing requirements, coefficient of thermal expansion (CTE) uniformity, ultra-stable mirror mounting methods, gravity off-loading uncertainty management consistent with requirements to fabricate a IR/O/UV Flagship, zero g surface in a 1 g environment, and mirror coating uniformity. Advanced mirror manufacturing, polishing, and coating technologies are required to avoid individual mirror segment figure control in the optical telescope assembly which would lead to a significant increase in wavefront sensing and control complexity. Advancing modeling methodologies need to continue to quantify spatial and temporal surface figure errors on coronagraph contrast to inform mirror requirements and wavefront sensing/control architectures. Coating performance at segment edges.	Studies of Capture Range Replication (CRR) indicate it is possible to achieve IR/O/UV Flagship mirror SFE over spatial frequency bands using precision mandrels in lieu of traditional mirror generating, grinding, and polishing processes. These methods reduce cost and schedule (Redding, 2018). Closed-back ULE mirror substrates achieve 7.5 nm rms SFE with no actuated figure correction; first free mode <200 Hz; ~10 Kg/m^2 areal density (Redding, 2019). CTE homogeneity distribution of 3 – 6.5 ppb/°C in a Zerodur mirror produces a thermal deformation SFE distribution of <6 nm rms (Stahl, 2020). Integrated model correlation of both ULE and Zerodur mirrors have shown gravity sag prediction agreement to within 31 nm rms difference between predicted and measured values (Stahl, 2020).	Advanced mirror technologies demonstrating the following: (a) Segment-to-segment alignment and radius matching with SFE < 5 nm rms over low spatial frequencies (6 cycles per aperture (cpa)). (b) Correct mid-spatial frequency (6 – 60 cpa) errors through deterministic finishing to <5 nm rms. (c) Achieve <1.5 nm rms SFE in high-spatial frequencies (>60 cpa) using stiffness polishing tools. (d) Demostrate 0.5 nm rms micro-roughness through optimized polishing parameters, slurry selection, and improved polishing tools consistent with a high-rate production schedules. (e) consideration of active surface figuring with actuators if required.
UV Coatings: Wavefront Effects	Mirror coatings allowing broadband performance into the UV while maintaining high reflectivity and low polarization aberrations over a broad 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 λ> 120 nm; 20% reflectivity λ < 120 nm	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.
Coronagraph Architecture	Coronagraph masks and archiectures that perform the necessary starlight suppression to image exo-Earths orbiting Sun-like stars, for a variety of telescope architectures, for both segmented and monolithic apertures.	Roman: Demonstration of ~10^{-8} contrast at an inner working angle (IWA) of 3 λ/D over a 10% bandpass with a significantly obscured monolithic aperture, but at limited throughput of the planet PSF (TRL 6). Decadal Survey Testbed: A classical Lyot coronagraph with an unobscured aperture, 10% bandpass, and IWA of 3 λ/D has achieved 3.8 x 10^{-10} contrast over a full dark-hole region (TRL 4). Apodized Pupil Lyot Coronagraph (APLC): The SCDA study resulted in several designs that achieve the necessary contrast, IWA, bandpass, and throughput to enable the LUVOIR science. Additional modeling has characterized the performance of the APLC masks in the presence of low-order, segment-level, and polarization aberrations, as well as stellar diameter. Masks have been fabricated and testbed demonstrations at moderate contrast and in air are underway (TRL 4). Vortex Coronagraph (VC): 1.8 x 10^{-9} contrast demonstrated at 10% BW from 3-8 λ/D on a clear aperture, 5 x 10^{-9} demonstrated on a simulated off-axis segmented static pupil. Nulling Coronagraph (NC): A lateral shearing NC was demonstrated at 10^{-9} contrast at the necessary IWA, but narrowband and with no shear implemented. This demonstration was performed with a segmented DM at a pupil, thus constitutes a demonstration with a segmented aperture (TRL 3). Hybrid Lyot (HL): Roman CGI has demonstrated 10^{-8} contrast as part of the Roman CGI technology development program, with a significantly obscured aperture (TRL 3). Phase Induced Amplitude Apodization (PIAA): 10^{-8} contrast achieved in 10% band with a a simulated off-axis segmented static pupil. (TRL3).	Raw Contrast: 1x10^{-10} Bandpass: >10% Inner Working Angle: < 4 λ/D High contrast spanning 300 nm to 2.5 microns High efficiency: an optimized combination of throughput, inner working angle, tolerance to aberrations, and bandwidth. Robust to stellar diameter and jitter. Telescope pupil shear compatible with contrast/inner working angle.

Deformable Mirrors	State-of-the-art coronagraphs rely on deformable mirrors to perform wavefront control. There is a need for flight-qualified, large-format, stable deformable mirrors to perform wavefront control and diffraction suppression for high-contrast coronagraph instruments, for both segmented and monolithic apertures.	Roman CGI: Electrostrictive PMN-based Xinetics DMs have been used in laboratory demonstrations of 3.8×10^{-10} contrast and are being baselined for the Roman CGI instrument. Segmented MEMS DMs have been used in a laboratory setting to achieve 5×10^{-9} contrast with a visible nuller coronagraph. Continuous facesheet MEMS DMs have been used in a laboratory setting to achieve 2x10-9 contrast with a vortex coronagraph. ExEP Deformable Mirror Trade Study provides further information (E. Bendek, JPL)	Actuator Format: Minimum 64 x 64; >100 x 100 preferred low surface figure error [pending trades]
Computational Throughput on Space-rated Processors	High-order wavefront control on future missions will require performing many trillions of floating-point operations (TFLOP). These operations would have to be computed within seconds to minutes to keep up with the instabilities of the primary telescope mirrors. Such computational throughput is not supported by existing radiation-hardened processors suitable for a Class-A mission as they lag by decades behind the commercial off-the-shelf components. Additionally, memory-access times are currently poorly constrained and might further degrade computational performance by an order of magnitude. Both the stability requirements on the primary mirrors and the contrast of the coronagraph are tightly connected to our ability to efficiently and quickly control the higher-order wavefront on space-rated processors.	The BAE RAD5545 is currently the most advanced radiation-hardened processor. It has a throughput of about 0.006 TFLOP/s (not including memory access time.) and supports 16 GB memory. A LUVOIR-type telescope will perform wavefront control at a cadence of seconds to minutes (Pueyo et al., 2021, SPIE) and require about 0.5 TFLOP and 250 GB to compute a single deformable mirror command (Belsten et al., 2021, SPIE). Radiation-hardened FPGAs generally have better performance than processors, at least in terms of raw throughput. FPGAs were descoped for the Roman Space Telescope due to the complexity involved with programming them. A lower-class co-flyer, similar to the Mars Cube One, can also expand the computational bottleneck by employing more powerful and replaceable but less radiation-tolerant processors. Defining and maturing a higher capability approach is a major effort. It is critical to immediately start developing computing capability and port wavefront control algorithms to space-rated hardware and increase their TRL to be able to achieve science requirements.	Achieve 1 TFLOP/s computation throughput with 1 TB optical science simulation models on a computational architecture that can reliably withstand the radiation levels at Lagrangian point 2 (L2).
High bandwidth optical communication between space and ground	High-order wavefront control on IR/O/UV flagship with many degrees of freedom my require ground-in-the-loop wavefront control, requiring bandwidth improvements.	Free-space laser communications has long been known for its ability to efficiently communicate at high rates over long distances. Examples include the Lunar Laser Communication Demonstration (LLCD) program, which successfully demonstrated 622 Mbit/s downlink rates over the 400,000 km Earth-Moon link in 2013, and the recently launched Laser Communications Relay Demonstration (LCRD), which will support downlink rates up to 1.2 Gb/s from GEO. Another near-term lasercom program is the Terabyte Infrared Delivery (TBIRD) program, which will field a LEO cubesat-based satellite that can support 200 Gbit/s data rates. Using a 1 W and 1.2 cm TX on the space terminal, a pair of up-screened wavelength division multiplexed (WDM) 100 Gbit/s commercial coherent transmitters will generate TX waveforms from the LEO satellite that will be received at the ground station with a commercial 40 cm telescope.	256 Gbps continuous downlink speeds
Coronagraph Efficiency	There is a need for greater coronagraph "efficiency". By "efficiency" we mean a combination of throughput, inner working angle, tolerance to aberrations, and bandwidth (i.e. factors that depend on coronagraph design), and exclude contrast, contrast stability (which are already listed as separate gaps), and exclude mirror reflectivities, detector QE, etc (i.e. factors that depend on component technologies). Because coronagraph parameters can be traded against each other, it makes sense to treat their combination as a single gap of "efficiency", rather than consider gaps in each parameter separately. We quantify this "efficiency" as the ratio of expected exoplanet yield between a real coronagraph and a theoretically optimal coronagraph (for a given target contrast, telescope, and DRM). Assuming that a coronagraph drives mission performance but not the cost, it is cost-effective to improve the coronagraph and other instrument technologies to theoretical limits, enabling savings on telescope requirements.	Current coronagraph designs considered for LUVOIR and HabEx (APLC, VC, PIAA, HLC, NC – see table 11-1 in LUVOIR final report and table 11.1-1 in HabEx final report) can still be substantially improved. As shown in Belikov et al. 2021 (Figure 10), theoretically optimal coronagraphs have 2-3x greater exoplanet yields for a given mission, even assuming no improvements in contrast, bandwidth, or component efficiencies. There are two possible general technology directions that can close this gap: "classical" architectures (mentioned above), and less common ones such as photonic chips and fiber bundle arrays. The former has the advantage of greater maturity, but it is not known whether they can fully close this gap, even in theory (although latest designs already improve yield by ~1.5x relative to LUVOIR/HabEx final reports). Conversely, photonic chips can close the full gap in theory, but it is not known how challenging that would be in practice.	The goal is to (a) design and (b) demonstrate a coronagraph that achieves at least 80% efficiency, for at least some points in the trade space of the IR/O/UV Flagship mission (preferably for telescopes with obstructed apertures and relaxed stability requirements). This efficiency can be measured by yield estimators such as AYO or EXOSIMS for a given mission and DRM. Abstracted theoretically optimal coronagraphs can be used as a reference benchmark for this measurement of efficiency.

Autonomous on board WFSC architectures	If onboard high-order wavefront control is required, A mismatch exists between the state-of-the-art algorithms for high-order wavefront sensing and control (HOWFSC), and the computing and storage capabilities required to implement them in onboard flight software, and this will be exacerbated by the steep scaling of performance cost vs. deformable mirror size. The tallest poles are for precomputation activities (e.g. computing and storing a "Jacobian" for use by wavefront control), but high-order wavefront sensing, high-order wavefront control, and alignment/calibration activities such as phase retrieval form the next set of limits.	Current algorithmic state of the art for HOWFSC is "pairwise probing" (Give'on, Kern, and Shaklan 2011) for wavefront sensing and "electric field conjugation" (e.g. Groff et al. 2016), which have demonstrated <4e-10 contrast in the ExEP Decadal Survey Testbed (e.g. Seo et al. 2019). Projections of computational usage and available flight-qualified computing hardware project that this implementation would be marginally-feasible to infeasible for CPU-based onboard computation for missions in the HabEx-to-LUVOIR scale. (Belsten et al. 2021) New algorithms (Will, Groff and Fienup 2021) shown promise in being able to strongly reduce the computation and storage costs associated with Jacobians, and show comparable performance to EFC at 1e-7 to 1e-8 contrasts in laboratory testing (Will et al. 2021). Computational costs for next level of tentpoles is not presently evaluated. Other options for addressing the mismatch could include hardware acceleration and offboarding computation; the RST Coronagraph Instrument uses a ground-in-the-loop (GITL) implementation of HOWFSC. Purely CPU-based onboard computation was infeasible for CGI.	The goal is 1) to select a mission computing architecture which is capable of supplying the end-to-end algorithmic needs of a flagship-class direct-imaging telescope, 2) create relevant performance metrics for evaluation, such as "overhead time per HOWFSC iteration", along with targets for these metrics, and 3) demonstrate that the relevant architecture is capable of meeting these targets for a large IR/O/UV telescope. There is a strong preference for this validation to be done under flight-like conditions (relevant flight software, hardware, and logicware, rather than simply algorithmic agreement on commercial hardware), as the low-level details of the computing architecture can play a outsize role in determining final performance, one which can be difficult to capture on paper without demonstration.
Integrated Modeling of Coronagraph/Telescope system	The proposed UVOIR flagship astrophysics architectures fundamentally challenge the current test-like-you-fly approach to space systems, because of their physical scale, multiple stages of on-orbit deployment, and extremely stringent optical performance requirements unique to visible-light coronagraph. The inability to exhaustively test, or in some cases test at all, in the laboratory necessitates system design verification and validation that relies on integrated modeling. Current modeling paradigms follow an outdated "bucket-brigade" approach, where models are treated independently, even though their model physics are inherently coupled in the observatory: optics, structural dynamics, thermal deformation, sensing, actuation and control. New integrated modeling tools and processes are needed to break down modeling-by-discipline barriers, so that integrated modeling can be solidly relied on at all phases of observatory design, integration, and test.	Integrated control, structural and optical modeling has been deployed to predict the quasi-static and dynamic wavefront error and line-of-sight of large astrophysics observatories (TPF: D.M. LeBosco et al (2004), NGST/JWST: O. de Weck et al (2000), RST : K.-C. Liu et al (2017)). It has generally been restricted to quantifying telescope dynamic stability from disturbances, and trading vibration isolation approaches (TPF-C: Dewell et al (2005), LUVOIR: Dewell et al (2019)). Existing modeling tools (such as IMOS (JPL) and DOCS) do not directly model science instrument performance (e.g., contrast in a coronagraph), nor include higher-order nonlinearities in optical sensitivities and kinematics that may drive science performance output where errors are measured in picometers of displacement and fractions of a milli-arcsecond of LOS error. Recent advances in reimagining the engineering and testing process using Digital Twins for terrestrial large-scale systems have yet to be applied to large-scale space systems.	• Develop integrated modeling environments from Digital Twin constructs that integrate component and subsystem test data over the engineering lifecycle, and that support a model-based assurance case for the full-scale non-testable system • Fundamental research into the validity of Finite Element Methods for predicting structural deformation at the picometer level • Incorporate multiple modeling fidelity levels (first-order linear vs. higher-order nonlinear) and multiple analysis modalities (time-domain, temporal/spatial frequency domain) in a multi-disciplinary modeling environment • Develop and integrate anchored mathematical models of UV, IR and Optical instruments that directly produce performance metrics that otherwise would be only measured in end-to-end testing
Ultra-stable telescope	High contrast imaging with a coronagraph requires wavefront stability of picometers in certain modes and thus optical system stability at the same level. The highest sensitivity regimes are "mid-temporal" (0.01-10 Hz) and "mid spatial" (segment rigid body or monolith mid-frequency)	WFSC in the coronagraph (using LOWFS/ZWFS/HOWFS) at the required temporal frequency requires either very bright stars (~mag 0) or an external laser guide star to provide sufficient signal for corrections. Another option for segmented architectures is direct metrology of the primary mirror using picometer-capable edge sensors (either capacitive or optical). Compensation of perturbations can be done directly at the mirror segments using picometer-capable actuators or offloaded to the deformable mirrors in the coronagraph. Active thermal sensing and control will minimize deformations and passive technologies like low-distortion mirror mounts, stable composite structures, and integrated structural damping will minimize perturbations. The ULTRA-TM program recently demonstrated closed loop gap stability of a capacitive sensor and 3 ultra-fine actuators to <2.5 pm RMS in gap (0.01-10 Hz) – (Y2 report submitted to NASA) Citation: Laura E. Coyle, J. Scott Knight, Laurent Pueyo, Matthew East, Robert Hellekson, Marcel Bluth, Sang Park, Brian Hicks, Benjamin Cromey, Ananya Sahoo, Sean Brennan, Todd Lawton, Michael Eisenhower, James R. Tucker, Jonathan Arenberg, "Technology maturation of key component-level technologies for ultra-stable optical systems," Proc. SPIE 11820, Astronomical Optics: Design, Manufacture, and Test of Space and Ground Systems III, 118200C (24 August 2021); https://doi.org/10.1117/12.2594643	Demonstrate an ultra-stable telescope (focus on actively controlled primary and secondary mirrors) using sub-scale but flight traceable optomechanics and active sensing and control systems.

Observatory Pointing Control Concept of Operation to Enable Coronagraph Science	Coronagraphs characterize exoplanets by creating a "dark hole," in the image plane with residual stellar intensity that is comparable to that of the planets of interest. The stellar intensity in the dark hole is dictated by the stability of the system. Once created, the dark hole must be maintained over an observation that may take 10-1000 hr. Stabilization of the wavefront is achieved using Wavefront Sensor and Deformable Mirror (DM) in the coronagraph, and telescope metrology and actuated mirror elements. Achieving contrast requires imaging a reference star of known point spread function, to correct for telescope effects, implying that the pointing during initialization of the coronagraph is different from long-duration imaging of the target star, resulting in thermal transient. Additionally, telescope roll maneuvers about boresight during imaging are necessary to enable Angular Differential Imaging (ADI) post-processing. Understanding the system control concept of operation that accommodates these pointing requirements is critical.	The Nancy Grace Roman Space Telescope design includes a coronagraph, and its concept of operation includes executing telescope roll maneuvers and imaging reference stars (Debes et al, 2015). Operations supporting reference star observations and associated maneuvers is also necessary for the MIRI instrument on JWST (Cavarroc et al, 2008). For the IR/O/UV Flagship coronagraph, there is a complex interplay between thermal transients introduced to the structure due to repositioning and the multiple control loops available to reject quasi-static wavefront error (either by means of coronagraph DM corrections or telescope segment shape control), and multiple actuators available for LOS repositioning (overall observatory inertial attitude control, vs. payload 2-axis gimbal articulation). At present, there is little understanding of the impact to repositioning slews on WFE control authority, which actuators should be used for the pointing, and how to optimize actuator usage to both support stellar reference imaging and maximize coronagraph availability.	• Integrated structural/thermal/optical modeling to quantify the quasi-static wavefront changes between reference and target stars, specifically traceable to specific science scenarios. • Analysis of active wavefront control authority and observability to reject differential thermally-induced wavefront error, including both telescope active optical element phasing and coronagraph deformable mirror and wavefront sensor. • Trade study of relative benefits between line-of-sight actuation approaches to support coronagraph calibration: spacecraft body steering versus payload two-axis gimbal actuation. • Identify mechanical methods for de-energizing the two-axis gimbal for periodic of extreme dynamic stability performance, while still supporting initial coronagraph calibration maneuvers
Wavefront Sensing (low-order and out-of-band)	Low-order wavefront sensing (LOWFS) is capable of tracking pointing errors, as well as slow drifts in low-order aberrations (global focus, astigmatism, coma, etc.). LOWFS systems are limited in the speed at which they can sense aberrations, and the spatial frequency of the sensed aberrations. Out-of-band wavefront sensing (OBWFS) uses light that is out-of-band (either spatially or spectrally) to determine wavefront drifts within the science band. It is possible to use the information from the OBWFS to monitor DM actuator drift, and even primary-mirror segment level aberrations. Furthermore, since the OBWFS would use broadband light outside of the 10-20% science band, or could use an off-axis bright guide star or even an internal light source, OBWFS would generally be able to sense the full range of wavefront drifts much faster than LOWFS. One approach to improving the speed of the wavefront sensing system is use an artificial guide star (AGS). Early studies have evaluated the use of a laser source on a cubeSat or smallSat platform, flying in formation with the telescope at a distance of 40,000-80,000 km. Such a source, coupled with an out-of-band Zernike wavefront sensor can improve sensing loop rates from < 1 Hz to > 10 Hz.	Current LOWFS technology has benefitted from years of investment as part of the Roman/CGI technology development effort, and will continue to be developed as that instrument matures. While OBWFS techniques are explored as a new technology, it is recommended that the Roman LOWFS system be adapted to LUVOIR as well – both to complement an OBWFS system, but also to serve as a fallback solution should OBWFS prove unviable. Roman: Low-order wavefront sensing has been demonstrated on a 10^{-8} contrast coronagraph testbed with realistic disturbances input to the coronagraph optics. The LOWFS demonstrated <0.5 mas RMS per axis line-of-site residual error and was sensitive to ~100 pm of focus error (TRL 6). Out-of-band wavefront sensing has been simulated with a LUVOIR like aperture and preliminary results show picometer-level sensitivity can be achieved for low and high-order terms with sufficient integration time (TRL 3). A smallSat / cubeSat artificial guide star study has defined the necessary performance requirements of the guide star platform to provide a sufficiently bright out-of-band source. Additional study is needed to continue refining the concept in conjunction with the out-of-band wavefront sensor (TRL 3). References B. Roman Space Telescope CGI: project status reports and review documentation, D. Segmented Coronagraph Design and Analysis (SCDA): reports and white papers available at https://exoplanets.nasa.gov/exep/technology/SCDA/, G. Multiple technology gap submissions from the ULTRA team (Ball Aerospace, Northrop Grumman, L3Harris): submitted to Program Offices in response to current call for input.	Wavefront Stability: ~10 pm RMS Control Bandwidth: ~1 Hz with Mv=9 or brighter source
Vibration Isolation & Pointing System Technology	Future space telescopes must achieve unprecedented levels of dynamics stability to maintain coronagraph contrasts of 10^{-10} necessary to image exoplanets by blocking the light of the parent star. Preliminary studies (Dewell et al. 2019) indicate vibration reduction in excess of 40 dB above 1 Hz are required to isolate the optical telescope from likely vibration (control moment gyroscopes, appendages dynamics, thruster impulses, etc) originating from the parent spacecraft. Vibration isolation systems possibly combined with means to reduce or eliminate shunt path such as harnesses used for data and electrical power transfer are needed.	(a) 5-DOF Disturbance Free Payload (DFP) laboratory demonstrations on subscale spacecraft and telescope payload test-bed achieved 40 dB to 60 dB of vibration isolation down to DC (Pedreiro & al, 2002) (b) Impact of harnesses on vibration isolation system performance evaluated on prior mission such as (1) GOES-R Earth Pointing Platform but with isolation corner frequency (~8-Hz) much higher than required (0.01-Hz) (Chapel & al, 2014), (2) International Space Station Microgravity Vibration Isolation Subsystem (MVIS) (https://www.asc-csa.gc.ca/eng/sciences/mvis.asp) but not at scale, (3) Lockheed 2-D Disturbance Free Payload (unpublished) (c) Technology for wireless Data/Communication as in Free Space optical communication exist but simplifications/packaging required for communication across non-contact isolation system (d) Multiple means of wireless power transfer (Wireless Power Transfer, Wikipedia) exist but maturation required for use across non-contact vibration isolation system taking into consideration range, impact on transmissibility, power coupling efficiency, reliability, etc	[Goals complement Astrophysics Strategic Technology Gap "Coronagraph Contrast Stability"] • Perform space flight demonstration of Vibration Isolation and Precision Pointing System • Advance additional vibration mitigation measures: Advance wireless data transfer and possibly wireless power transfer as well to reduce number of cables required at interface between optical telescope and parent spacecraft • Reduce knowledge gap: Characterize regime between position-dependent and rate-dependent damping mechanism in representative harnesses in subscale demonstration--rate damping being most detrimental to transmissibility at high-frequencies. Project measuring transmissibility between two rigid bodies connected by representative harness would close that gap and provide data needed to validate harness models and/or bound harness impact. LUVOIR concept had requirements of Transmissability Isolation: >40 dB at frequencies > 1 Hz.

Laser Gauges for Optical Telescope Assembly Metrology	Future space telescopes must achieve unprecedented levels of wavefront control of the large segmented primary in order to maintain coronagraph contrasts of 10^{-10} necessary to image exoplanets by blocking the light of the parent star. Preliminary studies (Lou J., 2018) indicate that a laser metrology truss from secondary to primary segments can achieve adequate wavefront control but levy requirements on individual laser gauges to have ~10 pm rms errors over the long integration times scales (10 min-1 hour) required. Additionally, the metrology components will need to be very volume-constrained in order to fit on the structure without obscuring the aperture.	a) Zero-path photonic integrated circuit (PIC) metrology gauges demonstrated 21.0 pm rms over 100 seconds (Nordt, TechMAST 2021). Imperfections in the PIC fabrication likely are the current limitation. b) Laser metrology for the JPL Space Interferometer Mission demonstrated 10's of pm cyclic error (An X., 2005). However, these were large metrology gauges, which may not be compact enough. c) PIC gauges for an LM program (unpublished) demonstrated 200-pm amplitude cyclic error. Cyclic error in PICs is not well understood. d) Laser frequency stabilization of <1 Hz over 1000 seconds has been demonstrated (Abich K., 2019) and <10 Hz is sufficient for 6-m-diameter-aperture-telescope secondary mirror truss structure. e) The desired PIC material (silicon nitride) for compact gauges has not flown in space. f) Laser metrology gauges demonstrated on GRACE Follow-on at nm class (TRL9), free space optics (Abich K., 2019)	• Advance Si_3N_4 fabrication capabilities to minimize waveguide loss into cladding modes • Develop and perform waveguide modeling to understand sources of cyclic error in PICs • Demonstrate <10 pm cyclic error with optimized design • Demonstrate PIC bonding in mounting structure with fraction of 10 pm drift over integration time scales • Develop calibrated test equipment capable of validated pm-class actuation to verify metrology gauge precision • Demonstrate multi-gauge (>=3 gauges) performance in a sub-scale truss consistent with analytical error accumulation based on single gauge performance. • Demonstrate thermal stability over required time scales. LUVOIR concept had requirements of Wavefront Stability: ~10 pm RMS, and Control Bandwidth: ~1 Hz with Mv=9 or brighter source
Segment Relative Pose Sensing & Control	Future space telescopes must achieve unprecedented levels of wavefront control and stability to maintain coronagraph contrasts of 10^{-10} necessary to image exoplanets by blocking the light of the parent star. An active sensing & control system robust to dynamics excitation including fine positioning actuators with picometer-resolution, low-drift, linear continuous operation, low-power dissipation in hold mode is required to position the primary mirror segments and realize the required wavefront quality while not impacting optical system thermal stability.	Sensing: Capacitive: 5 pm in gap dimension, 0-60 Hz (TRL 3) Inductive: 1 nm/sqrt(Hz) for 1-100 Hz in shear; 100 nm / sqrt(Hz) for 1-10 Hz in gap (TRL 3) Optical: 20 pm / sqrt(Hz) up to 100 Hz (TRL 3) High-speed Speckle Interferometry: < 5 pm RMS at kHz rates; requires center of curvature location and high-speed computing (TRL 3) Prior high precision actuation experience is primarily in 100 pm to 1-nm resolution regime. Picometer actuation is a nascent technology. (a) JWST coarse-fine primary mirror segment positioning actuators (Warden & al. 2006) provide example space qualified system for 6-DOF positioning of mirrors in segmented primary mirror but not traceable in resolution (10-nm), repeatability (2-nm), or operation (set-and-forget instead of continuous). Gear stepper-motor design is unsuitable as point of departure for fine stage due to inherent limitation in resolution and micro-dynamics stability. (b) Piezoelectric, electrostrictive, and voice-coil actuators all offer high-bandwidth and positioning resolution limited only by drive electronics with applications including linear stages (P753 hpps://www.pi-usa.us being representative), deformable mirrors (Xinetics), and mirror nanopositioning (TMT), respectively, operating in the 100-pm to 1-nm resolution regime. Electro-strictive stacks offer high-stiffness and are likely preferred over piezoelectric due to lower hysteresis, and over voice-coil due to near-zero power dissipation under hold force. (c) European Nano-Trace project aiming for 10-pm "accuracy" metrology (Pisani et al., 2018)	[Goals complement Astrophysics Strategic Technology Gap "CG-6 Mirror Segment Phasing Sensing and Control", Exoplanet Exploratory Program, 2019 Technology Plan Appendix, JPL Document Number: D-102506, Page 37] • Advance coarse-fine actuation system for relative pose-control of primary mirror segments in optical telescope assembly. Expect coarse stage to emphasize stability but otherwise be conventional. Expect innovation is in fine flexure-stage with following characteristics: picometer-level resolution, high-linearity, continuous operation, low-drift, near-zero power dissipation under hold force, and high-stiffness for reduced optical system susceptibility to dynamics excitation. Requirements from LUVOIR concept: Sensitivity: < 4 pm at 50-100 Hz loop rate (5-10 Hz control bandwidth)

Telescope Thermal Sensing & Control	Future space telescopes must achieve unprecedented levels of wavefront control and stability projected at (10-pm)/(10-minutes) or longer integration times to maintain coronagraph contrasts of 10^{-10} necessary to image exoplanets by blocking the light of the parent star. As a measure of the difficulty in achieving such levels of wavefront stability, Crill indicates "JWST is predicted to have a 31-nm rms WFE response to a worst-case thermal slew of 0.22 K and take 14 days to passively achieve < 10-pm per 10-min stability" (Crill, JPL D-102506). Such thermal sensitivies are consistent with optical pathlength displacements observed on prototype all-zerodur-structure interferometer test-bed for Space Interferometer Mission of 7.7pm/mK at 0.5-meter scale. Advances in passively thermally stable telescope architectures, thermal sensing and active thermal control technologies operating in mK stability regime over 10 minutes or longer are needed to supplement active wavefront control—feasibility of wavefront stability objective in open telescope not established.	Experimental evidence in thermal stabilization at mK-level is limited and lacks traceability at scale and in open telescope architectures (a) Technology maturation on Space Interferometer Mission provides valuable experience, highlights thermal modeling challenges, and achieved (10 mK)/hour control of thermal boundary on TOM-3 interferometer test-bed in vacuum chamber (Gouilloud, 2006) (b) mK thermal stabilization at small scale achieved in refractometry apparatus at NIST (Egan, 2011) (c) Study indicates <10mK temperature stability required to bound uncorrected wavefront errors due to higher spatial frequency mirror surface figure errors to <6 pm rms (Stahl, 2020) (d) Ultra-stable mirror demonstrator achieved <0.4mK/(80 hour) stabilization and 50 uK peak-valley sensing at small scale (Park, 2019) (e) Thermal sensing at submilliKelvin demonstrated in concept photonic thermometer (Zhang, 2020) (f) HabEx study projects (10 pm)/(10 min) wavefront stability achievable in closed telescope architecture by controlling shroud temperature (Brooks, 2017)	• System engineering, problem understanding, and open-telescope-architecture feasibility given low control over thermal boundary (a) Quantify thermal-induced wavefront errors (on both temporal and spatial scales) in purely passive segmented open telescope architectures in expected operational thermal environment and quantify residual errors after active wavefront control (b) Advance telescope design achieving best trade-off in wavefront stability performance and system complexity between active wavefront control and thermal stabilization (c) Evaluate benefits of designing for constant dissipated electrical power throughout individual components to eliminate thermal transients during operation (d) Validate thermal modeling tools predictions (numerical analyses must remain accurate over large dynamic range covering both absolute temperatures to capture T^4 radiative dependencies and submilliKelvin temperature differences throughout optical system) since we cannot accurately test in laboratory (e) Goal is to arrive at simplest telescope architecture (close to being thermally passive) and avoid active mirror-segment surface figure control in particular • Advance thermal sensing (resolution and stability) and active thermal control (logic strategies and actuation implementation) technologies for operation in mK stability regime over 10 minutes or longer • Demonstrate active thermal control system first on prototypes and next on subscale test-bed in thermal-vacuum chamber in representative thermal operational environment
Optimal Wavefront Sensing and Control Algorithms for Space Coronagraphs	Directly imaging Earth-like exoplanets relies on the ability of the coronagraphs to reach a contrast of 1e10 and maintain it throughout observations. This will be achieved by several wavefront sensing and control loops working in tandem. To achieve the best performance, the fundamental limits of the instrument need to be analyzed. Current algorithms can maintain a contrast at least a factor of 10 worse than the fundamental limits. The algorithms need to be improved to fully exploit all available sources of information in the photon-limited observation including priors on wavefront evolution, model uncertainties, and interaction between control loops. After development, these advanced algorithms need to be tested at 1e10 contrast (which is difficult even for standard algorithms). Algorithms that operate at the fundamental limits will significantly improve detection threshold and science yield.	The Roman Coronagraph has two wavefront control loops. The high-order wavefront control relies on decade-old algorithms that can only be used to achieve the desired contrast on a bright star. They can be substantially improved before they reach theoretical efficiency limits. Roman's strategy of switching to bright reference stars several times a day will be infeasible on the Large IR/Optical/UV Telescope due to the much faster control cadence of seconds to minutes (Pueyo et al., 2021, SPIE). The low-order wavefront control loop will operate continuously on Roman, but its influence on the high-order control loop has not been studied in-depth. Recent theory (Pogorelyuk et al., 2021, ApJS) offers bounds on the performance of the multiple wavefront control loops. Advanced algorithms that come close to these bounds are in an early stage of development and achieve 10 times better closed-loop contrast than existing algorithms (Pogorelyuk et al., 2021, ApJS).	Achieve closed-loop wavefront stability that is within a factor of 4 of the photon-noise limit for each wavefront sensor.
Disturbance Reduction and Observatory Stability	From the current Coronagraph Contrast Stability gap, "The capability to maintain the deep starlight suppression provided by a coronagraph for a time period long enough to detect light from an exo-Earth." From the HabEx study report, this drives the requirement for an overall line-of-site (LOS) pointing requirement of ≤2.0 mas rms with a stability of ≤4 mas rms. For future time-domain astrometry and gravity wave missions, ≤5 mas attitude stability and ≤10 nm/√Hz positional (drag-free) with ≤10 nrad/√Hz (~2 mas precision pointing) observatory stability requirements have been established for GAIA and LISA, respectively, and should still apply to any similar future concept. Multiple spacecraft constellations for interferometric observations have positional stability requirements on the order of a fraction of the wavelength of light being observed and combined.	Disturbance reduction systems include spacecraft attitude determination and control systems (ADCS) (i.e. reaction wheels, thrusters and control algorithms) as well as the observatory structure, mirror control, and any vibration isolation subsystems. While still challenging, Hubble-class pointing (7-10 mas) represents the TRL 9 state-of-the-art in the US along with 5 mas performance on ESA's GAIA mission. The US Space Technology 7 Disturbance Reduction System (ST7-DRS) provided a space-based demonstration of precision position control and drag-free operation (≤10 nm/√Hz) (see Anderson, G., et al. Physical Review D 98.10 (2018): 102005.) that brings this technology to TRL 7; however, the lifetime required of the single-string colloid microthrusters was only 90 days and improving that to multiple years reduces the overall system TRL to 4/5 with components / assemblies completing environmental testing under the previous LISA program. An independent NASA Engineering and Safety Center report, "Application of Micro-Thruster Technology for Space Observatory Pointing Stability" (NASA/TM−20205011556, NESC-RP-18-01375) showed that <1 mas precision and stability performance for both HabEx and LUVOIR-like observatories was possible	Disturbance reduction systems include spacecraft attitude determination and control systems (ADCS) (i.e. reaction wheels, thrusters and control algorithms) as well as the observatory structure, mirror control, and any vibration isolation subsystems. System level performance requirements for the observatory: • ≤2 mas rms pointing accuracy and stability (goal of ≤1 mas rms) • ≤10 nm/√Hz spacecraft position stability (goal of 5 nm/√Hz) • ≥5 year lifetime with ≥10 years of expendables (i.e. propellant)

		using a microthruster-based approach without reaction wheels or vibration isolation with a TRL depending on the thrust level required and ultimately the solar pressure induce torque on the observatory.	
Precision Pointing Stability for High-Contrast Imaging	High contrast imaging with a coronagraph requires wavefront stability of picometers in certain modes and thus optical system stability at the same level. Precision pointing stability is important because line-of-sight deviations will cause beam walk on the optics, which will couple into high spatial frequency errors that are difficult to correct. While a fine steering mirror can correct the line-of-sight and is a necessary part of the architecture, it does not address beam walk in the telescope or the instrument. Preliminary analysis suggests ~1 milliarcsecond pointing stability is needed to keep this WFE contribution small. Development of larger area, highly stable fine steering mirrors is also needed, since they are part of the optical train and small changes to the pointing angle will add WFE.	Pointing stability primarly requires minimizing dynamic perturbations of the observatory. This can be achieved by isolating the payload from the spacecraft or having a "quiet" spacecraft. Active isolation approaches include active struts or voice coil-based isolation systems. Quiet spacecrafts can use micro-thrusters during science operations and reaction wheels for slews. Citation: Laura E. Coyle, J. Scott Knight, Laurent Pueyo, Matthew East, Robert Hellekson, Marcel Bluth, Sang Park, Brian Hicks, Benjamin Cromey, Ananya Sahoo, Sean Brennan, Todd Lawton, Michael Eisenhower, James R. Tucker, Jonathan Arenberg, "Technology maturation of key component-level technologies for ultra-stable optical systems," Proc. SPIE 11820, Astronomical Optics: Design, Manufacture, and Test of Space and Ground Systems III, 118200C (24 August 2021); https://doi.org/10.1117/12.2594643	Demonstrate a combined payload (including fine steering mirror)/spacecraft with sub-milliarcsecond pointing stability (likely simulation, potentially cubesat demo).
NIR Low-noise Detector	Low-noise, large-format detectors with high quantum efficiency between 1000 – 2000 nm enable high-contrast exoplanet spectroscopy in the NIR. For LUVOIR, operating temperatures above ~70 K are necessary to be consistent with currently anticipated thermal architecture.	HgCdTe photodiode arrays are high-TRL, high-performance near-infrared (NIR) detectors. Teledyne H4RG-10 detectors have direct heritage to the H4RG detectors baselined on Roman, and H2RG detectors used in JWST. However, for use in a high-contrast coronagraph, it is desirable to reduce read noise and dark current further, if possible. Roman: H4RG detectors developed for Roman already exhibit exceptionally good noise performance (single-digit read noise, 10^{-3} dark current), as well as large-format tileable arrays (TRL 6). SAPHIRA linear mode avalanche HgCdTe photodiode sensors have demonstrated 0.1 e- rms read noise, 0.02 e-/pix/s dark current, 320 $\times$ 255 pixel format (TRL 4). Reference A. Roman Space Telescope WFI: project status reports and review documentation	Array Format: 4k x 4k Read Noise: < 3 e- Dark Current: < 1 x 10^{-3} e-/pix/s Quantum Efficiency: >90% over band Operating Temperature: > 70 K Explore two engineering paths that have been identified to potentially achieve H4RG noise reduction goals: reducing the pixel size (to smaller than 10 μm), and optimizing the readout electronics for lower-noise performance. Invest in the development of a 1k x 1k HgCdTe APD array and evaluate its noise and sensitivity performance relative to the H4RG. Select a single candidate technology for continued development. Following selection of a NIR detector candidate, continue investment in optimizing detector performance for use with a high-contrast imaging system. Specific attention should be made to the operational thermal environment that is required to achieve the best performance, and how that thermal environment might be enabled in the context of the overall LUVOIR system. (see LUVOIR final report for more detailed plan, schedule, and cost)

UV/VIS Low-noise Detector	Low-noise, large-format detectors with high quantum efficiency between the bands 200-525 nm and 500-1030 nm enable high-contrast imaging and spectroscopy. For the LUVOIR visible band (500-1030 nm), emphasis on improved quantum efficiency between 800 and 1000 nm is desired to maximize exoEarth yields.	Electron-multiplying CCDs (EMCCDs) are being developed for Roman/CGI, and can achieve the low read- and dark-noise requirements for high-contrast imaging (Nemati 2014). However, radiation exposure reduces the long-term performance of these devices (Nemati et al. 2016). An improvement in quantum efficiency at the red end of the visible spectrum (~800 – 1000 nm) may be needed to enhance exoEarth detection yields (TRL 6). Hole-multiplying CCDs (HMCCDs) should also be developed as a potential alternative. HMCCDs are inherently radiation hard, and do not suffer long-term degradation under continuous exposure. Furthermore, this radiation hardness allows thicker substrates to be used in the devices, improving long-wavelength quantum efficiency (TRL 3).	Array Format: 4k x 4k (or buttable 1k x 1k) Read Noise: << 1 e- Dark Current: < 3 x 10^{-5} e-/pix/s Quantum Efficiency: >80% at all detection wavelengths EMCCD development should be continued in the context of a LUVOIR coronagraph system. Focus on improving radiation tolerance through shielding design and readout electronics optimization, and on improved red-end quantum efficiency via substrate thickness and optical coatings. Building off current development activities that are already funded, design and fabricate a 1k x 1k pixel HMCCD device and evaluate its noise and sensitivity performance relative to the existing EMCCDs. Select a single candidate technology for continued development. Incorporate this 1k x 1k candidate into coronagraph testbeds for validation at the system level. Following the candidate down-select, design and fabricate a 4k x 4k device, including all necessary readout electronics. Complete functional, performance, radiation, and environmental qualification testing to achieve a component-level TRL 6. (see LUVOIR final report for more detailed plan, schedule, and cost)
Rad-Hard, High-QE, Energy Resolving, Noiseless Single Photon Detector Arrays for the NIR, VIS, and UV	The search for life on exoplanets via direct imaging is fundamentally photon starved. For context, the median observation time to collect a single exoEarth twin spectra shown in Astro2020 Fig 7.5, (for SNR=8.5, 6.5 m aperture LUVOIR-B) from the biased catalog of exoEarth candidates is ~12 years. Collecting the lowest hanging fruit, the bottom 25% (2.5%) of biased catalog distribution still takes 2.5 (0.26) years. Additionally, most of the mission is spent finding planets and not collecting spectra (2-2.5 years vs 0.5 year). An efficient spectroscopy detection solution is needed to collect spectra during all phases of the mission without penalty and increased spectra collection rate. This calls for rad-hard, ultra-high QE, energy-resolving, noiseless single photon detector arrays to provide the increased throughput to find and spectrally characterize rocky Earth-like exoplanets. Such an approach dramatically increases science yield and the chance of finding, recognizing, and quantifiying life—enabling the required statistical significance with a smaller aperture.	Photoconducting detectors are not noiseless (falsely report photons: dark counts, read noise, spurious charge, charge transfer inefficiency, charge trapping, after pulsing), not energy resolving thus requiring dispersive optics to provide spectroscopy. EMCCDs needs improved radiation hardness, reduced susceptiblity to cosmic ray events. TESs, MKIDs, and STJs are cryogenic energy resolving detectors (up to the Fano noise limit). STJs are difficult to read-out larger arrays whereas TESs and MIKDs use similar multiplexing techniques. TESs have achieved >99% QE narrowband and averaging 97% broadband for VIS and NIR. MKID efficiencies of 70%/40% at 0.4/1 µm. Szypryt et al 2014.	Need arrayable rad-hard (no performance degradation in 5+ year mission with margin), high-QE detectors (QE>90% across the whole bandpass), operating in the NIR, VIS, and UV that spectrally resolve targeted life-identifying biosignatures for the specific mission bandpass(es). NIR (1000-2000 nm), R>200 or fundamental limits, VIS (515-1030 nm), R>140, UV (200-500 nm), R>10.
Detectors for high-resolution, cross-dispersed spectrographs	Ground-based extreme-precision radial velocity (EPRV) spectrographs require large-format, deep-well, precisely-ruled, uniformly-efficient, well-characterized 2D detectors (Crass, J., et. al., 2021 arXiv: 2107.14291). Though industry and other scientific applications has driven detector development, the particular requirements for EPRV of exquisite uniformity have not been advanced. RV precision achievable with current detectors is hindered by numerous effects including saturation, limited full well capacity, fringing, pixel size variations, “tree rings,” cross-talk, cosmic rays, “brighter/fatter” effect, stitching errors, persistence, imperfect charge transfer efficiency (CTE), intra-pixel structure, readout time lost, readout noise, pixel-to-pixel variations, flat-fielding, long- and short-term thermal stabilization, and deformation during readout. The corresponding RV error is estimated to be up to ~40 cm/s on Habitable Zone Planet Finder (HPF; Ninan et al. 2019; Bechter et al. 2019) for its H2RG detectors, and 8.1 cm/s for NEID (Halverson et al. 2016) from its CCD detectors. Further, with changing commercial demands and a decrease in the manufacturing base for the current generation of CCD	Current visible-light spectrographs use 9k by 9k CCDs with 10 micron pitch. Next generation IR spectrographs are baselining 4k by 4k H4RGs. CCD pixel-positioning non-uniformity (PPNU) in commercial CCDs is typically around 0.02 pixels. Charge transfer inefficiency (CTI) may result in charge being read out from a pixel other than the one it originated in, producing asymmetries in line profiles that can manifest as spurious Doppler shifts. CTI is a function of S/N that can change over time. CTI may be the largest uncertainty among detector-related radial velocity errors. Spectral orders are curved in 2D and project across the detector resulting in pixels on one side of an order readout with different detector amplifiers that contribute to line asymmetry. (Blackman, R.T., et. al., 2020 arXiv:2003.08852v1). Mosaicking of detectors, in an attempt to achieve larger formats introduces gabs, edges, and seams, causing significant systematic irregularities, and is to be avoided. TRL details: Though CCD technology is quite mature (high TRL), the uniformity requirements needed by EPRV are not met. CMOS architectures have yet to achieve the large formats (9k x 9k) required by EPRV without mosaicking.	1. Develop a detailed characterization program of existing detectors/detector technologies to identify the underlying physical detector characteristics which limit performance. Assessment should also include technologies which currently have limited use in the context of EPRV, for example CMOS, but may be needed in future programs. 2. Work with industry partners, work to develop and demonstrate new detector designs and fabrication processes which may overcome current limitations. Current detector architectures, while well suited for imaging, may benefit from alternative designs (for example electronics architecture) or fabrication processes for EPRV applications. 3. Extend the format size (> 8k x 8k) of CMOS detectors without mosaicking. 4. Use a combination of laboratory and on-sky testing to verify findings and demonstrate improved detector performance.

	detectors, there is concern that availability of these detectors may become challenging.		
High-Precision, High-Throughput, High-Spectral Resolution Dispersive Optics	Ground-based extreme-precision radial velocity (EPRV) spectrographs require echelle gratings with low wavefront error and high efficiency to maximize spectral stability, throughput, resolution, and bandwidth. EPRV instrumentation require high efficiency, steep blaze angle echelle gratings to achieve high spectral resolutions of R > 100,000 for both seeing-limited and diffraction-limited systems.	Currently available echelle gratings with steep blaze angles (~76 deg.) reach a limiting size of only ~190×400 mm with absolute peak efficiency around 50%. In ground-based seeing-limited PRV spectrographs, the grating dimensions scale with the size of the telescope aperture for a fixed spectral resolution. It has been necessary to stitch gratings together in order to achieve the total required diffraction aperture for R~100,000, even for moderately-sized telescopes (D > 2.5 m). The NEID spectrograph (3.5 m) uses a 2x1 grating mosaic while ESPRESSO (8 m) uses 3 separate gratings. The registration of these stitched gratings introduces significant wavefront error, and greatly complicates the fabrication process. For decades, echelle gratings have been fabricated by diamond ruling, but it is difficult to achieve all aspects of the performance required for PRV instruments with this technique. Newer grating fabrication techniques using lithographic methods to form the grooves may be a promising approach. TRL details: Lithographic fabricated grooves are at TRL 3 with respect to current requirements. Initial experiments have shown success in experimental proof-of-concept, but performance in a spectrograph and scaling has yet to be demonstrated.	Develop grating fabrication techniques as alternatives to the traditional diamond-ruled process to achieve large-format, high-efficiency, steep blaze angle, low wavefront error echelle gratings for both seeing-limited and diffraction-limited spectrographs. These are required to achieve high spectral resolutions of R > 100,000 with high throughput and high image quality. • Size (seeing-limited): ~200×1200 mm (width × length for the clear aperture at the blaze angle) • Size (diffraction-limited): ~50×200 mm (width × length) • Steep blaze angles (>76 deg or >R4) for achieving higher spectral resolutions >100,000 (e.g., R6 for a 150,000 resolution). • Higher efficiency, both by reducing diffraction effects and improving coatings. The state of the art is ~50–60% at peak, while >70% is sought. • Better wavefront error (<lambda/8) across the aperture. This is important for diffraction-limited, adaptive optics-fed systems where maintaining the point spread function (PSF) profile is required to achieve high resolutions (Bechter, E. B., et al., 2021, JATIS, accepted), as well as seeing-limited instruments that strive to achieve sharp image quality to mitigate the effects of variable pupil illumination. • Lower line density echelles < 13 lines per mm to be more compatible with detector array widths in diffraction limited spectrographs.

Advanced Photonics for extreme-precision radial velocity spectroscopy	Current ground-based radial velocity (RV) instruments use large, cross-dispersed echelle gratings and prisms fed by multi-mode fibers to achieve high resolution (R>100,000). However, these systems are large, complex, expensive and have been only able to achieve RV precision of 20-30 cm/s about an order of magnitude above the precision needed to detect Earth-mass planets around sun-like stars.	The recent generation of cross-dispersed, multi-mode fiber, RV spectrographs, EXPRES, NEID and ESPRESSO are demonstrating intrinsic instrument resolution between 20 and 30 cm/s. They are limited by the environmental stability due to their size proscribed by multi-mode fiber, the optical stability limitations of multi-mode fiber, and the manufacturing precision limitations of the gratings and detectors, among others. The objectives are for spectrographs that are capable of, higher resolution (RV precision), higher bandwidths, smaller size (more easily stabilized), and lower cost.	• Develop photonic spectrographs based on lithographically formed arrayed waveguide gratings (Jovanovic et al. 2017b), "spectrograph on a chip". Such monolithic devices would occupy a small fraction of the volume of existing RV spectrographs and potentially offer lower cost and greater stability. • Develop the use of photonic lanterns to convert a multimode fiber input into separate SMF outputs by sampling multiple positions centered on the near-diffraction limited input. By using the SMF outputs from such a system, these can illuminate separate traces of a diffraction-limited spectrometer (Schwab et al. 2014; Mawet et al. 2019). Photonic lanterns are an attractive technology that can provide an interface between single-mode and multimode optical fibers. This allows a potential pathway to increase diffraction-limited EPRV capabilities into the blue visible. • Develop externally dispersed spectrograph designs (e.g., VERVE (Vacuum Extreme Radial Velocity Experiment), Van Zandt et al. 2019) integrating interferometry with spectroscopy thereby relaxing the calibration requirements. • Develop an on-chip photonic spectral flattener to take Laser Frequency Comb (LFC) output with its wide range (10s of dB) of brightness across the wavelength band and produce an output which is spectrally uniform at the level of <5 db. • Develop the ability to do integrated, end-to-end modeling of electro-mechanical system designs.

Ground-based Visible-light Adaptive Optics	Visible-light adaptive optics (Visible AO) systems capable of achieving diffraction-limited seeing, would enable the use of single-mode fibers (SMF) for feeding extreme-precision radial velocity (EPRV) spectrographs. This approach would break the telescope aperture-to-spectrograph beam scaling relation between the size of spectrograph and the size of the telescope aperture, permitting much smaller, lower cost, and more easily stabilized RV spectrographs. This design family would allow spectrographs to be designed independently of the intended aperture, allowing for a standardized spectrograph design that could enable further cost savings.	High Strehl AO in the near-infrared has been demonstrated at numerous telescopes including the Keck 10 m telescope and the Palomar 5 m telescope with peak K-band Strehl ratios of ~0.65-0.85. Strehls of 0.60 have been demonstrated in the Y-band at the LBT 8.4 m telescope on bright targets. Reaching comparable Strehls at visible wavelengths has yet to be demonstrated routinely, but significant efforts are underway at a number of observatories, including at the Magellan 6 m telescope (Close 2016; Close et al. 2018) where the MagAO-X system (new extreme AO system for the Magellan Clay 6.5 m telescope) has achieved Strehls of ~50% at 900 nm in initial commissioning with an eventual expected performance of 70% at Hα (656 nm) in median seeing conditions (Males et al. 2020). GPI/Sphere/SCEXAO can achieve >90% Strehl at H-band under good conditions on bright stars. Additional 'extreme-AO' systems include SCExAO (Subaru Coronagraphic Extreme Adaptive Optics), which is on-sky at the Subaru Telescope in Hawaii (Lozi et al. 2020), and SOUL (Single conjugated adaptive Optics Upgrade), which is undergoing commissioning at the LBT in Arizona (Pinna et al. 2016). TRL details: Demonstration of visible-light AO has been achieved in a laboratory environment, but at wavelengths only into the red and at lower Strehl numbers. Work is on-going to assess, demonstrate and optimize on-sky performance at large ground-based telescope facilities.	- Developing optics (i.e., PIAA lenses) for reshaping the beam into a Gaussian shape with minimal loss of light, allowing for theoretical coupling efficiencies close to 100% (see, e.g., Jovanovic et al. 2017a); - Removing non-common path aberrations; and - Identifying the optimal method for maintaining fiber coupling and positioning (e.g., with tip/tilt, nodding, or other methods); - Development of high throughput, broad wavelength coverage Atmospheric Dispersion Correction optics; - Optimization of performance of fiber optics for broad wavelength operation in single mode; - Optimization of low loss fiber optics switchyards and automated attenuators for Laser Frequency comb control; - Development of advanced photonic lanterns, multi-core fibers, few mode fibers (with appropriate DM-based scrambling techniques) to improve light capture efficiency in low Strehl regimes, while conserving single-mode output properties (or equivalent). Strehl ratio improvements can be accomplished by: - Reducing the fitting error of the wavefront with a high number of actuators and more stroke in deformable mirrors; - Wavefront sensor choice/development for reduced noise characteristics; - Latency reduction through judicious choice of real-time controllers (both firmware and processors). Up to 2 kHz is a reasonable present-day assumption; - Automated parameter correction for adaptive/predictive control (for large apertures); - High-precision NCPA compensation algorithms using single-mode fiber output; - High-precision high-speed acquisition and tracking methods for drift compensation and tip-tilt jitter control. Single-mode fiber polarization improvements: An advantage of using single-mode fibers for illumination is their spatial stability in illumination, which overcomes the 'modal-noise' that must be suppressed in the multimode fibers. However, two polarization states in SMF remain and must be controlled in order to avoid polarization noise in an EPRV system (Halverson et al. 2015; Bechter et al. 2020). Therefore, polarization mitigation in SMF needs to be developed. May need technology to enable required sky coverage.

Precision calibration for extreme-precision radial velocity spectroscopy	Extreme-precision radial velocity (EPRV) spectrographs require accurate and precise calibration in order to achieve the ability to detect and measure the mass of Earth-mass planets around sun-like stars. And, the calibration must be traced to an absolute standard.	Classically, RV spectrograph calibration has relied on atomic hollow cathode lamps (HCL), molecular absorption cells (e.g., I2) and etalons with wavelength reference for precise wavelength determination. However, these methods have a variety of shortcomings when pushing towards the highest precisions, and have usually been limited at the ~1 m/s RV precision level on-sky. More recently, broadband optical laser frequency combs (LFCs) have been developed for the highest-precision RV applications. LFCs intrinsically produce a uniformly spaced, dense grid of laser lines, each with a frequency known to better than 10^{-12} fractional accuracy. LFCs represent the pinnacle of RV calibration systems, providing wide bandwidth calibration at levels of precision far better than those set by other instrument systematics. Commercial designs (e.g., Menlo Systems) employ mode filtering of amplified, low repetition rate (~100–200 MHz) fiber combs through a series of 3 Fabry-Perot filter cavities, thus eliminating ~99% of the comb lines to achieve the sparse line spacing (10–30 GHz) needed to match typical EPRV spectrograph resolutions (R > 100,000). But these Astrocombs are highly complex devices that require significant engineering efforts to make them 'turn-key' and suffer from several drawbacks. These devices are relatively expensive (~$1M), and have yet to demonstrate both long-term operability at the observatory and reasonable performance at wavelengths blueward of 500 nm. Furthermore, these systems require periodic maintenance to replace consumable components, such as the photonic crystal fiber (PCF) that enables spectral broadening of the combs, compounding the high costs. NIR astrocombs have been implemented (Metcalf et al. 2019) and operating nearly continuously for years (Frederick et al. 2020). However, broadening NIR combs into the visible range with 10–30 GHz line spacing is challenging because at these high pulse repetition rates, it is difficult to achieve the threshold pulse energies needed to realize the non-linear optical effects without substantial pulse amplification. Broadening well into the blue-visible has been demonstrated with low repetition rate combs. Thus, exploring methods for reducing the line density of such combs using, for example, pulse rate multiplication (Haboucha et al. 2011) is an interesting avenue. Fabry-Perot etalons are also being used as spectrograph calibration sources for on-sky observations, HPF (Terrien et al. 2021), ESPRESSO (Schmidt et al. 2021), HARPS (Wildi, Chazelas & Pepe 2012), CARMENES (Bauer, Zechmeister & Reiners 2015), and MAROON-X (Stürmer et al. 2016). TRL details: Other methods of achieving reliable visible band, 10–30 GHz repetition rate LFCs for EPRV applications are being investigated by multiple groups; most of these approaches involve nonlinear spectral broadening and second harmonic generation of NIR frequency combs generated through either electro-optic modulation (EOM) of a CW laser, or in high-Q disk or ring microresonators through nonlinear optical processes – so-called Kerr microcombs (Del'Haye et al. 2007; Kippenberg, Holzwarth & Diddams 2011), or a combination of both, i.e., pulse-pumped microcombs.	• EPRV spectrograph calibration source must have spectral coverage from 380 nm through 930 nm, with line spacing in the 10–30 GHz range, and uniform intensity across the full bandpass that can be matched to the intensity of the stellar target. Wavelength coverage further into the infrared can further stellar variability mitigation. • Fractional frequency stability should be better than ~3×10^{-11} over ~100 s integration times or longer, corresponding to an RV accuracy of 1 cm/s. • The power per mode variation across the comb spectrum must be spectrally "flattened." Flattening is typically achieved using spatial light modulator (SLM) technology. Develop arrayed photonic waveguide devices to flatten the spectrum at reduced volume. • Develop etalon technologies that leverage fully single-mode operation, have broad wavelength coverage that extends into the blue (<500 nm), are contained in a compact design that is easily thermally stabilized, provide high line brightness and good uniformity, and are referenced to a proven frequency standard. • Develop advanced hybrid comb-etalon concept based on crystalline CaF_2 and MgF_2 whispering gallery mode (WGM) resonators that may overcome some of the challenges of traditional FP etalons. • Calibration sources must be robust, long-lived, stable over years, and fiber-coupled for instrument interface.