The 2024 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: - Stable Mirrors - Stable Structures - Thermal Sensing & Control System - Ground Support Technology: Metrology - Mirror Rigid-Body Actuators - Mirror Baffle Assembly - Ground Support Technology: Gravity Sag Offloader - UV Coatings: Wavefront Effects

		- Ground Support Technology: Characterization of Thermal Expansion Characterization
Segmented-Pupil Coronagraph Contrast and Efficiency in Visible Band 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 across the wavelength range 400-1000 nm.	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:4.2×10^{-8} raw contrast in 10% band 2-13 λ/D (PAPLC demo in HiCAT)	Maximized science yield in imaging and spectroscopy for a direct imaging telescope/mission. Assuming a ~6m space telescope, this implies ≤ 10^{-10} raw contrast, >30% core throughput, inner working angle ≤ 3 λ/D, outer working angle >= 45 λ/D [TBD], 20% bandwidth; obscured/segmented pupil Sub-gaps that could partially or fully close this gap: - Small Inner Working Angle Single-mode Coronagraph - Starlight Suppression Optics - Deformable Mirrors - WFSC - High-contrast Spectroscopy - Computational Throughput on Space-rated processors
Coronagraph Contrast and Efficiency in the Near Infrared 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 across the wavelength range 1-2 microns.	JWST NIRSPEc typical performance 1.0×10-4 raw contrast (no wavefront control), after post processing 10-5 at ~2 lambda/D, 3×10^{-8} > 30 λ /D JWST MIRI 1.0×10^{-4} raw contrast working angle 2 λ/D (4-5 micron wavelength) Ground based 1.0×10^{-5} raw contrast at 8 λ/D working angle (Gemini Planet Imager wavefront control for atmosphere correction)	R~40 spectroscopy in the infrared between 1 and 1.8 micron wavelengths [TBD] for a direct imaging telescope mission. ~1×10^{-9} flux ratio at the detector; >30% core throughput, inner working angle ≤ 2 λ/D at 1.6 micron; 20% bandwidth; obscured/segmented pupil
Coronagraph Contrast and Efficiency in the Near Ultraviolet 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 across the wavelength range 200-400 nm.	None	R~7 spectrophotometry in the near ultraviolet between 200 and 450 micron wavelengths for a direct imaging telescope/mission. ≤ 1×10^{-10} raw contrast, >20% core throughput, inner working angle ≤ 10 λ/D at 200 nm, 20% bandwidth; obscured/segmented pupil.

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: - Tuned Mass Damping - Edge Sensor - PM-SM-Instrument Bench Metrology - Wavefront Sensing for segment phasing & alignment - Out-of-Field WFS - Low Disturbance Systems: Active & Passive Isolation, Microthrusters, low-disturbance cryo-cooler - Control Algorithms
Integrated Modeling: Multi-Physics Systems Modeling, Uncertainty Quantification and Model Validation The capability to perform accurate and precise integrated modeling for a telescope/coronagraph system.	Self-assessed model TRL with respect to likely HWO requirements as of summer 2024. For model validation & fidelity of uncontrolled WFE predictions: TRL 9 for microns WFE TRL 9 for 15nm WFE (JWST) TRL 5-7 expected for 1-5 nm ground , 1nm flight (once Roman completes I&T and flight commissioning) TRL 5-7 transient time constants (JWST, to be improved by Roman) TRL 1 for pm/sub mK residuals post control	Automate Integrated Modeling Pipeline o Improve the modeling efficiency to reduce the modeling cycle time from the current norm of ~6 months, including parallel multi-processor options, and interoperability for end-to-end sensitivities, control and design optimization. o Investigate parallel processing capabilities of large model size (>> 10M dofs) and reduced model methodologies o Investigate surrogate modeling techniques to gauge improvements in modeling turnaround time and impact to prediction accuracy. o Identificaty and eliminate of tools that severely limit parallel predicitive multi-physics model execution due to license constraints or other costs, and replace with less restrictive tools. o Identify and adopt shared, platform-independent deployment environment of multi-physics IM codes, that are extensible over the 20-30 year span of the flagship missions.

	Ability to predict and validate starlight suppression models at HWO levels (~10^{-12}) TRL 6 for static raw coherent contrast (10^{-8}) with validated Roman CGI model through TVAC validation TRL 2-3 for Static Raw Contrast (SOA 10^{-9} w/ Shaped Pupil and Hybrid Lyot masks, to be evaluated for HWO mask)) TRL 1 for Contrast Stability (no demo of contrast stability has been performed, let alone model validation) Ability to accurately quantify model uncertainty TRL 5-6 for 50nm/5mas stability JWST demonstrated flight performance within predictions + Model Uncertainty Factors (MUF)s for Thermal/Thermal Distortion at ~15nm. Jitter was harder to evaluate as cryocooler and reaction wheel jitter were not studied in depth on orbit, but data suggest predictions were over conservative. Microdynamics and Segment/Wing tilts were not included in pre-launch analyses. WF stability issues due to workmanship of harness rogue paths and MLI tensioning weren't identified on JWST until the OTIS cryo vac tests at JSC. While fortunately none of these affected JWST's ability to meet requirements because of a robust margin, the risk remains in future missions. Roman/CGI may provide better opportunities for model validation and uncertainty quantification assuming they are adequate provided engineering time to collect the required flight data. TRL 1 for pm, /sub mK residuals post control, 10^{-12} contrast stability The other identified IM gaps, such as interoperability, multi-domain sensitivity and optimization, uncertainty quantification methods in general are at low to mid levels of development maturity for HWO. Standard IM practices support modeling cycles on order of 6 months and require large-scale Monte Carlo studies or engineering	o Investigate how AI/ML can improve the IM and Systems Engineering process. Develop and demonstrate Uncertainty Quantification methods to bound known and unknown probabilistic error forms o Develop an alternative to Monte Carlo techniques to derive MUFs (Model Uncertainty Factors). o Apply UQ and statistical methods to the process of robust margin estimation. o Demonstrate how UQ can help optimize design options and avoid over-designing by relying on worse-case simulations. Collaborate with other Technology threads on testbed model validation o Formulate Model Validation success criteria commensurate with the modeling discipline's intended use on HWO and demonstrate model validation on technology testbed to within acceptable level of uncertainty. Domains of interest are those affecting oberservatory stability at the pm, mK, mas, 10-12 levels: transient thermal, thermal distortion, structural jitter, vibration isolation or control, line-of-sight pointing and control, system and coronagraph wavefront sensing and control, starlight suppression, speckle post processing. Includes defining the level of allowable uncertainty between test data and model predictions. o Validate the limits of prediction accuracy capability at the pm-level on testbed models and verify sensitivities and the quantified model uncertainty for robust error budgets. o Demonstrate the practice of over-drive testing to validate models at levels higher than the intended application when there are performance limits in the infrastructure or with the test metrology. Investigate whether there is loss of predictiive accuracy to within acceptable uncertainty. o Improve model updating methodologies from test data to improve on model validation outcomes. Investigate cross-discipline model validation and updating techniques (e.g. update thermal distortion model based on coronagraph or WFE measurements, when there are insufficient local measurements of temperature or thermal distortions) Develop and define model standards

	judgement to define model uncertainty factors. Current models and coronagraph testbeds diverge at a few*10^{-10} level.The DOE Sandia tools Dakota/PCMM are being demonstrated on the Mars Sample Return Entry Descent and Landing flight mechanics IM, but these have never been applied to IM for large precision NASA observatories and would be at TRL 2-3 for HWO by NASA flight standards. JWST & Roman/CGI represent the state-of-the-art of Multi-Physics Systems IM for large astrophysics observatories. The authors of this paper are the Systems Modeling leads for these missions and have first hand knowledge of existing modeling capabilities and limitations, model validation and uncertainty quantification accomplishments, including JWST flight model validation and IM lessons learned (Levine & Mosier, keynote SPIE 2023).	o Define requirements on model formulation, verification and validation, including documented credibility assessment upon delivery of flight models, with the same level of rigor as delivery of flight hardware. o Demonstrate the numerical limits of prediction accuracy capability at the pm-level. Incorporate in models all physics which otherwise are approximated (eg nonlinearities) to gauge range of predictions. Perform model discretization convergence studies.
Vis/NIR Detection Sensitivity The capability to detect single photons in the Vis and NIR to enable imaging and spectroscopy of Earth-like exoplanets.	Visible The Nancy Grace Roman Space Telescope (Roman) Coronagraph Instrument (CGI) will fly EMCCDs. EMCCDs are TRL8 for Roman CGI requirements today. 1k×1k (in frame-transfer mode) 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 Roman Coronagraph Instrument Photon Counting Mode) after irradiation when cooled to 165.15 K (Roman; Morrisey et al 2023); 4k×4k EMCCD fabricated. Single Photon Sensing and Photon Number Resolving silicon CMOS image sensors are now in commercial production in formats from 1 to 163 Mpixel. They have a dark current <0.002 e-/pix/s at T~230-250 K, 0.2 e- read noise, 90% peak QE at 500 nm with sensitivity from 200	Near IR (roughly 900 nm to 2.5 μm) and visible-band (roughly 400-900nm) extremely low noise detectors for exo-Earth spectral characterization with spectrographs or intrinsic spectral resolution with quantum efficiency, QE>90% across all wavelengths for all modes on the focal plane. The boundary between visible and near-IR is not fixed. Depending on the visible detector that is used, the visible could be extended to include an exoplanet H2O vapor feature at 940 nm. NIR Read noise < 0.15 e- rms for photon counting, spurious count rate (dark current+glow) < 0.001 e-/pix/s, Vis band read noise < 0.15 e- rms for photon counting; CIC < 3×1e-3 e-/px/frame; dark current < 1e-4 e-/px/sec , all performance requirements met at end of life (5 year mission requirement; 10 year goal); large ≥ 2k×2k format is the minimum format for a R~50 spectrograph for likely bandwidth and FOV. Spectrally resolving detectors need fewer pixels (≥10k) to achieve imaging and spectroscopy goals, with spectral resolving power R=150 at λ=760 nm and R=200 at λ=1590 nm).

	nm – 1100 nm. The read noise is effectively unchanged after irradiation of up to 10 mission lifetimes (50 krad(Si)), and the dark current increase can be brought back to beginning of life levels with modest additional cooling, i.e. ~5 K for a single mission lifetime. Thick, large format, fully depleted, p-channel “Skipper” CCDs successfully count photons using non-destructive readout with ultra-low dark current, although the readout time needs to be reduced for use in space. Multi-Amplifier Sensing CCDs (MAS-CCD) promise shorter readout times. These are entering test now. Small format SiSERO sensors have also demonstrated photon counting capabilities with non-destructive readout at significantly higher speeds than skipper-CCDs, further development and readout optimization of large format SiSERO still needs to be done before use in space. Near Infrared Megapixel format HgCdTe near-IR arrays are proven, mature flight technology. 2k×2K format devices are TRL9 for JWST and Euclid. Conventional HgCdTe photodiode arrays have read noise ≲ 2 e- rms with multiple nondestructive reads; 4k×4k format (Roman WFI; TRL8); dark current < 0.001 e-/s/pix; very radiation tolerant (JWST), high QE down to 600 nm (JWST & Roman); HgCdTe LmAPDs demonstrated a spurious count rate dominated by ROIC glow at 0.01 e-/frame (Bottom et al 2024 in prep), RN ~ 0.5 e- CDS and 1k×1k format with 15 micron pixels. Spurious count rate and read noise can be traded to some degree. Low Temperature Detectors Superconducting photon-counting detectors (SNSPDs): . spectrally-resolving detectors (MKID,TES): 0 read noise/dark current; MKID space radiation tolerance not systematically studied; MKID Exoplanet Camera (MEC) on Subaru is 140x146 format (Walter et al 2020); TESs	Sub-gaps that could partially or fully close this gap: - NIR Low-noise Detector - UV/VIS Low-noise Detector - Noiseless Single-photon Detectors for NIR/VIS

	have sounding rocket heritage, demonstrated radiation hardness/vibe/aging, and demonstrated spectral resolution R=90 in visible (R=3000 in x-ray)	
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) and ~60 cm/s over a month (Zhao et al. 2023). 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 the masses of temperate, Earth-mass exoplanets over several orbital periods. The radial velocity semi-amplitude of a Solar-mass star due to an orbiting Earth-mass planet at 1 AU is 9 cm/s. Capability to maintain the stability of an EPRV instrument and its absolute calibration over decade-long time scales. Theoretical understanding of astrophysical noise sources (stellar variability) and how to mitigate them at a level commensurate with detecting temperate, Earth-mass planets around Sun-like stars. Technology sub-gaps that could partially or fully close this gap: - Tailored high performance detectors for high-resolution, cross-dispersed spectrographs - High-Precision, High-Throughput, High-Spectral Resolution Dispersive Optics - Advanced Photonics for EPRV spectroscopy - Ground-based, Visible-light Adaptive Optics - Precise, stable, and reliable calibration sources 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 microacrseconds on bright targets after all systematics are calibrated Demonstration (Bendek) of diffractive pupil showed 1.58×10^{-5} λ/D or 0.75 microarcsecond on a Hubble class telescope Preliminary study of 1-m space telescope and instrument with in-situ detector calibration can achieve 0.8 micro arcsecond in 1 hr.	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 Theoretical understanding of astrophysical noise sources (star spots) and prospects for mitigating them.
Starshade Deployment and Shape Stability	Manufacture/deploy accuracy, shape stability and shape error over temperature are all demonstrated to 3σ maximum expected levels consistent with 5×10^{-11}	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-

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.	contrast, for the Roman telescope sensitivities at 1.5 λ /D IWA.	diameter starshade; tolerances scale roughly linearly with starshade diameter), and be optically opaque. Performance goals are under re-evaluation for Habitable Worlds 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 12% bandpass in the visible using 24 mm starshade in Princeton testbed with F = 13. Optical model of starshade perturbations validated to within a factor 1.25 for petal shape and factor of 2 for petal position. Etched amorphous metal edges with anti-reflection coating demonstrated to meet scatter specs with margin; integrated in-plane shape tolerance demonstrated. Remaining tests to validate low scatter and in-plane shape simultaneously.	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 a factor of 2. 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) ~30. Performance goals are under re-evaluation for Habitable Worlds 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/cm2/s; QE: 75% ; Resolution size ≤ 10 mm; 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 terrestrial exoplanets in the Habitable Zone of M-dwarf stars.	JWST/MIRI is expected to achieve 30-50 ppm transit stability. Spitzer IRAC Si:As detector data have demonstrated about 60 ppm precision in transit observations of several hours. Lab demonstration of TES bolometers achieving < 5 ppm over 6 hours.	Ultrastable detectors (< 5 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.

ExEP Sub-Gaps

Subgap Name	Description	Current State-of-the-Art	Performance Goals and Objectives
Small Inner Working Angle Single-mode Coronagraph	The Habitable Worlds Observatory will need a small inner working angle (IWA) to see 25 terrestrial exoplanets. Most exoplanets discovered so far lie closer to their host stars than typical coronagraphic IWAs of a few lambda/D. Single-mode cross-aperture nulling interferometry can observe to within about 0.5 lambda/D, so can be used to extend HWO's either to smaller angles, or to longer wavelengths	1. E. Serabyn, B. Mennesson, S. Martin et al., "Nulling at short wavelengths: theoretical performance constraints and a demonstration of faint companion detection inside the diffraction limit with a rotating-baseline interferometer," Mon. Not. R. Astron. Soc. 489, 1291–1303 (2019). 2. D. Echeverri, J. W. Xuan, J. D. Monnier et al., "Vortex Fiber Nulling for Exoplanet Observations: First Direct Detection of M Dwarf Companions around HIP 21543, HIP 94666, and HIP 50319," Astophys. J. Lett. 965, L15, 1-9 (2024). 3. E. Serabyn, K. Liewer & G. Ruane, "A geometric-phase-based phase-knife mask for stellar nulling and coronagraphy," Opt. Exp., 32, 19924 2024	A capability to observe inside the inner working angle of standard coronagraphs, potentially to within about 0.5 lambda/D. This can potentially be used to extend HWO's observational capabilities either to smaller angles, or to longer wavelengths. Such cross-aperture nullers have been demonstrated on sky, but at worse contrast than needed for HWO, so the TRL is likely 3, except that full on-sky systems have also been demonstrated. The main goals are thus to push the contrast down at these very small angles, and to extend performance to longer (i.e., NIR) wavelengths
Tuned Mass Damping	Actively tunable, broadband, structural vibration suppression capability is needed for reducing dynamic wavefront error during observations made by HWO, and reducing the settling time during transient slews to new targets and while digging the dark hole with the coronagraph. Active tuning enables on-orbit adjustments when errors in predicted behavior are discovered. Broadband reduces the sensitivity to resonant mode frequency predictions. As telescopes get larger, operate at shorter wavelengths, and incorporate starlight suppression systems (e.g., coronagraph), WFE and LOS requirements tighten. JWST and HWO have segmented primary mirrors for deployment and quasi-static WFE control. While JWST is infrared with ~10 nm WFE, HWO is NIR-Vis-NUV requiring ~10 pm WFE. Filling this gap complements the traditional use of 2-stage isolation on JWST and RST by actually removing the vibration energy from the structure.	Tuned Mass Dampers (TMDs) have flown on spacecraft (TRL-9). They provide high, narrow band damping when tuned to a single model (e.g., solar array bending). Tuning requires accurate knowledge of the resonant frequency and separate TMDs are needed for each resonant mode. Knowledge of the frequency to within the half power bandwidth of a lightly damped resonance is difficult to estimate prior to launch. On-orbit tunability (either automated or via ground) would help but is at TRL-4. Active vibration suppression has been developed for multiple applications: launch load alleviation through Soft-Ride (TRL-9), NASA's Control of Flexible Structures program (COFS) (TRL-5), the Middeck Active Control Experiment (MACE) on STS-67 and ISS Expeditions 1 & 2 (TRL-6). AFRL has also developed active isolators (TRL-6?). These technologies are either too immature, too sensitive to modeling errors, or have insufficient suppression capabilities relative to the three orders of magnitude needed for HWO. • Grocott, et al, "Robust Control Design and Implementation on the Middeck Active Control Experiment (MACE),"AIAA Journal of Guidance, Control, and Dynamics, Vol. 17, No 3., pp. 1163-1170, Nov-Dec 1994. • Bronowicki, "Vibration Isolator for Large Space Telescopes," Journal of Spacecraft and Rockets, Vol. 43, No. 1, Jan-Feb 2006. • Chey, "Semi-Active Tuned Mass Damper Building Systems: Design," Journal of the International Assoiciation for Earthquake Engineering, 9-June-2009. • Tuttle, Seering, "Vibration Reduction in Flexible Space Structures using Input Shaping on MACE: Mission Results," IFAC Proceedings, Vol. 29, Issue 1, June-July 1996, pp. 1500-1505 • Moog Soft Ride: https://www.moog.com/products/vibration-suppression-control.html	The goal is to ensure that the requisite ~10 picometer wavefront stability of HWO can be achieved. For HST, JWST, and RST, the dominant dynamic disturbances are from reaction wheel imbalances, solar panel modes, cryocoolers and microdynamic snap due to deployment stresses and thermal transients. Fortunately, their sources are predominantly on the spacecraft side of the telescope-bus isolator. For HWO, primary mirror segment adjustments are estimated to introduce tens of nanometers of transient dynamic motion on the telescope side of the isolator. And, given the tighter WFE requirements of HWO, will need to adjust more often than JWST. As telescopes get larger, their inertia grows making them more difficult to slew. Reaction wheels and control moment gyros introduce too much vibration at short wavelengths requiring softer isolators and lower torque devices (e.g., electric thrusters) causing longer slews that reduce science. Furthermore, using a barrel instead of a sunshade will likely create more thermal transients during slew. As of yet, the gap of active vibrational energy removal has not been an available tool to solve these issues.
VIS Low-Noise Detector		Array format: CGI EMCCD is 1k x 1k in frame transfer mode; 4k x 4k has been manufactured Read noise: EMCCD ~effectively zero, sCMOS < 0.3 e-, Skipper CCD < 0.2 e-/frame (400 reads) Spurious/Dark count rate: EMCCD @165K ~ 7e-4 e-/p/s, sCMOS @238 K < 4e-3 e-/p/s, Skipper CCD <5e-8 e-/p/s Clock-induced charge: EMCCD ~0.01 e-/p/s	EMCCD, Skipper/MAS CCD or CMOS, SiSeRO CCD, SPS/PNR CMOS Array format: >2k x 2k buttable 1k x 1k (for spectroscopy) Read noise: <0.15 e- (correlated double sampling) Spurious/Dark count rate: <1e-4 e-/p/s Clock-induced charge: <3e-3 e-/p/frame QE: > 90% at specified wavelengths (~>950 nm) Lifetime: stable performance over 5 years after exposure to radiation environment.
NIR Low-Noise Detector		Array format: H4RG 4k x 4k three-side buttable, LMAPD 1k x 1k Read noise: H4RG < 2e-, LMAPD ~0.5 e- Spurious/Dark count rate: H4RG 1e-3 e-/p/s, LMAPD 1e-2 e-/p/frame QE: Lifetime: H4RG is radiation hard Operating Temp: H4RG ~90 K (Roman)	H4RG, HgCdTe LM-APDs Array format: >2k x 2k buttable 1k x 1k (for spectroscopy) Read noise: <0.15 e- (correlated double sampling) Spurious/Dark count rate: <0.001 e-/p/s QE: > 90% at specified wavelengths (~>950 nm) Lifetime: stable performance over 5 years after exposure to radiation environment. Operating Temp: > 70 K

Noiseless Single-photon Detectors for UV/VIS		Array format: QE: MKID ~70% @ 0.4 um, ~40% @ 1.0 um at 0.1 K; TES ~97% at 0.05 K Lifetime: R (if energy resolving): TES ~4	TES, MKID, SNSPD Array format: for TES & MKID energy resolving, 1k x 1k is sufficient, otherwise > 2k x 2k for spectroscopy QE: > 90% at specified wavelengths (~>950 nm) Lifetime: stable performance over 5 years after exposure to radiation environment. R (if energy resolving): ~200 for NIR, ~140 VIS
Stable Mirrors		Stiffness: <5 nm surface deformation uncertainty due to gravity Areal Density: 10 kg/m2 (MMSD, ULE) Surface Figure Error: 8 nm RMS (MMSD, ULE) Surface Roughness: Edge Roll-off: CTE Knowledge: Thermal Sensing & Control: Operating Temperture: 265-293 K	ULE, Zerodur Stiffness: <0.1 nm surface deformation uncertainty due to gravity Areal Density: <17 kg/m^2 Surface Figure Error: Surface Roughness: <5 Å RMS, <2% variation at TBD spatial frequency Edge Roll-off: < 1 mm CTE Knowledge: Thermal Sensing & Control: Operating Temperature: 270-293K
Stable Structures		Component Interfaces: CTE Control: <1e-8 strain/K CME & Creep Control: <1e-10 strain/hour Verification & Test: Thermal Sensing & Control: <1 mK variation achieved in lab environment Modeling & Validation: <5 nm structure deformation uncertainty due to gravity	Component Interfaces: Accommodate metrology & sensors; stable mount for mirrors CTE Control: <1e-9 strain/K uncertainty; prefer post-fab tuning methods to manage scrap rate CME & Creep Control: Method needed to enalbe dryout/energy release during early phase of mission; Facilities & methods to generate long-term drift for creep characterization; More comprehensive material data database. Verification & Test: Verification of flight piece-parts to required uncertainty; verification of sub-assembly stability performance. Modeling & Validation: <0.1 nm structure deformation uncertainty due to gravity; Need facility and metrology to test JWST-like BSTA to picometer level.
Thermal Sensing & Control System		Sense & Control Error: <1 mK	Sense & Control Error: sub-mK expected Rate: 0.5-1 Hz thermal sensing and control for 100s of sensors Component Interface: Low-distortion-inducing temperature sensors & heaters, including cable management; High-conductance heat-transfer materials (i.e. pipes & straps, etc.) Electronics noise: Low Can trade mirror thermal mass against sensing & control speed.
Metrology		Surface Metrology: Radius-of-Curvature Matching:	Surface Metrology: Radius-of-Curvature Matching: GSE capability for in-process metrology
Mirror Rigid-Body Actuators		Stroke: >20 mm achieved with JWST mechanical actuators Coarse Precision: <10 nm with JWST mechanical actuators Fine Precision: PZT actuators < 1pm with 100g mass; < 100 pm with PMSA-like mass Aboslute deployed positioning: JWST mechanical acutators with ~7 mm gaps	Solid-state, mechanical, hybrid, PZT walker, PZT or PMN flexure. Stroke: +/-5 mm Coarse Precision: <1 um Fine Precision: < 1 pm Absolute deployed positioning: enable 4-6 mm physical gaps between segments
Low Disturbance Systems: Active & Passive Isolation, Microthrusters, low-disturbance cryo-cooler		Disturbance free payload hardware is ~TRL4 with respect to HWO, and microthrusters have been used on missions with different requirements than HWO. Low/No-disturbance cryo-coolers require characterization and evaluation for impact to coronagraph performance.	Active & Passive Isolation, Microthrusters, low-disturbance cryo-coolers ~40 dB isolation / suppression of disturbances > 1 Hz
Mirror Baffle Assembly		JWST sunshield represents state-of-the-art deployable membrane	Deployable Membrane Robust to micrometeoroids, low complexity deployment, low thermal impact on OTE
Starlight Suppression Optics		Aperture Geometry: Most are theorectically compatible with segmented apertures with varying degrees of impact to performance. VVC4, PAPLC demonstrated with segmented aperture testbed; PIAA-CMC demonstrated with on-axis segmented aperture testbed. Instantaneous Spectral Bandwidth: ~10% routinely demonstrated, several limited demonstrations up to 20% with degraded contrast	CLC, HLC, VVC4, PAPLC, PIAA CMC, etc. Aperture Geometry: Compatible with segmented apertures; on-axis apertures enable larger overall diameter Instantaneous Spectral Bandwidth: >10%

		IWA: Nominal dark holes demonstrated 3-10 lam/D; PAPLC demonstrated to 2-13 lam/D; PIAA-CMC demonstrated to 3.5-8 lam/D Raw Contrast: VVC4 ~4.7e-8; PAPLC ~4.2e-8 (in air), PIAA-CMC~1.8e-8 Core Throughput: VVC4~0.4; PAPLC~0.5; PIAA-CMC~0.6 Simultaneous achievement of 1e-10 contrast, with > 0.3 core throughput at 3 lam/D with 20% bandpass has not been demonstrated.	IWA: <3.5 lam/D Raw Contrast: < 1e-10 Core Throughput: >0.3
Deformable Mirrors		Actuator Count: ~48x48 for both candidates Production Yield: Actuator Drift: PMN-based actuators are susceptible to this Mirror Surface Quality: MEMS technologies have surface errors limiting contrast to 1e-9 level Electronics / Connectorization: CGI DMs are state-of-the-art which had a large number of individual connectors for each DM Operating Temperature: 293K	Xinetics PMN, MEMS Actuator Count: 96 x 96 Production Yield: TBD Actuator Drift: TBD Mirror Surface Quality: Does not limit contrast at the 1e-10 level Electronics / Connectorization: Robust, low complexity Operating Temperature: 293K
Wavefront Sensing and Control		Contrast Stability: ?	Low-order, Out-of-band, High-order WFS Contrast stability: <3e-11 over temporal regimes consistent with HWO thermal & dynamic environment
High-contrast Spectroscopy		R: ?	IFS, Energy-resolving Detectors R: ~70 for VIS, ~140 for NIR Need to understand how contrast gain scales with spectral resolution and what impact speckle chromaticiy at the 1e-10 level has on continuum measurements.
NUV Starlight Suppression		Concepts from VIS coronagraph extend down to NUV, however, many questions pertaining to materials, coatings, scatter, etc. remain open. Starshade of appropriate scale for NUV is in-family with S5 program, however additional study needed to address questions on edges, contamination, and contrast for NUV.	Coronagraphy, Starshade Achieve R~5-7 high-contrast photometry between 250-450 nm to search for ozone features
Edge Sensor		Precision: Capacitive lab demo @3.6 pm RMS; Michelson laser gauge < 4pm; Heterodyne laser gauge <4-100 pm; Capacitive TMT @ 3 nm z, 136 nm gap; Inductive 6 nm z, 15 nm gap Temporal Bandwidth: Capacitive lab demo @100ms-1s; Michelson laser gauge 10ms - 5ks; Heterodyne laser gauge 15ms - 2s; Inductive 1-100 Hz, 500Hz sample rate; Capactive TMT @400Hz sample rate	Capacitive, Inductive, Laser Gauge (Michelson, Heterodyne), etc. Precision: < 1 pm preferred (<4 pm threshold) Stroke: +/-5 mm Temporal bandwidth: 1 ms - 10 ks preferred (100 ms - 600 s threshold)
Primary Mirror – Secondary Mirror – Instrument Bench Metrology		Precision: Heterodyne laser metrology < 1 nm; Frequency Tracking metrology TBD Temporal Bandwidth: ?	Laser Distance Gauge Precision: < 1 pm preferred (<4 pm threshold) Temporal bandwidth: 1ms - 10 ks (100ms -600s threshold)
Wavefront Sensing for Segment Phasing and Alignment		Accuracy: <1 nm RMS WFE (JWST phase retrieval) Capture Range: >1 mm Repeatability: <<1 nm	Phase retrieval, white-light interferometry, dispersed Hartmann/fringe sensor Accuracy: < 1 nm - 100 nm RMS WFE Capture Range: > 1 mm Repeatability: << 1 nm
Out-of-Field Wavefront Sensing		Accuracy: <1 nm RMS WFE Sensing Rate: TBD	Phase retrieval, speckle boiling Accuracy: <5 pm Sensing Rate: Segment piston/tip/tilt at 10-100 s; 3rd order SFE at 100-10ks
Control Algorithms		10 nm RMS stability with 0.1 Hz bandwidth	Loop-shaping, LQG, LMS, feedback/forward, command input shaping ~10 Hz, -3dB bandwidth to maintain in LOWFS capture range

Ground Support Technology: 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.
Ground Support Technology: 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) Demonstrate 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 $\lambda > 120$ nm; 20% reflectivity $\lambda < 120$ 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.
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	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-	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).

	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.	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.	
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 have 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 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, long readout times, readout noise, pixel-to-pixel efficiency variations, fixed-pattern-noise long- and short-term thermal stabilization, and deformation during readout. The corresponding RV errors are 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 detectors, there is concern that availability of these detectors may become challenging.	Current visible-light EPRV spectrographs use 9k by 9k or 10k by 10k CCDs with 9-10 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), which 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 at the m s^{-1} level. 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 provides larger formats but introduces gaps, edges, and seams and causes significant systematic irregularities. 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. Current generation IR detectors with potential improvements implemented during the development of RST have yet to be quantified in the context of EPRV.	● 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. ● 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. ● Use a combination of laboratory and on-sky testing to verify findings and demonstrate improved detector performance.
High-Precision, High-Throughput, High-Spectral Resolution Dispersive Optics	Ground-based EPRV spectrographs require echelle gratings with low wavefront error and high efficiency to maximize spectral stability, throughput, resolution, and bandwidth. EPRV instrumentation requires 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 the high spectral resolutions of R > 190,000 (potentially up to 300,000, see Palumbo et al. 2024) that may be necessary to detect and mitigate stellar granulation while preserving high throughput and high image quality. Desired specifications include: ○ Size (seeing-limited): ~200×1200 mm (width × length for the clear aperture at the blaze angle) ○ Size (diffraction-limited): ~50×200 mm (width × length) up to ~75x300 mm (width × length) for R > 190k designs ○ 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 (less than λ/8) across the aperture ○ Lower line density echelles (less than 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, and expensive and scaling them to the sizes required for the R > 190k resolutions recommended for detecting stellar granulation is a challenging and cost-intensive effort for seeing-limited instruments.	The recent generation of cross-dispersed, multi-mode fiber, RV spectrographs, EXPRES, NEID, ESPRESSO, and KPF are demonstrating intrinsic instrumental floors of ~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 (stellar activity mitigation), smaller size (more easily stabilized), and lower cost.	● Develop photonic spectrographs based on lithographically formed arrayed waveguide gratings (Jovanovic et al. 2017b), which would occupy a small fraction of existing RV spectrographs and potentially offer lower cost and simpler stabilization. ● Develop the use of photonic lanterns to convert a multimode fiber input into separate single mode fiber outputs which can then illuminate separate traces of a diffraction-limited spectrometer (Schwab et al. 2014; Mawet et al. 2019). ● Develop externally dispersed spectrograph designs (e.g., Van Zandt et al. 2019) that integrate interferometry with spectroscopy and potentially relax 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, 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, with peak H-band Strehl of >90% (GPI/Sphere/SCEXAO), peak K-band Strehl ratios of 65-85% on the Keck and Palomar telescopes, and peak Y-band Strehls of 60% on the Large Binocular Telescope. Comparable Strehl ratios at visible wavelengths have yet to be demonstrated, but MagAO-X has produced an on-sky Strehl of 60% at 900 nm (Males et al. 2022) with an eventual expected performance of 70% at Hα (656 nm) in median seeing conditions (Males et al. 2020). Additional 'extreme-AO' systems include SCExAO (Subaru Coronagraphic Extreme Adaptive Optics) on Subaru (Lozi et al. 2020) and SOUL (Single conjugated adaptive Optics Upgrade) at the LBT in Arizona (Pinna et al. 2019). TRL details: Demonstration of visible-light AO has been achieved in a laboratory environment, but only at wavelengths 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.	● Advance AO performance at 550nm towards Strehl ratios currently achieved in the NIR. ● Develop a visible band AO system with optimized fiber coupling capabilities to test new ways to increase coupling efficiency into an optical fiber while taking into account atmospheric dispersion correction (ADC) and PIAA pupil mapping. Such a system may require a testbed spectrometer to fully assess performance. ● Carry out a parametric study of AO system design as a function of aperture size, observing site (average seeing), spectral band, and target star magnitude to inform the design of EPRV-specific AO systems. ● Develop techniques to control and/or mitigate the two polarization states present in single mode fibers (Halverson et al. 2015; Bechter et al. 2020) to avoid contributions from polarization noise in a corresponding EPRV system

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). But they can suffer from significant chromatic drifts (Terrien+2021, Schmidt+2022) which complicates their long-term use as standalone calibrators, as well as methodologies that rely on a single frequency reference. 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.	● Develop wavelength calibration sources that span wavelength ranges commensurate with modern EPRV instruments (e.g. 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. 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. ● Develop capability to spectrally flatten the power per mode variation across the comb spectrum. Assess the viability of using arrayed photonic waveguide devices to flatten the spectrum at reduced volume compared to the current spatial light modulator approach. ● 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 calibration sources that are robust (>99% operational reliability), long-lived (life times of 10+ years), stable over years, and fiber-coupled for instrument interface.